Enabling Collaborative Edge Computing for Software Defined Vehicular Networks

Kai Wang, Hao Yin, Wei Quan, and Geyong Min

ABSTRACT

Edge computing has great potential to address the challenges in mobile vehicular networks by transferring partial storage and computing functions to network edges. However, it is still a challenge to efficiently utilize heterogeneous edge computing architectures and deploy large-scale IoV systems. In this article, we focus on the collaborations among different edge computing anchors and propose a novel collaborative vehicular edge computing framework, called CVEC. Specifically, CVEC can support more scalable vehicular services and applications by both horizontal and vertical collaborations. Furthermore, we discuss the architecture, principle, mechanisms, special cases, and potential technical enablers to support the CVEC. Finally, we present some research challenges as well as future research directions.

INTRODUCTION

Every year millions of people are injured in traffic accidents. Human error causes nearly 90 percent of these accidents. Leveraging the fast development of the Internet-of-Things (IoT) and the mobile Internet [1], a promising industrial perspective, Internet-of-Vehicles (IoV), is expected to reduce the traffic accident rate, as well as improve traffic efficiency and traveling convenience. However, they all require *ultra-low latency* for communications, which is a big challenge for current IoV applications [2]. Due to the highly-coupled host-to-host architecture, it is difficult for the traditional Internet to meet various pressing demands in heterogeneous vehicular scenarios.

Nowadays, software-defined networking (SDN) has become a hot technology for the innovative network paradigm. It features the decoupling of the network control from the data transmission. This shift gives the whole network system flexible scalability, programmability, great service capability and convenient management. Recently, software-defined vehicular networks (SDVNs) [3] have been proposed to achieve a flexible vehicular network by embedding SDN into vehicular networks. Some special issues for SDVN have also been researched. For example, W. Quan *et al.* first considered crowd collaboration for SDVN [4]. With logical centralized controlling, SDVN provides a powerful platform for reliable communications in various vehicular scenarios.

On the other hand, edge computing is an available and promising approach to access huge data locally and avoid long latency [5, 6]. When vehicular users issue services through a core network from edge networks far away from the cloud, it may cause long latency. Edge computing is pioneered to overcome the disadvantages of traditional cloud computing [7, 8]. Up to now, many types of research have focused on vehicular edge computing (VEC). N. Kumar *et al*. [9] proposed using mobile edge computing (MEC) to deal with charging decisions for vehicular networks. Most current research focused on the VEC architecture design, yet failed to analyze how to utilize different architectures and their functions collaboratively.

Although there are multiple edge computing types available for vehicular networks, cooperation abilities among different edge computing approaches are required for vehicular networks. To the best of our knowledge, there are few studies on the collaborations among different edge computing solutions. This article proposes a collaborative edge computing framework for vehicular networks that aims to overcome the limited capabilities of a single edge computing solution. We highlight that multiple cooperation achieves the best tradeoffs to benefit from the powerful computing resources to solve the real-time and high-bandwidth problems in vehicular networks. The main contributions of this article are as follows:

- This article proposes a *collaborative vehicular edge computing framework*, called CVEC. This framework is the first approach that highlights collaborative edge computing to organize available network resources in vehicular scenarios and provide efficient vehicular services.
- This article further analyzes *software-defined collaborative edge computing* to deploy efficient CVEC systems. By leveraging hierarchical software defined controllers, the collaborating policies are conducted in both the horizontal and vertical planes.
- This article investigates the potential VEC cases, practical deployment technologies and promising technical enablers, including SDN, network function virtualization (NFV), smart collaborative networking (SCN) and blockchain. We also discuss the main challenges and future research directions to enhance CVEC systems.

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Item	MEC (ETSI, 2014)	Fog computing (CISCO, 2011)	Cloudlet (CMU, 2013)	Cloud computing
Node types	Servers in base stations	Routers, access points, gateways	Small data center	Huge data center
Deployment location	Network edge	Network edge or near edge	Network edge	Remote network
Context awareness	High	Medium	Low	No
Proximity	One or multiple hops	One hop	One hop	Multiple hops
Scope	Medium	Small		Large
Cooperation	No	Partially	No	No
Supporting mobility	Yes	Yes	Yes	Partially
Business interest	5G requirements	Internet of things	Mobile applications	Mobile computing
Structural pattern	Decentralized, distributed, three or more tiers			Centralized, two tiers
Scalability	High			Low
Software architecture	Based on mobile orchestrator	Based on fog abstraction	Based on cloudlet agent	Based on cloud agent

TABLE 1. A multiple-dimension comparison of different edge computing paradigms.

COLLABORATIVE VEHICULAR EDGE COMPUTING

MOTIVATIONS AND CONSIDERATIONS

Edge computing can be used to improve vehicular services by distributing computation tasks between edge resources and local vehicular terminals. The application services can be in proximity to the vehicular users or even perform computing directly at the vehicles. It offers many advantages, such as lower latency, higher efficiency, and proximity services. There are many approaches that push cloud computing capabilities to the network edge, including MEC, fog computing, and cloudlets. Although all these solutions for edge computing have the same intention and motivation, different edge computing paradigms also have their particular features. These concepts are partially overlapping but also complementary. A multiple-dimension comparison among three edge computing paradigms as well as cloud computing is illustrated in Table 1.

How to let the differentiated VEC paradigms collaborate is critical to promote VEC deployment. To this end, by leveraging the basic idea of edge computing, we propose a customized architecture, embedding collaborative edge computing considerations, to achieve an efficient vehicular network, called the CVEC framework. By collaborating different VEC solutions, CVEC aims to manage and control heterogeneous network resources smartly to meet diversified vehicular demands.

OVERALL CVEC ARCHITECTURE

Figure 1 shows the architecture of CVEC. In particular, CVEC employs a software-based controller to program, manipulate and configure networking in a logically centralized way. This centralized structure allows ubiquitous edge infrastructures to be flexibly managed to serve various applications on demand.

The CVEC architecture can support collaborations in multiple aspects. On the one hand, it can unite different edge computing solutions through *inter-domain* and *intra-domain* collaborations to optimize edge computing resources. On the other hand, CVEC can collaborate resources among cloud computing, edge computing, and local computing to take full advantage of them. Shown in Fig. 1, collaborations in CVEC include two categories: horizontal collaboration (X-collaboration) and vertical collaboration (Y-collaboration).

The X-collaborations include inter-domain and intra-domain collaborations. For certain application scenarios, multiple edge computing units or agents may exist simultaneously. Efficient cooperation among these edge computing units or agents, that is, inter-domain collaborations, must be considered. These agents should have some predefined rules and can exchange information with each other. For example, it mainly includes collaborations among MEC, fog computing, and cloudlets. As for the intra-domain collaborations, different edge computing solutions may employ different functional components. For example, in MEC, the collaboration can be divided into MEC server collaboration and infrastructure collaboration. In fog computing, it includes the collaboration of fog nodes, which mainly contain collaborations among small-scale distributed cloud in Cloudlets.

Similarly, Y-collaborations represent collaboration possibilities among various layers. In particular, the CVEC architecture includes three layers: the infrastructure layer, the edge computing layer, and the core computing layer. Each layer corresponds to a type of computing resource with different levels respectively, that is, local computing, edge computing, and remote cloud computing. Information interaction and processing is required when a Y-collaboration operation occurs between any two neighbor layers. Correspondingly, remote cloud computing can collaborate with edge computing; meanwhile, edge computing can collaborate with local computing. Through the Y-collaboration in the vertical direction, CVEC can easily achieve offloading and guarantee quality of service (QoS), and hence provide an excellent user experience [10].

By introducing collaborative edge computing, various flexible computing and storage resources can be distributed more efficiently at the network edges, including radio access networks, edge routers, gateways, access points, roadside units, mobile devices, and so on.

DEPLOYMENT AND APPLICATIONS

How to manage the collaborating operations is an extremely complex task. In a practical deployment, the idea of SDN is borrowed into the CVEC to satisfy its challenging requirements. Due to its high-flexibility, an SDN-based CVEC controller guides the collaborating operations efficiently and economically. On the one hand, SDN can simplify the cost of both development and deployment of new protocols and

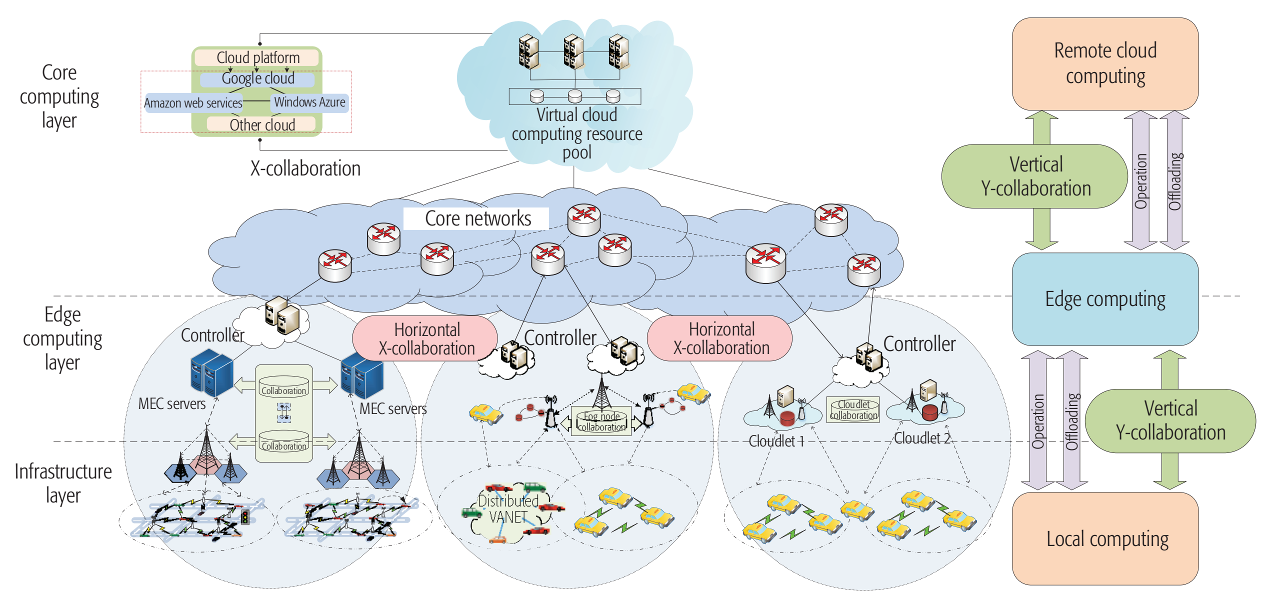

FIGURE 1. The architecture of CVEC.

applications. On the other hand, SDN adopts a logically centralized controller, which can access the global knowledge of the network state and make controlling more efficient and timely due to the centralized management. In addition, SDN controls the network infrastructure in a vendor-independent manner, which is more flexible.

There are many different derivations of edge computing, including MEC, fog computing and cloudlet [11]. As for the basic application cases, we primarily analyze the collaborations in different cases separately. Figure 2 shows the deployment and typical application cases of CVEC. In a practical deployment, a CVEC controller is equipped globally and connects each edge computing scenario. This controller is associated with a cloud computing or big data platform [12, 13]. It can be aware of the status of the entire network and publish the corresponding policies to different scenarios.

MEC Collaboration for Vehicular Networks: Mobile edge computing is a typical derivation of edge computing, especially for mobile scenarios, which have drawn much attention from both academia and industry. Through MEC collaboration, the MEC servers are located in the proximity of base stations (BSs). They can either handle a request from a vehicular node and respond directly to the vehicular node or forward the request to remote computing centers or content distribution networks. Through these MEC servers, it can assist the SDN controllers to improve the QoS of the whole network system.

Fog Computing Collaboration for Vehicular Networks: Slightly different from the MEC, fog computing is an edge computing platform designed mainly for IoT cases [14]. In the view of fog computing, fog nodes are massively distributed in the wide area, surrounding all kinds of user devices, including mobile and immobile vehicles. All fog nodes build the edge, which links to the core network or a data center. In Fig. 2, the link L1 is in charge of controlling the fog computing collaboration for SDVN. It contains three layers: the cloud layer, the fog layer, and the device layer. The fog layer may contain multiple tiers according to certain requirements. The fog node could be small BSs, vehicles, WiFi access points, and even user terminals. The vehicular devices can be allocated with the most appropriate fog node and associated with this node according to the local controller.

Similar to MEC, fog computing has advantages in three aspects: exploiting storage, computing and control functions, communication and networking. The main feature of fog computing collaboration is that it utilizes collaborations among multiple vehicular devices or near-user edge devices to help data processing and storage.

Cloudlet Collaboration for Vehicular Networks: The cloudlet, another example of edge computing, adopts a three-tier architecture to achieve collaborations among local devices, cloudlet and cloud [15]. Cloudlets are deployed at access points or BSs. In Fig. 2, the link L3 is in charge of controlling the cloudlet collaboration for SDVN. For example, many vehicular applications require end-to-end latency less than 1 ms. Assuming packet propagation at the speed of light, this requires a cloudlet within 300 km. In reality, cloudlets should be deployed much closer to ensure the delay requirement. The combination of 5G cellular networks and cloudlets will make this possible.

In short, different from centralized cloud computing with resources at one or a few certain locations, CVEC is supposed to be deployed in a fully distributed manner. Due to the multiple collaborations, CVEC can better perform computing directly on mobile vehicles, allowing several vehicular nodes in proximity to combine their computing power, and thus process highly demanding applications locally. This design offers several advantages:

- Offers significantly lower latencies and jitter for reliable vehicular services.
- Enables sophisticated applications for vehicular users.
- Provides higher data storage capabilities and faster data computing capability.

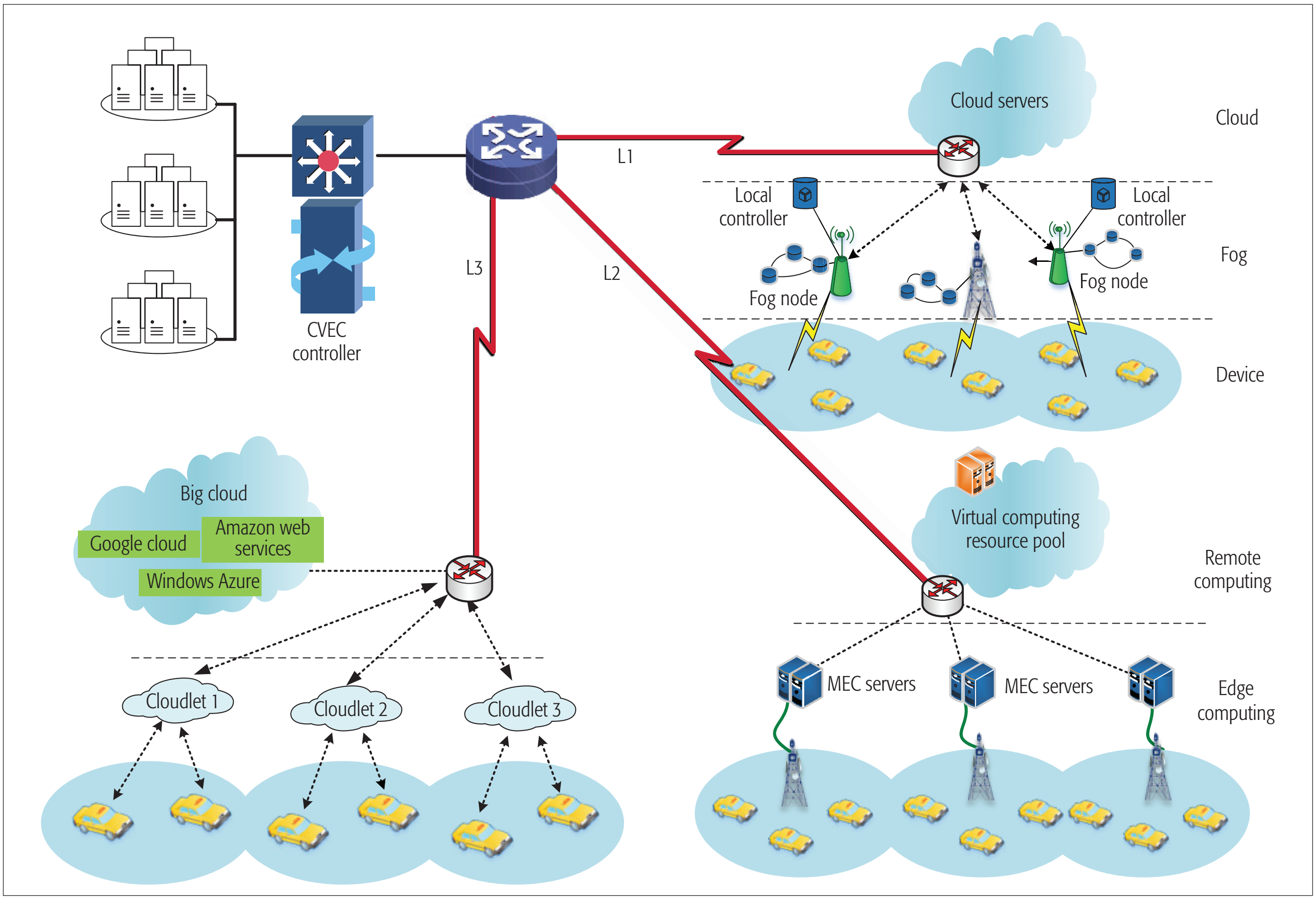

FIGURE 2. The deployment and typical application cases of CVEC.

- Saves energy consumption by offloading energy consuming computations to the edge clouds.

POTENTIAL ENABLING TECHNOLOGIES

This section presents several key technologies that enable the concept of CVEC to become a reality. These technologies provide flexibility, scalability and operating efficiency to the CVEC framework.

NETWORK FUNCTION VIRTUALIZATION

Network Function Virtualization (NFV) is a key tool to realize the CVEC by using software to finish the full collaboration functions. NFV is virtualization technology to segment the functions of network nodes into several functional blocks. It is implemented separately in software and no longer confined to the hardware architecture. It provides network capabilities and applications that are usually found in hardware, such as route, caching, security, strategy, and so on. The core of NFV is the virtual network function. NFV technology, however, requires the integration of applications, business processes and infrastructure software that can be integrated and adjusted. The goal of NFV technology is to provide network functionality on standard servers rather than on custom devices.

SOFTWARE DEFINED NETWORKING

SDN can provide efficient network management and configuration for CVEC, but it is still developing. SDN introduces the concept of southbound and northbound interfaces. The southbound interface refers to the interface and protocol between programmable switches (SDN-capable switches) and the software controller. The northbound interface determines how to express operational tasks and network policies, and also how to translate them into a form the controller can understand. SDN is a novel paradigm that enables the separation of the data plane and the control plane. In the data plane, network switches are simple packet forwarding devices. SDN controllers manage and control the entire network through a logically centralized software program. NFV is responsible for virtualization of various network elements, and SDN is responsible for virtualization of the network itself.

SMART COLLABORATIVE NETWORKING

Smart Collaborative Networking (SCN) was first proposed to design smart Internet architectures [16]. SCN supports the idea that the future Internet paradigm should make the essential shift from the current "service provisioning using controlled ownership of infrastructures" to the future "unified management framework full of flexible control and collaboration among users, networks, and services using network virtualization and programmability." Smart Identifier Network (SINET) is a specific instance of SCN architecture, which can promote the deployment of CVEC [17]. SINET can easily accomplish optimal decisions, task allocation and resource dynamic scheduling by managing network function groups logically. It enables network devices such as routers, content servers, sensors, mobile terminals and interfaces to carry

The use of smart contracts is the key. Specifically, smart contracts are deterministic exchange mechanisms controlled by blockchain that can carry out the direct transaction of value between untrusted agents as an incentive, whenever the collaborative edge computing finishes. Through on-chain smart contracts, the credibility and initiative of edge computing nodes can be guaranteed.

out a specific task collaboratively, for example, traffic controlling based on deep learning [18].

BLOCKCHAIN

Security is one of the biggest challenges for edge computing, and fortunately, blockchain can guarantee collaborating security in the CVEC solution, which is a distributed computing technology with high fault tolerance. In blockchain, each block contains a timestamp and a link to its previous block. The decentralized consensus makes it potentially suitable for identity management, behavior recording, event statistics and other management activities in edge computing. The security level of blockchain is very high since the peer to peer connection and interaction can be verified by every on-chain entity. Besides, blockchains are capable of exchanging computing resources among untrusted nodes for edge computing. The use of smart contracts is the key. Specifically, smart contracts are deterministic exchange mechanisms controlled by blockchain that can carry out the direct transaction of value between untrusted agents as an incentive, whenever the collaborative edge computing finishes. Through on-chain smart contracts, the credibility and initiative of edge computing nodes can be guaranteed.

OPEN CHALLENGES

The decentralization and proximity of the service infrastructure to the edge offers various benefits for vehicular networks, such as low latency, low delay, high energy efficiency, and higher throughput. However, a variety of issues and challenges also emerge. In the following sections, we illustrate challenges that might become stumbling blocks to collaborative edge computing.

MOBILITY MANAGEMENT

The mobility of vehicles is a great challenge. The velocity of vehicles has a significant impact on data processing and computation offloading. On the one hand, to ensure the timeliness and effectiveness of information processing, CVEC networks should provide accurate and real-time mobility awareness. On the other hand, concerning the movement of vehicles, it is critical to decide when and how to offload computing tasks and which elements of the computing tasks should be offloaded. Especially in heterogeneous networks, computing tasks can be offloaded to edge servers as well as cloud computing center devices.

SECURITY AND PRIVACY

With the explosive growth of the number of cars, the interaction of data and information is also increasing significantly. To ensure communication safety and information privacy in vehicular networks of edge computing, we should take a higher secure and private measure. According to some studies, the security applied in current cloud computing may not reach the security standards for edge computing, which may put edge devices and user information into an unsafe position. Also, authentication at different levels of the gateway and the smart monitor is another important security issue to guarantee privacy and resist network attack, which needs more effort to be realized.

SCALABILITY

The centralized controller offers great opportunities as well as great challenges for real-time applications. Massive new mobile applications are increasing dramatically, leading to an exponential growth of demand not only in high data rate but also high computational capability. There is a variety of data information, such as route planning, traffic alert dissemination, context-aware infotainment, and mobile vehicular cloud services. The lack of a dedicated mechanism for resources and connectivity management makes some services infeasible. How to reduce significant execution delay is challenging, consisting of the time to deliver offloaded applications to the cloud and the time of computation at the cloud.

DEPLOYMENT AND STANDARDIZATION

The CVEC network is a logically centralized yet physically dispersed network. In practice, distributed edge computing devices might be owned by different infrastructure providers. How and where to deploy these edge data centers to manage users' available resources is the first question we should take into consideration. Additionally, the edge infrastructures of CVEC networks should cooperate with each other regardless of the position, that is, the agreements and standards for communication among these edge elements pose great challenges to our current research.

In addition, there are many challenges when managing interconnected edge networks in practical vehicular networks, including:

- Difficulties in both deployment and management.
- Huge load overhead on both radio and backhaul.
- Traffic control on large-scale vehicular devices.
- Vehicular applications across multiple VEC platforms.

CONCLUSIONS

This article focuses on how to enable edge computing to collaborate, to achieve efficient vehicular networks. We first investigate and compare multiple edge computing solutions for vehicular networks, such as mobile edge computing, fog computing, and cloudlet. Then, we propose CVEC, a novel collaborative edge computing framework for efficient vehicular networks. CVEC includes both horizontal and vertical collaborations. Subsequently, we discuss the key technical enablers of CVEC and present the open research challenges as well as future directions. In future work, we will further enhance collaborations for edge computing and explore their potential advantages by leveraging advanced technologies such as blockchain, deep learning, and artificial intelligence.

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