Mobile Edge Computing and Networking for Green and Low-Latency Internet of Things

Ke Zhang, Supeng Leng, Yejun He, Sabita Maharjan, and Yan Zhang

Abstract

IoT, a heterogeneous interconnection of smart devices, is a great platform to develop novel mobile applications. Resource constrained smart devices, however, often become the bottlenecks to fully realize such developments, especially when it comes to intensive-computation-oriented and low-latency-demanding applications. MEC is a promising approach to address such challenges. In this article, we focus on MEC applications for IoT, and address energy efficiency as well as offloading performance of such applications in terms of end-user experience. In this regard, we present a mobility-aware hierarchical MEC framework for green and low-latency IoT. We deploy a game theoretic approach for computation offloading in order to optimize the utility of the service providers while also reducing the energy cost and the task execution time of the smart devices. Numerical results indicate that the proposed scheme does brings significant enhancement in both energy efficiency and latency performance of MEC applications for IoT.

Introduction

Along with the advancement of technologies in mobile sensing and wireless communication, the concept of the Internet of Things (IoT) has evolved significantly. IoT is widely envisioned as a global network consisting of pervasive smart mobile devices that measure and understand environmental characteristics, and interact with each other. IoT networks have led to the introduction and facilitation of many novel mobile applications, and they possess the potential to enable many more. However, due to the inherent characteristics of IoT devices, such as low computation power, storage, and battery, supporting large number of computation-intensive applications on resource constrained devices is a big challenge [1].

To cope with the growing application demands from mobile devices, cloud computing gathers abundant computation resources from remote servers to which to offload the application tasks. However, considerable transmission cost and latency are two big issues that may considerably degrade the user experience.

Mobile edge computing (MEC) brings the possibility to enable applications that require low latency with high bandwidth utilization. Even so, ensuring low latency as required can be quite a challenge, especially in an "Internet of Everything" that is becoming a reality with advanced IoT technologies [2]. Moreover, while energy efficiency is an extremely important aspect in designing MEC solutions, lack of proper coordination among selfish smart devices for offloading may lead to higher energy costs and also higher latencies. A few studies have focused on energy-efficient offloading in MEC. In [3], energy consumption of MEC-based mobile applications was reduced through joint resource allocation. In [4], an energy-efficient computation offloading mechanism was proposed for MEC for fifth generation (5G) heterogeneous networks.

In this article, we present a comprehensive description of MEC technology as well as the emerging MEC applications in IoT. Then we focus on exploiting MEC for mobile smart devices, and propose a green MEC offloading scheme with low latency. The main contributions of this article can be summarized as follows.

We review the most recent emerging MEC applications for a wide range of IoT applications, including various characteristics, specific requirements, and corresponding strategic approaches.

We propose a mobility-aware hierarchical edge computing framework, and design a cross-layer computing resource sharing mechanism between edge computing servers.

Finally, we develop an incentive-based optimal computation offloading scheme that maximizes the utilities of the service provider while also reducing smart device energy consumption and task execution time.

The rest of this article is organized as follows. We introduce MEC technologies (Fig. 1) and illustrate the emerging MEC applications for IoT in the following section. Next, we develop a mobility-aware edge computing scenario, and address energy efficiency and low latency requirements for computing task offloading. Then we evaluate the performance of our proposed schemes through numerical results. Conclusions are presented in the final section.

The authors focus on MEC applications for IoT, and address energy efficiency as well as offloading performance of such applications in terms of end-user experience. They present a mobility-aware hierarchical MEC framework for green and low-latency IoT. They deploy a game theoretic approach for computation offloading in order to optimize the utility of the service providers while also reducing the energy cost and the task execution time of the smart devices.

Emerging MEC Applications in IoT

MEC Overview

Connected smart IoT devices often require information processing. The computing capacity of nearby MEC servers helps them realize sensing, interaction, and control efficiently [5]. The main characteristics of MEC are as follows.

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In an intelligent transportation system, autonomous driving is probably the most attractive application. Aided by MEC service, the safety-oriented tasks of sensory data analysis and appropriate navigation path identification can be offloaded from the vehicles to roadside units or other proximate nodes, where real-time data processing and feedback are achieved.

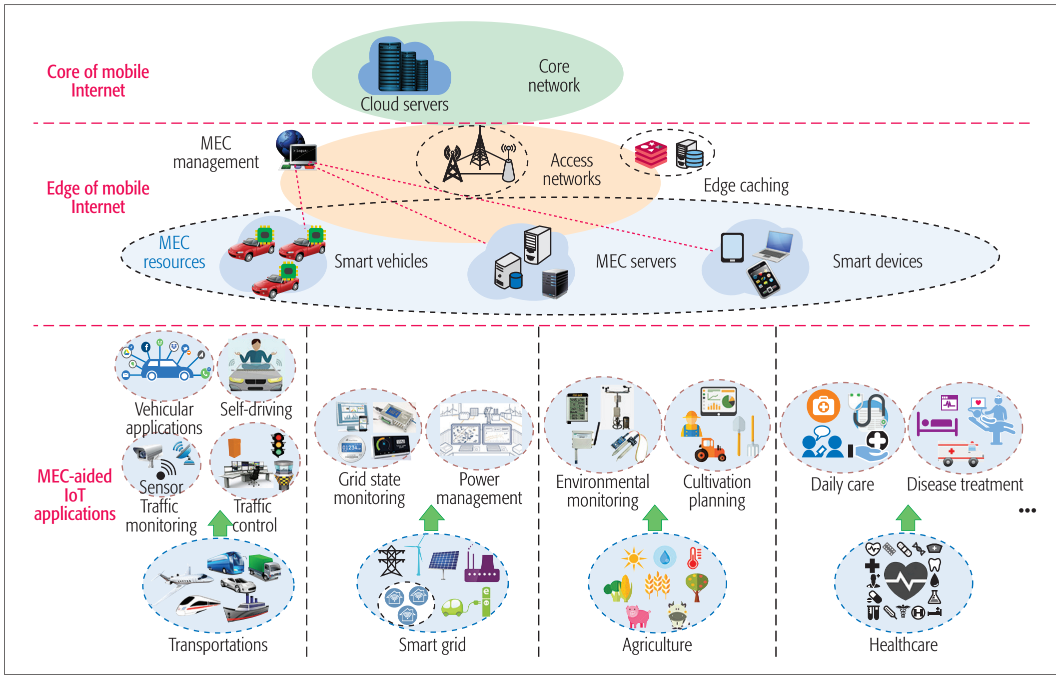

Figure 1. Emerging MEC applications in IoT.

Proximity: Being deployed in proximity to the smart devices, MEC is suitable for analyzing key features in IoT data generated by these devices.

Low Latency: Shifting data offloading from core network, MEC speeds up application response, improves user experience, and reduces potential network congestion.

High Bandwidth: The data transmission between MEC servers and smart devices fully exploits the bandwidth of access networks, and gains high speed.

Location and Network Context Awareness: MEC servers use received information from smart devices within the local access network to determine the specific location of these devices. Based on the local real-time information, applications running on the devices can estimate states of the network.

Flexible Deployment: MEC is readily applicable for hosting novel mission-critical applications, which are deployed by both cellular operators and authorized third-party developers [6].

Heterogeneous Resource Synergy: To tackle a huge amount of computing task demands, it is necessary to jointly exploit both cloud computing and edge computing. In addition, synergizing heterogeneous resources, such as computing, caching, and communication, is also necessary in order to satisfy diverse performance requirements of IoT applications.

Mobility Awareness: Mobility is a key feature of ubiquitous smart devices [7]. When devices move along, tasks may be offloaded to several MEC servers. The need for a continuously task offloading service necessitates a seamlessly integrated computing platform.

Security and Privacy Protection: In an IoT network, MEC servers can be vulnerable to attacks such as distributed denial of service (DDoS) attacks. Furthermore, privacy information contained in applications may be revealed in the offloading process. The way to protect MEC servers and personal privacy from attacks while maintaining their operational efficiency is a critical challenge.

Real-Time Response: IoT emergency applications require real-time response [8]. As the latency of the offloading process is not only affected by the states of various resources, but also by the strategies of the other devices, designing computation offloading schemes that can guarantee low latency requirements is not trivial.

Next, we introduce six distinct potential IoT applications of MEC, and discuss the opportunities as well as new challenges for realizing those applications.

MEC for Intelligent Transportation

Powered by IoT technologies, intelligent transportation is a new concept, where environmental awareness, interactive communication, and information processing capabilities are incorporated into transportation networks.

In an intelligent transportation system, autonomous driving is probably the most attractive application. Aided with MEC service, the safety-oriented tasks of sensory data analysis and appropriate navigation path identification can be offloaded from the vehicles to roadside units (RSUs) or other proximate nodes, where real-time data processing and feedback are possible.

However, high-speed mobility, a unique and inherent characteristic of vehicles, brings unprecedented challenges in the performance of MEC solutions for intelligent transportation. With dense deployment of wireless access points in 5G networks, a vehicle may pass several MEC servers during its high-speed movement. Due to the capacity limitation of individual MEC servers as well as the heavy computation requirements of vehicular applications, the task may not be accomplished by one MEC server before the vehicle moves out of its proximity. Efficient task decomposition algorithms and cooperative resource assignment among these MEC servers are therefore necessary.

Furthermore, the communication between vehicles and MEC servers may seriously affect the performance of task offloading. The communication in vehicular networks includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) modes. When vehicles run along a road, handover between access points occurs in V2I mode. This handover adds task file transmission latency, which may limit the performance of the cooperative task offloading solution.

To address the problem, offloading tasks in V2V mode is an alternative and feasible approach. As vehicles also have a certain computing capability, a mobile vehicular edge computing platform can be formed via cooperation among a number of task-free vehicles. Since the relative speed between vehicles is much smaller than that between vehicles and RSUs, a more stable communication relation between vehicles can be anticipated. Thus, the handover cost in the task offloading process can be reduced. In addition, V2V communication mode is uniquely well suited for the task file transmission between vehicles, because of high bandwidth and low latency.

MEC for Smart Grid

Smart grid is a modern electrical power grid system that can generate and distribute power to its consumers in a more efficient, flexible, and reliable manner [9]. To continuously monitor the grid state, a large number of connected sensors and devices are used. These devices continuously generate large amounts of data.

MEC facilitates data collecting and processing at distributed computing servers located near the energy distribution network, which help reduce the transmission cost while improving the efficiency of power management. However, a number of issues must first be addressed before adopting MEC for smart grid applications, which are briefly discussed next.

Due to the large scale of the grid and the hugely diverse types of sensory data in different subsystems of the grid, offloading data processing tasks to MEC servers can be quite burdensome even for the MEC servers unless they are deployed on a massive scale. In addition, due to inherent stochasticity and corresponding uncertainties brought in by renewable energy resources into the smart grid, effective energy utilization requires more sophisticated control systems together with more computing resources. Furthermore, with the increasing popularity of electric vehicles, their charging and discharging operations may affect the state of the grid. The energy exchange process between electric vehicles and the grid also needs to be monitored and managed.

To alleviate the burden, taking the computation capacity of electric vehicles to share the tasks with MEC servers is a promising approach. As the charging or discharging process of electric vehicles is fairly long, during this period, the vehicles stay in parks or charging stations. The static topology benefits the vehicular computing resource management and scheduling. Furthermore, adopting power line communication mode, the task file can be transmitted to the vehicles through charging cables, which may help reduce offloading cost and latency.

MEC for Agricultural IoT

Technological advancements in IoT have greatly changed modern agriculture, where various sensors as well as automated devices are employed to replace large amounts of human work. In the plant cultivation process, environmental factors, such as weather, temperature, soil moisture, and plant growth status, are collected. The continuous monitoring data of these factors needs to be analyzed for providing real-time feedback on proper planting adjustment. With MEC, the collected data can be transmitted to and processed in edge computing servers located near farmlands.

For a given area, its weather follows a regular pattern. Integrating artificial intelligence into MEC servers to learn and utilize the patterns can improve the forecasting accuracy and help farmers better plan agricultural activities. Furthermore, we notice that the agricultural environments of adjacent areas often have strong correlation. For instance, the rainfall water in an area may bring moisture to neighboring areas. Motivated by such observations, multiple MEC servers in several adjacent areas can form an agricultural data processing collaboration to share the analysis outputs. In this way, accurate and valuable agricultural planting can be done, while also improving the resource utilization of MEC servers.

MEC for Intelligent Healthcare

Smart and connected devices are also envisioned to be active enablers of healthcare services anytime and anywhere. Such systems will assume both receptive and proactive roles such as measurement of temperature, blood pressure, heart rate, and so on, and also diagnosis and treatment recommendations. Such services require wide-range data collection, multi-domain collaboration, as well as deep information analysis, which mainly depend on powerful data transmission and processing capability [10]. In this regard, the resource constrained smart devices may become bottlenecks, and lead to data processing delays, consequently degrading end-user experience. Utilization of MEC servers to fuse and analyze collected health data within close proximity to users opens up possibilities to address the above mentioned issues.

For using MEC for health management on a regular basis (e.g., daily), it is necessary to distribute health statistics analysis to multiple MEC servers. This necessitates cooperation among the servers so that health data from various areas and populations can be jointly processed. In this context, information privacy is an important issue, thus making it feasible to only share permitted data when it comes to sensitive data such as health-related data. The health data related to personal privacy should be shared based on prearranged permissions.

Besides daily healthcare, MEC also revolutionizes patient treatment for clinicians, where a clinician can easily get patient data, and can access it to diagnose reports from a medical information platform at the edge. Although treatment efficiency can be greatly improved by MEC technologies, appropriate treatment decisions for emergency medical situations, such as a patient in the ICU or

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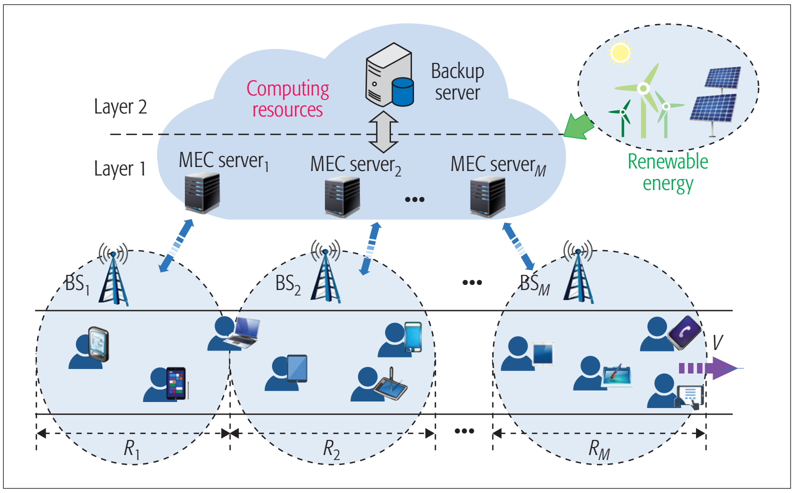

Figure 2. Mobility-aware hierarchical MEC framework.

a patient with heart failure, cannot wait that long. More advanced methods are necessary to enhance MEC capability while ensuring that patients get treated in near real time. One promising way to reduce treatment latency is the synergy of MEC and caching technologies [11]. When a patient arrives at a hospital, his healthcare data should be gathered and cached in the MEC servers that will be used in the process of treatment. For emergency cases, the cached data can be offered to MEC processing without data acquisition delay.

MEC for Smart Buildings

A smart building is a structure that utilizes sensors, cameras, and actuators to collect building environmental data and to automatically control the building's operations, where the temperature, light, gas level, and humidity can be managed according to customer preferences. By deploying MEC servers in smart buildings, the collected information is shared and processed locally, which improves the building control efficiency and also adapts decision making for new situations.

Apart from MEC server synergy inside buildings, if MEC servers can also connect to and cooperate with control centers or servers outside, diverse functionalities including safety can be embedded into smart buildings. For instance, the cooperation of MEC servers for building fire detectors and the dispatch center of a fire brigade increases firefighting efficiency. The connection between MEC servers in smart buildings and a smart grid control center enables the servers to dynamically adjust power consumption in the buildings according to the real-time states and power price of the grid, consequently resulting in savings in electricity bills of the buildings [12]. As the control centers may be located outside the access network of the buildings, cooperation between MEC servers in the building and with remote control centers can be severely affected by long distance data transmission. Thus, it is necessary to jointly design cooperation and communication among those servers for enabling such applications.

MEC for Smart Retail

The imperative IoT devices and wireless networks have greatly changed the business model, and have brought to us the concept of smart retail. Based on the gathered large-scale information of cargo storage and customer preferences, MEC servers in a smart retail store can effectively guide customers in their shopping experience. In addition, retailers may utilize MEC servers' analytical technology to optimize operations with rapid response to customer requirements and market trends.

Due to a large number of customers and a wide variety of goods, retailers collect huge amounts of data. Big data has become a promising approach for the retail industry in studying consumers' purchasing patterns and making changes accordingly.

While IoT is expected to create a new surge of mobile applications and form an extensive interconnection between ubiquitous things, various data-driven tasks as well as the exponential growth of data generated from diverse devices have emerged. Understanding the relationship, patterns and hidden values of the data may be very helpful in accomplishing these tasks efficiently. Powered with advanced analytics methods, big data has evolved as a powerful paradigm to handle the voluminous and complex data. In this regard, integrating MEC and cloud computing with big data analysis is a research area that will benefit numerous current and emerging IoT applications.

Green and Low-Latency Offloading Schemes in MEC Networks

In this section, we propose an optimal computation offloading scheme of mobile smart devices. The proposed scheme is a paradigm for addressing the task offloading challenges in intelligent transportation systems with highly dynamic topology. Furthermore, our proposed cross-layer computing resource sharing mechanism between MEC servers can alleviate the heavy burden of an individual server, and is helpful in fulfilling IoT applications with intensive computation demands.

Mobility-Aware Hierarchical MEC Framework

Figure 2 shows the proposed hierarchical MEC framework. We consider two-layer MEC resource management, where the computing servers are powered by renewable energy. Compared to mobile devices, these servers have higher computing energy efficiency. The first layer resources consist of M MEC servers, whose computation capacities are $\{f_k^{max}\}$, where $k = \{1, 2, ..., M\}$. These MEC servers are equipped separately on M base stations (BSs) located along a road. The second layer of the resources is formed by a backup computing server, which shares the computing tasks with the MEC servers in the case when their computing resources are inadequate to meet the demands of smart devices. When MEC servers choose to offload their tasks to the backup server, they need to pay price y to the server for using its unit computing resource.

There are N mobile smart devices arriving at the starting point of the road. All the devices travel at a constant speed v. Each device has a computing task, which is denoted as $T_i = \{d_i, b_i, t_i^{max}\}$, $i \in \{1, 2, ..., N\}$. Here, d_i and b_i are the size of the task input data and the amount of required computing resources, respectively. t_i^{max} is the delay constraint for this task.

For each smart device, its task can be accomplished either remotely on an MEC server through task offloading or locally on its own computing resources. Let $a_{i,k}$ denote the choice of device i, where $a_{i,k} = 1$ indicates that the device chooses to offload task T_i to MEC server k, and $a_{i,k} = 0$, otherwise. When device i chooses local computing, the task completion time is given as $t_{i,0}$. In contrast to this choice, when the device offloads task T_i to MEC server k, the total time cost $t_{i,k}$ consists of three parts, namely device running time to access MEC server k, task input data transmission time, and computation execution time. Thus, $t_{i,k}$ can be shown as $t_{i,k} = \sum_{j=1}^{k-1} R_j/v + d_i/r_k + b_i/f_{i,k}$, where R_j is the length of the road segment covered by BS j, r_k is the data transmission rate for a device accessing BS k, and $f_{i,k}$ is the amount of computing resources allocated by MEC server k for offloading task T_i.

Problem Formulation: Optimal Green Offloading with Low Latency

The utility of device i gained through offloading task T_i to MEC server k is denoted as U_i, which mainly depends on the delay reduction as well as the energy efficiency improvement of the task accomplishment and the offloading service cost. Since the users of the smart devices are rational, they attempt to maximize their utilities within the delay constraints by selecting the offloading target MEC servers. Given set $\{x_k\}$, which is the price for using a unit computing resource of MEC server k, the optimization problem for device i is

$$\max_{\{a_{i,k},f_{i,k}\}} U_i = \sum_{k=1}^{M} a_{i,k}\left(\lambda(t_{i,0}-t_{i,k})+\xi(e_{i,0}-e_{i,k}) - x_k f_{i,k}\right)$$
$$\text{s.t.} \quad \sum_{k=1}^{M} a_{i,k} t_{i,k} \le t_i^{\max}, \quad \sum_{i=1}^{N} a_{i,k} f_{i,k} \le f_k^{\max} + f_k^b, \quad a_{i,k} = \{0,1\}, \quad \sum_{k=1}^{M} a_{i,k} \le 1, \tag{1}$$

where $t_{i,0}$ and $e_{i,0}$ are the time and energy consumption for accomplishing the task locally on the smart device, respectively. $e_{i,k}$ is the energy cost for offloading task T_i to server k. λ and ξ are coefficients. f_k^b is the amount of computing resource bought from the backup server by MEC server k.

Due to the limitation of the computation capacity of each MEC server, devices may need to compete for the task offloading target servers and for utilizing server resources, which makes a non-cooperative game an appropriate approach to model the server selection process. As the task offloading game between the devices is a concave multi-player game, a Nash equilibrium exists for the game [13].

Being offloading service providers, the MEC servers aim to maximize their utilities by selling computing resources to the devices. Since the selling price heavily affects the offloading decisions made by smart devices, price adjustment is one of the incentive strategies of the MEC servers to attract more customers. Besides price adjustment, a resource exhausted MEC server may buy supplementary computing capacity from the backup server to serve more tasks for a higher utility.

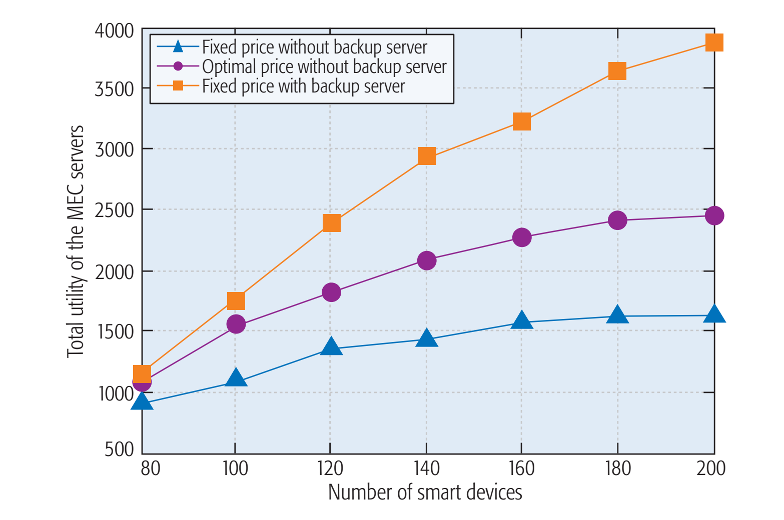

Figure 3. Total utility of the MEC servers with different offloading schemes.

Thus, in the non-cooperative game between the MEC servers in the offloading process, the strategy set of server k can be given as (x_k, f_k^b). The utility optimization problem for MEC server k can be formulated as

$$\max_{\{x_k,f_k^b\}} U_k^S = x_k \sum_{i=1}^{N} f_{i,k} - \beta_k \min\left(\sum_{i=1}^{N} f_{i,k}, f_k^{\max}\right) - y f_k^b$$
$$\text{s.t.} \quad x_k > 0, \quad f_k^b \ge 0, \tag{2}$$

where β_k is the operation cost for server k providing a unit of computing resource. As utility function U_k^S is continuous and quasi-concave in terms of x_k and f_k^b, the game between the MEC servers possesses a Nash equilibrium [14].

Solutions: A Stackelberg Game Approach

In the task offloading process, the offloading strategies chosen by the smart devices are motivated by the computing resource price of MEC servers. In addition, acting as the service providers, the MEC servers are also indirectly coupled through their resource prices in the service competition with each other. Thus, the price can be taken as a link to couple these two non-cooperative games between devices and MEC servers.

Considering that the offloading decisions of the devices are in response to the prices advertised by the MEC servers, a Stackelberg game is an appealing approach to model and address the two-layer offloading problem. Since the individual games between smart devices and between MEC servers have Nash equilibrium, it is clear that a Stackelberg equilibrium exists for the Stackelberg game [15]. The Stackelberg equilibrium is a solution of the optimal offloading problem, where the utility of the MEC servers is maximized while the task latency and energy consumption are also reduced. A heuristic iterative approach can be used to obtain this solution. In each iteration, the smart devices make the best response to the prices announced by the MEC servers, and the MEC servers draw their optimal strategies based on the known response of the devices. When no strategy updates change the utilities for both the sides, the iterative process stops.

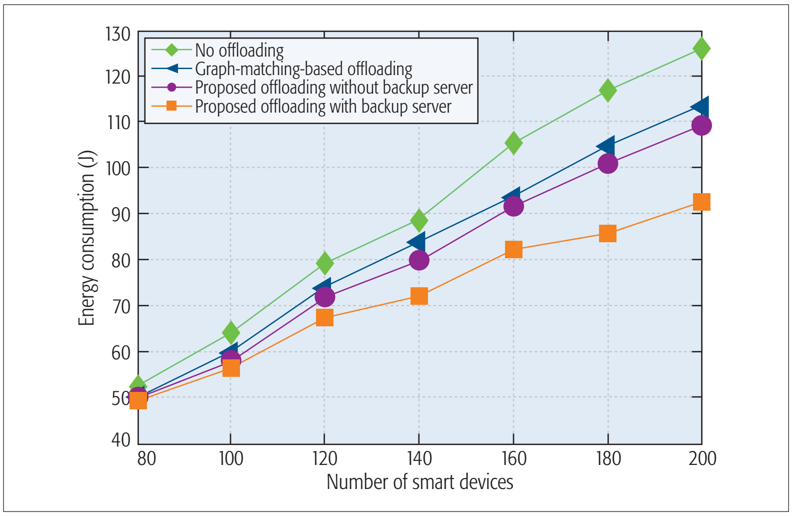

Figure 4. Energy consumption of the task execution with different schemes.

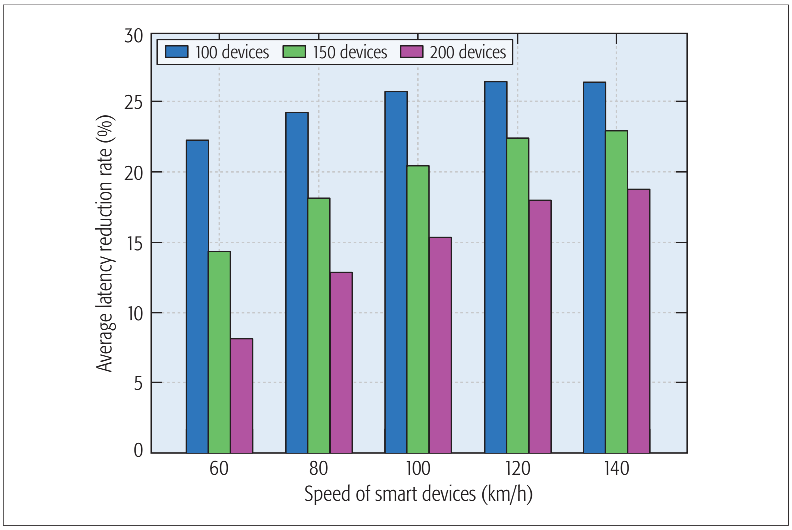

Figure 5. Comparison of average task latency reduction rates with various device speeds.

Illustrative Results

In this section, we evaluate the performance of our proposed offloading schemes. We consider a scenario where the mobile smart devices are on vehicles moving at a speed of 120 km/h. Each device has a computation task. The amount of the computing resources required by these tasks are random values in the range of (20, 70) units.

Figure 3 shows the total utility of the MEC servers using different offloading schemes. Compared to the scheme with fixed price, the ones adopting the optimal price scheme have higher utilities. In the fixed price scheme, the utility gained by the servers is strictly proportional to the amount of resources they have at their disposal. On the contrary, the schemes with optimal price, which is obtained through Stackelberg game analysis, are able to dynamically adjust resource price. Higher utility can be gained by raising the price when there are more task offloading requests. As the number of devices increases, the utility of the optimal price scheme without backup server cannot increase, especially in the case where the number of devices is higher than 200. Facing a large number of task demands, the available resources of the MEC servers under the task delay constraint may be exhausted. Without the backup server, no further offloading service can be provided. Thus, the upper limit of the utility is reached. However, the two-layer resource structure with backup server may help shift this upper limit, and gain high utility even with heavy offloading demands, which corroborates the efficiency of our proposed hierarchical offloading scheme.

Figure 4 illustrates energy consumption of the tasks accomplished with different schemes. Compared to the cost of the scheme without any offloading service, the three offloading schemes greatly reduce energy cost by executing the tasks on the servers with high energy efficiency, especially with high device number. In addition, from Fig. 4, it is clear that our proposed mobility-aware optimal offloading schemes result in less energy consumption than the graph-matching-based approach, especially for the scheme with backup server. The reason is that the matching solution only considers the computing and communication resources in the current location of the devices, and fails to consider that the MEC servers currently out of this range can be accessed by the devices as they move. In contrast, our proposed mobility-aware offloading schemes effectively utilize these remote resources, and lead to lower energy consumption in the offloading process. In our proposed two offloading schemes, although little gain is brought by the backup server when the number of devices is 80, the reduction in energy consumption becomes more pronounced as the device number increases. This proves that the proposed hierarchical offloading framework aided by a backup server can alleviate extensive computing resource requirements on the MEC servers, and make the edge computing network energy-efficient.

Figure 5 compares the average latency reduction rates of the tasks with various device speeds adopting our proposed mobility-aware offloading schemes. Higher speed means less time spent on device traveling and accessing farther MEC servers. Under the delay constraints, our proposed scheme incentivizes tasks to be offloaded to farther servers with less cost. Thus, more MEC servers can be utilized, and task execution latency is reduced. In Fig. 5, as the speed gets higher, the rates increase in all the scenarios with different device numbers. The effect of speed on latency reduction is more significant with higher device numbers, where the resources of the MEC servers near the starting point of the road are more likely to be exhausted.

Conclusions

In this article, we investigate MEC technologies in the context of emerging IoT applications. Both essential characteristics and underlying challenges as well as addressing approaches are analyzed and presented. Then we focus on computation offloading of mobile smart devices. We propose a mobility-aware hierarchical framework for computation offloading of mobile smart devices, and design an energy-efficient offloading scheme with low task latency. The efficiency of our proposed schemes was illustrated through numerical results.

Despite much promising recent work in the area of MEC-aided IoT applications, extensive and high-quality-oriented computing requests as well as dynamic and complex offloading pose critical challenges that still need to be addressed. For instance, how to further improve the efficiency of task execution through exploiting the relevance of applications is still an unexplored question. While applying IoT in a hostile environment, one possible research direction is securing the privacy of users and protecting MEC servers from being attacked. Furthermore, with advancements in artificial intelligence (AI), the way to integrate AI into MEC offloading process is also an interesting topic.

Acknowledgment

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Despite much promising recent work in the area of MEC aided IoT applications, extensive and high quality-oriented computing requests as well as dynamic and complex offloading pose critical challenges that still need to be addressed. For instance, how to further improve the efficiency of task execution through exploiting the relevance of applications is still an unexplored question.