A Hierarchical Architecture for the Future Internet of Vehicles

Kai Liu, Xincao Xu, Mengliang Chen, Bingyi Liu, Libing Wu, and Victor C. S. Lee

Abstract

Recent advances in wireless communication, sensing, computation and control technologies have paved the way for the development of a new era of Internet of Vehicles (IoV). Demanded by the requirements of information-centric and data-driven intelligent transportation systems (ITS), it is of great significance to explore new paradigms of IoV in supporting large-scale, real-time, and reliable information services. In this article, we propose a hierarchical system architecture, which aims at synthesizing the paradigms of software defined networking and fog computing in IoV and best exploiting their synergistic effects on information services. Specifically, a four-layer architecture is designed, comprising the application layer, the control layer, the virtualization layer, and the data layer, with objectives of enabling logically centralized control via the separation of the control plane and the data plane; facilitating adaptive resource allocation and QoS oriented services based on network functions virtualization and network slicing, and enhancing system scalability, responsiveness, and reliability by exploiting the networking, computation, communication, and storage capacities of fog-based services. On this basis, we further analyze newly arising challenges and discuss future research directions by presenting a cross-layer protocol stack. Finally, for the proof of concept, we implement the system prototype and give two case studies in real-world IoV environments. The results of field tests not only demonstrate the great potential of the new architecture, but also give insight into the development of future ITS.

Introduction

With the boom in wireless communication, sensing, computation, and control technologies, the Internet of Vehicles (IoV) is emerging as the most promising paradigm for enabling cutting-edge smart applications such as intelligent transportation systems (ITS), intelligent vehicles, and autonomous driving. Meanwhile, driven by vehicle-to-everything (V2X) communications, big data analytic, artificial intelligence, and autonomous control capabilities of future IoV, we may envision that the next revolution in automotive industry is around the corner. By looking back on the history of mobile phones in the past decade, they evolve from conventional calling and messaging tools to current smart devices with impressive functions. It is foreseeable that in the near future, similar trends will happen on vehicles such that they are not just transportation tools, but will form the basis of vehicular networks immersed in existing smart applications. Clearly, there is an urgent need for developing new paradigms for future IoV. Accordingly, this article is dedicated to proposing a novel hierarchical system architecture, which synthesizes the paradigms of software defined networking (SDN) and fog computing, aiming to best exploit their synergistic effects on providing real-time, reliable, and large-scale information services in IoV.

SDN was originally proposed for renovating conventional network architectures and enabling rapid network innovation, and has shown great advantage in control and management in cloud systems [1]. The core idea of SDN is to simplify network management and expedite system evolution by decoupling the control plane and the data plane, where the network intelligence is logically centralized in the software-based controller, and the network nodes such as switches will forward data packets based on the decisions made by the controller. Apparently, considering the features of IoV, such as dynamic network topology, high mobility of vehicles, and heterogeneous communication interfaces, it is desired to have an SDN-based framework for abstracting resources and implementing optimal service scheduling in such a system.

Fog computing is an emerging networking paradigm for enabling low-latency and high-reliability information services for billions of connected devices in the Internet of Things (IoT) by offloading computing, networking, storage, communication, and data resources closer to end users [2]. It is designed to complement conventional cloud-based services in supporting high-density device connection, massive volume of data transmission, and intensive computation at the network edge. According to the forecast, over 300 million vehicles will emerge into the IoV market by 2020. Moreover, IoV not only represents the connection among vehicles, but also implies the collaboration among pedestrians, roads, infrastructures, and so on. Undoubtedly, as one of the most representative application scenarios in IoT, IoV is expected to benefit tremendously from the development of fog-based services. In addition, with the maturity of ultra-reliable and low-latency fifth generation

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Digital Object Identifier: 10.1109/MCOM.2019.1800772

0163-6804/19/$25.00

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(5G) technology, as well as the fast development of modern vehicles with respect to their computation, storage, and communication capabilities, there are strong driving forces for bringing fog computing into IoV.

With the above motivations, this article starts by reviewing the state of the art of wireless communication standards, service architectures, and scheduling algorithms in IoV. Then we propose a hierarchical architecture for information services in IoV, consisting of the application layer, control layer, virtualization layer, and data layer, which integrates both the SDN and fog computing paradigms by considering the unique characteristics of vehicular networks, including high vehicle mobility, intermittent service connections, dynamic network topologies, and heterogeneous resources. Specifically, we give comprehensive analysis in IoV with respect to the separation of control and data planes, network functions virtualization (NFV) in heterogeneous resource environments, network slicing (NS) for services with different quality of service (QoS) requirements, and the offloading of computation, storage, control, and communication capacities with fog-based services. Further, we discuss new challenges arising in such a paradigm and suggest future research directions by presenting a cross-layer protocol stack for IoV. Finally, we build a system prototype and implement two applications in realistic IoV environments.

State of the Art

For communication standards in IoV, IEEE proposed the dedicated short-range communication (DSRC) in 2003, and the protocol stack called Wireless Access in Vehicular Environments (WAVE) was formally released in 2010, which includes IEEE 802.11p, the IEEE 1609.1/.2/.3/.4 protocol family, and the SAE J2735 message set dictionary [3]. 75 MHz of the spectrum in the 5.9 GHz band is allocated for DSRC, which is divided into one control channel (CCH) and six service channels (SCH). In DSRC, the roadside unit (RSU) is a static infrastructure installed along the road, while the onboard unit (OBU) is a mobile device mounted in vehicles. DSRC enables vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications.

Meanwhile, with the rapid development of cellular based mobile communication technologies, the Long-Term Evolution-Vehicle (LTE-V) standard is being developed to enable V2X communication [4]. Moreover, the IMT-2020 (5G) Promotion Group, which is a major platform for 5G technology innovation in China, established a Cellular V2X (C-V2X) Working Group in April 2017 to accelerate the evolution to 5G-based V2X communications. As envisioned, future vehicular networks will be operated in a heterogeneous wireless communication environment.

For service architectures and scheduling algorithms in IoV, great efforts have been devoted to investigating SDN and fog-computing-based paradigms. Z. He *et al*. [5] proposed an SDN-based architecture to enable rapid network innovation in heterogeneous vehicular communication environments. X. Huang *et al*. [6] proposed 5G-enabled software defined vehicular networks (5G-SDVNs) for service provision. K. Liu *et al*. [7] proposed a scheduling algorithm in an SDVN for cooperative data dissemination via hybrid V2I/V2V communications. P. Dai *et al*. [8] proposed SDN-based scheduling for temporal information services with time constraint in heterogeneous vehicular networks. G. Luo *et al*. [9] proposed an SDN-based medium access control (MAC) protocol to improve communication performance in dynamic vehicular networking environments. K. Liu *et al*. [10] presented an SDN-based service architecture and combined vehicular caching and network coding to enhance bandwidth efficiency.

I. Stojmenovic and S. Wen [11] first proposed to integrate fog computing into SDVN. W. Zhang *et al*. [12] proposed a cooperative fog computing architecture for big data processing in IoV. X. Hou *et al*. [13] proposed a vehicular fog computing (VFC) architecture, in which vehicles are considered as mobile infrastructures and their individual resources are aggregated to have better communication and computation services. C. Huang *et al*. [14] provided a case study of a fog-assisted traffic control system, and discussed the potential benefits, security issues, and forensic challenges in VFC-based services. Z. Ning *et al*. [15] presented a VFC architecture with cloud, cloudlet, and fog layers, which is applied to distributed and real-time traffic management in smart cities.

Architecture Design

In this part, we propose a novel hierarchical architecture for IoV, which aims to enhance the scalability and reliability of information services, improve agility and flexibility of application management, and lay a solid foundation for enabling future ITSs. As shown in Fig.1, the architecture consists of four layers, namely, the application layer, the control layer, the virtualization layer, and the data layer. In general, the hierarchical architecture is designed to integrate the paradigms of SDN and fog computing and best exploit their synergistic effects on information services in IoV. The primary objectives include:

- To enable logically centralized control in mobile and dynamic networking environments
- To implement NFV in heterogeneous vehicular environments and realize NS for services with different QoS requirements
- To maximize the utilization of networking, computation, communication, and storage resources in vehicular networks by coordinating between cloud and fog-based services

Detailed system implementation is presented as follows.

SDN-Based Framework in IoV

First, as shown in the control layer of the hierarchical architecture, the SDN controller resides in the backbone network, which connects to cloud data centers and the Internet via the core network. Second, similar to traditional SDN components, the controller communicates with upper layer applications such as data sensing, road safety management, and ITS management via the northbound interface. Dedicated application programming interfaces (APIs) can be designed based on particular application requirements, including functions for computation, communication, and storage resource allocation, functions for service delay, coverage, security requirements, functions for access control, and so on. Third, the SDN controller communicates with the underlying resources via the southbound interface. As elaborated below, instead of managing heterogeneous physical resources directly, the SDN controller can obtain a uniform view of virtual resources based on the resource abstraction at the virtualization layer, which facilitates the service scheduling at the controller.

NFV and NS in IoV

Although the technologies of NFV and NS have been widely studied in the 5G network, it is nontrivial to migrate them into IoV, especially when considering the characteristics such as highly heterogeneous and distributed underlying resources, as well as highly dynamic and various service requirements imposed by upper layer applications. Accordingly, we present a tailored virtualization layer, which is responsible for the abstraction of networking, computation, communication, and storage resources in IoV. Nevertheless, due to the fast-changing network topology, varying radio coverage of different wireless communication interfaces, and a vast amount of information continually generated, sensed, and shared among the nodes in the data layer, it is challenging to maintain an accurate logical view of underlying resources. In this regard, we consider another virtual layer by abstracting part of the data nodes as fog nodes, in which certain intelligence is implemented, including the provision of certain services based on local computation, communication, and data resources, and the abstraction and management of available local resources. This not only reduces the dynamics of underlying resources, but also alleviates the workload of resource virtualization for the upper layer. Moreover, such a hierarchical architecture facilitates the vertical implementation for the NFV and NS. For example, given a set of applications with their respective QoS requirements, the virtual resources can be orchestrated in different ways based on either distributed scheduling at the fog layer or centralized scheduling at the SDN controller. In either way, the services are transparent and self-contained for individual upper layer applications.

Fog-Based Services in IoV

The data layer of the architecture consists of nodes with heterogeneous wireless communication interfaces such as LTE base stations, RSUs, WiFi access points (APs), 5G small cells, and vehicles. In addition to radio access, we consider that these nodes are also equipped with certain computation and storage capacities, and some of them are abstracted as fog nodes for distributed service provision. Unlike previous standalone fog-based services adopted in vehicular networks, the designed virtualization layer smoothly bridges the gap between the logically centralized control at the SDN and the distributed services at the fog layer. Specifically, in this architecture, both mobile and static data nodes can be dynamically assigned as fog nodes based on the scheduling for different services. When acting as fog nodes, they can not only perform operations based on the rules deployed by the SDN controller, but also implement certain intelligence for local services. In addition, the fog nodes will perform certain aggregation and abstraction for underlying resources and update real-time status to the virtualization layer, which in turn helps the management of virtual resources and facilitates the scheduling for service offloading and load balancing at the SDN controller.

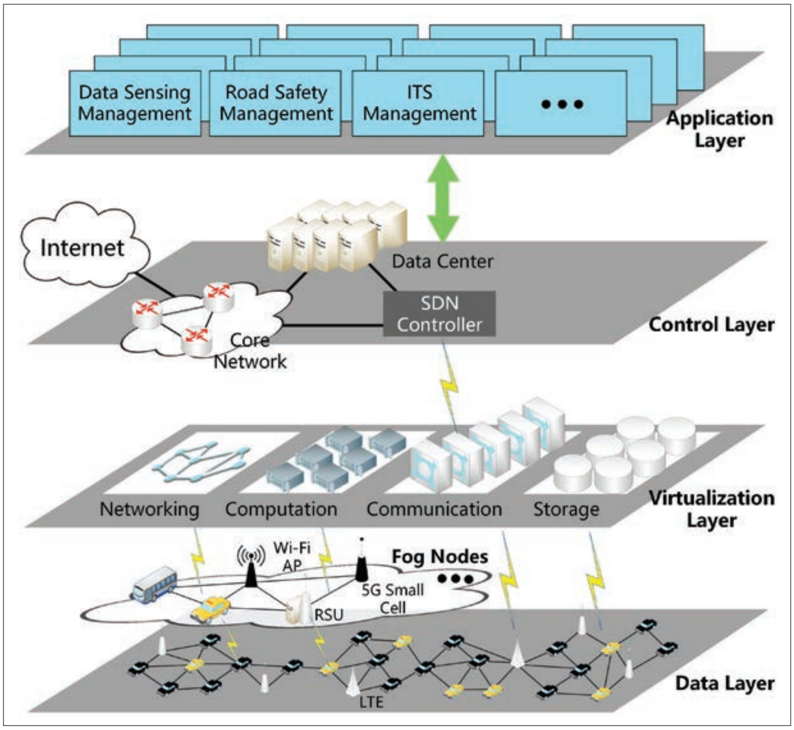

Figure 1. Hierarchical architecture for IoV.

Challenges and Research Opportunities

In this part, we discuss newly arising challenges and future research directions based on the proposed architecture. In addition, a cross-layer protocol stack is presented as a guide for designing communication protocols and service algorithms for future IoV.

Global System Knowledge Acquisition at the Control Layer

To enable logically centralized control, the SDN controller is expected to acquire global knowledge of the system accurately and rapidly, including service status, resource status, vehicle status, and so on. Nevertheless, in such intermittent wireless connections and highly dynamic vehicular networks, some vital problems such as transmission delay, packet loss, and bandwidth contention are inevitable, which may severely hinder the performance of system knowledge acquisition and monitoring at the control layer. Furthermore, in practice, SDN controllers are actually deployed distributedly in a large-scale service area. Therefore, how to efficiently synthesize information from multiple controllers and form a global view of the system is critical to realize logically centralized control.

In future research, new modules are expected to be incorporated at the control layer, aiming at bridging the gap between the biased view at the SDN controller and the authentic system status, and new technologies are needed for efficiently

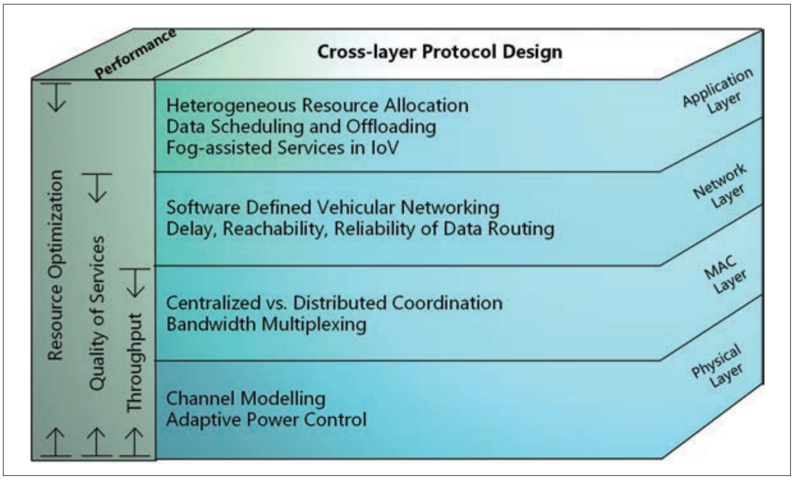

Figure 2. Overview of the cross-layer protocol stack.

synthesizing local and distributed system status and constructing a logical view of global system knowledge.

Heterogeneous Resource Management at the Virtualization Layer

First, due to the highly diverse and dynamic features of resources in IoV, it is nontrivial to characterize them in a uniform and coherent way, which is one of the key issues to enable NS. For example, different wireless communication interfaces have different radio coverage, transmission rate, and access capacity, and the link availability and connection capacities of different communication resources may also change dynamically with the varying network topologies. Moreover, other resources such as computation and storage capabilities may also keep changing due to the inherent dynamics and complexity of the system status. For instance, data nodes such as vehicles or RSUs may constantly sense and generate new data items for computing, transmitting, and storing. Therefore, how to construct a uniform and coherent view of heterogeneous resources and virtualize them as sliced entities is another critical issue deserving future efforts.

Second, considering dynamic and various QoS requirements imposed by upper layer applications, the NFV and NS are supposed to enable service orchestration with virtualized entities. Nevertheless, it is difficult to realize transparent and adaptive services to guarantee the QoS requirements in such circumstances. For example, when virtualizing the routing function, although the data plane and the control plane could be decoupled based on SDN, it still cannot guarantee the allocation of continuous resources for constantly moving vehicles in fast changing networking environments. Therefore, it is imperative to further investigate the coordination between fog and cloud-based services in IoV for better resource management and allocation in both centralized and distributed ways.

Third, although the proposed fog-based service at the data layer helps in resource abstraction, due to large-scale distribution and high heterogeneity of underlying resources, it is still challenging to enable seamless and flexible management of virtual resources in IoV.

Large-Scale Data Transmission at the Data Layer

With rapid growth of service scales and the blooming of data-driven applications in modern IoV, off-the-shelf communication protocols cannot efficiently support parallel I2V/V2V communica tions, especially in high density and high mobility traffic environments. In addition, as the current de facto standard for I2V/V2V communications, IEEE 802.11p adopts carrier sense multiple access (CSMA) at the MAC layer, which has been demonstrated to be very ineffective in terms of bandwidth utilization when large amounts of I2V/V2V-based data transmissions are taking place concurrently within a certain area. With the proposed architecture, it is desirable to have a cross-layer design of communication protocols for enhancing resource utilization on concurrent data transmissions. For instance, the co-design between the power control in the physical layer and the multiple access protocol in the MAC layer is expected to improve data throughput by striking a balance among transmission ranges, data rates, and interferences.

On the other hand, it is critical to better coordinate heterogeneous resources at the data layer to enable large-scale data services. Nevertheless, considering the heterogeneity of data nodes with respect to storage, computation, and communication capacities, as well as mobility of data nodes, it is challenging to optimize resource utilization at the data layer. In future research, mobility patterns and trajectories of different types of vehicles could be exploited to further improve system performance.

A Cross-Layer Protocol Stack

With the new system architecture, it is essential to have co-design of corresponding communication protocols and service algorithms. In this regard, we present a cross-layer protocol stack as a guide for future IoV.

As shown in Fig. 2, the overall objectives of such a cross-layer protocol stack include the optimization of heterogeneous resources, the enhancement of system responsiveness, reliability, and scalability, and the improvement of wireless communication performance. Specifically, there are several open issues under this protocol stack, which are expected to be co-considered in future research:

- Design of channel modeling and the adaptive power control policies for cooperative I2V/V2V communications
- Design of bandwidth multiplexing mechanisms and adaptive resource allocation policies for concurrent data transmission
- Design of QoS-oriented data routing protocols based on SDN
- Design of scheduling algorithms for task offloading and balancing via fog-based services

Case Studies

As a proof of concept, we have developed two system prototypes in realistic IoV environments based on the proposed architecture. Specifically, two services are implemented in the application layer, namely, "See Through" and "Collision Warning" services. A cloud server is subscribed as the SDN controller, which connects to the backbone network and exercises centralized control via the

LTE-based communication. Cohda Wireless MK5 RSUs and OBUs are adopted for V2V and V2I communications via DSRC. Specifically, in the fog layer, an RSU is installed at the road intersection and is connected to a notebook, which acts as the fog server. Each vehicle is equipped with an OBU, as well as a tablet/notebook with the LTE interface, via which vehicles can communicate with the SDN controller. The communication, computation, and storage capabilities of RSUs and vehicles can be abstracted as virtual resources. Given service requirements stipulated by the application layer, the resources can be adaptively allocated based on certain scheduling algorithms exercised at the SDN controller. In the following, we introduce details of the two service scenarios.

See Through Service

The primary objective of this service is to share the real-time view of a front vehicle to its following vehicles so that vehicles driving behind are able to "see through" to the view ahead. With the proposed system architecture, any vehicle that is willing to share its view filmed by its video camera can register its service at the SDN controller via LTE-based communication. Based on the global view of vehicle topology and registered services, the SDN controller is able to notify available services to particular vehicles via the control messages. Vehicles may request corresponding services from the SDN controller via the LTE-based communication. Once the service starts, the video streaming will be transmitted from the service provider to requesting vehicles via DSRC at the fog layer, which resembles fog-based services.

As shown in Fig. 3, we consider a small-scale See Through scenario in which three vehicles are equipped with OBUs for V2V communications. Each OBU is connected with a notebook, in which the service application is executed. The notebook is able to communicate with the SDN controller via a personal hotspot shared by a mobile phone with LTE interface. The cloud server is configured with a 2.5 GHz CPU and 8 GB memory. As shown, V1 has registered the service, which is requested by V2 and V3. Then, when the service starts, the real-time view of V1 is broadcast to V2 and V3 via DSRC. For clear illustration, we place a piece of luggage in front of V1, and we may observe that video streams filmed by V1 are displaying in V2 and V3 in real time via the application interface.

For comparison purposes, we also implement a cloud-based service where the real-time view of V1 is transmitted to the SDN controller via LTE-based communication. Then the cloud server unicasts the video to V2 and V3 via LTE. 500 video frames are extracted with the average size of 34.19 kB, ranging from 28.57 kB to 42.41 kB. Figure 4 shows the end-to-end delay of these video frames received by V2 via both cloud and fog-based services. As noted, the video transmission via the fog-based service achieves much better performance. Specifically, the average end-to-end delay via fog-based service at V2 and V3 are 100.8 ms and 99.7 ms, respectively. In contrast, the average end-to-end delay via cloud-based service at V2 and V3 are 306.73 ms and 308.93 ms, respectively. In addition, note that the video frames are broadcast to V2 and V3 via

Figure 3. The See Through service scenario.

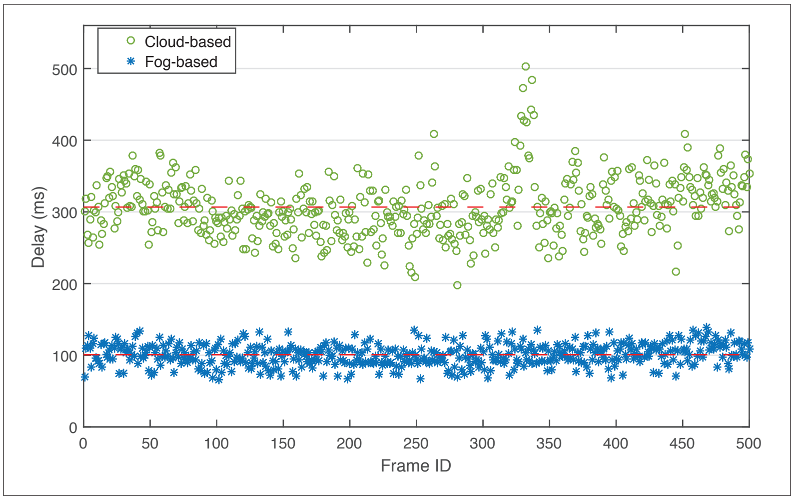

Figure 4. End-to-end delay of video frames.

DSRC, whereas the LTE-based communication only supports unicast in this application. Evidently, from the viewpoint of resource utilization, the fog-based service is promising to improve bandwidth efficiency and enhance system scalability.

Collision Warning Service

The primary objective of this service is to trigger warning messages if there is potential collision between two vehicles. In this implemented system, the cloud server is configured with a 2.5 GHz CPU and 2 GB memory. The SDN controller can communicate with vehicles via LTE-based communication. To support large-scale and real-time services of collision warning, the computation and communication workload is offloaded to the fog server, in which the service function is implemented.

As shown in Fig. 5, we consider the scenario where an RSU is installed at the road intersection. A notebook is connected to the RSU, which acts as the fog server, with the configuration of 1.6 GHz CPU and 8 GB memory. Two vehicles (i.e., V1 and V2) are moving toward the intersection and are approaching each other. Each vehicle is equipped with an OBU connected to an Android-based tablet, in which an app is developed for collecting real-time status of vehicles, including GPS coordinates, velocity, acceleration, direction, timestamps, and so on. For the fog-based

Figure 5. Collision warning system via V2I communication.

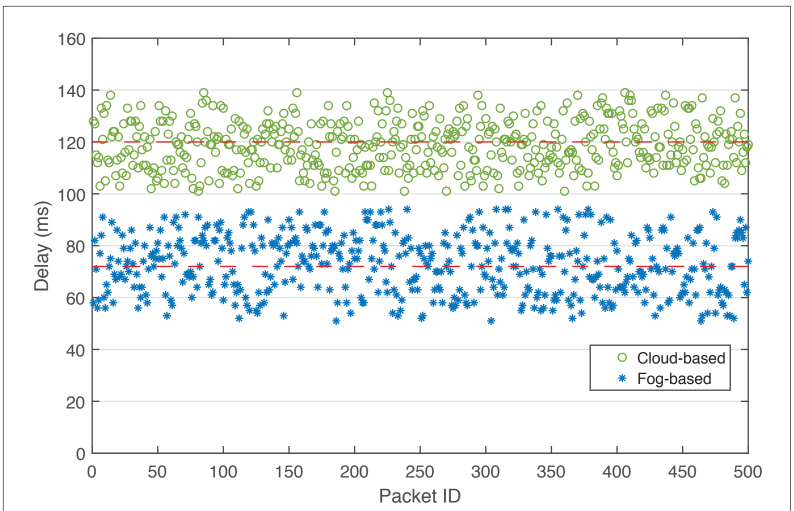

Figure 6. End-to-end delay of data packets.

service, vehicles update their status to the fog server via DSRC at a frequency of 10 Hz. With information received from different vehicles, the fog server executes the service program for collision detection. Once it estimates that there is a risk of collision, the warning message is triggered and transmitted to the corresponding vehicles via I2V communication. Then a stop sign is displayed on the tablet along with vibration and a warning beep.

Meanwhile, we also implement a cloud-based service in which vehicles update their status to the cloud server via LTE, and the service program for collision detection is implemented in the SDN controller. Once a potential collision is detected, the warning messages will be transmitted from the cloud server to the vehicles via LTE. Given the packet size of 10,200 bytes, Fig. 6 compares the packet delay of V1 via fog and cloud-based services. As noted, the fog server can receive the updates from vehicles with shorter delay, which is critical for safety-related services such as collision warning. Specifically, the average delay via fog-based service for V1 and V2 are 72.01 ms and 74.03 ms, respectively, whereas the average delay via cloud-based service for V1 and V2 are 120.08 ms and 104.97 ms, respectively.

Remarks

As an early stage of the new IoV paradigm, as well as due to the resource and environment constraints, in the above two case studies, only part of the architecture is implemented and evaluated in a small-scale environment. Nevertheless, the case study results not only demonstrate the superiority of fog-based services in terms of reducing service delay, but also give insight into the implementation of future ITSs. For example, as observed from the statistics, even in a relatively ideal environment, such as low density (2~3 vehicles), slow speed (around 25 km/h), and short distance of I2V (around 20~50 m) and V2V (around around 3~10 m) communications, the data rate with respect to the application payload (i.e., the ratio of data size to end-to-end delay) by DSRC is much lower than its theoretical rate at the physical layer. For instance, the average data rate of V2V communication in the See Through service is around 2.72 Mb/s (34 kB/100 ms), which is much lower than the claimed rates of 3~27 Mb/s by DSRC. Therefore, even with fog-based services, emerging techniques such as 5G are still urgently needed to enable ultra-low latency and safety-critical applications in IoV. Finally, there are still many merits to be further evaluated in future study, such as enabling adaptive resource allocation and QoS-oriented services based on NFV and NS, and enabling large-scale and distributed services based on service offloading.

Conclusion

In this article, we propose a hierarchical architecture for large-scale, real-time, and reliable information services in future IoV. Specifically, considering unique characteristics of vehicular networks, such as highly heterogeneous resources and highly dynamic system status, the new architecture enables logically centralized control by decoupling control and data planes; facilitates NFV and NS by abstracting and virtualizing heterogeneous resources; and enhances system scalability, reliability, and flexibility by synthesizing SDN and fog-based services. Further, we provide a detailed discussion of arising challenges as well as opportunities in such a new paradigm, and a cross-layer protocol stack is presented. Finally, we implement the system prototype in real-world IoV environments and present two case studies, which demonstrate great potential of the new architecture.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China under Grant 61872049, Grant 61572088, Grant 61802288, and Grant 61772377; the Fundamental Research Funds for the Central Universities (No. 2018CDQYJSJ0034); and the Natural Science Foundation of Hubei Province of China (No. 2017CFA007).

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