Collaborative Task Offloading in Vehicular Edge Multi-Access Networks

Guanhua Qiao, Supeng Leng, Ke Zhang, and Yejun He

The authors introduce a vehicular edge multi-access network that treats vehicles as edge computation resources to construct the cooperative and distributed computing architecture. For immersive applications, co-located vehicles have the inherent properties of collecting considerable identical and similar computation tasks. They propose a collaborative task offloading and output transmission mechanism to guarantee low latency as well as the application-level performance.

ABSTRACT

Mobile edge computing (MEC) has emerged as a promising paradigm to realize user requirements with low-latency applications. The deep integration of multi-access technologies and MEC can significantly enhance the access capacity between heterogeneous devices and MEC platforms. However, the traditional MEC network architecture cannot be directly applied to the Internet of Vehicles (IoV) due to high speed mobility and inherent characteristics. Furthermore, given a large number of resource-rich vehicles on the road, it is a new opportunity to execute task offloading and data processing onto smart vehicles. To facilitate good merging of the MEC technology in IoV, this article first introduces a vehicular edge multi-access network that treats vehicles as edge computation resources to construct the cooperative and distributed computing architecture. For immersive applications, co-located vehicles have the inherent properties of collecting considerable identical and similar computation tasks. We propose a collaborative task offloading and output transmission mechanism to guarantee low latency as well as the application-level performance. Finally, we take 3D reconstruction as an exemplary scenario to provide insights on the design of the network framework. Numerical results demonstrate that the proposed scheme is able to reduce the perception reaction time while ensuring the application-level driving experiences.

INTRODUCTION

The Internet of Vehicles (IoV) is evolving as an emerging paradigm that supports the advanced driver assistant system (ADAS) and autonomous driving, which instill the innovation of immersive vehicular applications in providing driving safety and convenience for everything. However, without the advanced computer vision system to analyze the real-time traffic environment, the self-driving vehicles cannot distinguish a rock of size that should be avoid immediately, or a crumpled paper bag on the vehicle's path, which can be run over. To possess the smart vision of a complicated driving environment, vehicles equipped with advanced facilities need to rapidly process a vast amount of sensor data (approximately 1Gb/s) to meet very smooth driving patterns and experiences [1, 2].

The autonomous driving applications require superhigh broadband connectivity and powerful computing capability. However, these resource-hungry and computation-intensive applications pose a significant challenge to meet the low latency requirement. As a promising technology, mobile edge computing (MEC) has been proposed to solve the explosive computation demands by migrating the computing function from the core network to the edge access network [3].

Meanwhile, the enormous computation tasks offloaded to MEC platforms have yielded a series of critical issues, such as the bottleneck of limited fronthaul and backhaul connectivity between the heterogeneous MEC platforms and smart vehicles. To cope with the limited connectivity problem, fog radio access networks, which actively exploit the systematic integration and convergence of multi-access and mobile edge computing (MA-MEC) technologies including fixed access (e.g., fiber) and mobile access, such as fifth generation (5G), Long Term Evolution Advanced (LTE-A), vehicle-to-vehicle (V2V), and Wi-Fi, have been applied to bring the ubiquitous connectivity and enhance access capacity. Moreover, the evolution toward ultra-dense deployment and heterogeneous networks (e.g., micro-, femtocells, WLAN access points) can realize the balancing between communication and computation load.

Recent research has identified and studied some key features in the realization of MEC network architecture as well as solutions for some key challenges. For instance, Peng *et al.* provide a fog-computing-based radio access network architecture to simplify network function in the centralized control [4]. For merging the disciplines of both mobile computing and wireless communication, much work has concentrated on the collaborative management of communication and computation resources. Joint optimization of computation offloading and resource allocation is proposed to minimize energy consumption [5]. Zhang *et al.* provide a cloud-based MEC framework to reduce the service latency and network operation cost [6]. In [7], a fog access network is introduced to realize the low-latency services and achieve the balancing among various resources. Leveraging the big data techniques, N. Kumar *et al.* combine MEC network and infrastructure of cloudification to manage the handoff and schedule charging/discharging requests in smart grid

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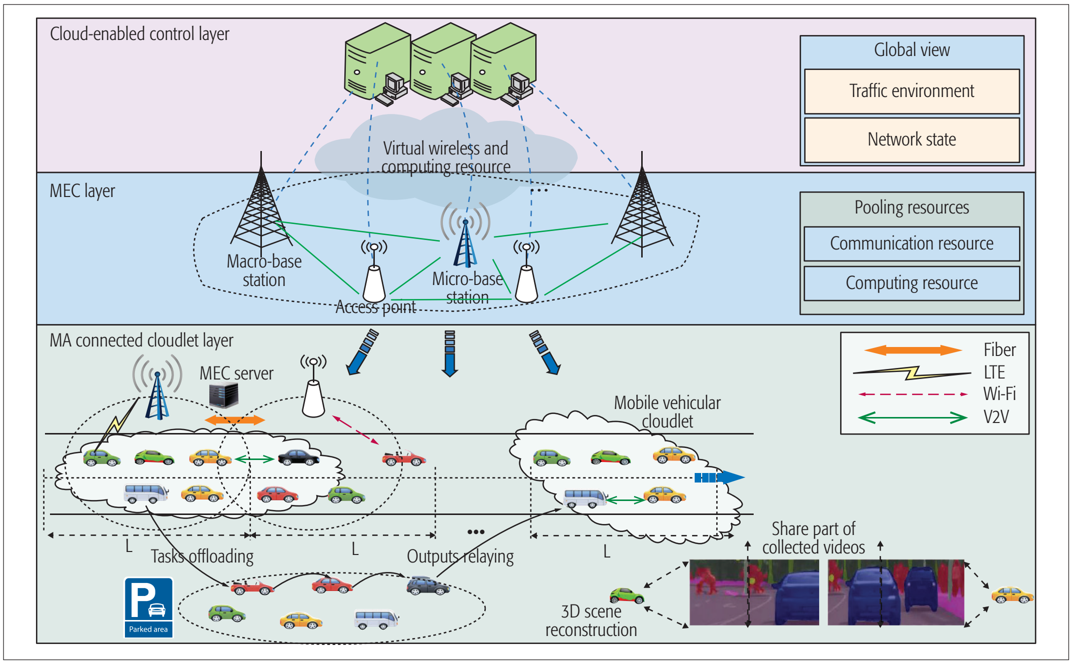

Figure 1. The hierarchical framework of mobile vehicular edge multi-access networks.

Leveraging the advanced data mining techniques, the necessary process toward network-level intelligence can meet the paradigm shift of network operation from reactive to proactive since some events can be accurately predicted. In this way, the cloud-enabled control layer can substantially reduce the time consumption of the network diagnosis and triggering action.

networks [8]. In order to guarantee network security and data privacy, Wu *et al.* propose an efficient data privacy protection mechanism for mobile crowdsensing [9].

The existing MEC research works focus only on the general quality of service (QoS), such as improving energy efficiency or reducing service latency. It is equally important to optimize some application-level metrics [10]. For instance, content integrity and high-definition video will become the new engines to boost a much safer and more convenient driving environment. For these immersive applications, vehicles driving in adjacent areas will have considerable similar or identical computation-intensive tasks. Co-located vehicles can benefit from cooperative data merging or video stitching in MEC platforms. In this way, the refined outputs are more accurate and complete than those created by individual vehicles. However, low latency may not be guaranteed if each vehicle offloads its own computation tasks to MEC platforms due to the fierce competition for communication and computation resources. Therefore, high application-level performance should be based on a series of actions in which the redundant computation tasks are removed in advance in a collaborative manner. Otherwise, enormous communication and computation resources will be consumed.

On the other hand, the resource-rich vehicles can also provide more powerful connection and computing capability to enhance the computation experience. Thus, it can facilitate better merging of the MA-MEC technologies into the IoV. Driven by the above issues and prospects, it is necessary to study how to design a feasible network architecture and task offloading scheme to ensure the low latency requirement as well as the application-level driving experience. To the best of our knowledge, these key issues have not been well investigated and addressed.

In this article, we are motivated to make several contributions to offer a comprehensive discussion on the overall system framework and technologies for immersive vehicular applications. Specifically, a hierarchical network framework of a vehicular edge multi-access network (VE-MAN) is presented. To highlight the advantages of multi-access technologies in the VA-MAN, we design a hybrid control scheme to construct the mobile vehicular cloudlet to remove redundant computation tasks. Furthermore, the collaborative task offloading scheme is discussed. We take a 3D scene reconstruction as an exemplary scenario for a case study and then conclude this article.

HIERARCHICAL FRAMEWORK OF VEHICULAR EDGE MULTI-ACCESS NETWORKS

The design goal of the existing MEC network framework aims to solve computation offloading and resource allocation arising from very fine time granularity. Different from the communication network, the variation of transportation flow in general changes more slowly than the variation of network traffic load. Thus, we provide a novel network framework to better merge the MEC technology and IoV network, which executes the flexible network optimization and resource management following the different time granularities. Figure 1 illustrates the hierarchical framework of a mobile VE-MAN, which is implemented on three layers: the cloud-enabled control layer, mobile edge computing layer, and multi-access connected cloudlet layer.

Cloud-Enabled Control Layer: A series of components work as a global controller to collect the spatiotemporal-varying environment view based on coarse time granularity, including transportation traffic, network state, and so on. Leveraging the advanced data mining techniques, the necessary process toward network-level intelligence can meet the paradigm shift of network operation from reactive to proactive since some events can be accurately predicted. In this way, the cloud-enabled control layer can substantially reduce the

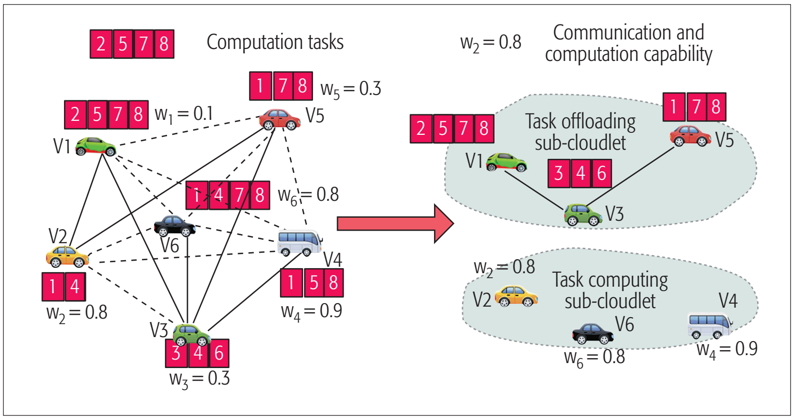

Figure 2. Illustration of application-specific vehicular functional partitioning.

time consumption of the network diagnosis and triggering action.

Mobile Edge Computing Layer: The different types of roadside units (RSUs), base stations (BSs), and WLAN access points (APs) are uniformly denoted as edge infrastructures, which provide the powerful MEC platforms. In order to improve the resource utilization, these physical infrastructures, multi-access technologies, and heterogeneous resources are abstracted as the pooling resources. Thanks to the monitoring information in the cloud-enabled controller, the MEC control layer is suitable for performing network-level operation and pre-allocation of resources for different transportation regions. For example, the MEC platform can adaptively control the ON/OFF operation state of edge infrastructures. Likewise, the number of MEC servers could be scheduled and optimized automatically to realize a green MEC network.

Multi-Access Connected Cloudlet Layer: By assigning the computation tasks to heterogeneous edge infrastructures, the MA connected cloudlet layer is responsible for providing a fine-grained resource allocation and task offloading scheme. Moreover, it is a novel paradigm that the resource-rich vehicles participate in cooperative task offloading through V2V communication and distributed computing. On the other hand, the driving vehicles in the adjacent area have a large amount of identical or similar data, especially in immersive applications. Based on self-organizing network technology, such as forming the mobile vehicular cloudlet, these neighboring vehicles can cooperatively share and offload computation tasks to achieve more integrated content as well as reduce the service latency.

Based on the collaborative interaction among these layers, the proposed VE-MAN framework is expected to bring a variety of benefits, summarized in the following advantages:

- **Merge the IoV and MEC network:** Based on the network-level control and fine-grained computation offloading, the VE-MAN framework can sufficiently utilize the multi-access technologies and underutilized resource in smart vehicles so as to reduce network operation cost and enhance resource utilization.
- **Improve QoS-level and application-level performance:** By utilizing the property of having considerable identical computation tasks, the VE-MAN framework can further reduce service latency and improve application-level performance by pruning the redundant computation tasks in a collaborative manner rather than consuming enormous computation and communication resources.
- **Service continuity provision:** Different from the infrastructure-centric MEC networks, the VE-MAN is a vehicle-centric network framework, where the mobile or parked vehicles in mobile vehicular cloudlets can provide the underutilized computation resource and the task relay function to guarantee service continuity.

Although the proposed VE-MAN is a promising solution to support immersive vehicular applications, there are many new challenges remain to be tackled. Based on the collaborative and distributed computing architecture, the first challenge is how to construct the mobile vehicular cloudlet and remove the considerable redundant tasks. Under ultra-dense network deployment, a key issue is how to assign computation tasks to associate the optimal infrastructure. In addition, the output size for immersive applications may be large compared with the input size. Thus, the output transmission scheme should also be carefully designed to reduce the transmission time.

COLLABORATIVE TASK OFFLOADING WITH MULTI-ACCESS MOBILE EDGE COMPUTING

In order to provide low latency while guaranteeing application-level performance, collaborative task offloading operation should be triggered based on a computation task and resource sharing mechanism to remove the redundant tasks in the mobile vehicular cloudlet. We first design a hybrid multi-access control scheme to establish and maintain a mobile vehicular cloudlet. The proposed hybrid control strategy can be briefly described as follows:

- **Vehicular cloudlet leader selection*:*** To accomplish the selection of a leader and delivery of registration, each vehicle that is interested in a certain application autonomically executes a leader selection algorithm, such as [11]. Then the selected leader sends a message (e.g., vehicle-ID, description of collecting data) to a global cloud-enabled controller, which executes the network-level control based on the current transportation and network state.
- **Vehicular cloudlet formation*:*** According to the specific applications and performance requirements, the cloudlet leader is responsible for configuring the size and function of a mobile vehicular cloudlet based on pre-allocated communication and computation resources.

The QoS-level and application-level metrics are two key parameter indicators to evaluate the network feasibility and tractability for the immersive vehicular applications. In this article, we introduce the perception reaction time (PRT) and the precise gain of content integrity to demonstrate the efficiency of the VE-MAN framework. Specifically, the PRT denotes the total service latency including the following cooperation processes: mobile cloudlet formation, task assignment, data computing, and output transmission back to all target vehicles. The precision gain describes the performance improvement of content integrity through sharing and processing the computation tasks generated by the vehicles in a cooperative way. Generally, the content integrity can be enhanced as more vehicles are involved in cloudlet. However, the improvement rate of precise gain will decrease due to adjacent vehicles having a large amount of identical and similar computation tasks in the mobile cloudlet. Thus, we should remove the redundant computation tasks in advance according to different applications' requirements.

On the other hand, the underutilized vehicular resources can be used to provide efficient support to MEC platforms. Due to the high mobility in ultra-dense networks, vehicles may pass through several edge infrastructures during the task offloading process. Thus, each vehicle should offload its computation tasks to the optimal edge infrastructure or resource-rich vehicles. To overcome the above challenges, we propose a collaborative task offloading scheme composed of two stages: the vehicular function partition and task assignment stages.

Application-Specific Vehicular Function Partition

Borrowing the ingenious idea of mobile social networks [12], the maximum weight independent set (MWIS) based on graph theory is proposed to realize the optimal function partition in a collaborative manner to remove redundant tasks. The basic idea is to divide the vehicles into two sub-cloudlets according to task similarity and computation capability. The vehicles in the sub-cloudlet (defined as the task offloading sub-cloudlet) offload their computation tasks to the MEC platforms or sub-cloudlet (defined as the task computing sub-cloudlet), where the vehicles can provide underutilized computation resource to process the assigned tasks collaboratively.

Figure 2 presents a graphic illustration to describe the scheme of application-specific vehicular function partition. After constructing the mobile cloudlet-based vehicular network, the cloudlet leader is responsible for calculating and analyzing the similarity of computation tasks for all vehicles. To avoid introducing a large amount of signaling overhead and transmission burden, each vehicle just needs to send the main feature of collected tasks to the cloudlet leader at the cloudlet formation phase. Then a virtual function graph is established according to the similarity of collected computation tasks as shown on the left side of Fig. 2, where the dashed and solid lines indicate the high computation task similarity and low computation task similarity between any two vehicles, respectively. For instance, the connection between vehicles V1 and V2 is shown by a solid line if the similarity degree is smaller than a predefined threshold according to different vehicular applications and service requirements. As a consequence, several candidate independent sets can be obtained based on the virtual function graph. The weighted value *W* is denoted as the dynamic resource utilization to describe the vehicle's capabilities of communication and computation at the formation phase of a mobile vehicular cloudlet. Moreover, the weighted value should be kept constant at the task offloading and output transmission process, and it will be updated if there are vehicles participate in and quit the mobile cloudlet. Finally, the optimal independent set is selected based on the weighted value *W*. As a result shown on the right side of Fig. 2, vehicles with large weighted values are partitioned into the task computing sub-cloudlet to provide underutilized communication and computation resources. Meanwhile, vehicles with small similarity are partitioned into the task offloading sub-cloudlet to assign their computation tasks to edge infrastructures or the task computing sub-cloudlet.

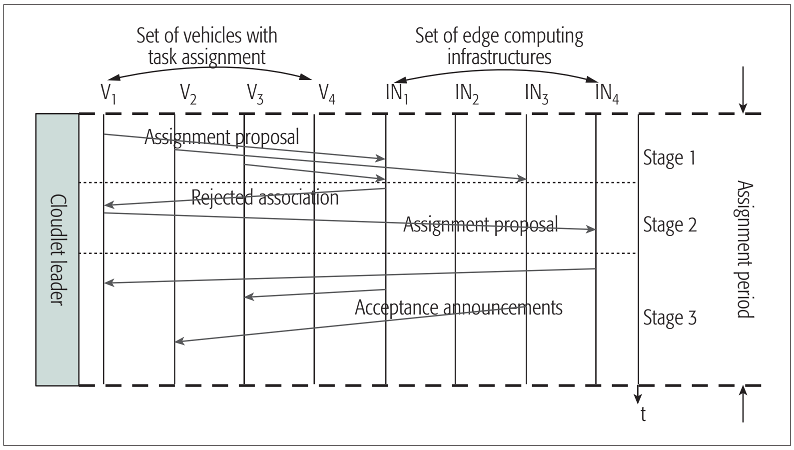

Figure 3. Timing diagram of the computation task assignment process.

Latency-Oriented Task Assignment Scheme

After removing the redundant computation tasks, we further propose a task assignment scheme to guarantee low service latency including communication and computation latency. How to assign the computation tasks to the optimal edge infrastructure (MEC platforms or task computing sub-cloudlet) is an essential issue. From the perspective of an individual vehicle, the objective is primarily to associate with the edge infrastructure that can provide the minimal service latency. On the other hand, the edge infrastructures not only select vehicles with low latency requirement, but also take into account the balance between computation and communication offloading among heterogeneous edge infrastructures. In order to solve the above issues, we propose a two-sided matching scheme for computation task assignment to achieve the balancing benefit of both sides.

In the two-sided matching process of computation task assignment, the vehicles in the task offloading sub-cloudlet and edge infrastructures (abbreviated as V and IN, respectively, for simplicity) implement the actions of proposal and decision, respectively, with the assistance of the cloudlet leader for signaling exchange, as shown in Fig. 3. Leveraging the VE-MAN framework, the task assignment proposal and matching decision can be transmitted with seamless coverage. The whole task assignment process is composed of three stages. Specifically, stage 1 is the information collection of task assignment proposals. Stage 2 is the matching process to reduce the task transmission and computation latency. Stage 3 announces the stable task assignment result between the edge infrastructures and the attached vehicles.

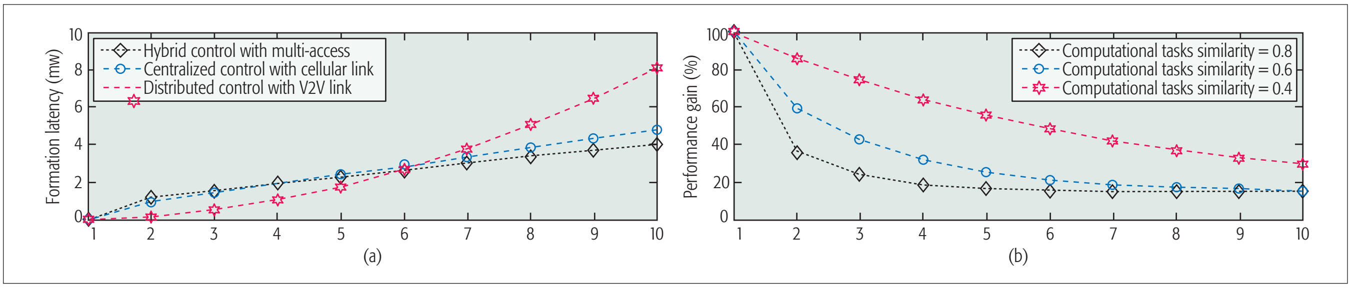

Figure 4. Cloudlet formation latency and performance gain vs. the number of vehicles participating in cloudlet.

According to the above graphic description, the decisions of task assignment are made by edge infrastructures based on the association proposals received from the vehicles in the task offloading sub-cloudlet. The final decisions are independent of the matching periods [13]. Therefore, we can focus on optimizing the task assignment for a single matching period. Specifically, each side first establishes and maintains the preference list based on individual utility function. Under the task assignment phase, the vehicular utility is defined as the service latency, including transmission and computation latency. On the other hand, we introduce the balancing utility to represent the network side utility. Specifically, the load balancing utility aims at adaptively adjusting the utilization of resources, which is the ratio of computing capability of edge infrastructure and task transmission rate. In general, the value of the load balancing factor can be selected as an efficient balancing trade-off among computation task and communication traffic load.

Through accepting the task offloading request based on individual preference, each edge infrastructure judges whether the number of attached vehicles exceeds the maximal quotas. If not, the edge infrastructure accepts these proposals, and arranges them into the matching list in ascending order. Finally, repeat the above matching process until all the vehicles are arranged in the final matching lists owned by edge infrastructures. Similar to Nash equilibrium [14], the termination of the matching process is to find a stable task assignment result between vehicles and edge infrastructures or a task computing sub-cloudlet with corresponding quota constraints. In addition, the computational complexity of the task assignment scheme in the worst case is $O(NQ)$, where N and Q are the total number of edge infrastructures and the number of vehicles in the task offloading sub-cloudlet, respectively. In a practical network environment, the computational complexity can be tolerable due to the number of infrastructures usually being far lower than the number of vehicles. Furthermore, we design a fast task assignment algorithm based on the proposed two-sided matching algorithm. This scheme can converge to a suboptimal and stable matching result according to the given service latency requirement. In this case, our proposed task assignment schemes have good feasibility and robustness in practical vehicular edge computing networks.

ADVANTAGE OF LEVERAGING MULTI-ACCESS FOR OUTPUT TRANSMISSION

For immersive vehicular applications, the size of output data for each vehicle may also be large compared to the size of input data. In order to discuss the output transmission time with the aid of multi-access technologies, we design an efficient transmission strategy from MEC platforms to all target vehicles of a mobile cloudlet. The whole procedure of output transmission includes two steps. Upon completion of the task merging and processing at MEC platforms, the output data is divided in an equal way and sent back to the target vehicles via cellular downlink. After receiving part of the output data, all the target vehicles exchange their data with each other via V2V communication.

We assume V2V communication has the extra transmission rate gain G compared to cellular communication. Let M denote the number of resource blocks required for transmitting one unit of output data. For the cellular downlink transmission process, the transmission time for each vehicle is $1/M$. Under the phase of output data exchange via V2V communication, the transmission time is $(K - 1)/(GM)$, where K is the total number of vehicles in the mobile cloudlet. Compared to the unicast transmission, the total output transmission latency is $(GK)/(G + K - 1)$ times less than unicast transmission supported by the same amount of resource blocks. Moreover, the improvement of performance gain is significant as the number of vehicles involved in collaborative task offloading increases. It can be found that the obtained performance gain is not at increasing cost in terms of system overhead.

PERFORMANCE EVALUATION OF VE-MAN

In this section, we take three-dimensional scene reconstruction (e.g., data merging or video stitching) as an immersive vehicular application to demonstrate the advantage of our proposed VE-MAN architecture and collaborative task offloading scheme. We use the PRT to describe the total service latency, which is served as the practical metric for autonomous driving. The precise gain of content integrity is proposed to describe the application-level metric. In addition, the two control schemes of mobile cloudlets and the three basic task offloading schemes are used as comparable benchmarks.

A typical intelligent transportation scenario is composed of heterogeneous infrastructures enabled by powerful MEC platforms, smart vehicles, and mobile devices [15]. We consider the different number of edge infrastructures located along a four-lane two-way road [6]. In this article, we consider three representative multi-access technologies: cellular communication, WLAN, and V2V communication. Typical of immersive vehicular application, computation tasks, such as the collected video, are set to 1024 × 768 pixels/

frame. Without loss of generality, the video is set as 25 frames/s.

Figure 4a shows the cloudlet formation latency with different numbers of vehicles involved in the cloudlet. The formation latency of a mobile vehicular cloudlet is defined as the duration needed to exchange all required signaling. Leveraging the advantage of V2V communication, the formation latency of distributed control is less than the other two schemes when the number of vehicles is less than 6. Similar to the centralized control method, the cloudlet leader is responsible for executing signaling exchange among vehicles and sending the essential information to the cloud-enabled controller. Due to low V2V communication latency and signaling overhead, the hybrid control scheme can reduce the formation latency when massive numbers of vehicles participate in the mobile cloudlet.

Figure 4b illustrates the precise gain of application-level performance under different similarity of computation tasks as the number of vehicles increases. Generally, the more computation tasks are offloaded to the edge infrastructures, the higher content integrity can be obtained under the unified data process algorithm. Furthermore, the result shows that the whole precise gain of outputs will be 50–60 percent reduction as the number of vehicles increases, especially in the large similarity of computation tasks. Based on the heuristic result, the proposed vehicular function partition scheme is needed to remove the redundant computation tasks before the task assignment process based on different IoV applications and performance requirements.

Figure 5 illustrates the variation of PRT with different numbers of vehicles participating in the mobile vehicular cloudlet. We compare the performance of our proposed task offloading scheme with the other three baseline schemes. The PRT increases as the number of vehicles increases. This can be explained by the fact that the massive amounts of vehicles lead to more complex operation of vehicular function partition and fierce resource competition in the task assignment phase. Specifically, we have the following observations:

1. The low-latency application cannot be satisfied under the local task computing scheme due to the total amount of computation tasks offloaded to the single edge infrastructure.
2. Based on the multi-access technologies and distributed computing architecture, the total service latency can be significantly reduced compared to the local computing scheme. Furthermore, leveraging the advantage of output transmission with the aid of multi-access technologies, the proposed collaborative task offloading scheme with MA-MEC experiences the lowest perception reaction time.
3. We design a fast task offloading scheme to quickly converge a stable matching result (e.g., an acceptable delay according to different IoV applications) when a large number of vehicles is involved in the mobile cloudlet. By leveraging the collaborative task offloading and distributed computing, our proposed VE-MAN has the potential advantages of realizing the low latency requirement as well as achieving a good application-level experience.

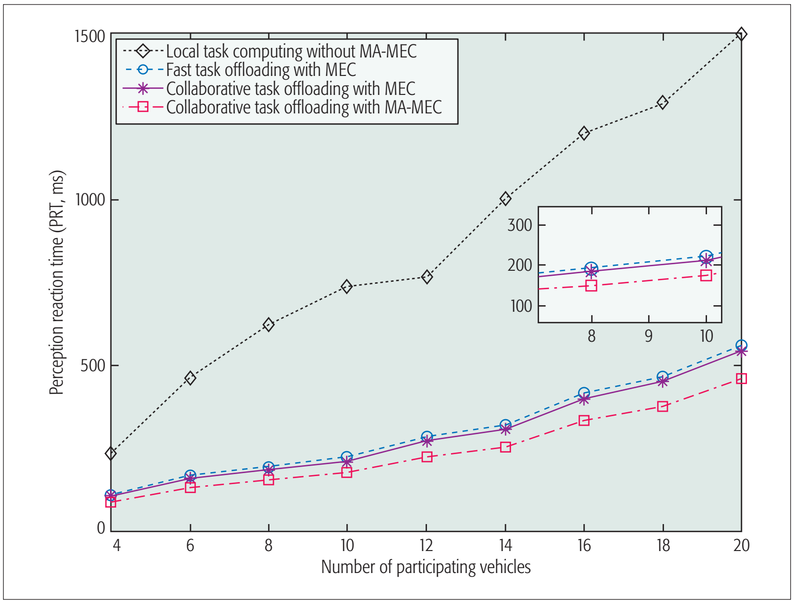

Figure 5. The impact of the number of participating vehicles on the PRT.

CONCLUSION

In this article, we first propose a collaborative VE-MAN framework and describe its operation for immersive vehicular applications. With this network framework, a novel paradigm is introduced to offload the computation-intensive tasks to the heterogeneous MEC platforms and resource-rich vehicles. Furthermore, a collaborative task offloading scheme is proposed to cooperatively share the computation tasks and guarantee low communication and computation latency. Numerical results demonstrate that our proposed scheme can reduce the perception reaction time while improving driving safety and convenience.

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