Chapter 11
Software-Defined Vehicular Networks (SDVN) for Intelligent Transportation Systems (ITS)

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ABSTRACT

Vehicular communication is going to play a significant role in the future intelligent transportation systems (ITS). Due to the highly dynamic nature of vehicular networks (VNs) and need for efficient real-time communication, the traditional networking paradigm is not suitable for VNs. Incorporating the SDN technology in VNs provides benefits in network programmability, heterogeneity, connectivity, resource utility, safety and security, routing, and traffic management. However, there are still several challenges and open research issues due to network dynamicity, scalability, heterogeneity, interference, latency, and security that need to be addressed. This chapter presents the importance of vehicular communication in future ITS, the significance of incorporating the SDN paradigm in VNs, taxonomy for the role of SDVN, the software-defined vehicular network (SDVN) architecture, and open research issues in SDVN.

INTRODUCTION

Over the years there has been tremendous advancement in vehicular technology. While network and communication technology made its way into the vehicles for applications such as comfort, driver assist, and fleet management, gradually vehicle communication is advancing towards vehicle-to-everything (V2X) scenarios. Under V2X communication, a vehicle is capable of Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Cloud (V2C), Vehicle-to-Pedestrian (V2P), Vehicle-to-Device (V2D), and Vehicle-to-Grid (V2G), to name a few. There are standards (including protocols) such as Cellular Vehicle-to-Everything (C-V2X) IEEE 802.11p, Wireless Access for Vehicular Environments (WAVE) and Dedicated Short Range Communication (DSRC), (Wang, Mao & Gong, 2017; Abboud, Omar & Zhuang, 2016; Storck & Duarte-Figueiredo, 2020; Jiang & Delgrossi, 2008; Morgan, 2010; Li, 2010),

DOI: 10.4018/978-1-7998-7646-5.ch011

defined to enable such communications. Enabling vehicles to communicate between each other and with their surroundings paves way for Intelligent Transportation Systems (ITS).

Tremendous rise in communication and computing devices in vehicular networks has led to a surge of the need for bandwidth, storage, and computing power in these networks (Chahal et al., 2017) and (Jaballah, Conti & Lal, 2019). Maintenance and management of contemporary networks using traditional networking techniques is complex and expensive. Hence, traditional networking is being enhanced with Software-Defined Networking (SDN) as it eliminates manual configuration of networking hardware and helps in attaining programmability and flexibility of networks where control and data planes are decoupled (Kirkpatrick, 2013). The SDN techniques facilitate service design, delivery and operational procedures by means of dynamic resource allocation and policy enforcement schemes, data models and automated configuration tasks.

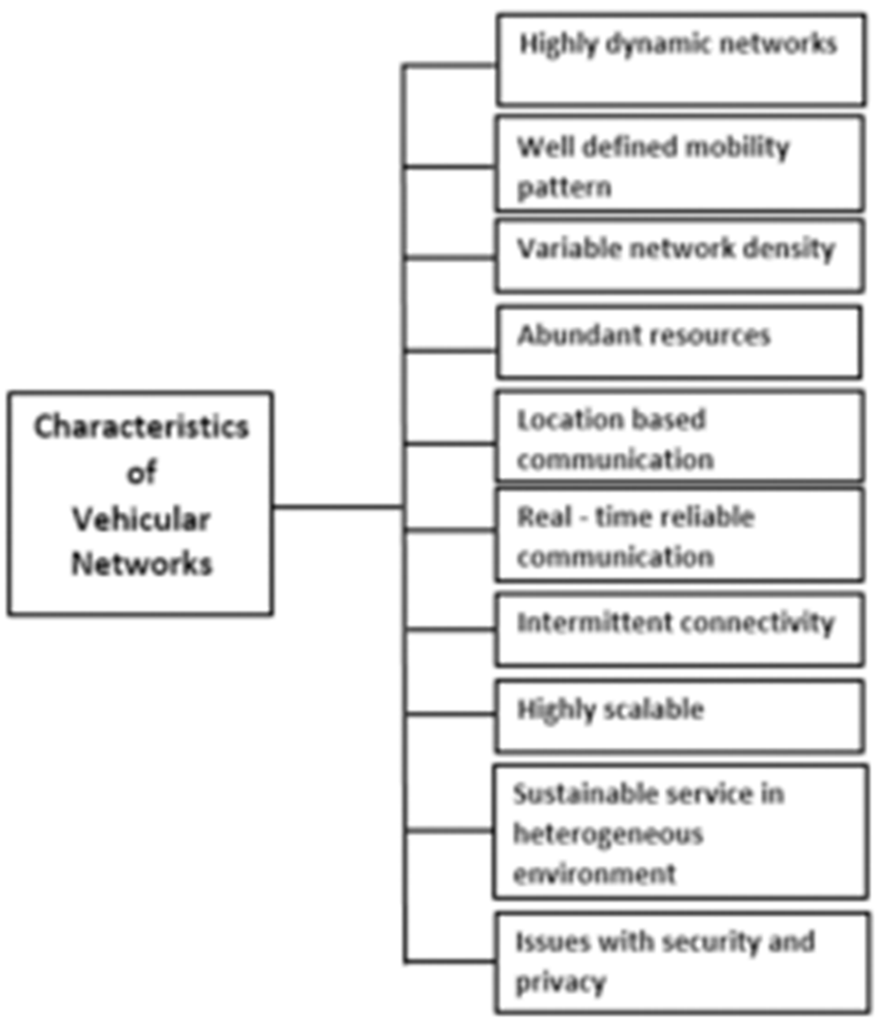
Vehicular communication is an enabler for autonomous vehicles of the future. It involves exchanging messages related to safety, navigation, traffic condition and congestion control, as well as multimedia, general purpose Internet access, location-based services (such as nearby hospitals, service stations, gas stations, parking places or restaurants), traffic conditions, and congestion control. These applications have different delay, and bandwidth requirements. The packet loss and propagation requirements (in terms of communication scheme for example unicast or multicast, symmetric or asymmetric, and bidirectional and unidirectional transmission). While applications such as vehicular safety, navigation, multimedia, traffic conditions, and congestion control require real-time performance, reliability, high bandwidth, and low-latency operation; other applications such as general-purpose Internet access and location-based services may be able to withstand nominal delays. Integration of SDN technology with vehicular networks (VNs) will facilitate the programmability of networks by means of dynamic network resource allocation schemes based on the application requirements and network constraints (among others) (Jaballah, Conti & Lal, 2019; Chahal et al., 2017). SDN-based VNs are termed as Software Defined Vehicular Networks (SDVN).

The remainder of this chapter is organized as follows. Section 2 presents the role of vehicular communication in ITS and the characteristics of vehicular networks. Section 3 discusses the importance of incorporating SDN architectures in vehicular network communication. The taxonomy for the role of SDVN in VN programmability, heterogeneity, connectivity, resource utilization, safety and security, routing and traffic management is provided. Section 4 presents the simplified view of the SDVN architecture comprising the three planes/layers and corresponding interfaces. The operations carried out by the three planes and their respective components are presented. Section 5 discusses the key challenges and open research issues in the area of SDVN. Section 6 concludes the chapter.

ITS and Vehicular Communication

One of the goals of ITS is to achieve high traffic efficiency while reducing the commuting times (e.g., home-to-office travel and back) and provide enhanced traffic safety and comfort. The ITS focuses on traffic management and safety, real-time traffic information and status, emergency and warning systems, infotainment and comfort, and autonomous driving. Vehicular communication plays a crucial role in the implementation and the operation of ITS. Vehicular communication involves real-time communication of vehicles with other vehicles (V2V), roadside infrastructure (V2I), cloud (V2C), other devices (V2D) and pedestrians (V2P). With such variety of communication, vehicular networks are deemed heterogeneous and dynamic. VNs comprising vehicles and other communication entities mentioned earlier exchange information in real time. In these networks, vehicles play the role of source, sink as well as routers. The vehicular networks operate based on peer-to-peer and client-server paradigms depending on the applications and communicating entities. Vehicular ad-hoc networks (VANETs) are the self-organizing V2V communication networks established between moving vehicles (Hartenstein & Laberteaux, 2008), (Hamdi et al., 2020) and (Amjid, Khan & Shah, 2020). In V2V communications all the vehicles are considered as peers, while in V2I and V2C communications a vehicle acts as a client who accesses servers possibly hosted in cloud infrastructures. The highly dynamic nature of VNs leads to constant change in the network topology and status of the communication links resulting in variation of network performance resulting in variation of network performance. Some of the important characteristics of VNs are presented in Figure 1.

Figure 1. Characteristics of VANETs



In the following some of the VN characteristics are further detailed:

1. **Highly dynamic networks:** Vehicular ad-hoc networks (VANETs) comprise vehicles that are highly mobile when compared to the mobile devices in a mobile ad-hoc network (MANET). High mobility of VANETs leads to constant change in the topology of these networks, which further leads to breakage of communication links leading to adverse effects on the network performance.
2. **Well-defined mobility pattern:** Unlike mobile ad-hoc networks (MANETs) wherein the mobile nodes move randomly, vehicular nodes usually move in a well-defined pattern such as on a road while following rules on traffic lanes and junctions. This well-defined mobility pattern provides certain predictability to the network topology and connectivity.
3. **Variable network density:** Due to high node mobility and changing node density due to varying terrain (e.g., from narrow city lanes leading to slow moving traffic and traffic jams, to broad highways and suburban areas where vehicles move at high speed) the network topology is highly inconsistent. In either of the cases, the network performance may degrade due to signal interference in dense areas or connection breakages due to sparse network wherein communicating nodes may not fall within communication range of each other or that of infrastructure leading to poor network coverage conditions that may degrade or even break communication.
4. **Sufficient resources:** A mobile network comprises mobile nodes such as laptops, smartphones or handheld mobile devices capable of establishing wireless communication. These devices have usually limited battery and computation power. Unlike these networks, the nodes in VNs are assumed to have enough resources to process and store the data exchanged over the network.
5. **Location-based communications:** Unlike computer networks or mobile networks wherein the communication is targeted to a specific user and the corresponding device using its device ID or group ID (e.g., 6 Byte long Hexadecimal address, MAC address); the related services and communication in a vehicular network are intended to nearby vehicles, i.e., based on the location of the vehicle (vehicular node). With the moving vehicle changing its location constantly, its surrounding environment and the reachability of other communicating nodes in its vicinity (other vehicles, infrastructures, pedestrians etc.) also change.
6. **Real-time reliable communications:** Applications related to VNs and ITS such as autonomous vehicles, electronic toll collection, collision avoidance systems, automated road speed enforcement, and many more, require real-time reliable communications. The response times need to be short for these applications. Therefore, it is required to ensure availability of sufficient resources, e.g. in terms of bandwidth for these applications to be implemented successfully.
7. **Intermittent connectivity:** Due to constant node mobility at variable speeds, over different terrains (urban, suburban, or hilly), varying topologies and network density (densely/sparsely populated networks), VNs encounter frequent link failures, poor network connectivity, and packet loss in a system that necessitates real-time reliable communications.
8. **Highly scalable:** VNs carrying out V2X communications consist of other vehicles, roadside infrastructure, pedestrians, cloud, and other devices. Depending on the terrain and network node density, the number of participating devices in the network can vary drastically. To accommodate these variable number of network devices, the VNs need to be scalable.
9. **Sustainable service in heterogeneous environment:** VNs are highly dynamic and scalable networks, comprising a large variety of participating nodes. These networks operate in heterogeneous environments. While operating in these environments, these networks need to support real-time

applications that require high reliability. Therefore, it is a challenge to achieve service continuity in heterogeneous environments.

10. **Enhanced security and privacy:** Reliability is crucial for VN communication. Vehicular data integrity must not be altered. Security (including the preservation of data privacy) is therefore essential for VN communications like in any other communication technology. While the security mechanisms are expected to be robust, the underlying mechanisms should raise neither computational complexity nor processing delay to unduly high figures.

Software-Defined Vehicular Networks (SDVN)

The constant increase in the demand for remaining connected while on the move, coupled with the essential requirement of traffic safety and efficiency, calls for robust and reliable VN communications. However, VNs encounter numerous challenges owing to their characteristics discussed in Section 2. To achieve robust and reliable VNs that can adapt to the varying network conditions due to the constant movement of the involved entities, Software-Defined Networking (SDN) is being considered as with a technique that can be useful for VN programmability (Zhu et al., 2015) and (He, Cao & Liu, 2016). This section examines the role of SDN in overcoming the challenges faced by the VNs through the SDVN use cases.

Role of SDN In VNs

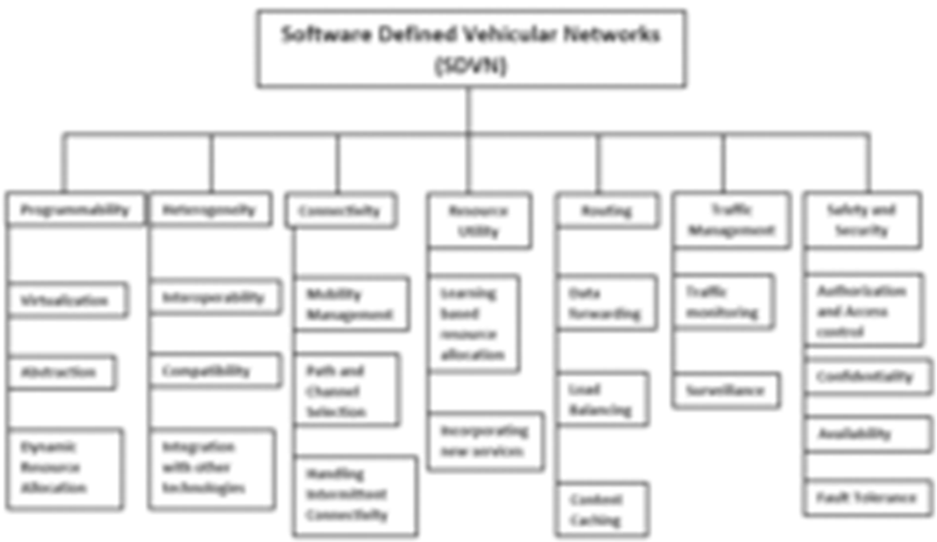
As discussed in Section 2, the VNs are characterized by a highly dynamic and heterogeneous network environments that require real-time and reliable communication. The varying range of applications and communication protocols supported by these networks raise various QoS requirements. Technologies/methods used for vehicular communication comprise IEEE 802.11p WAVE, DSRC, Wi-Fi, C-V2X, wireless sensor networks, ad-hoc networks and infrared communication. These involve complex algorithms that deal with the issues in routing, connectivity, heterogeneity, scalability, reliability, and security. Also, proprietary and tightly coupled solutions (solutions developed by one manufacturer are unable to work with devices/solutions developed by other manufacturers) make the implementation of VNs complex and inefficient (Yaqoob et al., 2017) and (Ku et al., 2014).

SDN is being considered as the most appropriate technology to deal with such requirements as Integration of SDN techniques facilitate VN programmability, which cannot be achieved by legacy networking techniques alone. The SDN computation logic (a.k.a. SDN controller) resides in the control plane and constantly monitors the network to assess its status and performance. To achieve efficient network communication and address various QoS requirements raised by a VN, an SDN controller helps optimizing the usage of network resources. The SDN controller maintains a global view of the network topology and facilitates efficient network management (Liyanage, 2018).

Since its inception, SDN has been primarily used for wired networks. However, over the years, researchers have developed solutions to deploy SDN architectures for wireless networks. Researchers have implemented the SDN architectures for ad-hoc networks combined with high speed wireless and mobile communication (Benalia, Bitam & Mellouk, 2020) and (Din et al., 2018). Considering the highly dynamic topology and heterogeneity of VNs, SDVN is considered to be the promising solution for VNs and future ITS solutions. SDVNs are composed of vehicles and user-based nodes, Road Side Units (RSUs), Road Side Unit Centers (RSUCs), Software-Defined Network Controllers (SDNC), and Base Stations (BSs) (Chahal et al., 2017; He, Cao & Liu, 2016; Alioua et al., 2017).

The role of SDVNs is presented in Figure 2. The important aspects of VNs wherein SDN plays a significant role are presented in the following subsections.

Figure 2. Taxonomy of the role of SDVN



Programmability

With the help of protocols such as OpenFlow, an SDN controller constantly communicates with the network devices such as RSUs, BSs, cloud computing clusters, and fog computing clusters (Zhang et al., 2018; Truong, Lee & Ghamri-Doudane, 2015). The dynamic nature of a VN may require constant programming and reprogramming of the network and its resources to keep up with the user demands. Using SDN in VN environments facilitates virtualization, abstraction and dynamic resource allocation. Vehicular cloud computing (VCC) is used by the vehicles for data and resource sharing. It helps with enhancing the scalability of VN services (Boukerche & Robson, 2018). Network function virtualization (NFV) and network abstraction are essential to programmable networks. SDN techniques can help mastering network virtualization, network abstraction and dynamic resource allocation based on network evolution and user/application demand (Ananth & Sharma, 2017) and (Ananth & Sharma, 2016).

Heterogeneity

A VN is composed of a variety of mobile and infrastructure nodes that enable VN communications. The V2X communication services involve other vehicles, RSUs, cloud, pedestrians, other devices as well as grid. For all these devices to properly interoperate, a standardization effort is required. The C-V2X system from the 3rd Generation Partnership Project (3GPP), the DSRC, and WAVE protocols from IEEE are such standard protocols that are designed to support Cooperative - Intelligent Transportation

Systems (C-ITS) (Zheng et al., 2015). The most important requirements to support heterogeneity in VNs are related to device interoperability. For these devices, protocol converters (e.g., Gateway devices/ protocol translators to deal with network heterogeneity) and efficient handoff/handover techniques are implemented. SDN helps in programming heterogeneous VN networks through standard interfaces by virtue of SDN-based network abstraction and virtualization, the heterogeneity of participating network devices can be concealed. The SDVN controller provides abstraction for the VN applications and infrastructure (He, Cao & Liu, 2016; Alioua et al., 2017).

Connectivity

Seamless connectivity is essential to the VNs to operate successfully and reliably. The ITS applications require real-time and robust network connectivity. Due to high mobility, these networks face issues of intermittent connectivity and frequent connection breakages. In a mobile network, high node density and mobility are the causes of network interference and connection breakage, respectively (Thriveni, Kumar & Sharma, 2013). Connectivity and vehicle mobility still remain a challenge for VNs. An SDN controller can maintain the vehicle movement history or anticipate its future trajectory based on GPS or cellular data and maps-based destination information. Authors in (Tang et al., 2019) have proposed a mobility prediction-based routing scheme. Through this scheme, the probability of successful transmission and the achieved average latency can be computed based on node mobility changes with respect to node topology which is estimated through the RSUs and BSs. A buffer-aware streaming approach to maintain an adequate level of QoS is proposed in (Lai et al., 2017) for infotainment multimedia applications over vehicular 5G networks. Based on QoS information, appropriate handoff/handover mechanisms are used by the eNodeBs to select the appropriate paths and communication channels to maintain network connectivity with minimum latency and required QoS.

Resource Utilization

As discussed earlier, VNs need to support real-time, reliable, and robust communications. To that aim, SDVN can be used to program dynamic resource allocation based on node mobility, node density, mobility patterns, and application-specific data rate requirements. Context-aware resource allocation is performed by the SDVN controller to make sure VN traffic is forwarded with the adequate levels of QoS and security, in particular. Machine learning (ML) and Deep Learning (DL) as techniques of Artificial Intelligence (AI) can be incorporated to detect overloaded paths/channels and to take corrective actions as appropriate (Tang et al., 2019) and (Jindal et al., 2018). These corrective actions may include traffic redirection or the allocation of extra bandwidth.

New services such as cloud, fog and edge computing are used for real-time data processing and data sharing (Meng et al., 2015). These services play a significant role in providing resources, in terms of sharing, storage, and processing of VN data. The combination of Multi-access Edge Computing (MEC) and NFV can optimize traffic forwarding and resource management (Peng, Ye & Shen, 2019). Authors of (Huang et al., 2017) have proposed Off-loading with handover decisions made by Software-Defined computation logics: load prediction control scheme wherein the SDN controller decides about data offloading based on vehicle's position, direction of movement, speed and neighboring RSUs/BSs. Future Internet technologies such as Content Centric Networking (CCN), Information Centric Networking (ICN), and Named Data Networking (NDN) which ambition to facilitate Content-based forwarding, supporting real-time, reliable, and robust transmission and processing of data in VN environments (Soua et al., 2017; Khelifi et al., 2019).

Routing

Efficient routing/forwarding within VNs is essential for their robust and reliable operation. In a VANET, the intermediate vehicles act as routers, while the RSUs, BSs, cloud computing and fog computing clusters also support traffic routing, switching, and forwarding capabilities. As the VN topology changes continuously due to node mobility, the VNs experience route changes quite often.

The flexibility, abstraction and programmability features of the SDN may play an important role in efficient traffic forwarding. The SDVN controller maintains the status of different routes. A route computation scheme based on link dynamics and stability in SDVN is proposed in (Sudheer, Ma & Chong, 2017; Sudheer, Ma & Chong, 2019). ML, mobility management along with the resource allocation techniques are used for path computation, selection, establishment and maintenance purposes (Xie et al., 2018; Sun, AlJeri & Boukerche, 2020). Some of the SDN-based routing protocols such as GeoSpray (a geographic routing protocol for vehicular networks), Cognitive Radio - Software Defined Vehicular Networks (CR-SDVN), Software Defined - Internet of Vehicles (SD-IoV) used in VNs are presented in (Sun, AlJeri & Boukerche, 2020; Abbas, Muhammad & Song, 2020; Zhu et al., 2015; Ghafoor & Koo, 2017; Ji, Yu, Fan & Fu, 2016; Venkatramana, Srikantaiah & Moodabidri, 2017). In case congestion path becomes congested, traffic is redirected towards other appropriate paths by virtue of multi-path routing. Traffic redirection accommodates overloaded path conditions, thereby reducing the risk of propagation delays, or packet loss. Load balancing is used to avoid overloading particular network devices and controllers, and to support efficient processing of data. However, it must be noted that a load balancer itself introduces processing delays as mentioned in (Sharma & Reddy, 2019), for example.

Technologies such as CCN, ICN, and NDN along with edge and fog computing clusters carry out content caching and processing at the intermediate nodes/devices for faster responses as required in real-time environments such as those VNs are typically operating in (Kadhim & Seno, 2019).

Traffic Management

Traffic management, including traffic monitoring is essential for appropriate VN and ITS operation, at least to make sure that the design of the VN can accommodate ITS service requirements. As the VNs are composed of highly mobile nodes leading to dynamic network topologies, traffic patterns vary frequently. To maintain network connectivity and allocate network resources, it is essential to constantly monitor network traffic. To avoid bandwidth scarcity, appropriate network planning and traffic engineering methods may be useful (Abugabah et al., 2020) and (Shu et al., 2020). Solutions such as Decentralized Congestion Control (DCC) (Campolo, Molinaro & Scopigno, 2015) enhance the computation of path load estimation, based upon input parameters taken from different vehicles and RSUs.

Safety and Security

VNs can undergo numerous attacks such as malicious applications, compromising server behavior, unauthorized access to the network, modification of flow rules (i.e., data traffic flow rules as defined for a routing mechanism), traffic hijacking, Man-In-The-Middle (MITM) attacks, fake service advertisement, fake devices and topology advertisements, to name a few (Arif et al., 2020)

and (Boualouache, Soua & Engel, 2020). SDVN controllers can constantly monitor the network flows and identify network intrusion by malicious traffic. SDN allows the network administrators to separate malicious traffic from legitimate traffic thereby preventing the network from getting compromised, eventually. However, it needs to be noted that SDVN controllers act as the single point of control and are themselves subject to attacks. Such attacks include (Distributed) Denial of Service (DDoS), the alteration of controller messages, the poisoning of the controller's network view, conflicting controller configuration tasks, etc. (Reynaud et al., 2016).

The SDVN Architecture

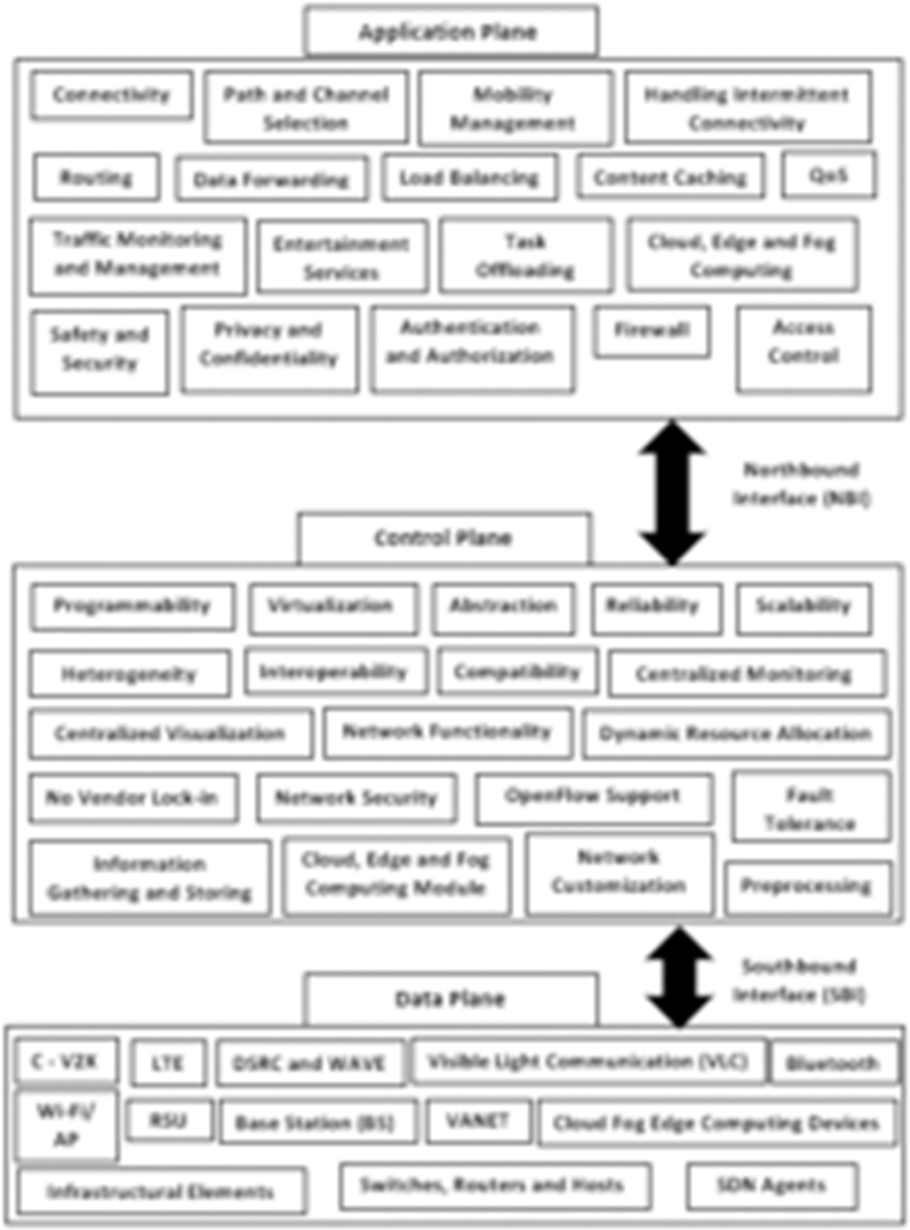
A simplified view of the SDVN architecture is presented in Figure 2. The SDVN architecture relies upon three planes and interfaces between the planes. The operations carried out by the three planes and their respective components are also presented in Figure 2. The upper plane is the "application plane" that is designed to provide certain applications and services to the VNs. The applications and services provided by the application plane of the SDVN architecture are presented in the application plane of the simplified view of the SDVN architecture. The "control plane" can be configured and re-programmed based on network requirements, in particular. The services provided by the control plane are presented in Figure 3. The "data plane" is responsible for network connectivity and communication. The technologies used and the required network devices/components are listed under the data plane in the SDVN architecture shown in Figure 3.

This section discusses the SDVN architecture and the roles of the application, control, and data planes of the SDVN architecture.

Application Plane

VNs support several ITS applications. Many non-safety and safety critical applications are handled by the VNs. The future VN technologies aim to make Autonomous Vehicle (AV) a reality. Some of the safety critical applications include traffic services, accident avoidance, driver assist, platooning, autonomous driving, alarm and warning messages (emergency brake/intersection collision/stationary warning systems). The non-safety critical applications include media streaming, infotainment, Internet access by commuters, and electronic toll payments. To support real-time processing of application flows, technologies such as cloud, edge and fog computing can be part of the VN network. A communication or diagnostic history can be stored in the cloud for future use. Information processing requests can be handled by the cloud, edge or fog computing resources. Traffic forwarding and content caching techniques also need to evolve to support VNs. Another important aspect that needs to be handled by the application plane is related to the safety and security of the network and the applications running over these networks. As VNs are highly dynamic and ad-hoc by nature, these networks are prone to attacks such as DDoS attacks, jamming attack, malicious participants, masquerading attack, illusion attack, altered / injected messages, sybil attack, GPS position alteration attack, timing attack, blackhole, and grayhole attacks. Secure vehicular communication requires authenticity, confidentiality, integrity, non-repudiation, privacy and availability. To mitigate these attacks, the VN networks must support message encryption and authentication capabilities, intrusion detection and prevention features, as well as firewalls and secure gateways.

Figure 3. The SDVN Architecture



Control Plane

The SDVN controller facilitates the implementation of new applications and allows testing of new services and protocols. The SDVN controller makes decisions about policy enforcement and resource allocation, as a function of various parameters that include (but are not limited to) the status of the network (load conditions, in particular), the nature of the ITS service, network-originated notifications, etc. The controller uses protocols such as open source based OpenFlow to communicate with the network devices. It controls the behavior of the network devices such as switches, routers, RSUs and BSs through the Southbound Interface (SBI). The SDVN controller makes decisions that may be inferred by application requirements, among other inputs.

As the SDVN supports applications ranging from traffic management and monitoring to infotainment services, the important characteristics of VNs such as multi-tenancy, scalability and flexibility are crucial for their performance. VN virtualization facilitates the flexibility in VNs in terms of the types of services offered by the network. To support multi-tenancy and ensure service availability, the virtualization of VN resources is required. One such framework is proposed in (Bhatia, Haribabu, Gupta & Sahu, 2018). The framework proposes the virtualization of the SDVN controller, resource manager, On Board Units (OBUs) and RSUs. The virtualization of network resources is meant to optimize the management of vehicle movement to avoid any service disruption when vehicles are not managed by a physical RSU (due to node mobility or absence of RSU deployment). The virtual OBUs (vOBUs) allows for slicing of the resources available at OBUs to be used by multiple tenants simultaneously. The availability of virtual RSUs (vRSUs) would provide the mobile nodes with seamless connectivity even when they move out of the communication range of the physical RSU. However, to enable this functionality, virtualization of BSs and (Access Points) APs is required. Virtual Resource Managers (vRM) allow the slicing of resources to better address QoS requirements through effective management of resources. The vRM in a VN enables multiple SDN controllers to share the physical resources. The virtual SDVN Controllers (vSDVNC) are used by the tenants to control their infrastructure (Li, Ota & Dong, 2016).

The SDVN scalability can be measured, for example, by the number of switches that a controller can support and the ability to deploy SDVNs over multiple domains. The SDVN controller facilitates network scalability by adapting the physical network capacity according to a scale-out model while managing the network as a single entity (as opposed to multiple network slices managed by different tenants). To maintain network performance and QoS the SDVN controller maintains flow tables that comprise rules for controlling and directing traffic flows in the network.

With route computation and route status management capabilities supported by the SDN controller traffic can be forwarded along different routes to optimize network resources. Also, the QoS parameters can be defined on a flow-by-flow basis, depending on the application requirements. Network reliability can be ensured by means of network redundancy schemes, among other designs. As the SDVN controller has the knowledge of the network configuration, it facilitates programming of network resources to maintain the required network performance and efficiency. VN security is of prime importance particularly because the vehicular nodes are involved in real-time communications and security gaps can be life threatening. SDVN controllers can support authentication and authorization capabilities to grant access to the network and its resources.

Data Plane

The data plane hosts forwarding capabilities. The RSUs, BSs, and APs are used for forwarding traffic from a vehicular node to the core networks and vice versa. These are controlled by an ITS service provider and are interconnected through a wired/wireless link. In case of VANETs, vehicles act as routers. The cloud, fog, and edge computing infrastructures provide storage and processing resources to address the need for efficiency, reliability and real-time processing. The data plane focusses on data collection and forwarding of data to the control plane using the forwarding resources such as routers/switches.

The cellular communication technologies can be adapted by the VNs as they provide very high network capacity capable of support applications requiring high throughput (e.g., autonomous driving, driver-assistance systems). The BSs and RSUs offer broader coverage for vehicles. The vehicles first access the RSUs, and then access the BSs if the RSUs are not able to provide enough resource for wireless access.

The cloud, fog and edge computing infrastructures make an important part of the data plane of SDN based VNs. The cloud computing infrastructure provides remote storage and computational facilities. However, there are concerns about delays involved in transferring the data from vehicles to cloud for storage / processing and retrieving the stored / processed data from the cloud. Due to these concerns, there arises the need to look for solutions that ensure reduced latency and uninterrupted service. To overcome these concerns, the fog and edge computing solutions are used.

The SDVN controller can control the operation of these infrastructure node and ad-hoc forwarding units through the SBI. The behavior of these devices can be programmed on a flow-by-flow basis depending on the application requirements. The transmission capacity in terms of communication channel bandwidth, as well as storage, and computing resources can be configured by the SDVN controller through the SBI.

In hybrid networks as presented in (Ku et al., 2014) and (Salahuddin, Al-Fuqaha & Guizani, 2014), the SDN controller offloads certain tasks to the RSUs and BSs and enforces certain policy rules such as traffic monitoring (traffic statistics and service access billing) and path load balancing (routing data based on application requirements for bandwidth and delay) associated with the forwarding of traffic over the network. The OpenFlow example described in the aforementioned reference, relies upon switches (e.g., OpenFlow-based) that are programmed by the controller to use per-hop criteria for flow control and resource allocation for forwarding and processing of data.

The SDN control is also extended to the vehicular nodes through the OBUs wherein, the OBUs can be programmed by the controller and prompted by the controller to perform certain actions. The SDN controller programs the forwarding devices for appropriate path to avoid interference and to control flows. The forwarding devices can be programmed by the controller with dynamic power transmission based on the vehicle density to avoid/minimize network interference.

The wireless communication technologies used for communication over the VNs are presented in Figure 2. These technologies vary in their data rates, communication range and operating frequency. In the heterogeneous VNs the participating nodes need to switch over between these network technologies or use them simultaneously for different purposes. The VN communication standards and protocols are defined by both 3GPP and IEEE. While 3GPP has defined Cellular - Vehicle to Everything (C-V2X) standards comprising of 4G/5G radio access such as LTE and LTE-A and New Radio (NR) technologies (both as cellular and as direct, side link variant), IEEE has defined the DSRC and WAVE standards. For short range Personal Area Network (PAN) communication technologies such as Bluetooth and VLC are used. Use of Radio Detection And Ranging (RADAR), Light Detection And Ranging (LIDAR) as well as sensors facilitates intra-vehicle and inter-vehicle communication for applications such as platooning, parking assistance, lane management, driver assist and obstacle detection. The channel access mechanisms such as Time Division Multiple Access (TDMA) or Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) can be programmed by the SDVN controller. As noted by the authors in (Fontes et al., 2017), TDMA is considered to be the better network access technology for low-latency, high-reliability applications in the autonomous vehicle approach.

The rules for traffic forwarding can be determined as a function of the location of the vehicle, as well as the density of vehicles. The geographical locations of the communicating node can be tracked by the

SDN controller through the RSUs or BSs, and the network infrastructure devices can be programmed for processing and traffic forwarding purposes.

KEY CHALLENGES AND RESEARCH ISSUES

As discussed in the previous sections, robust, reliable and efficient VN communication is crucial for the future ITS. The research community is working towards making VN communications and autonomous vehicles a reality. However, issues such as high node mobility, dynamic topology, intermittent connectivity, efficient network resource utilization, interference avoidance, load balancing, and network security still remain major challenges. As legacy networking techniques are not considered to be suitable for VNs, researchers are considering the development of SDVN architectures and related solutions to overcome these challenges. The programmability, scalability, and flexibility offered by SDN can help improve QoS, network's efficiency and reliability. Combining the SDN with cloud/edge/fog computing and NDN/CCN/ICN technology aims to enhance the VN functionality and performance further. The NDN/CCN/ICN are related technologies that carry out data-centric forwarding. Since the users are interested in the content rather than the source of the information, the information distribution is based on the named 'content' rather than numerically addressed hosts. For this, the intermediate nodes cache the information for respective content queries. When a mobile node requests for any information, the nearest host can answer for that query instead of sending the request packet all the way to the server and getting the information. While reducing the delays in fetching the required information, this mechanism also reduces the load on the server.

This section first presents the key pending challenges and open research issues in the field of SDVN. After discussing the challenges and open research issues, the ongoing research and solutions under development in this field are presented.

Key challenges in SDVN are as follows:

1. **Dynamic network topology and node mobility:** Vehicle mobility leads to constantly changing network topology and intermittent connectivity. This constant change in network topology and connectivity makes it difficult for the SDVN controller to manage network resources and maintain an accurate view of the topology. The SDVN controller needs to track node association and disassociation, gather information about network topology, maintain routes/routing tables, and compute appropriate routes for traffic forwarding purposes.
   To deal with this issue, researchers proposed routing principles in SDVN (Zhao et al., 2020). For example, a mobile vehicle sends an association request to the RSU/BS to access the controller, by using suitable a selection mechanism as proposed in (Correia, Boukerche & Meneguette, 2017; Zhu et al., 2015). The controller maintains the changes in network topology. A centralized or hybrid mode of route selection can be used. In the centralized route selection beacons are sent to the central controller while in hybrid mode, the SDVN controller instructs the RSUs that in turn instruct the vehicles about the routing policies to enforce. Based on the network topology, the routing and forwarding mechanisms can be classified into three categories namely centralized and hybrid, single-path and multi-path, beacon based and prediction based (Bozkaya & Canberk, 2015). While researchers have proposed numerous approaches to deal with the issues of dynamic network topology and routing in VNs, these solutions vary in terms of complexity, communication overhead,

scalability, and achieved quality of calculated routes such as available bandwidth, Signal-to-Noise Ratio (SNR) and Signal-to-Interference-Noise Ratio (SINR).

Some of the open research issues in this field are:

- Development of dedicated trajectory prediction algorithms.
- Reduction of communication overhead.
- Development of a framework for route selection and management.
- Development of routing algorithms to be run by the SDN controller.
- Application of AI to route computation by the SDN controller.
- Development of mechanisms to overcome failed routing instructions (e.g., broken routes considering node mobility).
- Development of multicast transmission schemes to be deployed in VNs.
- Security of routing protocols.

2. **Heterogeneous network:** VNs and V2X involve communications between devices of different characteristics. The participating entities may have been developed by different manufacturers and may support different features. The difference between the communicating nodes, because of their different characteristics, features, protocols, leads to numerous constraints that need to be addressed for seamless communication purposes (thereby avoiding service disruption). For short distance communications, nodes in VNs use Bluetooth, VLC, LIDAR, or sensor networking. For medium distance communications, the IEEE 802.11 based WAVE and DSRC protocols, low-power wide area network (LPWAN), or 3GPP-based C-V2X sidelink technology for V2V connectivity is used. Long distance communication is achieved using cellular 3GPP technology such as LTE or 5G-NR (5^{th} Generation New Radio). Fog, edge, and cloud computing supports remote data access and processing. The 5G-PPP (5^{th} Generation Public Private Partnership Group) is investigating 5G Automotive Vision to attain high data rates, better connectivity and frequent handoffs. All these technologies and protocols involved in successful and efficient communication in VNs vary in their characteristics and features. The heterogeneous radio interfaces on VN nodes find it difficult to interoperate. The future ITS communication platform will be a combination of diverse wireless communication technologies. While the incorporation of SDN relieves the network from the issue of vendor lock-in to some extent, the end nodes may still face challenges. Therefore, it is essential to standardize the communication technologies and protocols in VNs. Many researchers, manufacturers and organizations are working towards the development of standardized solutions for VNs (Mahmood, Zhang & Sheng, 2019). Researchers are working towards of the use of a centralized intelligence in coordination with local computation logics to overcome the single point of failure due to potential outage of centralized SDN controller (Zhu et al., 2016; Dey et al., 2016).

   Open research issues to overcome the challenge of heterogeneous networks are as follows:

   - Attain ubiquitous and seamless network connectivity.
   - Handover target selection, necessity and triggering condition estimation (that is, when should the handover take place or should be initiated).
   - Multi-hop routing over heterogeneous network technologies.
   - Node location maintenance and travel trajectory anticipation for handover purposes.

3. **Network Scalability:** The number of nodes/vehicles that will be part of the network at any given time is highly unpredictable due to the dynamicity of the network. The SDVN controller needs to constantly monitor the network and allocate network resources accordingly. Therefore, network resource management and data processing are the main challenges in scalable VNs. Researchers

who aim to address this challenge have developed AI/ML-based solutions to predict the node mobility and network density, so that network resources can be managed efficiently (Correia & Boukerche, 2017). In case the network infrastructure does not function properly due to overload or malfunctioning conditions, the SDVN controller needs to monitor such conditions, either allocate new resources or redirect traffic in order to maintain the adequate level of service quality (Smida et al., 2019).

Some of the open research challenges in this field are:

- Maintenance of network agility and responsiveness with scalability.
- Data offloading and load sharing when the amount of traffic increases.
- Network resource management based on prediction of node mobility and network density.
- Node position sensing and resource allocation.
- Interface sensing and radio resource management.

4. **Network interference and latency control:** VNs use wireless communication media that are prone to signal attenuation and interference. Wireless signals undergo multipath propagation leading to Inter Symbol Interference (ISI), Doppler effect, reflections, scattering, and diffraction. The vehicular communication quality is also challenged due to dense network deployment and heterogeneity, but also because of the difference between uplink/downlink transmission powers of vehicular nodes and RSUs, as well as possible restrictions on public/private network access leading to some interference.

   Although current technologies such as Multi Input Multi Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) are efficient enough to overcome these effects in wireless networks, the node mobility raises additional challenges in VNs. Efficient path and channel selection algorithms are developed to avoid interference. Dual Polarized Directional Antenna (DPDA) is proposed to reduce channel interference while enhancing network efficiency (Rinki, 2014). While Dual Polarization (DP) supports simultaneous transmission over vertical and horizontal polarizations, Directional Antenna (DA) thanks to its broader communication range compared to omnidirectional antenna (OA) reduces latency by reducing the number of intermediate hops in multi-hop communication (Sharma et al., 2016). The Dual Polarized Directional Antenna based Medium Access Control (DPDA-MAC) (Sharma et al, 2015a) and Dual Polarized Directional Antenna based Multipath Routing Protocol (DPDA-MRP) (Sharma et al., 2015b) describe protocols which have been proved to enhance network performance in MANETs thanks to increased throughput, Packet Delivery Ratio (PDR) and reduced latency; and these protocols can be implemented in VANETs as well. Some of the path and channel selection algorithms for VANETs are proposed in (Jang & Lee, 2010; Fazio, De Rango & Sottile, 2015).

   Some of the open research issues in this field are:

   - Intermittent connectivity and unstable bandwidth usage due to node mobility.
   - Channel state estimation in highly dynamic vehicular networks.
   - Directional beam steering with rapidly changing node location.
   - Enhancement of standardized cellular network architecture to support high mobility VNs.
   - Application of deep learning for channel state estimation and optimization.

5. **Network Security:** Network security still remains a significant problem in SDN-based architectures. As an SDN controller is a logically centralized entity, in case the controller is attacked, the whole network operation can be jeopardized. If the SDVN controller is compromised, the whole network can be affected. This issue can be carefully taken into account when exposing Application

Programming Interfaces (APIs). However, there is a lack of standard SDVN APIs, which makes controllers vulnerable to network security attacks (Akhunzada & Khan, 2017).

To overcome the failure of SDVN controllers, some research activities propose the use of primary and secondary network controllers. However, resiliency of SDN controllers still remains an open research challenge. While current research investigates how SDN-based networks can be more secure, in case of SDVN this remains a concern as a compromised controller can endanger human life. Apart from the SDN controller, vehicular nodes are vulnerable too. Electronic Control Units (ECUs) in an intelligent vehicle are exposed to attacks and tampering. Interfaces subject to attacks can be accessed through direct access, short- and long-range wireless communication. The On-Board Diagnostics (OBD) port and compact disc player give direct and largely unrestricted access to the in-vehicle communication network. Short-range wireless attack surfaces include remote keyless breach, Tire Pressure Monitoring System (TPMS), Bluetooth and Wi-Fi. The long-range wireless attacks often use satellite or AM/FM radio interfaces, as well as the cellular communication interfaces. Over The Air (OTA) updates are another major cause of attack in intelligent vehicles. Some of the prominent threats in VNs are MITM, DoS, DDoS, replay attack, bluejacking/bluebugging (sending unsolicited messages over Bluetooth), unauthorized control of vehicle parameters, collection of vehicle's private information, concealing location information, false alerts and tampering of ECU data blue. Some of the solutions proposed to mitigate these attacks are message encryption and authentication, firewalls, use of intrusion detection and prevention capabilities, domain isolation through gateways, secure boot runtime integrity, secure Machine-to-Machine (M2M) integration and secure key storage. Blockchain-based framework for VN security is presented in (Yahiatene et al., 2019). Usage of ML to detect security vulnerabilities and attacks is presented in (Tang et al., 2019).

Some of open research challenges in this area are:

- Standard northbound/southbound/eastbound/westbound APIs to address security vulnerabilities and attacks.
- Authentication codes (secure boot), run-time integrity protection and resource control (resource virtualization).
- Secure messaging and OTA updates.
- Solutions for firewalls, context-aware message filtering and Intrusion Detection System (IDS).
- Isolation of vulnerable interfaces such as Transmission Control Units (TCU) and OBD.
- D2D/M2M authentication solutions.

CONCLUSION

This chapter presents the role of SDN in VNs and the importance of SDVN. The SDVN use cases and related research present the vehicular application areas where SDN can be instrumental for proper VN design, delivery and operation. The chapter also discusses the ongoing research in this field.

The SDVN architecture is presented and roles of the SDVN application, control and data planes are discussed. The chapter outlines and discusses the research challenges and opportunities in the area of SDVN with the aim of investigating and presenting recent research advances in SDVN.

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KEY TERMS AND DEFINITIONS

Intelligent Transportation Systems (ITS): A amalgamation of contemporary information and communication technologies used for transportations and traffic management systems to efficiently monitor and manage transportation system and enhance their efficiency, safety, and sustainability.

Mobile Ad-hoc Networks (MANETs): A temporary and infrastructure-less network of mobile nodes, wherein the mobile nodes communicate when they are within communication range of each other. The nodes in a MANET can act as source, sink, or router.

Software-Defined Networking (SDN): A networking architecture that decouples network control and forwarding functions and enables the network control to become directly programmable.

Software-Defined Vehicular Networks (SDVN): A Software Defined Networking (SDN) based vehicular network that facilitates programmability of vehicular networks to deal with issues in routing, connectivity, heterogeneity, scalability, reliability, and security.

Vehicle-to-Everything (V2X): Communication between a vehicle and other parts of the traffic system such as other vehicles, infrastructure, Internetwork, cloud, pedestrians, grid, and devices.

Vehicular Ad-hoc Networks (VANETs): A temporary and infrastructure-less network of vehicles that communicate when they come within communication range of each other. Like in MANETs, the vehicles in VANETs can act as source, sink, or router.

Vehicular Communication: Comprises of a communication system and technologies that enable communication between vehicles, roadside units, and other components of a vehicular network.

Vehicular Networks: A network of vehicles, roadside infrastructure, internetwork, cloud, pedestrians, grid, and devices that communicate using wireless communication technologies.