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A Survey on Software-defined Vehicular Networks

Yi Fan[1], and Ning Zhang[2*]

[1] College of Economics, Central South University of Forestry and Technology
Changsha, Hunan 410004, China

[2] College of Finance and Statistics, Hunan University,
Changsha, Hunan 410006, China
fanyi811027@gmail.com; ning.zhang.hunan@gmail.com

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Abstract. This article focuses on previous research and future challenges on software-defined vehicular network (SDVN). Development of intelligent transportation systems has suffered from enormous number of connected vehicles, heterogeneous network environments, and complexity of network topology changes. Software-defined networks (SDN) provide a solution for these problems, through network function virtualization and centralized controls. By simplifying network complexity and separating control plane from data plane, the SDN enjoys the merit of flexibility as well as programmability, and can address major challenges in vehicular networks. Therefore, this article introduces the basic concept of the SDVN framework, and provides several future challenges on SDVNs.

Keywords: software-defined network, software-defined vehicle network, vehicular ad hoc networks

1 Introduction

As a main component of intelligent transportation systems (ITSs), vehicular adhoc networks (VANETs) suffer from a lot of problems, including inflexibility of the architecture, enormous number of vehicles, heterogeneity among data streams and vehicles, frequent topology change due to rapid movements of vehicles, and so on. Through network function virtualization and centralized controls, software-defined vehicular network (SDVN) emerges to provide a pleasing solution to implement VANETs. A sound ITS could be effectively established by incorporating features of SDVNs to achieve more driving safety and comfortability.

Consider an SDVN deployed on a road illustrated in Fig. 1, in which communications between two vehicles and between vehicles and roadside units (RSUs) are achieved by wireless networks of WiFi/dedicated short-range communication (DSRC); the vehicles outside the DSRC coverage region communicate with a base stations (BS) through cellular networks; and communications among RSUs, BSs, and SDN controllers are achieved by wired optical fiber networks. The SDN controller is a logically centralized control center, and has two features: programmability and flexibility. It separates the network functions of RSUs and BSs from the original VANET, and makes them be virtualized and controlled in a centralized way. Hence, RSUs and BSs only left with the function of network connectivity and flow tables for transmissions. The abstracted network function is centralized to be controlled by the SDN controller, which has a global knowledge perspective, and hence can remotely control all packet flows in the VANET. Therefore, the SDN techniques are able to complement the elements lacked by conventional VANETs.

VANET has received much attention. A detail survey on VANET architectures can be found [1]. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are achieved through connectivity among RSUs and on-board units (OBUs), to increase not only the driving safety but also

* Corresponding Author

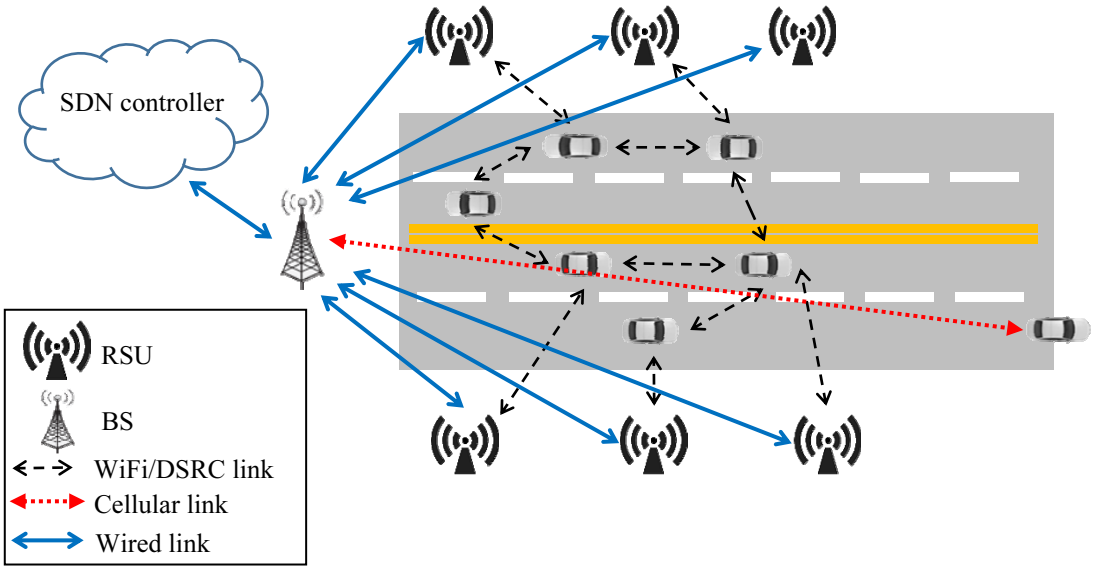

Fig. 1. Illustration of an SDVN

entertainment on vehicles. The 3rd Generation Partnership Project (3GPP) has focused on formulating the protocol of vehicle-to-everything (V2X) for communications between user equipment (UEs) in vehicles and hand-held UE. With rapid development of smart vehicles, various types of vehicles will be invented, and diversified services are required to be supported. To respond to this trend, the conventional solution is to deploy more RSUs to serve more vehicles of various types, but it wastes a lot of resources.

To increase quality of service (QoS) and save hardware costs, the SDVN that applies the solution of SDN to implement VANETs can address the difficulties in conventional VANETs. Proposed by the Open Networking Foundation (ONF), a main feature of the SDN is to decouple the network system into control plane and data plane. The control plane is a logically centralized control center, in charge of making packet forwarding decisions. The data plane is in charge of transmitting requests to the control plane and processing the packet forwarding decisions made by the control plane. The decoupling approach is more flexible as compared to the conventional approach based on hardware communication infrastructures. The SDN can flexibly allocate network resources by only needing to adjust parameters in the control plane, without changing hardware facilities. Through the SDN architecture, the problems arising in conventional VANETs can be addressed, and efficiencies of V2V and V2I communications can be promoted. In addition, possibilities of future V2X applications could be increased.

From vehicular evolution, a vehicle was just a transportation tool, and then had the function of receiving radio so that the driver can obtain in-time traffic information to avoid traffic congestion. Later, GPS systems and audio-visual entertainment facilities enriched and diversified the functions of vehicles. Entering the era of ITS, the benefits of diversified networking services are several times before. Based on the estimation of GSMA and SBD, 60% of new vehicles will be equipped with the function of V2X in year 2018, and the total market will achieve 39 billion Euros. And, all vehicles could be equipped until year 2020. Consequently, a perfect architecture that incorporates the SDN and VANETs is required, to create a safe and pleasant driving environment.

Recently, a lot of works on SDN-based VANETs have been proposed. However, to the best of our understanding, there is no work to conduct a comprehensive survey on these works. Consequently, this article surveys theses related works on SDVNs, and proposes a classification for some representative works to provide readers understand the current progresses along this line of research. In addition, several future challenges are introduced to inspire future research. Therefore, this article first gives the system framework of SDVN, then surveys some previous works according to a classification, and finally proposes several future lines of research on SDVNs.

This paper is structured as follows: The basic concept of the SDVN framework, and related works on SDVNs and a classification for some representative existing works are introduced in Section II. Sections III provides several future challenges on SDVNs, followed by Section IV, which concludes this paper.

2 Related Works

Noticeable improvement of wireless computing/communications and the tremendous growth with the proliferation of mobile devices have made intelligent vehicular networks no longer a future promise but rather than an emerging technology to meet the imminent demands focused on security, safety and efficiency. Except the purpose of safety and security, there are increasing demands from VANET users to access Internet for infotainment, particularly for those real-time services, e.g., video streaming and web browsing. Today's VANET applications become much richer in content and more diverse in traffic patterns, while latency or delay plays a critical role in user experience.

In addition to the advances of wireless computing/communications, cloud/fog computing as a pseudo-centralized control and management solution has become mature, representing an indispensable component for VANET and next generation intelligent transportation systems. In particular, the software-defined vehicular network (SDVN) has been emerging as a promising paradigm to control the network in a systematic way. Software-defined network (SDN) deployed on the top of VANET as a software-defined vehicular network (SDVN) architecture has been regarded as a promising paradigm for the next generation intelligent transportation systems.

This section introduces some recent representative works on SDVNs. Recent development on technologies of VANETs can be referred to the work [2]. Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band to be used by the DSRC, in which 7 channels are available for safety and nonsafety applications. The DSRC is used for PHY and MAC layers in IEEE 802.11p (WAVE) and IEEE 1609.1/.2/.3/.4. Most SDNs applied the OpenFlow protocol [3], which considers a packet-relaying machine with multiple flow entries. When receiving a packet, the machine checks whether the packet is matched with some flow entry and takes the corresponding actions. If the packet is not matched with any flow entry, it is transferred to a controller for later computations [4]. Another commonly used SDN framework is the ForCES [5] proposed by the IETF Forwarding and Control Element Separation Working Group. Like the OpenFlow that separates control and data planes, the ForCES separates Control Elements (CE) from Forwarding Element (FE), but CE and FE are still in the same device in the ForCES. In addition, the ForCES has a Logical Function Block (LFB) residing on the FEs, which allows CE to control FE configurations.

Most related works on SDNs focused on topology establishment and trajectory decision. In general, topology establishment is based on "trajectory prediction" to judge the position and "reconnection to the next RSU" of each vehicle. Path decision is concerned with "packet flow selection" and "channel selection" during transmitting packets. In addition, "content distribution" and "decentralization" have also been investigated recently. Based on these attributes above and the classification of VANETs, some representative works on SDVNs are classified in Table 1 [4].

Table 1. Pervious works on SDVNs [4]

Type	Feature	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]
SDN	Trajectory prediction	v	v	v							v	
	Reconnection		v								v	
	Packet flow selection			v	v	v	v	v	v	v		
	Channel selection	v		v		v			v		v	
	Content distribution	v										
	Decentralization					v						v
VANET	Large-scale vehicle traffic	v			v	v		v			v	v
	Heterogeneous vehicles			v					v			
	Limited bandwidth resources	v				v	v	v			v	v
	Trajectory uncertainty	v									v	
	Short lived connection	v	v									
	Energy cost			v	v	v	v		v	v		

Three works on topology establishment are reviewed as follows. Cao, Guo and Wu considered an SDVN based on type-based content distribution (TBCD) to support distribution of large-scale data-intensive content in VANET [6]. The SDN controller constructs the network topology by predicting vehicle trajectory according to positions and speeds of vehicles. For content distribution, the proposed

TBCD is to classify large-size data into a number of small-size data according to interest groups of vehicles [4]. Then, the vehicles that loss connection with an RSU can receive the data through V2V communications with other vehicles in the same interest group. To avoid high packet loss or low transmission rate due to rapid vehicle movement, Khan and Ratha [7] proposed an SDVN based on time series prediction to estimate the topology in the next short future time. If a vehicle moves out of an RSU coverage, then it temporarily stores the data that is not finished yet, and handles the reconnection of the next RSU. He, Cao and Liu proposed an SDVN architecture with status manager and topology manager to address heterogeneity of network facilities, whose network functions are virtualized and centralized to be controlled by the SDN controller [8]. This logically centralized controller can find the optimal packet flow and channels in this heterogeneous VANET, and make judgements in advance according to vehicle driving information, to avoid additional transmissions and save energy costs [4].

The remaining works are based on path decisions, and are reviewed as follows. When the number of vehicles becomes larger, data traffic may become unbalanced among vehicles. Ku et al. [9] proposed an SDVN architecture to effectively plan packet transmissions and select channels to reduce the energy cost due to large-scale data traffic congestion. Truong, Lee and Ghamri-Doudane [10] incorporated SDVNs with the distributed concept of fog computing, in which the SDN enjoys the merits of flexibility and programmability; and the fog computing can reduce the delay of transmitting back to the SDN controller. They considered that if only a centralized controller handles all requests from a huge number of vehicles, then it may be overloading. Therefore, by referring to the hybrid control model in [9], they proposed that the SDN controller does not have a full control for the packet flow of the whole system, but it provides policy rules to RSUs or BSs with fog computing abilities, based on which the optimal packet transmission path and channel selection will be found, so that the energy cost of frequent transmissions of the SDN controller could be reduced.

Salahuddin, Al-Fuqaha and Guizani proposed an RSU cloud, which includes not also a conventional RSU, but also an RSU microdatacenter with virtualized network functions [11]. They applied a Markov decision process to determine a transmission path with minimal bandwidth resources and energy costs [4]. Kai, Ng, Lee, Son and Stojmenovic [12] addressed the cooperative data scheduling (CDS) problem in SDVNs, which maximizes the number of vehicles that retrieve their requested data. They showed the CDS problem to be NP-hard through maximum weighted independent set problem. Their proposed algorithm is based on the collaboration of V2V and V2I to decide the optimal transmission path.

He, Zhang and Liang considered heterogeneous SDVNs in single-hop and multi-hop cases [13]. They applied the greedy method to find the optimal packet transmission path and channel selection with the minimal energy cost.

To save excessive consumption of network resources due to periodic warning messages from RSUs, Liu, Chen and Chakraborty proposed an SDVN based on GeoBroadcast architecture [14]. To avoid the overheads of the packets broadcasted from a source RSU to other RSUs that are transmitted to the data center and are then transferred, the source RSU transmits a packet-in message to the SDN controller, and then the controller helps transmit the packets to the destination according to topological and geographical information [4].

Bozkaya and Canberk considered flow and power management in the SDN controller [15]. The RSU first computes the quality of experience (QoE) of vehicles, and marks those with QoE below a threshold as unsatisfactory vehicle. Then the manager adopts a Kriging spatial interpolation method to compute the strength of the optimal signal of each unsatisfied vehicle. Then, the unsatisfied vehicle is switched to be served and allocated with a bandwidth according to its signal strength by another closest RSU [4].

Aside from topology establishment and path decision, decentralization of SDVN also received much attention. Kazmi, Khan and Akram proposed a decentralized SDVN [16]. To address the delay owing to handling large-scale networks in a centralized way, they divided the SDN controller into root controller (RC) and domain controller (DC). Each domain has a DC, in charge of the flow scheduling of this domain. RC is in charge of resource management and forwarding rules manager.

3 Future Trend and Challenges

Based on the above recent works on SDVNs, some main future trend and challenges are introduced.

3.1 Architecture Design

A line of future trend is to provide a more unified, flexible, and reliable SDN architecture for VANETs. First, the most important feature of designing an SDVN architecture is to achieve safety of vehicle driving and pedestrian. Statistical results show that the smart phone ownership ratio in 56 major countries has achieved 60%. If all vehicles can be connected with all pedestrian smart phones in the SDVN architecture, error of image recognition for safety could be avoided, and the whole connected network can be extended. In addition, stronger communication abilities between RSUs can speed up the SDVN system. For instance, when a vehicle moves from an RSU coverage to another RSU coverage, this vehicle could relay some messages in the former RSU to the latter RSU. If trajectory prediction can be skipped, network resources can be saved. Another instance considers disaster management. When some broken infrastructures due to the disaster are not functioned to transmit packets, the SDN controller should flexibly assign other facilities to help, to maintain the QoS stability [17].

3.2 Self-Organizing Network

Network intelligence is crucial to SDVNs. Energy cost could be reduced through self-organization of SDVNs. For instance, in the data plane, since the geographical environment differs a lot, it is important to investigate how spectrum or channels of RSUs are adjusted autonomously by analyzing QoS and packet delivery success rates. Therefore, the SDN controller should analyze the data collected from the data plane to achieve self-organization of this network. In addition, different traffic flow and weather conditions cause various self-organizing results, and further influence trajectory prediction and dynamic computing resource allocation. However, too much automatic adaption could be out of control, and hence the safety and robustness should also be concerned.

3.3 Protocols and Standards

A lot of techniques and protocols for SDVNs are required to be developed, and further become standards for effective interoperability. For instance, open channels and trajectory prediction could lead to threats of safety and privacy. The attacker could broadcast malicious messages, spy vehicles, and distort data to evade the responsibility of some car accident. Therefore, frequent replacements of certificates or other approaches are required. In addition, more improvements could be made for the techniques for DSRC, because the DSRC is a radio frequency technique, which is easily blocked by obstacles and could be diffracted.

3.4 Device-to-Device Communications

There appears a tradeoff between centralized and distributed VANET, and the optimum tradeoff has been widely studied. This research reveals that fixed network architectures may fossilize the performance and flexibility, which consequently inspired the “OpenFlow” and software-defined networking (SDN) to dynamically optimize the network behavior, which is known as a cloud-down design, and practical examples are device-to-device (D2D) proximity services in 3GPP Release 12/13 [4]. 3GPP V2X radio access aims at enabling a vehicle to exchange data with everything as illustrated in Fig. 2.

3.5 Vehicular Cloud Networking (VCN)

As computing and communication technologies have been rapidly developed, the vehicles with powerful computing abilities are advocated to be regarded as service providers rather than being only service consumers. As a result, the concept of Vehicular Cloud Computing (VCC) has been proposed, that jointly makes use of computation, communication and storage resources in vehicle equipments, e.g., on- board computer/communication devices or mobile user equipments arrived by passengers. In general, services in the VCC system can be divided into four types according to the function of the resources, i.e., “Network-as-a-Service (NaaS),” “Storage-as-a-Services (StaaS),” “Sensing-as-a-Service (SaaS),” and “Computation-as-a-Service (CaaS).” Differently from the traditional cloud computing system, the VCC system has its unique features [18]. For example, one of them is the variability of the available computation resources in Vehicular Clouds (VCs). Due to the uncertainty of the vehicle behavior, i.e.,

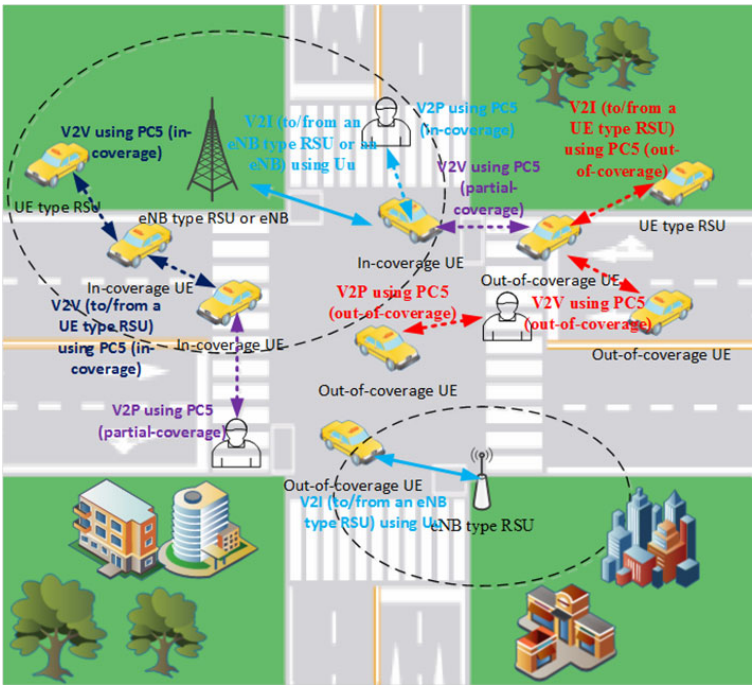

Fig. 2. 3GPP V2X Communications.

vehicles may randomly join or leave VCs, the resources in VCs are time varying. Another obvious feature is the heterogeneity of VCs resources. Vehicles are produced by different vendors and thus have inherently different computation resources. Therefore, there are lots of problems in vehicular cloud networking needed to be solved [18].

3.6 Small Cell

The small cell represents that it has a smaller transmission range and lower construction cost. According to the coverage in descending order are Microcell, Picocell and Femtocell. The transmission range and construction cost are in direct proportion normally. The transmission radius of Microcell is around kilometer, and hundreds of meters with Picocell and Femtocell [19-20].

Obstacles and buildings cause the non-line-of-sight propagation problem no matter indoor or outdoor. Small cell aims at improving the signal dead zone in a small area. For example, Femtocell is usually placed in a house and Picocell is deployed for a building, and Microcell is constructed in a school or a community. The researchers in investigated to improve signal and to increase capacity by deploying small cells in small-cell networks (SCNs). Small cell uses the larger bandwidth and higher frequency band to reach the outstanding transmission rate. Small cell can adopt beamforming technique to overcome the low penetration defect. The Inter-Cell Interference Coordination (ICIC) approach allocates radio resource to reduce the interference, or another method is to use fiber link at the backhaul link between Macrocell and small cell [19].

3.7 Debugging Mechanism

Even though the IP-based network had been proposed for many years, it is still hard to debug and troubleshoot systematically. This situation gets worse in SDN. Erickson mentioned that most network operators use ping, traceroute, and simple network management protocol agents to diagnose network problems. However users are always in the first alignment that encounters problems. The ping and traceroute commands are based on internet control message protocol (ICMP). Commands based on ICMP work finely in traditional IP networks [20]. Deng et al. proposed a debug tool for SDN users by using the same commands [20].

Existing tools are designed for network administrators rather than users. All tools need administrator authority but users are always the first line to encounter network problems. Thereby, the SDN Ping (sPing) is proposed for SDN users in defining traffic patterns and presenting the flow path of a packet.

The sPing works miracles for debugging only with defining packet header information. The modification of network architecture is unneeded, no additional network traffic while using sPing. The sPing discovers the information of data link layer that it is the first achievable debugger to existing literatures on SDN [21]. Needless to say, in SDVN we will face the same problem.

3.8 Fog Computing

Some previous works have incorporated the SDN with Fog computing techniques so that RSUs can possess a partial function of the SDN controller to achieve real-time computing. Further research on defining this integrated technique in different application scenarios could be conducted. For instance, the priority of packets (e.g., those for safety) should be considered in optimizing performance of fog computing. Or, geographical information of RSUs could help SDN fog computing provide more localized unsafety applications.

3.9 Heterogeneous of RSUs

According to real application environments, heterogeneity of RSUs leads to various designs of SDVNs. For instance, in the city area, complicated traffic requires frequent adaption of the network topology. Hence, the ability of computing topologies in RSUs should be enhanced. In the application in highways, vehicle trajectory does not differ a lot, and hence, trajectory prediction in RSUs would not be crucial. In the suburb area, the number of vehicles is small, and hence, the ability of computing multi-hop transmissions in RSUs could be reduced.

3.10 Latency Control in SDVN

In VANET, there is no guarantee that a particular wireless service of all vehicles are able to successfully receive on time. Although the overall network performance can be optimized in any desired aspects through the universal resource optimization in cloud computing. However, the cost of utilizing cloud computing in VANET is becoming unaffordable as the number of supported vehicles explosively grows. Such cost includes collecting user information in terms of channel conditions, location tracking, quality-of-service (QoS) requirements, passing user information to CUs in the cloud, computational workload in the cloud, disseminating the optimum resource allocation to users, and most importantly, latency of all above operations. Hence, latency control in VANET could be an important issue in the future VANETs [4].

3.11 Confliction Detection

Large network scale and increasing network resource demands lead to lots of conflictions among existing policy rules in SDVNs, so that the overall performance of the SDVN would be reduced. Therefore, an efficient automatic confliction detection scheme in SDVNs is required.

4 Conclusions

A new standardization activity has been started by 3GPP in 2015 to address the issue of providing ubiquitous vehicle connections over a wide geographic area. By leveraging LTE infrastructure, LTE based vehicle-to-everything (V2X) transmission will offer better quality-of-service (QoS), communication reliability and cost-efficiency in practical deployment and operation. Entering the V2X era, the market becomes enormous and diversified. The SDN provides an important foundation for future V2X applications. This article has first introduced the basic concept and framework for SDVNs, then provided a classification for some recent representative works from various aspects of SDVNs, and suggested some future trends and challenges, including architecture design, self-organization, protocols and standards, fog computing, heterogeneity of RSUs, and confliction detection, to provide a reference for future design and development of SDVNs.

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