VIP-WAVE: On the Feasibility of IP Communications in 802.11p Vehicular Networks

Sandra Céspedes, *Student Member, IEEE*, Ning Lu, *Student Member, IEEE*, and
Xuemin (Sherman) Shen, *Fellow, IEEE*

***Abstract*—Vehicular communication networks, such as the 802.11p and Wireless Access in Vehicular Environments (WAVE) technologies, are becoming a fundamental platform for providing real-time access to safety and entertainment information. In particular, infotainment applications and, consequently, IP-based communications, are key to leverage market penetration and deployment costs of the 802.11p/WAVE network. However, the operation and performance of IP in 802.11p/WAVE are still unclear as the WAVE standard guidelines for being IP compliant are rather minimal. This paper studies the 802.11p/WAVE standard and its limitations for the support of infrastructure-based IP applications, and proposes the Vehicular IP in WAVE (VIP-WAVE) framework. VIP-WAVE defines the IP configuration for extended and non-extended IP services, and a mobility management scheme supported by Proxy Mobile IPv6 over WAVE. It also exploits multi-hop communications to improve the network performance along roads with different levels of infrastructure presence. Furthermore, an analytical model considering mobility, handoff delays, collisions, and channel conditions is developed for evaluating the performance of IP communications in WAVE. Extensive simulations are performed to demonstrate the accuracy of our analytical model and the effectiveness of VIP-WAVE in making feasible the deployment of IP applications in the vehicular network.**

***Index Terms*—Internet protocol (IP), multi-hop networks, Proxy Mobile IPv6 (PMIP), vehicle to infrastructure (V2I), vehicular networks, Wireless Access in Vehicular Environments (WAVE), 802.11p.**

I. Introduction

THE TECHNOLOGIES and standards that allow for interoperable and seamless communication systems in the automotive industry have been intensively developed over the last decade. Such communication systems are meant to enable the deployment of safety and emergency services, as well as informational and entertainment applications. In addition, communications in the vehicular network are to be established in all possible directions: among vehicles [i.e., vehicle-to-vehicle (V2V)], among vehicles and the infrastructure [i.e., vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V)], and eventually among vehicles and other devices.

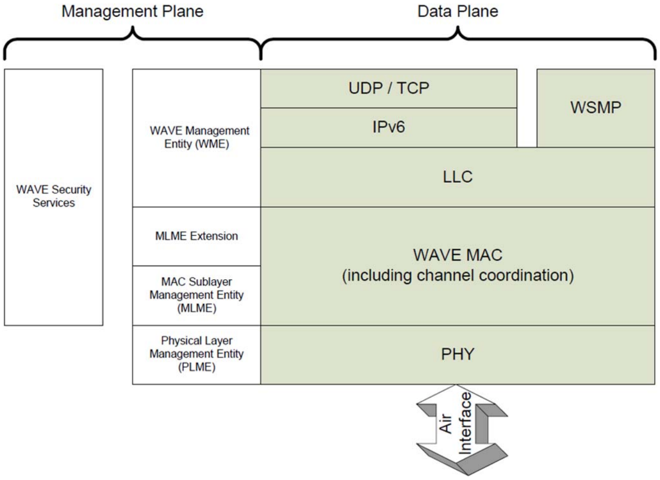


Fig. 1. WAVE stack of protocols as defined in IEEE 1609.4-2010 [5].

Under this perspective, existent radio access networks such as cellular (e.g., GSM/GPRS and UMTS) and WiFi may be employed to enable vehicular communications [1], [2]. Moreover, commercial products are already venturing in the transportation market with solutions that enable drive-thru Internet access over existent networks [3]. However, the strict latency requirement for safety-oriented and emergency communications has resulted in the definition of the IEEE 802.11p and the Wireless Access in Vehicular Environments (WAVE) technologies and standards [4]–[6], which together define a low-latency alternative network for vehicular communications.

Although the main focus of WAVE has been the effective, secure, and timely delivery of safety related information, the deployment of infotainment applications certainly would help accelerate the market penetration and leverage the deployment costs of the vehicular network. Thus, in order to support infotainment traffic, WAVE also includes IPv6 and transport protocols such as TCP and UDP. By supporting IP-based communications, the vehicular network may use well-known IP-based technologies and readily be connected to other IP-based networks.

Fig. 1 shows the WAVE stack of protocols. The standard specifies two network layer data services: 1) WAVE Short Message Protocol (WSMP), which has been optimized for low latency communications, and 2) IPv6. Although the operation of WSMP has been fully specified in the IEEE 1609.3 standard,

---

Manuscript received February 24, 2012; revised May 16, 2012; accepted June 13, 2012. This work was supported in part by the Bell Scholarship, Ontario, Canada, and in part by Icesi University, Cali, Colombia. The Associate Editor for this paper was F.-Y. Wang.

S. Céspedes is with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada, and also with the Department of Information and Communications Technology, Icesi University, Cali, Colombia (e-mail: slcesped@uwaterloo.ca).

N. Lu and X. Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: n7lu@uwaterloo.ca; sshen@uwaterloo.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TITS.2012.2206387

it has been found that recommendations for the operation of IPv6 over WAVE are rather minimal [7]. Protocols in which the operation of IPv6 relies for addressing configuration and IP-to-link-layer address translation (e.g., the Neighbor Discovery protocol) are not recommended in the standard.

Additionally, IPv6 works under certain assumptions for the link model that do not necessarily hold in WAVE. For instance, IPv6 assumes symmetry in connectivity among neighboring interfaces. However, interference and different levels of transmission power may cause unidirectional links to appear in WAVE, which may severely affect IPv6's effectiveness in its operation. Furthermore, interference and mobility may cause inability to communicate with other WAVE devices unless relaying is employed. For example, there are cases in which the Road Side Unit (RSU) (i.e., the point of attachment to the infrastructure) has to deliver configuration information for IPv6 to a vehicle through a multi-hop path. However, the multi-hop support of infrastructure-based IP services is not currently permitted in the IEEE 1609.3 standard.

With many open operational aspects of IPv6, providing access to infrastructure-based IP applications, such as assisted parking, route management, and eventually Internet access, becomes a challenging task in 802.11p/WAVE networks. Previous works evaluate the performance of IP-based applications in I2V vehicular environments, but they often employ traditional 802.11 b/g technologies that do not resemble the intricacies of 802.11p/WAVE for IP communications. In [7], the limitations of the operation of IPv6 in 802.11p/WAVE have also been identified, but they can only be used as guidelines regarding the incompatibilities of the two technologies.

Therefore, we address the problem of I2V/V2I IP-based communications in 802.11p/WAVE networks by providing the Vehicular IP in WAVE (VIP-WAVE) framework. Our main contributions are summarized as follows:

1) to design an efficient mechanism for the assignment, maintenance, and duplicate detection of IPv6 global addresses in WAVE devices, which is customized according to the type of user service;
2) to support the per-application and on-demand IP mobility for seamless infrastructure-based communications;
3) to design a relay detection and routing mechanism for the delivery of IP packets through one-hop and two-hop communications in 802.11p/WAVE networks.

Furthermore, we develop an analytical model for evaluating and comparing the throughput performance of the standard WAVE and the proposed VIP-WAVE. The model integrates the vehicle's mobility and considers the delays due to handoff, the packet collisions due to the media access control (MAC) layer conditions, and the connectivity probability from vehicles to the infrastructure according to the channel model.

The remainder of this paper is organized as follows. Section II discusses the 802.11p/WAVE standard and reviews the previous works. Section III describes our network model and introduces the VIP-WAVE framework and its extensions for the support of multi-hop communications. Section IV presents the proposed analytical model. The performance evaluation of our framework is presented in Section V. Concluding remarks are provided in Section VI.

II. RELATED WORK

In this section, we present the main concepts described in the 802.11p/WAVE standards that are relevant for the transmission of data frames and for the operation of IP-based services. We also describe previous works dedicated to the support of IP-based communications in 802.11p/WAVE networks.

A. 802.11p/WAVE Standards

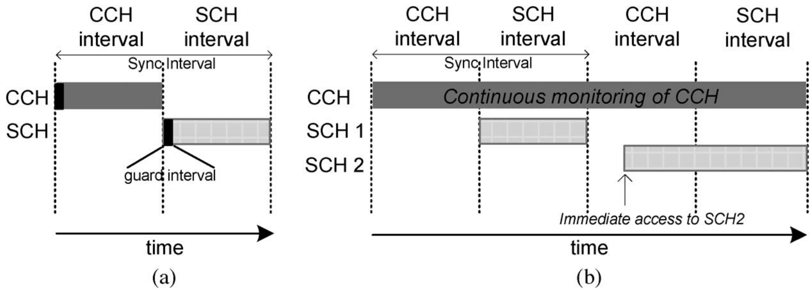
The 802.11p technology works in the 5.9-GHz frequency band and employs orthogonal frequency-division multiplexing modulation. It also employs carrier sense multiple access with collision avoidance (CSMA/CA) as the fundamental access method to the wireless media. The MAC layer of 802.11p includes the 802.11e enhanced distributed channel access (EDCA) function to manage access categories and priorities.

On the other hand, the WAVE standards, namely, 1609.4-2010 [5] and 1609.3-2010 [6], define the medium-access channel capabilities for multichannel operation, and the management and data delivery services between WAVE devices. In [5], the WAVE frequency spectrum is divided into one control channel (CCH) and six service channels (SCHs), each with 10 MHz bandwidth. In addition, each channel has its own set of access categories and its own instance of the 802.11p MAC layer.

Among the different types of frames that can be exchanged in WAVE, management frames can be transmitted in either CCH or SCH. Conversely, data frames (i.e., WSMP and IPv6 data frames) should be transmitted in SCH, although WSMP frames are also allowed in the CCH. Furthermore, the 802.11p radios can be single-physical layer (single-PHY) or multiple-physical layer (multi-PHY). The former means the radio is able to exchange information only in one single channel at all times; therefore, a single-PHY has to continuously switch between CCH and SCHs every certain time (the default is 50 ms). The latter indicates the radio is able to monitor the CCH while at the same time it can exchange data in one or more SCHs. Examples of single-PHY and multi-PHY radios accessing the channels are illustrated in Fig. 2.

The 1609.3 standard for networking services provides more details regarding the support of IP communications. It specifies as mandatory the support of IPv6 link-local, global, and multicast addresses in WAVE devices. Regarding the IP configuration, it indicates that link-local addresses should be derived locally, and WAVE devices should accept traffic directed to well-known IPv6 multicast addresses (e.g., all-nodes multicast address). It also states that "WAVE devices may implement any Internet Engineering Task Force (IETF) protocol"; however, it does not specify the operation conditions for the Neighbor Discovery (ND) for IPv6 protocol [8].

According to [6], the announcement of IP services takes place in the Wave Service Advertisement (WSA) management frame. The WAVE device announcing the service takes the role



(a) (b)

Fig. 2. Multichannel synchronization in WAVE. (a) Single-PHY channel access. (b) Multi-PHY channel access.

of “provider,” whereas the one receiving the WSA and indicating interest in the service takes the role of “user.” Each WSA includes 0 to 32 `ServiceInfo` segments, 0 to 32 `ChannelInfo` segments, and up to one `WaveRoutingAdvertisement(WRA)` segment. A `ServiceInfo` includes the definition of the service, the provider information (including its IP address if it is an IP service), the Received Channel Power Indicator (RCPI) level (dBm) recommended to accept the service (also known as the RCPI threshold), and the index for the `ChannelInfo` segment in the WSA that corresponds to the announced service. A `ChannelInfo` includes the service transmission characteristics (e.g., Tx power and data rate), the channel number, and the type of access in the SCH (i.e., continuous access or alternating access between SCH and CCH).

Similarly, if the WSA has at least one `ServiceInfo` segment for an IP service, it should also include a `WRA` for global IPv6 addressing configuration and Internetwork connectivity. A `WRA` segment includes the IP prefix, prefix length, default gateway, domain name system, and router lifetime, among other extension fields relevant for IP configuration at the WAVE user’s side. Once the WAVE user receives a WSA with an announced IP service of its interest, it calculates a global IP address by means of stateless configuration, based on the IP prefix received in the `WRA` segment and its own MAC address. After the configuration, the WAVE user is ready to start consuming the service. `WRA`s are meant to replace the standard ND protocol as a means to minimize the overhead and latency associated with such a protocol.

From the described operation of IP services in 802.11p/WAVE networks, one can identify the following limitations.

Lack of Duplicate Address Detection (DAD) Mechanism: Given the broadcast nature of WSA messages, a WAVE user interested in a specific IP service is allocated with the same IP prefix of all other users subscribing to any other IP service announced in the same WSA. On the one hand, that forces nodes to perform some kind of DAD procedure to guarantee the uniqueness of IP addresses among all users. The need for DAD comes mainly from the fact that WAVE devices may support readdressing to provide pseudonymity. Therefore, a MAC address may be changed at any moment and be randomly generated, which would increase the chances of collisions for autoconfigured IP addresses based on MAC addresses. Nonetheless, as we mentioned before, the ND operation, which includes the standard DAD procedure for IPv6, is not recommended in WAVE.

On the other hand, suppose the infrastructure provides Internet access or route management services. These are examples of extended IP services that are provided through the entire 802.11p/WAVE network, and are continuously announced by all the RSUs. Thus, even if a WAVE device actually performs DAD and confirms the uniqueness of its IP address among other neighboring users, the DAD will be invalidated as soon as the vehicle moves to the area of coverage of a different RSU, since the set of neighbors will also change. Furthermore, the DAD will be invalidated when the WAVE user switches to a different SCH to consume another service for which the same `WRA` has been announced.

Lack of Seamless Communications for Extended Services: Suppose the DAD problem is alleviated by having each RSU to advertise a unique set of IP prefixes among all the other RSUs. Then, the IP address uniqueness may be guaranteed at the RSU service area level. Although this solution would work for non-extended services, it would cause breakage of extended services, because when a user moves its connection to a different RSU, it receives a different IP addressing configuration. Therefore, transport layer sessions will have to be reset, and service disruption will be experienced as a result of the reconfiguration.

Lack of Support for Multi-Hop Communications: The current standard allows for a WAVE user to consume infrastructure-based IP services only if there is a direct connection between RSU (i.e., WAVE provider) and WAVE user. We consider such condition as an undesired limitation of the 802.11p/WAVE standards. Vehicular networks experience highly variable channel conditions due to mobility, obstacles, and interference. Therefore, it is desirable to take advantage of intermediary WAVE devices to relay packets from/to the infrastructure. In this way, access to the IP services could be extended further than one-hop connections, when there are WAVE users that do not directly hear the RSU. In addition, service could be provided to users that do hear the RSU but with a signal level below the one recommended by the RCPI threshold.

Extensive research has shown that mobile networks may benefit from multi-hop communications in terms of improving the network capacity and throughput [9]. Moreover, by serving as relays, nodes may obtain benefits from the network, like earning credits that reward them for their relay services [10]. Following that approach, other standards for vehicular communications have already considered the support of IPv6 multi-hop communications by means of sub-IP geo-routing [11].

B. *Previous Works*

IP becomes a natural solution for providing addressing services in WAVE and for enabling access to existent IP networks (e.g., the Internet), legacy applications, and innovative services. Therefore, the IP addressing configuration in vehicular networks has been further investigated in numerous studies [12]–[14]. While these studies enable IP configuration in moving vehicles, they are often limited to guarantee uniqueness in a specific area (e.g., around the leading vehicle acting as DHCP server [12], around the service area of RSU [13], or around a specific lane [14]). As a result, they limit the deployment of extended IP services and seamless communications in 802.11p/WAVE. Instead, we address this limitation by designing an IP addressing scheme for 802.11p/WAVE that employs a differentiated treatment for location-dependant and extended services in a way that it does not overload the network and at the same time guarantees uniqueness throughout the entire network.

In terms of mobility management, host mobility solutions for vehicular networks, based on the Network Mobility (NEMO) Basic Support Protocol, are proposed and evaluated in [15]–[18]. Baldessari *et al.* [15] define a MANET-centric solution that exploits multi-hop communications so that each vehicle is treated as a NEMO mobile router. Prakash *et al.* [16] propose a vehicle-assisted cross-layer handover scheme for vehicles to help relay signaling and data packets of a handover vehicle. In [17], on the other hand, vehicular clusters are employed so that cluster heads are in charge of the IP mobility for other vehicles. A survey on NEMO-based solutions can be found in [18]. Different from the aforementioned works, network-based mobility with Proxy Mobile IPv6 (PMIP) has been proposed in [19] and [20]. Soto *et al.* [19] enable mobility for broadband Internet access to be provided in a transparent way in automotive scenarios, whereas Lee *et al.* [20] propose a set of network mobility support protocols for Intelligent Transport Systems.

In general, those schemes reduce the handover delay and improve the throughput in vehicular networks. However, none of them specifically consider the use of 802.11p for infrastructure-based communications. Instead, they employ a general 802.11 network for connectivity to the infrastructure or theoretical performance evaluations. In our work, we select the network-based mobility approach since it confines the signaling overhead at the infrastructure side, and it does not require a mobility management protocol to be included in the on-board unit (OBU) stack (illustrated in Fig. 1). Furthermore, we adapt the signaling and movement detection mechanisms required for mobility management in a way that WAVE's CCH does not suffer from excessive overhead or congestion. Thus, we propose a customized mobility management mechanism tailored to the characteristics of 802.11p/WAVE networks.

Our premise of extending the network coverage in areas with different levels of infrastructure presence leads to a proposal for multi-hop communications. Employing intermediate nodes to extend the network coverage and to improve performance has previously been investigated in the context of vehicular networks [9]–[11]. We take the advantage from the findings of these works and further define the relaying services in 802.11p/WAVE by considering the many SCHs of this network, the different levels of availability of neighboring vehicles as relays, and the restrictions imposed over the CCHs to carry data that may interfere with the delivery of emergency and safety information.

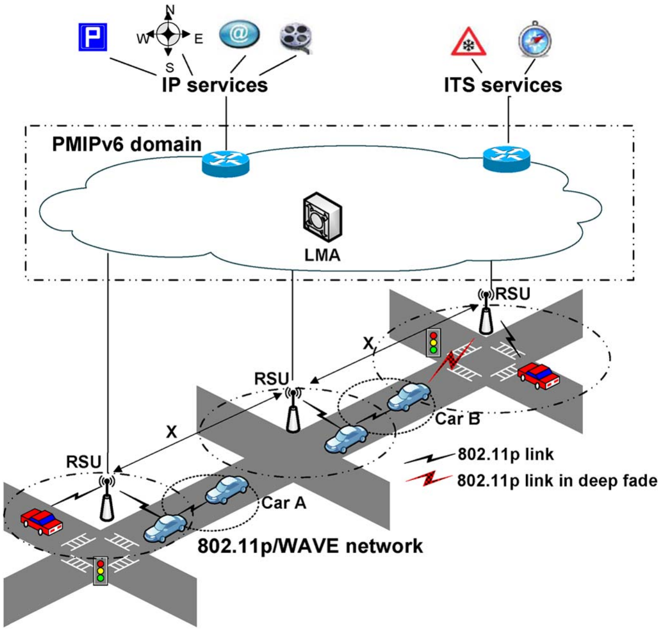


Fig. 3. IP-enabled 802.11p/WAVE network model.

Although a collection of works are devoted to provide measurement studies of the IP-based application performance over V2I communications [2], [21], they often employ traditional 802.11b/g technologies and obviate the limitations existent in the current 802.11p/WAVE standard for IP communications. In [22], they do provide an evaluation of UDP/TCP applications in 802.11p/WAVE, but their main focus is to reduce the problem of bandwidth wastage resulting from the switching operation in single-PHY environments. In parallel to those measurement studies, extensive research has been devoted to provide theoretical models for evaluating mobility and spatio-temporal relations, connectivity and access probabilities, MAC layer performance, handovers, and relay strategies in vehicular environments (see [23]–[29] and references therein). Although we have been inspired by these works, our work is different in that we integrate these many aspects to provide a closed-form expression, from a microscopic point of view, for the throughput evaluation of IP applications in the 802.11p/network.

III. THE VEHICULAR IP IN WAVE (VIP-WAVE) FRAMEWORK

A. *Network Model*

Consider the infrastructure-based vehicular network shown in Fig. 3. The connection to the infrastructure is provided by RSUs located along the road. Vehicles are equipped with OBUs that enable connections to the infrastructure and to other vehicles. Every RSU and OBU is equipped with 802.11p/WAVE radios. It is assumed that RSUs and OBUs are multi-PHY. In this way, we alleviate problems such as bandwidth wastage, long queuing, and high end-to-end delay, which have been previously identified as the consequences of the channel switching operation performed by 802.11p single-PHY radios [30], [31].

Two different infrastructure-based IP services are provided in the 802.11p/WAVE network: 1) extended services that are continuously announced by all RSUs in the network, such as mapping applications, route planning, and Internet access; and 2) non-extended services that are location-dependant, such as assisted-parking, and that are provided only by some RSUs.

For a given channel model $\mathcal{C}$, vehicles may establish a direct connection to the RSU. Some other vehicles, however, are located in areas uncovered by the infrastructure (see car A in Fig. 3) or with a communication link in deep fade toward the RSU (see car B in Fig. 3). Inside such areas, we exploit the use of multi-hop communications, so that at most one intermediate vehicle acts as a relay for another vehicle communicating with the RSU [24]. Since the transmission power of the RSU is higher than the transmission power of OBU, this leads to the RSU radio range R to be wider than the OBU radio range r.

Furthermore, in the case of extended services, we have selected the standard PMIP protocol to manage the IP mobility of the OBUs. PMIP defines two entities: 1) the Mobility Anchor Gateway (MAG), which is in charge of detecting when a node joins or moves through the PMIP domain; and 2) the Local Mobility Anchor (LMA), which is the central entity in charge of assigning the IP prefixes to mobile nodes. The MAGs emulate a home link for the mobile node so that the node believes it is always connected to the same access router. The MAG and the LMA use Proxy Binding Updates (PBU) and Proxy Binding Acknowledgments (PBA), respectively, for requesting and assigning IP prefixes to mobile nodes.

The general integration of PMIP with the 802.11p/WAVE network has been illustrated in Fig. 3. When a MAG detects a new connection, it sends a PBU to the LMA on behalf of the mobile node. The LMA then assigns an IP prefix and creates a tunnel through which all traffic from/to the mobile node is encapsulated toward the serving MAG. When the mobile node changes its location, the LMA has to change the tunnel's end-point upon reception of a PBU from the new serving MAG. This way, the mobile node does not detect any changes at the network layer and can maintain active its IP sessions. We also consider the whole 802.11p/WAVE network as a single PMIP domain and colocate the MAG functionalities with the RSU.

B. VIP-WAVE Architecture

As denoted in Section II-A, one of the 802.11p/WAVE's biggest issues, in terms of IP operation, is the announcement of a per-WSA IP prefix, which forces WAVE users of all IP services announced in a specific WSA (up to 32 services per WSA) to belong to the same IP network. This causes not only a necessity for often having to detect duplicate addresses throughout the network and other SCHs, but contradicts one of the main assumptions IPv6 has for the link-layer model as well. This assumption says that all nodes belonging to the same IP prefix are able to communicate directly with each other, which does not hold when there are WAVE users that are scattered along different locations or along different SCHs.

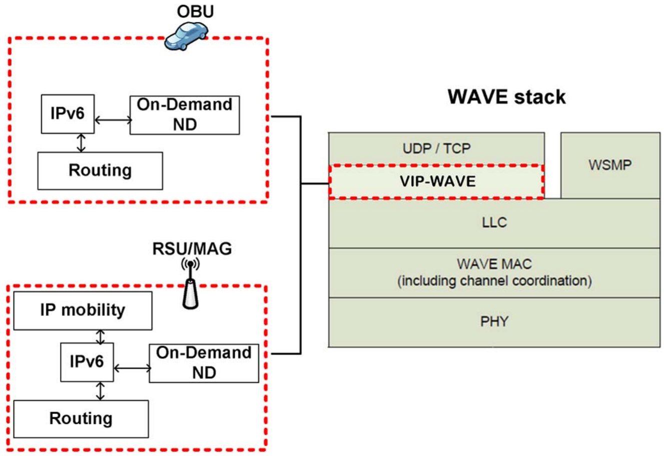


Fig. 4. VIP-WAVE architecture.

Additionally, there is a shortage in differentiating extended from non-extended services, and no IP mobility support is indicated to provide seamless communications in the case of extended services. Last, but not least, multihop communications are not exploited in the 802.11p/WAVE network, although they could boost the network's performance and increase the IP service availability.

The general idea behind our framework is to address those limitations by integrating IP configuration and IP mobility in order to provide differentiated treatment for extended and non-extended services. We intend to enable a per-user IP prefix for accessing extended services and for guaranteeing seamless communications. Moreover, we intend to improve the coverage of IP services by extending the access to OBUs located two hops away from the RSU.

The architecture of VIP-WAVE is illustrated in Fig. 4. VIP-WAVE is located in the data plane of the WAVE stack of protocols, and it defines three main components that interact with the standard IPv6 protocol: 1) the IP addressing and mobility block (only in the RSU), which is in charge of assigning global IPv6 prefixes to vehicles and guaranteeing IP mobility for extended services throughout the network; 2) the on-demand ND block, which is a lightweight adaptation of the standard ND; and 3) the routing block, which enables relay selection for multi-hop communications when a user fails to directly consume the IP service from the RSU. Due to our selection of PMIP for the network-based mobility, the OBUs do not have to include any component for IP mobility, as depicted in Fig. 4.

In the following sections, we describe the interaction of VIP-WAVE's components for the support of IP services to vehicles directly connected (i.e., one-hop away) to the infrastructure, and then we introduce the extensions required for enabling support of two-hop connections in VIP-WAVE.

IP Service Establishment: The RSU that announces an IP service includes besides the type of service (i.e., extended or non-extended), the global IP address of the hosting server, its own MAC address that identifies it as the WAVE provider, and the RCPI threshold. Such information is included in the extension fields of `ServiceInfo`, as specified in [6]. The WSA is transmitted in the CCH. Since OBU has a radio dedicated to monitor the CCH, all one-hop users in the area

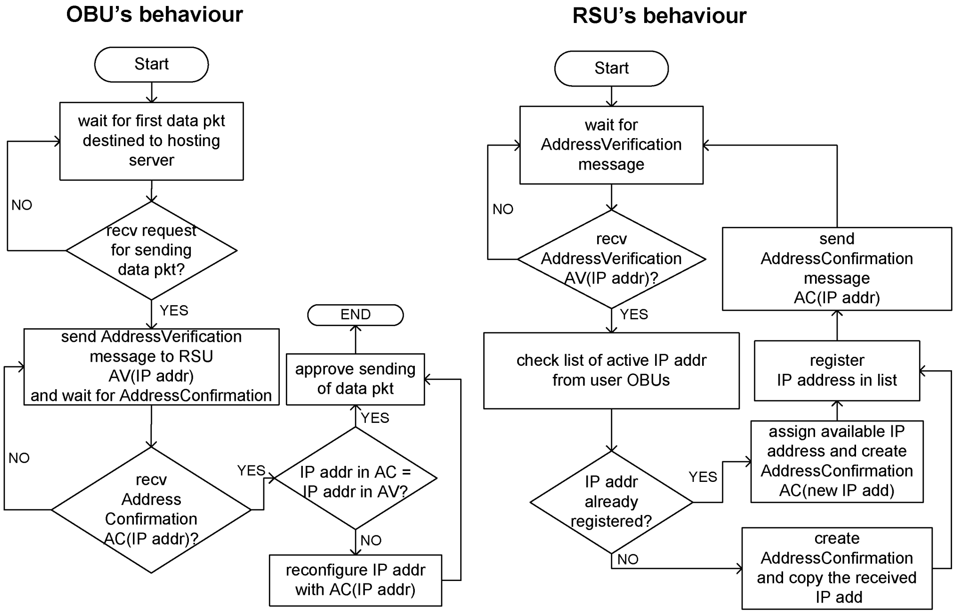


Fig. 5. DAD mechanism in VIP-WAVE for nonextended services.

of service of the RSU can receive the WSA. Upon WSA reception, a WAVE user determines if it wants to access the service, and it checks the type of service to proceed in the following way.

a) If service is extended: The OBU tunes a radio to the SCH specified in the `ChannelInfo` segment. At that point, the OBU does not have a global IP address to initiate communications with the hosting server; therefore, the IPv6 module requests the on-demand ND module to trigger a router solicitation (RS) message. The RS message is destined to the all-router multicast address as indicated in [8], and it is handed to the routing module for determining the next-hop destination. Since the user is directly connected to the RSU, the routing module selects the WAVE provider's MAC address (i.e., RSU MAC address) as the MAC layer frame destination; thus, instead of multicast, the RS is delivered as a unicast message. The RSU then exchanges PBU/PBA messages with the LMA for IP prefix assignment, after which the RSU sends a unicast router advertisement (RA) message to the OBU.

The RA message includes all the information required by IPv6 for a proper configuration. Once the global IP address has been calculated, the OBU may start exchanging IP data packets with the hosting server. Note that no DAD mechanism is required after IP address configuration, since the IP address uniqueness is guaranteed by having an IP prefix uniquely assigned per OBU.

b) If service is non-extended: The OBU employs the IP prefix announced in `WRA` to calculate a global IP address. After IP configuration, the OBU tunes to the proper SCH. Since the IP prefix is shared among other users consuming non-extended IP services announced in the same WSA, a DAD procedure has to be executed before the OBU may start transferring IP packets. Hence, our on-demand ND defines a centralized DAD mechanism controlled by the RSU, which is only triggered when the first IP data transmission request appears at the OBU. The RSU keeps a list of the active OBUs and their IP addresses in order to be able to detect duplicates.

The details of the DAD procedure are depicted in Fig. 5. The OBU's IP configuration for non-extended services is only valid inside the area of coverage of the serving RSU; thus, the IP uniqueness only needs to be guaranteed at the serving RSU level instead of at the entire network level. Once the DAD has been completed, the OBU may start exchanging IP data packets with the hosting server.

Handover of IP Services: An OBU transitions through the RSU service areas at vehicular speeds. Therefore, we introduce a handover mechanism that allows for seamless communications of extended IP services in the 802.11p/WAVE network. When an OBU is consuming an extended service, it continues monitoring the CCH while roaming toward a new RSU. Consequently, the reception of a WSA that announces the same extended service, but from a different WAVE provider, serves as a movement detection hint. This is detected thanks to the WAVE provider field in `ServiceInfo`, which should include a different MAC address. The movement is then notified by the MAC layer to the VIP-WAVE layer in the OBU. Upon the movement notification, the on-demand ND module triggers the sending of an RS message, which is transmitted over the SCH in which the service is being provided.

The reception of the RS message is then employed by the RSU for connection detection, and it proceeds to exchange PBU/PBA signaling with the LMA. As a result, the LMA is able to resume packets forwarding toward the OBU as soon as it sends the PBA to the new RSU. Upon reception of the PBA, the new RSU sends an RA to the recently detected OBU. The OBU, on the other hand, is able to resume packet transmission toward the hosting server once it receives the RA.

Note that our on-demand ND does not require the frequent sending of messages. We have replaced the necessity of receiving frequent RA messages by the reception of WSAs that are

TABLE I
RELAY SETUP PROCEDURE IN VIP-WAVE

Procedure at user OBU

Relay detection

```
1:  if (WSAs from the RSU are no longer received or received WSA signal < RCPI threshold)
2:      create a ServiceInfo to announce the Relay Service solicitation.
3:      include this OBU's ID and IP address in the extension fields of ServiceInfo.
4:      associate a ChannelInfo segment with SCH number of active IP service.
5:      send a WSA with the Relay Service announcement in CCH.
6:  else
7:      keep using one-hop connection to RSU.
```

Relay setup

```
25: if (Relay Service announcement has been sent and WSA with Relay Maintenance announcement is received)
26:     set the relay OBU's MAC address as next-hop for reaching the RSU.
```

Procedure at relay OBU

Relay provision

```
8:  if (reception of WSA with Relay Service solicitation and availability to serve as relay)
9:      tune to the SCH of the service as indicated in ChannelInfo.
10:     create a Relay Notification message.
11:     include the user OBU's information in the Relay Notification message.
12:     set Relay Notification's destination address to ALL_ROUTERS.
13:     send Relay Notification message through SCH.
```

Relay setup

```
21: if (reception of Relay Confirmation)
22:     create a ServiceInfo to announce the Relay Maintenance to the user OBU.
23:     send a WSA with the Relay Maintenance announcement in CCH.
24:     set the forwarding route for packets from/to the user OBU.
```

Procedure at RSU

Relay setup

```
14: if (reception of Relay Notification and user OBU's information corresponds to an active user OBU)
15:     create a Relay Confirmation message.
16:     set relay OBU's MAC address in Relay Confirmation's MAC frame destination.
17:     send Relay Confirmation message to relay OBU in SCH.
18:     set the relay OBU's MAC address as next-hop for reaching user OBU.
19: else if Relay Confirmation has been already sent
20:     discard Relay Notification.
```

already defined in the standard WAVE. Thus, an IP prefix does not expire, unless announcements for the service that is currently being consumed are no longer received. Consequently, the WSA message reception aids the VIP-WAVE layer in two ways: 1) It helps the maintenance of IP addresses by replacing the non-solicited RA messages defined in the standard ND; and 2) it solves the IP-to-link-layer address translation, because the WSA already includes the MAC address of the current WAVE provider. In addition, we alleviate possible congestion in the CCH by having the on-demand ND messages (e.g., RS or RA) being transmitted only over the SCH.

In the case of non-extended services, they are no longer available when the OBU moves to a new service area; thus, they do not require the definition of a handover mechanism.

C. VIP-WAVE Extensions for Two-Hop Scenarios

In Section II-A, we have introduced the advantages of enabling multihop communications in vehicular networks. Therefore, in this section we define the necessary features and services to extend the support of VIP-WAVE in two-hop scenarios. We start by defining two services that are closely related: 1) the relay service, which is registered in the `ProviderServiceRequestTable` of all OBUs, and it is announced only when they require another OBU to serve as a relay; a request for relay service may only be sent after the user OBU has started consuming a given service (i.e., after the OBU has acquired its IP configuration from the RSU); and 2) the relay maintenance, which is announced by the intermediary OBU that has been selected as a relay for IP communications.

Intermediate OBUs may serve as relays for extended and non-extended services. However, only those OBUs with availability to serve as temporary relays will take action when they receive a relay service request. The procedure for setting up a relay OBU is located in the routing module and described in detail in Table I. Once the procedure has been completed, the RSU and user OBU have the necessary information for delivering packets through a two-hop path and the exchange of IP packets may be resumed.

***Routing Through a Relay**:* Depending on the direction of traffic, the routing protocol works in the following way for multi-hop communications.

a) Traffic from hosting server to user OBU: Once the packet arrives at the RSU, the IPv6 module queries the routing module about the next hop to reach the user OBU. The routing module selects the relay OBU MAC address as the MAC layer frame destination, as per configured by the relay setup procedure. The packet is then forwarded to the relay OBU.

b) Traffic from user OBU to hosting server: Once the data packet is generated at the user OBU, the IP layer determines if the hosting server belongs to an external network; thus, it then decides that the packet should be sent toward the default gateway, which in this case is the RSU. The IPv6 module then queries the routing module about the next hop to reach the RSU. As configured by the relay setup procedure, the route to reach the RSU indicates the relay OBU as the next hop; therefore, the relay OBU MAC address is selected as the MAC layer frame destination. The packet is then forwarded to the relay OBU.

If at any moment during the two-hop communications the user OBU receives the WSA directly from the RSU with a signal level above the RCPI threshold, the user OBU will send an RS to reestablish direct communications with the RSU. In such a case, the RA response message sent by the RSU is overheard and employed by the relay OBU for terminating the relay service.

***Handover in Two-Hop Scenarios**:* When the vehicle is in motion, it may experience handovers in different scenarios: 1) It may move the connection to a relay OBU, where both relay and user OBUs remain in the service area of the same RSU; and 2) it may move the connection to a relay OBU, where the relay OBU is connected to an RSU different from the user OBU's serving RSU. The first case holds for extended and non-extended services, whereas the second case only holds for extended services. Note that the handover procedure when the vehicle maintains a direct connection to the RSU has been already defined in Section III-B.

a) Handover to a relay in the same service area: In this scenario, the signaling required to maintain seamless communications is no different from that described in Table I. Since both relay OBU and user OBU remain in the service area of the same RSU, after the RSU receives the relay notification message (step 14), it finds the information about the user OBU registered in its list of active IP users. Therefore, it does not require to trigger any signaling for IP mobility. Moreover, the procedure is the same regardless of whether the service is extended or non-extended.

b) Handover to a relay in a different service area: The procedure of two-hop handover to a different service area is illustrated in Fig. 6. In this scenario, the handover may be triggered by the conditions described in Table I (step 1), and therefore, the relay detection procedure is started. However, given that the relay is connected to a different service area, when the RSU receives the relay notification message (step 14), it does not have an active tunnel configured for the user OBU. Therefore, the RSU uses the relay notification message as a hint for connection detection and triggers the PBU/PBA signaling toward the LMA. Once the PMIP signaling is completed, the RSU continues with the sending of relay confirmation (step 15) to the relay OBU. This message serves for triggering the relay maintenance announcements from relay OBU to user OBU (step 23), after which bidirectional communications are resumed.

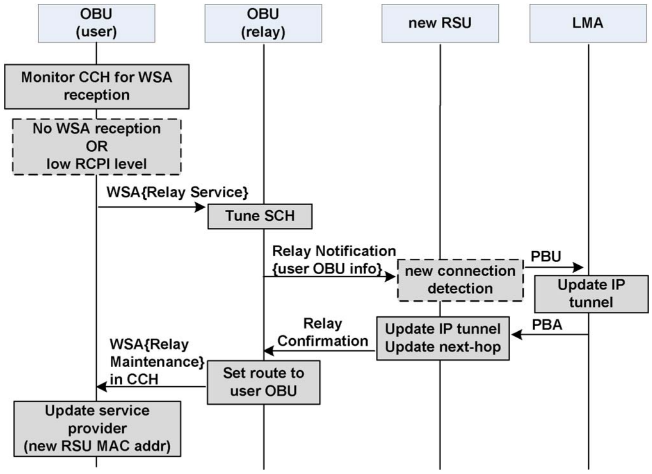


Fig. 6. Handover of extended IP services through a relay in VIP-WAVE.

IV. Analytical Model

We derive an analytical model to evaluate the performance of the proposed VIP-WAVE framework compared with the standard network layer in WAVE. The analysis focuses on modeling the OBU's mobility and calculating the handover delay and packet collision probability. Based on those aspects, we examine a randomly tagged vehicle and calculate its nodal downstream throughput when it is consuming an extended IP service in the 802.11p/WAVE network.

A. Mobility Model

Consider the network depicted in Fig. 3. To make our analysis tractable, assume that the RSUs are uniformly distributed along the roads and separated by a distance X. Similar to [24], we analyze the subnetwork placed in the range $[0, X]$ and bounded by two consecutive RSUs. We further divide such subnetwork in smaller segments $\mathbb{S} = \{1, 2, 3, \ldots N\}$, where each $s \in \mathbb{S}$ is of length d_s. A vehicle that moves along the 802.11p/WAVE network iteratively transits through the segments while traversing the different subnetworks. Thus, we model the mobility of the vehicle using a Markov chain model, inspired by [25], where the states correspond to the different segments in $[0, X]$. Nonetheless, in our model, we define the spacial zones as segments placed between two adjacent RSUs, whereas in [25], such zones are placed within the radio coverage of a single RSU.

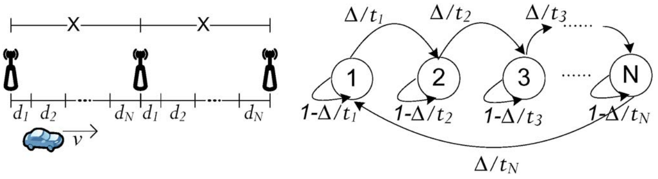


Fig. 7. Spacial division of 802.11p/WAVE network and Markov chain model for a vehicle's mobility.

The Markov chain model, its relation to the spacial division of the 802.11p/WAVE network, and the vehicle's mobility are shown in Fig. 7. The residence times in each segment are considered to be geometrically distributed with mean t_s, so that in a small duration Δ, the vehicle transitions to the next segment with probability Δ/t_s and remains with probability $1 - \Delta/t_s$. The mean residence time in each segment is determined by $t_s = d_s/v$, where v is the average velocity of the vehicle. Given the transition probability matrix $\mathbf{P}$, the steady state probability matrix $\boldsymbol{\pi} = \{\pi_s\}$ of the Markov chain can be derived by solving the following set of linear equations:

$$\begin{cases} \boldsymbol{\pi}\mathbf{P} = \boldsymbol{\pi} \\ \sum_{s=1}^{N} \pi_s = 1. \end{cases}$$

On the other hand, for a user OBU subscribed to an IP service, its connection to the RSU may be of three different types: 1) direct connection (i.e., one hop); 2) connection through a relay (i.e., two hop); and 3) no connection at all. In [24], for a vehicle located at x in $[0, X]$, $p_1(x)$ denotes the probability of the vehicle to be directly connected either to RSU in 0 or RSU in X, and $p_2(x)$ denotes the probability of the vehicle to be connected to at least one relay (where a relay is any vehicle with direct connection). These access probabilities are defined as

$$p_1(x) = 1 - \left(1 - g_b^{\mathcal{C}}(x)\right)\left(1 - g_b^{\mathcal{C}}(X - x)\right), \tag{1}$$

$$p_2(x) = 1 - e^{-\int_0^X g_v^{\mathcal{C}}(\|x-y\|)\rho p_1(y)dy}, \tag{2}$$

where $g_b^{\mathcal{C}}(x)$ and $g_b^{\mathcal{C}}(X - x)$ are the V2I connectivity probabilities for a given channel model $\mathcal{C}$ and a given location with respect to both RSUs (i.e., at x for RSU in 0, and at $X - x$ for RSU in X). $g_v^{\mathcal{C}}(\|x - y\|)$ is the V2V connectivity probability between two vehicles located at x and y, respectively, and ρ represents the density in vehicles per meter (vpm).

The number of vehicles in $[0, X]$ is assumed to be Poisson distributed with mean ρX. Despite the fact that our model relies on the assumption of a Poisson distributed population of vehicles, it has been previously demonstrated, by means of validation with real world traffic traces and synthetic mobility models [32], [33], that it is a reasonable assumption that does not detract the adequacy of our model; instead, it helps to make our analysis tractable. Moreover, although a Poisson distribution is commonly employed for sparse vehicular ad hoc networks, the results in [33] show that, for all traffic densities, the exponential distribution accurately estimates the intervehicle spacing distribution, especially for a spacing larger than 50 m.

Accordingly, we represent the connection type of a vehicle in segment $s \in \mathbb{S}$ as $G_s = \{1, 2, 0\}$ for one-hop, two-hop, and no connection, respectively. Thus, for a vehicle located in segment s, the probability distribution of G_s can be calculated as

$$P\{G_s = a\} = \begin{cases} p_1(\omega_s), & \text{if } a = 1 \\ (1 - p_1(\omega_s))p_2(\omega_s), & \text{if } a = 2 \\ (1 - p_1(\omega_s))(1 - p_2(\omega_s)), & a = 0. \end{cases} \tag{3}$$

For the simplicity of the analysis, we use the middle point of the segment, ω_s, to represent the location of vehicles in that segment. The connection type of the user OBU is therefore integrated with our Markov chain model, in such a way that $P\{G_s = a\}$ represents the probability of the user OBU of having connection type a to the RSU when the process is in state $s \in \mathbb{S}$.

B. Handover Delay

Definition 1: The handover delay H_G is the time duration between the breakage of the user OBU's connection to the infrastructure (i.e., through direct or relayed connection) and the resumption of data packet transmission from the infrastructure to the user OBU. The handover delay varies according to the type of connection (G) acquired by the user OBU in the new location.

Handover Delay in Standard WAVE: We define two possible configurations for the standard WAVE. In scenario A, we consider the current standard as-is with no mobility management scheme. Then, it is reasonable to assume that each RSU includes a different IP prefix in its `WRA`, as mentioned in Section II-A. In such a case, the vehicle should reset its connection for an extended IP service every time it enters the service area of a new RSU. In addition, in the standard WAVE, the vehicle may experience only two states: directly connected to RSU or disconnected. The handover delay of this scenario is calculated as follows:

$$H_{G=1}^{\text{WV-A}} = R_{\text{WSA}} + RESET, \tag{4}$$

where R_{WSA} indicates the time delay for the user OBU to receive a WSA from the new RSU. $RESET$ corresponds to the time for a user OBU's transmission of a connection reset toward the server, and the corresponding reconfiguration time above the network layer (e.g., the three-way TCP handshake).

In scenario B, we consider the standard 802.11p/WAVE network to be PMIP-enabled so that network-based mobility is provided to maintain the IP prefix assignment of the OBUs across the domain. Although this configuration is not mentioned in the standard, by considering this scenario, we account for basic IP mobility management employed in the standard WAVE at the same time that we provide a fair comparison to our proposed VIP-WAVE framework. Note that this scenario would require a basic ND signaling in order to reestablish the flow of IP traffic at the new location. The handover delay of this scenario is derived as follows:

$$H_{G=1}^{\text{WV-B}} = R_{\text{WSA}} + T_{\text{RS}} + RTT_{\text{PMIP}} + R_{\text{RA}}, \tag{5}$$

where T_{RS} indicates the transmission time for the RS message, RTT_{PMIP} indicates the round trip time for exchanging PBU/PBA messages between MAG and LMA, and R_{RA} indicates the time delay for the user OBU to receive the RA message from the infrastructure.

Handover Delay in VIP-WAVE: In VIP-WAVE, a roaming vehicle may experience different types of connection breakages. When in a one-hop connection, the vehicle may lose signal reception due to distance, blocking of line of sight, or poor signal quality reception. Such conditions can also cause breakage of a two-hop connection. In addition, the OBU may terminate its current two-hop connection when it again detects a one-hop connection with better link quality conditions.

Among all those possibilities, we analyze the worst-case scenario, in which every time the vehicle experiences a change of connection (i.e., to one-hop or two-hop), it involves also a change of RSU; hence, it triggers PMIP signaling at the infrastructure side. Although this may not be the case for real deployments, because the OBU may change its type of connection and still be connected to the same RSU, the assumption allows us to give an upper bound estimation of the handover delay induced by the proposed VIP-WAVE framework.

The handover delay in VIP-WAVE is calculated as follows:

$$H_{G=1}^{\text{VIP}} = R_{\text{WSA}} + T_{\text{RS}} + RTT_{\text{PMIP}} + R_{\text{RA}}, \tag{6}$$

$$H_{G=2}^{\text{VIP}} = T_{\text{R.SOL}} + T_{\text{R.NOT}} + RTT_{\text{PMIP}} + T_{\text{R.CONF}} + R_{\text{R.MAIN}}. \tag{7}$$

In (7), we do not require waiting for WSA reception as the relay selection and configuration process start as soon as the user OBU stops receiving WSAs from the RSU (or when the RCPI threshold is no longer met). The calculation involves the transmission and reception delays for R.SOL,R.NOT,R.CONF, and R.MAIN, i.e., the messages defined in Table I for selecting and setting the relayed connection.

C. Packet Collision Probability

Definition 2: The packet collision probability p_{col} is the probability of packet losses due to collisions occurring between two or more nodes transmitting at the same time, when they are all tuned to the same SCH.

Packet Collision Probability in Standard WAVE: Let M_s denote the mean population of vehicles in segment s, $s \in \mathbb{S}$. Then, M_s can be expressed by

$$M_s = \rho d_s \tag{8}$$

where ρ is the density of vehicles (vpm), and d_s is the length of segment s (m). Let us consider P_α as the probability that an OBU subscribed to service α is active (i.e., the OBU is tuned to the SCH where service α is being provided and is transmitting/receiving data packets). Then, the conditional transmission probability $\tau_1(s)$ given that a vehicle is located in segment s is given by

$$\tau_1(s) = P\{G_s = 1\} P_\alpha \tag{9}$$

where $P\{G_s = 1\}$ is the one-hop connectivity of vehicles in segment s.

For the standard WAVE, we denote by $p_{\text{col}}^{\text{WV}}(s)$ the conditional collision probability of a tagged node in segment s given that the tagged node is active. Thus

$$p_{\text{col}}^{\text{WV}}(s) = 1 - (1 - \tau_1(s))^{M_s - 1} \prod_{s' \in S_r(s), s' \neq s} (1 - \tau_1(s'))^{M_{s'}}, \tag{10}$$

where S_r denotes the set of segments that fall into the radio range of the tagged vehicle. For simplicity of the analysis, if the middle point of the segment falls into the radio range of the tagged vehicle, that segment is considered in S_r. Therefore, we have

$$S_r(s) = \{s' | \omega_s - r < \omega_{s'} < \omega_s + r\}. \tag{11}$$

Packet Collision Probability in VIP-WAVE: In VIP-WAVE, a vehicle communicates with the RSU either directly or through two-hop relaying. Then, the conditional transmission probability $\tau_2(s)$ given that a vehicle is located in segment s is given by

$$\tau_2(s) = \left(P\{G_s = 1\} + P\{G_s = 2\}\right) P_\alpha. \tag{12}$$

Recall that $P\{G_s = 2\}$ is the two-hop connectivity of vehicles in segment s. For VIP-WAVE, we denote by $p_{\text{col}}^{\text{VIP}}(s)$, shown in (13), the conditional collision probability of a tagged node in segment s given that the tagged node is active. $S_r(s)$ in (13) is defined by (11) and $S'_r(s)$ is given by

$$S'_r(s) = \{s' | \omega_s - 2r < \omega_{s'} < \omega_s + 2r\}. \tag{14}$$

S'_r indicates that for guaranteeing the transmission of the tagged vehicle, vehicles within the two-hop range of the tagged vehicle should be inactive.

D. Nodal Downstream Throughput

Definition 3: The nodal downstream throughput T is the average rate of packets received at the user OBU when traversing the subnetwork in $[0, X]$. It is expressed in bits per seconds.

Let B denote the total number of bits received by an individual OBU when traversing the subnetwork in $[0, X]$. According

---

$$p_{\text{col}}^{\text{VIP}}(s) = \begin{cases} 1 - (1 - \tau_2(s))^{M_s - 1} \prod\limits_{s' \in S_r(s), s' \neq s} (1 - \tau_2(s'))^{M_{s'}}, & \text{If } G_s = 1 \\ 1 - (1 - \tau_2(s))^{M_s - 1} \prod\limits_{s' \in S'_r(s), s' \neq s} (1 - \tau_2(s'))^{M_{s'}}, & \text{If } G_s = 2 \end{cases} \tag{13}$$

to the mobility model, we interpret d_s/v as the average time the vehicle spends in each segment s. Consequently, the expected number of bits received while in segment s, $E[B_s]$, and the total number of bits B received in $[0, X]$ are computed as follows:

$$E[B_s] = \sum_{a=0}^{2} B_s P\{G_s = a\}, \tag{15}$$

$$B = \sum_{s=1}^{N} E[B_s]. \tag{16}$$

The average nodal downstream throughput T experienced by the tagged vehicle is then expressed as

$$T = \frac{B}{\left(\sum_{s=1}^{N} d_s\right)/v}. \tag{17}$$

Nodal Downstream Throughput in Standard WAVE: We express the number of bits received in state s, B_s^{WV}, as follows:

$$B_s^{\mathrm{WV}} = \begin{cases} \lambda_d \left(1 - p_{\mathrm{col}}^{\mathrm{WV}}(s)\right)\left(d_s/v - H_{G_s}^{\mathrm{WV}}\right), & \text{If } G_s = 1 \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

where λ_d is the downstream data rate (in bits per second) from the IP server to the OBU, and H_G^{WV} is given by either (4) or (5). Overall, the expression computes the total number of bits received during the available transmission time (i.e., after deducting the handover delay), while the OBU is in segment s. Note that an OBU operating under the standard WAVE does not receive data packets when $G_s = 2$ or $G_s = 0$.

Nodal Downstream Throughput in VIP-WAVE: The number of bits B_s^{VIP} received in state s while the OBU operates under VIP-WAVE is defined as

$$B_s^{\mathrm{VIP}} = \begin{cases} \lambda_d \left(1 - p_{\mathrm{col}}^{\mathrm{VIP}}(s)\right)\left(\frac{d_s}{v} - H_{G_s}^{\mathrm{VIP}}\right), & \text{if } G_s = 1 \\ \lambda_d \left(1 - p_{\mathrm{col}}^{\mathrm{VIP}}(s)\right)\left(\frac{d_s}{2v} - H_{G_s}^{\mathrm{VIP}}\right), & \text{if } G_s = 2 \\ 0, & \text{if } G_s = 0. \end{cases} \tag{19}$$

Note that for $G_s = 2$, the effective time available for transmission is considered to be roughly $d_s/2v - H_{G_s}^{\mathrm{VIP}}$ since the packets go through an intermediary node before they can be forwarded to the user OBU.

V. PERFORMANCE EVALUATION

For evaluation purposes, we compare VIP-WAVE with the standard WAVE with no mobility management (WAVE-A), and with the standard WAVE with PMIP (WAVE-B). The comparisons evaluate the nodal downstream throughput for variable network characteristics, as well as the delay due to handovers and during data packets delivery.

A. Model Validation

We calculate the numerical results of our analytical model in Matlab. The average nodal downstream throughput in standard WAVE is obtained by replacing (18) in (15), and by calculating B^{WV} and T^{WV} according to (16) and (17), respectively. The average nodal downstream throughput in VIP-WAVE is obtained by replacing (19) in (15), and by calculating B^{VIP} and T^{VIP} according to (16) and (17), respectively.

TABLE II
PERFORMANCE EVALUATION PARAMETERS

Parameter	Value
Tx Power RSU	50mw (500m radio range)
Tx Power OBU	11mW (250m radio range)
Frequency band	5.9GHz
Link data rate	6Mbps
PHY/MAC Layer	Inetmanet 802.11p / CSMA-CA
RCPI threshold	-85dBm
Download data rate (λ_d)	100Kbps (default) ∼ 3Mbps
Available relays (p_r)	40%, 70%, 100%
Average speed (v)	35Km/h (default) ∼ 100Km/h
Density (ρ)	1/25vpm
RSUs inter-distance (X)	500m ∼ 2000m
Segment length (d_s)	50m
R_{WSA}	25ms
$RESET$	150ms
T_{RS}, R_{RA}	5ms
$T_{\mathrm{R.SOL}}$, $T_{\mathrm{R.NOT}}$, $T_{\mathrm{R.CONF}}$, $R_{\mathrm{R.MAIN}}$	5ms
RTT_{PMIP}	10ms
P_α	1% ∼ 12%
Session time	600s

The settings for such evaluation are provided in Table II. In order to obtain $P\{G_s\}$, we calculate $p_1(\omega_s)$ by assuming a unit disk model $\mathcal{U}$ so that connectivity is determined mainly by the distance between vehicle and RSU. However, we also integrate the RCPI threshold in determining connectivity, because a received power level below the RCPI threshold results in a disconnection from the vehicle to the provider RSU. Thus, we calculate the V2I connectivity probability as

$$\text{(unidirectional) } g_b^{\mathcal{U}}(\omega_s) = \begin{cases} 1, & \text{if } (\omega_s \leq R) \\ & \text{and } (rxPw \geq RCPI) \\ 0, & \text{otherwise} \end{cases} \tag{20}$$

where $rxPw$ is the OBU's reception power level calculated as $rxPw = 10\log_{10}(\mathrm{TxPowerRSU}) - PL$, which is a reduction of the log-normal path loss model to the unit disk model when the path loss component PL has no shadowing [24].

We also consider a more restrictive bidirectional connectivity probability. This is to account for the asymmetry existent in the transmission power of RSUs and OBUs, in which case a distance $\omega_s \leq R$ only guarantees connection from RSU to OBU, but not from OBU to RSU. Thus, to guarantee bidirectionality, we have

$$\text{(bidirectional) } g_b^{\mathcal{U}}(\omega_s) = \begin{cases} 1, & \text{if } (\omega_s \leq r) \\ & \text{and } (rxPw \geq RCPI) \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

In other words, the unidirectional connectivity probability given by (20) allows for one-way reception of traffic from RSU to OBU, but it does not necessarily enable reception from OBU to RSU. Examples of such IP-based applications that require one-way reception of traffic are audio and video streaming. In the case of bidirectional connectivity probability, as calculated by (21), two-way reception of traffic is enabled between RSU and OBU when they meet the connectivity conditions.

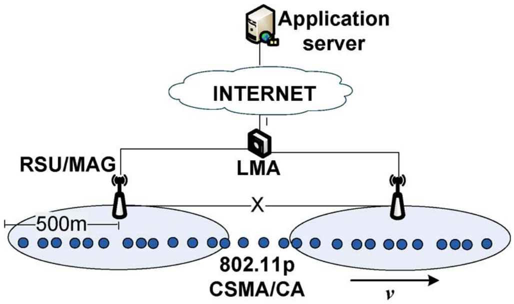


Fig. 8. Simulation setup in Omnet++.

Examples of IP-based applications that require two-way reception of traffic are IP telephony and general TCP-based applications.

In the calculation of $p_2(\omega_s)$, we modify the integral limits in (2) to calculate the average number of nodes in $[\omega_s - r, \omega_s + r]$ and consider only a percentage of that number, given by the parameter p_r, as available to serve as relays (i.e., OBUs that process relay service requests and are also available at the time of reception of a request).

B. Simulation Settings

Extensive simulation results have been obtained based on the discrete event simulator Omnet++. The simulation parameters are presented in Table II, and a simulated sample topology is depicted in Fig. 8. RSUs and OBUs are equipped with two wireless interfaces transmitting in different channels. In this way, we emulate the multi-PHY capabilities with simultaneous transmissions over CCH and SCH. Each radio implements the Inetmanet 802.11p PHY and MAC model, and parameters are set according to the recommended values in [4]. Connectivity among nodes is initially determined by a unit disk model. However, signals are attenuated following a log-normal propagation model with path loss exponent of 2.4. We have also modified the Inetmanet package so that it delivers the OBU's received power to the network layer; thus, we can employ the RCPI threshold to determine connectivity between OBU and RSU. An Internet-located application server for the downloading of data traffic is connected to the 802.11p/WAVE network with an RTT of 40 ms.

RSUs are uniformly distributed along the road segment with distance X. A one-way lane is simulated, where vehicles are moving at a constant average velocity v. We employ randomly generated topologies and a different tagged vehicle per topology. Topologies have, in average, a number ρX of vehicles per subnetwork in $[0, X]$. Only application layer packets, sent from the application server and received at the user OBU, are considered for the throughput calculation in each simulation run. The results are plotted with a 95% confidence interval.

C. Level of Presence of Infrastructure

Fig. 9 shows the throughput obtained when X increases from 500 to 2000 m. The analytical results are verified by the simulation results for both one-way and two-way traffic scenarios. Although we have employed the memoryless assumption in modeling the vehicle's mobility (i.e., geometrically distributed residence times in each segment), during the simulations, we have relaxed such assumption and instead employed a more realistic constant average velocity. Nevertheless, the analytical model has proved to be accurate in the long-term sense for calculating the average nodal throughput.

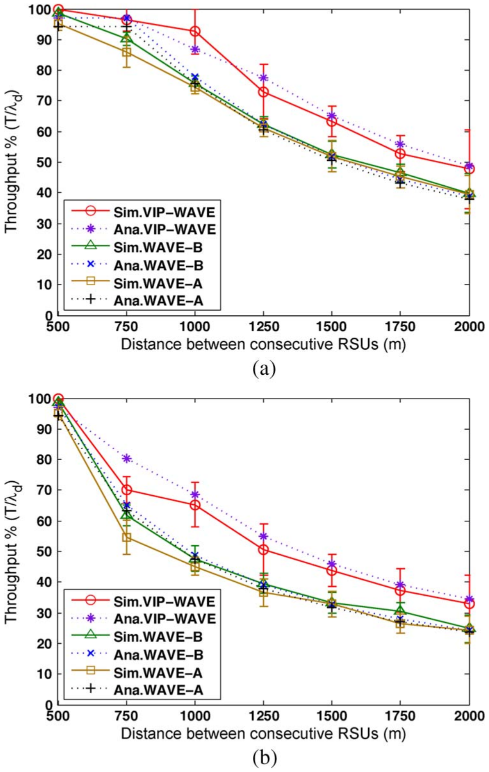
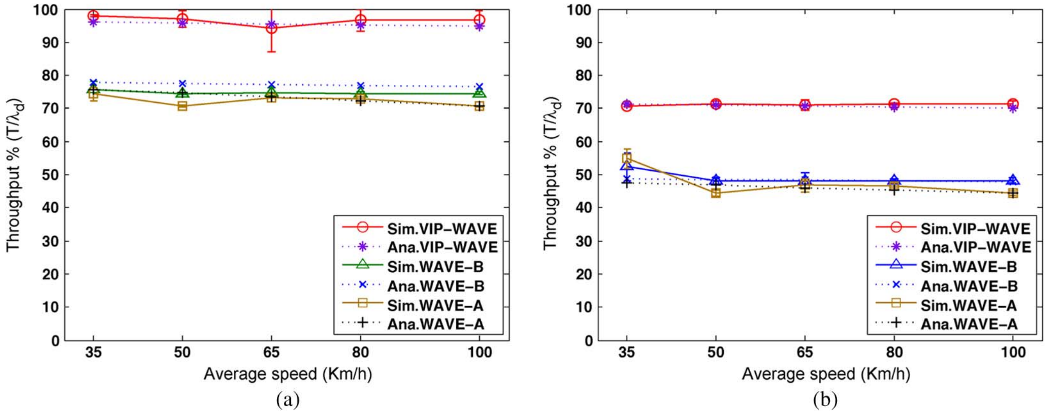


Fig. 9. Nodal downstream throughput for different levels of presence of infrastructure, average speed $v = 35$ Km/h, constant density $\rho = 1/25$ vpm, and $p_r = 0.4$. (a) One-way traffic. (b) Two-way traffic.

Furthermore, as shown in Fig. 9(a), the performance of VIP-WAVE outperforms the standard one even when the same IP mobility protocol is employed. It is also observed how the effective throughput drops for all as soon as $X > 2R$. This is due to the existence of uncovered areas between consecutive RSUs; in the case of VIP-WAVE, the greater X is, the more the vehicle depends on the density ρ for being able to find a two-hop connection toward an RSU, as shown later in Section V-E. Furthermore, it is observed that it is more probable for vehicles to find a two-hop connection to the RSU when $X < 2R + r$. However, this condition only benefits the VIP-WAVE scheme as neither WAVE-A nor WAVE-B supports multihop communications. On the other hand, in Fig. 9(b), it can be seen how the reduced coverage observed by two-way traffic applications results in a steeper decrease in throughput. In such a case, due to a shorter connectivity range, the effective throughput starts decreasing as soon as $X > 2r$.

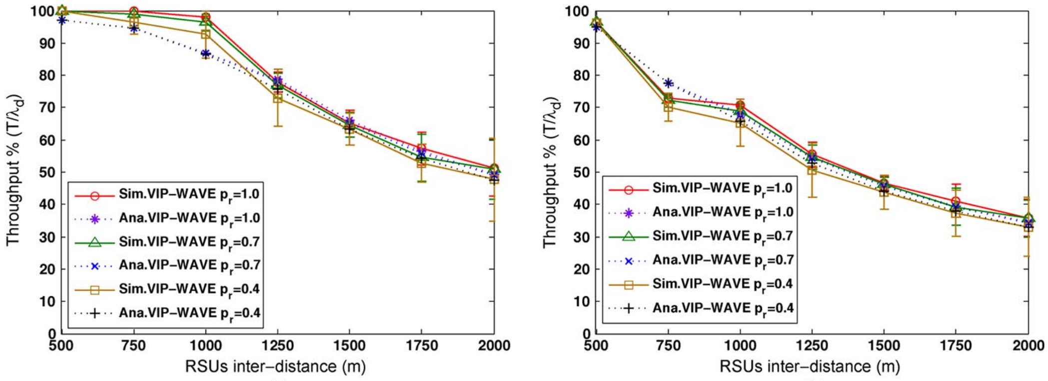
D. Impact of Velocity and Available Relays

The impact on throughput performance given different values of v is illustrated in Fig. 10. Once more, the numerical results are shown to be accurate when compared to simulation results. It is observed that both VIP-WAVE and standard WAVE are stable for different average speeds. With regard to the type of



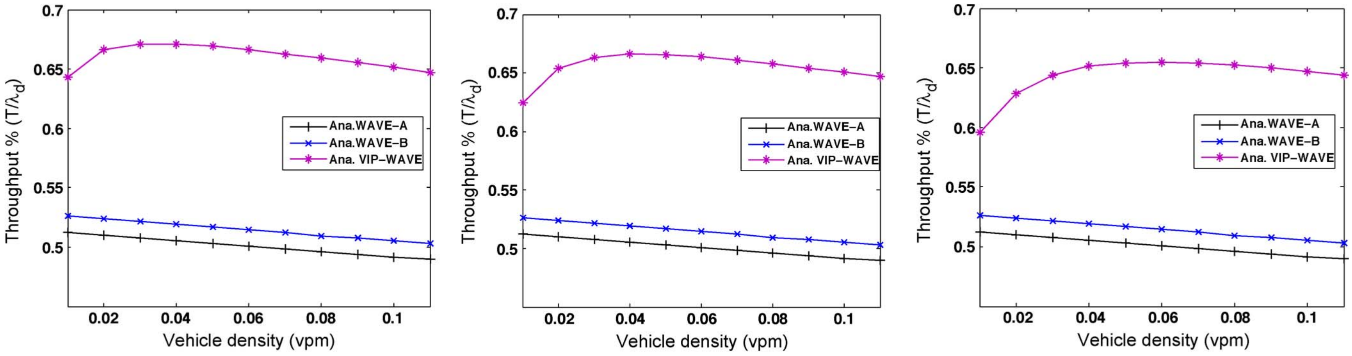
(a) (b)

Fig. 10. Nodal downstream throughput for different average speeds, RSU interdistance $X = 1000$ m, and constant density $\rho = 1/25$ vpm. (a) One-way traffic. (b) Two-way traffic.



(a) (b)

Fig. 11. Nodal downstream throughput for different relay availability and RUS interdistance, RSU interdistance $X = 1000$ m, average speed $v = 35$ Km/h, and constant density $\rho = 1/25$ vpm. (a) One-way traffic. (b) Two-way traffic.



(a) (b) (c)

Fig. 12. Nodal downstream throughput for different vehicle densities, RSU interdistance $X = 1500$ m, and average speed $v = 35$ Km/h. (a) $p_r = 1.0$. $p_r = 0.7$. (c) $p_r = 0.4$.

traffic, in Fig. 10(b), we observe nearly a 30% reduction of successful reception of packets when the IP application requires bidirectional connection. However, the extended area of coverage provided by the relay-aided communications in VIP-WAVE demonstrates its benefit: it improves the effective throughput by nearly 20% compared to the standard WAVE. Consequently, we also evaluate the impact of the available number of OBUs willing to serve as relays (i.e., p_r) in VIP-WAVE. The results of these experiments are depicted in Fig. 11. The figure indicates that even for a low availability of 40%, the difference in the effective throughput is minimum, i.e., VIP-WAVE only requires one neighboring OBU to be available (and connected to the RSU) to take advantage of two-hop connections in uncovered areas.

E. Impact of Vehicle Density

Fig. 12 depicts the analytical throughput given different densities in a low-level presence of infrastructure (i.e., $X = 1500$ m). The trends of throughput can be observed in

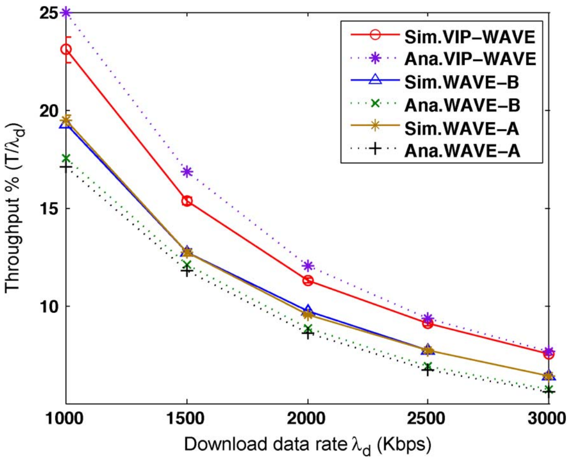


Fig. 13. Nodal downstream throughput under saturated conditions for highly demanding IP applications, RSU interdistance $X = 1500$ m, average speed $v = 35$ Km/h, and constant density $\rho = 1/25$ vpm.

terms of vehicle density when the percentage of available relays decreases from 100% to 70% and 40%. For both WAVE-A and WAVE-B, the throughput decreases almost linearly when the vehicle density increases, regardless of the values of p_r. This is the result of an increase in congestion when there are more nodes in the vehicular network. Instead, in the case of VIP-WAVE, since it supports multihop communications, a greater p_r value directly translates into an increase of throughput and a better performance than that obtained by the standard WAVE in all three cases. However, it can also be observed that VIP-WAVE's throughput increases up to the maximal value, but thereafter it starts decreasing with the increase of vehicle density. The reason of the throughput increase before the maximum point is due to a greater number of available relays when the vehicle density increases. After the maximum point, the throughput decreases because as there are more vehicles on the road, the congestion of communications is dominant over the benefit from the increase of available relays. Fig. 12(a)–(c) exemplify how the maximum point varies according to the different values of p_r.

F. Impact of Download Data Rates

An evaluation of how data rate demanding IP applications (i.e., $\lambda_d > 1$ Mpbs) affect the overall performance of the nodal throughput is illustrated in Fig. 13. In the experiment, we calculate the throughput of VIP-WAVE and WAVE standards under saturated conditions for a vehicular network with low-level presence of infrastructure. In all three cases, simulation and analytical results are configured to allow for 60% of the nodes around the tagged vehicles to be actively transmitting in the same SCH. Since every active vehicle intends to transmit at a larger data rate, the congestion of communications becomes more and more severe, and thus, the performance of throughput degrades when the data rate increases. At the same time, a larger amount of data packets are lost when the OBU is experiencing a handover.

We can also observe that the improvement obtained by VIP-WAVE compared to the standard WAVE tends to be reduced due to the congestion of communications becoming dominant for larger data rates. However, these throughput measurements may actually be better in real life scenarios, since the MAC layer in 802.11p/WAVE allows for prioritization of traffic by means of the EDCA mechanism (for simplicity, our simulation employs a single access category queue). Furthermore, access control and quality of service policies could be imposed in order to guarantee the minimum level of quality to the OBUs that are consuming the IP service [34].

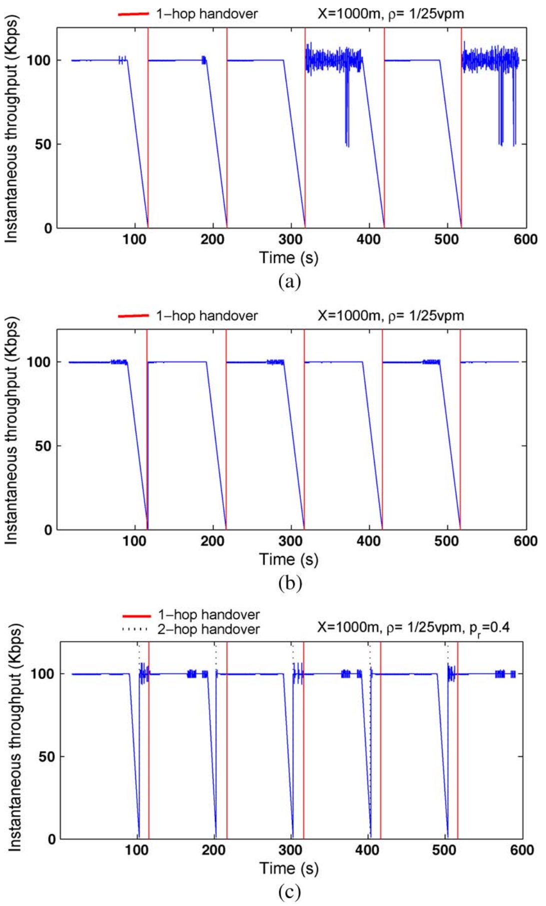


Fig. 14. Instantaneous throughput and handover delay for different WAVE schemes. (a) WAVE-A. (b) WAVE-B. (c) VIP-WAVE.

G. Instantaneous Throughput and Delay

In order to evaluate the throughput behavior during a given session time, we show in Fig. 14 the instantaneous throughput for the different schemes. In all three schemes, 60% of the nodes around the tagged vehicles are subscribed to the same service, which means that there are other nodes that are actively transmitting in the same SCH. In the case of VIP-WAVE, this condition translates to having a 40% probability of finding an available relay among the neighboring vehicles.

The figures illustrate the times at which every handover occurs. Given the constant average speed and the fixed distance between RSUs, it is expected for the handovers to occur every fixed number of seconds. Nonetheless, the results help understand the behavior during handovers in each scheme. It is observed how the presence of an IP mobility management scheme makes smoother the transition during handovers

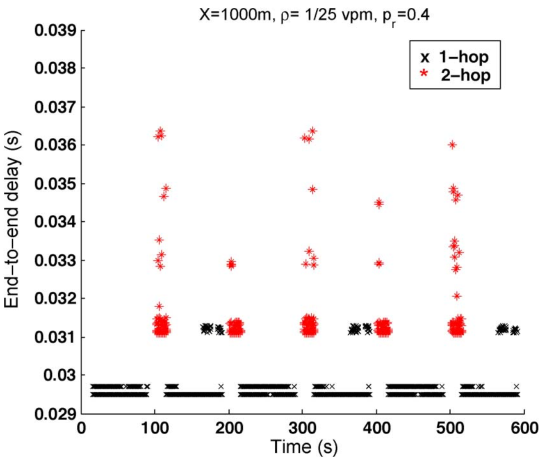


Fig. 15. Data packet end-to-end delay in VIP-WAVE.

when comparing WAVE-A [see Fig. 14(a)] with WAVE-B [see Fig. 14(b)]. Moreover, although the region between RSUs is fully covered when $X = 1000$ m, the handover delay in WAVE-A and WAVE-B is longer than that experienced in VIP-WAVE. This is because the OBU needs to reestablish the connection with the new RSU, and given that $r < R$, it takes some time until the RSU is able to receive the location update in the form of an RS or a RESET message from the OBU. Such reception is only possible when $x < R$ or $x > X–R$, where x is the OBU's location. This phenomenon has a smaller impact in VIP-WAVE, since the framework allows for two-hop communications toward the RSU when the OBU is unable to communicate directly. Thus, the total handover delay in VIP-WAVE is reduced, and a smaller number of packet losses is perceived by the IP application.

Additionally, in Fig. 14(c), it can be observed that the overhead incurred in establishing the relayed connection plays a minor impact in the overall performance of the end-to-end communications. Thus, the throughput remains fairly stable at the same time the relaying helps reduce the total packet losses.

Furthermore, as many IP applications are delay sensitive, we evaluate the effect of two-hop communications in the data packet end-to-end delay. Fig. 15 shows the latency experienced by individual packets received at the OBU during a session time. For those packets being transmitted through a two-hop connection in the 802.11p network, they perceive a slightly higher latency than those using a one-hop connection. However, the total delay, which is less than 37 ms in all cases, fits well into the delay requirements for the main multimedia applications, such as 150 ms for real time audio and 250 ms for video conferencing and video streaming. The variations observed in the delay of packets using the same number of hops come from the MAC layer retransmissions that are caused when there are colliding packets in the wireless domain.

VI. CONCLUSION

In this paper, we have proposed a novel framework for the support of IP communications in 802.11p/WAVE networks. In particular, we have studied the limitations in the 802.11p/WAVE standard for the operation and differentiation of IP applications, and have proposed the VIP-WAVE framework to address such limitations. VIP-WAVE has demonstrated to notably improve the performance of IP applications even when a low presence of infrastructure results in large gaps between areas of coverage. Moreover, the protocols and mechanisms proposed in VIP-WAVE for IP addressing, mobility management, and multi-hop communications have been all designed according to the intricacies and special characteristics of 802.11p/WAVE networks. In addition, we have provided an accurate analytical model that allows for the integration of aspects from different layers, such as mobility and channel conditions, probability of connectivity to the infrastructure, handover delays, and packet collision probabilities, in order to estimate the nodal downstream throughput perceived by a WAVE user that is consuming an IP service from the infrastructure.

We conclude by reinforcing our observation that the individual downloading data rate perceived by an OBU is highly dependant on the road density and the interdistance of the RSUs. Our results suggest that it is beneficial for 802.11p/WAVE networks to put in place multi-hop communications, which extend the area of coverage and help to make smoother the transitions during handovers. As a next step, we plan to further improve the relay selection mechanism to incorporate policies of selection that choose the best relay based on different parameters, such as relay reliability and link duration.

ACKNOWLEDGMENT

The authors would like to thank their colleagues, Dr. M. Asefi, and the members of the VANET/DTN-BBCR group for the lively discussions that have significantly improved the quality of this paper. Thanks are also extended to the anonymous reviewers for their careful reading and insightful comments. Part of this work will be presented in IEEE Globecom 2012.

REFERENCES

[1] C. Wewetzer, M. Caliskan, K. Meier, and A. Luebke, “Experimental evaluation of UMTS and wireless LAN for inter-vehicle communication,” in *Proc. 7th ITST*, 2007, pp. 1–6.
[2] J. Eriksson, H. Balakrishnan, and S. Madden, “Cabernet: Vehicular content delivery using WiFi,” in *Proc. ACM MobiCom*, 2008, pp. 199–210.
[3] Autonet Mobile. [Online]. Available: http://www.autonetmobile.com/
[4] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment: Wireless Access in Vehicular Environments*, IEEE Std. P802.11p, Jul. 15, 2010.
[5] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) Multi-channel Operation*, IEEE Std. 1609.4-2010, Feb. 7, 2011 (Rev. IEEE Std. 1609.4-2006).
[6] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)—Networking Services*, IEEE Std. 1609.3-2010, Dec. 30, 2010 (Rev. IEEE Std. 1609.3-2007).
[7] E. Baccelli, T. Clausen, and R. Wakikawa, “IPv6 operation for WAVE - Wireless access in vehicular environments,” in *Proc. IEEE VNC*, 2010, pp. 160–165.
[8] T. Narten, E. Nordmark, W. Simpson, and H. Soliman, “Neighbor discovery for IP version 6 (IPv6),” IETF, RFC 4861 (Draft Standard), Sep. 2007. [Online]. Available:http://www.ietf.org/rfc/rfc4861.txt
[9] M. Grossglauser and D. Tse, “Mobility increases the capacity of ad hoc wireless networks,” *IEEE/ACM Trans. Netw.*, vol. 10, no. 4, pp. 477–486, Aug. 2002.
[10] M. E. Mahmoud and X. Shen, “PIS: A practical incentive system for multihop wireless networks,” *IEEE Trans. Veh. Technol.*, vol. 59, no. 8, pp. 4012–4025, Oct. 2010.

[11] *Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 6: Internet Integration; Sub-Part 1: Transmission of IPv6 Packets Over GeoNetworking Protocols*, Technical Specification, European Telecommunications StandardsInstitute (ETSI), vol. 1, pp. 1–45, TS 102 636-6-1, Nov. 2011.

[12] S. D. Maria Fazio, "Automatic IP address configuration in VANETs," in *Proc. ACM VANET*, 2006, pp. 100–101.

[13] R. Baldessari, C. J. Bernardos, and M. Calderon, "GeoSAC—Scalable address autoconfiguration for VANET using geographic networking concepts," in *Proc. IEEE PIMRC*, 2008, pp. 1–7.

[14] T. Kato, K. Kadowaki, T. Koita, and K. Sato, "Routing and address assignment using lane/position information in a vehicular ad hoc network," in *Proc. IEEE APSCC*, 2008, pp. 1600–1605.

[15] R. Baldessari, W. Zhang, A. Festag, and L. Le, "A MANET-centric solution for the application of NEMO in VANET using geographic routing," in *Proc. TridentCom*, 2008, pp. 1–7.

[16] A. Prakash, S. Tripathi, R. Verma, N. Tyagi, R. Tripathi, and K. Naik, "Vehicle assisted cross-layer handover scheme in NEMO-based VANETs (VANEMO)," *Int. J. Internet Protocol Technol.*, vol. 6, no. 1/2, pp. 83–95, Jun. 2011.

[17] B. Azzedine, Z. Zhenxia, Fei, and Xin, "Reducing handoff latency for NEMO-based vehicular ad hoc networks," in *Proc. IEEE GLOBECOM*, 2011, pp. 1–5.

[18] S. Céspedes, X. Shen, and C. Lazo, "IP mobility management for vehicular communication networks: Challenges and solutions," *IEEE Commun. Mag.*, vol. 49, no. 5, pp. 187–194, May 2011.

[19] I. Soto, C. J. Bernardos, M. Calderon, A. Banchs, and A. Azcorra, "Nemo-enabled localized mobility support for Internet access in automotive scenarios," *IEEE Commun. Mag.*, vol. 47, no. 5, pp. 152–159, May 2009.

[20] J.-H. Lee, T. Ernst, and N. Chilamkurti, "Performance analysis of PMIPv6-based network mobility for intelligent transportation systems," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 74–85, Jan. 2012.

[21] M. Tsukada, I. B. Jemaa, H. Menouar, W. Zhang, M. Goleva, and T. Ernst, "Experimental evaluation for IPv6 over VANET geographic routing," in *Proc. IWCMC*, 2010, pp. 736–741.

[22] S.-Y. Wang, H.-L. Chao, K.-C. Liu, T.-W. He, C.-C. Lin, and C.-L. Chou, "Evaluating and improving the TCP/UDP performances of IEEE 802.11(p)/1609 networks," in *Proc. IEEE ISCC*, 2008, pp. 163–168.

[23] M. J. Khabbaz, W. F. Fawaz, and C. M. Assi, "A simple free-flow traffic model for vehicular intermittently connected networks," *IEEE Trans. Intell. Transp. Syst.*, pp. 1–15, 2012, DOI: 10.1109/TITS.2012.2188519, to be published.

[24] S. C. Ng, W. Zhang, Y. Zhang, and Y. Yang, "Analysis of access and connectivity probabilities in vehicular relay networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 140–150, Jan. 2011.

[25] T. H. Luan, X. Ling, and X. Shen, "MAC in motion: Impact of mobility on the MAC of drive-thru Internet," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 305–319, Feb. 2012.

[26] A. Abdrabou and W. Zhuang, "Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 129–139, Jan. 2011.

[27] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, "Analytical study of the IEEE 802.11p MAC sublayer in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 873–886, Jun. 2012.

[28] Y. Kim, K. Kim, S. Pack, and W. Lee, "Analysis of session handoff probability in NEMO-based vehicular networks," *Wireless Pers. Commun.*, vol. 61, no. 4, pp. 697–710, Dec. 2011.

[29] M. Khabbaz, W. Fawaz, and C. Assi, "Probabilistic bundle relaying schemes in two-hop vehicular delay tolerant networks," *IEEE Commun. Lett.*, vol. 15, no. 3, pp. 281–283, Mar. 2011.

[30] Y. Du, L. Zhang, Y. Feng, Z. Ren, and Z. Wang, "Performance analysis and enhancement of IEEE 802.11 p/1609 protocol family in vehicular environments," in *Proc. IEEE ITSC*, 2010, pp. 1085–1090.

[31] S. Eichler, "Performance evaluation of the IEEE 802.11p WAVE communication standard," in *Proc. IEEE VTC*, 2007, pp. 2199–2203.

[32] W. L. Tan, W. C. Lau, O. Yue, and T. H. Hui, "Analytical models and performance evaluation of drive-thru Internet systems," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 207–222, Jan. 2011.

[33] W. Tonguz, O. K. Viriyasitavat, and F. Bai, "Modeling urban traffic: A cellular automata approach," *IEEE. Commun. Mag.*, vol. 47, no. 5, pp. 142–150, May 2009.

[34] H. T. Cheng, H. Shan, and W. Zhuang, "Infotainment and road safety service support in vehicular networking: From a communication perspective," *Mech. Syst. Signal Process.*, vol. 25, no. 6, pp. 2020–2038, Aug. 2011.

Sandra Céspedes (S'09) received the B.Sc. (Hons.) and Specialization degrees in telematics engineering and management of information systems from Icesi University, Cali, Colombia, in 2003 and 2007, respectively. She is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada.

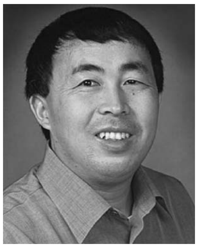
She is also currently an Assistant Professor with the Department of Information and Communications Technology, Icesi University. Her research focuses on the topics of mobility management and routing in vehicular communication systems and smart grid communications.

Ms. Céspedes served as a Technical Program Committee member for the IEEE Fall 2010 Vehicular Technology Conference. She received the Returning Fellowship to the Internet Engineering Task Force from the Internet Society in 2007, 2009, 2010, and 2012.

Ning Lu (S'12) received the B.Sc. and M.Sc. degrees from Tongji University, Shanghai, China, in 2007 and 2010, respectively. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada.

His current research interests include capacity and delay analysis, media access control, and routing protocol design for vehicular networks.

Mr. Lu served as a Technical Program Committee Member for IEEE 2012 International Symposium on Personal, Indoor, and Mobile Radio Communications.



Xuemin (Sherman) Shen (M'97–SM'02–F'09) received the B.Sc. degree from Dalian Maritime University, Dalian, China, 1982 and the M.Sc. and Ph.D. degrees in electrical engineering from Rutgers University, Camden, NJ, 1987 and 1990, respectively.

He is a Professor and the University Research Chair with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. He was the Associate Chair for Graduate Studies from 2004 to 2008. He is the coauthor/editor of six books and has published many papers and book chapters on wireless communications and networks, control, and filtering. His research focuses on resource management in interconnected wireless/wired networks, wireless network security, wireless body area networks, vehicular ad hoc, and sensor networks.

Dr. Shen served as the Technical Program Committee Chair for IEEE VTC'10 Fall, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC'08, the Technical Program Committee Chair for IEEE Globecom'07, the General Co-Chair for Chinacom'07 and QShine'06, the Chair for IEEE Communications Society Technical Committee on Wireless Communications, and Peer-to-Peer Communications and Networking. He also serves/served as the Editor-in-Chief for *IEEE Network, Peer-to-Peer Networking and Application, and IET Communications*; a Founding Area Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS; an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *Computer Networks, ACM/Wireless Networks*, etc.; and a Guest Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, *IEEE Wireless Communications, IEEE Communications Magazine, and ACM Mobile Networks and Applications*. He received the Excellent Graduate Supervision Award in 2006 and the Outstanding Performance Award in 2004, 2007, and 2010 from the University of Waterloo; the Premier's Research Excellence Award in 2003 from the Province of Ontario; and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. He is a Registered Professional Engineer of Ontario, an Engineering Institute of Canada Fellow, and a Distinguished Lecturer of the IEEE Vehicular Technology and Communications Societies.