Cloud-enabled Software-Defined Vehicular Networks: Architecture, Applications and Challenges

Qianpeng Wang, Deyun Gao, Wanting Zhu

School of Electronic and Information Engineering, Beijing Jiaotong University, China
{qianpengwang, gaody, 11111019}@bjtu.edu.cn

Abstract

As one of the significant parts for Internet of Everything (IoE), vehicular networks provide network services for things in intelligent transport systems. In vehicular networks, vehicle can communicate with vehicles, pedestrians and infrastructures (Internet) by exploiting vehicle to everything (V2X) technologies. Nowadays, emerging applications in vehicular networks require more rich resources and more flexible management mode, while existing technologies of vehicular networks fail to provide these capacities. As two promising network technologies, cloud computing and Software-Defined Networking (SDN) are introduced to vehicular networks to solve these problems. In this paper, we introduce the development of cloud-enabled software-defined vehicular networks (cloud-enabled SDVNs) with focus on its architecture, applications and challenges. We discuss the technical advantages of cloud computing and SDN that can be applied to vehicular networks. The architectures of cloud-enabled SDVNs are presented and the components of the architectures are analyzed. We also provide an overview of some typical applications. In addition, discussion of challenges for using cloud computing and SDN for vehicular networks is presented.

Keywords: Vehicular networks, Cloud computing, Software-Defined Networking, Applications

1 Introduction

With the integration of the transportation industries and advanced information and communications technologies, the number of connected vehicles on the road is increasing. Research and applications on intelligent transportation and vehicular services have become the central of people's attention. The technologies of vehicular networks provide a solution in support of transportation safety, efficiency and sustainability, user comfort and convenience. Vehicular network is an extension of the Internet of Everything in the field of transportation [1]. In vehicular networks, vehicles can collect information about the surrounding environment [2-3] and their own statuses through the inside sensors, GPS, camera and some other sensing devices. Moreover, vehicle can communicate with everything around it, such as roadside infrastructures, other vehicles, pedestrians and Internet, etc., based on standards for vehicular networks. The vehicle to everything (V2X) paradigm [4-5] can make traffic management, information services [6] and vehicle control more intelligent and efficient.

With increasing public concern about road safety, travel efficiency and driving comfort, vehicular networks were asked to undertake more emerging applications that presents new features. On the one hand, these applications have high requirements for the capacities of computing, storing, networking or sensing. On the other hand, some applications need to analyze massive data from multiple dimensions in centralized authorities [7]. For example, applications like traffic congestion harness needs firstly to collect various roads information and transmit the data to traffic management department; then the data are analyzed via big data related technologies; lastly the administrator takes actions accordingly (scheduling traffic lights, publishing congestion information, etc.) to decrease traffic congestion. However, existing vehicular technologies can hardly satisfy the performance requirements of emerging applications, so new technologies need to be introduced urgently.

As a mature technology, cloud computing [8] has been widely used in information and communication fields. Cloud computing can provide enough computing resources, storage resources and networking resources and has three service models: Software as a Service, Platform as a Service, Infrastructure as a Service [9]. Cloud computing are essentially characterized by on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service. The introduction of cloud computing technologies makes resource-intensive vehicular network applications become easy. Public travel efficiency can be improved by collecting and analyzing the road condition data comprehensively in the clouds.

*Corresponding Author: Deyun Gao; E-mail: gaody@bjtu.edu.cn
DOI: 10.3966/160792642019102006012

Conventional cloud computing provides customer with nearly unlimited computing resources, but these resources are located in core network and thus are far away from users of vehicular network. When these resources are used, it will bring high latencies, which is unacceptable to latency-sensitive real-time vehicular network applications, such as collision avoiding application which is closely related to human life safety. Therefore, clouds were pushed to the edge of the network [10-11] and located on roadside units or base stations.

From a communication point of view, vehicle itself can be seen as a mobile terminal. With the rise of a variety of on-board equipment and increasingly enhanced capacity, the resources of vehicle become richer [12], but they are not used all the time. Sometimes these resources are under-utilized. Based on this, Eltoweissy et al. proposed the concept of Autonomous Vehicular Clouds (AVCs) [13]. In AVCs, every vehicle acts as cloud computing node and under-utilized vehicle resources (including computing resources, storage resources, networking resources and sensing resources) are pooled to provide services for those who starve for resources. With the help of AVCs architecture, users can get entertainment content by downloading collaboratively and content sharing, which can not only improve spectrum efficiency but also mitigate the traffic burden of core networks. Cars in parking lots can also become a AVC. In a shopping mall, all the parked cars can be connected to provide computing resources for the mall management. And customers can also be offered some rewards for sharing their car resources [14]. Recently, fog computing [15] has been a hot topic. In fact, according to the definition of fog computing in [16], vehicular cloud is an instance of fog computing in the scenario of vehicular networks.

Cloud computing in vehicular network can be mainly classified into three types: core clouds, edge clouds, and vehicular clouds. These clouds all have different characteristics in terms of function and performance. The introduction of cloud computing technologies in vehicular network is facing numerous challenges. Firstly, there are many use cases in vehicular network and these applications have various requirements on resources and their performance. Thus, effective resources adaption schemes are needed in cloud-enabled vehicular networks. Secondly, as vehicles move at high speed on the road, handover between clouds may happen when vehicles are served by the cloud. Thirdly, some applications are accomplished relying on the collaboration of multiple types of clouds. To meet these challenges, it is necessary for vehicular network to choose flexible and manageable network architecture.

Software-Defined Networking (SDN) [17] is a revolutionary change to the traditional network architecture. Its basic concept is to separate the control function from the network switching equipment to form a logically independent and centralized control layer. Therefore, SDN consists of an abstracted control plane and a physical data plane. The data plane is composed of ordinary network switching devices, and the data forwarding and processing mechanism are controlled by the control plane through the forwarding instruction set. The control plane is logically centralized, which can simplify network management and make network more proactive in virtualization. Virtualization technologies make it possible to enable network functions in the universal hardware platform. It is an important trend in future network. The network protocol of the underlying forwarding device can be simplified due to the characteristics of SDN. SDN allows the network control to be programmable [18], which can be able to flexibly schedule and control network resources with software. Furthermore, it can provide a good platform for rapid innovation of research and application.

Introducing the SDN concept into the vehicular networks can help the vehicular networks to obtain simple data transmission and centralized network control. It can make the vehicular communication services more flexible, agile and efficient, and also can simplify the vehicular network management effectively [19-20]. Salahuddin et al. [21] proposed RSU cloud (edge cloud) and exploited SDN to dynamically reconfigure data forwarding rules and instantiate, migrate, and replicate services in RSU cloud. The services of the RSU cloud are expected to meet changing demands of vehicular networks benefiting from the flexibility and programmability of SDN. Moreover, in the framework of SDN, Yu et al. [22] conducted resource sharing between nearby cloudlets in vehicular networks. Managers made resources allocation decision in management plane and the decision was performed in data plane. Therefore, the introduction and use of the SDN principle for solving the difficult problem in vehicular networks is the further trend, which is conducive to promoting network development. In this paper, we aim at presenting the architectures, applications and challenges of Cloud-enabled Software-Defined Vehicular Networks (SDVNs). We expect it can provide inspiration for further research, deployment and application of vehicular network technologies.

Our contributions in this paper are threefold. Firstly, we present potential architectures of cloud-enabled SDVNs and provide comprehensive comparisons of various types of could computing in vehicular networks. Secondly, we summary some typical applications in vehicular networks that have employed cloud-enabled SDVNs to improve network performance. Thirdly, we discuss remaining challenges for using cloud computing and SDN for vehicular networks and point out corresponding research directions.

The remainder of this paper is organized as follows. We introduce the architecture of Cloud-enabled SDVNs in Section 2. Then, we provide an overview of the main applications and services of Cloud-enabled SDVNs in Section 3. In Section 4, some challenges for future research are discussed. Finally, Section 5 concludes this paper.

2 The Architecture of Cloud-enabled SDVNs

Cloud-enabled Software-Defined Vehicular Networks consist of the following two parts, as shown in Figure 1.

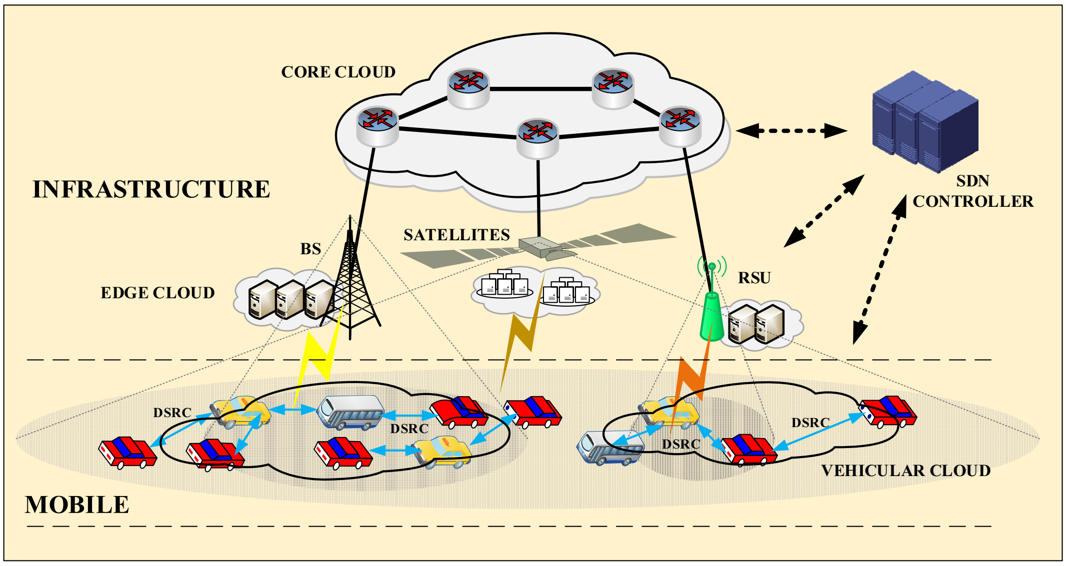

Figure 1. Cloud-enabled software-defined vehicular networks

- **The mobile part:** the vehicle is the main communication entity. Communication modes mainly include vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication. In this part, vehicles that have under-utilized resources and are willing to share them can form vehicular clouds by the way of mutual collaboration. Vehicular clouds are oriented by services and have a life cycle. When user of vehicular network requests a specific service, vehicular cloud comes into being and cloud resources are adapted dynamically according to the service requirements; vehicular cloud disappear after the service is satisfied. The attributes that vehicle nodes have independent ownership and vehicles move randomly at high speed make vehicular clouds volatile and fragile, so it is necessary to design effective mechanism to maintain the quality of vehicular cloud services. Besides, since vehicles are closely related with human activities, vehicular clouds present strong sociality; vehicles are equipped with varieties of sensors and thus vehicular clouds have rich sensing resources.
- **The infrastructure part:** the network can be divided into access network and core network, providing access to the Internet and other application services for vehicles. Forwarding devices in access network can include RSUs, cellular base stations, satellites and so on. Both core clouds and edge clouds are in the infrastructure part and these two kinds of clouds have all the capacities (computing, storing, and networking) of the conventional cloud computing. The core clouds lie in core network. They have strong ability to manage and control the entire network and have extremely adequate resources. These characteristics make the core clouds have advantages on applications like big-data-related traffic management. Edge clouds are in the edge of the network and generally are located on roadside unit, base station, or the terrestrial part of the satellites. One of the most evident advantages for edge cloud is that it is close to users and thus has lower latency, which is very critical to delay-sensitive applications.

In order to understand the three kinds of cloud computing comprehensively, the paper compares them by examining service latencies, capacities of service, organization mode, deployment, ownership, and typical applications. The results are shown in Table 1.

Next, the paper first introduces two basic architectures for SDVNs, and then proposes a new hybrid architecture for SDVNs.

2.1 SDVNs Architecture with Limited Control

In the first SDVNs architecture, the decoupling of control and forwarding occurs only in the infrastructure part [23]. For the convenience of description, we simplify the types of devices in the infrastructure part, which are represented by the controller and the SDN-enabled RSU. The controller cannot directly control the vehicle forwarding in the mobile part.

Table 1. Comparisons of three types of cloud computing in vehicular networks

	Core Cloud	Edge Cloud	Vehicular Cloud
Range of Coverage	large area	small area	smaller area
Ownership	owned by a few famous cloud service providers	owned by operators or cloud service providers	every cloud unit (vehicle) is owned by individuals
Service Latencies	high	low	low
Deployment	deploy proactively according to specific requirement	deploy proactively according to specific requirement	establish on-demand
Organization Mode	centralized	centralized	decentralized
Typical Applications	traffic congestion avoiding, environment monitoring	autonomous vehicles, collision avoiding	entertainment content sharing, mobile social application

- **Controller.** The logical control center of the SDVNs, which is used to control the network behavior of the entire system. It has dynamic global network interconnection knowledge.
- **SDN-enabled RSU.** Stationary infrastructure device in data plane that are deployed at road sides. Its behavior can be controlled by the controller. Each SDN-enabled RSU maintains flow tables that pertain to the forwarding policies and receives flow rules from controller. Moreover, SDN-enabled RSU can communicate with the neighborhood vehicles via wireless interface.
- **Vehicle.** The main communication body in the mobile part. The vehicle can support the communication protocols that are designed for traditional vehicular ad hoc networks. In this architecture, the forwarding behaviors of vehicles are not controlled by the controller.

The vehicle sends a message to the RSU. If this is a new message, the RSU cannot match the existing flow entry in its flow table. Then, it will send corresponding control message to inform the controller. The controller determines the forwarding path for this new message, and then controls the flow table content of the RSUs. When the RSU receives the subsequent same messages again, it can perform the action according to the matching entry in the flow table without the participation of the controller.

The Limited Control SDVNs architecture can leverage the benefits of SDN logically centralized control to improve network performance. This system is simple and easy to implement. However, it does not integrate vehicular network with SDN thoroughly. Considering the sparse deployment and limited communication range, RSUs may not cover all vehicles on the roads. However, the control center only distributes flow rules to RSUs and cannot control the vehicle forwarding. Therefore, the controller’s ability to manage and control the V2V communication is weak. It cannot better play the advantages of flexible, convenient and fast inter-vehicle communication.

2.2 SDVNs Architecture with Full Control

In the second SDVNs architecture, the data forwarding plane devices include SDN-enabled vehicles as well as the SDN-enabled RSUs [24]. In this mode, the controller can control all the actions of underlying vehicles and RSUs through pushing down the flow rules. The definitions of the controller and the SDN-enabled RSU are the same with the first architecture mentioned above. The SDN-enabled vehicle will be introduced as follow:

- **SDN-enabled vehicle.** The mobile device in the data plane. Its behavior can be controlled by the controller. Vehicles can communicate with RSUs and other vehicles via wireless interface. A significant feature of the ad hoc network is that the node can act as host and router. Therefore, a SDN-enabled vehicle can be both a forwarding device and a terminal device.

Compared with the limited control SDVNs architecture, the Full Control SDVNs architecture can more fully grasp the global information of networks and make better decisions. Network management will be more thorough. This can make the network more flexible and suitable for reacting to the changing requirements. For the full control SDVNs architecture, learning the network topology is important. Each vehicle can learn information about neighbors via beacon messages. And the vehicle information can be periodically updated to the controller. Controller can build a node connectivity graph for making intelligent decisions, such as the selection of routing paths through the network. Therefore, this architecture can provide better management of mobility in mobile part.

However, due to the large scale of the network and the rapid movement of vehicles, in order to ensure that the controller can get the latest network topology and update information timely and accurately, the vehicles need to report the latest changes to the controller frequently. The amount of generated data about the vehicle status and communication link is very large, which may lead to huge network pressure and bandwidth consumption.

2.3 SDVNs Architecture with Hybrid Control Based on Public Bus

In the paper, we propose the hybrid control SDVNs architecture, the controller can control both the infrastructure part of the network and a part of the mobile part. There are four components in this architecture: the controller, the SDN-enabled RSU, the SDN-enabled Bus, and the ordinary vehicle, as shown in Figure 2. Except the SDN-enabled bus, the other three components are identical with the limited control SDVNs architecture. The basic function of SDN-enabled Bus is introduced as follow:

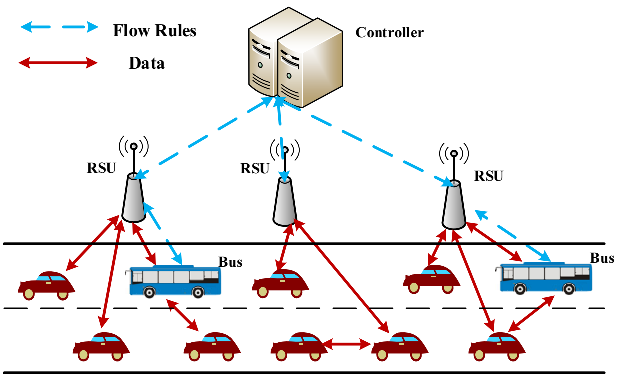

Figure 2. Hybrid control SDVNs architecture based on public bus

- **SDN-enabled Bus.** The mobile device in data plane. The SDN-enabled bus will inform controller of its state information and the controller will control the bus by flow rules. The ordinary vehicles can choose RSU or Bus to forward data depending on its current wireless environment.

In this architecture, buses can support both SDN-based forwarding and traditional forwarding. Messages sent by ordinary vehicles can be delivered to the controller via buses or RSUs. The forwarding paths of the messages are determined by the controller. Then, the RSUs and the buses can forward the messages according to the forwarding rules received from controller, and also can forward the data needed by the ordinary vehicle to them.

Because these public buses usually have fixed travel routes and predictable arrival times, the frequency of updating information caused by the vehicle movement can be greatly reduced with the preset information in the controller. Therefore, the Hybrid Control SDVNs architecture has lower management overhead than the full control SDVNs architecture. Moreover, compared with the limited control SDVNs architecture, the hybrid control SDVNs architecture can manage the network more flexible and intelligent by utilizing the advantages of the bus's mobility and widespread deployment. In addition, buses are quite common on the road and can provide Internet access for a large set of the passengers. They are usually designed to cover almost all parts of the urban, which can improve the network connectivity. And they have higher security and trustworthiness for the general public. The management, deployment and update of public buses will also be easier than that of the private cars. These advantages make it easier to promote the deployment and application of the SDVNs.

3 Applications

Many works have been proposed to take advantage of the cloud-enabled SDVNs. In the following, we will present some application examples.

3.1 Sensory Data Transmission

The sensory data transmission is an important and fundamental application in vehicular networks. Today there have been more than 100 sensors equipped on the modern vehicles [25]. Vehicles can provide these sensory parameters via the onboard diagnostic (OBD) interface and share sensory data via wireless communication. Moreover, with the development of wireless technologies, vehicular networking is becoming heterogeneous. Data transmission over this heterogeneous network should be considered.

In [24], the researchers proposed a novel data transmission method based on the SDVNs architecture, which utilizing the unified abstraction to manage heterogeneous network resources. In this solution, different network resources can be scheduled under unified management for minimizing communication cost. Whenever there is data to be transmitted, SDVNs can adaptively choose appropriate network interfaces. The scheduling problem is formulated as a discrete optimization issue. Moreover, the researchers provided two mathematical models to describe the dynamic nature of SDVNs for one-hop and multiple-hop communications respectively. With the benefits brought by SDN, the researchers can use minimized communication cost to collect the network information and obtain better overall network performance.

3.2 Content Distribution

It is not easy to achieve large scale high data rate content distribution in vehicular networks. Because the network connectivity is intermittent due to the sparse deployment of RSUs, the short communication ranges of the vehicles, and the high vehicle mobility. Connections between vehicles and RSUs are frequently broken and reestablished. Transmitting a large amount of data in a short time is not an easy thing.

In [26], the researchers proposed a Type-Based Content Distribution approach utilizing the SDN technology to support the replication and caching. The content types include real-time traffic information and bandwidth-intensive media data. According to the types of the content and the number of subscribers, a push-and-pull pattern is designed to transmit the content more efficiently. In this push-and-pull pattern, an appropriate connection between the server and the subscriber can be established through deploying the SDN logic agents on server, switches and RSUs. With the help of the SDN technology, the proposed approaches can balance the reliability and the redundancy of the content forwarding, and minimize the impact of disconnection.

With the evolvement of vehicular technology, a variety of software are equipped on modern vehicles and software update becomes a challenging problem. Azizian et al. [27] proposed to distribute vehicle software updates based on SDN and cloud computing. In the proposed architecture, data centers, RSUs, and BSs form a cloud together. Vehicles and cloud element act as SDN devices and SDN controllers are located in some of the data centers or edge equipment. Vehicles that can connect to BSs or RSUs send their neighborhood information to the SDN controller. With this information, the controller acquires the vehicles' connectivity graph and then updates flow tables. Besides, the controller also assigns the frequency band to vehicles. Finally, the SDN devices distribute software updates to vehicles according to flow rules and the allocated frequency band.

3.3 Data Scheduling and Offloading

Efficient data scheduling is essential for the implementation of vehicular networks. The quality of such services is largely dependent on the communication efficiency between the RSUs and the vehicles.

Liu et al. [28] proposed a cooperative data scheduling in hybrid vehicular ad hoc networks considering the delay-sensitive applications, such as intersection control systems, speed advisory systems, traffic management systems, etc. The cooperative data scheduling is based on a logically centralized control at the RSU. The RSU can instruct the vehicles to switch channel and transmit/receive data by delivering scheduling decisions to vehicles. The centralized scheduling is entirely the responsibility of the RSU and the vehicle does not need to maintain control information. In the proposed scheduling approach, vehicles can switch between infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communications. In the future work, the coordination of the RSUs can be considered resembling the logically centralized control of SDN in distributed networks.

In [29], SDN and mobile edge computing were used to offload communication data in cellular network by V2V communication mode. Firstly, vehicle's context information was collected and transmitted to the centralized management platform; then routing paths between vehicles were calculated by SDN controller; finally, the controller notified vehicles of the calculated results and vehicles would change the links from cellular network to vehicular networks. In the proposed architecture, the SDN controller was located in the edge of the network (the Base Station) to satisfy the requirement of latency in vehicular networks.

3.4 Privacy Protection

In order to be accepted by the public and realize the commercial deployment, the practical designs of vehicular networks have to be able to meet the security requirements. Considering the close relationship between the vehicle and drivers' privacy, the privacy has been a key concern in vehicular networks. Malicious nodes could trace or profile the driver's activities by analyzing the information transmitted from the targeted vehicle. Therefore, the privacy protection is an important aspect of security problems, which should be considered and tackled.

Pseudonym is the basis for vehicles to protect location privacy. In [30], the researchers proposed a software-defined pseudonym system for secure vehicular clouds taking the flexibility and efficiency of pseudonym management into account. SDN technology is exploited to improve the pseudonym resource utilization, simplify the pseudonym management and enhance the location privacy. An optimal pseudonym resource scheduling strategy can be determined by SDN controller from a global perspective. A hierarchical manner is used to promptly schedule and elastically manage the distributed pseudonym pools. Moreover, the researchers adopted a two-side matching theory to solve the pseudonym matching problem, which decreased the system overheads.

4 Challenges and Research Directions

Though having bright prospects, the cloud-enabled SDVNs are facing many challenges. In this section, we will point out some main challenges and future research directions in cloud-enabled SDVNs. Handling these challenges will make the cloud-enabled SDVNs more feasible.

4.1 Heterogeneous Networks

The technical development of wireless communications will increase the heterogeneity of vehicular networks [31-32]. Smart vehicles can access the Internet via cellular networks with the technologies of the Universal Mobile Telecommunications System (UMTS), the fourth generation (4G) Long Term Evolution (LTE), and the direct Device-to-Device (D2D) communication included in the upcoming fifth generation (5G) networks. Meanwhile, many wireless communication technologies can be used to establish vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, such as the Dedicated Short-Range Communication (DSRC), WiFi, WiMAX, and so on. Moreover, the wireless technologies like ZigBee, Bluetooth, RFID are also applied in different vehicular application scenarios. A vehicle can support multiple wireless technologies simultaneously. The heterogeneity of networks usually leads to the inefficiency of network resource utilization and poor interoperability.

The heterogeneity of vehicular networks poses a challenge to vehicular clouds. The design of vehicular cloud architecture should take into account diversity of wireless technologies in vehicular networks. The technologies used to connect vehicles to be a cloud should be compatible to different communication modes of physical layer.

An example scenario of the heterogeneous vehicular networks (HetVNETs) is shown in Figure 3. The SDN technology can bring many benefits to the HetVNETs.

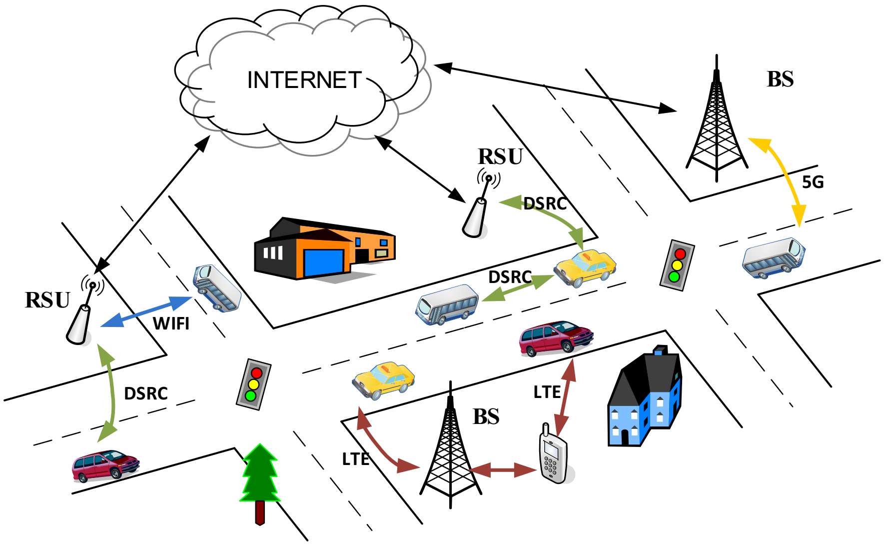

Figure 3. A scenario of heterogeneous vehicular networks

- **Better interoperability.** With the decoupling of the control plane and data plane of SDN, all forwarding devices supporting different wireless technologies can be abstracted as SDN switches. The control plane can provide unified control and management, which promotes the network integration.
- **Higher network resource utilization.** Different wireless technologies in HetVNETs can bring more opportunities to transmit data with lower communication cost. With the logically centralized control and global knowledge of controller, SDN makes the coordination and allocation of HetVNETs network resources easier and more effective.

Different from other types of heterogeneous networks, applying SDN to HetVNETs poses more challenges because of the high mobility of nodes, ad-hoc communication model and so on, which needs to be properly considered. The high vehicle mobility and ad-hoc communication model make the vehicular network topology highly dynamic. The statuses of mobile vehicles change frequently. It is difficult for the controller to maintain the accuracy and consistence of network topology information. Hence, the SDN management overhead will increase.

4.2 Network Virtualization

In the information communication technologies, virtualization provides a mechanism that separates the system services from its underlying physical infrastructure and improves the entire system performance greatly. Now the virtualization of storing resources and computing resources has been fully developed while the network virtualization is still in its infancy. Besides the ability to deal with the heterogeneity of underlying network devices, network virtualization technologies has great advantages in network resource sharing, network users isolation, network resource aggregation, resource dynamic allocation and network management [33]. The emerging SDN provides a good opportunity for the development of network virtualization.

It is a growing trend to introduce network virtualization into the future vehicular network. Firstly, the future vehicular network is a heterogeneous network that contains varieties of underlying network infrastructure, such as RSUs, cell base stations and satellites etc. Virtualization technology is a suitable way to solving network heterogeneity problem. Then, in the design of the architecture of vehicular network, it has to be taken into consideration that the drastic fluctuation of the number of vehicular users and the requirement of service in time and space. For example, in the same day, there are more vehicular users during the period of commute than other period of the day; on the same road, there are more vehicular users on the congested sections than other sections of the road. These dynamic requirements for network resource can be satisfied by the flexible allocation to network resource, in which the network virtualization technology has inherent advantages. Thirdly, with the aid of virtualization technologies, vehicular network can be slicing into various virtual parts to decrease chances of packet broadcast collision, reduce packet delivery delay and enhance the network performance.

4.3 Security

The security is one of the key challenges in vehicular networks [34]. Unlike traditional wired networks, vehicular network lacks defense such as firewalls and gateways. And it also inherits the security weaknesses of Mobile Ad Hoc Networks (MANETs) [35]. For example, the data is easily monitored, altered and forged. Due to the open environment of vehicular networks, security attacks could come from various sources and imperil all nodes. Malicious attacks and service abuses could bring great threats to drivers. Moreover, the large scale of the network and the high vehicle mobility make the design of security protocols more challenging. Therefore, vehicular network is suffering from more security problems. Security concern has been a decisive factor in the wide acceptance of vehicular networks to the public and impacted the commercial deployment.

Security problem is especially important in vehicular clouds [36]. Vehicular clouds are formed by resource sharing in participants and one of the most important conditions for resource sharing is building trust relationship. Here, the trust is bidirectional. On the one hand, a vehicle is only willing to join vehicular cloud that is secure. Participating an insecure cloud environment may expose itself to the possibility of danger. On the other hand, it is necessary for vehicular cloud to assure that the new members of the cloud are trustful. vehicular cloud should have the ability to prevent malicious vehicle node to join the cloud.

Benefiting from the features of the SDN, such as the logically centralized control, the global knowledge of network state and the programmability of networks, novel effective solutions can be designed and deployed to address network security problems. SDN provides centralized control to make sure that the protection strategies and configurations can meet the security requirements proactively. Moreover, potential security threats can be detected through the analysis of traffic patterns based on the collection of global network status. If the attacks are detected, SDN can dynamically quarantine the malicious nodes and block the attack traffic. In addition, SDN permits programmatic control over the network, which can provide more opportunities to implement novel and flexible network security policies.

5 Conclusion and Future Work

This paper has discussed the potential of the cloud-enabled SDN paradigm in vehicular networking environment. First, we introduce the architecture of the cloud-enabled SDVNs. From various perspectives, the properties of core cloud, edge cloud and vehicular cloud have been analyzed. These kinds of cloud computing show their outstanding performance in certain aspects separately and can provide better services for corresponding use cases in vehicular networks. And we also introduce three kinds of SDVNs architectures including the limited control SDVNs architecture, the full control SDVNs architecture and the hybrid control SDVNs architecture. They are classified according to the control capability of SDN controller and the kinds of devices in the data plane. Then, we present some applications and services of cloud computing and SDN for vehicular networks, such as data transmission, content distribution, data scheduling, privacy protection. Finally, we believe that cloud-enabled SDVNs is a promising direction for future development of the vehicular networks. Meanwhile, it also faces many challenges due to the high mobility of vehicles and dynamic network topology. Some future research challenges are discussed in terms of heterogeneous network, network virtualization and security. We expect that this work can provide help for further research of cloud-enabled SDVNs technologies.

Acknowledgements

This work was supported by NSFC under Grant No. 61971028.

References

[1] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, C. Liu, Routing in Internet of Vehicles: A Review, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 16, No. 5, pp. 2339-2352, October, 2015.

[2] M. Gerla, L. Kleinrock, Vehicular Networks and the Future of the Mobile Internet, *Computer Networks*, Vol. 55, No. 2, pp. 457- 469, 2011.

[3] R. Du, C. Chen, B. Yang, N. Lu, X. Guan, X. Shen, Effective Urban Traffic Monitoring by Vehicular Sensor Networks, *IEEE Transactions on Vehicular Technology*, Vol. 64, No. 1, pp. 273-286, January, 2015.

[4] 3GPP, *Architecture Enhancements for V2X Services*, Report No. TS 23.285 v14.1.0, December, 2016.

[5] 3GPP, *Study on Enhancement of 3GPP Support for 5G V2X Services*, Report No. TR 22.886 v16.1.1, September, 2018.

[6] W. Zhu, D. Gao, C. H. Foh, H. Zhang, H. Chao, Reliable Emergency Message Dissemination Protocol for Urban Internet of Vehicles, *IET Communications*, Vol. 11, No. 8, pp. 1275-1281, June, 2017

[7] N. Cheng, F. Lyu, J. Chen, W. Xu, H. Zhou, S. Zhang, X. S. Shen, Big Data Driven Vehicular Networks, *IEEE Network*, Vol. 32, No. 6, pp. 160-167, November, 2018.

[8] R. Buyya, C. S. Yeo, S. Venugopal, J. Broberg, I. Brandic, Cloud Computing and Emerging IT Platforms: Vision, Hype, and Reality for Delivering Computing as the 5th Utility, *Future Generation Computer Systems*, Vol. 25, No. 6, pp. 599- 616, 2009.

[9] P. Mell, T. Grance, The NIST Definition of Cloud Computing, *National Institute of Standards and Technology*, September, 2011.

[10] N. Abbas, Y. Zhang, A. Taherkordi, T. Skeie, Mobile Edge Computing: A Survey, *IEEE Internet of Things Journal*, Vol.

5, No. 1, pp. 450-465, February, 2018.

[11] J. Liu, J. Wan, B. Zeng, Q. Wang, H. Song, M. Qiu, A Scalable and Quick-Response Software Defined Vehicular Network Assisted by Mobile Edge Computing, *IEEE Communications Magazine*, Vol. 55, No.7, pp. 94-100, July, 2017.

[12] S. Abdelhamid, H. S. Hassanein, G. Takahara, Vehicle as a Resource (VaaR), *IEEE Network*, Vol. 29, No. 1, pp. 12-17, January, 2015.

[13] M. Eltoweissy, S. Olariu, M. Younis, Towards Autonomous Vehicular Clouds, in *International Conference on Ad Hoc Networks: ADHOCNETS*, Berlin, Heidelberg, 2010, pp. 1-16.

[14] M. Whaiduzzaman, M. Sookhak, A. Gani, R. Buyya, A Survey on Vehicular Cloud Computing, *Journal of Network and Computer Applications*, Vol. 40, pp. 325- 344, April, 2014.

[15] C. Mouradian, D. Naboulsi, S. Yangui, R. H. Glitho, M. J. Morrow, P. A. Polakos, A Comprehensive Survey on Fog Computing: State-of-the-Art and Research Challenges, *IEEE Communications Surveys Tutorials*, Vol. 20, No. 1, pp. 416-464, First Quarter, 2018.

[16] M. Vaquero, L. Rodero-Merino, Finding your Way in the Fog: Towards a Comprehensive Definition of Fog Computing, *ACM SIGCOMM Computer Communication Review*, Vol. 44, No. 5, October, 2014.

[17] W. Xia, Y. Wen, C. H. Foh, D. Niyato, H. Xie, A Survey on Software-Defined Networking, *IEEE Communications Surveys & Tutorials*, Vol. 17, No. 1, pp. 27-51, First Quarter, 2015.

[18] N. Feamster, J. Rexford, E. Zegura, The Road to SDN: An Intellectual History of Programmable Networks, *ACM Sigcomm Computer Communication Review*, Vol. 44, No. 2, pp. 87-98, April, 2014.

[19] I. Jang, S. Choo, M. Kim, S. Pack, G. Dan, The Software-Defined Vehicular Cloud: A New Level of Sharing the Road, *IEEE Vehicular Technology Magazine*, Vol. 12, No. 2, pp.78-88, June, 2017.

[20] K. Wang, H. Yin, W. Quan, G. Min, Enabling Collaborative Edge Computing for Software Defined Vehicular Networks, *IEEE Network*, Vol. 32, No. 5, pp. 112-117, September, 2018.

[21] M. A. Salahuddin, A. Al-Fuqaha, M. Guizani, Software-Defined Networking for RSU Clouds in Support of the Internet of Vehicles, *IEEE Internet of Things Journal*, Vol. 2, No. 2, pp. 133-144, April, 2015.

[22] R. Yu, J. Ding, X. Huang, M. Zhou, S. Gjessing, Y. Zhang, Optimal Resource Sharing in 5G-Enabled Vehicular Networks: A Matrix Game Approach, *IEEE Transactions on Vehicular Technology*, Vol. 65, No. 10, pp. 7844-7856, October, 2016.

[23] Y. C. Liu, C. Chen, S. Chakraborty, A Software Defined Network Architecture for GeoBroadcast in VANETs, *2015 IEEE International Conference on Communications (ICC)*, London, UK, 2015, pp. 6559-6564.

[24] Z. He, D. Zhang, J. Liang, Cost-Efficient Sensory Data Transmission in Heterogeneous Software-Defined Vehicular Networks, *IEEE Sensors Journal*, Vol. 16, No. 20, pp. 7342-7354, October, 2016.

[25] W. J. Fleming, New Automotive Sensors: A Review, *IEEE Sensors Journal*, Vol. 8, No. 11, pp. 1900-1921, November, 2008.

[26] Y. Cao, J. Guo, Y. Wu, SDN Enabled Content Distribution in Vehicular Networks, in *2014 Fourth International Conference on Innovative Computing Technology (INTECH)*, Luton, UK, 2014, pp. 164-169.

[27] M. Azizian, S. Cherkaoui, A. S. Hafid, Vehicle Software Updates Distribution with SDN and Cloud Computing, *IEEE Communications Magazine*, Vol. 55, No. 8, pp. 74-79, August, 2017.

[28] K. Liu, J. K. Y. Ng, V. C. S. Lee, S. H. Son, I. Stojmenovic, Cooperative Data Scheduling in Hybrid Vehicular Ad Hoc Networks: VANET as a Software Defined Network, *IEEE/ACM Transactions on Networking*, Vol. 24, No. 3, pp. 1759-1773, June, 2016.

[29] C. Huang, M. Chiang, D. Dao, W. Su, S. Xu, H. Zhou, V2V Data Offloading for Cellular Network Based on the Software Defined Network (SDN) Inside Mobile Edge Computing (MEC) Architecture, *IEEE Access*, Vol.6, pp. 17741-17755, March, 2018.

[30] X. Huang, R. Yu, J. Kang, N. Wang, S. Maharjan, Y. Zhang, Software Defined Networking with Pseudonym Systems for Secure Vehicular Clouds, *IEEE Access*, Vol. 4, pp. 3522-3534, April, 2016.

[31] Z. He, J. Cao, X. Liu, SDVN: Enabling Rapid Network Innovation for Heterogeneous Vehicular Communication, *IEEE Network*, Vol. 30, No. 4, pp. 10-15, July, 2016.

[32] K. Zheng, L. Hou, H. Meng, Q. Zheng, N. Lu, L. Lei, Soft-Defined Heterogeneous Vehicular Network: Architecture and Challenges, *IEEE Network*, Vol. 30, No. 4, pp. 72-80, July, 2016.

[33] R. Jain, S. Paul, Network Virtualization and Software Defined Networking for Cloud Computing: A Survey, *IEEE Communications Magazine*, Vol. 51, No. 11, pp. 24-31, November, 2013.

[34] I. A. Sumra, A. Abdullah, I. Ahmad, A. Alghamdi, Towards Improving Security in VANET: Some New Possible Attacks and Their Possible Solutions, Journal of Internet Technology, Vol. 17, No. 4, pp. 821-829, July, 2016.

[35] F. Qu, Z. Wu, F. Y. Wang, W. Cho, A Security and Privacy Review of VANETs, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 16, No. 6, pp. 2985-2996, December, 2015.

[36] G. Yan, D. Wen, S. Olariu, M. C. Weigle, Security Challenges in Vehicular Cloud Computing, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 14, No. 1, pp. 284-294, March, 2013.

Biographies

Qianpeng Wang received his B.S. degree from Shanxi Agricultural University in 2013. He is currently working toward his Ph.D. degree in the School of Electronic and Information Engineering at Beijing Jiaotong University. His research interests are vehicular networks, cloud computing, and software defined networking.

Deyun Gao received BEng and MEng degrees in electrical engineering and a Ph.D. degree in computer science from Tianjin University, China, in 1994, 1999, and 2002, respectively. He spent one year and three years as a Postdoc at Hong Kong University of Science and Technology and Nanyang Technological University, respectively. In 2007, he joined the faculty of Beijing Jiaotong University. His research interests are in the area of Internet of Things, vehicular networks and next-generation Internet.

Wanting Zhu received her B.S. degree in telecommunication engineering, and a Ph.D. degree in communication and information system from Beijing Jiaotong University in 2011 and 2017 respectively. Currently, she is currently a Network Engineer with the China Academy of Electronics and Information Technology. Her research interests include vehicular networks, network security, and mobility management.