DOI: 10.1109/ACCESS.2017.2671030

Received December 15, 2016, accepted January 25, 2017. Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.2671030

From Theory to Experimental Evaluation: Resource Management in Software-Defined Vehicular Networks

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This work was supported in part by FAPESP Grant 14/18482-4.

ABSTRACT Managing resources in dynamic vehicular environments is a tough task, which is becoming more challenging with the increased number of access technologies today available in connected cars (e.g., IEEE 802.11, LTE), in the variety of applications provided on the road (e.g., safety, traffic efficiency, and infotainment), in the amount of driving awareness/coordination required (e.g., local, context, and cooperative awareness), and in the level of automation toward zero-accident driving (e.g., platooning and autonomous driving). The open programmability and logically centralized control features of the software–defined networking (SDN) paradigm offer an attractive means to manage communication and networking resources in the vehicular environment and promise improved performance. In this paper, we enumerate the potentials of software-defined vehicular networks, analyze the need to rethink the traditional SDN approach from theoretical and practical standpoints when applied in this application context, and present an emulation approach based on the proposed *node car* architecture in Mininet-WiFi to showcase the applicability and some expected benefits of SDN in a selected use case scenario.

INDEX TERMS Vehicular ad hoc networks, V2X communication, software-defined networking, resource management, Mininet-WiFi.

I. INTRODUCTION

New-generation cars are becoming multi-faceted elements with high storage-processing capabilities, equipped with cameras, sensors, radars, and positioning devices [1], [2]. They will be connected through multiple radio access technologies, like Dedicated Short Range Communications (DSRC), IEEE 802.11 (a.k.a. Wi-Fi), cellular technologies such as Long Term Evolution (LTE) and its enhancements towards fifth-generation (5G) networks. Available radio interfaces allow vehicular on-board units (OBUs) to interact among each other (Vehicle-to-Vehicle, V2V), with nearby/remote stations and entities (Vehicle-to-Infrastructure, V2I), with vulnerable road users (Vehicle-to-Pedestrians, V2P). In short, vehicles are enabled to communicate with *everything*, according to the Vehicle-to-Everything (V2X) paradigm, that is seen as a key enabler for safer, greener, smarter, more connected and autonomous transport.

Connected cars will manage a wide plethora of applications, roughly classified as *safety* and *non-safety*. The former type of applications aims to improve road safety and traffic efficiency, making vehicles aware of road hazards (e.g., emergency brake light warning, stationary vehicle warning) or hidden objects (e.g., intersection collision warning); the latter one includes comfort and infotainment applications. There are, however, technological obstacles to be overcome before achieving large market penetration of connected cars. Most of them are related to the distributed and local control of vehicular communications that poorly copes with the guaranteed low delay and high reliability requirements in highly-dynamic topology environments.

The Software Defined Networking (SDN) paradigm [3], through control and data plane separation and centralized intelligence, is considered a key technology enabler to achieve flexible, programmable, and high-performing next-generation vehicular networks. SDN has been mainly conceived for carrier infrastructures, especially in data centers domains and access networks. Its application to Vehicular Ad-hoc NETworks (VANETs) has been proposed only in recent years. Since the pioneering work in [4], preliminary investigations, mainly at high architectural and theoretical level, have been proposed to show the potential of SDN to enhance resource management in VANETs [5]–[11]. On the other hand, practical implementations are missing that quantitatively evaluate to which extent SDN can bring benefits to VANETs, either by leveraging popular simulation frameworks, like Network Simulator (ns-2, ns-3), emulation tools like Mininet [12], or by deploying testbeds with switch boards running e.g., OpenvSwitch, and SDN controllers installed on personal computers.

This paper makes a step forward in the topic and differs from previous works in two main directions. Firstly, we debate how rethinking the traditional SDN approach to be applied in this challenging context. The analysis is not only meant to provide a survey of the most representative existing literature solutions, but to clearly pinpoint possible research directions addressed so far, plus our perspectives not yet tackled in the literature. Secondly, we describe the *node car* extension we conceived for a recent wireless SDN network emulator, Mininet-WiFi [13]. The latter one is a fork of the most popular Mininet platform, which supports emulated OpenFlow-enabled network devices, both switches and Wi-Fi Access Points (APs), interactions with real SDN controllers and devices, wireless medium and mobile user devices. The proposed extension is meant to bring the programmability of the SDN paradigm to multi-interface devices on board of vehicles. Such a contribution is also aimed to fill the gap in the evaluation platforms for SDN in the context of VANETS. Early evaluation results have been provided to showcase the potential benefits of SDN in managing a video streaming over multiple wireless interfaces, jointly relying on V2V and V2I communications.

The remainder of the work is organized as follows. Section II provides background information on VANETs and vehicular applications. Section III introduces SDN principles and then discusses the extensions for matching the vehicular environment peculiarities, through literature survey, whenever possible, and the authors' perspective, otherwise. Sections V and VI focus on the practical considerations and the conceived *node car* architecture implemented in the Mininet-WiFi emulation platform used for proof-of-concept validation of an SDN-driven VANETs use case scenario.

II. VANETs: A PRIMER

After more of a decade of research and deployment efforts, vehicular networking technologies are ready to be rolled-out and are catalyzing the interest of academia, telco and automotive industries, and standard development organizations.

IEEE 802.11 and its customization for vehicular connectivity in the 5.9 GHz band, i.e., the DSRC/WAVE (Wireless Access in Vehicular Environments) and the European Telecommunication Standard Institute (ETSI) Intelligent Transport Systems (ITS) station, is considered the *de-facto* standard for VANETs. Field-trials have successfully tested its performance to support a basic set of road-safety applications [14], and initiatives are currently running to demonstrate platooning and isolated cases of autonomous driving everywhere in the world.

In the meanwhile, the role of the 3rd Generation Partnership Program (3GPP) has been steadily and rapidly growing. Started with the support of telematics and infotainment services for connected cars, cellular networks are now noticeably involved at a much wider scope, with V2X as part of 3GPP LTE Release 14 [15], and with a clear roadmap for 5G networks to provide the ultra-high reliability and ultra-low latency demands of tomorrow V2X applications (e.g., autonomous driving).

Such communication technologies are demanded to support a plethora of vehicular applications with heterogeneous requirements (e.g., in terms of reliability, latency), getting more and more advanced and complex. The roadmap towards *accident-free* driving entails the evolution from road-safety to more complex applications such as *cooperative* driving (e.g., lane-merging assistance, platooning) that enable vehicles to control their driving pattern decisions based on prediction of what other vehicles will do, and *autonomous* driving, where vehicles exchange and synchronize driving trajectories among each other [14].

Non-safety applications encompass traditional infotainment and convenient services, like web browsing, social network and cloud computing access, video streaming, on line multi-player gaming, but also specific services conceived for the vehicular environment, e.g., remote vehicle diagnostics, fee notifications by electric vehicles (EV) charging stations, smart parking.

They will likely be a key driver for the market penetration of VANET technologies and their synergies with other vertical industries (e.g., smart grid, smart cities) and some of them will become more common as autonomous cars will get popular (e.g., multimedia access).

There are still many barriers to the widespread and successful deployment of vehicular networking technologies which impair the effective and efficient support of envisioned applications, which can be summarized as follows:

- the *distributed nature of inter-vehicle communication* forces vehicles to take decisions based only on their local perception of the surrounding environment, thus decisions can be suboptimal.
- *dynamic topologies and high channel fluctuations*, coupled with *high vehicle density* and *mobility* and *limited allocated spectrum* may result in inefficient network utilization, high interference, unbalanced traffic flow, poor reliability and scalability.
- *heterogeneous radio interfaces barely interoperate*. 3GPP and non-3GPP technologies typically work as stand-alone alternative solutions, with no options of boosting connectivity performance.
- protocols show *poor flexibility* and *adaptability* because they are either designed with a specific application in mind or provided with hard-wired parameters and configurations, not taking into account the

time- and spatial-varying environment/topology and diversified application requirements.

We firmly believe that vehicular networks as conceived today, at best, *just work*, and hence, there is wide room for improvements by leveraging novel concepts such as SDN which may revolutionize the way networks can be designed and operated.

III. SDN FOR VANETs: A THEORETICAL PERSPECTIVE

SDN has been emerging as a promising paradigm to control the network infrastructure in a centralized and programmable way. SDN overcomes the well-known limitations of traditional networks, where the *control plane* (that decides how to handle network traffic) and the *data plane* (that forwards traffic according to the decisions made by the control plane) are bundled inside the networking devices. SDN breaks the vertical integration by separating the control plane from the data plane. In doing so, network switches and routers become simple forwarding devices, and the control logic, which determines how traffic flows should be treated in the network, is implemented in a *logically centralized* controller that has a global view of the network [3].

The SDN controller tracks the status of the data plane elements and injects forwarding rules into them via a well-defined application programming interface (API), the so-called *Southbound Interface* (SBI). The most prominent SBI is OpenFlow (OF). On top of the controller, a common programming abstraction to the upper layers, i.e., the network applications, is provided by the *Northbound Interface* (NBI).

There is a wide consensus on the beneficial effects of extending SDN principles (flexibility, programmability, and centralized control) to manage networking and communication resources in vehicular networks, e.g., to optimize channel allocation and network selection and reduce interference in multi-channel, multi-radio environment, to improve packet routing decisions in multi-hop environments, to effectively handle mobility in high-speed scenarios.

In the following, we survey the main research directions addressed so far, and pinpoint further directions not yet tackled in the literature.

A. HIERARCHICAL AND HYBRID SDN CONTROL TO FACE REAL-TIME CONSTRAINTS

A fully centralized SDN architecture with a unique controller could not fit the ultra-low latency requirements of future vehicular applications, because of the huge exchange of status information between the controller and the controlled network elements. This may slow-down (or prevent) real-time control actions and complicate the controller design. A *hierarchical* organization of controllers can be a preferred solution, such as in [7], where a primary controller is responsible to maintain a global view of the network and secondary controllers are in charge of managing applications with stricter real-time constraints.

A *hybrid* control mode, where the SDN controller shares some tasks with local base stations (BSs) and Road-side Units (RSUs), is considered in [4] and [5]. The controller decides some generic abstract policy rules, which are enforced and customized at BSs and RSUs according to their local knowledge. To reduce the overhead incurred in tracking the quickly varying vehicle positions at the control plane, both direct status collection and estimation through trajectory prediction schemes are leveraged in [6].

B. EXTENDING THE SDN CONTROL TOWARDS OBUs

The most straightforward extension of SDN for VANETs is to make RSUs SDN-enabled [4], [5], e.g., programmable by a Controller like other OpenFlow switches. In addition, the Controller scope can be extended to OBUs, which can act as end-users and can be abstracted as forwarding elements belonging to the data plane [4]–[6] just as RSUs and other infrastructure nodes do. Hence, OBUs may be triggered by the Controller to perform actions, e.g., for multi-hop V2V data dissemination.

C. BROADENING THE SDN SCOPE BEYOND PACKET FORWARDING

SDN has been initially conceived to dynamically adapt forwarding decisions by leveraging information collected by the SDN controller from multiple sources. Indeed, network utilization and communication reliability can be improved by setting up multiple redundant paths to satisfy multicast flow requirements, e.g., for surveillance purpose [4].

In vehicular environments, an SDN controller with global network view can help to control other functions rather than forwarding, e.g., setting the transmission power levels to control interference under variable vehicle density [4], [6]. Other non-routing related functions that could get improved performance in software-defined VANETs are discussed in the remainder of this subsection.

1) CONGESTION CONTROL

In traditional VANETs, decisions like setting the transmission parameters, such as the data rate, the transmission power, the inter-packet generation interval, are either hard coded or taken in an autonomous manner by vehicles, based on local information collected in the one-hop or two-hop neighborhood. With SDN running into the game, the performance would significantly improve, being it based on non-local only knowledge. For example, the critical decentralized congestion control (DCC) [14] would significantly benefit from channel load estimations taken by multiple vehicles and processed by the controller before configuring the transmission parameters of each vehicle.

2) MULTI-RADIO MULTI-CHANNEL RESOURCE ASSIGNMENT

In multi-radio OBUs the operating channel to be assigned to a given radio interface, and the type of data traffic to be delivered on each channel can be dynamically decided by the controller, according to e.g., the interference level and the data priority, with potentially high improvement in performance of the medium access control protocol (MAC) [4], [6].

3) HETEROGENEOUS ACCESS TECHNOLOGIES

Multi-interface vehicular devices require widening the scope of SDN to multiple communication technologies available in VANETs. The instructions of the controller may regard the selection of the access technology (e.g., LTE, LTE Direct, DSRC) at a given time. Different technologies can be assigned to the control and the data plane (in [4] and [5], respectively, LTE/WiMax and Wi-Fi). An heterogeneous data plane is considered in [6] and [7]. In [7] the Cloud-Radio Access Network (C-RAN) technology is exploited to flexibly shape the connectivity offered by a given BS, e.g., according to the measured traffic load and service requirements.

4) VIRTUAL MAC

The recent advancements in virtualization techniques and, in particular, in the MAC protocol design, will allow the SDN controller to instruct a given RSU/OBU for loading the proper MAC instance, e.g. Time Division Multiple Access (TDMA), Carrier-sense Multiple Access (CSMA/CA), on a given channel, to meet the specific demands of some vehicular applications in given scenarios at a given time. For instance, TDMA is better suited to match the ultra-low latency and ultra-high reliability requirements of autonomous driving applications.

D. SEMANTIC-RICH SDN RULES DEFINITION

In VANETs, packets forwarding may be driven by the vehicleâĂŹs positions rather than the vehicleâĂŹs MAC/IP addresses [6]. This is the case of *GeoNetworking* protocols that support message dissemination based on geographical positions. In [10] the SDN controller tracks the RSU positions and the geographical scope of a packet, and instructs switches to forward packets from vehicles to multiple RSUs, which in their turn disseminate messages in the destination area.

E. PUSHING SDN BEYOND NETWORKING AND COMMUNICATIONS MANAGEMENT

The SDN philosophy can be extended to configure more than only networking (e.g., forwarding paths) and communication resources (e.g., channel bandwidth, radio resource blocks) in RSUs and vehicles. Indeed, cloud-like resources, such as computing and storage resources, can be configured in each controlled node.

In accordance to the fog/mobile edge computing paradigms, RSUs and cellular BSs, hosting micro-data centers, can offer localized services. In [8] SDN is used to dynamically reconfigure service deployment (e.g., by migrating Virtual Machines) and related data forwarding information, to satisfy the vehicles demands. Similarly, the SDN controller orchestrates cloud-like resources in RSUs and BSs. In [7], the resources of OBUs in a micro cloud are managed through SDN, along with local and remote cloud resources.

In [16] a controller in the backhaul, predicting vehicles' trajectories and content requests, is in charge of defining which content chunks should be located at edge nodes to serve the requests of passing by vehicles in order to reduce the backhaul overhead and the content availability.

F. BEYOND IP PROTOCOLS

Information-centric networking (ICN) solutions are gaining momentum as complementary/alternative networking technologies to IP in vehicular environments [17]. The main ICN tenets, i.e., name-based communication and in-network caching, perfectly fit the demands of time-based and spatially-relevant contents that are requested by vehicles regardless of their provenance. Di Maio *et al.* [9] describe how SDN can support ICN by coordinating caching strategies, packet forwarding decisions and policies, which are typically managed in a distributed manner.

G. NETWORK SLICING SUPPORT

Network slicing leverages virtualization techniques to support different services with heterogeneous requirements over a shared physical network infrastructure. With SDN, slicing can be software implemented, so fitting the dynamic vehicular environment. Thanks to its global view, SDN can allow multiple applications to be delivered in an isolated manner, while guaranteeing their performance requirements, e.g., by leveraging different interfaces/channels, configuring disjoint routing paths, filtering traffic classes at some intermediate nodes [4], [6].

H. SECURITY SUPPORT

The usage of SDN is expected to be beneficial also to build adequate countermeasures against security and privacy issues affecting vehicular applications [11], [18]. Thanks to its intelligence and centralized network view, an SDN controller could perform anomaly detection based on traffic analysis of the data plane elements by identifying potential attacks, and isolate malicious or infected nodes accordingly. Moreover, as proposed in [11], the SDN controller can coordinate a trust-based authorization scheme and give the authorization to an intermediate node to act as a relay, according to its reputation, as advertised by the community. A similar approach is followed in [18]. Such schemes may be particularly crucial for the dissemination of safety-critical emergency data.

I. LESSONS LEARNT

From the conducted analysis it clearly emerges that, when applied to VANETs, the SDN paradigm requires proper extensions and modifications to enrich its scope beyond its original design, much more than in other wireless networks.

Figure 1 graphically sketches a high-level reference architecture summarizing the main debated findings and perspectives on software-defined VANETs. The data plane hosts not only switches, RSUs, and cellular network nodes, but also vehicular devices. At the control plane different types of controllers may be included, e.g., legacy (OpenFlow) ones, and others specifically conceived to enforce the policies required by the applications at the upper plane. The latter ones may be classified according to the specific target: *(i)* adapting and configuring communication/radio access settings/protocols, *(ii)* driving routing and forwarding decisions, either IP-based or non-IP based networking schemes (e.g., geocasting and ICN), *(iii)* enforcing security policies, *(iv)* supporting vertical

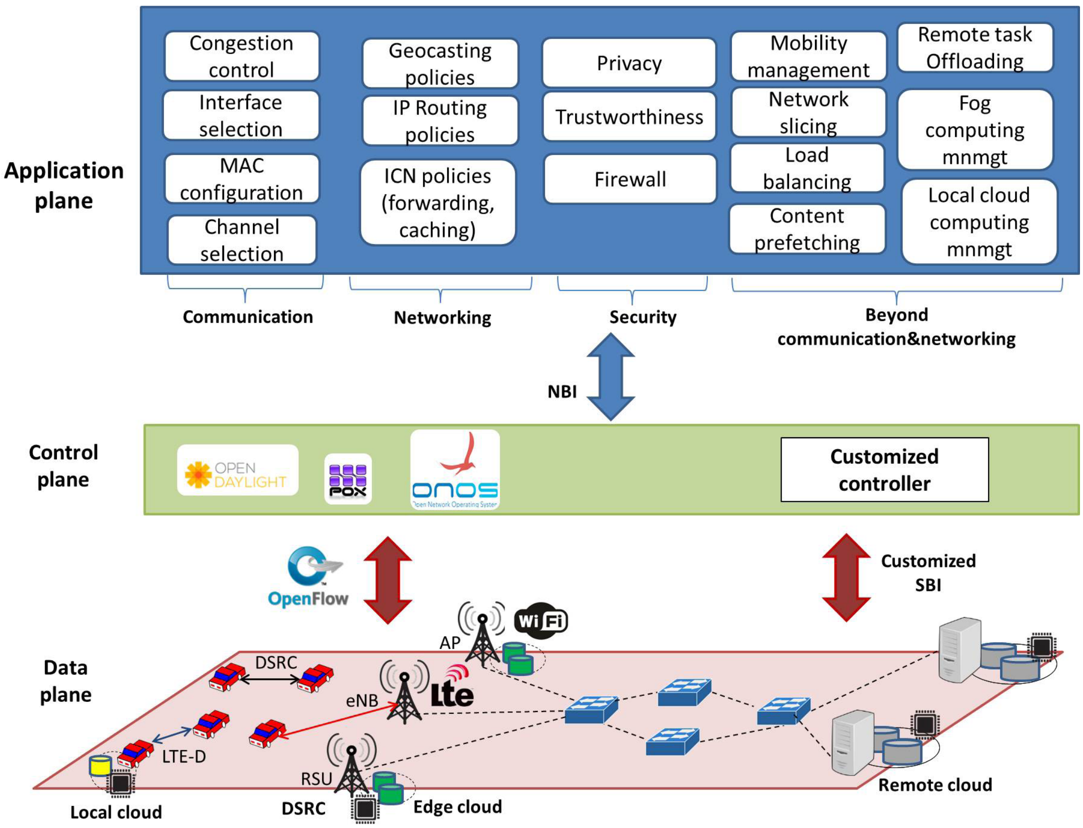

FIGURE 1. Reference Software-Defined Vehicular Networks architecture.

management of resource applications for improved content delivery, network utilization and orchestration of computing resources.

IV. GOING PRACTICAL WITH MININET-WIFI NODE CAR

Multifaceted possibilities of applying SDN principles to VANETs are being discussed but they often ignore practical considerations that appear when prototyping, experimenting, and in real deployment. Critical issues that emerge when trying to put SDN-augmented VANETs into practice include (*i*) full-featured OpenFlow protocol stacks; (*ii*) implementation of wireless and experimenter extensions; (*iii*) in-band and out-of-band deployment considerations and SDN control choice (e.g., protocol plug-ins, core services, northbound APIs and east/west interfaces); (*iv*) realistic experimental evaluation (e.g., real/deployable code, network conditions, mobility, physical-virtual integration, overall reproducibility), among others.

In order to allow realistic research in arbitrary SDN-enabled VANET scenarios, we have designed and implemented a suitable node *car* architecture in Mininet-WiFi [13], an OpenFlow-enabled network emulator based on lightweight virtualization (Linux LXC containers) forked from Mininet to add wireless channel emulation and mobility support.

The proposed *node car* architecture consists of the combination of two nodes already available in Mininet-WiFi: *station* and *switch*, that, respectively, emulate end-devices and switches/Wi-Fi APs. V2I communications, i.e., between *Cars* and *RSUs* or cellular base stations, *eNodeBs*, are established through host nodes providing *Leaf1* wireless interfaces, in the so-called *wireless-v2i* mode. Communications among *Cars* (i.e., V2V), instead, are established using hosts with *Leaf2* wireless interfaces in the so-called *wireless-v2v* mode. A *Root-Spine Switch* is introduced in the node car architecture to attach up to *n* Leaf hosts (LeafN) with network space isolated interfaces.

The advantage of the proposed architecture is empowering the researcher to define the vehicular data traffic behaviour at the Root-Spine Switch and unlocking any approach of OpenFlow control. From the user perspective, any application must be run in Leaf1 and to reach other cars through the wireless v2v interface the packets cross the Root-Spine Switch allowing programmable flow management by an SDN controller.

Multiple wireless interfaces can be supported at Leaf1 to communicate with the infrastructure, for example, LTE and Wi-Fi, and further wireless interfaces can be present at other Leaf nodes. As illustrated in Fig. 2, the node car architecture allows SDN programmability using all available interfaces at

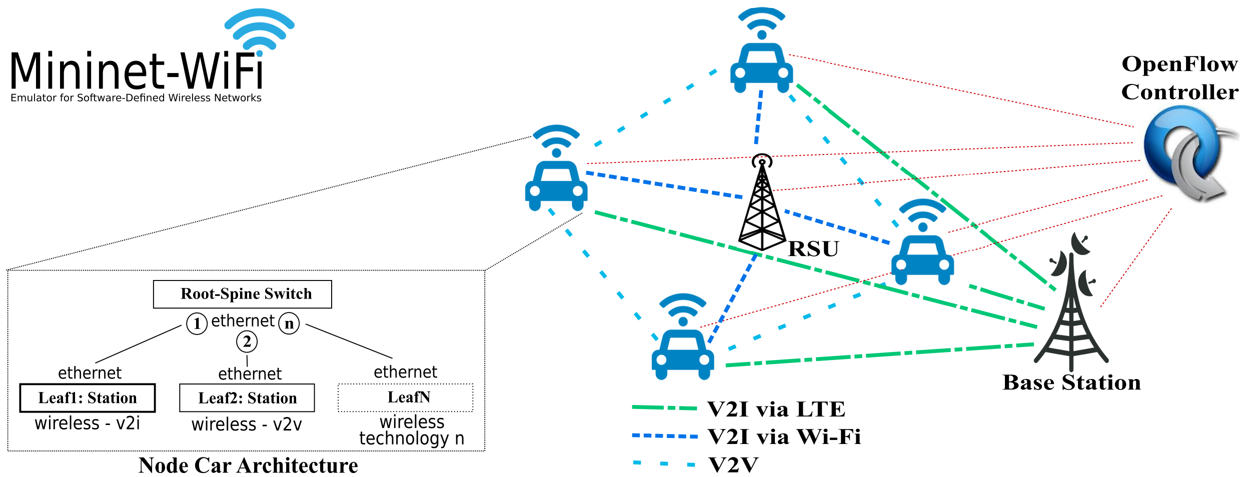

FIGURE 2. **Overview of the devised OpenFlow programmability in the VANETs scenario and the node car architecture in Mininet-WiFi.**

the same time, without introducing constraints on the choice of centralized or distributed OF controllers.

V. PROOF-OF-CONCEPT EXPERIMENT

For the sake of validating the conceived node car architecture, we prototyped a proof-of-concept to experiment on resilient resource aggregating mechanisms in a SDN-based VANET scenario where the SDN/OpenFlow controller is responsible for managing all emulated nodes (*Cars*, *RSUs* and *eNodeBs*). The use case features a car (*car0* in Fig. 3) streaming video during one minute to an operation center for safety, traffic monitoring and/or surveillance purposes (e.g., the video recording of an accident area, the recording of the surrounding area as captured from the on-board camera to be shared with a cloud application for tele-operated or cloud-assisted autonomous driving purposes). In the most general case, the operation center can be either located at a remote location or hosted at the edge of the network, as in the emulated case. In our demonstration, the OF controller selects the most appropriate wireless technology(ies) of *car0* to transmit the video stream (see Figure 3).

A. CAR MOBILITY

In order to emulate the mobility of the cars in a controlled (script-based) fashion, static flows are installed and modified in the wired aggregation switch which has its ports wired to the different wireless access points. During the first phase of the experiment (Fig. 3(a)), *car0* acts as a server transmitting a live video stream to the safety center client attached to port 4 of the aggregation switch, and the OF controller exploits the 3-hops V2V path from *car0* to *car3* resulting in the video stream arriving to the safety station (client) through *eNodeB1*. Afterwards, in the second phase (Fig. 3(b)), all the cars move around, *car0* leaves the coverage of the *eNodeB1*, the OF controller detects this new condition, thus it lets *car0* connect to both *RSU1* and *eNodeB2* and the live video stream is sent through ports 2 and 3 of the aggregation switch. Finally, during the third phase of the experiment (Fig. 3(c)), all the cars keep moving around and *RSU1* is out-of-range of *car0*, the latter one is only connected with *eNodeB2* and the live video is sent only through port number 2 of the switch.

B. NETWORK PERFORMANCE

Figure 4 reports the number of exchanged packets sent from the car and received by the wired client and the throughput measured during the experiment. As we can observe, the amount of received data varies as the OF controller chooses the most appropriate wireless technologies and network paths exploiting V2V and V2I connectivity where possible. We can notice that, during phase 2, the client receives a larger number of packets, since the car sends the live video stream simultaneously through *RSU1* and *eNodeB2*.

C. CONTROLLED EXPERIMENTATION AND REPRODUCIBILITY

The script responsible for installing static flows contains pre-programmed instructions to realize *Phases 1, 2* and *3*.[1] Since Mininet-WiFi provides vehicular mobility support (including the coupling with the realistic SUMO mobility patterns generator [19]), the experiment can be better defined by specifying the mobility models of choice and having an SDN application managing the network operations based on the position of the nodes, the quality of the radio signal, and so on. A video clip[2] available on the web for anyone who wants to reproduce this PoC illustrates all the phases commented before and also the results presented in Figure 4.

D. DISCUSSION

In order to keep the PoC simple, only one controller is used despite the interesting trade-offs of having multiple controllers for different purposes, for instance: *(a)* offloading requirements, or *(b)* allow specialized controllers aware of specific wireless technologies. One important issue related

[1] https://github.com/intrig-unicamp/mininet-wifi/tree/master/demos/vanet.py

[2] https://www.youtube.com/watch?v=kO3O9EwrP_s

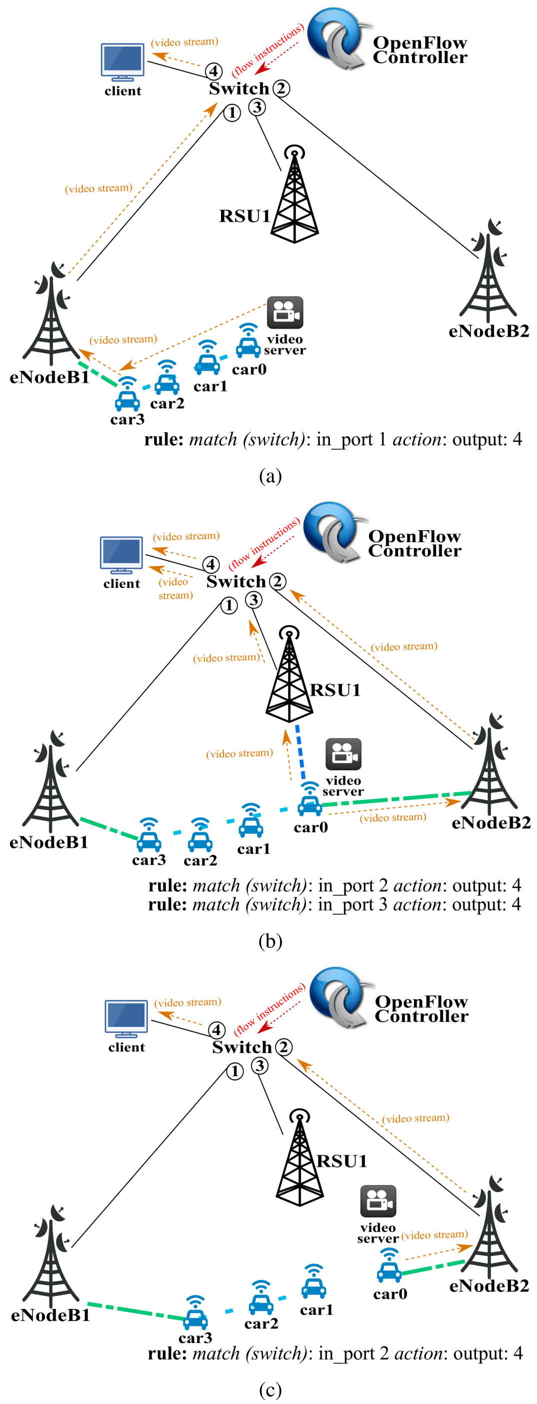

FIGURE 3. Flow management performed in Mininet-WiFi by an SDN controller in the reference use case. (a) Phase 1. (b) Phase 2. (c) Phase 3.

to the OF control channel touches the in-band and/or out-of-band mode of operation. While the former uses the same path (i.e., same network) for both data traffic and control traffic, the latter one does not. Although the PoC experiment does not take into account the most appropriate choice of the controller deployment, initial insights suggest that V2I communication can be established through out-of-band OF controllers, while V2V communications should be in-band. In addition, further considerations are required regarding fall-back mechanisms

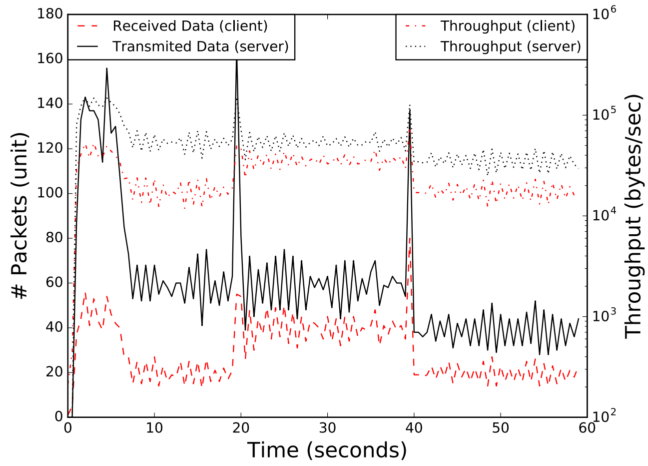

FIGURE 4. Observed network performance obtained during the live video stream from car0 to the client.

to conventional operations capable of providing minimum performance once connection to the controller is lost or disrupted [4], [6], [8]. Those are some of the critical practical aspects that can be experimentally evaluated with the proposed node car architecture in Mininet-WiFi.

VI. CONCLUSIONS AND FUTURE WORK

Software-Defined Networking (SDN) has been increasingly extending its footprint beyond single-domain, wired managed networks (e.g., intranets, data centers) to wireless dynamic environments such as VANETs. While the SDN benefits are sound in theory, practical validation is a next step that commonly includes unanticipated critical implementation and deployment issues. Following the fast prototyping and experimentation approach of the Mininet SDN emulator, in this work we are making some practical steps ahead useful to the wider research efforts on SDN for VANETS by extending Mininet-WiFi to include a car node that allows rich and realistic experimentation options. For strawman validation purposes, we present a proof of concept experiment where SDN/OpenFlow programmability allows new degrees of wireless and wired resource management in dynamic vehicular environments.

Our ongoing work includes more larger and more complex scenarios with OpenFlow wireless extensions under discussion in the Open Networking Foundation (ONF) Wireless and Mobile Working Group (WMWG) for diverse configuration, deployment, and algorithmic options to realistically evaluate the actual potential of SDN in wireless realms, including hybrid physical-virtual experimental environments [20].

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