Non-Orthogonal Multiple Access Assisted Secure Computation Offloading via Cooperative Jamming

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***Abstract*—In this paper, we investigate non-orthogonal multiple access (NOMA) assisted secure computation offloading under the eavesdropping-attack, in which a malicious node overhears the edge-computing user's (EU's) offloading transmission to the edge-computing server (ES), and NOMA is used for the EU's offloading and meanwhile for providing artificial jamming to the eavesdropper. Since multi-user simultaneous transmission over a same frequency channel can be enabled by NOMA, a wireless user (WU) can form a NOMA pair with the EU to provide cooperative jamming to the eavesdropper while also gaining an opportunity of sending its data. Focusing on the EU-WU pair with the fixed WU's energy-provisioning, we exploit the physical layer security to quantify the EU's offloading throughput with the help of WU's jamming. We then study the joint optimization of the EU's computation offloading and the EU-WU's NOMA transmission for minimizing the EU's total energy consumption subject to its latency-requirement in completing the computation-task. By utilizing the feature of analytical solution of the WU's transmission, we then investigate the WU's optimal energy-provisioning for the EU-WU pair, such that both the EU and WU can benefit from the cooperative jamming in a fairness manner. Specifically, we formulate the EU-WU's cooperation as a Nash bargaining game. By identifying the monotonic feature of Nash bargaining problem, we propose a polyblock approximation based algorithm for determining the WU's optimal energy-provisioning to achieve the win-win solution for the paired EU and WU. Finally, we investigate the scenario of multiple EUs and WUs, and aim at finding the stable pairing between the EUs and WUs, such that no individual EU (or WU) would like to change its partner. An efficient algorithm, which is based on the Gale-Shapley theory while exploiting the quantitative feature of EUs' and WUs' net-rewards, is proposed to achieve the stable EU-WU pairings. Numerical results are provided to validate our proposed algorithms and demonstrate the advantage of our proposed NOMA assisted computation offloading via cooperative jamming.**

***Index Terms*—Secure computation offloading, non-orthogonal multiple access, cooperative jamming, fairness and stable pairing.**

I. Introduction

THE past decades have witnessed an explosive growth of computation-intensive mobile services and applications, e.g., autonomous driving, unmanned and smart manufacturing, realtime video analytics, and augmented/virtual reality, all of which necessitate a cost-efficient approach to provide computation resources to vast wireless terminals with limited computation-units. Mobile edge computing (MEC), which deploys edge-computing servers (ESs) with sufficient computation/storage units at the edge of wireless networks, has been envisioned as a promising approach to address this requirement [1]–[3]. Because of the close proximity to the ESs, wireless terminals can actively offload their computation tasks to the ESs with short transmission latency and exploit the vast computation-units at the ESs for processing the offloaded workloads, which thus effectively reduces the overall latency in completing the tasks. The advantages of MEC have attracted lots of research interests, especially the joint management of task offloading and computation/communication resource allocation [4]–[15].

However, offloading computational tasks to the ESs via wireless channel may suffer from the potential eavesdropping-attack, in which a malicious node may intensionally overhear the offloaded data to the ESs by collecting and further decoding the radio signal in a brute-force manner. Such an eavesdropping issue has raised several research attentions regarding how to achieve a secure computation offloading [16]–[20], in which the theory of physical layer security (PLS) [21] has been adopted to quantify how much of the offloading transmission cannot be overheard by

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any malicious node from the information-theoretic perspective. In particular, artificial jamming has been exploited as an effective way to encounter the eavesdropping-attack [22], in which some helper-nodes provide artificial interference to the malicious user to reduce the channel capacity of the eavesdropping-path and thus mitigate the eavesdropping-attack. There have been some studies exploiting the artificial jamming for enhancing the secrecy of the offloading transmission [23]–[25]. However, using artificial jamming consumes additional radio resources, e.g., transmit-power, and many existing studies consider that the helper-nodes are voluntary in contributing the artificial jamming without requiring any compensation.

Non-orthogonal multiple access (NOMA) has been envisioned as one of the key schemes for enabling highly spectrum-efficient multiple access in future wireless networks [26], [27]. In NOMA, a group of wireless terminals can form a NOMA-cluster to transmit their data over a same frequency channel and adopt the successive interference cancellation (SIC) to mitigate their co-channel interference. Because of the great potential in improving the spectrum-efficiency and accommodating massive connectivity, there have been many studies leveraging NOMA for various wireless services, including content caching and transmission, machine-type communications, and integrated sensing and communications, wireless federated learning, etc [28]–[31]. The advantage of NOMA provides an efficient approach for enabling the multi-access mobile edge offloading [32]–[36].

In particular, NOMA enables a cost-efficient way for providing artificial jamming, i.e., the simultaneous transmissions of multiple users in a NOMA-cluster can provide beneficial jamming for each other to encounter the eavesdropping-attacks [37], [38]. Due to this feature, NOMA can be further exploited for secure computation offloading, in which NOMA is adopted for offloading tasks and meanwhile providing artificial jamming to the eavesdropper. Motivated by this idea, in this work we investigate NOMA assisted secure computation offloading, in which a malicious node overhears the edge-computing user's (EU's) offloading transmission to the ES (which is co-located with the cellular base station, BS). Meanwhile, a wireless user (WU) forms a NOMA-cluster with the EU to provide a cooperative jamming to the eavesdropper while gaining the opportunity of sending its data. Our key contributions can be summarized as follows.

- *(Single EU-WU pair with fixed WU's energy-provisioning):* We firstly consider that a WU forms a NOMA pair with the EU to provide a cooperative jamming to the eavesdropper while gaining the opportunity of sending its data to the cellular BS. Focusing on the EU-WU pair with the fixed WU's energy-provisioning, we exploit the PLS to quantify the EU's offloading throughput with the help of EU's cooperative jamming, and study the joint optimization of the EU's computation offloading and the EU-WU's NOMA transmission for minimizing the EU's total energy consumption subject to its latency-requirement in completing the computation-task.
- *(Optimized WU's energy-provisioning for win-win cooperation):* Exploiting the feature of analytical solution of the WU's transmission, we then investigate the WU's optimal energy-provisioning for the EU-WU pair, such that both the EU and WU can benefit from the cooperative jamming in a fairness manner. We formulate the EU-WU's cooperation as a Nash bargaining game [41]–[43]. By identifying the monotonic feature of Nash bargaining problem, we propose a polyblock approximation based algorithm for determining the WU's optimal energy-provisioning which can achieve the win-win solution for the paired EU and WU.
- *(Stable pairings for the multi-EU multi-WU scenario):* With the solution for each individual EU-WU pair, we finally investigate the scenario of multiple EUs and WUs and aim at finding the stable pairing between the EUs and WUs, such that no individual EU (or WU) would like to change its partner. An efficient algorithm, which is based on the Gale-Shapley (GS) theory [49] while exploiting the quantitative feature of the EUs' and WUs' net-rewards, is proposed to achieve the stable EU-WU pairings and meanwhile reduce the number of the total iterations for reaching convergence in comparison with the conventional GS algorithm.

II. Related Work

In this section, we review the related work from the following two aspects, i.e., the resource allocation for MEC and secure computation offloading via physical layer security.

- *(Resource allocation for MEC and energy efficiency):* Joint computation and communication resources allocations have been expected to play as a crucial role in reaping the benefits of MEC. Many studies have been devoted to optimizing the task-execution latency [12]–[15]. In [12], Ren *et al.* considered a multi-user computation offloading system with time-division multiple access, and proposed a joint communication and computation resource allocation for the latency-minimization. In [13], a joint optimization of computation offloading and interference management for minimizing the task-execution latency of all devices has been proposed for device-to-device enabled MEC paradigm. In [14], Feng *et al.* investigated the task partitioning and user association in an MEC system for minimizing the average latency of all users. In [15], a joint energy and latency cost minimization problem has been studied while satisfying vehicular node mobility and end-to-end latency deadline constraints. Driven by the concern on the rapidly growing energy consumption of information and communications technologies, energy efficiency of MEC has attracted lots of interests [5]–[11]. In [5], a joint optimization of task offloading and transmission/computation-time for minimizing the energy consumption for completing all tasks has been proposed. In [6], a multi-task multi-access computation offloading scenario is considered, and the authors proposed a joint optimization of computation offloading and NOMA transmission for minimizing the total energy consumption. In [7], the authors designed a metric of computation efficiency which is defined as the number of calculated data bits divided by the corresponding energy consumption, and further proposed a joint optimization of local computing and data offloading for maximizing the computation efficiency. In [8], Ale *et al.* proposed an energy efficient computation offloading with the awareness of latency by leveraging the deep reinforcement learning. In [9], Li *et al.* exploited dynamic voltage scaling for improving the energy-efficiency of task offloading. To further improve the efficiency of energy utilizations, several studies have been devoted to exploiting wireless power transfer for MEC [10], [11].

- *(Secure computation offloading via physical layer security):* Under the presence of eavesdropping-attack, the secure capacity based on the PLS [21] provides a fundamental measure of throughput which cannot be overheard by any malicious eavesdropper. In [16], Bai *et al.* exploited the physical layers security to study the secure computing offloading schemes for UAV-MEC systems. In [17], a design of energy consumption minimization of the edge-computing user subject to the eavesdropping-attack has been studied but without considering the cooperative jamming provided by the WU. In this work, the WU's jamming via NOMA transmission and the consequent design of win-win cooperation between the EU and WU are considered. In [18], a latency minimization problem subject to the eavesdropping-attack has been investigated, which jointly optimizes the users' transmit-power, computing capacity allocation, and user association. As mentioned before, the advantages of NOMA have attracted lots of attentions in exploiting NOMA for multi-user computation offloading. In [19], the authors considered a NOMA MEC scenario and adopted the secrecy outage probability to measure the secrecy performance of computation offloading under the eavesdropping-attack. However, the effect of cooperative jamming is not exploited. In particular, artificial jamming provides an effective approach for enhancing the secure throughput by intentionally sending interference (i.e., jamming) signal to the eavesdropper [22]. The multi-user co-channel interference in NOMA provides an efficient way to generate the artificial jamming and to lower the channel capacity of the eavesdropping-path [37], [38]. In [37], Zhao *et al.* proposed artificial jamming which is generated together with the legitimate information in NOMA transmission to disrupt the eavesdropping without affecting the legitimate transmission. In [38], cooperative interference under different paradigms of NOMA transmissions has been proposed for enhancing the secrecy. Due to this advantage of NOMA in providing artificial jamming, there have been some recent studies exploiting artificial jamming provided by NOMA for secure computation offloading [23]–[25]. In [23], Li *et al.* proposed a two-slotted structure for exploiting the cooperative interference between NOMA user pairs to enhance the security of offloading, in which the interference to the eavesdropper comes from the task signal and the jamming signal. In [24], Han *et al.* exploited the co-channel interference in NOMA and proposed an energy-efficient secure computation offloading for Internet of Things. In [25], conventional cellular users have been exploited for providing the artificial jamming to the eavesdropper via NOMA transmission. However, most of the aforementioned studies (e.g., [23]–[25], [37], [38]) consider that the helper-nodes are voluntary in contributing the artificial jamming without requiring any compensation for the additional energy consumption for providing artificial jamming. To the authors' best knowledge, it is still an open question regarding how to motivate the cooperative jamming in a NOMA-cluster such that different users in a cluster can benefit in a desirable manner (e.g., a fairness manner), and moreover, how to properly pair different users into NOMA-clusters for conducting the cooperative jamming. These motivate our study here.

III. System Model

Fig. 1(a) illustrates the system model considered in this paper. There exist a group of edge-computing users (EUs) denoted by $\mathcal{K} = \{1, 2, \ldots, K\}$, with each EU k aiming at completing a computation-task which is characterized by a tuple of $(S_k^{\text{tot}}, T_k^{\max})$. Parameter S_k^{tot} denotes the total computation-workload of EU k, and $T_k^{\max}$ denotes the corresponding latency-limit to complete this task. There is an ES which is co-located with the cellular BS and processes the offloaded computation-workloads from the EUs. We consider that each EU k adopts the partial offloading [4], [39], [40] and use $s_{(ik)} \in [0, S_k^{\text{tot}}]$ to denote its offloaded workloads to the ES. However, when each EU k offloads its data to the BS, there exists a malicious eavesdropper which intensionally overhears EU k's offloading transmission.[1]

We exploit NOMA transmission to encounter the eavesdropping-attack. Specifically, in our model, there also exist a group of wireless users (WUs) $\mathcal{I} = \{1, 2, \ldots, I\}$, with each WU i having a targeted data volume V_i^{req} to be delivered to the BS. As shown in Fig. 1(b) for a detailed pairing of EU k and WU i, EU k selects WU i to form a NOMA group for sending their respective offloaded workloads $s_{(ik)}$ and data-volume V_i^{req} to the BS.[2] In particular, we use the subscript (ik) in variable $s_{(ik)}$ to denote that EU k's offloaded workload depends on its selected WU i, which will be reflected in our following problem formulation in Section IV. Due to the feature of simultaneous transmission over a same resource block in NOMA, WU i not only gains the opportunity of sending its data volume to the BS, but also provides a beneficial jamming to the eavesdropper, which enhances the secrecy of EU k's offloading transmission. Nevertheless, it is a critical question about how much of the resource (e.g., energy consumption) WU i would like to devote to its data transmission to the BS as well as cooperative jamming to the eavesdropper, such that both EU k and WU i can satisfactorily benefit. To investigate this problem, we adopt a two-step approach. In Section IV and Section V, we firstly consider one pair of EU k and WU i with WU i providing a fixed energy-budget for cooperation, and we aim at minimizing EU k's total energy consumption for completing its task subject to its latency-limit as well as the eavesdropping-attack. Then, in Section VI, we further investigate how WU i can optimize its energy-budget such that both EU k ad WU i can simultaneously benefit. Finally, in Section VII, we extend our single EU-WU pair to the scenario of multiple EUs and WUs, and investigate how different EUs

[1] Due to the nature of broadcasting, the eavesdropper can collect the radio signal from the EUs and decode the data afterwards (e.g., in a brute-force manner).

[2] In this work, we treat the BS and ES interchangeably.

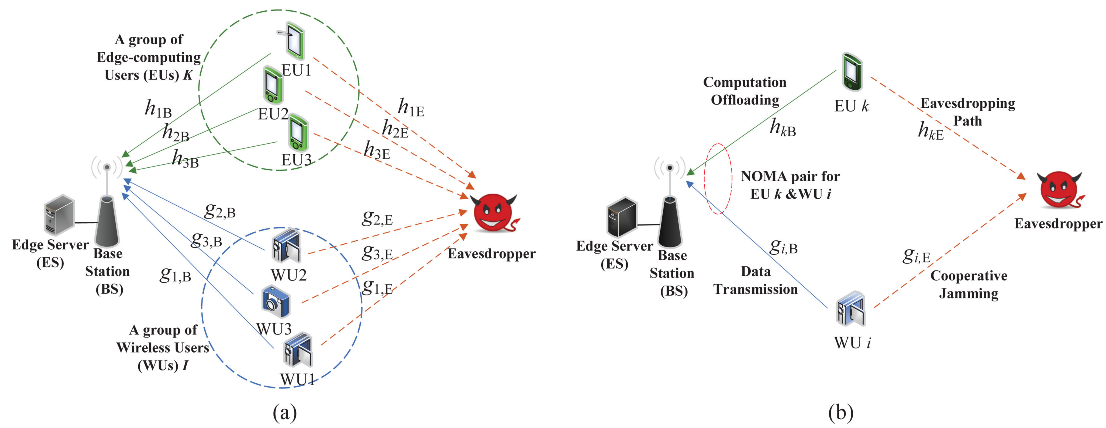

Fig. 1. System model considered in this work. (a) Illustrative scenario of 3-EU and 3-WU. (b) Detailed illustration of one pair of EU *k* and WU *i*.

can select different WUs for cooperative jamming, such that all EUs and WUs can achieve stable cooperations. We conclude this work in Section IX and discuss the future directions.

IV. Single EU-WU Pair With Fixed WU's Energy-Provisioning

As shown in Fig. 1(b), we firstly focus on a single pair of EU k and WU i which form a NOMA group for transmitting to the BS. EU k offloads its offloaded computation-workloads $s_{(ik)}$ to the ES, and WU i sends its data-volume V_i^{req} to the BS. In particular, in this section, we consider that WU i provides a fixed energy-budget $e_{(ik)}^{\text{bud}}$ for cooperation.

A. Modeling of NOMA Assisted Secure Computation Offloading

Regarding the pair of EU k and WU i (which is denoted by EU-WU pair (ik) in the following), we use $q_{(ik)}$ to denote EU k's transmit-power for its offloading transmission, and use $p_{(ik)}$ to denote WU i's transmit-power for sending its data to the BS (while providing cooperative jamming to the malicious node). Since the uplink NOMA allows an arbitrary decoding order in the SIC, we consider that WU i's is subject to the EU's interference and decoded prior to EU k. As a result, in this EU-WU pair (ik), we can express WU i's throughput as

$$R_{(ik)} = W \log_2 \left(1 + \frac{p_{(ik)} g_{i,\text{B}}}{n_\text{B} + q_{(ik)} h_{k\text{B}}} \right), \qquad (1)$$

where W denotes the channel bandwidth for each EU's computation offloading, $g_{i,\text{B}}$ denotes the channel power gain form WU i to the BS, $h_{k\text{B}}$ denotes the channel power gain from EU k to the BS (i.e., the ES), and n_B is the background noise power at the BS.

With the measure of physical layer security [21], we express EU k's secure offloading throughput in this EU-WU pair (ik) as:

$$R_{(ik)}^{\text{sec}} = \left[W \log_2 \left(1 + \frac{q_{(ik)} h_{k\text{B}}}{n_\text{B}} \right) - W \log_2 \left(1 + \frac{q_{(ik)} h_{k\text{E}}}{n_\text{E} + p_{(ik)} g_{i,\text{E}}} \right) \right]^+, \qquad (2)$$

where $[x]^+ = \max(x, 0)$, and $h_{k\text{E}}$ (and $g_{i,\text{E}}$) denotes the channel power gains from EU k (and WU i) to the malicious node, respectively. Parameter n_E denotes the power of the background noise at the malicious node. In this work, we assume that the eavesdropper is interested in overhearing the EU's offloaded data, while being not interested in the WU's data. For instance, the EU is executing a secrecy-sensitive task, while the WU is the conventional sensors which collect the secrecy-insensitive data from environment. Thus, we adopt (1) for the WU's throughput without considering the eavesdropping-attack, and adopt eq. (2) to quantify the EU's secure offloading throughput under the eavesdropping-attack but with the help of the WU's cooperative jamming to the eavesdropper. In particular, as a key feature of invoking SIC in NOMA, the BS can eliminate the WU's interference when receiving the EU's offloaded data, while enjoying the jamming effect (provided by the WU's interference) to the eavesdropper.

However, the exact values of $h_{k\text{E}}$ and $g_{i,\text{E}}$ are difficult to obtain, since the malicious node may intentionally hide its location. To address this challenge, in [18], [44], [45], a bounded uncertainty model is adopted for quantifying the channel power gains to the eavesdropper. Specifically, it is assumed that the eavesdropper will be occasionally active, and the EU thus can capture the signalling feature of eavesdropper and estimate the channel power gain to the eavesdropper but with a bounded error. In our work, we adopt the similar model by focusing on modelling the NOMA assisted cooperative jamming in computation offloading and quantifying the consequent benefits of both the EU and WU in this cooperative jamming. Specifically, similar to the modelings in [18], [44], [45], the value of $h_{k\text{E}}$ can be modeled to belong to an interval as $\mathcal{H}_\text{E} = \{h_{k\text{E}} || h_{k\text{E}} - \tilde{h}_{k\text{E}}| \leq \delta\}$, where $\tilde{h}_{k\text{E}}$ denotes the expectation of $h_{k\text{E}}$ and δ denotes the deviation of the estimation. Similarly, the value of $g_{i,\text{E}}$ is modeled to belong to an interval $\mathcal{G}_\text{E} = \{g_{i,\text{E}} || g_{i,\text{E}} - \tilde{g}_\text{E}| \leq \delta\}$, where $\tilde{g}_{i,\text{E}}$ denotes the expectation of $g_{i,\text{E}}$. With the above modelings, we can express the EU's secure offloading throughput under the worst case as

$$R_{(ik)}^{\text{sec-wr}} = \left[W \log_2 (1 + \frac{q_{(ik)} h_{k\text{B}}}{n_\text{B}}) - W \log_2 (1 + \frac{q_{(ik)} h_{k\text{E}}^{\max}}{n_\text{E} + p_{(ik)} g_{i,\text{E}}^{\min}}) \right]^+, \qquad (3)$$

where $h_{k\text{E}}^{\max} = \tilde{h}_{k\text{E}} + \delta$, and $g_{i,\text{E}}^{\min} = \tilde{g}_{i,\text{E}} - \delta$.

We introduce variable $t_{(ik)}$ to denote the transmission duration of this NOMA pair of EU k and WU i. In this work, similar to [20], [35], we consider that the size of the computation-result after being processed by the ECS is relatively small, and thus the consequent transmission latency of the computation result is negligible and is not considered in the system model. As a result, we can express EU k's overall latency for completing its workload-requirement S_k^{tot} as:

$$d_{(ik)}^{\text{overall}} = \max\left\{\frac{S_k^{\text{tot}} - s_{(ik)}}{\mu_{k,\text{loc}}}, t_{(ik)} + \frac{s_{(ik)}}{\mu_{\text{ecs}}}\right\}. \quad (4)$$

In (4), parameter $\mu_{k,\text{loc}}$ denotes EU k's local processing-rate, and parameter μ_{ecs} denotes the ES's fixed processing-rate. Notice that for the sake of clear notations, we consider that both $\mu_{k,\text{loc}}$ and μ_{ecs} are measured by the unit of the number of processed bits per second[3].

B. Problem Formulation for Total Energy Minimization

With the above modeling of EU-WU pair (ik), we investigate the following problem, i.e., given WU i's energy budget $e_{(ik)}^{\text{bud}}$, what is EU k's minimum energy consumption for completing its task k? To this end, we formulate the following energy-minimization (EM) problem.

$$\text{(EU-TEM): } E_{\text{EU},(ik)}^{\min}(e_{(ik)}^{\text{bud}}) = \min q_{(ik)}t_{(ik)} + \rho\mu_{\text{loc}}^2\left(S_k^{\text{tot}} - s_{(ik)}\right)$$

$$\text{subject to: } \max\{\frac{S_k^{\text{tot}} - s_{(ik)}}{\mu_{\text{loc}}}, t_{(ik)} + \frac{s_{(ik)}}{\mu_{\text{ecs}}}\} \le T_k^{\max}, \quad (5)$$

$$\frac{s_{(ik)}}{t_{(ik)}} \le R_{(ik)}^{\text{sec-wr}}, \quad (6)$$

$$\frac{n_{\text{B}} + q_{(ik)}h_{k\text{B}}}{g_{i,\text{B}}}(2^{\frac{V_i^{\text{req}}}{t_{(ik)}W}} - 1) \le p_{(ik)}, \quad (7)$$

$$0 \le p_{(ik)} \le P_i^{\max}, \quad (8)$$

$$0 \le q_{(ik)} \le Q_k^{\max}, \quad (9)$$

$$0 \le s_{(ik)} \le S_k^{\text{tot}}, \quad (10)$$

$$p_{(ik)}t_{(ik)} \le e_{(ik)}^{\text{bud}}, \quad (11)$$

$$\text{variables: } s_{(ik)}, q_{(ik)}, p_{(ik)}, \text{ and } 0 \le t_{(ik)} \le T_k^{\max}.$$

In Problem (EU-TEM), focusing on the EU-WU pair (ik), we jointly optimize EU k's transmit-power $q_{(ik)}$ and offloaded workload $s_{(ik)}$, WU i's transmit-power $p_{(ik)}$, and the NOMA transmission-duration $t_{(ik)}$, with the objective of minimizing the energy consumption of EU k, which includes (i) the energy consumption for EU k's offloading transmission (i.e., $q_{(ik)}t_{(ik)}$), and (ii) the energy consumption for EU k's local computing (i.e., $\rho\mu_{\text{loc}}^2(S_k^{\text{tot}} - s_{(ik)})$)[4].

In Problem (EU-TEM), constraint (5) ensures that the overall-latency for completing EU k's cannot exceed its latency-limit $T_k^{\max}$. Constraint (6) ensures the secrecy of EU k's offloaded workload according to the secure throughput quantified in (3). Constraint (7) guarantees that WU i can completely send its required data volume V_i^{req} with duration $t_{(ik)}$ (i.e., the offloading-duration for task k). Constraint (8) means that WU i's transmit-power cannot exceed its power-limit $P_i^{\max}$. Constraint (9) means that EU k's transmit-power $q_{(ik)}$ cannot exceed its power-limit $Q_k^{\max}$. Finally, constraint (11) represents WU i's energy consumption cannot exceed its energy budget $e_{(ik)}^{\text{bud}}$ provided. We use $E_{\text{EU},(ik)}^{\min}(e_i)$ to denote EU k's minimum energy consumption (i.e., the optimal value) of Problem (EU-TEM), which depends on WU i's energy-budget $e_{(ik)}^{\text{bud}}$.

For the sake of clear presentation, we use $\{s_{(ik)}^*, q_{(ik)}^*, p_{(ik)}^*, t_{(ik)}^*\}$ to denote the optimal solution of Problem (EU-TEM), namely,

$$\{s_{(ik)}^*, q_{(ik)}^*, p_{(ik)}^*, t_{(ik)}^*\} = \arg\min q_{(ik)}t_{(ik)} + \rho\mu_{\text{loc}}^2\left(S_k^{\text{tot}} - s_{(ik)}\right),$$

subject to: constraints $(5) - (11)$.

We emphasize that the optimal solutions of Problem (EU-TEM) and the corresponding optimal value (i.e., all $\{s_{(ik)}^*, q_{(ik)}^*, p_{(ik)}^*, t_{(ik)}^*\}$ and $E_{\text{EU},(ik)}^{\min}(e_{(ik)^{\text{bud}}})$), can all be treated as functions WU i's energy-budget $e_{(ik)}^{\text{bud}}$ for this EU-WU pair (ik).

Problem (EU-TEM) is strictly non-convex optimization problem, and thus there exist no general algorithms which can solve it efficiently. We thus focus on proposing algorithms for solving Problem (EU-TEM) efficiently in the next subsection. Before leaving this section, it is worth pointing out that it is a trivial solution when the EU's secure throughput $R_{\text{EU}}^{\text{sec-wr}}$ is non-positive, which leads to that the EU cannot offload any workload to the ES. As a result, the EU's total energy consumption can be directly given by $\rho\mu_{\text{loc}}^2 S_k^{\text{tot}}$. Therefore, in the rest of this paper, we focus on the case that $R_{\text{EU}}^{\text{sec-wr}}$ is positive.

We make two assumptions regarding the EU-WU pair (ik) as

$$\text{(A1): } \frac{S_k^{\text{tot}}}{\mu_{\text{loc}}} \le T_k^{\max}, \quad (12)$$

$$\text{(A2): } T_k^{\max}\frac{n_{\text{B}}}{g_{i,\text{B}}}(2^{\frac{V_i^{\text{req}}}{T_k^{\max}W}} - 1) \le e_{(ik)}^{\text{bud}}, \quad (13)$$

where (A1) means that EU k can complete its task locally within its latency-limit, and (A2) means that given its energy-budget, WU i can complete sending its data to the BS. Both (A1) and (A2) are consistent with the intuitions, and they work together to guarantee that Problem (EU-TEM) is always feasible.

[3]Similar to [18], [47], both $\mu_{k,\text{loc}}$ and μ_{ecs} can be calculated according to the EU's and ES's CPU-rates and the number of the CPU-cycles for processing each bit. We will specify the detailed parameter-settings in Section VIII.

[4]Specifically, similar to [40], we model the EU's power consumption for its local computing as $\rho\mu_{\text{loc}}^3$, where ρ is a coefficient depending on the EU's CPU feature.

C. An Equivalent Form of Problem (EU-TEM)

Directly solving Problem (EU-TEM) is challenging due to its strict non-convexity. In this subsection, we firstly derive an equivalent form of Problem (EU-TEM), which then enables us to propose a decomposition structure in Section IV-D. To this end, we firstly transform constraint (5) into

$$S_k^{\text{tot}} - \mu_{\text{loc}} T_k^{\max} \leq s_{(ik)}, \tag{14}$$

$$s_{(ik)} \leq (T_k^{\max} - t_{(ik)})\mu_{\text{ecs}}. \tag{15}$$

With (10) before and the above (14) and (15), we can obtain a viable interval for $s_{(ik)}$ as

$$\max\{0, S_k^{\text{tot}} - \mu_{\text{loc}} T_k^{\max}\} \leq s_{(ik)} \leq \min\{(T_k^{\max} - t_{(ik)})\mu_{\text{ecs}}, S_k^{\text{tot}}\}. \tag{16}$$

Further based on the assumption that $R_i^{\text{sec-wr}}$ is positive, we can transform constraint (6) into

$$\frac{n_{\text{B}} + q_{(ik)} h_{k\text{B}}}{n_{\text{B}}} \cdot \frac{n_{\text{E}} + p_{(ik)} g_{i,\text{E}}^{\min}}{n_{\text{E}} + p_{(ik)} g_{i,\text{E}}^{\min} + q_{(ik)} h_{k\text{E}}^{\max}} \geq 2^{\frac{s_{(ik)}}{t_{(ik)} W}}. \tag{17}$$

With (7), (8) and (11), we obtain an equivalent interval for p_k as

$$\frac{n_{\text{B}} + q_{(ik)} h_{k\text{B}}}{g_{i,\text{B}}} \left(2^{\frac{V_i^{\text{req}}}{t_{(ik)} W}} - 1\right) \leq p_{(ik)} \leq \min\{\frac{e_{(ik)}^{\text{bud}}}{t_{(ik)}}, P_i^{\max}\}. \tag{18}$$

The above (18) leads to an equivalent interval for $q_{(ik)}$ as

$$q_{(ik)} \leq \frac{1}{h_{k\text{B}}} \left(\min\{\frac{e_{(ik)}^{\text{bud}}}{t_{(ik)}}, P_i^{\max}\} \cdot \frac{g_{i,\text{B}}}{2^{\frac{V_i^{\text{req}}}{t_{(ik)} W}} - 1} - n_{\text{B}} \right), \tag{19}$$

such that the interval of (18) is non-empty.

Constraint (9) before and (19) above together provide the following viable interval for $q_{(ik)}$:

$$0 \leq q_{(ik)} \leq q_{(ik)}^{\text{upp}}, \tag{20}$$

where the upper bound $q_{(ik)}^{\text{upp}}$ is defined as:

$$q_{(ik)}^{\text{upp}} = \min \left\{ \frac{1}{h_{k\text{B}}} \left(\min\{\frac{e_{(ik)}^{\text{bud}}}{t_{(ik)}}, P_i^{\max}\} \cdot \frac{g_{i,\text{B}}}{2^{\frac{V_i^{\text{req}}}{t_{(ik)} W}} - 1} - n_{\text{B}} \right), Q_i^{\max} \right\}. \tag{21}$$

Based on the above operations, we can obtain an equivalent form of Problem (EU-TEM) as

$$\text{(EU-TEM-E)}: E_{\text{EU},(ik)}^{\min} = \min q_{(ik)} t_{(ik)} - \rho \mu_{\text{loc}}^2 s_{(ik)}$$
$$\text{subject to: constraints} (16), (17), (18), \text{ and } (20),$$
$$\text{variables: } s_{(ik)}, q_{(ik)}, p_{(ik)}, \text{ and } 0 \leq t_{(ik)} \leq T_k^{\max}.$$

D. Vertical Decomposition of Problem (EU-TEM-E)

Despite the non-convexity of Problem (EU-TEM-E), we propose a vertical decomposition of Problem (EU-TEM-E) into a top-problem and a corresponding subproblem as follows.

1) (Subproblem to Optimize $(s_{(ik)}, q_{(ik)}, p_{(ik)})$ Under Given $t_{(ik)}$): We firstly assume that the value of $t_{(ik)}$ is given in advance, and aim at solving the consequent subproblem that optimizes variables $(s_{(ik)}, q_{(ik)}, p_{(ik)})$ as follows:

$$\text{(EU-TEM-Sub)}: E_{(t_{(ik)})}^{\text{sub,min}} = \min q_{(ik)} t_{(ik)} - \rho \mu_{\text{loc}}^2 s_{(ik)}$$
$$\text{subject to: constraints} (16), (17), (18), \text{ and } (20).$$
$$\text{variables: } s_{(ik)}, q_{(ik)}, \text{ and } p_{(ik)}.$$

In particular, we denote the optimal value of Problem (EU-TEM-Sub) as $E_{(t_{(ik)})}^{\text{sub,min}}$, which depends on the specified $t_{(ik)}$ from the top-problem.

2) (Top-Problem to Optimize $t_{(ik)}$): With $E_{(t_{(ik)})}^{\text{sub,min}}$ from Problem (EU-TEM-Sub) for each specified $t_{(ik)}$, we next solve the top-problem that focuses on optimizing $E_{(t_{(ik)})}^{\text{sub,min}}$, i.e.,

$$\text{(EU-TEM-Top)}: E_{\text{EU},(ik)}^{\min} = \min E_{(t_{(ik)})}^{\text{sub,min}}$$
$$\text{variable } 0 \leq t_{(ik)} \leq T_k^{\max}.$$

Remark 1: The advantage of the above vertical decomposition is as follows. By exploiting the special feature of Problem (EU-TEM-Sub), we can analytically derive its optimal solution for each given $t_{(ik)}$ (the details will be presented in the next section) and thus obtain the value of $E_{(t_{(ik)})}^{\text{sub,min}}$. Furthermore, by exploiting the nature of single-variable optimization of Problem (EU-TEM-Top), we can enumerate $t_{(ik)} \in [0, T_k^{\max}]$ with a small step-size to find the best value of $t_{(ik)}$ that can minimize $E_{(t_{(ik)})}^{\text{sub,min}}$, which thus solves Problem (EU-TEM-Top) numerically.

V. Proposed Algorithms for Problem (EU-TEM)

We focus on proposing an algorithm for solving Problem (EU-TEM) in this section. In Section V-A, we firstly derive an equivalent form of Problem (EU-TEM-Sub). We then derive the analytical solution of Problem (EU-TEM-Sub) in Section V-B and propose a subroutine for obtaining this optimal solution. We finally propose an algorithm, which exploits the aforementioned subroutine, for solving Problem (EU-TEM-Top) in Section V-C.

A. An Equivalent Form of Problem (EU-TEM-Sub)

Although Problem (EU-TEM-Sub) is again a non-convex optimization problem, a keen observation is that (17) provides an upper bound on $s_{(ik)}$ as follows (recall that the value of $t_{(ik)}$ is given in Problem (EU-TEM-Sub)):

$$s_{(ik)} \leq t_{(ik)} W \Lambda(q_{(ik)}, p_{(ik)}), \tag{22}$$

where function $\Lambda(q_{(ik)}, p_{(ik)})$ is

$$\Lambda(q_{(ik)}, p_{(ik)}) = \log_2 \left(\frac{n_{\text{B}} + q_{(ik)} h_{k\text{B}}}{n_{\text{B}}} \frac{n_{\text{E}} + p_{(ik)} g_{i,\text{E}}^{\min}}{n_{\text{E}} + p_{(ik)} g_{i,\text{E}}^{\min} + q_{(ik)} h_{k\text{E}}^{\max}} \right). \tag{23}$$

We characterize the following feature of $\Lambda(q_{(ik)}, p_{(ik)})$ regarding $p_{(ik)}$.

Lemma 1: Given $q_{(ik)}$, function $\Lambda(q_{(ik)}, p_{(ik)})$ is an increasing function with respect to $p_{(ik)}$.

Proof: Given $q_{(ik)}$, it can be verified that there always exists

$$\frac{d}{dp_{(ik)}}\frac{n_{\mathrm{E}}+p_{(ik)}g_{i,\mathrm{E}}^{\min}}{n_{\mathrm{E}}+p_{(ik)}g_{i,\mathrm{E}}^{\min}+q_{(ik)}h_{k\mathrm{E}}^{\max}}>0, \tag{24}$$

meaning that $\Lambda(q_{(ik)},p_{(ik)})$ is increasing in $p_{(ik)}$. ■

Proposition 1: $p^*_{(ik)}=\min\{\frac{e^{\mathrm{bud}}_{(ik)}}{t_{(ik)}},P_i^{\max}\}$ suffices to be an optimal solution of Problem (EU-TEM-Sub) under each given $t_{(ik)}$.

Proof: An important observation on (18) is that the upper-bound of $p_{(ik)}$ is fixed without depending on $q_{(ik)}$ (recall that the value of $t_{(ik)}$ is given in the subproblem). Therefore, according to Lemma 1, using $p_{(ik)}=\min\{\frac{e^{\mathrm{bud}}_{(ik)}}{t_{(ik)}},P_i^{\max}\}$ in (17) can yield the *largest* upper-bound for $s_{(ik)}$ as follows:

$$\begin{aligned}s_{(ik)}&\le H(q_{(ik)})\\&=t_{(ik)}W\log_2\left(\frac{n_{\mathrm{B}}+q_{(ik)}h_{k\mathrm{B}}}{n_{\mathrm{B}}}\frac{A_{ik}}{A_{ik}+q_{(ik)}h_{k\mathrm{E}}^{\max}}\right),\end{aligned} \tag{25}$$

where parameter A_{ik} is given by

$$A_{ik}=n_{\mathrm{E}}+\min\{\frac{e^{\mathrm{bud}}_{(ik)}}{t_{(ik)}},P_i^{\max}\}g_{i,\mathrm{E}}^{\min}. \tag{26}$$

In addition, it can be observed that both (16) and (20) are independent on $p_{(ik)}$.

As a summary, setting $p_{(ik)}=\min\{\frac{e^{\mathrm{bud}}_{(ik)}}{t_{(ik)}},P_i^{\max}\}$ can yield the largest feasible region for $(s_{(ik)},q_{(ik)})$ without violating any constraint in Problem (EU-TEM-Sub). Meanwhile, the objective function Problem (EU-TEM-Sub) (i.e., $q_{(ik)}t_{(ik)}-\rho\mu_{\mathrm{loc}}^2 s_{(ik)}$) only depends on the tuple of $(s_{(ik)},q_{(ik)})$. As a result, $p^*_{(ik)}=\min\{\frac{e^{\mathrm{bud}}_{(ik)}}{t_{(ik)}},P_i^{\max}\}$ suffices to be the optimal solution of Problem (EU-TEM-Sub). ■

The results in Proposition 1 are consistent with the intuitions well. To minimize EU k's energy consumption, WU i needs to use up its energy-budget $e^{\mathrm{bud}}_{(ik)}$. In Section VI, we will further optimize WU i's $e^{\mathrm{bud}}_{(ik)}$ to optimize WU i's reward.

Based on Proposition 1, we can thus equivalently transform Problem (EU-TEM-Sub) into

$$\begin{aligned}&\text{(EU-TEM-Sub'): } E^{\mathrm{sub,min}}_{(t_{(ik)})}=\min q_{(ik)}t_{(ik)}-\rho\mu_{\mathrm{loc}}^2 s_{(ik)}\\&\quad\text{subject to: constraints (16), (20), and (25),}\\&\quad\text{variables: } s_{(ik)} \text{ and } q_{(ik)}.\end{aligned}$$

B. *Solution of Problem (EU-TEM-Sub') and a Subroutine*

In this subsection, we analytically derive the optimal solution of Problem (EU-TEM-Sub'). First of all, we derive the first-order derivative of function $H(q_{(ik)})$ in (25) as follows

$$\frac{dH(q_{(ik)})}{dq_{(ik)}}=tW\frac{1}{\ln 2}\frac{h_{k\mathrm{B}}A_{ik}-h_{k\mathrm{E}}^{\max}n_{\mathrm{B}}}{(n_{\mathrm{B}}+q_{(ik)}h_{k\mathrm{B}})(A_{ik}+q_{(ik)}h_{k\mathrm{E}}^{\max})}. \tag{27}$$

The result in (27) indicates that we need to consider two cases as follows.

First, if $h_{k\mathrm{B}}A_{ik}-h_{k\mathrm{E}}^{\max}n_{\mathrm{B}}<0$ holds, then $H(q_{(ik)})$ is non-increasing in $q_{(ik)}$. Meanwhile, it can be identified that the maximum value of $H(q_{(ik)})$ is equal to $H(0)=0$ (i.e., when $q_{(ik)}=0$). This leads to a trivial solution $(s_{(ik)},q_{(ik)})=(0,0)$ (if it is feasible) for Problem (EU-TEM-Sub').

Second, if $h_{k\mathrm{B}}A_{ik}-h_{k\mathrm{E}}^{\max}n_{\mathrm{B}}>0$ holds, then $H(q_{(ik)})$ is monotonically increasing in $q_{(ik)}$. For the sake of clear presentation, we denote the bounds for $s_{(ik)}$ as

$$s^{\mathrm{low}}_{(ik)}=\max\{0,S_k^{\mathrm{tot}}-\mu_{\mathrm{loc}}T_k^{\max}\}, \tag{28}$$

$$s^{\mathrm{upp}}_{(ik)}=\min\{(T_k^{\max}-t_{(ik)})\mu_{\mathrm{ecs}},S_k^{\mathrm{tot}}\}, \tag{29}$$

according to (16). Thus, by exploiting the feature that $H(q_{(ik)})$ is monotonically increasing and comparing $H(q^{\mathrm{upp}}_{(ik)})$ (recall that the value of $q^{\mathrm{upp}}_{(ik)}$ is defined in (21) before) with $s^{\mathrm{low}}_{(ik)}$ (as well as $s^{\mathrm{upp}}_{(ik)}$), we need to consider the following three cases for solving Problem (EU-TEM-Sub') analytically, i.e., Case I when $H(q^{\mathrm{upp}}_{(ik)})\ge s^{\mathrm{upp}}_{(ik)}$, Case II when $s^{\mathrm{upp}}_{(ik)}>H(q^{\mathrm{upp}}_{(ik)})\ge s^{\mathrm{low}}_{(ik)}$, and Case III when $s^{\mathrm{low}}_{(ik)}>H(q^{\mathrm{upp}}_{(ik)})$. The details are as follows.

1) (Solution Under Case I With $H(q^{upp}_{(ik)})\ge s^{upp}_{(ik)}$): Under Case I, Problem (EU-TEM-Sub') can be equivalently expressed into the following form:

$$\begin{aligned}&\text{(Case-I): } E^{\mathrm{sub,min}}_{(t_{(ik)})}=\min q_{(ik)}t_{(ik)}-\rho\mu_{\mathrm{loc}}^2 H(q_{(ik)})\\&\text{subject to: } \underline{q}_{(ik)}\le q_{(ik)}\le\overline{q}_{(ik)}\\&\text{variable: } q_{(ik)}.\end{aligned} \tag{30}$$

In constraint (30), the lower-bound $\underline{q}_{(ik)}$ is derived by setting $H(\underline{q}_{(ik)})=s^{\mathrm{low}}_{(ik)}$, and it is given by

$$\underline{q}_{(ik)}=\frac{A_{ik}(2^{\frac{s^{\mathrm{low}}_{(ik)}}{t_{(ik)}W}}-1)n_{\mathrm{B}}}{A_{ik}h_{k\mathrm{B}}-n_{\mathrm{B}}h_{k\mathrm{E}}^{\max}2^{\frac{s^{\mathrm{low}}_{(ik)}}{t_{(ik)}W}}}. \tag{31}$$

Similarly, the upper-bound $\overline{q}_{(ik)}$ is derived by setting $H(\overline{q}_{(ik)})=s^{\mathrm{upp}}_{(ik)}$, and it is given by

$$\overline{q}_{(ik)}=\frac{A_{ik}(2^{\frac{s^{\mathrm{upp}}_{(ik)}}{t_{(ik)}W}}-1)n_{\mathrm{B}}}{A_{ik}h_{k\mathrm{B}}-n_{\mathrm{B}}h_{k\mathrm{E}}^{\max}2^{\frac{s^{\mathrm{upp}}_{(ik)}}{t_{(ik)}W}}}. \tag{32}$$

Notice that in Problem (Case-I), the viable interval of $q_{(ik)}$ in (30) is consistent with the viable interval of $s_{(ik)}$ according to (28) and (29). Thus, to minimize the objective function of Problem (EU-TEM-Sub'), it suffices for us to use the upper-bound of $s_{(ik)}$ (i.e., $H(q_{(ik)})$ according to (25)) to replace $s_{(ik)}$ without violating any constraint, which thus leads to the objective function of Problem (Case-I). Moreover, we have the following result regarding the optimal solution of Problem (Case-I).

Proposition 2: Problem (Case-I) is a strictly convex optimization problem, and its optimal solution can be expressed as:

$$q^*_{(ik)}=\begin{cases}\underline{q}_{(ik)} & \text{if } q^{\mathrm{root}}_{(ik)}<\underline{q}_{(ik)}\\ q^{\mathrm{root}}_{(ik)} & \text{if } \underline{q}_{(ik)}\le q^{\mathrm{root}}_{(ik)}\le\overline{q}_{(ik)}\\ \overline{q}_{(ik)} & \text{if } q^{\mathrm{root}}_{(ik)}>\overline{q}_{(ik)}\end{cases} \tag{33}$$

with $q_{(ik)}^{\text{root}}$ given by

$$q_{(ik)}^{\text{root}} = \frac{-(A_{ik}h_{k\text{B}} + n_{\text{B}}h_{k\text{E}}^{\max}) + \sqrt{\Delta_{ik}}}{2h_{k\text{E}}^{\max}h_{k\text{B}}}. \tag{34}$$

In (34), the value of Δ_{ik} is given by

$$\Delta_{ik} = (A_{ik}h_{k\text{B}} - n_{\text{B}}h_{k\text{E}}^{\max})^2 + 4h_{k\text{E}}^{\max}h_{k\text{B}}M_{ik}, \tag{35}$$

with parameter M_{ik} give by

$$M_{ik} = \frac{W}{\ln 2}\rho\mu_{\text{loc}}^2(h_{k\text{B}}A_{ik} - h_{k\text{E}}^{\max}n_{\text{B}}). \tag{36}$$

Moreover, the optimal value of $s_{(ik)}^*$ for Problem (EU-TEM-Sub') under Case-I can be directly given by $s_{(ik)}^* = H(q_{(ik)}^*)$.

Proof: It can be identified that

$$\frac{1}{dq_{(ik)}}d\left(q_{(ik)}t_{(ik)} - \rho\mu_{\text{loc}}^2 H(q_{(ik)})\right) = t_{(ik)} - \rho\mu_{\text{loc}}^2\frac{dH(q_{(ik)})}{dq_{ik}}, \tag{37}$$

is increasing in $q_{(ik)}$, since $\frac{dH(q_{(ik)})}{dq}$ is decreasing in $q_{(ik)}$ according to (27) before. Therefore, Problem (Case-I) is a strictly convex optimization problem, based on the theory of convex optimization. The convexity of Problem (Case-I) enables us to exploit the Karush-Kuhn-Tucker (KKT) conditions for deriving the optimal solution. Specifically, by setting the first order derivative of the objective function in (37) equal to zero, and performing some further manipulations, we can obtain the following quadratic equation

$$h_{k\text{E}}^{\max}h_{k\text{B}}q_{(ik)}^2 + (A_{ik}h_{k\text{B}} + n_{\text{B}}h_{k\text{E}}^{\max})q_{(ik)} + A_{ik}n_{\text{B}} - M_{ik} = 0, \tag{38}$$

where parameter M_{ik} is given in (36) before.

A keen observation on (38) is that it always has two solutions since the value of Δ_{ik} given in (35) is always positive when $h_{k\text{B}}A_{ik} - h_{k\text{E}}^{\max}n_{\text{B}} > 0$ holds. Moreover, the quadratic equation (38) has at most one positive root which is given by $q_{(ik)}^{\text{root}}$ in (34). Further taking constraint (30) into account, we can thus express the optimal solution $q_{(ik)}^*$ of Problem (Case-I) as in (33). Moreover, since $H(q_{(ik)}^*)$ is feasible with respect to (28) and (29). Thus, to minimize the objective function of Problem (EU-TEM-Sub'), we can directly set $s_{(ik)}^* = H(q_{(ik)}^*)$ for Problem (EU-TEM-Sub') under Case-I without violating any constraint. ∎

2) (Solution Under Case II With $s_{(ik)}^{upp} > H(q_{(ik)}^{upp}) \geq s_{(ik)}^{low}$): Under Case II, Problem (EU-TEM-Sub') can be equivalently expressed into the following form:

$$\begin{aligned} &\text{(Case-II)}: E_{(t_{(ik)})}^{\text{sub,min}} = \min q_{(ik)}t_{(ik)} - \rho\mu_{\text{loc}}^2 H(q_{(ik)}) \\ &\text{subject to: } \underline{q}_{(ik)} \leq q_{(ik)} \leq q_{(ik)}^{\text{upp}}, \\ &\text{variable: } q_{(ik)}, \end{aligned} \tag{39}$$

in which the lower-bound $\underline{q}_{(ik)}$ is given in (31) before.

We have the following result regarding the optimal solution of Problem (Case-II).

Proposition 3: Problem (Case-II) is a strictly convex optimization problem, and its optimal solution can be expressed as:

$$q_{(ik)}^* = \begin{cases} \underline{q}_{(ik)} & \text{if } q_{(ik)}^{\text{root}} < \underline{q}_{(ik)} \\ q_{(ik)}^{\text{root}} & \text{if } \underline{q}_{(ik)} \leq q_{(ik)}^{\text{root}} \leq q_{(ik)}^{\text{upp}} \\ q_{(ik)}^{\text{upp}} & \text{if } q_{(ik)}^{\text{root}} > q_{(ik)}^{\text{upp}} \end{cases} \tag{40}$$

with $q_{(ik)}^{\text{root}}$ given in (34). Moreover, the optimal value of $s_{(ik)}^*$ for Problem (EU-TEM-Sub') under Case-II is $s^*(ik) = H(q_{(ik)}^*)$.

Proof: The proofs are similar as those for Proposition 2. ∎

3) (Solution Under Case III With $s_{(ik)}^{low} > H(q_{(ik)}^{upp})$): In this case, Problem (EU-TEM-Sub') is infeasible under the currently given $t_{(ik)}$ (in other words, we need to consider another value of $t_{(ik)}$).

Until now, we have completed solving Problem (EU-TEM-Sub') under the given $t_{(ik)}$ and obtaining the corresponding value $E_{(t_{(ik)})}^{\text{sub,min}}$ (i.e., the EU's minimum energy consumption under the given $t_{(ik)}$).

As a summary of the above three Case-I, Case-II, and Case-III (as shown in Table I), we firstly propose a subroutine for solving Problem (EU-TEM-Sub') under the given value of $t_{(ik)}$ and outputting the optimal solutions $(q_{(ik)}^*, s_{(ik)}^*)$ as well as the corresponding $E_{(t_{(ik)})}^{\text{sub,min}}$. Recall that we can directly set $p_{(ik)}^* = \min\{\frac{e_{(ik)}^{\text{bud}}}{t_{(ik)}}, P_i^{\max}\}$ according to Proposition 1. The details are shown in Subroutine-TEM below.

- Step 6 to Step 11 evaluate the case of $h_{k\text{B}}A_{ik} - h_{k\text{E}}^{\max}n_{\text{B}} < 0$ (i.e., $H(q_{(ik)})$ is decreasing). In this case, the optimal solution is directly given by $(q_{(ik)}^*, s_{(ik)}^*) = (0, 0)$ if $s_{(ik)}^{\text{low}} = 0$ (otherwise, Problem (EU-TEM-Sub') is infeasible under the currently given value of $t_{(ik)}$).
- Step 12 to Sep 20 evaluate the case of $h_{k\text{B}}A_{ik} - h_{k\text{E}}^{\max}n_{\text{B}} > 0$ (i.e., $H(q_{(ik)})$ is increasing). In this case, we evaluate one of the three possible cases, i.e., Case-I from Step 12 to Step 14, Case-II from Step 15 to Step 17, and Case-III in Steps 19-20.
- Finally, from Step 21 to Step 28, Subroutine-TEM outputs the optimal solution $(q_{(ik)}^*, s_{(ik)}^*)$ for Problem (EU-TEM-Sub'), and the corresponding value of $E_{(t_{(ik)})}^{\text{sub,min}}$ under the given $t_{(ik)}$.

Notice that if Problem (EU-TEM-Sub') is infeasible (i.e., when flag $= 0$), Subroutine-TEM sets $E_{(t_{(ik)})}^{\text{sub,min}}$ as an extremely large number, which will facilitate the operations of our following proposed Algorithm-TEM for solving Problem (TEM-E-Top).

C. Proposed Algorithm-Top for Solving Problem (EU-TEM-Top)

Until now, for each given value of $t_{(ik)}$, we can use Subroutine-TEM to solve Problem (EU-TEM-Sub') and obtain the corresponding value of $E_{(t_{(ik)})}^{\text{sub,min}}$. We next aim at solving Problem (EU-TEM-Top). In particular, $E_{(t_{(ik)})}^{\text{sub,min}}$ can be regarded as an implicit function of $t_{(ik)}$, whose analytical form, however, cannot be directly given. Fortunately, we notice that Problem (EU-TEM-Top) is a single-variable optimization of $t_{(ik)}$ within

Subroutine-TEM: To solve Problem (EU-TEM-Sub) and obtain the value of $E^{\text{sub,min}}_{(t_{(ik)})}$ under the given $t_{(ik)}$.

1: **Input:** The value of $t_{(ik)}$.
2: Initialize flag $= 1$.
3: Set $q^{\text{upp}}_{(ik)}$ according to (21).
4: **if** $q^{\text{upp}}_{(ik)} < 0$ **then**
5: Update flag $= 0$.
6: Go to Step 28.
7: **else if** $q^{\text{upp}}_{(ik)} = 0$ **then**
8: Set $q^*_{(ik)} = 0$.
9: Go to Step 28.
10: **end if**
11: Set $s^{\text{low}}_{(ik)}$ according to (28) and $s^{\text{upp}}_{(ik)}$ according to (29).
12: Set A_{ik} according to (26).
13: **if** $h_{k\text{B}} A_{ik} - h^{\max}_{k\text{E}} n_{\text{B}} < 0$ **then**
14: **if** $s^{\text{low}}_{(ik)} = 0$ **then**
15: Set $q^*_{(ik)} = 0$.
16: **else**
17: Update flag $= 0$.
18: **end if**
19: **else if** $H(q^{\text{upp}}_{(ik)}) \geq s^{\text{upp}}_{(ik)}$ **then**
20: Set $\underline{q}_{(ik)}$ according to (31) and $\overline{q}_{(ik)}$ according to (32).
21: Compute $q^*_{(ik)}$ according to (33).
22: **else if** $s^{\text{upp}}_{(ik)} > H(q^{\text{upp}}_{(ik)}) \geq s^{\text{low}}_{(ik)}$ **then**
23: Set $\underline{q}_{(ik)}$ according to (31).
24: Compute $q^*_{(ik)}$ according to (40).
25: **else**
26: Update flag $= 0$.
27: **end if**
28: **if** flag $= 1$ **then**
29: Set $s^*_{(ik)} = H(q^*_{(ik)})$.
30: Set $E^{\text{sub,min}}_{(t_{(ik)})} = \min q^*_{(ik)} t_{(ik)} - \rho \mu^2_{\text{loc}} s^*_{(ik)}$.
31: **else**
32: Set $(q^*_{(ik)}, s^*_{(ik)}) = \emptyset$.
33: Set $E^{\text{sub,min}}_{(t_{(ik)})} = \infty$.
34: **end if**
35: **Output**: $E^{\text{sub,min}}_{(t_{(ik)})}$ as well as the tuple of $(q^*_{(ik)}, s^*_{(ik)})$.

a fixed interval $[0, T^{\max}_k]$. Therefore, to solve Problem (EU-TEM-Top), we adopt a line-search with a small step-size to numerically look for the best value of $t_{(ik)}$ (i.e., $t^*_{(ik)}$) that can minimize $E^{\text{sub,min}}_{(t_{(ik)})}$. The details are shown in our Algorithm-TEM. In the WHILE-LOOP from Step 2 to Step 9, we execute the line-search of $t_{(ik)} \in [0, T^{\max}_k]$ with a small step-size denoted by Δ_t. For each value of $t_{(ik)}$ being enumerated, we invoke Subroutine-TEM to obtain the value of $E^{\text{sub,min}}_{(t^{\text{cur}})}$ in Step 3. Finally, Algorithm-TEM outputs the optimal solution $t^*_{(ik)}$, as well as the corresponding $(q^*_{(ik)}, s^*_{(ik)})$ and $p^*_{(ik)} = \min\{\frac{e^{\text{bud}}_{(ik)}}{t^*_{(ik)}}, P^{\max}_i\}$ (according to Proposition 1 before). Fig. 2 in Section VIII will

Algorithm-TEM: to solve Problem (EU-TEM-Top).

1: **Initialization:** Set CBV $= \infty$ and CBS $= \varnothing$. Set $t^{\text{low}} = 0$, $t^{\text{upp}} = T^{\max}_k$. Set $t^{\text{cur}} = t^{\text{low}}$ and a very small step-size Δ_t.
2: **while** $t^{\text{cur}} \leq T^{\max}_k$ **do**
3: Invoke Subroutine-TEM to obtain the value of $E^{\text{sub,min}}_{(t^{\text{cur}})}$.
4: **if** $E^{\text{sub,min}}_{(t^{\text{cur}})} <$ CBV **then**
5: Update CBV $= E^{\text{sub,min}}_{(t^{\text{cur}})}$,
6: Update CBS $= (t^{\text{cur}}, q^*_{(ik)}, s^*_{(ik)})$.
7: **end if**
8: Update $t^{\text{cur}} = t^{\text{cur}} + \Delta_t$.
9: **end while**
10: **Output**: Output the optimal value $E^{\text{mid,min}}_{(ik)} =$ CBS as the optimal solution for Problem (TEM).

illustrate the examples of the line-search over $t_{(ik)}$ in Algorithm-TEM and show the values of $E^{\text{sub,min}}_{(t_{(ik)})}$ versus different $t_{(ik)}$. In particular, the results in Fig. 2 indicate that neither a too small value nor a too large value of $t_{(ik)}$ is beneficial, which thus requires us to carefully search for the optimal $t^*_{(ik)}$ to minimize $E^{\text{sub,min}}_{(t_{(ik)})}$. Until now, we complete solving the original Problem (TEM).

It is worth noticing that with the characterized Case I, Case II, and Case III in Section V.B and Proposition 2 and Proposition 3 that respectively provide the analytical solutions under Case I and Case II, our Subroutine-TEM does not require any iterative operation. Therefore, the overall complexity of Algorithm-TEM mainly comes from executing the line-search on t^{cur}, and the overall complexity can be directly given by $O(\frac{T^{\max}_k}{\Delta_t})$. In this paper, we mainly consider a centralized approach for solving Problem (EU-TEM) and Problem (EnergyAllo). For instance, the BS collects all the required information from the considered EU-WU pair. Then, the BS executes Algorithm-TEM for solving Problem (EU-TEM) and executes Algorithm-MO to solve Problem (EnergyAllo). Afterwards, the BS will send the corresponding solutions to the EU and WU for their following operations.

VI. Optimal WU's Energy-Budget for EU-WU Pair

A. Problem Formulation Based on Nash Bargaining Solution

In Section IV and Section V, we consider an EU-WU pair (ik) with fixed WU i's energy-budget and aim at minimize EU k's total energy consumption, which can be regarded as the EU's benefit from the EU-WU cooperation (at the expense of the WU's energy consumption). In this section, we further investigate how WU i can optimize its energy budget $e^{\text{bud}}_{(ik)}$ such that both EU k and WU i can benefit from their cooperation in a fairness manner. To this end, we present the following modelings for the EU-WU pair (ik).

Firstly, with the optimal solution $(t^*_{(ik)}, p^*_{(ik)})$ and $E^{\min}_{\text{EU},(ik)}(e^{\text{bud}}_{(ik)})$ from Problem (EU-TEM), we model EU k's *net-reward* as the saved energy consumption against the benchmark case without any WU's cooperative jamming,

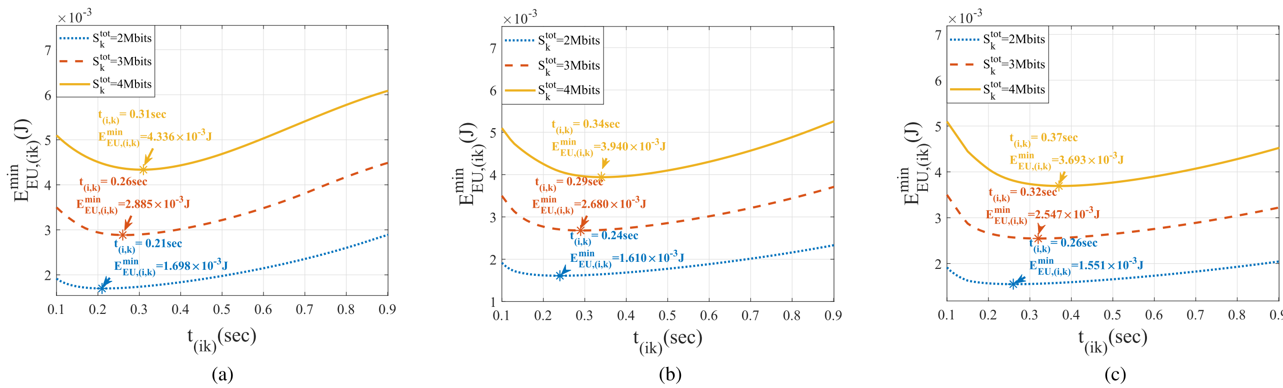

Fig. 2. Illustrative examples of $E^{\text{sub,min}}_{(t_{(ik)})}$ versus $t_{(ik)}$. (a) $e^{\text{bud}}_{(ik)} = 0.04$J. (b) $e^{\text{bud}}_{(ik)} = 0.05$J. (c) $e^{\text{bud}}_{(ik)} = 0.06$J.

namely,

$$\pi_{\text{EU}-k,(ik)} = \theta_k \left(E^{\text{wo}}_{\text{EU},k} - E^{\text{min}}_{\text{EU},(ik)}(e^{\text{bud}}_{(ik)}) \right), \tag{41}$$

In (41), $E^{\text{wo}}_{\text{EU},k}$ denotes EU k's benchmark energy consumption without any WU's jamming. We provide a detailed problem formulation to compute $E^{\text{wo}}_{\text{EU},k}$ in Appendix A. Here in (41), we treat $E^{\text{wo}}_{\text{EU},k}$ as a constant. As stated before, the gap $(E^{\text{wo}}_{\text{EU},k} - E^{\text{min}}_{\text{EU},(ik)}(e^{\text{bud}}_{(ik)}))$ measures the saved EU k's total energy consumption, and we use parameter θ_k in (41) to denote EU k's marginal cost for its energy consumption.

Similarly, we model WU i's *net-reward* under the EU-WU pair (ik) as follows:

$$\pi_{\text{WU}-i,(ik)} = U_i(V_i^{\text{req}}) - \phi_i t^*_{(ik)} p^*_{(ik)} - U_i^{\text{ben}}. \tag{42}$$

In (42), $U_i(V_i^{\text{req}})$ denotes WU i's utility in delivering its data to the BS.[5] Parameter ϕ_i denotes the marginal cost for WU i's energy consumption. Parameter U_i^{ben} denotes WU i's minimum reward required from the cooperation. In other words, WU i will not collaborate with EU k, if WU i's net-reward cannot reach U_i^{ben}.

Based on the above modelings in (41) and (42), we adopt the theory of Nash Bargaining Solution (NBS) to model the setting of WU i's energy-budget, such that both EU k and WU i can simultaneously benefit from their cooperation in a fairness manner. As one of the typical cooperative game models, NBS provides a promising approach for modeling the resource allocation (or division) problems in which different participants are of conflictive interests, and they all expect to benefit from the bargaining process in a fairness manner [41]–[43]. Thus, the NBS provides a suitable tool for modelling the optimization of the WU's energy budget for achieving the win-win cooperation between the EU and WU. Based on the principle of NBS, we formulate the following optimization problem:

$$\text{(EnergyAllo): } \max \left(U_i(V_i^{\text{req}}) - \phi_i t^*_{(ik)} p^*_{(ik)} - U_i^{\text{ben}} \right)^{\frac{\beta_{\text{WU},i}}{\beta_{\text{WU},i}+\beta_{\text{EU},k}}} \times \left(E^{\text{wo}}_{\text{EU},k} - E^{\text{min}}_{\text{EU},(ik)}(e^{\text{bud}}_{ik}) \right)^{\frac{\beta_{\text{EU},k}}{\beta_{\text{WU},i}+\beta_{\text{EU},k}}}$$

$$\text{variable:} \underline{E}_{(ik)} \le e^{\text{bud}}_{(ik)} \le E_i^{\text{max}},$$

where parameter E_i^{max} denotes WU i's energy capacity. Parameters $\beta_{\text{WU},i}$ and $\beta_{\text{EU},k}$ capture the bargaining-powers of WU i and EU k's bargaining-power, respectively. Notice that the lower-bound $\underline{E}_{(ik)}$ is set according to (13) before, i.e.,

$$\underline{E}_{(ik)} = T_k^{\text{max}} \frac{n_{\text{B}}}{g_{i,\text{B}}} (2^{\frac{V_i^{\text{req}}}{T_k^{\text{max}} W}} - 1), \tag{43}$$

which ensures that the consequent Problem (EU-TEM) is feasible.

Remark 2: We emphasize that according to the optimal solution of Problem (EU-TEM), $t^*_{(ik)}$, $p^*_{(ik)}$, and $E^{\text{min}}_{\text{EU},(ik)}(e^{\text{bud}}_{(ik)})$ are all functions of $e^{\text{bud}}_{(ik)}$ in Problem (EnergyAllo). Thus, we treat $e^{\text{bud}}_{(ik)}$ as the single variable in Problem (EnergyAllo).

B. *Proposed Algorithm for Solving Problem (EnergyAllo)*

In this subsection, we propose an algorithm to solve Problem (EnergyAllo), which is based on the key idea of identifying the hidden monotonicity of Problem (EnergyAllo) (after some equivalent transformations). The details are as follows.

Based on Proposition 1, we can identify an important feature as follows.

Corollary 1: There exists an upper-bound (which is denoted by $\overline{E}_{(ik)}$) regarding EU k's energy-budget under the EU-WU pair (ik), such that $p^*_{(ik)} t^*_{(ik)} = e^{\text{bud}}_{(ik)}$ holds at the optimum of Problem (EU-TEM) when $e^{\text{bud}}_{(ik)} \le \overline{E}_{(ik)}$.

In other words, in the EU-WU pair (ik), WU i's energy-budget will be completely utilized when $e^{\text{bud}}_{(ik)} \le \overline{E}_{(ik)}$, and the value of $\overline{E}_{(ik)}$ can be given by

$$\overline{E}_{(ik)} = \arg\max\{e^{\text{bud}}_{(ik)} \in [0, E_i^{\text{max}}] | t^*_{(ik)} p^*_{(ik)} = e^{\text{bud}}_{(ik)}\}. \tag{44}$$

Notice that the value of $\overline{E}_{(ik)}$ can also be obtained via a bisection search.

Corollary 1 indicates that there is no need for WU i to set its $e^{\text{bud}}_{(ik)} > \overline{E}_{(ik)}$, since part of WU i's allocated energy-budget will be wasted. Exploiting Corollary 1 and $\overline{E}_{(ik)}$, we can equivalently transform Problem (EnergyAllo) into the following expression:

$$\text{(EnergyAllo-E): } \max \left(U_i(V_i^{\text{req}}) - \phi_i e^{\text{bud}}_{(ik)} - U_i^{\text{ben}} \right)^{\frac{\beta_{\text{WU,i}}}{\beta_{\text{WU,i}}+\beta_{\text{EU,k}}}}$$

[5]For instance, we can express $U_i(V_i^{\text{req}}) = \varpi V_i^{\text{req}}$, where parameter ϖ denotes the marginal reward in the delivered data.

$$\times \left(E^{\mathrm{wo}}_{\mathrm{EU},k} - E^{\min}_{\mathrm{EU},(ik)}(e^{\mathrm{bud}}_{(ik)})\right)^{\frac{\beta_{\mathrm{EU,k}}}{\beta_{\mathrm{WU,i}}+\beta_{\mathrm{EU,k}}}}$$

$$\text{constraint:} \underline{E}_{(ik)} \leq e^{\mathrm{bud}}_{(ik)} \leq \min\{\overline{E}_{(ik)}, \frac{U_i(V_i^{\mathrm{req}}) - U_i^{\mathrm{ben}}}{\phi_i}\}, \tag{45}$$

$$\text{variable: } e^{\mathrm{bud}}_{(ik)}.$$

Constraint (45) specifies a viable interval for $e^{\mathrm{bud}}_{(ik)}$ according to (43) and (44) before, and $e^{\mathrm{bud}}_{(ik)} < \frac{U_i(V_i^{\mathrm{req}})-U_i^{\mathrm{ben}}}{\phi_i}$ ensures a positive net-reward for WU i. Although Problem (EnergyAllo-E) is still a non-convex optimization problem, we identify an important feature that Problem (EnergyAllo-E) can be equivalently transformed into a monotonic optimization problem [52], which can thus be solved efficiently via the so-called polyblock approximation algorithm. We will illustrate the details in the next subsection.

C. Proposed Algorithm for Solving Problem (EnergyAllo) Via Monotonic Optimization

For the sake of clear presentation, we introduce two functions, i.e.,

$$f_{\mathrm{EU}}(e^{\mathrm{bud}}_{(ik)}) = \left(E^{\mathrm{wo}}_{\mathrm{EU},k} - E^{\min}_{\mathrm{EU},(ik)}(e^{\mathrm{bud}}_{(ik)})\right)^{\frac{\beta_{\mathrm{EU,k}}}{\beta_{\mathrm{WU,i}}+\beta_{\mathrm{EU,k}}}},$$

$$f_{\mathrm{WU}}(e^{\mathrm{bud}}_{(ik)}) = \left(U_i(V_i^{\mathrm{req}}) - \phi_i e^{\mathrm{bud}}_{(ik)} - U_i^{\mathrm{ben}}\right)^{\frac{\beta_{\mathrm{WU,i}}}{\beta_{\mathrm{WU,i}}+\beta_{\mathrm{EU,k}}}}.$$

In particular, it can be observed that $f_{\mathrm{EU}}(e^{\mathrm{bud}}_{(ik)})$ is increasing in $e^{\mathrm{bud}}_{(ik)} \in [\underline{E}_{(ik)}, \min\{\overline{E}_{(ik)}, \frac{U_i(V_i)-U_i^{\mathrm{ben}}}{\phi_i}\}]$, while $f_{\mathrm{WU}}(e^{\mathrm{bud}}_{(ik)})$ is decreasing.

Let us denote $\underline{f}_{\mathrm{WU}}$ as the minimum reward of WU i under the EU-WU pair (i,k). The value of $\underline{f}_{\mathrm{WU}}$ can be given by

$$\underline{f}_{\mathrm{WU}} = \min_{\underline{E}_{(ik)} \leq e^{\mathrm{bud}}_{(ik)} \leq \min\{\overline{E}_{(ik)}, \frac{U_i(V_i)-U_i^{\mathrm{ben}}}{\phi_i}\}} f_{\mathrm{WU}}(e^{\mathrm{bud}}_{(ik)})$$

$$= \left(U_i(V_i^{\mathrm{req}}) - \phi_i \min\{\overline{E}_{(ik)}, \frac{U_i(V_i)-U_i^{\mathrm{ben}}}{\phi_i}\} - U_i^{\mathrm{ben}}\right)^{\frac{\beta_{\mathrm{WU,i}}}{\beta_{\mathrm{WU,i}}+\beta_{\mathrm{EU,k}}}}.$$

Furthermore, we introduce an auxiliary variable r as

$$r = \frac{f_{\mathrm{WU}}(e^{\mathrm{bud}}_{(ik)})}{\underline{f}_{\mathrm{WU}}}, \tag{46}$$

and further define an auxiliary function

$$F(e^{\mathrm{bud}}_{(ik)}, r) = \underline{f}_{\mathrm{WU}} r f_{\mathrm{EU}}(e^{\mathrm{bud}}_{(ik)}). \tag{47}$$

With r and $F(e^{\mathrm{bud}}_{(ik)}, r)$, we can transform Problem (EnergyAllo-E) into the following form:[6]

$$\text{(EnergyAllo-Mono): } \max F(e^{\mathrm{bud}}_{(ik)}, r)$$

$$\text{subject to: } r - \frac{f_{\mathrm{WU}}(e^{\mathrm{bud}}_{(ik)})}{\underline{f}_{\mathrm{WU}}} \leq 0, \tag{48}$$

$$r \geq 1, \tag{49}$$

$$\text{constraint}(45),$$

$$\text{variables:} e^{\mathrm{bud}}_{(ik)} \text{ and} r.$$

Recall that in (45), $\underline{E}_{(ik)}$ and $\overline{E}_{(ik)}$ are specified by (43) and (44) before, respectively.

Regarding Problem (EnergyAllo-Mono), we have the following important feature.

Proposition 4: Problem (EnergyAllo-Mono) is a standard monotonic optimization problem with respect to the tuple of variables $(e^{\mathrm{bud}}_{(ik)}, r)$.

Proof: It can be identified that the objective function of Problem (EnergyAllo-Mono) is increasing in $(e^{\mathrm{bud}}_{(ik)}, r)$. Meanwhile, it can be found that the left-hand-side of constraint (48) in increasing in $(e^{\mathrm{bud}}_{(ik)}, r)$. As a result, the feasible interval of Problem (EnergyAllo-Mono) can be expressed as an intersection of a compact normal set $\mathcal{G}$ (defined in (50)) and a reverse normal set $\mathcal{H}$ (defined in (51)) as follows:

$$\mathcal{G} = \{(e^{\mathrm{bud}}_{(ik)}, r) | r - \frac{f_{\mathrm{WU}}(e^{\mathrm{bud}}_{(ik)})}{\underline{f}_{\mathrm{WU}}} \leq 0,$$

$$e^{\mathrm{bud}}_{(ik)} \leq \min\{\overline{E}_{(ik)}, \frac{U_i(V_i) - U_i^{\mathrm{ben}}}{\phi_i}\}\} \tag{50}$$

$$\mathcal{H} = \{(e^{\mathrm{bud}}_{(ik)}, r) | r \geq 1, e^{\mathrm{bud}}_{(ik)} \geq \underline{E}_i\}. \tag{51}$$

Therefore, according to the theory of monotonic optimization, Problem (EnergyAllo-Mono) is a standard monotonic optimization problem with respect to the tuple of variables $(e^{\mathrm{bud}}_{(ik)}, r)$. ■

Exploiting the monotonicity of Problem (EnergyAllo-E-Monotonic), we can propose Algorithm-Mono below, which is based on the idea of polyblock approximation [52], for finding the optimal solution. Specifically, the output of Algorithm-Mono, i.e., $e^{\mathrm{bud}*}_{(ik)}$ suffices to be the optimal solution of Problem (EnergyAllo), i.e., WU i's optimal energy-budget allocation for the EU-WU pair (ik).

Notice that the output of our Algorithm-MO, i.e., $e^{\mathrm{bud}*}_{(ik)}$, suffices to be the optimal solution of Problem (EnergyAllo). With $e^{\mathrm{bud}*}_{(ik)}$, we can further obtain the corresponding offloading solutions, i.e., $(s^*_{(ik)}, p^*_{(ik)}, q^*_{(ik)}, t^*_{ik})$ for the EU-WU pair (ik) by using Algorithm-TEM for solving Problem (EU-TEM).

VII. Scenario of Multiple WUs and EUs and Optimal EU-WU Pairings

As a brief summary of our designs in Section IV and Section VI, by leveraging the WU's jamming to the eavesdropper, the EU can increase its secure offloading throughput to the edge-computing server or equivalently, the EU's minimum energy consumption for reaching a secure computation offloading to the edge-computing server can be reduced. Thanks to this EU's reduced energy consumption, the EU can positively benefit from the EU-WU cooperation. Meanwhile, despite consuming the energy consumption for jamming the eavesdropper, the WU can also benefit from this cooperation, since the WU can obtain

[6] It is worth pointing out that (46) is not the only way to transform Problem (EnergyAllo) into a monotonic form. Nevertheless, introducing r in (46) leads to a low-bound of r in (49), which can facilitate the operations of our following proposed algorithm based on the polyblock approximation.

Algorithm-MO: To Solve Problem (EnergyAllo-E-Monotonic).

Initialization: Define $F(e^{\text{bud}}_{(ik)}, r) = \underline{f}_{\text{WU}} r f_{\text{EU}}(e^{\text{bud}}_{(ik)})$. Initialize $\mathcal{T} = \{(e^{\text{bud}}_{(ik)}, r) = (\min\{\overline{E}_{(ik)}, \frac{U_i(V_i) - U_i^{\text{ben}}}{\phi_i}\}, \frac{f_{\text{WU}}(\underline{E}_i)}{\underline{f}_{\text{WU}}})\}$. and initialize CBV $= -\infty$. Set $\epsilon \geq 0$ as a small positive number.
repeat
  From $\mathcal{T}$, find the vertex $\mathbf{z} = (e^{\text{bud}}_{(ik)}, r) \in \arg\max\{F(e^{\text{temp}}_{(ik)}, r^{\text{temp}}) | (e^{\text{temp}}_{(ik)}, r^{\text{temp}}) \in \mathcal{T}\}$ (notice that for each vertex $(e^{\text{temp}}_{(ik)}, r^{\text{temp}})$, we invoke Algorithm-TEM to obtain the value of $F(e^{\text{temp}}_{(ik)}, r^{\text{temp}})$)
  Use the bisection search to find the projection of $\mathbf{z}$ on the boundary of $\mathcal{G}$, and denote this projection of $\mathbf{z}$ on $\mathcal{G}$ as $\tau\mathcal{G}(\mathbf{z})$.
  if $|\tau\mathcal{G}(\mathbf{z}) - \mathbf{z}| \leq \epsilon$ **then**
    Update CBS $= \mathbf{z}$ and CBV $= F(\mathrm{z})$.
  else
    if $\tau\mathcal{G}(\mathrm{z}) \in \mathcal{G} \cap \mathcal{H}$ and $F(\tau\mathcal{G}(\mathrm{z})) \geq$ CBV **then**
      Update CBS $= \tau\mathcal{G}(\mathrm{z}_k)$ and CBV $= F(\tau\mathcal{G}(\mathrm{z}_k))$.
    end if
    Set $\mathbf{x} = \tau\mathcal{G}(\mathrm{z})$ and update $\mathcal{T} = (\mathcal{T} \backslash \mathrm{z}) \cup \{(x_1, z_2), (z_1, x_2)\}$, where x_i denotes the i-th element of vector $\mathbf{x}$, and z_i denotes the i-the element of vector $\mathbf{z}$.
    Update $\mathcal{T} = \{\mathrm{v} \in \mathcal{T} | \mathrm{v} \notin \mathcal{H}\}$ to remove the improper vertexes.
  end if
until $|F(\mathrm{z}) - \text{CBV}| \leq \epsilon$.
Output: Output the optimal solution $(r^*, e^{\text{bud}*}_{(ik)}) =$ CBS for Problem (EnergyAllo-E-Monotonic). Notice that $e^{\text{bud}*}_{(ik)}$ is also the solution to Problem (EnergyAllo).

the chance for reusing the EU's channel via NOMA to send its data to the BS. In other words, both the EU and WU in the considered EU-WU pair can benefit from the enhanced security of the EU's computation offloading via our designs in Section IV and Section VI. Our study on the single pair of EU-WU collaboration with optimized WU's energy provisioning can be exploited for investigating more complicated scenarios. In this section, we further investigate the scenario of multiple WUs and multiple EUs, in which each EU selects one of the WUs to provide the cooperative jamming. To this end, we introduce an one-to-one mapping $\{\mu(k) \in \mathcal{I}\}_{k \in \mathcal{K}}$ to denote the profile of pairings between the EUs and WUs. Specifically,

$$\mu(k) = i, k \in \mathcal{K} \text{and} i \in \mathcal{I}, \tag{52}$$

means that EU k from $\mathcal{K}$ selects WU i from $\mathcal{I}$ to form a pair. For the sake of clear modeling, we assume that the number of the EUs is equal to that of the WUs (i.e., $K = I$). Our following proposed algorithm can be extended for other scenarios with $I \neq K$ by introducing additionally virtual WUs (or EUs). Our objective in this section is to determine *the stable pairings*, which is denoted by $\{\mu^{\text{sta}}(k)\}_{k \in \mathcal{K}}$, between the EUs and the WUs, such that no individual EU (or WU) will have any incentive to be paired with another WU (or EU) $\{\mu^{\text{sta}}(k)\}_{k \in \mathcal{K}}$. In other words, supposing that $\mu^{\text{sta}}(k) = i$, WU i is the best yet available choice from EU k's perspective, and meanwhile, EU k is the best available choice from WU i's perspective.

A. Preference Lists of EUs and WUs

To determine the stable pairing, we firstly model the EUs and WUs' preference lists, which can be determined by each EU's and WU's optimal net-rewards from solving Problem (Energy-Allo) for each EU-WU pair (ik). Specifically, followed by the net-rewards defined in (41) and (42) as well as the optimal solution of Problem (Energy-Allo) (provided by our Algorithm-MO), we can calculate EU k's and WU i's respective *net-rewards* from the EU-WU pair (ik) as

$$\pi^*_{\text{EU}-k,(ik)} = E^{\text{wo}}_{\text{EU},k} - E^{\min}_{\text{EU},(ik)}(e^{\text{bud}*}_{(ik)}) \tag{53}$$

$$\pi^*_{\text{WU}-i,(ik)} = U_i(V_i^{\text{req}}) - \phi_i e^{\text{bud}*}_{(ik)} - U_i^{\text{ben}} \tag{54}$$

With $\{\pi^*_{\text{EU}-k,(ik)}\}_{i \in \mathcal{I}}$, we can establish EU k's preference with respect to two different WUs i and i' as

$$i \succ_{\text{EU}-k} i' \Leftrightarrow \pi^*_{\text{EU}-k,(ik)} > \pi^*_{\text{EU}-k,(i'k)}. \tag{55}$$

Based on (55), we can establish EU k's preference list $\mathcal{P}_{\text{EU}-k}$ of all WUs in $\mathcal{I}$ according to the descending order of the values of $\{\pi^*_{\text{EU}-k,(ik)}\}_{i \in \mathcal{I}}$, namely, the top WU in EU k's preference list $\mathcal{P}_{\text{EU}-k}$ can be given by $\arg\max_{i \in \mathcal{I}}\{\pi^*_{\text{EU}-k,(ik)}\}$.

With $\{\pi^*_{\text{WU}-i,(ik)}\}_{k \in \mathcal{K}}$, we establish WU i's preference with respect to two different EUs k and k' as

$$k \succ_{\text{WU}-i} k' \Leftrightarrow \pi^*_{\text{WU}-i,(ik)} > \pi^*_{\text{WU}-i,(ik')}. \tag{56}$$

Based on (56), we can establish WU i's preference list $\mathcal{P}_{\text{WU}-i}$ of all EUs in $\mathcal{K}$ according to the descending order of the values of $\{\pi^*_{\text{WU}-i,(ik)}\}_{k \in \mathcal{K}}$, namely, the top EU in WU i's preference list can be given by $\arg\max_{k \in \mathcal{K}}\{\pi^*_{\text{WU}-i,(ik)}\}$.

B. Modeling of Stability and Proposed Algorithm for Stable Pairing

With the EUs' preference lists in (55) and the WUs' preference lists in (56), we aim at finding the stable pairing $\{\mu^{\text{sta}}(k)\}_{k \in \mathcal{I}}$ (which is defined in (52)), such that WU $\mu^{\text{sta}}(k)$ is the best yet currently available choice from EU k's perspective, and meanwhile, EU k is the best yet currently available choice from WU $\mu^{\text{sta}}(k)$'s perspective. To this end, we provide the following definition of the *blocking-pair*.

Definition 1: (Blocking-pair): Given the pairing $\{\mu(k) = i\}_{k \in \mathcal{K}}$ between $k \in \mathcal{K}$ and $i \in \mathcal{I}$, EU k and WU i' (who are currently unpaired, i.e., $i' \neq \mu(k)$) is considered to form a blocking-pair with respect to $\{\mu(k)\}_{k \in \mathcal{K}}$, if the following two conditions hold simultaneously:

$$\text{(C1)}: i' \succ_{\text{EU}-k} \mu(k)$$

$$\text{(C2)}: k \succ_{\text{WU}-i'} k,' \text{ where } \mu(k') = i'.$$

Condition (C1) means that EU k prefers WU i' more than its currently paired $\mu(k)$, and condition (C2) means that WU i' prefers EU k than its currently paired EU k' (i.e., $\mu(k') = i'$ under the current pairing). Condition (C1) and condition (C2) together mean that both EU k and WU i' prefer to changing

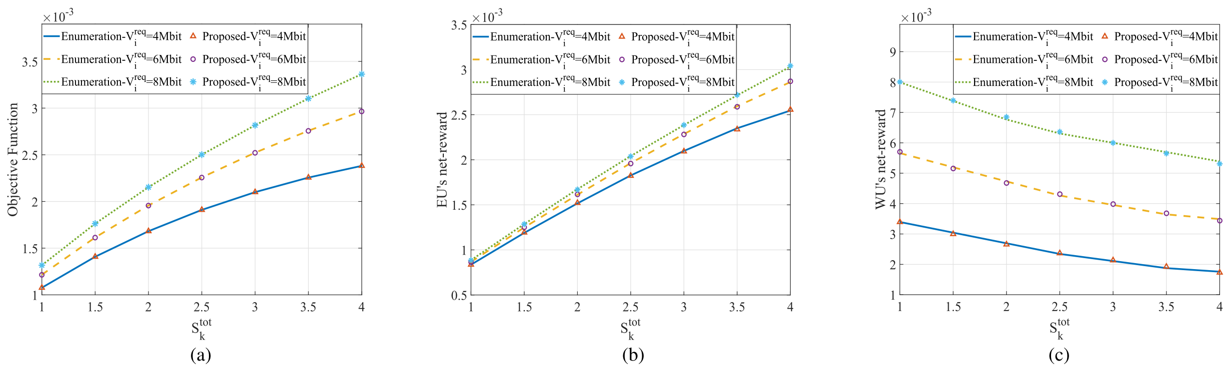

Fig. 3. Accuracy of our Algorithm-MO to solve Problem (EnergyAllo). (a) Comparison of objective function. (b) Comparison of EU's net-reward. (c) Comparison of WU's net-reward.

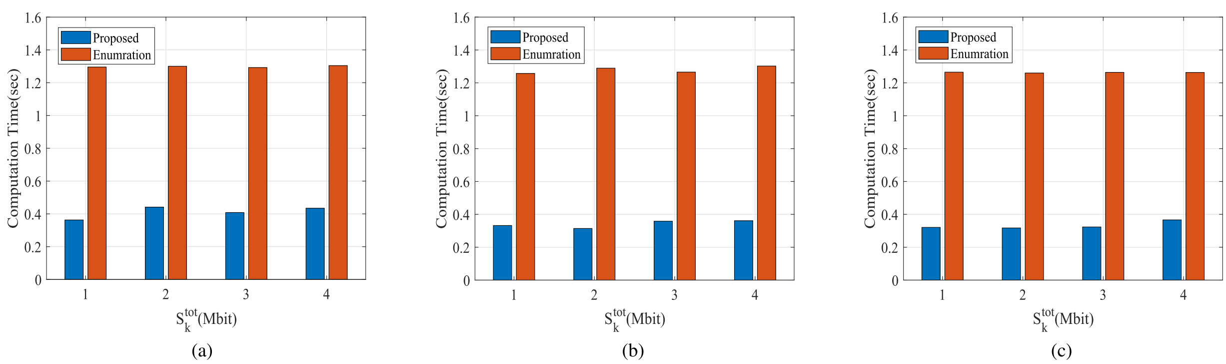

Fig. 4. Efficiency of our Algorithm-MO to solve Problem (EnergyAllo). (a) $V_i^{\text{req}} = 4$ Mbits. (b) $V_i^{\text{req}} = 6$ Mbits. (c) $V_i^{\text{req}} = 8$ Mbits.

TABLE I
THREE DIFFERENT CASES FOR SOLVING PROBLEM (EU-TEM-SUB') WHEN $h_{k\text{B}}a_{ik} - h_{k\text{E}}^{\text{MAX}} n_{\text{B}} > 0$ HOLDS

Case I	$H(q_{(ik)} = q_{(ik)}^{\text{upp}}) \geq s_{(ik)}^{\text{upp}}$	$\underline{q}_{ik} \leq q_{(ik)}^{\text{root}} \leq \overline{q}_{ik}$	$q_{(ik)}^{*} = q_{(ik)}^{\text{root}}$
		$q_{(ik)}^{\text{root}} > \overline{q}_{ik}$	$q_{(ik)}^{*} = \overline{q}_{ik}$
Case II	$s_{(ik)}^{\text{upp}} \geq H(q_{(ik)} = q_{(ik)}^{\text{upp}}) \geq s_{(ik)}^{\text{low}}$	$q_{(ik)}^{\text{root}} < \underline{q}_{ik}$	$q_{(ik)}^{*} = \underline{q}_{ik}$
		$\underline{q}_{ik} \leq q_{(ik)}^{\text{root}} \leq \overline{q}_{ik}$	$q_{(ik)}^{*} = q_{(ik)}^{\text{root}}$
		$q_{(ik)}^{\text{root}} > \overline{q}_{ik}$	$q_{(ik)}^{*} = \overline{q}_{ik}$
Case III	$H(q_{(ik)} = q_{(ik)}^{\text{upp}}) \leq s_{(ik)}^{\text{low}}$	Infeasible	

their respective partners, such that they both can benefit simultaneously (that is why the EU-WU pair $(i'k)$ is called as a blocking-pair) [48], [49].

Definition 2: (Stable pairing): A pairing $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{I}}$ is stable, if there exists no blocking-pair with respect to $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{I}}$.

To find $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{I}}$, we propose a stable-pairing (SP) algorithm, i.e., Algorithm-SP shown below. The key of our Algorithm-SP is essentially based on the Gale-Shapley (GS) theory [49], which is a classic methodology for yielding the stable matching between two separated groups of agents, with each individual agent having its own preference list. Due to the feature of stable matching, GS theory has been exploited in many studies for reaching the stable matching [48].

However, as a key difference from conventional GS algorithms, we exploit that each EU k's currently maximum reward (which is denoted by CMR_k) can be exactly quantified (instead of solely relaying on the preference list), and there thus exists no need for WU i to make a proposal (for pairing) to EU k if $\pi^*_{\text{EU}-k,(ik)} < \text{CMR}_k$ under the EU-WU pair (ik). Such a choice will effectively reduce the number of the WUs' unnecessary proposals to the EUs and thus reduce the number of iterations. Fig. 6 in Section VIII will validate this advantage. Specifically, in each round of iteration, our SP-Algorithm works as follows.

- Each WU i selects the most preferred EU $\hat{k}_i$ for its preference list, which also meets the following two conditions: (i) $\pi_{\text{EU}-\hat{k}_i,(i\hat{k}_i)} > \text{CMR}_{\hat{k}_i}$ and (ii) EU $\hat{k}_i$ did not reject WU i before. Then, WU i sends a proposal to this selected EU $\hat{k}_i$.
- After receiving the proposals from the WUs, each EU k updates its currently paired WU $\mu(k)$ if necessary, namely, if the currently best WU i^{best} can provide $\pi_{\text{EU}-k,(i^{\text{best}}k)} > \pi_{\text{EU}-k,(\mu(k),k)}$, then EU k updates its paired WU $\mu(k) = i^{\text{best}}$.

The above iterations continue until each EU k has a non-empty paired WU, and all WUs in $\mathcal{I}$ have been selected, i.e., $\Phi = \emptyset$.

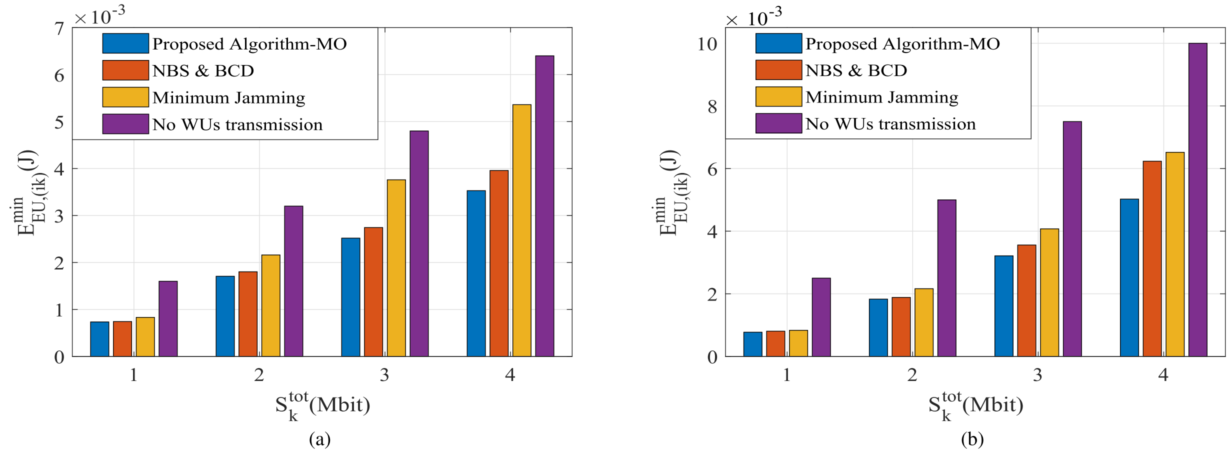

Fig. 5. Performance advantage of our cooperative jamming via NOMA with the WU's maximum energy capacity $E_i^{\max} = 0.1$J. (a) EU's local processing-rate $\mu_{\text{loc}} = 4$ Mbits/sec. (b) EU's local processing-rate $\mu_{\text{loc}} = 5$ Mbits/sec

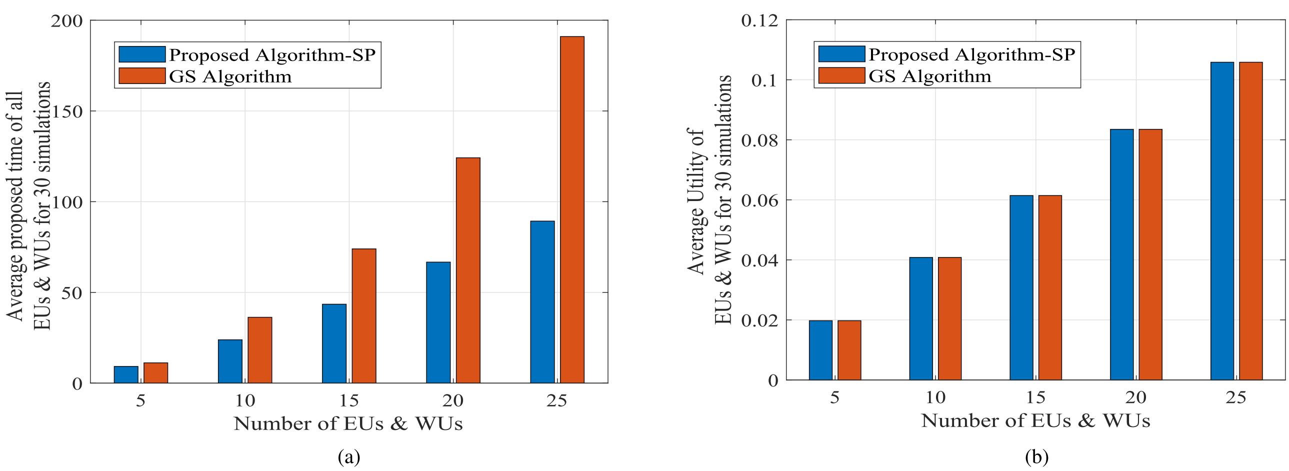

Fig. 6. Performance of our proposed Algorithm-SP in comparison with the conventional Gale-Shapley algorithm. (a) Number of proposals. (b) Average of utility.

Finally, the output of our SP-Algorithm yields the stable pairings $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{K}}$ between the EUs and WUs.

The convergence of SP-algorithm can be explained as follows.

Proposition 5: Our SP-algorithm converges within a finite number of the WUs' proposals.

Proof: The proof follows the operations of our SP-algorithm. Specifically, it is noticed that in our SP-algorithm, each WU i sequentially makes a proposal to the EUs in $\mathcal{K}$ according to WU i's preference list. Moreover, WU i will not re-propose (i.e., re-visit) to an EU who has rejected WU i before. In other words, each WU i will not make the proposal to a same EU twice. As a result, before for reaching the convergence of our SP-Algorithm, the total number of the proposals made by all WUs is limited (notice that the upper bound can be directly given by IK). ■

Proposition 6: Our SP-Algorithm yields a stable pairing $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{K}}$ according to Definition 2.

Proof: The key of the proof is to show that there exists no blocking-pair with respect to $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{K}}$ which is generated by our Algorithm-SP. Suppose that there exists another EU $k' \neq k$ (where $\mu^{\text{sta}}(k) = i$ under the current stable pairing) with $k' \succ_{\text{WU}-i} k$. Then, according to the operations of Algorithm-SP, WU i should make a proposal to EU k' in advance to EU k. However, since Algorithm-SP outputs $\mu^{\text{sta}}(k) = i$, it implies that either WU i was rejected by EU k' before or the current maximum reward of EU k' is greater than the reward which EU k' can obtain from the EU-WU pair (ik'). Both cases indicate that there should exist another WU i', there exists $i' \succ_{\text{EU}-k'} i$ from the perspective of EU k'. As a result, according to Definition 1, the pair of EU k' and WU i should not be a blocking-pair. We thus complete the proof. ■

Before leaving this section, it is noticed that our proposed Algorithm-SP, which is based on the GS theory, is ready to be implemented in a distributed manner. Specifically, in our Algorithm-SP, in each round of iteration, each unpaired WU sends its proposal to its most preferred EU for the purpose of pairing. Afterwards, from its collected proposals, each EU chooses the best WU to form a pair. Such an iterative process continues until no WU sends its proposal to any EU.

Proposed Algorithm-SP: to determine the stable pairings $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{I}}$ between the EUs and WUs.

Each EU k initializes its currently paired WU $\mu(k)=\emptyset$ and its currently maximum reward $\text{CMR}_k=0$. Initialize $\Phi=\mathcal{I}$.
Each EU k broadcasts its CMR_k to all WUs.
while $\Phi\neq\emptyset$ **do**
  for Each WU $i\in\Phi$ **do**
    From its preference-list $\mathcal{P}_{\text{WU}-i}$, WU i selects the most-top (i.e., the most preferred) EU $\hat{k}_i$ which also satisfies the following two conditions: (i) $\pi_{\text{EU}-\hat{k}_i,(i\hat{k}_i)}>\text{CMR}_{\hat{k}_i}$ and (ii) EU $\hat{k}_i$ did not reject WU i before. Then, WU i sends a proposal to this selected EU $\hat{k}_i$.
  end for
  for Each EU $k\in\mathcal{K}$ **do**
    Denote Ω_k as the set of WUs which have sent proposals to EU k in the current round of iteration, and denote $i^{\text{best}}=\arg\max_{i\in\Omega_k}\{\pi_{\text{EU}-k,(ik)}\}$ as the best WU in Ω_k from the perspective of WU k.
    if $\pi_{\text{EU}-k,(i^{\text{best}}k)}>\pi_{\text{EU}-k,(\mu(k),k)}$ **then**
      EU k sends a reject-signal to its currently paired WU $\mu(k)$, and updates $\Phi=\{\Phi\setminus\mu(k)\}\bigcup\{i^{\text{best}}\}$.
      EU k updates its $\mu(k)=i^{\text{best}}$ and its $\text{CMR}_k=\pi_{\text{EU}-k,(i^{\text{best}}k)}$. EU k broadcasts its CMR_k to all WUs in Φ.
    end if
  end for
end while
Output: Each EU k outputs its currently paired WU $\mu(k)$ as the stable pairings, i.e., $\mu^*(k)=\mu(k),\forall k\in\mathcal{K}$.

VIII. Numerical Results

A. Single-Pair Scenario With Fixed WU's Energy-Budget

We evaluate the performance of our proposed Algorithm-TEM in this subsection. To this end, we generate a scenario in which the BS is located at (0,0)m, and the eavesdropper is located at (100,0)m. The EU is randomly located within a plane whose center is (40,40)m and the radius is 25 m. Meanwhile, the WU is randomly located within a plane whose center is $(60,-40)$m and the radius is 25 m. We use the pass-loss model to generate the channel power gains, and in this tested case of EU k and WU i, their randomly generated channel power gains are $g_{i,\text{B}}=7.81\times10^{-9}$, $g_{i,\text{E}}=8.53\times10^{-9}$, $h_{k\text{B}}=6.14\times10^{-9}$, and $h_{k\text{E}}=1.62\times10^{-8}$. Moreover, similar to [18], we set the channel estimation error δ as 10% of the corresponding path loss, and set the power of the background noise as $n_{\text{B}}=n_{\text{E}}=10^{-10}$W. We set the channel bandwidth $W=20$MHz. Similar to [34], [46], we set EU k's latency-limit $T_k^{\max}=1$sec and its maximum transmit-power $Q_k^{\max}=0.2$W, and set WU i's maximum transmit-power $P_i^{\max}=0.4$W. In addition, according to to the parameter-settings in [18], [47], we consider that processing each bit requires 100 CPU-cycles and set each EU's CPU-rate as 400 MHz which corresponds to its processing-rate as $\mu_{\text{loc}}=4$Mbits per second and the ES's CPU-rate as 4 GHz which corresponds to its processing-rate $\mu_{\text{ecs}}=40$ Mbits per second.

Fig. 2 presents the detailed examples to illustrate $E^{\text{sub,min}}_{(t_{(ik)})}$ versus $t_{(ik)}$, which thus illustrate our rationale behind Algorithm-TEM, i.e., executing a line-search on $t_{(ik)}$ and invoking Subroutine-TEM to obtain $E^{\text{sub,min}}_{(t_{(ik)})}$ for each $t_{(ik)}$ being evaluated. We test three cases of $e^{\text{bud}}_{(ik)}=0.04$J, 0.05 J, and 0.06 J in the three respective subplots, and in each subplot, we vary $S_k^{\text{tot}}=2,3$, and 4Mbits. As shown in Fig. 2, neither a too small value nor a too large value of $t_{(ik)}$ will be beneficial to reduce $E^{\text{sub,min}}_{(t_{(ik)})}$, which thus motivates us to find the optimal $t^*_{(ik)}$ for minimizing $E^{\text{sub,min}}_{(t_{(ik)})}$.

Fig. 3 illustrates the accuracy of our Algorithm-MO to solve Problem (EnergyAllo). Regarding the considered bargaining model, we set that both WU i's and EU k's bargaining powers (i.e., $\beta_{\text{WU,i}}$ and $\beta_{\text{EU,k}}$) are randomly selected according to a uniform distribution within [0,1], and we set $E_i^{\max}=0.1$J for each WU i. For the purpose of comparison, we also use a line-search method with a very small step-size to enumerate $e^{\text{bud}}_{(ik)}$ directly to solve Problem (EnergyAllo). Fig. 3(a) shows the comparison between the optimal objective function values of Problem (EnergyAllo) achieved by Algorithm-MO and those achieved by the enumeration method, by varying EU k's total workload S_k^{tot} from 1Mbits to 4Mbits. Fig. 3(b) demonstrates the comparison of EU k's optimal net-rewards versus different S_k^{tot}, and Fig. 3(c) demonstrates the comparison of WU k' optimal net-rewards versus different S_k^{tot}. All the three subplots show that our Algorithm-MO can achieve the solutions exactly same as those of the enumeration method, which thus validates the accuracy of Algorithm-MO. In particular, the results in Fig. 3(b) demonstrate that EU k's optimal net-reward gradually increases when its computation-requirement S_k^{tot} increases. This result indicates that by exploiting the proposed cooperative jamming, the EU's achieved net-reward (due to its reduced energy consumption) will be more significant with a growing total computation-requirement, which is consistent with our expectation. However, due to providing more energy for cooperative jamming when S_k^{tot} grows, WU i's optimal net-reward gradually decreases as shown in Fig. 3(c), which is also a reasonable trend. Nevertheless, the fairness still is maintained between the EU's and WU's respectively achieved net-rewards, since the NBS is utilized for the formulation of Problem (EnergyAllo). To further demonstrate the advantage of our proposed Algorithm-MO, we show the comparison between the computation-time used by our Algorithm-MO and the computation-time used by the exhaustive search method for solving Problem (EnergyAllo-E) directly. Fig. 4 demonstrates the comparison results. For all the tested cases shown in Fig. 4, our Algorithm-MO can effectively reduce the computation-time compared to the exhaustive search method (all these results are obtained with a PC of Intel(R) Core(TM)i7-9700 CPU@3.6 GHz).

Fig. 5 further demonstrates the advantage of exploiting the cooperative jamming provided by NOMA. Specifically, in Fig. 5, we demonstrate the EU's minimum energy consumption which is provided by the optimal solution of Problem (EnergyAllo) by using our proposed Algorithm-MO. For the purpose of comparison, we also use three different benchmark schemes. In the first benchmark scheme, we adopt the block coordinate descent (BCD) algorithm as [50] to solve Problem (EU-TEM) and again use the polyblock approximation to determine the WU's optimal energy provisioning (we refer to this scheme as "NBS $\&$ BCD"). In particular, the BCD method has been considered as an effective approach for addressing complicated optimization problems with coupled decision variables. However, due to the non-convexity of Problem (EU-TEM), the BCD based scheme may suffer from being trapped by some local optimums. In the second benchmark scheme, WU i sets its transmit-power such that constraint (7) is strictly binding, i.e., WU i just sets its transmit-power as the minimum required level for completing sending its data volume, and no additional transmit-power is provided by WU i for jamming the eavesdropper. We denote this benchmark scheme as the "minimum jamming". The third benchmark scheme does not invoke any WU's jamming (or transmission), which is denoted by "no WD's transmission". The results in Fig. 5(a) demonstrate the comparison results under the EU's local processing-rate $\mu_{\text{loc}} = 4$Mbits/sec, and Fig. 5(b) demonstrate the results under $\mu_{\text{loc}} = 5$Mbits/sec. The results in both subplots validate that our proposed cooperative jamming via NOMA can effectively reduce the EU's total energy consumption in comparison with the three benchmark schemes, which is consistent with our expectation well.

Finally, Fig. 6 shows the performance of our proposed Algorithm-SP, which aims at determining the stable pairings $\{\mu^{\text{sta}}(k)\}_{k\in\mathcal{I}}$ between the EUs and WUs, in comparison with the conventional Gale-Shapley (GS) [49] based algorithm. Specifically, Fig. 6(a) shows the comparison between the total number of the proposals (made by the WUs) of our Algorithm-SP and that of the conventional GS algorithm. For the purpose of testings, we vary the number of the EUs (and the WUs) from 5 to 25. In each tested case, we set that each EU's computation-requirement is randomly generated according to a uniform distribution within [1,4]Mbits, and each WU's maximum energy-capacity and data-volume are randomly yet uniformly generated from $[0.1, 0.2]$J and [4,8]Mbits, respectively. Moreover, each result shown in Fig. 6(a) represents the average result of 30 realizations of the above randomly generated parameters. As shown in Fig. 6(a), our proposed Algorithm-SP can effectively reduce the total number of the proposals which are made by the WUs during the iterative process, in comparison with the conventional GS-Algorithm. Such an advantage is meaningful, since it not only effectively reduces the number of the iterations for reaching the stable pairings between the EUs and WUs, but also helps save the WUs' energy consumptions (for sending their proposals to the EUs). Correspondingly, Fig. 6(b) shows the comparison between the consequent total net-reward of all EU-WU pairs achieved by our Algorithm-SP and the total net-reward achieved by the conventional GS algorithm. The results demonstrate that our Algorithm-SP can achieve the exactly same total net-reward (of all EU-WU pairs) as the conventional GS-Algorithm, which thus validates the accuracy of our Algorithm-SP.

IX. Conclusion

We have investigated NOMA assisted secure computation offloading under the eavesdropping-attack, in which a WU forms a NOMA pair with an EU to provide a cooperative jamming to the eavesdropper while gaining the opportunity of sending its data. Focusing on the EU-WU pair, we firstly quantified the EU's offloading throughput with the WU's cooperative jamming and studied the joint optimization of the EU's computation offloading and the EU-WU's NOMA transmission for minimizing the EU's total energy consumption. We then investigated the WU's optimal energy-provisioning for the EU-WU pair such that both the EU and WU can benefit from the cooperative jamming in a fairness manner, which is formulated as a Nash bargaining problem. By identifying the monotonic feature of bargaining problem, we proposed a polyblock approximation based algorithm for determining the WU's optimal energy-provisioning to achieve the win-win solution for the EU-WU pair. Using our solution for the EU-WU pair as a basis, we further investigated the scenario of multiple EUs and WUs, and aimed at finding the stable pairing between the EUs and WUs. We proposed an algorithm, which is based on the Gale-Shapley theory while exploiting the quantitative feature of EUs' and WUs' net-rewards, to achieve the stable EU-WU pairings. Numerical results have been provided to validate our proposed algorithms and demonstrate the advantage of our proposed NOMA assisted computation offloading via cooperative jamming. In our future work, we will further investigate a time-varying scenario in which each WU may dynamically join and leave the networks. Another important direction is to further take the secrecy of the WUs' transmissions into account, such that we can provide secrecy-provisioning for both the EUs and WUs.

Appendix A
A Benchmark Case with no WU's Transmission

We consider a benchmark case in which no WU's transmission is allowed. As a result, the EU's computation offloading is subject to the eavesdropping without any cooperative jamming from the WU. To evaluate the EU's total energy consumption, we formulate the following optimization problem.

$$\text{(TEM-WO):} E_{\text{EU},k}^{\text{wo}} = \min q_k t_k + \rho \mu_{\text{loc}}^2 \left(S_k^{\text{tot}} - s_k\right)$$

$$\text{subject to} : \max\{\frac{S_k^{\text{tot}} - s_k}{\mu_{\text{loc}}}, t_k + \frac{s_k}{\mu_{\text{ecs}}}\} \leq T_k^{\max}, \tag{57}$$

$$\frac{s_k}{t_k} \leq \left[W \log_2(1 + \frac{q_k h_{k\text{B}}}{n_{\text{B}}}) - W \log_2(1 + \frac{q_k h_{k\text{E}}^{\max}}{n_{\text{E}}})\right]^+, \tag{58}$$

$$0 \leq q_k \leq Q^{\max}, \tag{59}$$

$$0 \leq s_k \leq S_k^{\text{tot}}, \tag{60}$$

$$\text{variables:} s_k, q_k, \text{ and } 0 \leq t_k \leq T_k^{\max}.$$

Problem (TEM-WO) can be regarded as a special case of Problem (EU-TEM) but with $p_{(ik)} = 0$. Thus, with proper modifications, our Algorithm-TEM (with its Subroutine-TEM) is also applicable for solving Problem (TEM-WO).

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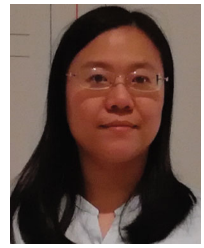

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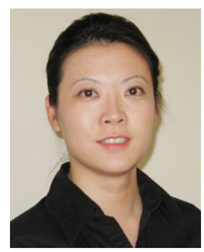

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