

QECO: A QoE-Oriented Computation Offloading Algorithm based on Deep Reinforcement Learning for Mobile Edge Computing

Iman Rahmati , Hamed Shah-Mansouri , and Ali Movaghar 

Abstract—In the realm of mobile edge computing (MEC), efficient computation task offloading plays a pivotal role in ensuring a seamless quality of experience (QoE) for users. Maintaining a high QoE is paramount in today's interconnected world, where users demand reliable services. This challenge stands as one of the most primary key factors contributing to handling dynamic and uncertain mobile environment. In this study, we delve into computation offloading in MEC systems, where strict task processing deadlines and energy constraints can adversely affect the system performance. We formulate the computation task offloading problem as a Markov decision process (MDP) to maximize the long-term QoE of each user individually. We propose a distributed QoE-oriented computation offloading (QECO) algorithm based on deep reinforcement learning (DRL) that empowers mobile devices to make their offloading decisions without requiring knowledge of decisions made by other devices. Through numerical studies, we evaluate the performance of QECO. **Simulation results reveal that compared to the state-of-the-art existing works, QECO increases the number of completed tasks by up to 14.4%, while simultaneously reducing task delay and energy consumption by 9.2% and 6.3%, respectively. Together, these improvements align with user preferences, resulting in a significant average QoE enhancement of 37.1%. This substantial improvement is achieved by accurately accounting for user dynamics and edge server workloads while making intelligent offloading decisions. This highlights QECO's effectiveness in enhancing MEC systems.**

Index Terms—Mobile edge computing, computation task offloading, quality of experience, deep reinforcement learning.

I. INTRODUCTION

MOBILE edge computing (MEC) [1] has emerged as a promising technological solution to overcome the challenges faced by mobile devices (MDs) when performing high computational tasks, such as real-time data processing and artificial intelligence applications [2] [3]. In spite of the MDs' technological advancements, their limited computing power and energy may lead to task drops, processing delays, and an overall poor user experience. By offloading intensive tasks to nearby edge nodes (ENs), MEC effectively empowers computation capability and reduces the delay and energy consumption. This improvement enhances the users' QoE, especially for time-sensitive computation tasks [4] [5].

Efficient task offloading in MEC is a complex optimization challenge due to the dynamic nature of the network and the

variety of MDs and servers involved [6] [7]. In particular, determining the optimal offloading strategy, scheduling the tasks, and selecting the most suitable EN for task offloading are the main challenges that demand careful consideration. **In addition to the dynamic network changes, the uncertain requirements and sensitive latency properties of computation tasks pose nontrivial challenges that can significantly impact the MEC systems.**

To cope with the dynamic nature of the network, recent research has proposed several task offloading algorithms using machine learning methods. In particular, reinforcement learning (RL) [8] holds promises to determine optimal decision-making policies by capturing the dynamics of environments and learning strategies for accomplishing long-term objectives. However, the traditional RL methods are not efficient to handle environments with high-dimensional state spaces. Deep reinforcement learning (DRL) combines traditional RL with deep neural networks to intelligently respond to the unknown and dynamic system when addressing the limitations of RL-based algorithms. Despite these advancements, task offloading still faces significant challenges in real-world scenarios with multiple MDs and ENs. In such scenarios, it is essential for MDs to make offloading decisions independently without prior knowledge of other MDs' tasks and offloading models. However, existing works fail to adequately address this challenge. In addition, QoE is a time-varying performance measure that reflects user satisfaction and is not affected only by delay [9], but also by energy consumption [10]. Albeit some existing works have investigated the trade-off between delay and energy consumption [11], they fail to properly estimate the QoE value and address the user demands and requirements. Although deep Q-networks (DQN) offer a valuable tool, a more comprehensive approach is required to accurately estimate the QoE while addressing the aforementioned challenges in practical scenarios where global information is limited.

In this study, we delve into the computation task offloading problem in MEC systems, where strict task processing deadlines and energy constraints can adversely affect the system performance. **We propose a distributed QoE-oriented computation offloading (QECO) algorithm to efficiently handle task offloading in uncertain loads at ENs.** This algorithm empowers MDs to make offloading decisions utilizing only locally observed information, such as task size, queue details, battery status, and historical workloads at the ENs. **To capture the dynamic nature of the MEC environment, we employ the dueling double deep Q-network (D3QN), which is a refined**

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improvement over standard DQN model. By integrating both double Q-learning [12] and dueling network architectures [13], D3QN reduces overestimation bias in action-value predictions and more accurately distinguishes the relative importance of states and actions. We also incorporate long short-term memory (LSTM) [14] into our D3QN model to continuously estimate dynamic workloads at ENs. This enables MDs to effectively handle the uncertainty of the MEC environment, where global information is limited, and proactively adjust the offloading strategies to improve their long-term QoE estimation. By adopting the appropriate policy based on each MD's specific requirements at any given time, the QECO algorithm significantly improves the QoE for individual users.

Our main contributions are summarized as follows:

- *Task Offloading Problem in the MEC System:* We consider queuing systems for MDs and ENs and formulate the task offloading problem as an MDP for time-sensitive tasks, taking into account the time-varying system environments (e.g., the arrival of new tasks, and the computational requirement of each task). We aim to maximize the long-term QoE, which reflects the task completion rate, task delay, and energy consumption of MDs. Our problem formulation effectively utilizes the resources and properly handles the dynamic fluctuations of workload at ENs.
- *DRL-based Offloading Algorithm:* To solve the problem of long-term QoE maximization in highly dynamic mobile environments, we propose the QECO algorithm based on DRL, which empowers each MD to make offloading decisions independently, without prior knowledge of other MDs' tasks and offloading models. Focusing on the MD's QoE preference, our approach leverages D3QN and LSTM to prioritize and strike an appropriate balance between QoE factors while accounting for workload uncertainty at the ENs. QECO empowers MDs to anticipate the EN's load level over time, leading to more accurate offloading strategies. We also analyze the training convergence and computational complexity of the proposed algorithm.
- *Performance Evaluation:* We conduct comprehensive experiments to evaluate QECO's performance and training convergence against baseline schemes as well as two state-of-the-art existing works. The results demonstrate that our algorithm effectively utilizes the computing resources of MDs and ENs while taking the dynamic workloads at ENs into consideration. In particular, it converges more quickly than vanilla DQN and DDQN methods. QECO also improves average QoE by 37.1% and 29.8% compared to the potential game-based offloading algorithm (PGOA) [15] and distributed and collective DRL-based offloading algorithm (DCDRL) [16], respectively.

The structure of this paper is as follows. Section II reviews the related works. Section III presents the system model, followed by the problem formulation in Section IV. In Section V, we present the algorithm, while Section VI provides an evaluation of its performance. Finally, we conclude in Section VII.

II. RELATED WORK

In recent years, numerous studies have focused on computation offloading in MEC, covering a broad range of applications, including IoTs [17], Internet of Vehicles (IoVs) [18], [19], and Industrial IoT (IIoT) [20]. To effectively tackle the challenges of MEC arising from the ever-changing nature of networks, recent research highlights the effectiveness of DRL in adapting to environmental changes and learning optimal strategies. In this section, we explore the current DRL-based state-of-the-art works and discuss their strengths and limitations. Table I provides an intuitive comparison of these works.

A. DRL-based Optimization Methods for MEC

Mainly, there are two primary categories of related researches based on the target objectives in resource management for MEC, single-objective optimization and multi-objective optimization methods, where DRL are mainstream optimization techniques.

1) *Single-Objective Optimization*: There has been a large amount of research studying single-objective optimization problems in the context of MEC, where only one objective is considered for optimization, e.g., delay or energy consumption. Sun *et al.* in [35] explored both computation offloading and service caching problems in MEC. They formulated an optimization problem that aims to minimize the long-term average service delay. They then proposed a hierarchical DRL framework, which effectively handles both problems under heterogeneous resources. Due to the dynamic nature of MEC systems, Li *et al.* [25] proposed an integrated optimization learning framework called DROO, which leverages past experience and model information to provide fast and robust real-time offloading control. Li *et al.* [39] proposed an offloading strategy through the DRL algorithm to design the system, where a DQN is used to automatically learn offloading decisions, optimize system performance, and train a neural network (NN) to predict offloading actions. To reduce the total delay and waiting time of mobile vehicle tasks, Tang *et al.* [40] established a dynamic offloading model of multiple mobile vehicles, dividing its tasks into sequential subtasks, and making the offloading decision more refined.

To minimize energy consumption, Munir *et al.* [29] developed a semi-distributed approach using a multi-agent RL framework for self-powered MEC. Zhou *et al.* in [24] proposed a Q-learning approach, which is an extension of RL to achieve optimal resource allocation strategies and computation offloading. Dai *et al.* in [27] introduced the integration of action refinement into DRL and designed an algorithm based on deep deterministic policy gradient (DDPG) to concurrently optimize resource allocation and computation offloading. Wang *et al.* [52] investigated the computation offloading problem in MEC systems with mobile awareness in cellular networks, proposing a joint task offloading and computation allocation based on mobile-aware migration. Their approach focuses on the task offloading cost caused by user mobility. In [28], Zhao *et al.* proposed a computation offloading algorithm based on DRL, which addresses the competition for wireless channels to optimize long-term downlink utility. In [32], the authors proposed an offloading algorithm using deep Q-learning for

wireless-powered IoT devices in MEC systems. This algorithm aims to minimize the task drop rate while the devices solely rely on harvested energy for operation.

2) *Multi-Objective Optimization*: In nature, multiple possibly conflicting objectives exist in UAV-assisted MEC. For example, one should consider the tradeoff between delay and energy consumption in the task offloading decision-making process; one should balance the energy consumption and flying speed when planning a UAV's trajectory. Some research efforts have been dedicated to multi-objective optimization problems. Huang *et al.* in [21], focused on a wireless-powered MEC and proposed a DRL-based approach, capable of attaining near-optimal decisions. This is achieved by selectively considering a compact subset of candidate actions in each iteration. Liu *et al.* in [22] investigated a two-timescale computing offloading and resource allocation problem and proposed a resource coordination algorithm based on multi-agent DRL, which can generate interactive information along with resource decisions. Wu *et al.* in [23] introduced a stochastic game-based resource allocation in the SDN-based MEC network. They used an MDP and proposed a multi-agent RL method to minimize both energy consumption and processing delay. Chen *et al.* in [25] addressed a joint optimization problem involving computation offloading and resource allocation, aiming to reduce both task processing delay and energy consumption across all MDs. To optimize privacy protection and quality of service, authors in [26] investigated the joint computation offloading and power allocation problems for the IIoT network. They modeled the problem as an MDP and proposed a multi-agent deep Q-network (DQN)-based algorithm.

To reflecting real-world scenarios more accurately, the authors applied queuing theory to model MEC systems. It helps in modeling the dynamic nature of network, allowing MEC systems to allocate computational and transmission resources more efficiently. Liao *et al.* in [30] introduced a double DQN (DDQN)-based algorithm for performing online computation offloading in MEC. This algorithm optimizes transmission power and scheduling of CPU frequency when minimizing both task computation delay and energy consumption. To address the privacy-aware computation offloading problem, Wu *et al.* in [31] modeled the problem as an MDP and proposed a DQN-based method to optimize the computation rate and energy consumption in a queuing-based IIoT network. Huang *et al.* in [33] proposed a DRL-based method based on a partially observable MDP (POMDP), which guarantees the deadlines of real-time tasks while minimizing the total energy consumption of MDs. This algorithm effectively tackles the challenges of dynamic resource allocation in large-scale heterogeneous networks. Gong *et al.* in [34] proposed a DRL-based network structure in the IIoT systems to jointly optimize task offloading and resource allocation to achieve lower energy consumption and decreased task delay. To optimize delay and energy consumption, Wu *et al.* in [36] investigated the computation offloading problem in a queuing-based MEC IIoT system. They modeled the problem as a POMDP and proposed a multi-agent proximal policy optimization (PPO)-based method to obtain the optimal offloading strategy in dynamic environments. Tang *et al.* in [37] investigated the task

offloading problem for indivisible and deadline-constrained computational tasks in MEC systems. The authors proposed a distributed DRL-based offloading algorithm designed to handle uncertain workload dynamics at the ENs. In [38], Gao *et al.* introduced an attention-based multi-agent algorithm designed for decentralized computation offloading.

B. Analysis and Motivation

Despite the ample research efforts dedicated, task offloading still faces significant challenges in real-world scenarios with multiple MDs and ENs. We discuss these challenges from two aspects, i.e., system modeling and optimization techniques.

1) *System modeling*: Some existing works, see [21]–[24], primarily investigate simplified MEC networks, focusing on single MEC network models, considering only single-server or single-user scenarios, which may not always reflect real-world scenarios. Some other in [21], [22] do not account for delay-sensitive tasks and may overlook critical performance factors in real-time applications. Comparing with the aforementioned works [10]–[15], we consider a different and more realistic MEC scenario involving multiple MDs and ENs, which take into account delay-sensitive tasks with processing deadlines. This is challenging to address, because the processing deadlines will affect the load level dynamics at the edge nodes and hence affect the delay of the offloaded tasks. Besides, some works with more advanced scenarios do not take into account the underlying resources scheduling systems. As a result, the processing and transmission of each task should always be accomplished within one time slot (or before the arrival of the next task), which may not always be guaranteed in practice. Different from those works [10]–[15], we consider delay-sensitive tasks together with queuing systems and take into account the practical scenario where the processing and transmission of each task can continue for multiple time slots.

2) *Algorithm design*: On the other hand, due to the limited processing capacities of ENs, the processing capacity that an EN allocates to an MD depends on the EN's workload each time. Treating this dynamic workload as part of the environment can negatively impact system performance and requires careful consideration. Some studies did not take into account the challenges of a dynamic network environment. For instance, in [25], MDs are assumed to have sufficient transmission and computation resources from ENs, which may not always align with real-world conditions. While the works of [26]–[28] investigated the limited resources in MEC, they did not consider the dynamic workload at ENs in decision making processes, imposing significant challenges in overall system performance. Although some existing works [34]–[38] have addressed the load levels at the edge nodes and proposed task offloading algorithms, however, these algorithms require global information of the system and may incur high signaling overhead. Different from those works [17]–[20], we aim to propose a DRL-based distributed algorithm that can address the unknown load dynamics at the edge nodes. It should also enable each MDs to make its offloading decision without knowing the information (e.g., task models, offloading decisions) of other mobile devices.

3) *Optimization objectives*: Considering delay and energy consumption as optimization objectives is one of the main research streams on MEC. Most existing works optimize the two individually. The fact that the conflicts between objectives are neglected easily leads to biased optimization results. Meanwhile, a few studies focus on the maximization of the number of completed tasks, which also reflects the benefits that an MEC system brings to us. Therefore, delay, energy consumption and the number of completed tasks are three important concerns when designing MEC systems. However, to the best of our knowledge, little research has been dedicated to a system with these three objectives taken into account. Different from the works [9]–[13], which only focus on delay-optimal optimization or energy-efficient optimization, we are motivated to emphasize MEC system with delay, energy consumption and the number of completed tasks as three objectives for QoE optimization. Other studies [14]–[20] mostly have investigated the trade-off between two or three of these factor but they fail to properly address the user demands and fulfill QoE requirements. QoE is a time-varying performance measure that reflects user satisfaction, where each user may have unique QoE requirements according to the MDs individual preferences. In contrast [14]–[20], to effectively address personalized QoE optimization, we define an adaptive trade-off between task completion and cost reduction, where a weighted sum between completion delay and energy consumption plays as an associated cost. Each MD dynamically adjusts these weights to reflect the importance of different factors based on its energy modes.

These works in [21], [22] do not account for delay-sensitive tasks and may overlook critical performance factors in real-time applications. Besides, these studies [21]–[24] primarily investigate simplified MEC networks, focusing on single MEC network models, considering only single-server or single-user scenarios, which may not always reflect real-world scenarios. Moreover, due to the absence of robust underlying resource scheduling systems, issues such as data congestion during transmission and resource allocation can arise, leading to suboptimal system performance. Therefore, more accurate MEC models are needed to address the complexities of dynamic resource scheduling in large-scale scenarios. These works did not take into account the challenges of a dynamic network environment. For instance, in [25], MDs are assumed to have sufficient transmission and computation resources from ENs, which may not always align with real-world conditions. While the works of [26]–[28] investigated the limited resources in MEC, they did not consider the dynamic workload at ENs in decision making processes, imposing significant challenges in overall system performance. In above research [29]–[33], while models were employed in several parts of the system, the offloading process was not approached as a holistic queuing system. Due to the limited processing capacities of ENs, the processing capacity that an EN allocates to an MD depends on the EN’s workload each time. Treating this dynamic workload as part of the environment can negatively impact system performance and requires careful consideration. Specifically, offloaded tasks may experience significant processing delays or be dropped if their deadlines expire. Some existing works have addressed the load levels at the edge nodes and proposed task offloading algorithms. However, these algorithms in [34]–[38] require global information of the system and may incur high signaling overhead.

TABLE I
COMPARISON OF RELATED WORKS

| Paper | Problem | Objective | Method | Limitation |
|-------|---|--|----------------------------------|--|
| [22] | Resource allocation and computation offloading | Minimize execution cost | Multi-agent actor-critic network | Not consider delay-sensitive tasks |
| [23] | Stochastic game-based resource allocation | Minimize energy consumption and processing delay | Multi-agent RL | Not consider tasks with maximum delay tolerance |
| [24] | Resource allocation and computation offloading | Minimize energy consumption of the entire system | DDQN | Only for a single MEC system model |
| [26] | Joint power allocation and computation offloading | Optimization of privacy protection and quality of service. | Multi-agent actor-critic network | Not take user's demand into consideration |
| [27] | Resource allocation and computation offloading | Minimize energy consumption | DDPG | Not take user's demand into consideration |
| [28] | User association and resource allocation | Optimize downlink utility | Multi-agent D3QN | Not consider system delay and energy consumption |
| [30] | Online computation offloading | Minimize computation delay and energy consumption | DDQN | Only for a single MEC system model |
| [31] | Privacy aware computation offloading | Optimization of computation rate and energy consumption | Actor-critic network | Not take user's demand into consideration |
| [32] | Energy harvesting computation offloading | Minimize drop rate and energy consumption. | DQN | Not consider computation delay |
| [33] | Computation offloading | Optimize drop rate and energy consumption | DDPG | Not consider computation delay |
| [34] | Resource allocation and computation offloading | Minimize task computation delay and energy consumption | DRL | Not take user's demand into consideration |
| [35] | Computation offloading and service caching | Minimize average service delay | Hierarchical DRL | Not consider system energy consumption |
| [36] | Computation offloading | Optimize delay and energy consumption | Multi-agent PPO | Not consider tasks with maximum delay tolerance |
| [37] | Computation offloading | Minimize drop rate and computation delay. | D3QN + LSTM | Not consider system energy consumption |
| [38] | Decentralized computation offloading | Optimize system cost and completion rates | Multi-agent actor-critic network | Not take user's demand into consideration |
| QECO | Computation offloading | Maximize the QoE of each MD individually | D3QN + LSTM | |

III. SYSTEM MODEL

We investigate a MEC system consisting of a set of MDs denoted by $\mathcal{I} = \{1, 2, \dots, I\}$, along with a set of ENs denoted by $\mathcal{J} = \{1, 2, \dots, J\}$, where I and J represent the number of MDs and ENs, respectively. We regard time as a specific episode containing a series of T time slots denoted by $\mathcal{T} = \{1, 2, \dots, T\}$, each representing a duration of τ seconds. As shown in Fig. 1, we consider two separate queues for each MD to organize tasks for local processing or dispatching to ENs, operating in a first-in-first-out (FIFO) manner. The MD's scheduler is responsible for assigning newly arrived tasks to each of the queues at the beginning of the time slot. On the other hand, we assume that each EN $j \in \mathcal{J}$ consists of I FIFO queues, where each queue corresponds to an MD $i \in \mathcal{I}$. When each task arrives at an EN, it is enqueued in the corresponding MD's queue.

We define $z_i(t)$ as the index assigned to the computation task arriving at MD $i \in \mathcal{I}$ in time slot $t \in \mathcal{T}$. Let $\lambda_i(t)$ denote the size of this task in bits. **The size of task $z_i(t)$ is selected randomly and uniformly from a discrete set $\Lambda = \{\lambda_1, \lambda_2, \dots, \lambda_\theta\}$, where θ represents the number of these values. Note that task sizes are drawn from a discrete set since, in many applications, tasks typically come with predefined sizes, [39], [40], [41]. We consider $\lambda_i(t) \in \Lambda \cup \{0\}$ to include the case that no task has arrived.** We also denote the task's processing density as $\rho_i(t)$ that indicates the number of CPU

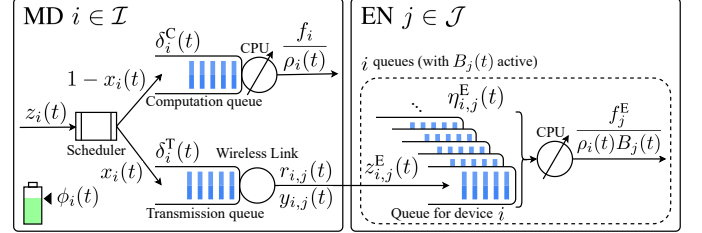


Fig. 1. An illustration of MD $i \in \mathcal{I}$ and EN $j \in \mathcal{J}$ in the MEC system.

cycles required to complete the execution of a unit of the task. Furthermore, we denote the deadline of this task by $\Delta_i(t)$ which is the number of time slots that the task must be completed to avoid being dropped.

We define two binary variables, $x_i(t)$ and $y_{i,j}(t)$ for $i \in \mathcal{I}$ and $j \in \mathcal{J}$ to determine the offloading decision and offloading target, respectively. Specifically, $x_i(t)$ indicates whether task $z_i(t)$ is assigned to the computation queue ($x_i(t) = 0$) or to the transmission queue ($x_i(t) = 1$), and $y_{i,j}(t)$ indicates whether task $z_i(t)$ is offloaded to EN $j \in \mathcal{J}$. If the task is dispatched to EN j , we set $y_{i,j}(t) = 1$; otherwise, $y_{i,j}(t) = 0$.

A. Communication Model

We consider that the tasks in the transmission queue are dispatched to the appropriate ENs via the MD wireless interface.

We denote the transmission rate of MD i 's interface when communicating with EN $j \in \mathcal{J}$ in time t as $r_{i,j}(t)$. In time slot $t \in \mathcal{T}$, if task $z_i(t)$ is assigned to the transmission queue for computation offloading, we define $l_i^T(t) \in \mathcal{T}$ to represent the time slot when the task is either dispatched to the EN or dropped. We also define $\delta_i^T(t)$ as the number of time slots that task $z_i(t)$ should wait in the queue before transmission. It should be noted that MD i computes the value of $\delta_i^T(t)$ before making a decision. The value of $\delta_i^T(t)$ is computed as follows:

$$\delta_i^T(t) = \left[\max_{t' \in \{0,1,\dots,t-1\}} l_i^T(t') - t + 1 \right]^+, \quad (1)$$

where $[\cdot]^+ = \max(0, \cdot)$ and $l_i^T(0) = 0$ for the simplicity of presentation. Note that the value of $\delta_i^T(t)$ only depends on $l_i^T(t')$ for $t' < t$. If MD $i \in \mathcal{I}$ schedules task $z_i(t)$ for dispatching in time slot $t \in \mathcal{T}$, then it will either be dispatched or dropped in time slot $l_i^T(t)$, which is

$$l_i^T(t) = \min \left\{ t + \delta_i^T(t) + \lceil D_i^T(t) \rceil - 1, t + \Delta_i(t) - 1 \right\}, \quad (2)$$

where $D_i^T(t)$ refers to the number of time slots required for the transmission of task $z_i(t)$ from MD $i \in \mathcal{I}$ to EN $j \in \mathcal{J}$. We have

$$D_i^T(t) = \sum_{j \in \mathcal{J}} y_{i,j}(t) \frac{\lambda_i(t)}{r_{i,j}(t)\tau}. \quad (3)$$

Let $E_i^T(t)$ denote the energy consumption of the transmission from MD $i \in \mathcal{I}$ to EN $j \in \mathcal{J}$. We have

$$E_i^T(t) = D_i^T(t)p_i^T(t)\tau, \quad (4)$$

where $p_i^T(t)$ represents the power consumption of the communication link of MD $i \in \mathcal{I}$ in time slot t .

B. Computation Model

The computation tasks can be executed either locally on the MD or on the EN. In this subsection, we provide a detailed explanation of these two cases.

1) *Local Execution*: We model the local execution by a queuing system consisting the computation queue and the MD processor. Let f_i denote the MD i 's processing power (in cycle per second). When task $z_i(t)$ is assigned to the computation queue at the beginning of time slot $t \in \mathcal{T}$, we define $l_i^C(t) \in \mathcal{T}$ as the time slot during which task $z_i(t)$ will either be processed or dropped. If the computation queue is empty, $l_i^C(t) = 0$. Let $\delta_i^C(t)$ denote the number of remaining time slots before processing task $z_i(t)$ in the computation queue. We have:

$$\delta_i^C(t) = \left[\max_{t' \in \{0,1,\dots,t-1\}} l_i^C(t') - t + 1 \right]^+. \quad (5)$$

In the equation above, the term $\max_{t' \in \{0,1,\dots,t-1\}} l_i^C(t')$ denotes the time slot at which each existing task in the computation queue, which arrived before time slot t , is either processed or dropped. Consequently, $\delta_i^C(t)$ denotes the number of time slots that task $z_i(t)$ should wait before being processed. We denote the time slot in which task $z_i(t)$ will be completely

processed by $l_i^C(t)$ if it is assigned to the computation queue for local processing in time slot t . We have

$$l_i^C(t) = \min \left\{ t + \delta_i^C(t) + \lceil D_i^C(t) \rceil - 1, t + \Delta_i(t) - 1 \right\}. \quad (6)$$

The task $z_i(t)$ will be immediately dropped if its processing is not completed by the end of the time slot $t + \Delta_i(t) - 1$. In addition, we introduce $D_i^C(t)$ as the number of time slots required to complete the processing of task $z_i(t)$ on MD $i \in \mathcal{I}$. It is given by:

$$D_i^C(t) = \frac{\lambda_i(t)}{f_i\tau/\rho_i(t)}. \quad (7)$$

To compute the MD's energy consumption in the time slot $t \in \mathcal{T}$, we define $E_i^L(t)$ as:

$$E_i^L(t) = D_i^C(t)p_i^C\tau, \quad (8)$$

where $p_i^C = 10^{-27}(f_i)^3$ represents the energy consumption of MD i 's CPU frequency [42].

2) *Edge Execution*: We model the edge execution by the queues associated with MDs deployed at ENs. **If computation task $z_i(t')$ is dispatched to EN j in time $t' < t$, we let $z_{i,j}^E(t)$, $\lambda_{i,j}^E(t)$ (in bits), and $\rho_{i,j}^E(t)$ denote the unique index of the task, the task size, and the number of CPU cycles required per unit of the task in the i th queue at EN j , respectively.** We define $\eta_{i,j}^E(t)$ (in bits) as the length of this queue at the end of time slot $t \in \mathcal{T}$. We refer to a queue as an active queue in a certain time slot if it is not empty. That being said, if at least one task is already in the queue from previous time slots or there is a task arriving at the queue, that queue is active. We define $\mathcal{B}_j(t)$ to denote the set of active queues at EN j in time slot t .

$$\mathcal{B}_j(t) = \left\{ i \mid i \in \mathcal{I}, \lambda_{i,j}^E(t) > 0 \text{ or } \eta_{i,j}^E(t-1) > 0 \right\}. \quad (9)$$

We introduce $b_j(t) \triangleq |\mathcal{B}_j(t)|$ that represents the number of active queues in EN $j \in \mathcal{J}$ in time slot $t \in \mathcal{T}$. In each time slot $t \in \mathcal{T}$, the EN's processing power is divided among its active queues using a generalized processor sharing method [43]. Let variable f_j^E (in cycles per second) represent the computational capacity of EN j . Therefore, EN j can allocate computational capacity of $f_j^E/(\rho_i(t)b_j(t))$ to each MD $i \in \mathcal{B}_j(t)$ during time slot t . To calculate the length of the computation queue for MD $i \in \mathcal{I}$ in EN $j \in \mathcal{J}$, we define $\omega_{i,j}(t)$ (in bits) to represent the number of bits from dropped tasks in that queue at the end of time slot $t \in \mathcal{T}$. The backlog of the queue, referred to as $\eta_{i,j}^E(t)$ is given by:

$$\eta_{i,j}^E(t) = \left[\eta_{i,j}^E(t-1) + \lambda_{i,j}^E(t) - \frac{f_j^E\tau}{\rho_{i,j}^E(t)b_j(t)} - \omega_{i,j}(t) \right]^+. \quad (10)$$

We also define $l_{i,j}^E(t) \in \mathcal{T}$ as the time slot during which the offloaded task $z_{i,j}^E(t)$ is either processed or dropped by EN j . Given the uncertain workload ahead at EN j , neither MD i nor EN j has information about $l_{i,j}^E(t)$ until the corresponding task $z_{i,j}^E(t)$ is either processed or dropped. Let $\hat{l}_{i,j}^E(t)$ represent

the time slot at which the execution of task $z_{i,j}^E(t)$ starts. In mathematical terms, for $i \in \mathcal{I}$, $j \in \mathcal{J}$, and $t \in \mathcal{T}$, we have:

$$\hat{l}_{i,j}^E(t) = \max\{t, \max_{t' \in \{0,1,\dots,t-1\}} l_{i,j}^E(t') + 1\}, \quad (11)$$

where $l_{i,j}^E(0) = 0$. Indeed, the initial processing time slot of task $z_{i,j}^E(t)$ at EN should not precede the time slot when the task was enqueued or when the previously arrived tasks were processed or dropped. Therefore, $l_{i,j}^E(t)$ is the time slot that satisfies the following constraints.

$$\sum_{t'=\hat{l}_{i,j}^E(t)}^{l_{i,j}^E(t)} \frac{f_j^E \tau}{\rho_{i,j}^E(t) b_j(t')} \mathbb{1}(i \in \mathcal{B}_j(t')) \geq \lambda_{i,j}^E(t), \quad (12)$$

$$\sum_{t'=\hat{l}_{i,j}^E(t)}^{l_{i,j}^E(t)-1} \frac{f_j^E \tau}{\rho_{i,j}^E(t) b_j(t')} \mathbb{1}(i \in \mathcal{B}_j(t')) < \lambda_{i,j}^E(t), \quad (13)$$

where $\mathbb{1}(z \in \mathbb{Z})$ is the indicator function. In particular, the total processing capacity that EN j allocates to MD i from the time slot $\hat{l}_{i,j}^E(t)$ to the time slot $l_{i,j}^E(t)$ should exceed the size of task $z_{i,j}^E(t)$. Conversely, the total allocated processing capacity from the time slot $l_{i,j}^E(t)$ to the time slot $l_{i,j}^E(t) - 1$ should be less than the task's size.

Additionally, we define $D_{i,j}^E(t)$ to represent the quantity of processing time slots allocated to task $z_{i,j}^E(t)$ when executed at EN j . This value is given by:

$$D_{i,j}^E(t) = l_{i,j}^E(t) - \hat{l}_{i,j}^E(t). \quad (14)$$

We also define $E_{i,j}^E(t)$ as the energy consumption of processing at EN j in time slot t by MD i . This can be calculated as:

$$E_{i,j}^E(t) = \sum_{t'=\hat{l}_{i,j}^E(t)}^{l_{i,j}^E(t)} \frac{p_j^E \tau}{b_j(t')} \mathbb{1}(i \in \mathcal{B}_j(t')), \quad (15)$$

where p_j^E is a constant value which denotes the energy consumption of the EN j 's processor when operating at full capacity.

In addition to the energy consumed by EN j for task processing, we also take into account the energy consumed by the MD i 's user interface in the standby state while waiting for task completion at the EN j . We define $E_i^I(t)$ as the energy consumption associated with the user interface of MD $i \in \mathcal{I}$, which is given by

$$E_i^I(t) = \sum_{j \in \mathcal{J}} y_{i,j}(t) D_{i,j}^E(t) p_i^I \tau, \quad (16)$$

where p_i^I is the standby energy consumption of MD $i \in \mathcal{I}$. Recall that $y_{i,j}(t)$ is Moreover, among all $j \in \mathcal{J}$, $y_{i,j} = 1$ only for one j which is the corresponding EN.

IV. TASK OFFLOADING PROBLEM FORMULATION

Based on the introduced system model, we present the computation task offloading problem in this section. Our primary goal is to enhance each MD's QoE individually by taking the dynamic demands of MDs into account. To achieve this, we approach the optimization problem as an MDP, aiming

to maximize the MD's QoE by striking a balance among key QoE factors, including task completion, task delay, and energy consumption. To prioritize QoE factors, we utilize the MD's **energy level of the battery**, which plays a crucial role in decision-making. Specifically, when an MD observes its state (e.g. task size, queue details, and **battery status**) and encounters a newly arrived task, it selects an appropriate action for that task. The selected action, based on the observed state, will result in enhanced QoE. Each MD strives to maximize its long-term QoE by optimizing the policy mapping from states to actions. In what follows, we first present the state space, action space, and QoE function, respectively. We then formulate the QoE maximization problem for each MD.

A. State Space

A state in our MDP represents a conceptual space that comprehensively describes the state of an MD facing the environment. We represent the MD i 's state in time slot t as vector $\mathbf{s}_i(t)$ that includes the newly arrived task size, the queues information, the MD's **energy level of the battery**, and the workload history at the ENs. The MD observes this vector at the beginning of each time slot. The vector $\mathbf{s}_i(t)$ is defined as follows:

$$\mathbf{s}_i(t) = \left(\lambda_i(t), \delta_i^C(t), \delta_i^T(t), \boldsymbol{\eta}_i^E(t-1), \phi_i(t), \mathcal{H}(t) \right), \quad (17)$$

where vector $\boldsymbol{\eta}_i^E(t-1) = (\eta_{i,j}^E(t-1))_{j \in \mathcal{J}}$ represents the queues length of MD i in ENs at the previous time slot and is computed by the MD according to (10). **Since MDs are assumed to be battery-operated, their operation modes are aligned with those of real-world devices. Let $\phi_i(t)$ represent the battery level percentage of MD i at time slot t , where $\phi_i(t)$ is selected from the discrete set $\Phi = \phi_1, \phi_2, \phi_3$, corresponding to ultra power-saving, power-saving, and performance modes, respectively.**

In addition, to predict future EN workloads, we define the matrix $\mathcal{H}(t)$ as historical data, indicating the number of active queues for all ENs. This data is recorded over T^s time slots, ranging from $t-T^s$ to $t-1$, in $T^s \times J$ matrix. For EN j workload history at i^{th} time slot from $T^s - t$, we define $h_{i,j}(t)$ as:

$$h_{i,j}(t) = b_j(t - T^s + i - 1). \quad (18)$$

EN $j \in \mathcal{J}$ broadcasts $b_j(t)$ at the end of each time slot.

We define vector \mathcal{S} as the discrete and finite state space for each MD. The size of the set \mathcal{S} is given by $\Lambda \times T^2 \times \mathcal{U} \times 3 \times I^{T^s \times J}$, where \mathcal{U} is the set of available queue length values at an EN over T time slots.

B. Action Space

The action space represents the agent's behavior and the decisions. In this context, we define $\mathbf{a}_i(t)$ to denote the action taken by MD $i \in \mathcal{I}$ in time slot $t \in \mathcal{T}$. These actions involve two decisions, (a) Offloading decision to determine whether or not to offload the task, and (b) Offloading target to determine the EN to send the offloaded tasks. Thus, the action of MD i in time slot t can be concisely expressed as the following action tuple:

$$\mathbf{a}_i(t) = (x_i(t), \mathbf{y}_i(t)), \quad (19)$$

where vector $\mathbf{y}_i(t) = (y_{i,j}(t))_{j \in \mathcal{J}}$ represents the selected EN for offloading this task. In Section V-B, we will discuss the size of this action space.

C. QoE Function

The QoE function reflects user satisfaction with task computation, whether using local or edge resources. QoE accounts for task completion rate, processing delay, and energy consumption. Each user may have unique QoE requirements [44]. Therefore, we define a multi-dimensional, adaptive structure to assess QoE, balancing these factors according to the MDs preferences, such as prioritizing reduced task delays or energy savings, which may vary over time [45], [46]. To capture personalized QoE requirements, we define QoE as a weighted sum of the above factors. Each MD dynamically adjusts these weights to reflect the importance of different factors based on its energy modes, which are performance, power-saving, and ultra-power-saving modes. We now calculate task delay and energy consumption and then introduce the associated cost and QoE function.

Given the selected action $\mathbf{a}_i(t)$ in the observed state $\mathbf{s}_i(t)$, we represent $\mathcal{D}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$ as the delay of task $z_i(t)$, which indicates the number of time slots from time slot t to the time slot in which task $z_i(t)$ is processed. It is calculated by:

$$\mathcal{D}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) = (1 - x_i(t)) \left(l_i^C(t) - t + 1 \right) + x_i(t) \left(\sum_{j \in \mathcal{J}} \sum_{t'=t}^T \mathbb{1}(z_{i,j}^E(t') = z_i(t)) l_{i,j}^E(t') - t + 1 \right), \quad (20)$$

where $\mathcal{D}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) = 0$ if task $z_i(t)$ is dropped. Correspondingly, we denote the energy consumption of task $z_i(t)$ when taking action $\mathbf{a}_i(t)$ in the observed state $\mathbf{s}_i(t)$ as $\mathcal{E}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$, which is:

$$\mathcal{E}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) = (1 - x_i(t)) E_i^L(t) + x_i(t) \left(E_i^T(t) + E_i^I(t) + \sum_{j \in \mathcal{J}} \sum_{t'=t}^T \mathbb{1}(z_{i,j}^E(t') = z_i(t)) E_{i,j}^E(t') \right). \quad (21)$$

To define associated cost, we use a weighted sum of task delay $\mathcal{D}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$ and energy consumption $\mathcal{E}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$, where the MD dynamically adjusts the weights based on its energy level to reflect the preference for each factor. Given the delay and energy consumption of task $z_i(t)$, we also define $\mathcal{C}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$ that denotes the associate cost of task $z_i(t)$ given the action $\mathbf{a}_i(t)$ in the state $\mathbf{s}_i(t)$.

$$\mathcal{C}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) = \phi_i(t) \mathcal{D}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) + (1 - \phi_i(t)) \mathcal{E}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)), \quad (22)$$

where $\phi_i(t)$ represents the MD i 's energy level. When the MD is operating in performance mode, the primary focus is on minimizing task delays, thus the delay contributes more to the cost. On the other hand, when the MD switches to ultra power-saving mode, the main attention is directed toward reducing power consumption.

Finally, we define $\mathbf{q}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$ as the QoE associated with task $z_i(t)$ given the selected action $\mathbf{a}_i(t)$ and the observed state $\mathbf{s}_i(t)$. The QoE function is defined as follows:

$$\mathbf{q}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) = \begin{cases} \mathcal{R} - \mathcal{C}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) & \text{if task } z_i(t) \text{ is processed,} \\ -\mathcal{E}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) & \text{if task } z_i(t) \text{ is dropped,} \end{cases} \quad (23)$$

where $\mathcal{R} > 0$ represents a constant reward for task completion. If $z_i(t) = 0$, then $\mathbf{q}_i(\mathbf{s}_i(t), \mathbf{a}_i(t)) = 0$. Throughout the rest of this paper, we adopt the shortened notation $\mathbf{q}_i(t)$ to represent $\mathbf{q}_i(\mathbf{s}_i(t), \mathbf{a}_i(t))$.

D. Problem Formulation

We define the task offloading policy for MD $i \in \mathcal{I}$ as a mapping from its state to its corresponding action, denoted by i.e., $\pi_i : \mathcal{S} \rightarrow \mathcal{A}$. Especially, MD i determines an action $\mathbf{a}_i(t) \in \mathcal{A}$, according to policy π_i given the observed environment state $\mathbf{s}_i(t) \in \mathcal{S}$. The MD aims to find its optimal policy π_i^* which maximizes the long-term QoE,

$$\pi_i^* = \arg \max_{\pi_i} \mathbb{E} \left[\sum_{t \in \mathcal{T}} \gamma^{t-1} \mathbf{q}_i(t) \middle| \pi_i \right], \quad (24)$$

where $\gamma \in (0, 1]$ is a discount factor and determines the balance between instant QoE and long-term QoE. As γ approaches 0, the MD prioritizes QoE within the current time slot exclusively. Conversely, as γ approaches 1, the MD increasingly factors in the cumulative long-term QoE. The expectation $\mathbb{E}[\cdot]$ is taken into consideration of the time-varying system environments. Solving the optimization problem in (24) is particularly challenging due to the dynamic nature of the network. To address this challenge, we introduce a DRL-based offloading algorithm to learn the mapping between each state-action pair and their long-term QoE.

V. DRL-BASED OFFLOADING ALGORITHM

We now present QECO algorithm so as to address the distributed offloading decision-making of MDs. The aim is to empower MDs to identify the most efficient action that maximizes their long-term QoE. In the following, we introduce a neural network that characterizes the MD's state-action Q-values mapping, followed by a description of the information exchange between the MDs and ENs.

A. DQN-based Approach

We utilize the DQN technique to find the mapping between each state-action pair to Q-values in the formulated MDP. As shown in Fig. 2, each MD $i \in \mathcal{I}$ is equipped with a neural network comprising six layers. These layers include an input layer, an LSTM layer, two dense layers, an advantage-value (A&V) layer, and an output layer. The parameter vector θ_i of MD i 's neural network is defined to maintain the connection weights and neuron biases across all layers. For MD $i \in \mathcal{I}$, we utilize the state information as the input of neural network. The state information $\lambda_i(t)$, $\delta_i^C(t)$, $\delta_i^T(t)$, $\phi_i(t)$, and $\boldsymbol{\eta}_i^E(t-1)$ are directly passed to the dense layer, while the state information

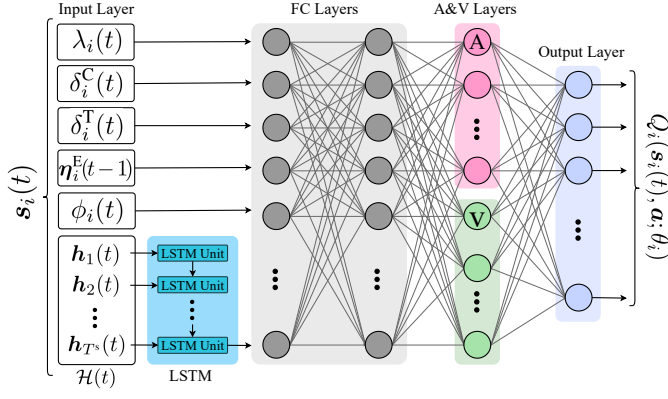


Fig. 2. The neural network of MD $i \in \mathcal{I}$, which characterizes the Q-value of each action $a \in \mathcal{A}$ under state $s_i(t) \in \mathcal{S}$.

$\mathcal{H}(t)$ is first supplied to the LSTM layer and then the resulting output is sent to the dense layer. The role and responsibilities of each layer are detailed as follows.

1) *Predicting Workloads at ENs*: In order to capture the dynamic behavior of workloads at the ENs, we employ the LSTM network [14]. This network maintains a memory state $\mathcal{H}(t)$ that evolves over time, enabling the neural network to predict future workloads at the ENs based on historical data. By taking the matrix $\mathcal{H}(t)$ as an input, the LSTM network learns the patterns of workload dynamics. The architecture of the LSTM consists of T^s units, each equipped with a set of hidden neurons, and it processes individual rows of the matrix $\mathcal{H}(t)$ sequentially. Through this interconnected design, MD tracks the variations in sequences from $\mathbf{h}_1(t)$ to $\mathbf{h}_{T^s}(t)$, where vector $\mathbf{h}_i(t) = (h_{i,j}(t))_{j \in \mathcal{J}}$, thereby revealing workload fluctuations at the ENs across different time slots. The final LSTM unit produces an output that encapsulates the anticipated workload dynamics, and is then connected to the subsequent layer neurons for further learning.

2) *State-Action Q-Value Mapping*: The pair of dual dense layers plays a crucial role in learning the mapping of Q-values from the current state and the learned load dynamics to the corresponding actions. The dense layers consist of a cluster of neurons that employ rectified linear units (ReLUs) as their activation functions. In the initial dense layer, connections are established from the neurons in the input layer and the LSTM layer to each neuron in the dense layer. The resulting output of a neuron in the dense layer is connected to each neuron in the subsequent dense layer. In the second layer, the outputs from each neuron establish connections with all neurons in the A&V layers.

3) *Dueling-DQN Approach for Q-Value Estimation*: In the neural network architecture, the A&V layer and the output layer incorporate the principles of the dueling-DQN [13] to compute action Q-values. The fundamental concept of dueling-DQN involves two separate learning components: one for action-advantage values and another for state-value. This approach enhances Q-value estimation by separately evaluating the long-term QoE attributed to states and actions.

The A&V layer consists of two distinct dense networks referred to as network A and network V. Network A's role is to learn the action-advantage value for each action, while network

Algorithm 1 Offloading Decision Algorithm at MD $i \in \mathcal{I}$

Input: state space \mathcal{S} , action space \mathcal{A}

Output: MD $i \in \mathcal{I}$ experience $(s_i(t), a_i(t), q_i(t), s_i(t+1))$

```

1: for episode 1 to  $N^{\text{ep}}$  do
2:   Initialize  $s_i(1)$ 
3:   for time slot  $t \in \mathcal{T}$  do
4:     if MD  $i$  receives a new task  $z_i(t)$  then
5:       Send an UpdateRequest to EN  $j_i$ ;
6:       Receive network parameter vector  $\theta_i^E$ ;
7:       Select action  $a_i(t)$  based on (26);
8:     end if
9:     Observe a set of QoEs  $\{q_i(t'), t' \in \mathcal{F}_i^t\}$ ;
10:    Observe the next state  $s_i(t+1)$ ;
11:    for each task  $z_i(t')$  where  $t' \in \mathcal{F}_i^t$  do
12:      Send  $(s_i(t'), a_i(t'), q_i(t'), s_i(t'+1))$  to EN  $j_i$ ;
13:    end for
14:  end for
15: end for

```

V focuses on learning the state-value. For an MD $i \in \mathcal{I}$, we define $V_i(s_i(t); \theta_i)$ and $A_i(s_i(t), a; \theta_i)$ to denote the state-value and the action-advantage value of action $a \in \mathcal{A}$ under state $s_i(t) \in \mathcal{S}$, respectively. The parameter θ_i is responsible for determining these values, and it can be adjusted when training the QECO algorithm.

For an MD $i \in \mathcal{I}$, the A&V layer and the output layer collectively determine $Q_i(s_i(t), a; \theta_i)$, representing the resulting Q-value under action $a \in \mathcal{A}$ and state $s_i(t) \in \mathcal{S}$, as follows:

$$Q_i(s_i(t), a; \theta_i) = V_i(s_i(t); \theta_i) +$$

$$\left(A_i(s_i(t), a; \theta_i) - \frac{1}{|\mathcal{A}|} \sum_{a' \in \mathcal{A}} (A_i(s_i(t), a'; \theta_i)) \right), \quad (25)$$

where θ_i establishes a functional relationship that maps Q-values to pairs of state-action.

B. QoE-Oriented DRL-Based Algorithm

The QECO algorithm is meticulously designed to optimize the allocation of computational tasks between MDs and ENs. Since the training of neural networks imposes an extensive computational workload on MDs, we enable MDs to utilize ENs for training their neural networks, effectively reducing their computational workload. For each MD $i \in \mathcal{I}$, there is an associated EN, denoted as EN $j_i \in \mathcal{J}$, which assists in the training process. This EN possesses the highest transmission capacity among all ENs. We define $\mathcal{I}_j \subset \mathcal{I}$ as the set of MDs for which training is executed by EN $j \in \mathcal{J}$, i.e. $\mathcal{I}_j = \{i \in \mathcal{I} | j_i = j\}$. This approach is feasible due to the minimal information exchange and processing requirements for training compared to MD's tasks. The algorithms to be executed at MD $i \in \mathcal{I}$ and EN $j \in \mathcal{J}$ are given in Algorithms 1 and 2, respectively. The core concept involves training neural networks with MD experiences (i.e., state, action, QoE, next state) to map Q-values to each state-action pair. This mapping allows MD to identify the action in the observed state with the highest Q-value and maximize its long-term QoE.

Algorithm 2 Training Process Algorithm at EN $j \in \mathcal{J}$

Input: experience $(s_i(t), a_i(t), q_i(t), s_i(t+1))$ from MD $i \in \mathcal{I}$
Output: The parameters vector θ_i^E

```

1: Initialize replay buffer  $\mathcal{M}_i$  for each MD  $i \in \mathcal{I}_j$ ;
2: Initialize  $Net_i^E$  and  $Net_i^T$  with random parameters  $\theta_i^E$  and  $\theta_i^T$  respectively, for each MD  $i \in \mathcal{I}_j$ ;
3: Set Count := 0
4: while True do ▷ infinite loop
5:   if receive an UpdateRequest from MD  $i \in \mathcal{I}_j$  then
6:     Send  $\theta_i^E$  to MD  $i \in \mathcal{I}_j$ ;
7:   end if
8:   if an experience  $(s_i(t), a_i(t), q_i(t), s_i(t+1))$  is received
9:     from MD  $i \in \mathcal{I}_j$  then
10:    Store  $(s_i(t'), a_i(t'), q_i(t'), s_i(t'+1))$  in  $\mathcal{M}_i$ ;
11:    Get a collection of experiences  $\mathcal{I}$  from  $\mathcal{M}_i$ ;
12:    for each experience  $i \in \mathcal{I}$  do
13:      Get experience  $(s_i(n), a_i(n), q_i(n), s_i(n+1))$ ;
14:      Generate  $\hat{Q}_{i,n}^T$  according to (27);
15:    end for
16:    Set vector  $\hat{\mathbf{Q}}_i^T := (\hat{Q}_{i,n}^T)_{n \in \mathcal{N}}$ ;
17:    Update  $\theta_i^E$  to minimize  $L(\theta_i^E, \hat{\mathbf{Q}}_i^T)$  in (28);
18:    Count := Count + 1;
19:    if mod(Count, ReplaceThreshold) = 0 then
20:       $\theta_i^T := \theta_i^E$ ;
21:    end if
22:  end if
23: end while

```

In detail, EN $j \in \mathcal{J}$ maintains a replay buffer denotes as \mathcal{M}_i with two neural networks for MD i : Net_i^E , denoting the evaluation network, and Net_i^T , denoting the target network, which have the same neural network architecture. However, they possess distinct parameter vectors θ_i^E and θ_i^T , respectively. Their Q-values are represented by $Q_i^E(s_i(t), a; \theta_i^E)$ and $Q_i^T(s_i(t), a; \theta_i^T)$ for MD $i \in \mathcal{I}_j$, respectively, associating the action $a \in \mathcal{A}$ under the state $s_i(t) \in \mathcal{S}$. The replay buffer records the observed experience $(s_i(t), a_i(t), q_i(t), s_i(t+1))$ of MD i . Moreover, Net_i^E is responsible for action selection, while Net_i^T characterizes the target Q-values, which represent the estimated long-term QoE resulting from an action in the observed state. The target Q-value serves as the reference for updating the network parameter vector θ_i^E . This update occurs through the minimization of disparities between the Q-values under Net_i^E and Net_i^T . In the following, we introduce the offloading decision algorithm of MD $i \in \mathcal{I}$ and the training process algorithm running in EN $j \in \mathcal{J}$.

1) *Offloading Decision Algorithm at MD $i \in \mathcal{I}$* : We analyze a series of episodes, where N^{op} denotes the number of them. At the beginning of each episode, if MD $i \in \mathcal{I}$ receives a new task $z_i(t)$, it initializes the state $\mathcal{S}_i(1)$ and sends an *UpdateRequest* to EN j_i . After receiving the requested vector θ_i^E of Net_i^E from EN j_i , MD i chooses the following action for task $z_i(t)$.

$$a_i(t) = \begin{cases} \arg \max_{a \in \mathcal{A}} Q_i^E(s_i(t), a; \theta_i^E), & \text{w.p. } 1 - \epsilon, \\ \text{pick a random action from } \mathcal{A}, & \text{w.p. } \epsilon, \end{cases} \quad (26)$$

where w.p. stands for with probability, and ϵ represents the random exploration probability. The value of $Q_i^E(s_i(t), a; \theta_i^E)$ indicates the Q-value under the parameter θ_i^E of the neural network Net_i^E . Specifically, the MD with a probability of $1 - \epsilon$ selects the action associated with the highest Q-value under Net_i^E in the observed state $s_i(t)$.

In the next time slot $t+1$, MD i observes the state $\mathcal{S}_i(t+1)$. However, due to the potential for tasks to extend across multiple time slots, QoE $q_i(t)$ associated with task $z_i(t)$ may not be observable in time slot $t+1$. On the other hand, MD i may observe a group of QoEs associated with some tasks $z_i(t')$ in time slots $t' \leq t$. For each MD i , we define the set $\mathcal{F}_i^t \subset \mathcal{T}$ to denote the time slots during which each arriving task $z_i(t')$ is either processed or dropped in time slot t , as given by:

$$\mathcal{F}_i^t = \left\{ t' \mid t' \leq t, \lambda_i(t') > 0, (1 - x_i(t')) l_i^C(t') + x_i(t') \sum_{j \in \mathcal{J}} \sum_{n=t'}^t \mathbb{1}(z_{i,j}^E(n) = z_i(t')) l_{i,j}^E(n) = t \right\}.$$

Therefore, MD i observes a set of QoEs $\{q_i(t') \mid t' \in \mathcal{F}_i^t\}$ at the beginning of time slot $t+1$, where the set \mathcal{F}_i^t for some $i \in \mathcal{I}$ can be empty. Subsequently, MD i sends its experience $(s_i(t), a_i(t), q_i(t), s_i(t+1))$ to EN j_i for each task $z_i(t')$ in $t' \in \mathcal{F}_i^t$.

2) *Training Process Algorithm at EN $j \in \mathcal{J}$* : Upon initializing the replay buffer \mathcal{M}_i with the neural networks Net_i^E and Net_i^T for each MD $i \in \mathcal{I}_j$, EN $j \in \mathcal{J}$ waits for messages from the MDs in the set \mathcal{I}_j . When EN j receives an *UpdateRequest* signal from an MD $i \in \mathcal{I}_j$, it responds by transmitting the updated parameter vector θ_i^E , obtained from Net_i^E , back to MD i . On the other side, if EN j receives an experience $(s_i(t), a_i(t), q_i(t), s_i(t+1))$ from MD $i \in \mathcal{I}_j$, the EN stores this experience in the replay buffer \mathcal{M}_i associated with that MD.

The EN randomly selects a sample collection of experiences from the replay buffer, denoted as \mathcal{N} . For each experience $n \in \mathcal{N}$, it calculates the value of $\hat{Q}_{i,n}^T$. This value represents the QoE in experience n and includes a discounted Q-value of the action anticipated to be taken in the subsequent state of experience n , according to the network Net_i^T , given by

$$\hat{Q}_{i,n}^T = q_i(n) + \gamma Q_i^T(s_i(n+1), \tilde{a}_n; \theta_i^T), \quad (27)$$

where \tilde{a}_n denotes the optimal action for the state $s_i(n+1)$ based on its highest Q-value under Net_i^E , as given by:

$$\tilde{a}_n = \arg \max_{a \in \mathcal{A}} Q_i^E(s_i(n+1), a; \theta_i^E). \quad (28)$$

In particular, regarding experience n , the target-Q value $\hat{Q}_{i,n}^T$ represents the long-term QoE for action $a_i(n)$ under state $s_i(n)$. This value corresponds to the QoE observed in experience n , as well as the approximate expected upcoming QoE. **Based on the set \mathcal{N} , the EN computes the vector $\hat{\mathbf{Q}}_i^T = (\hat{Q}_{i,n}^T)_{n \in \mathcal{N}}$ and trains the MD's neural network (steps 11-21 of Algorithm 2) to update the parameter vector θ_i^E in Net_i^E for the next MD's *UpdateRequest*.** The key idea of updating Net_i^E is to minimize the disparity in Q-values between Net_i^E and Net_i^T , as indicated by the following loss function:

TABLE II
SIMULATION PARAMETERS

| Parameter | Value |
|---|---------------------------------------|
| Computation capacity of MD f_i | 2.6 GHz |
| Computation capacity of EN f_j^E | 42.8 GHz |
| Transmission capacity of MD $r_{i,j}(t)$ | 14 Mbps |
| Task arrival rate | 150 Task/sec |
| Size of task $\lambda_i(t)$ | $\{1.0, 1.1, \dots, 7.0\}$ Mbits |
| Required CPU cycles of task $\rho_i(t)$ | $\{0.197, 0.297, 0.397\} \times 10^3$ |
| Deadline of task Δ_i | 10 time slots (1 Sec) |
| Percentage of MD i 's battery level $\phi_i(t)$ | $\{25, 50, 75\}$ |
| Computation power of EN p_j^E | 5 W |
| Transmission power of MD p_i^T | 2.3 W |
| Standby power of MD p_i^I | 0.1 W |

$$L(\theta_i^E, \hat{Q}_i^T) = \frac{1}{|\mathcal{N}|} \sum_{n \in \mathcal{N}} \left(Q_i^E(s_i(n), \mathbf{a}_i(n); \theta_i^E) - \hat{Q}_{i,n}^T \right)^2. \quad (29)$$

In every *ReplaceThreshold* iterations, the update of Net_i^T will involve duplicating the parameters from Net_i^E ($\theta_i^T = \theta_i^E$). The objective is to consistently update the network parameter θ_i^T in Net_i^T , which enhances the approximation of the long-term QoE when computing the target Q-values in (27).

3) *Computational Complexity*: The computational complexity of the QECO algorithm is determined by the number of experiences required to discover the optimal offloading policy. Each experience involves backpropagation for training, which has a computational complexity of $\mathcal{O}(C)$, where C represents the number of multiplication operations in the neural network. During each training round triggered by the arrival of a new task, a sample collection of experiences of size $|\mathcal{N}|$ is utilized from the replay buffer. Since the training process encompasses N^{ep} episodes and there are K expected tasks in each episode, the computational complexity of the proposed algorithm is $\mathcal{O}(N^{\text{ep}} K |\mathcal{N}| C)$, which is polynomial. Given the integration of neural networks for function approximation, the convergence guarantee of the DRL algorithm remains an open problem. In this work, we will empirically evaluate the convergence of the proposed algorithm in Section VI-B.

VI. PERFORMANCE EVALUATION

In this section, we first present the simulation setup and training configuration. We then illustrate the convergence of the proposed DRL-based QECO algorithm, and evaluate its performance in comparison to three baseline schemes in addition to the existing state-of-the-art works [15], [16].

A. Simulation Setup

We consider a MEC environment with 50 MDs and 5 ENs, similar to [37]. We also follow the model presented in [24] to determine the energy consumption. All the parameters are given in Table II. Since there is no real dataset due to the challenges of capturing representative samples over extended

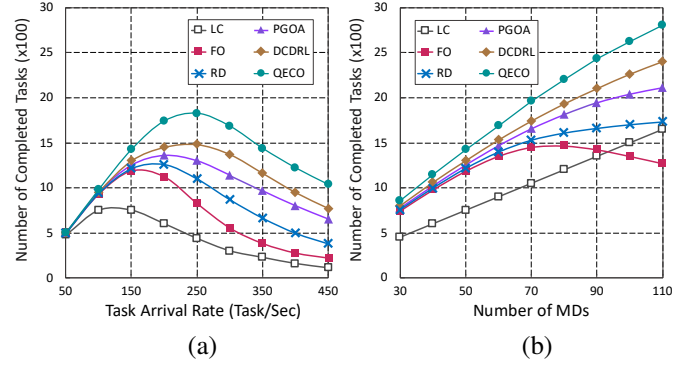


Fig. 3. The number of completed tasks under different computation workloads: (a) task arrival rate; (b) the number of MDs.

periods, we use a simulated MEC system that enables DRL agents to continuously gather experience and improve their performance based on system feedback (e.g., QoE). To train the MDs' neural networks, we adopt a scenario comprising 1000 episodes. Each episode contains 100 time slots, each of length 0.1 second. The QECO algorithm incorporates real-time experience into its training process to continuously enhance the offloading strategy. Specifically, we employ a batch size of 16, maintain a fixed learning rate of 0.001, and set the discount factor γ to 0.9. The probability of random exploration gradually decreases from an initial value 1, progressively approaching 0.01, all of which is facilitated by an RMSProp optimizer. The algorithm's source code is available at [47].

We use the following methods as benchmarks.

- 1) **Local Computing (LC)**: The MDs execute all of their computation tasks using their own computing capacity.
- 2) **Full Offloading (FO)**: Each MD dispatches all of its computation tasks while choosing the offloading target randomly.
- 3) **Random Decision (RD)**: In this approach, when an MD receives a new task, it randomly makes the offloading decisions and selects the offloading target if it decides to dispatch the task.
- 4) **PGOA [15]**: This existing method is a distributed optimization algorithm designed for delay-sensitive tasks in an environment where MDs interact strategically with multiple ENs.
- 5) **DCDRL [16]**: This method is based on the actor-critic framework [48], which underpins many state-of-the-art DRL algorithms, such as DDPG [49], and PPO [50]. DCDRL is designed for distributed computation offloading in a queuing-based MEC environment.

B. Performance Comparison and Convergence

We first evaluate the number of completed tasks when comparing our proposed QECO algorithm with the other four schemes. As illustrated in Fig. 3 (a), the QECO algorithm consistently outperforms the benchmark methods when we vary the task arrival rate. At a lower task arrival rate (i.e., 50), most of the methods demonstrate similar proficiency in completing tasks. However, as the task arrival rate increases, the efficiency of QECO becomes more evident. Specifically,

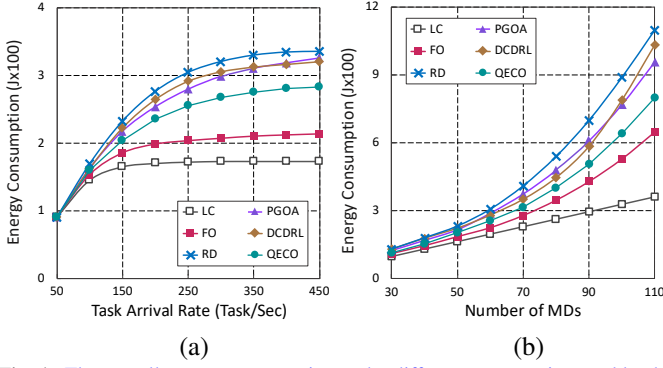


Fig. 4. The overall energy consumption under different computation workloads: (a) task arrival rate; (b) the number of MDs.

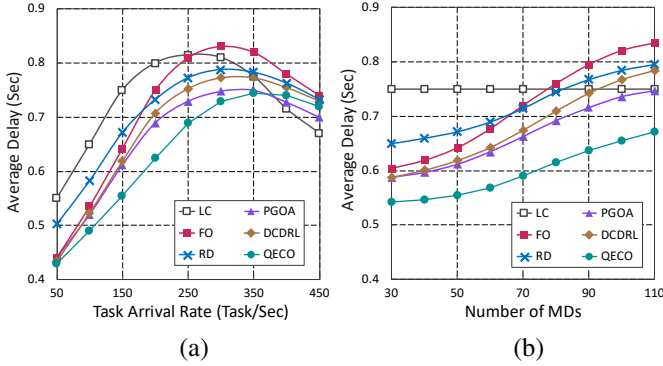


Fig. 5. The average delay under different computation workloads: (a) task arrival rate; (b) the number of MDs.

when the task arrival rate increases to 250, our algorithm can increase the number of completed tasks by 72.1%, 46.8%, and 28.6% compared to RD, PGOA, and DCDRL, respectively. Similarly, in Fig. 3 (b), as the number of MDs increases, QECCO shows significant improvements in the number of completed tasks compared to other methods, especially when faced with a large number of MDs. When there are 110 MDs, our proposed algorithm can effectively increase the number of completed tasks by at least 22.8% comparing with other methods. This achievement is attributed to the QECCO's ability to effectively handle unknown workloads and prevent congestion at the ENs.

Figs. 4 (a) and 4 (b) illustrate the overall energy consumption for different values of task arrival rate and the number of MDs, respectively. At the lower task arrival rate, the total energy consumption of all methods is close to each other. The total energy consumption increases when we have a higher task arrival rate. As can be observed from Fig. 4 (a), at task arrival rate 450, QECCO effectively reduces overall energy consumption by 18.6%, 15.5%, and 13.9% compared to RD, PGOA, and DCDRL, respectively, as it takes into account the **energy level** of the MD in its decision-making process. However, it consumes more energy compared to LC and FO because they do not utilize all computing resources. In particular, LC only uses the MD's computational resources, while FO utilizes the allocated EN computing resources. In Fig. 4 (b), an increasing trend in overall energy consumption is observed as the number of MDs increases since the number of resources available in the system increases, which leads to higher energy consumption. The QECCO algorithm consistently outperforms other methods

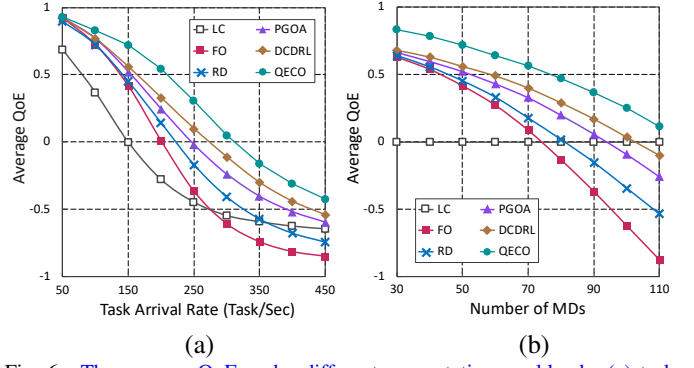


Fig. 6. The average QoE under different computation workloads: (a) task arrival rate; (b) the number of MDs.

in overall energy consumption, especially when there are a large number of MDs. Specifically, QECCO demonstrates a 27.4%, 16.7%, and 23.5% reduction in overall energy consumption compared to RD, PGOA, and DCDRL, respectively, when the number of MDs increases to 110.

As shown in Fig. 5 (a), the QECCO algorithm maintains a lower average delay compared to other methods as the task arrival rate increases from 50 to 350. Specifically, when the task arrival rate is 200, it reduces the average delay by at least 12.4% compared to other methods. However, for task arrival rates exceeding 350, QECCO may experience a higher average delay compared to some of the other methods. This can be attributed to the fact that the other algorithms drop more tasks while our proposed algorithm is capable of completing a higher number of tasks, potentially leading to an increase in average delay. In Fig. 5 (b), as the number of MDs increases, we observe a rising trend in the average delay. It can be inferred that an increase in computational load in the system can lead to higher queuing delays and computations at ENs. Considering the QECCO's ability to schedule workloads, when the number of MDs increases from 30 to 110, it consistently maintains a lower average delay which is at least 8.3% less than the other methods.

We further investigate the overall improvement achieved by the QECCO algorithm in comparison to other methods in terms of the average QoE. This metric signifies the advantages MDs obtain by utilizing different algorithms. Fig. 6 (a) shows the average QoE for different values of the task arrival rate. This figure highlights the superiority of the QECCO algorithm in providing MDs with an enhanced experience. At lower task arrival rates (i.e., 50-150), QECCO performs optimally and maintains an average QoE of at least 0.72, while the other methods experience a steeper decline, with average QoE dropping to 0–0.56. Specifically, at a task arrival rate of 200, QECCO improves the average QoE by at least 65.7% compared to other methods in the positive average QoE range. As task arrival rates increase to 300, the average QoE significantly decreases for all methods due to increased competition for resources in the MEC system. However, QECCO still maintains a positive average QoE, while other methods fall to negative values, with a decline of up to -0.17. For higher task arrival rates (i.e., 350–450), QECCO experiences a negative average QoE, but it shows at least a 42.6%, 28.5%, and 22.6% smaller

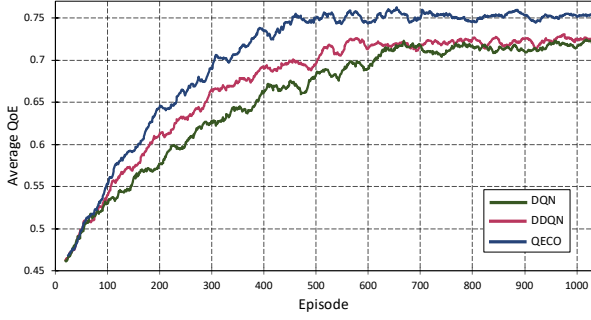


Fig. 7. The convergence of the average QoE across episodes under different DQN-based methods.

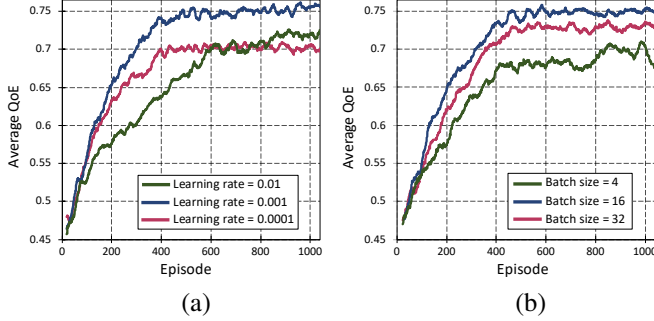


Fig. 8. The convergence of the average QoE across episodes under different hyper-parameters: (a) Learning rate; (b) Batch size.

reduction in average QoE compared to RD, PGOA, and DCDRL, respectively.

Fig. 6 (b) illustrates the average QoE when we increase the number of MDs. The EN's workload grows when there are a larger number of MDs, leading to a reduction in the average QoE of all methods except LC. However, QECO effectively manages the uncertain load at the ENs. When the number of MDs increases from 30 to 110, QECO consistently maintains at least a 24.8% higher QoE compared to the other methods. Specifically, at a moderate number of 70 MDs, QECO achieves an average QoE of 0.57, showing a 70.3% and 44.7% improvement compared to PGOA and DCDRL, respectively. It is worth noting that although improvements in each of the QoE factors can contribute to enhancing system performance, it is essential to consider the user's demands in each time slot. Therefore, the key difference between QECO and other methods is that it prioritizes users' demands, enabling it to strike an appropriate balance among them, ultimately leading to a higher QoE for MDs.

We finally delve into the investigation of the convergence performance of the QECO algorithm in Fig. 7 and Fig. 8. To validate the effectiveness of the QECO algorithm, we assess its convergence rate compared to the vanilla DQN and DDQN configurations [12], measured by the average QoE across episodes. As shown in Fig. 7, as the episodes progress, the MD's network learns efficient policies, ultimately stabilizing as it approaches convergence. Specifically, the DQN, DDQN, and our proposed QECO algorithm converge after approximately 650, 550, and 450 iterations, respectively. The QECO algorithm demonstrates the faster convergence while achieves a higher average QoE than the other methods. underscore the beneficial impact of workload prediction by the LSTM network and

highlight its effectiveness in efficiently utilizing the processing capabilities of MDs and ENs.

Furthermore, we explore the impact of two main hyper-parameters on the convergence speed and the converged result of the proposed algorithm. Fig. 8 (a) illustrates the convergence of the proposed algorithm under different learning rates, where the learning rate regulates the step size per iteration towards minimizing the loss function. The QECO algorithm achieves an average QoE of 0.75 when the learning rate is 0.001, indicating relatively rapid convergence. However, with smaller learning rates (e.g., 0.0001) or larger values (e.g., 0.01), a slower convergence is observed. Fig. 8 (b) shows the convergence of the proposed algorithm under different batch sizes, which refer to the number of sampled experiences in each training round. An improvement in convergence performance is observed as the batch size increases from 4 to 16. However, further increasing the batch size from 16 to 32 does not notably enhance the converged QoE or convergence speed. Hence, a batch size of 16 may be more appropriate for training processes.

VII. CONCLUSION

In this paper, we focused on addressing the challenge of offloading in MEC systems, where strict task processing deadlines and energy constraints adversely impact system performance. We formulated an optimization problem that aims to maximize the QoE of each MD individually, while QoE reflects the energy consumption and task completion delay. To address the dynamic and uncertain mobile environment, we proposed a QoE-oriented DRL-based computation offloading algorithm called QECO. Our proposed algorithm empowers MDs to make offloading decisions without relying on knowledge about task models or other MDs' offloading decisions. The QECO algorithm not only adapts to the uncertain dynamics of load levels at ENs, but also effectively manages the ever-changing system environment. Through extensive simulations, we showed that QECO outperforms several established benchmark techniques, while demonstrating a rapid training convergence. Specifically, QECO increases the average user's QoE by 29.8%–37.1% compared to several existing algorithms. This advantage can lead to improvements in key performance metrics, including task completion rate, task delay, and energy consumption, under different system conditions and varying user demands.

There are multiple directions for future work. A complementary approach involves extending the task model by considering interdependencies among tasks. This can be achieved by incorporating a task call graph representation. Furthermore, in order to accelerate the learning of optimal offloading policies, it will be beneficial to take advantages of federated learning techniques in the training process. This will allow MDs to collectively contribute to improving the offloading model and enable continuous learning when new MDs join the network.

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