Workgroup: IPWAVE Working Group
Internet-Draft:
draft-ietf-ipwave-vehicular-networking-25
Published: 13 February 2022
Intended Status: Informational
Expires: 17 August 2022
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IPv6 Wireless Access in Vehicular Environments (IPWAVE): Problem Statement and Use Cases

Abstract

This document discusses the problem statement and use cases of IPv6-based vehicular networking for Intelligent Transportation Systems (ITS). The main scenarios of vehicular communications are vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communications. First, this document explains use cases using V2V, V2I, and V2X networking. Next, for IPv6-based vehicular networks, it makes a gap analysis of current IPv6 protocols (e.g., IPv6 Neighbor Discovery, Mobility Management, and Security & Privacy), and then enumerates requirements for the extensions of those IPv6 protocols for IPv6-based vehicular networking.

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Table of Contents

1. Introduction
2. Terminology
3. Use Cases
   3.1. V2V
   3.2. V2I
   3.3. V2X
4. Vehicular Networks
   4.1. Vehicular Network Architecture
   4.2. V2I-based Internetworking
   4.3. V2V-based Internetworking
5. Problem Statement
   5.1. Neighbor Discovery
      5.1.1. Link Model
      5.1.2. MAC Address Pseudonym
      5.1.3. Routing
   5.2. Mobility Management
6. Security Considerations
   6.1. Security Threats in Neighbor Discovery
   6.2. Security Threats in Mobility Management
   6.3. Other Threats
7. IANA Considerations
8. References
   8.1. Normative References
   8.2. Informative References
Appendix A. Support of Multiple Radio Technologies for V2V
Appendix B. Support of Multihop V2X Networking
Appendix C. Support of Mobility Management for V2I
Appendix D. Acknowledgments
Appendix E. Contributors
Author's Address

1. Introduction

Vehicular networking studies have mainly focused on improving safety and efficiency, and also enabling entertainment in vehicular networks. The Federal Communications Commission (FCC) in the US allocated wireless channels for Dedicated Short-Range Communications (DSRC) [DSRC] in the Intelligent Transportation Systems (ITS) with the frequency band of 5.850 - 5.925 GHz (i.e., 5.9 GHz band). DSRC-

based wireless communications can support vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) networking. The European Union (EU) allocated radio spectrum for safety-related and non-safety-related applications of ITS with the frequency band of 5.875 - 5.905 GHz, as part of the Commission Decision 2008/671/EC [EU-2008-671-EC].

For direct inter-vehicular wireless connectivity, IEEE has amended standard 802.11 (commonly known as Wi-Fi) to enable safe driving services based on DSRC for the Wireless Access in Vehicular Environments (WAVE) system. The Physical Layer (L1) and Data Link Layer (L2) issues are addressed in IEEE 802.11p [IEEE-802.11p] for the PHY and MAC of the DSRC, while IEEE 1609.2 [WAVE-1609.2] covers security aspects, IEEE 1609.3 [WAVE-1609.3] defines related services at network and transport layers, and IEEE 1609.4 [WAVE-1609.4] specifies the multi-channel operation. IEEE 802.11p was first a separate amendment, but was later rolled into the base 802.11 standard (IEEE 802.11-2012) as IEEE 802.11 Outside the Context of a Basic Service Set (OCB) in 2012 [IEEE-802.11-OCB].

3GPP has standardized Cellular Vehicle-to-Everything (C-V2X) communications to support V2X in LTE mobile networks (called LTE V2X) and V2X in 5G mobile networks (called 5G V2X) [TS-23.285-3GPP] [TR-22.886-3GPP][TS-23.287-3GPP]. With C-V2X, vehicles can directly communicate with each other without relay nodes (e.g., eNodeB in LTE and gNodeB in 5G).

Along with these WAVE standards and C-V2X standards, regardless of a wireless access technology under the IP stack of a vehicle, vehicular networks can operate IP mobility with IPv6 [RFC8200] and Mobile IPv6 protocols (e.g., Mobile IPv6 (MIPv6) [RFC6275], Proxy MIPv6 (PMIPv6) [RFC5213], Distributed Mobility Management (DMM) [RFC7333], Network Mobility (NEMO) [RFC3963], Locator/ID Separation Protocol (LISP) [I-D.ietf-lisp-rfc6830bis], and Asymmetric Extended Route Optimization (AERO) [I-D.templin-6man-aero]). In addition, ISO has approved a standard specifying the IPv6 network protocols and services to be used for Communications Access for Land Mobiles (CALM) [ISO-ITS-IPv6][ISO-ITS-IPv6-AMD1].

This document describes use cases and a problem statement about IPv6-based vehicular networking for ITS, which is named IPv6 Wireless Access in Vehicular Environments (IPWAVE). First, it introduces the use cases for using V2V, V2I, and V2X networking in ITS. Next, for IPv6-based vehicular networks, it makes a gap analysis of current IPv6 protocols (e.g., IPv6 Neighbor Discovery, Mobility Management, and Security & Privacy), and then enumerates requirements for the extensions of those IPv6 protocols, which are tailored to IPv6-based vehicular networking. Thus, this document is intended to motivate development of key protocols for IPWAVE.

2. Terminology

This document uses the terminology described in [RFC8691]. In addition, the following terms are defined below:

*Class-Based Safety Plan: A vehicle can make a safety plan by classifying the surrounding vehicles into different groups for safety purposes according to the geometrical relationship among them. The vehicle groups can be classified as Line-of-Sight Unsafe, Non-Line-of-Sight Unsafe, and Safe groups [CASD].

*Context-Awareness: A vehicle can be aware of spatial-temporal mobility information (e.g., position, speed, direction, and acceleration/deceleration) of surrounding vehicles for both safety and non-safety uses through sensing or communication [CASD].

*DMM: "Distributed Mobility Management" [RFC7333][RFC7429].

*Edge Computing (EC): It is the local computing near an access network (i.e., edge network) for the sake of vehicles and pedestrians.

*Edge Computing Device (ECD): It is a computing device (or server) for edge computing for the sake of vehicles and pedestrians.

*Edge Network (EN): It is an access network that has an IP-RSU for wireless communication with other vehicles having an IP-OBU and wired communication with other network devices (e.g., routers, IP-RSUs, ECDs, servers, and MA). It may have a Global Positioning System (GPS) radio receiver for its position recognition and the localization service for the sake of vehicles.

*IP-OBU: "Internet Protocol On-Board Unit": An IP-OBU denotes a computer situated in a vehicle (e.g., car, bicycle, autobike, motor cycle, and a similar one) and a device (e.g., smartphone and Internet-of-Things (IoT) device). It has at least one IP interface that runs in IEEE 802.11-OCB and has an "OBU" transceiver. Also, it may have an IP interface that runs in Cellular V2X (C-V2X) [TS-23.285-3GPP] [TR-22.886-3GPP] [TS-23.287-3GPP]. It can play a role of a router connecting multiple computers (or in-vehicle devices) inside a vehicle. See the definition of the term "OBU" in [RFC8691].

*IP-RSU: "IP Roadside Unit": An IP-RSU is situated along the road. It has at least two distinct IP-enabled interfaces. The wireless PHY/MAC layer of at least one of its IP-enabled interfaces is configured to operate in 802.11-OCB mode. An IP-RSU communicates with the IP-OBU over an 802.11 wireless link operating in OCB mode. Also, it may have an IP interface that runs in C-V2X along

with an "RSU" transceiver. An IP-RSU is similar to an Access Network Router (ANR), defined in [RFC3753], and a Wireless Termination Point (WTP), defined in [RFC5415]. See the definition of the term "RSU" in [RFC8691].

*LiDAR: "Light Detection and Ranging". It is a scanning device to measure a distance to an object by emitting pulsed laser light and measuring the reflected pulsed light.

*Mobility Anchor (MA): A node that maintains IPv6 addresses and mobility information of vehicles in a road network to support their IPv6 address autoconfiguration and mobility management with a binding table. An MA has End-to-End (E2E) connections (e.g., tunnels) with IP-RSUs under its control for the address autoconfiguration and mobility management of the vehicles. This MA is similar to a Local Mobility Anchor (LMA) in PMIPv6 [RFC5213] for network-based mobility management.

*OCB: "Outside the Context of a Basic Service Set - BSS". It is a mode of operation in which a Station (STA) is not a member of a BSS and does not utilize IEEE Std 802.11 authentication, association, or data confidentiality [IEEE-802.11-OCB].

*802.11-OCB: It refers to the mode specified in IEEE Std 802.11-2016 [IEEE-802.11-OCB] when the MIB attribute dot11OCBActivited is 'true'.

*Platooning: Moving vehicles can be grouped together to reduce air-resistance for energy efficiency and reduce the number of drivers such that only the leading vehicle has a driver, and the other vehicles are autonomous vehicles without a driver and closely follow the leading vehicle [Truck-Platooning].

*Traffic Control Center (TCC): A system that manages road infrastructure nodes (e.g., IP-RSUs, MAs, traffic signals, and loop detectors), and also maintains vehicular traffic statistics (e.g., average vehicle speed and vehicle inter-arrival time per road segment) and vehicle information (e.g., a vehicle's identifier, position, direction, speed, and trajectory as a navigation path). TCC is part of a vehicular cloud for vehicular networks.

*Vehicle: A Vehicle in this document is a node that has an IP-OBU for wireless communication with other vehicles and IP-RSUs. It has a GPS radio navigation receiver for efficient navigation. Any device having an IP-OBU and a GPS receiver (e.g., smartphone and tablet PC) can be regarded as a vehicle in this document.

*Vehicular Ad Hoc Network (VANET): A network that consists of vehicles interconnected by wireless communication. Two vehicles

in a VANET can communicate with each other using other vehicles as relays even where they are out of one-hop wireless communication range.

*Vehicular Cloud: A cloud infrastructure for vehicular networks, having compute nodes, storage nodes, and network forwarding elements (e.g., switch and router).

*V2D: "Vehicle to Device". It is the wireless communication between a vehicle and a device (e.g., smartphone and IoT device).

*V2I2D: "Vehicle to Infrastructure to Device". It is the wireless communication between a vehicle and a device (e.g., smartphone and IoT device) via an infrastructure node (e.g., IP-RSU).

*V2I2V: "Vehicle to Infrastructure to Vehicle". It is the wireless communication between a vehicle and another vehicle via an infrastructure node (e.g., IP-RSU).

*V2I2X: "Vehicle to Infrastructure to Everything". It is the wireless communication between a vehicle and another entity (e.g., vehicle, smartphone, and IoT device) via an infrastructure node (e.g., IP-RSU).

*V2X: "Vehicle to Everything". It is the wireless communication between a vehicle and any entity (e.g., vehicle, infrastructure node, smartphone, and IoT device), including V2V, V2I, and V2D.

*VIP: "Vehicular Internet Protocol". It is an IPv6 extension for vehicular networks including V2V, V2I, and V2X.

*VMM: "Vehicular Mobility Management". It is an IPv6-based mobility management for vehicular networks.

*VND: "Vehicular Neighbor Discovery". It is an IPv6 ND extension for vehicular networks.

*VSP: "Vehicular Security and Privacy". It is an IPv6-based security and privacy for vehicular networks.

*WAVE: "Wireless Access in Vehicular Environments" [WAVE-1609.0].

3. Use Cases

This section explains use cases of V2V, V2I, and V2X networking. The use cases of the V2X networking exclude the ones of the V2V and V2I networking, but include Vehicle-to-Pedestrian (V2P) and Vehicle-to-Device (V2D).

IP is widely used among popular end-user devices (e.g., smartphone and tablet) in the Internet. Applications (e.g., navigator application) for those devices can be extended such that the V2V use cases in this section can work with IPv6 as a network layer protocol and IEEE 802.11-OCB as a link layer protocol. In addition, IPv6 security needs to be extended to support those V2V use cases in a safe, secure, privacy-preserving way.

The use cases presented in this section serve as the description and motivation for the need to extend IPv6 and its protocols to facilitate "Vehicular IPv6". Section 5 summarizes the overall problem statement and IPv6 requirements. Note that the adjective "Vehicular" in this document is used to represent extensions of existing protocols such as IPv6 Neighbor Discovery, IPv6 Mobility Management (e.g., PMIPv6 [RFC5213] and DMM [RFC7429]), and IPv6 Security and Privacy Mechanisms rather than new "vehicular-specific" functions.

3.1. V2V

The use cases of V2V networking discussed in this section include

- Context-aware navigation for safe driving and collision avoidance;
- Cooperative adaptive cruise control in a roadway;
- Platooning in a highway;
- Cooperative environment sensing;
- Collision avoidance service of end systems of Urban Air Mobility (UAM) [I-D.templin-ipwave-uam-its].

These five techniques will be important elements for autonomous vehicles, which may be either terrestrial vehicles or UAM end systems.

Context-Aware Safety Driving (CASD) navigator [CASD] can help drivers to drive safely by alerting them to dangerous obstacles and situations. That is, a CASD navigator displays obstacles or neighboring vehicles relevant to possible collisions in real-time through V2V networking. CASD provides vehicles with a class-based automatic safety action plan, which considers three situations, namely, the Line-of-Sight unsafe, Non-Line-of-Sight unsafe, and safe situations. This action plan can be put into action among multiple vehicles using V2V networking.

Cooperative Adaptive Cruise Control (CACC) [CA-Cruise-Control] helps individual vehicles to adapt their speed autonomously through V2V

communication among vehicles according to the mobility of their predecessor and successor vehicles in an urban roadway or a highway. Thus, CACC can help adjacent vehicles to efficiently adjust their speed in an interactive way through V2V networking in order to avoid a collision.

Platooning [Truck-Platooning] allows a series (or group) of vehicles (e.g., trucks) to follow each other very closely. Trucks can use V2V communication in addition to forward sensors in order to maintain constant clearance between two consecutive vehicles at very short gaps (from 3 meters to 10 meters). Platooning can maximize the throughput of vehicular traffic in a highway and reduce the gas consumption because the leading vehicle can help the following vehicles to experience less air resistance.

Cooperative-environment-sensing use cases suggest that vehicles can share environmental information (e.g., air pollution, hazards/ obstacles, slippery areas by snow or rain, road accidents, traffic congestion, and driving behaviors of neighboring vehicles) from various vehicle-mounted sensors, such as radars, LiDARs, and cameras, with other vehicles and pedestrians. [Automotive-Sensing] introduces millimeter-wave vehicular communication for massive automotive sensing. A lot of data can be generated by those sensors, and these data typically need to be routed to different destinations. In addition, from the perspective of driverless vehicles, it is expected that driverless vehicles can be mixed with driver-operated vehicles. Through cooperative environment sensing, driver-operated vehicles can use environmental information sensed by driverless vehicles for better interaction with the other vehicles and environment. Vehicles can also share their intended maneuvering information (e.g., lane change, speed change, ramp in-and-out, cut-in, and abrupt braking) with neighboring vehicles. Thus, this information sharing can help the vehicles behave as more efficient traffic flows and minimize unnecessary acceleration and deceleration to achieve the best ride comfort.

A collision avoidance service of UAM end systems in air can be envisioned as a use case in air vehicular environments. This use case is similar to the context-aware navigator for terrestrial vehicles. Through V2V coordination, those UAM end systems (e.g., drones) can avoid a dangerous situation (e.g., collision) in three-dimensional space rather than two-dimensional space for terrestrial vehicles. Also, UAM end systems (e.g., flying car) with only a few meters off the ground can communicate with terrestrial vehicles with wireless communication technologies (e.g., DSRC, LTE, and C-V2X). Thus, V2V means any vehicle to any vehicle, whether the vehicles are ground-level or not.

To encourage more vehicles to participate in this cooperative environmental sensing, a reward system will be needed. Sensing activities of each vehicle need to be logged in either a central way through a logging server (e.g., TCC) in the vehicular cloud or a distributed way (e.g., blockchain [Bitcoin]) through other vehicles or infrastructure. In the case of a blockchain, each sensing message from a vehicle can be treated as a transaction and the neighboring vehicles can play the role of peers in a consensus method of a blockchain [Bitcoin][Vehicular-BlockChain].

To support applications of these V2V use cases, the required functions of IPv6 include IPv6-based packet exchange and secure, safe communication between two vehicles. For the support of V2V under multiple radio technologies (e.g., DSRC and 5G V2X), refer to Appendix A.

3.2. V2I

The use cases of V2I networking discussed in this section include

- *Navigation service;
- *Energy-efficient speed recommendation service;
- *Accident notification service;
- *Electric vehicle (EV) charging service;
- *UAM navigation service with efficient battery charging.

A navigation service, for example, the Self-Adaptive Interactive Navigation Tool(SAINT) [SAINT], using V2I networking interacts with a TCC for the large-scale/long-range road traffic optimization and can guide individual vehicles along appropriate navigation paths in real time. The enhanced version of SAINT [SAINTplus] can give fast moving paths to emergency vehicles (e.g., ambulance and fire engine) to let them reach an accident spot while redirecting other vehicles near the accident spot into efficient detour paths.

Either a TCC or an ECD can recommend an energy-efficient speed to a vehicle that depends on its traffic environment and traffic signal scheduling [SignalGuru]. For example, when a vehicle approaches an intersection area and a red traffic light for the vehicle becomes turned on, it needs to reduce its speed to save fuel consumption. In this case, either a TCC or an ECD, which has the up-to-date trajectory of the vehicle and the traffic light schedule, can notify the vehicle of an appropriate speed for fuel efficiency. [Fuel-Efficient] studies fuel-efficient route and speed plans for platooned trucks.

The emergency communication between accident vehicles (or emergency vehicles) and a TCC can be performed via either IP-RSU or 4G-LTE networks. The First Responder Network Authority (FirstNet) [FirstNet] is provided by the US government to establish, operate, and maintain an interoperable public safety broadband network for safety and security network services, e.g., emergency calls. The construction of the nationwide FirstNet network requires each state in the US to have a Radio Access Network (RAN) that will connect to the FirstNet's network core. The current RAN is mainly constructed using 4G-LTE for the communication between a vehicle and an infrastructure node (i.e., V2I) [FirstNet-Report], but it is expected that DSRC-based vehicular networks [DSRC] will be available for V2I and V2V in the near future.

An EV charging service with V2I can facilitate the efficient battery charging of EVs. In the case where an EV charging station is connected to an IP-RSU, an EV can be guided toward the deck of the EV charging station through a battery charging server connected to the IP-RSU. In addition to this EV charging service, other value-added services (e.g., air firmware/software update and media streaming) can be provided to an EV while it is charging its battery at the EV charging station.

A UAM navigation service with efficient battery charging can plan the battery charging schedule of UAM end systems (e.g., drone) for long-distance flying [CBDN]. For this battery charging schedule, a UAM end system can communicate with an infrastructure node (e.g., IP-RSU) toward a cloud server via V2I communications. This cloud server can coordinate the battery charging schedules of multiple UAM end systems for their efficient navigation path, considering flight time from their current position to a battery charging station, waiting time in a waiting queue at the station, and battery charging time at the station.

The existing IPv6 protocol must be augmented through protocol changes in order to support wireless multihop V2I communications in a highway where RSUs are sparsely deployed, so a vehicle can reach the wireless coverage of an RSU through the multihop data forwarding of intermediate vehicles. Thus, IPv6 needs to be extended for multihop V2I communications.

To support applications of these V2I use cases, the required functions of IPv6 include IPv6-based packet exchange, transport-layer session continuity, and secure, safe communication between a vehicle and an infrastructure node (e.g., IP-RSU) in the vehicular network.

3.3. V2X

The use case of V2X networking discussed in this section is for a pedestrian protection service.

A pedestrian protection service, such as Safety-Aware Navigation Application (SANA) [SANA], using V2I2P networking can reduce the collision of a vehicle and a pedestrian carrying a smartphone equipped with a network device for wireless communication (e.g., Wi-Fi) with an IP-RSU. Vehicles and pedestrians can also communicate with each other via an IP-RSU. An edge computing device behind the IP-RSU can collect the mobility information from vehicles and pedestrians, compute wireless communication scheduling for the sake of them. This scheduling can save the battery of each pedestrian's smartphone by allowing it to work in sleeping mode before the communication with vehicles, considering their mobility.

For Vehicle-to-Pedestrian (V2P), a vehicle can directly communicate with a pedestrian's smartphone by V2X without IP-RSU relaying. Light-weight mobile nodes such as bicycles may also communicate directly with a vehicle for collision avoidance using V2V.

The existing IPv6 protocol must be augmented through protocol changes in order to support wireless multihop V2X or V2I2X communications in an urban road network where RSUs are deployed at intersections, so a vehicle (or a pedestrian's smartphone) can reach the wireless coverage of an RSU through the multihop data forwarding of intermediate vehicles (or pedestrians' smartphones) as packet forwarders. Thus, IPv6 needs to be extended for multihop V2X or V2I2X communications.

To support applications of these V2X use cases, the required functions of IPv6 include IPv6-based packet exchange, transport-layer session continuity, and secure, safe communication between a vehicle and a pedestrian either directly or indirectly via an IP-RSU.

4. Vehicular Networks

This section describes the context for vehicular networks supporting V2V, V2I, and V2X communications. It describes an internal network within a vehicle or an edge network (called EN). It explains not only the internetworking between the internal networks of a vehicle and an EN via wireless links, but also the internetworking between the internal networks of two vehicles via wireless links.

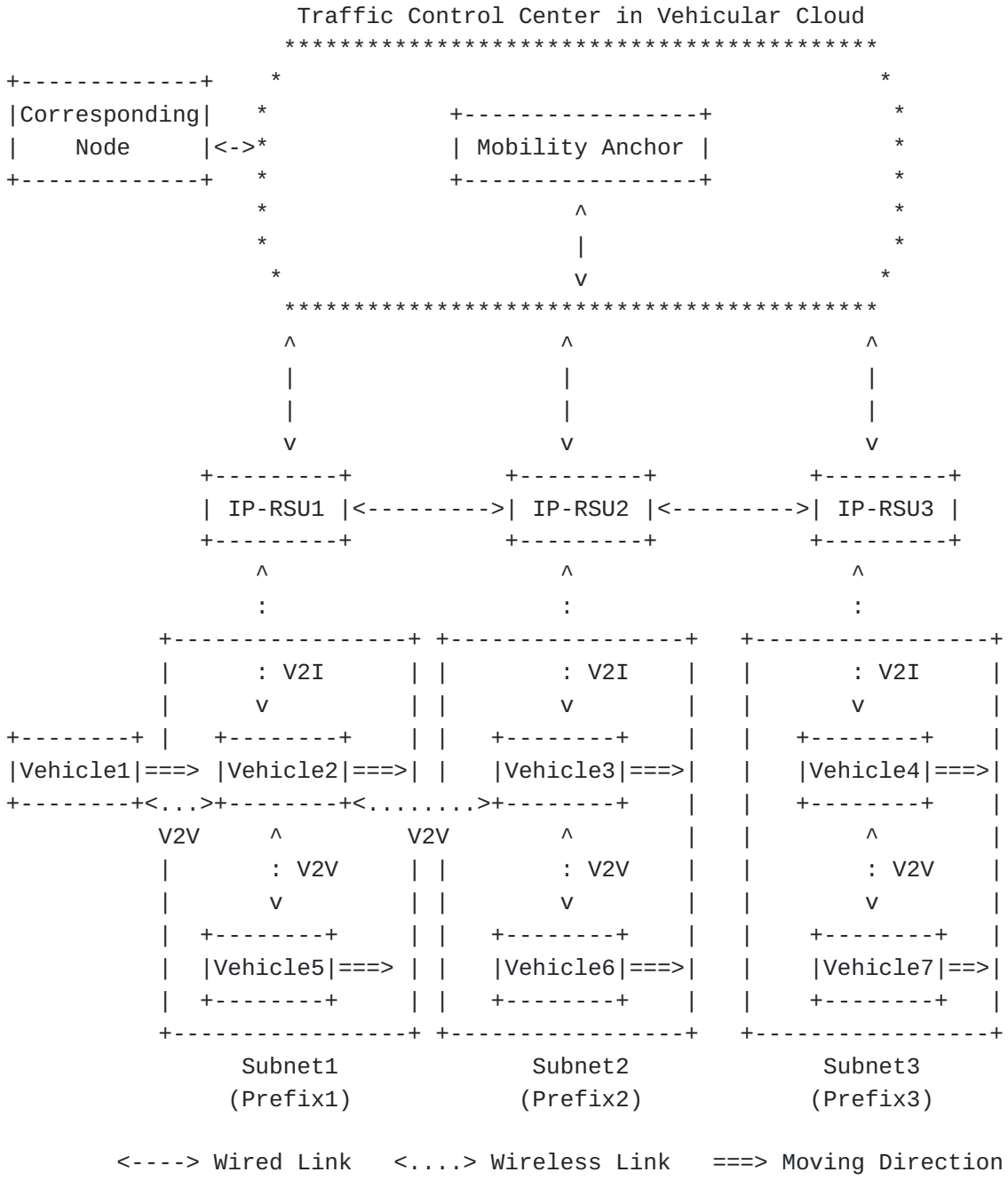


Figure 1: An Example Vehicular Network Architecture for V2I and V2V

4.1. Vehicular Network Architecture

Figure 1 shows an example vehicular network architecture for V2I and V2V in a road network. The vehicular network architecture contains vehicles (including IP-OBU), IP-RSUs, Mobility Anchor, Traffic Control Center, and Vehicular Cloud as components. These components are not mandatory, and they can be deployed into vehicular networks in various ways. Some of them (e.g., Mobility Anchor, Traffic Control Center, and Vehicular Cloud) may not be needed for the vehicular networks according to target use cases in Section 3.

Existing network architectures, such as the network architectures of PMIPv6 [RFC5213], RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [RFC6550], and OMNI (Overlay Multilink Network Interface) [I-D.templin-6man-omni], can be extended to a vehicular network architecture for multihop V2V, V2I, and V2X, as shown in Figure 1. Refer to Appendix B for the detailed discussion on multihop V2X networking by RPL and OMNI.

As shown in this figure, IP-RSUs as routers and vehicles with IP-OBU have wireless media interfaces for VANET. Furthermore, the wireless media interfaces are autoconfigured with a global IPv6 prefix (e.g., 2001:DB8:1:1::/64) to support both V2V and V2I networking. Note that 2001:DB8::/32 is a documentation prefix [RFC3849] for example prefixes in this document, and also that any routable IPv6 address needs to be routable in a VANET and a vehicular network including IP-RSUs.

In Figure 1, three IP-RSUs (IP-RSU1, IP-RSU2, and IP-RSU3) are deployed in the road network and are connected with each other through the wired networks (e.g., Ethernet). A Traffic Control Center (TCC) is connected to the Vehicular Cloud for the management of IP-RSUs and vehicles in the road network. A Mobility Anchor (MA) may be located in the TCC as a mobility management controller. Vehicle2, Vehicle3, and Vehicle4 are wirelessly connected to IP-RSU1, IP-RSU2, and IP-RSU3, respectively. The three wireless networks of IP-RSU1, IP-RSU2, and IP-RSU3 can belong to three different subnets (i.e., Subnet1, Subnet2, and Subnet3), respectively. Those three subnets use three different prefixes (i.e., Prefix1, Prefix2, and Prefix3).

Multiple vehicles under the coverage of an RSU share a prefix just as mobile nodes share a prefix of a Wi-Fi access point in a wireless LAN. This is a natural characteristic in infrastructure-based wireless networks. For example, in Figure 1, two vehicles (i.e., Vehicle2, and Vehicle5) can use Prefix 1 to configure their IPv6 global addresses for V2I communication. Alternatively, mobile nodes can employ a "Bring-Your-Own-Addresses (BYOA)" technique using their own IPv6 Unique Local Addresses (ULAs) [RFC4193] over the wireless network, which does not require the messaging (e.g., Duplicate Address Detection (DAD)) of IPv6 Stateless Address Autoconfiguration (SLAAC) [RFC4862].

In wireless subnets in vehicular networks (e.g., Subnet1 and Subnet2 in Figure 1), vehicles can construct a connected VANET (with an arbitrary graph topology) and can communicate with each other via V2V communication. Vehicle1 can communicate with Vehicle2 via V2V communication, and Vehicle2 can communicate with Vehicle3 via V2V communication because they are within the wireless communication range of each other. On the other hand, Vehicle3 can communicate

with Vehicle4 via the vehicular infrastructure (i.e., IP-RSU2 and IP-RSU3) by employing V2I (i.e., V2I2V) communication because they are not within the wireless communication range of each other.

As a basic definition for IPv6 packets transported over IEEE 802.11-OCB, [RFC8691] specifies several details, including Maximum Transmission Unit (MTU), frame format, link-local address, address mapping for unicast and multicast, stateless autoconfiguration, and subnet structure.

An IPv6 mobility solution is needed for the guarantee of communication continuity in vehicular networks so that a vehicle's TCP session can be continued, or UDP packets can be delivered to a vehicle as a destination without loss while it moves from an IP-RSU's wireless coverage to another IP-RSU's wireless coverage. In Figure 1, assuming that Vehicle2 has a TCP session (or a UDP session) with a corresponding node in the vehicular cloud, Vehicle2 can move from IP-RSU1's wireless coverage to IP-RSU2's wireless coverage. In this case, a handover for Vehicle2 needs to be performed by either a host-based mobility management scheme (e.g., MIPv6 [RFC6275]) or a network-based mobility management scheme (e.g., PMIPv6 [RFC5213] and AERO [I-D.templin-6man-aero]). This document describes issues in mobility management for vehicular networks in Section 5.2.

4.2. V2I-based Internetworking

This section discusses the internetworking between a vehicle's internal network (i.e., moving network) and an EN's internal network (i.e., fixed network) via V2I communication. The internal network of a vehicle is nowadays constructed with Ethernet by many automotive vendors [In-Car-Network]. Note that an EN can accommodate multiple routers (or switches) and servers (e.g., ECDs, navigation server, and DNS server) in its internal network.

A vehicle's internal network often uses Ethernet to interconnect Electronic Control Units (ECUs) in the vehicle. The internal network can support Wi-Fi and Bluetooth to accommodate a driver's and passenger's mobile devices (e.g., smartphone or tablet). The network topology and subnetting depend on each vendor's network configuration for a vehicle and an EN. It is reasonable to consider the interaction between the internal network and an external network within another vehicle or an EN.

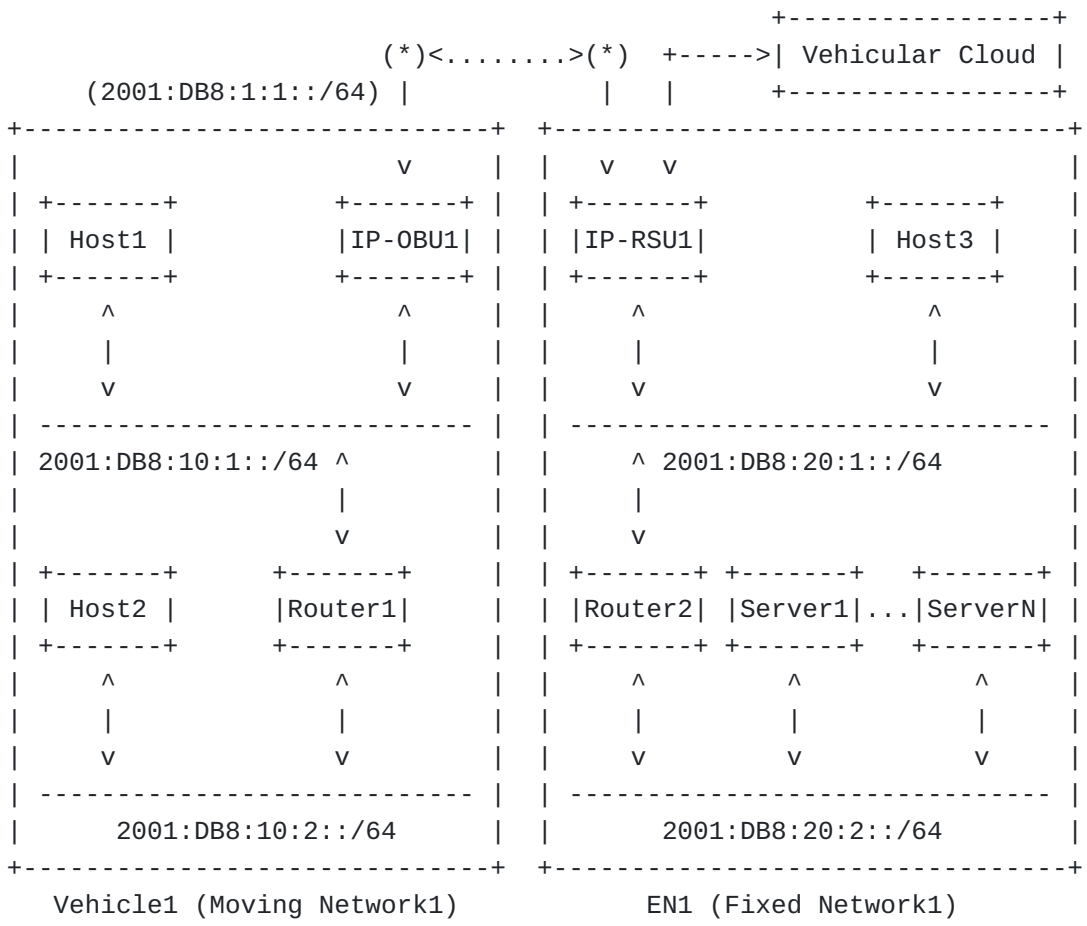


Figure 2: Internetworking between Vehicle and Edge Network

As shown in Figure 2, as internal networks, a vehicle's moving network and an EN's fixed network are self-contained networks having multiple subnets and having an edge router (e.g., IP-OBU and IP-RSU) for the communication with another vehicle or another EN. The internetworking between two internal networks via V2I communication requires the exchange of the network parameters and the network prefixes of the internal networks. For the efficiency, the network prefixes of the internal networks (as a moving network) in a vehicle need to be delegated and configured automatically. Note that a moving network's network prefix can be called a Mobile Network Prefix (MNP) [RFC3963].

Figure 2 also shows the internetworking between the vehicle's moving network and the EN's fixed network. There exists an internal network (Moving Network1) inside Vehicle1. Vehicle1 has two hosts (Host1 and Host2), and two routers (IP-OBU1 and Router1). There exists another internal network (Fixed Network1) inside EN1. EN1 has one host (Host3), two routers (IP-RSU1 and Router2), and the collection of servers (Server1 to ServerN) for various services in the road

networks, such as the emergency notification and navigation. Vehicle1's IP-OBU1 (as a mobile router) and EN1's IP-RSU1 (as a fixed router) use 2001:DB8:1:1::/64 for an external link (e.g., DSRC) for V2I networking. Thus, a host (Host1) in Vehicle1 can communicate with a server (Server1) in EN1 for a vehicular service through Vehicle1's moving network, a wireless link between IP-OBU1 and IP-RSU1, and EN1's fixed network.

For the IPv6 communication between an IP-OBU and an IP-RSU or between two neighboring IP-OBUs, they need to know the network parameters, which include MAC layer and IPv6 layer information. The MAC layer information includes wireless link layer parameters, transmission power level, and the MAC address of an external network interface for the internetworking with another IP-OBU or IP-RSU. The IPv6 layer information includes the IPv6 address and network prefix of an external network interface for the internetworking with another IP-OBU or IP-RSU.

Through the mutual knowledge of the network parameters of internal networks, packets can be transmitted between the vehicle's moving network and the EN's fixed network. Thus, V2I requires an efficient protocol for the mutual knowledge of network parameters.

As shown in Figure 2, the addresses used for IPv6 transmissions over the wireless link interfaces for IP-OBU and IP-RSU can be link-local IPv6 addresses, ULAs, or global IPv6 addresses. When global IPv6 addresses are used, wireless interface configuration and control overhead for DAD [RFC4862] and Multicast Listener Discovery (MLD) [RFC2710][RFC3810] should be minimized to support V2I and V2X communications for vehicles moving fast along roadways.

Let us consider the upload/download time of a vehicle when it passes through the wireless communication coverage of an IP-RSU. For a given typical setting where 1km is the maximum DSRC communication range [DSRC] and 100km/h is the speed limit in highway, the dwelling time can be calculated to be 72 seconds by dividing the diameter of the 2km (i.e., two times of DSRC communication range where an IP-RSU is located in the center of the circle of wireless communication) by the speed limit of 100km/h (i.e., about 28m/s). For the 72 seconds, a vehicle passing through the coverage of an IP-RSU can upload and download data packets to/from the IP-RSU.

4.3. V2V-based Internetworking

This section discusses the internetworking between the moving networks of two neighboring vehicles via V2V communication.

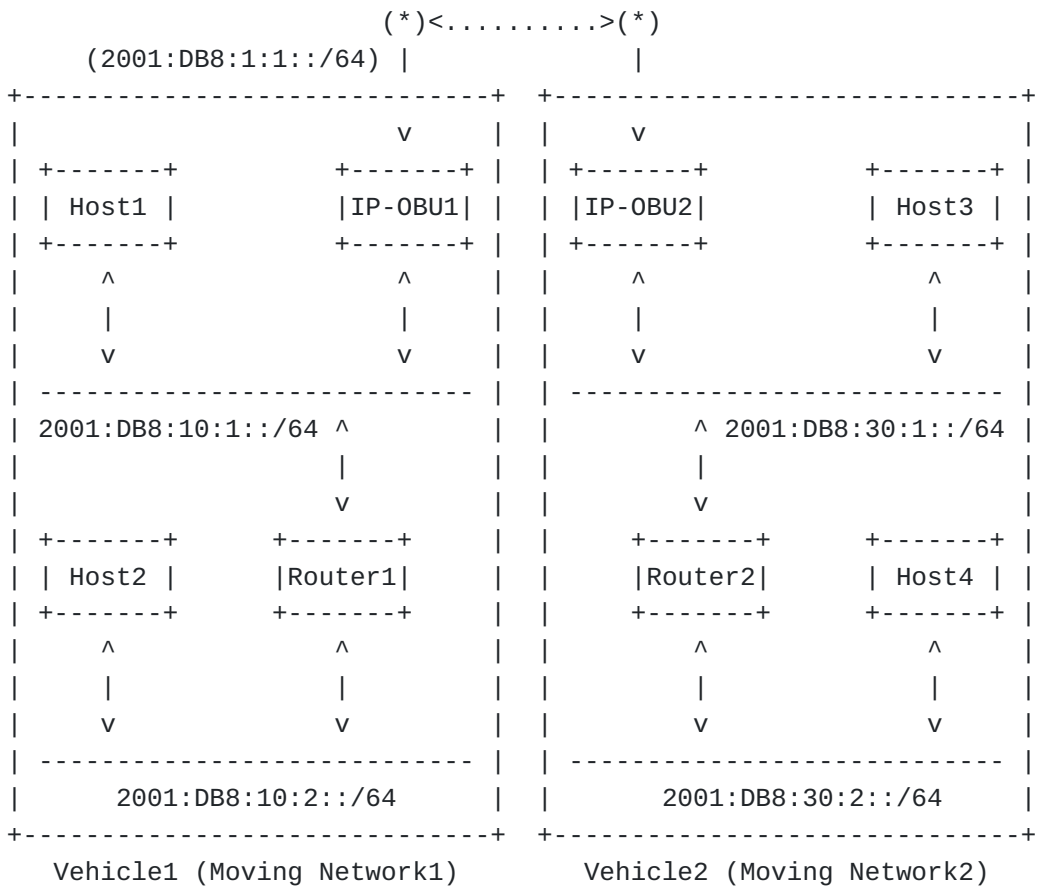


Figure 3: Internetworking between Two Vehicles

Figure 3 shows the internetworking between the moving networks of two neighboring vehicles. There exists an internal network (Moving Network1) inside Vehicle1. Vehicle1 has two hosts (Host1 and Host2), and two routers (IP-OBU1 and Router1). There exists another internal network (Moving Network2) inside Vehicle2. Vehicle2 has two hosts (Host3 and Host4), and two routers (IP-OBU2 and Router2). Vehicle1's IP-OBU1 (as a mobile router) and Vehicle2's IP-OBU2 (as a mobile router) use 2001:DB8:1:1::/64 for an external link (e.g., DSRC) for V2V networking. Thus, a host (Host1) in Vehicle1 can communicate with another host (Host3) in Vehicle2 for a vehicular service through Vehicle1's moving network, a wireless link between IP-OBU1 and IP-OBU2, and Vehicle2's moving network.

As a V2V use case in Section 3.1, Figure 4 shows the linear network topology of platooning vehicles for V2V communications where Vehicle3 is the leading vehicle with a driver, and Vehicle2 and Vehicle1 are the following vehicles without drivers.

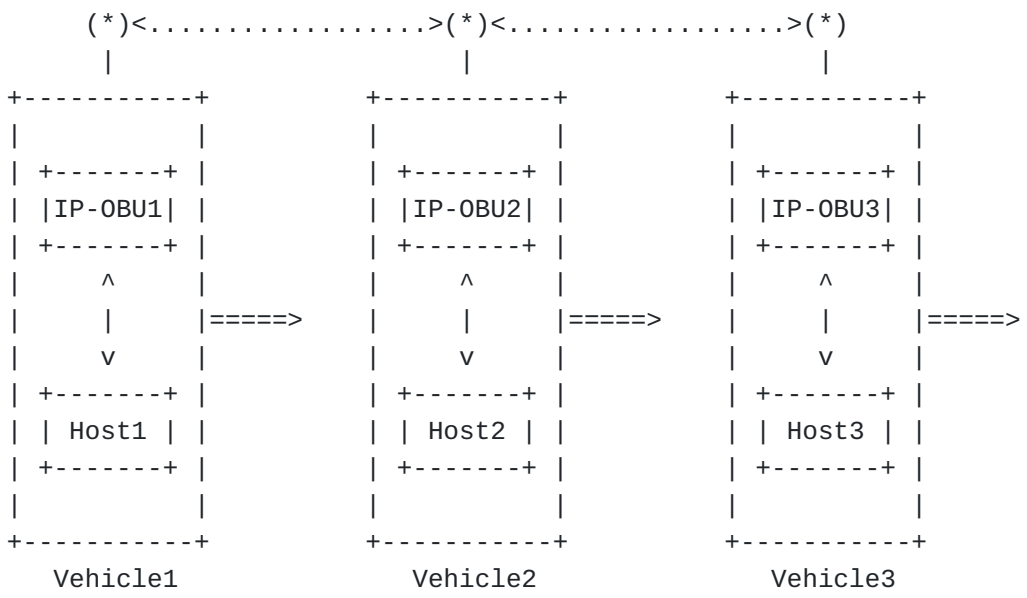


Figure 4: Multihop Internetworking between Two Vehicle Networks

As shown in Figure 4, multihop internetworking is feasible among the moving networks of three vehicles in the same VANET. For example, Host1 in Vehicle1 can communicate with Host3 in Vehicle3 via IP-OBU1 in Vehicle1, IP-OBU2 in Vehicle2, and IP-OBU3 in Vehicle3 in the VANET, as shown in the figure.

In this section, the link between two vehicles is assumed to be stable for single-hop wireless communication regardless of the sight relationship such as line of sight and non-line of sight, as shown in Figure 3. Even in Figure 4, the three vehicles are connected to each other with a linear topology, however, multihop V2V communication can accommodate any network topology (i.e., an arbitrary graph) over VANET routing protocols.

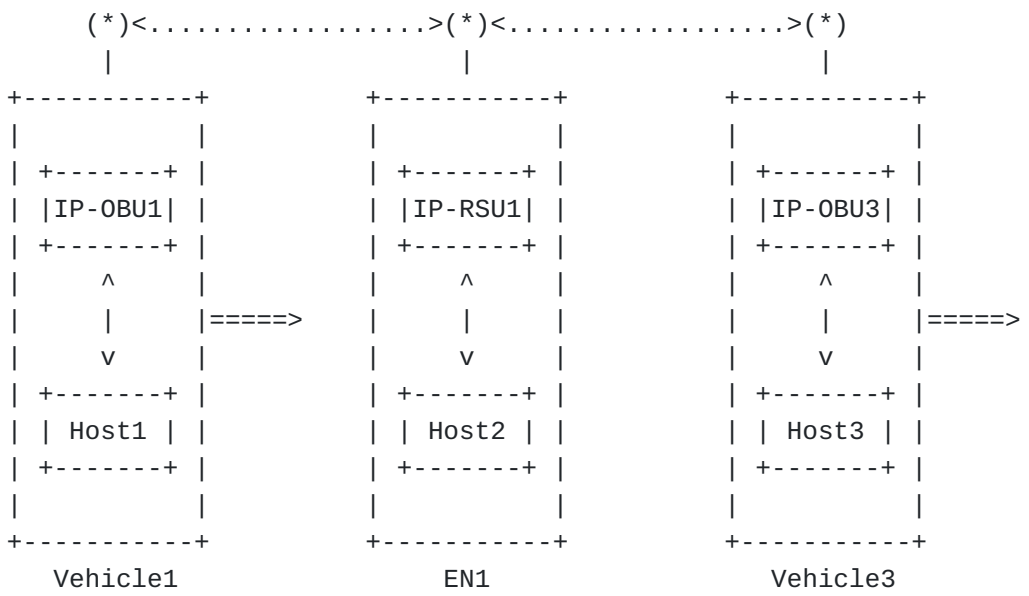


Figure 5: Multihop Internetworking between Two Vehicle Networks via IP-RSU (V2I2V)

As shown in Figure 5, multihop internetworking between two vehicles is feasible via an infrastructure node (i.e., IP-RSU) with wireless connectivity among the moving networks of two vehicles and the fixed network of an edge network (denoted as EN1) in the same VANET. For example, Host1 in Vehicle1 can communicate with Host3 in Vehicle3 via IP-OBU1 in Vehicle1, IP-RSU1 in EN1, and IP-OBU3 in Vehicle3 in the VANET, as shown in the figure.

For the reliability required in V2V networking, the ND optimization defined in MANET [RFC6130] [RFC7466] improves the classical IPv6 ND in terms of tracking neighbor information with up to two hops and introducing several extensible Information Bases, which serves the MANET routing protocols such as the difference versions of Optimized Link State Routing Protocol (OLSR) [RFC3626] [RFC7181] [RFC7188] [RFC7722] [RFC7779] [RFC8218] and the Dynamic Link Exchange Protocol (DLEP) with its extensions [RFC8175] [RFC8629] [RFC8651] [RFC8703] [RFC8757]. In short, the MANET ND mainly deals with maintaining extended network neighbors. However, an ND protocol in vehicular networks shall consider more about the geographical mobility information of vehicles as an important resource for serving various purposes to improve the reliability, e.g., vehicle driving safety, intelligent transportation implementations, and advanced mobility services. For a more reliable V2V networking, some redundancy mechanisms should be provided in L3 in the case of the failure of L2.

5. Problem Statement

In order to specify protocols using the architecture mentioned in Section 4.1, IPv6 core protocols have to be adapted to overcome certain challenging aspects of vehicular networking. Since the vehicles are likely to be moving at great speed, protocol exchanges need to be completed in a time relatively short compared to the lifetime of a link between a vehicle and an IP-RSU, or between two vehicles.

For safe driving, vehicles need to exchange application messages every 0.5 second [NHTSA-ACAS-Report] to let drivers take an action to avoid a dangerous situation (e.g., vehicle collision), so IPv6 protocol exchanges need to support this order of magnitude for application message exchanges. Also, considering the communication range of DSRC (up to 1km) and 100km/h as the speed limit in highway, the lifetime of a link between a vehicle and an IP-RSU is 72 seconds, and the lifetime of a link between two vehicles is 36 seconds. Note that if two vehicles are moving in the opposite directions in a roadway, the relative speed of this case is two times the relative speed of a vehicle passing through an RSU. This relative speed leads the half of the link lifetime between the vehicle and the IP-RSU. In reality, the DSRC communication range is around 500m, so the link lifetime will be a half of the maximum time. The time constraint of a wireless link between two nodes (e.g., vehicle and IP-RSU) needs to be considered because it may affect the lifetime of a session involving the link. The lifetime of a session varies depending on the session's type such as a web surfing, voice call over IP, DNS query, and context-aware navigation (in Section 3.1). Regardless of a session's type, to guide all the IPv6 packets to their destination host(s), IP mobility should be supported for the session. In a V2V scenario (e.g., context-aware navigation), the IPv6 packets of a vehicle should be delivered to relevant vehicles in an efficient way (e.g., multicasting). With this observation, IPv6 protocol exchanges need to be done as short as possible to support the message exchanges of various applications in vehicular networks.

Therefore, the time constraint of a wireless link has a major impact on IPv6 Neighbor Discovery (ND). Mobility Management (MM) is also vulnerable to disconnections that occur before the completion of identity verification and tunnel management. This is especially true given the unreliable nature of wireless communication. Meanwhile, the bandwidth of the wireless link determined by the lower layers (i.e., link and PHY layers) can affect the transmission time of control messages of the upper layers (e.g., IPv6) and the continuity of sessions in the higher layers (e.g., IPv6, TCP, and UDP). Hence the bandwidth selection according to Modulation and Coding Scheme (MCS) also affects the vehicular network connectivity. Note that

usually the higher bandwidth gives the shorter communication range and the higher packet error rate at the receiving side, which may reduce the reliability of control message exchanges of the higher layers (e.g., IPv6). This section presents key topics such as neighbor discovery and mobility management for links and sessions in IPv6-based vehicular networks.

5.1. Neighbor Discovery

IPv6 ND [RFC4861][RFC4862] is a core part of the IPv6 protocol suite. IPv6 ND is designed for link types including point-to-point, multicast-capable (e.g., Ethernet) and Non-Broadcast Multiple Access (NBMA). It assumes the efficient and reliable support of multicast and unicast from the link layer for various network operations such as MAC Address Resolution (AR), DAD, MLD and Neighbor Unreachability Detection (NUD).

Vehicles move quickly within the communication coverage of any particular vehicle or IP-RSU. Before the vehicles can exchange application messages with each other, they need to be configured with a link-local IPv6 address or a global IPv6 address, and run IPv6 ND.

The requirements for IPv6 ND for vehicular networks are efficient DAD and NUD operations. An efficient DAD is required to reduce the overhead of the DAD packets during a vehicle's travel in a road network, which can guarantee the uniqueness of a vehicle's global IPv6 address. An efficient NUD is required to reduce the overhead of the NUD packets during a vehicle's travel in a road network, which can guarantee the accurate neighborhood information of a vehicle in terms of adjacent vehicles and RSUs.

The legacy DAD assumes that a node with an IPv6 address can reach any other node with the scope of its address at the time it claims its address, and can hear any future claim for that address by another party within the scope of its address for the duration of the address ownership. However, the partitioning and merging of VANETs makes this assumption frequently invalid in vehicular networks. The merging and partitioning of VANETs frequently occurs in vehicular networks. This merging and partitioning should be considered for the IPv6 ND such as IPv6 Stateless Address Autoconfiguration (SLAAC) [RFC4862]. Due to the merging of VANETs, two IPv6 addresses may conflict with each other though they were unique before the merging. An address lookup operation may be conducted by an MA or IP-RSU (as Registrar in RPL) to check the uniqueness of an IPv6 address that will be configured by a vehicle as DAD. Also, the partitioning of a VANET may make vehicles with the same prefix be physically unreachable. An address lookup operation may be conducted by an MA or IP-RSU (as Registrar in RPL) to check

the existence of a vehicle under the network coverage of the MA or IP-RSU as NUD. Thus, SLAAC needs to prevent IPv6 address duplication due to the merging of VANETs, and IPv6 ND needs to detect unreachable neighboring vehicles due to the partitioning of a VANET. According to the merging and partitioning, a destination vehicle (as an IPv6 host) needs to be distinguished as either an on-link host or an off-link host even though the source vehicle can use the same prefix as the destination vehicle [I-D.ietf-intarea-ippl].

To efficiently prevent IPv6 address duplication due to the VANET partitioning and merging from happening in vehicular networks, the vehicular networks need to support a vehicular-network-wide DAD by defining a scope that is compatible with the legacy DAD. In this case, two vehicles can communicate with each other when there exists a communication path over VANET or a combination of VANETs and IP-RSUs, as shown in Figure 1. By using the vehicular-network-wide DAD, vehicles can assure that their IPv6 addresses are unique in the vehicular network whenever they are connected to the vehicular infrastructure or become disconnected from it in the form of VANET.

For vehicular networks with high mobility and density, the DAD needs to be performed efficiently with minimum overhead so that the vehicles can exchange driving safety messages (e.g., collision avoidance and accident notification) with each other with a short interval suggested by NHTSA (National Highway Traffic Safety Administration) [NHTSA-ACAS-Report]. Since the partitioning and merging of vehicular networks may require re-perform the DAD process repeatedly, the link scope of vehicles may be limited to a small area, which may delay the exchange of driving safety messages. Driving safety messages can include a vehicle's mobility information (i.e., position, speed, direction, and acceleration/deceleration) that is critical to other vehicles. The exchange interval of this message is recommended to be less than 0.5 second, which is required for a driver to avoid an emergency situation, such as a rear-end crash.

ND time-related parameters such as router lifetime and Neighbor Advertisement (NA) interval need to be adjusted for vehicle speed and vehicle density. For example, the NA interval needs to be dynamically adjusted according to a vehicle's speed so that the vehicle can maintain its neighboring vehicles in a stable way, considering the collision probability with the NA messages sent by other vehicles. The ND time-related parameters can be an operational setting or an optimization point particularly for vehicular networks.

For IPv6-based safety applications (e.g., context-aware navigation, adaptive cruise control, and platooning) in vehicular networks, the

delay-bounded data delivery is critical. IPv6 ND needs to work to support those IPv6-based safety applications efficiently.

From the interoperability point of view, in IPv6-based vehicular networking, IPv6 ND should have minimum changes with the legacy IPv6 ND used in the Internet, including the DAD and NUD operations, so that IPv6-based vehicular networks can be seamlessly connected to other intelligent transportation elements (e.g., traffic signals, pedestrian wearable devices, electric scooters, and bus stops) that use the standard IPv6 network settings.

5.1.1. Link Model

A subnet model for a vehicular network needs to facilitate the communication between two vehicles with the same prefix regardless of the vehicular network topology as long as there exist bidirectional E2E paths between them in the vehicular network including VANETs and IP-RSUs. This subnet model allows vehicles with the same prefix to communicate with each other via a combination of multihop V2V and multihop V2I with VANETs and IP-RSUs. [I-D.thubert-6man-ipv6-over-wireless] introduces other issues in an IPv6 subnet model.

IPv6 protocols work under certain assumptions that do not necessarily hold for vehicular wireless access link types [VIP-WAVE] [RFC5889]. For instance, some IPv6 protocols assume symmetry in the connectivity among neighboring interfaces [RFC6250]. However, radio interference and different levels of transmission power may cause asymmetric links to appear in vehicular wireless links. As a result, a new vehicular link model needs to consider the asymmetry of dynamically changing vehicular wireless links.

There is a relationship between a link and a prefix, besides the different scopes that are expected from the link-local and global types of IPv6 addresses. In an IPv6 link, it is defined that all interfaces which are configured with the same subnet prefix and with on-link bit set can communicate with each other on an IPv6 link. However, the vehicular link model needs to define the relationship between a link and a prefix, considering the dynamics of wireless links and the characteristics of VANET.

A VANET can have a single link between each vehicle pair within wireless communication range, as shown in Figure 4. When two vehicles belong to the same VANET, but they are out of wireless communication range, they cannot communicate directly with each other. Suppose that a global-scope IPv6 prefix (or an IPv6 ULA prefix) is assigned to VANETs in vehicular networks. Even though two vehicles in the same VANET configure their IPv6 addresses with the same IPv6 prefix, they may not communicate with each other not in

one hop in the same VANET because of the multihop network connectivity between them. Thus, in this case, the concept of an on-link IPv6 prefix does not hold because two vehicles with the same on-link IPv6 prefix cannot communicate directly with each other. Also, when two vehicles are located in two different VANETs with the same IPv6 prefix, they cannot communicate with each other. When these two VANETs converge to one VANET, the two vehicles can communicate with each other in a multihop fashion, for example, when they are Vehicle1 and Vehicle3, as shown in Figure 4.

From the previous observation, a vehicular link model should consider the frequent partitioning and merging of VANETs due to vehicle mobility. Therefore, the vehicular link model needs to use an on-link prefix and off-link prefix according to the network topology of vehicles such as a one-hop reachable network and a multihop reachable network (or partitioned networks). If the vehicles with the same prefix are reachable from each other in one hop, the prefix should be on-link. On the other hand, if some of the vehicles with the same prefix are not reachable from each other in one hop due to either the multihop topology in the VANET or multiple partitions, the prefix should be off-link. In most cases in vehicular networks, due to the partitioning and merging of VANETs, and the multihop network topology of VANETS, off-link prefixes will be used for vehicles as default.

The vehicular link model needs to support multihop routing in a connected VANET where the vehicles with the same global-scope IPv6 prefix (or the same IPv6 ULA prefix) are connected in one hop or multiple hops. It also needs to support the multihop routing in multiple connected VANETs through infrastructure nodes (e.g., IP-RSU) where they are connected to the infrastructure. For example, in Figure 1, suppose that Vehicle1, Vehicle2, and Vehicle3 are configured with their IPv6 addresses based on the same global-scope IPv6 prefix. Vehicle1 and Vehicle3 can also communicate with each other via either multihop V2V or multihop V2I2V. When Vehicle1 and Vehicle3 are connected in a VANET, it will be more efficient for them to communicate with each other directly via VANET rather than indirectly via IP-RSUs. On the other hand, when Vehicle1 and Vehicle3 are far away from direct communication range in separate VANETs and under two different IP-RSUs, they can communicate with each other through the relay of IP-RSUs via V2I2V. Thus, two separate VANETs can merge into one network via IP-RSU(s). Also, newly arriving vehicles can merge two separate VANETs into one VANET if they can play the role of a relay node for those VANETs.

Thus, in IPv6-based vehicular networking, the vehicular link model should have minimum changes for interoperability with standard IPv6 links in an efficient fashion to support IPv6 DAD, MLD and NUD operations.

5.1.2. MAC Address Pseudonym

For the protection of drivers' privacy, a pseudonym of a MAC address of a vehicle's network interface should be used, so that the MAC address can be changed periodically. However, although such a pseudonym of a MAC address can protect to some extent the privacy of a vehicle, it may not be able to resist attacks on vehicle identification by other fingerprint information, for example, the scrambler seed embedded in IEEE 802.11-OCB frames [Scrambler-Attack]. The pseudonym of a MAC address affects an IPv6 address based on the MAC address, and a transport-layer (e.g., TCP and SCTP) session with an IPv6 address pair. However, the pseudonym handling is not implemented and tested yet for applications on IP-based vehicular networking.

In the ETSI standards, for the sake of security and privacy, an ITS station (e.g., vehicle) can use pseudonyms for its network interface identities (e.g., MAC address) and the corresponding IPv6 addresses [Identity-Management]. Whenever the network interface identifier changes, the IPv6 address based on the network interface identifier needs to be updated, and the uniqueness of the address needs to be checked through the DAD procedure.

5.1.3. Routing

For multihop V2V communications in either a VANET or VANETs via IP-RSUs, a vehicular Mobile Ad Hoc Networks (MANET) routing protocol may be required to support both unicast and multicast in the links of the subnet with the same IPv6 prefix. However, it will be costly to run both vehicular ND and a vehicular ad hoc routing protocol in terms of control traffic overhead [RFC9119].

A routing protocol for a VANET may cause redundant wireless frames in the air to check the neighborhood of each vehicle and compute the routing information in a VANET with a dynamic network topology because the IPv6 ND is used to check the neighborhood of each vehicle. Thus, the vehicular routing needs to take advantage of the IPv6 ND to minimize its control overhead.

RPL [RFC6550] defines a routing protocol for low-power and lossy networks, which constructs and maintains Destination-Oriented Directed Acyclic Graphs (DODAGs) optimized by an Objective Function (OF). A defined OF provides route selection and optimization within an RPL topology. The RPL nodes use an anisotropic Distance Vector (DV) approach to form a DODAG by discovering and aggressively maintaining the upward default route toward the root of the DODAG. Downward routes follow the same DODAG, with lazy maintenance and stretched Peer-to-Peer (P2P) routing in the so-called storing mode. It is well-designed to reduce the topological knowledge and routing

state that needs to be exchanged. As a result, the routing protocol overhead is minimized, which allows either highly constrained stable networks or less constrained, highly dynamic networks. Refer to Appendix B for the detailed description of RPL for multihop V2X networking.

An address registration extension for 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Network) in [RFC8505] can support light-weight mobility for nodes moving through different parents. [RFC8505], as opposed to [RFC4861], is stateful and proactively installs the ND cache entries, which saves broadcasts and provides a deterministic presence information for IPv6 addresses. Mainly it updates the Address Registration Option (ARO) of ND defined in [RFC6775] to include a status field that can indicate the movement of a node and optionally a Transaction ID (TID) field, i.e., a sequence number that can be used to determine the most recent location of a node. Thus, RPL can use the information provided by the Extended ARO (EARO) defined in [RFC8505] to deal with a certain level of node mobility. When a leaf node moves to the coverage of another parent node, it should de-register its addresses to the previous parent node and register itself with a new parent node along with an incremented TID.

RPL can be used in IPv6-based vehicular networks, but it is primarily designed for lossy networks, which puts energy efficiency first. For using it in IPv6-based vehicular networks, there have not been actual experiences and practical implementations for vehicular networks, though it was tested in IoT low-power and lossy networks (LLN) scenarios.

Moreover, due to bandwidth and energy constraints, RPL does not suggest to use a proactive mechanism (e.g., keepalive) to maintain accurate routing adjacencies such as Bidirectional Forwarding Detection [RFC5881] and MANET Neighborhood Discovery Protocol [RFC6130]. As a result, due to the mobility of vehicles, network fragmentation may not be detected quickly and the routing of packets between vehicles or between a vehicle and an infrastructure node may fail.

5.2. Mobility Management

The seamless connectivity and timely data exchange between two end points requires efficient mobility management including location management and handover. Most vehicles are equipped with a GPS receiver as part of a dedicated navigation system or a corresponding smartphone App. Note that the GPS receiver may not provide vehicles with accurate location information in adverse environments such as a building area or a tunnel. The location precision can be improved

with assistance of the IP-RSUs or a cellular system with a GPS receiver for location information.

With a GPS navigator, efficient mobility management can be performed with the help of vehicles periodically reporting their current position and trajectory (i.e., navigation path) to the vehicular infrastructure (having IP-RSUs and an MA in TCC). This vehicular infrastructure can predict the future positions of the vehicles from their mobility information (i.e., the current position, speed, direction, and trajectory) for efficient mobility management (e.g., proactive handover). For a better proactive handover, link-layer parameters, such as the signal strength of a link-layer frame (e.g., Received Channel Power Indicator (RCPI) [VIP-WAVE]), can be used to determine the moment of a handover between IP-RSUs along with mobility information.

By predicting a vehicle's mobility, the vehicular infrastructure needs to better support IP-RSUs to perform efficient SLAAC, data forwarding, horizontal handover (i.e., handover in wireless links using a homogeneous radio technology), and vertical handover (i.e., handover in wireless links using heterogeneous radio technologies) in advance along with the movement of the vehicle.

For example, as shown in Figure 1, when a vehicle (e.g., Vehicle2) is moving from the coverage of an IP-RSU (e.g., IP-RSU1) into the coverage of another IP-RSU (e.g., IP-RSU2) belonging to a different subnet, the IP-RSUs can proactively support the IPv6 mobility of the vehicle, while performing the SLAAC, data forwarding, and handover for the sake of the vehicle.

For a mobility management scheme in a domain, where the wireless subnets of multiple IP-RSUs share the same prefix, an efficient vehicular-network-wide DAD is required. If DHCPv6 is used to assign a unique IPv6 address to each vehicle in this shared link, the DAD is not required. On the other hand, for a mobility management scheme with a unique prefix per mobile node (e.g., PMIPv6 [RFC5213]), DAD is not required because the IPv6 address of a vehicle's external wireless interface is guaranteed to be unique. There is a tradeoff between the prefix usage efficiency and DAD overhead. Thus, the IPv6 address autoconfiguration for vehicular networks needs to consider this tradeoff to support efficient mobility management.

Even though the SLAAC with classic ND costs a DAD during mobility management, the SLAAC with [RFC8505] does not cost a DAD. SLAAC for vehicular networks needs to consider the minimization of the cost of DAD with the help of an infrastructure node (e.g., IP-RSU and MA). Using an infrastructure prefix over VANET allows direct routability to the Internet through the multihop V2I toward an IP-RSU. On the other hand, a BYOA does not allow such direct routability to the

Internet since the BYOA is not topologically correct, that is, not routable in the Internet. In addition, a vehicle configured with a BYOA needs a tunnel home (e.g., IP-RSU) connected to the Internet, and the vehicle needs to know which neighboring vehicle is reachable inside the VANET toward the tunnel home. There is nonnegligible control overhead to set up and maintain routes to such a tunnel home over the VANET.

For the case of a multihomed network, a vehicle can follow the first-hop router selection rule described in [RFC8028]. For example, an IP-OBU inside a vehicle may connect to an IP-RSU that has multiple routers behind. In this scenario, because the IP-OBU can have multiple prefixes from those routers, the default router selection, source address selection, and packet redirect process should follow the guidelines in [RFC8028]. That is, the vehicle should select its default router for each prefix by preferring the router that advertised the prefix.

Vehicles can use the TCC as their Home Network having a home agent for mobility management as in MIPv6 [RFC6275] and PMIPv6 [RFC5213], so the TCC (or an MA inside the TCC) maintains the mobility information of vehicles for location management. IP tunneling over the wireless link should be avoided for performance efficiency. Also, in vehicular networks, asymmetric links sometimes exist and must be considered for wireless communications such as V2V and V2I.

Therefore, for the proactive and seamless IPv6 mobility of vehicles, the vehicular infrastructure (including IP-RSUs and MA) needs to efficiently perform the mobility management of the vehicles with their mobility information and link-layer information. Also, in IPv6-based vehicular networking, IPv6 mobility management should have minimum changes for the interoperability with the legacy IPv6 mobility management schemes such as PMIPv6, DMM, LISP, and AERO.

6. Security Considerations

This section discusses security and privacy for IPv6-based vehicular networking. Security and privacy are paramount in V2I, V2V, and V2X networking along with neighbor discovery and mobility management.

Vehicles and infrastructure must be authenticated in order to participate in vehicular networking. For the authentication in vehicular networks, vehicular cloud needs to support a kind of Public Key Infrastructure (PKI) in an efficient way. To provide safe interaction between vehicles or between a vehicle and infrastructure, only authenticated nodes (i.e., vehicle and infrastructure node) can participate in vehicular networks. Also, in-vehicle devices (e.g., ECU) and a driver/passenger's mobile devices (e.g., smartphone and tablet PC) in a vehicle need to

communicate with other in-vehicle devices and another driver/passenger's mobile devices in another vehicle, or other servers behind an IP-RSU in a secure way. Even though a vehicle is perfectly authenticated and legitimate, it may be hacked for running malicious applications to track and collect its and other vehicles' information. In this case, an attack mitigation process may be required to reduce the aftermath of malicious behaviors.

For secure V2I communication, a secure channel (e.g., IPsec) between a mobile router (i.e., IP-OBU) in a vehicle and a fixed router (i.e., IP-RSU) in an EN needs to be established, as shown in Figure 2 [RFC4301][RFC4302] [RFC4303][RFC4308] [RFC7296]. Also, for secure V2V communication, a secure channel (e.g., IPsec) between a mobile router (i.e., IP-OBU) in a vehicle and a mobile router (i.e., IP-OBU) in another vehicle needs to be established, as shown in Figure 3. For secure communication, an element in a vehicle (e.g., an in-vehicle device and a driver/passenger's mobile device) needs to establish a secure connection (e.g., TLS) with another element in another vehicle or another element in a vehicular cloud (e.g., a server). IEEE 1609.2 [WAVE-1609.2] specifies security services for applications and management messages, but this WAVE specification is optional. Thus, if the link layer does not support the security of a WAVE frame, either the network layer or the transport layer needs to support security services for the WAVE frames.

6.1. Security Threats in Neighbor Discovery

For the classical IPv6 ND, the DAD is required to ensure the uniqueness of the IPv6 address of a vehicle's wireless interface. This DAD can be used as a flooding attack that uses the DAD-related ND packets disseminated over the VANET or vehicular networks. [RFC6959] introduces threats enabled by IP source address spoofing. This possibility indicates that vehicles and IP-RSUs need to filter out suspicious ND traffic in advance. [RFC8928] introduces a mechanism that protects the ownership of an address for 6loWPAN ND from address theft and impersonation attacks. Based on the SEND [RFC3971] mechanism, the authentication for routers (i.e., IP-RSUs) can be conducted by only selecting an IP-RSU that has a certification path toward trusted parties. For authenticating other vehicles, the cryptographically generated address (CGA) can be used to verify the true owner of a received ND message, which requires to use the CGA ND option in the ND protocols. For a general protection of the ND mechanism, the RSA Signature ND option can also be used to protect the integrity of the messages by public key signatures. For a more advanced authentication mechanism, a distributed blockchain-based approach [Vehicular-BlockChain] can be used. However, for a scenario where a trustable router or an authentication path cannot be obtained, it is desirable to find a solution in which vehicles

and infrastructures can authenticate each other without any support from a third party.

When applying the classical IPv6 ND process to VANET, one of the security issues is that an IP-RSU (or an IP-OBU) as a router may receive deliberate or accidental DoS attacks from network scans that probe devices on a VANET. In this scenario, the IP-RSU can be overwhelmed for processing the network scan requests so that the capacity and resources of IP-RSU are exhausted, causing the failure of receiving normal ND messages from other hosts for network address resolution. [RFC6583] describes more about the operational problems in the classical IPv6 ND mechanism that can be vulnerable to deliberate or accidental DoS attacks and suggests several implementation guidelines and operational mitigation techniques for those problems. Nevertheless, for running IPv6 ND in VANET, those issues can be more acute since the movements of vehicles can be so diverse that it leaves a large room for rogue behaviors, and the failure of networking among vehicles may cause grave consequences.

Strong security measures shall protect vehicles roaming in road networks from the attacks of malicious nodes, which are controlled by hackers. For safe driving applications (e.g., context-aware navigation, cooperative adaptive cruise control, and platooning), as explained in Section 3.1, the cooperative action among vehicles is assumed. Malicious nodes may disseminate wrong driving information (e.g., location, speed, and direction) for disturbing safe driving. For example, a Sybil attack, which tries to confuse a vehicle with multiple false identities, may disturb a vehicle from taking a safe maneuver.

To identify malicious vehicles among vehicles, an authentication method may be required. A Vehicle Identification Number (VIN) and a user certificate (e.g., X.509 certificate [RFC5280]) along with an in-vehicle device's identifier generation can be used to efficiently authenticate a vehicle or its driver (having a user certificate) through a road infrastructure node (e.g., IP-RSU) connected to an authentication server in the vehicular cloud. This authentication can be used to identify the vehicle that will communicate with an infrastructure node or another vehicle. In the case where a vehicle has an internal network (called Moving Network) and elements in the network (e.g., in-vehicle devices and a user's mobile devices), as shown in Figure 2, the elements in the network need to be authenticated individually for safe authentication. Also, Transport Layer Security (TLS) certificates [RFC8446][RFC5280] can be used for an element's authentication to allow secure E2E vehicular communications between an element in a vehicle and another element in a server in a vehicular cloud, or between an element in a vehicle and another element in another vehicle.

6.2. Security Threats in Mobility Management

For mobility management, a malicious vehicle can construct multiple virtual bogus vehicles, and register them with IP-RSUs and MA. This registration makes the IP-RSUs and MA waste their resources. The IP-RSUs and MA need to determine whether a vehicle is genuine or bogus in mobility management. Also, the confidentiality of control packets and data packets among IP-RSUs and MA, the E2E paths (e.g., tunnels) need to be protected by secure communication channels. In addition, to prevent bogus IP-RSUs and MA from interfering with the IPv6 mobility of vehicles, mutual authentication among them needs to be performed by certificates (e.g., TLS certificate).

6.3. Other Threats

For the setup of a secure channel over IPsec or TLS, the multihop V2I communications over DSRC or 5G V2X (or LTE V2X) is required in a highway. In this case, multiple intermediate vehicles as relay nodes can help forward association and authentication messages toward an IP-RSU (gNodeB, or eNodeB) connected to an authentication server in the vehicular cloud. In this kind of process, the authentication messages forwarded by each vehicle can be delayed or lost, which may increase the construction time of a connection or some vehicles may not be able to be authenticated.

Even though vehicles can be authenticated with valid certificates by an authentication server in the vehicular cloud, the authenticated vehicles may harm other vehicles. To deal with this kind of security issue, for monitoring suspicious behaviors, vehicles' communication activities can be recorded in either a central way through a logging server (e.g., TCC) in the vehicular cloud or a distributed way (e.g., blockchain [Bitcoin]) along with other vehicles or infrastructure. To solve the issue ultimately, we need a solution where, without privacy breakage, vehicles may observe activities of each other to identify any misbehavior. Once identifying a misbehavior, a vehicle shall have a way to either isolate itself from others or isolate a suspicious vehicle by informing other vehicles. Alternatively, for completely secure vehicular networks, we shall embrace the concept of "zero-trust" for vehicles in which no vehicle is trustable and verifying every message is necessary. For doing so, we shall have an efficient zero-trust framework or mechanism for vehicular networks.

For the non-repudiation of the harmful activities of malicious nodes, a blockchain technology can be used [Bitcoin]. Each message from a vehicle can be treated as a transaction and the neighboring vehicles can play the role of peers in a consensus method of a blockchain [Bitcoin] [Vehicular-BlockChain]. For a blockchain's efficient consensus in vehicular networks having fast moving

vehicles, a new consensus algorithm needs to be developed or an existing consensus algorithm needs to be enhanced.

To prevent an adversary from tracking a vehicle with its MAC address or IPv6 address, especially for a long-living transport-layer session (e.g., voice call over IP and video streaming service), a MAC address pseudonym needs to be provided to each vehicle; that is, each vehicle periodically updates its MAC address and its IPv6 address needs to be updated accordingly by the MAC address change [RFC4086][RFC8981]. Such an update of the MAC and IPv6 addresses should not interrupt the E2E communications between two vehicles (or between a vehicle and an IP-RSU) for a long-living transport-layer session. However, if this pseudonym is performed without strong E2E confidentiality (using either IPsec or TLS), there will be no privacy benefit from changing MAC and IPv6 addresses, because an adversary can observe the change of the MAC and IPv6 addresses and track the vehicle with those addresses. Thus, the MAC address pseudonym and the IPv6 address update should be performed with strong E2E confidentiality.

7. IANA Considerations

This document does not require any IANA actions.

8. References

8.1. Normative References

[RFC2710] Deering, S., Fenner, W., and B. Haberman, "Multicast Listener Discovery (MLD) for IPv6", RFC 2710, DOI 10.17487/RFC2710, October 1999, <https://www.rfc-editor.org/info/rfc2710>.

[RFC3626] Clausen, T., Ed. and P. Jacquet, Ed., "Optimized Link State Routing Protocol (OLSR)", RFC 3626, DOI 10.17487/RFC3626, October 2003, <https://www.rfc-editor.org/info/rfc3626>.

[RFC3753] Manner, J., Ed. and M. Kojo, Ed., "Mobility Related Terminology", RFC 3753, DOI 10.17487/RFC3753, June 2004, <https://www.rfc-editor.org/info/rfc3753>.

[RFC3810] Vida, R., Ed. and L. Costa, Ed., "Multicast Listener Discovery Version 2 (MLDv2) for IPv6", RFC 3810, DOI 10.17487/RFC3810, June 2004, <https://www.rfc-editor.org/info/rfc3810>.

[RFC3849] Huston, G., Lord, A., and P. Smith, "IPv6 Address Prefix Reserved for Documentation", RFC 3849, DOI 10.17487/

RFC3849, July 2004, <https://www.rfc-editor.org/info/rfc3849>.

[RFC3963] Devarapalli, V., Wakikawa, R., Petrescu, A., and P. Thubert, "Network Mobility (NEMO) Basic Support Protocol", RFC 3963, DOI 10.17487/RFC3963, January 2005, <https://www.rfc-editor.org/info/rfc3963>.

[RFC3971] Arkko, J., Ed., Kempf, J., Zill, B., and P. Nikander, "SEcure Neighbor Discovery (SEND)", RFC 3971, DOI 10.17487/RFC3971, March 2005, <https://www.rfc-editor.org/info/rfc3971>.

[RFC4086] Eastlake 3rd, D., Schiller, J., and S. Crocker, "Randomness Requirements for Security", BCP 106, RFC 4086, DOI 10.17487/RFC4086, June 2005, <https://www.rfc-editor.org/info/rfc4086>.

[RFC4193] Hinden, R. and B. Haberman, "Unique Local IPv6 Unicast Addresses", RFC 4193, DOI 10.17487/RFC4193, October 2005, <https://www.rfc-editor.org/info/rfc4193>.

[RFC4301] Kent, S. and K. Seo, "Security Architecture for the Internet Protocol", RFC 4301, DOI 10.17487/RFC4301, December 2005, <https://www.rfc-editor.org/info/rfc4301>.

[RFC4302] Kent, S., "IP Authentication Header", RFC 4302, DOI 10.17487/RFC4302, December 2005, <https://www.rfc-editor.org/info/rfc4302>.

[RFC4303] Kent, S., "IP Encapsulating Security Payload (ESP)", RFC 4303, DOI 10.17487/RFC4303, December 2005, <https://www.rfc-editor.org/info/rfc4303>.

[RFC4308] Hoffman, P., "Cryptographic Suites for IPsec", RFC 4308, DOI 10.17487/RFC4308, December 2005, <https://www.rfc-editor.org/info/rfc4308>.

[RFC4861] Narten, T., Nordmark, E., Simpson, W., and H. Soliman, "Neighbor Discovery for IP version 6 (IPv6)", RFC 4861, DOI 10.17487/RFC4861, September 2007, <https://www.rfc-editor.org/info/rfc4861>.

[RFC4862] Thomson, S., Narten, T., and T. Jinmei, "IPv6 Stateless Address Autoconfiguration", RFC 4862, DOI 10.17487/RFC4862, September 2007, <https://www.rfc-editor.org/info/rfc4862>.

[RFC5213] Gundavelli, S., Ed., Leung, K., Devarapalli, V., Chowdhury, K., and B. Patil, "Proxy Mobile IPv6", RFC

5213, DOI 10.17487/RFC5213, August 2008, <https://www.rfc-editor.org/info/rfc5213>.

[RFC5280] Cooper, D., Santesson, S., Farrell, S., Boeyen, S., Housley, R., and W. Polk, "Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile", RFC 5280, DOI 10.17487/RFC5280, May 2008, <https://www.rfc-editor.org/info/rfc5280>.

[RFC5415] Calhoun, P., Ed., Montemurro, M., Ed., and D. Stanley, Ed., "Control And Provisioning of Wireless Access Points (CAPWAP) Protocol Specification", RFC 5415, DOI 10.17487/RFC5415, March 2009, <https://www.rfc-editor.org/info/rfc5415>.

[RFC5881] Katz, D. and D. Ward, "Bidirectional Forwarding Detection (BFD) for IPv4 and IPv6 (Single Hop)", RFC 5881, DOI 10.17487/RFC5881, June 2010, <https://www.rfc-editor.org/info/rfc5881>.

[RFC5889] Baccelli, E., Ed. and M. Townsley, Ed., "IP Addressing Model in Ad Hoc Networks", RFC 5889, DOI 10.17487/RFC5889, September 2010, <https://www.rfc-editor.org/info/rfc5889>.

[RFC6130] Clausen, T., Dearlove, C., and J. Dean, "Mobile Ad Hoc Network (MANET) Neighborhood Discovery Protocol (NHDP)", RFC 6130, DOI 10.17487/RFC6130, April 2011, <https://www.rfc-editor.org/info/rfc6130>.

[RFC6250] Thaler, D., "Evolution of the IP Model", RFC 6250, DOI 10.17487/RFC6250, May 2011, <https://www.rfc-editor.org/info/rfc6250>.

[RFC6275] Perkins, C., Ed., Johnson, D., and J. Arkko, "Mobility Support in IPv6", RFC 6275, DOI 10.17487/RFC6275, July 2011, <https://www.rfc-editor.org/info/rfc6275>.

[RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <https://www.rfc-editor.org/info/rfc6550>.

[RFC6583] Gashinsky, I., Jaeggli, J., and W. Kumari, "Operational Neighbor Discovery Problems", RFC 6583, DOI 10.17487/RFC6583, March 2012, <https://www.rfc-editor.org/info/rfc6583>.

[RFC6775] Shelby, Z., Ed., Chakrabarti, S., Nordmark, E., and C. Bormann, "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)", RFC 6775, DOI 10.17487/RFC6775, November 2012, <https://www.rfc-editor.org/info/rfc6775>.

[RFC7149] Boucadair, M. and C. Jacquenet, "Software-Defined Networking: A Perspective from within a Service Provider Environment", RFC 7149, DOI 10.17487/RFC7149, March 2014, <https://www.rfc-editor.org/info/rfc7149>.

[RFC7181] Clausen, T., Dearlove, C., Jacquet, P., and U. Herberg, "The Optimized Link State Routing Protocol Version 2", RFC 7181, DOI 10.17487/RFC7181, April 2014, <https://www.rfc-editor.org/info/rfc7181>.

[RFC7188] Dearlove, C. and T. Clausen, "Optimized Link State Routing Protocol Version 2 (OLSRv2) and MANET Neighborhood Discovery Protocol (NHDP) Extension TLVs", RFC 7188, DOI 10.17487/RFC7188, April 2014, <https://www.rfc-editor.org/info/rfc7188>.

[RFC7296] Kaufman, C., Hoffman, P., Nir, Y., Eronen, P., and T. Kivinen, "Internet Key Exchange Protocol Version 2 (IKEv2)", STD 79, RFC 7296, DOI 10.17487/RFC7296, October 2014, <https://www.rfc-editor.org/info/rfc7296>.

[RFC7333] Chan, H., Ed., Liu, D., Seite, P., Yokota, H., and J. Korhonen, "Requirements for Distributed Mobility Management", RFC 7333, DOI 10.17487/RFC7333, August 2014, <https://www.rfc-editor.org/info/rfc7333>.

[RFC7429] Liu, D., Ed., Zuniga, JC., Ed., Seite, P., Chan, H., and CJ. Bernardos, "Distributed Mobility Management: Current Practices and Gap Analysis", RFC 7429, DOI 10.17487/RFC7429, January 2015, <https://www.rfc-editor.org/info/rfc7429>.

[RFC7466] Dearlove, C. and T. Clausen, "An Optimization for the Mobile Ad Hoc Network (MANET) Neighborhood Discovery Protocol (NHDP)", RFC 7466, DOI 10.17487/RFC7466, March 2015, <https://www.rfc-editor.org/info/rfc7466>.

[RFC7722] Dearlove, C. and T. Clausen, "Multi-Topology Extension for the Optimized Link State Routing Protocol Version 2

(OLSRv2)", RFC 7722, DOI 10.17487/RFC7722, December 2015, <https://www.rfc-editor.org/info/rfc7722>.

[RFC7779] Rogge, H. and E. Baccelli, "Directional Airtime Metric Based on Packet Sequence Numbers for Optimized Link State Routing Version 2 (OLSRv2)", RFC 7779, DOI 10.17487/RFC7779, April 2016, <https://www.rfc-editor.org/info/rfc7779>.

[RFC8028] Baker, F. and B. Carpenter, "First-Hop Router Selection by Hosts in a Multi-Prefix Network", RFC 8028, DOI 10.17487/RFC8028, November 2016, <https://www.rfc-editor.org/info/rfc8028>.

[RFC8175] Ratliff, S., Jury, S., Satterwhite, D., Taylor, R., and B. Berry, "Dynamic Link Exchange Protocol (DLEP)", RFC 8175, DOI 10.17487/RFC8175, June 2017, <https://www.rfc-editor.org/info/rfc8175>.

[RFC8200] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", STD 86, RFC 8200, DOI 10.17487/RFC8200, July 2017, <https://www.rfc-editor.org/info/rfc8200>.

[RFC8218] Yi, J. and B. Parrein, "Multipath Extension for the Optimized Link State Routing Protocol Version 2 (OLSRv2)", RFC 8218, DOI 10.17487/RFC8218, August 2017, <https://www.rfc-editor.org/info/rfc8218>.

[RFC8446] Rescorla, E., "The Transport Layer Security (TLS) Protocol Version 1.3", RFC 8446, DOI 10.17487/RFC8446, August 2018, <https://www.rfc-editor.org/info/rfc8446>.

[RFC8505] Thubert, P., Ed., Nordmark, E., Chakrabarti, S., and C. Perkins, "Registration Extensions for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Neighbor Discovery", RFC 8505, DOI 10.17487/RFC8505, November 2018, <https://www.rfc-editor.org/info/rfc8505>.

[RFC8629] Cheng, B. and L. Berger, Ed., "Dynamic Link Exchange Protocol (DLEP) Multi-Hop Forwarding Extension", RFC 8629, DOI 10.17487/RFC8629, July 2019, <https://www.rfc-editor.org/info/rfc8629>.

[RFC8651] Cheng, B., Wiggins, D., and L. Berger, Ed., "Dynamic Link Exchange Protocol (DLEP) Control-Plane-Based Pause

Extension", RFC 8651, DOI 10.17487/RFC8651, October 2019, <https://www.rfc-editor.org/info/rfc8651>.

[RFC8691] Benamar, N., Härri, J., Lee, J., and T. Ernst, "Basic Support for IPv6 Networks Operating Outside the Context of a Basic Service Set over IEEE Std 802.11", RFC 8691, DOI 10.17487/RFC8691, December 2019, <https://www.rfc-editor.org/info/rfc8691>.

[RFC8703] Taylor, R. and S. Ratliff, "Dynamic Link Exchange Protocol (DLEP) Link Identifier Extension", RFC 8703, DOI 10.17487/RFC8703, February 2020, <https://www.rfc-editor.org/info/rfc8703>.

[RFC8757] Cheng, B. and L. Berger, Ed., "Dynamic Link Exchange Protocol (DLEP) Latency Range Extension", RFC 8757, DOI 10.17487/RFC8757, March 2020, <https://www.rfc-editor.org/info/rfc8757>.

[RFC8928] Thubert, P., Ed., Sarikaya, B., Sethi, M., and R. Struik, "Address-Protected Neighbor Discovery for Low-Power and Lossy Networks", RFC 8928, DOI 10.17487/RFC8928, November 2020, <https://www.rfc-editor.org/info/rfc8928>.

[RFC8981] Gont, F., Krishnan, S., Narten, T., and R. Draves, "Temporary Address Extensions for Stateless Address Autoconfiguration in IPv6", RFC 8981, DOI 10.17487/RFC8981, February 2021, <https://www.rfc-editor.org/info/rfc8981>.

[RFC9119] Perkins, C., McBride, M., Stanley, D., Kumari, W., and JC. Zúñiga, "Multicast Considerations over IEEE 802 Wireless Media", RFC 9119, DOI 10.17487/RFC9119, October 2021, <https://www.rfc-editor.org/info/rfc9119>.

8.2. Informative References

[RFC6959] McPherson, D., Baker, F., and J. Halpern, "Source Address Validation Improvement (SAVI) Threat Scope", RFC 6959, DOI 10.17487/RFC6959, May 2013, <https://www.rfc-editor.org/info/rfc6959>.

[I-D.ietf-intarea-ippl] Nordmark, E., "IP over Intentionally Partially Partitioned Links", Work in Progress, Internet-Draft, draft-ietf-intarea-ippl-00, 30 March 2017, <https://www.ietf.org/archive/id/draft-ietf-intarea-ippl-00.txt>.

[I-D.ietf-lisp-rfc6830bis] Farinacci, D., Fuller, V., Meyer, D., Lewis, D., and A. Cabellos, "The Locator/ID Separation

Protocol (LISP)", Work in Progress, Internet-Draft, draft-ietf-lisp-rfc6830bis-36, 18 November 2020, <https://www.ietf.org/archive/id/draft-ietf-lisp-rfc6830bis-36.txt>.

[I-D.templin-6man-aero]
Templin, F. L., "Automatic Extended Route Optimization (AERO)", Work in Progress, Internet-Draft, draft-templin-6man-aero-38, 31 December 2021, <https://www.ietf.org/archive/id/draft-templin-6man-aero-38.txt>.

[I-D.templin-6man-omni] Templin, F. L. and T. Whyman, "Transmission of IP Packets over Overlay Multilink Network (OMNI) Interfaces", Work in Progress, Internet-Draft, draft-templin-6man-omni-52, 31 December 2021, <https://www.ietf.org/archive/id/draft-templin-6man-omni-52.txt>.

[I-D.templin-ipwave-uam-its]
Templin, F. L., "Urban Air Mobility Implications for Intelligent Transportation Systems", Work in Progress, Internet-Draft, draft-templin-ipwave-uam-its-04, 4 January 2021, <https://www.ietf.org/archive/id/draft-templin-ipwave-uam-its-04.txt>.

[I-D.ietf-dmm-fpc-cpdp]
Matsushima, S., Bertz, L., Liebsch, M., Gundavelli, S., Moses, D., and C. E. Perkins, "Protocol for Forwarding Policy Configuration (FPC) in DMM", Work in Progress, Internet-Draft, draft-ietf-dmm-fpc-cpdp-14, 22 September 2020, <https://www.ietf.org/archive/id/draft-ietf-dmm-fpc-cpdp-14.txt>.

[I-D.thubert-6man-ipv6-over-wireless]
Thubert, P., "IPv6 Neighbor Discovery on Wireless Networks", Work in Progress, Internet-Draft, draft-thubert-6man-ipv6-over-wireless-11, 15 December 2021, <https://www.ietf.org/archive/id/draft-thubert-6man-ipv6-over-wireless-11.txt>.

[DSRC] ASTM International, "Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems - 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications", ASTM E2213-03(2010), October 2010.

[EU-2008-671-EC] European Union, "Commission Decision of 5 August 2008 on the Harmonised Use of Radio Spectrum in the 5875 - 5905 MHz Frequency Band for Safety-related Applications

of Intelligent Transport Systems (ITS)", EU 2008/671/EC, August 2008.

[IEEE-802.11p] "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 6: Wireless Access in Vehicular Environments", IEEE Std 802.11p-2010, June 2010.

[IEEE-802.11-OCB] "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", IEEE Std 802.11-2016, December 2016.

[WAVE-1609.0] IEEE 1609 Working Group, "IEEE Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture", IEEE Std 1609.0-2013, March 2014.

[WAVE-1609.2] IEEE 1609 Working Group, "IEEE Standard for Wireless Access in Vehicular Environments - Security Services for Applications and Management Messages", IEEE Std 1609.2-2016, March 2016.

[WAVE-1609.3] IEEE 1609 Working Group, "IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services", IEEE Std 1609.3-2016, April 2016.

[WAVE-1609.4] IEEE 1609 Working Group, "IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation", IEEE Std 1609.4-2016, March 2016.

[ISO-ITS-IPv6] ISO/TC 204, "Intelligent Transport Systems - Communications Access for Land Mobiles (CALM) - IPv6 Networking", ISO 21210:2012, June 2012.

[ISO-ITS-IPv6-AMD1] ISO/TC 204, "Intelligent Transport Systems - Communications Access for Land Mobiles (CALM) - IPv6

Networking - Amendment 1", ISO 21210:2012/AMD 1:2017, September 2017.

[TS-23.285-3GPP] 3GPP, "Architecture Enhancements for V2X Services", 3GPP TS 23.285/Version 16.2.0, December 2019.

[TR-22.886-3GPP] 3GPP, "Study on Enhancement of 3GPP Support for 5G V2X Services", 3GPP TR 22.886/Version 16.2.0, December 2018.

[TS-23.287-3GPP] 3GPP, "Architecture Enhancements for 5G System (5GS) to Support Vehicle-to-Everything (V2X) Services", 3GPP TS 23.287/Version 16.2.0, March 2020.

[VIP-WAVE] Cespedes, S., Lu, N., and X. Shen, "VIP-WAVE: On the Feasibility of IP Communications in 802.11p Vehicular Networks", IEEE Transactions on Intelligent Transportation Systems, vol. 14, no. 1, March 2013.

[Identity-Management] Wetterwald, M., Hrizi, F., and P. Cataldi, "Cross-layer Identities Management in ITS Stations", The 10th International Conference on ITS Telecommunications, November 2010.

[SAINT] Jeong, J., Jeong, H., Lee, E., Oh, T., and D. Du, "SAINT: Self-Adaptive Interactive Navigation Tool for Cloud-Based Vehicular Traffic Optimization", IEEE Transactions on Vehicular Technology, Vol. 65, No. 6, June 2016.

[SAINTplus] Shen, Y., Lee, J., Jeong, H., Jeong, J., Lee, E., and D. Du, "SAINT+: Self-Adaptive Interactive Navigation Tool+ for Emergency Service Delivery Optimization", IEEE Transactions on Intelligent Transportation Systems, June 2017.

[SANA] Hwang, T. and J. Jeong, "SANA: Safety-Aware Navigation Application for Pedestrian Protection in Vehicular Networks", Springer Lecture Notes in Computer Science (LNCS), Vol. 9502, December 2015.

[CASD] Shen, Y., Jeong, J., Oh, T., and S. Son, "CASD: A Framework of Context-Awareness Safety Driving in Vehicular Networks", International Workshop on Device Centric Cloud (DC2), March 2016.

[CA-Cruise-Control] California Partners for Advanced Transportation Technology (PATH), "Cooperative Adaptive Cruise Control", Available: https://path.berkeley.edu/research/connected-and-automated-vehicles/cooperative-adaptive-cruise-control, 2022.

[Truck-Platooning] California Partners for Advanced Transportation Technology (PATH), "Automated Truck Platooning", Available: https://path.berkeley.edu/research/connected-and-automated-vehicles/truck-platooning, 2022.

[FirstNet] U.S. National Telecommunications and Information Administration (NTIA), "First Responder Network Authority (FirstNet)", Available: https://www.firstnet.gov/, 2022.

[FirstNet-Report] First Responder Network Authority, "FY 2017: ANNUAL REPORT TO CONGRESS, Advancing Public Safety Broadband Communications", FirstNet FY 2017, December 2017.

[SignalGuru] Koukoumidis, E., Peh, L., and M. Martonosi, "SignalGuru: Leveraging Mobile Phones for Collaborative Traffic Signal Schedule Advisory", ACM MobiSys, June 2011.

[Fuel-Efficient] van de Hoef, S., H. Johansson, K., and D. V. Dimarogonas, "Fuel-Efficient En Route Formation of Truck Platoons", IEEE Transactions on Intelligent Transportation Systems, January 2018.

[Automotive-Sensing] Choi, J., Va, V., Gonzalez-Prelcic, N., Daniels, R., R. Bhat, C., and R. W. Heath, "Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing", IEEE Communications Magazine, December 2016.

[NHTSA-ACAS-Report] National Highway Traffic Safety Administration (NHTSA), "Final Report of Automotive Collision Avoidance Systems (ACAS) Program", DOT HS 809 080, August 2000.

[CBDN] Kim, J., Kim, S., Jeong, J., Kim, H., Park, J., and T. Kim, "CBDN: Cloud-Based Drone Navigation for Efficient Battery Charging in Drone Networks", IEEE Transactions on Intelligent Transportation Systems, November 2019.

[In-Car-Network] Lim, H., Volker, L., and D. Herrscher, "Challenges in a Future IP/Ethernet-based In-Car Network for Real-Time Applications", ACM/EDAC/IEEE Design Automation Conference (DAC), June 2011.

[Scrambler-Attack] Bloessl, B., Sommer, C., Dressier, F., and D. Eckhoff, "The Scrambler Attack: A Robust Physical Layer Attack on Location Privacy in Vehicular Networks", IEEE 2015 International Conference on Computing, Networking and Communications (ICNC), February 2015.

[Bitcoin]
Nakamoto, S., "Bitcoin: A Peer-to-Peer Electronic Cash System", URL: https://bitcoin.org/bitcoin.pdf, May 2009.

[Vehicular-BlockChain] Dorri, A., Steger, M., Kanhere, S., and R. Jurdak, "BlockChain: A Distributed Solution to Automotive Security and Privacy", IEEE Communications Magazine, Vol. 55, No. 12, December 2017.

Appendix A. Support of Multiple Radio Technologies for V2V

Vehicular networks may consist of multiple radio technologies such as DSRC and 5G V2X. Although a Layer-2 solution can provide a support for multihop communications in vehicular networks, the scalability issue related to multihop forwarding still remains when vehicles need to disseminate or forward packets toward multihop-away destinations. In addition, the IPv6-based approach for V2V as a network layer protocol can accommodate multiple radio technologies as MAC protocols, such as DSRC and 5G V2X. Therefore, the existing IPv6 protocol can be augmented through the addition of a virtual interface (e.g., Overlay Multilink Network (OMNI) Interface [I-D.templin-6man-omni]) and/or protocol changes in order to support both wireless single-hop/multihop V2V communications and multiple radio technologies in vehicular networks. In such a way, vehicles can communicate with each other by V2V communications to share either an emergency situation or road hazard information in a highway having multiple kinds of radio technologies.

Appendix B. Support of Multihop V2X Networking

The multihop V2X networking can be supported by RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [RFC6550] and Overlay Multilink Network Interface (OMNI) [I-D.templin-6man-omni].

RPL defines an IPv6 routing protocol for low-power and lossy networks (LLN), mostly designed for home automation routing, building automation routing, industrial routing, and urban LLN routing. It uses a Destination-Oriented Directed Acyclic Graph (DODAG) to construct routing paths for hosts (e.g., IoT devices) in a network. The DODAG uses an objective function (OF) for route selection and optimization within the network. A user can use different routing metrics to define an OF for a specific scenario. RPL supports multipoint-to-point, point-to-multipoint, and point-to-point traffic, and the major traffic flow is the multipoint-to-point traffic. For example, in a highway scenario, a vehicle may not access an RSU directly because of the distance of the DSRC coverage (up to 1 km). In this case, the RPL can be extended to support a multihop V2I since a vehicle can take advantage of other vehicles as

relay nodes to reach the RSU. Also, RPL can be extended to support both multihop V2V and V2X in the similar way.

RPL is primarily designed to minimize the control plane activity, which is the relative amount of routing protocol exchanges versus data traffic; this approach is beneficial for situations where the power and bandwidth are scarce (e.g., an IoT LLN where RPL is typically used today), but also in situations of high relative mobility between the nodes in the network (also known as swarming, e.g., within a variable set of vehicles with a similar global motion, or a variable set of drones flying toward the same direction).

To reduce the routing exchanges, RPL leverages a Distance Vector (DV) approach, which does not need a global knowledge of the topology, and only optimizes the routes to and from the root, allowing Peer-to-Peer (P2P) paths to be stretched. Although RPL installs its routes proactively, it only maintains them lazily, that is, in reaction to actual traffic, or as a slow background activity. Additionally, RPL leverages the concept of an objective function (called OF), which allows to adapt the activity of the routing protocol to use cases, e.g., type, speed, and quality of the radios. RPL does not need converge, and provides connectivity to most nodes most of the time. The default route toward the root is maintained aggressively and may change while a packet progresses without causing loops, so the packet will still reach the root. There are two modes for routing in RPL such as non-storing mode and storing mode. In non-storing mode, a node inside the mesh/swarm that changes its point(s) of attachment to the graph informs the root with a single unicast packet flowing along the default route, and the connectivity is restored immediately; this mode is preferable for use cases where Internet connectivity is dominant. On the other hand, in storing mode, the routing stretch is reduced, for a better P2P connectivity, while the Internet connectivity is restored more slowly, during the time for the DV operation to operate hop-by-hop. While an RPL topology can quickly scale up and down and fits the needs of mobility of vehicles, the total performance of the system will also depend on how quickly a node can form an address, join the mesh (including Authentication, Authorization, and Accounting (AAA)), and manage its global mobility to become reachable from another node outside the mesh.

OMNI defines a protocol for the transmission of IPv6 packets over Overlay Multilink Network Interfaces that are virtual interfaces governing multiple physical network interfaces. OMNI supports multihop V2V communication between vehicles in multiple forwarding hops via intermediate vehicles with OMNI links. It also supports multihop V2I communication between a vehicle and an infrastructure access point by multihop V2V communication. The OMNI interface

supports an NBMA link model where multihop V2V and V2I communications use each mobile node's ULAs without need for any DAD or MLD Messaging.

Appendix C. Support of Mobility Management for V2I

The seamless application communication between two vehicles or between a vehicle and an infrastructure node requires mobility management in vehicular networks. The mobility management schemes include a host-based mobility scheme, network-based mobility scheme, and software-defined networking scheme.

In the host-based mobility scheme (e.g., MIPv6), an IP-RSU plays a role of a home agent. On the other hand, in the network-based mobility scheme (e.g., PMIPv6, an MA plays a role of a mobility management controller such as a Local Mobility Anchor (LMA) in PMIPv6, which also serves vehicles as a home agent, and an IP-RSU plays a role of an access router such as a Mobile Access Gateway (MAG) in PMIPv6 [RFC5213]. The host-based mobility scheme needs client functionality in IPv6 stack of a vehicle as a mobile node for mobility signaling message exchange between the vehicle and home agent. On the other hand, the network-based mobility scheme does not need such a client functionality for a vehicle because the network infrastructure node (e.g., MAG in PMIPv6) as a proxy mobility agent handles the mobility signaling message exchange with the home agent (e.g., LMA in PMIPv6) for the sake of the vehicle.

There are a scalability issue and a route optimization issue in the network-based mobility scheme (e.g., PMIPv6) when an MA covers a large vehicular network governing many IP-RSUs. In this case, a distributed mobility scheme (e.g., DMM [RFC7429]) can mitigate the scalability issue by distributing multiple MAs in the vehicular network such that they are positioned closer to vehicles for route optimization and bottleneck mitigation in a central MA in the network-based mobility scheme. All these mobility approaches (i.e., a host-based mobility scheme, network-based mobility scheme, and distributed mobility scheme) and a hybrid approach of a combination of them need to provide an efficient mobility service to vehicles moving fast and moving along with the relatively predictable trajectories along the roadways.

In vehicular networks, the control plane can be separated from the data plane for efficient mobility management and data forwarding by using the concept of Software-Defined Networking (SDN) [RFC7149][I-D.ietf-dmm-fpc-cpdp]. Note that Forwarding Policy Configuration (FPC) in [I-D.ietf-dmm-fpc-cpdp], which is a flexible mobility management system, can manage the separation of data-plane and control-plane in DMM. In SDN, the control plane and data plane are separated for the efficient management of forwarding elements (e.g.,

switches and routers) where an SDN controller configures the forwarding elements in a centralized way and they perform packet forwarding according to their forwarding tables that are configured by the SDN controller. An MA as an SDN controller needs to efficiently configure and monitor its IP-RSUs and vehicles for mobility management, location management, and security services.

Appendix D. Acknowledgments

This work was supported by Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea MSIT (Ministry of Science and ICT) (R-20160222-002755, Cloud based Security Intelligence Technology Development for the Customized Security Service Provisioning).

This work was supported in part by the MSIT, Korea, under the ITRC (Information Technology Research Center) support program (IITP-2021-2017-0-01633) supervised by the IITP.

This work was supported in part by the IITP (2020-0-00395, Standard Development of Blockchain based Network Management Automation Technology).

This work was supported in part by the French research project DataTweet (ANR-13-INFR-0008) and in part by the HIGHTS project funded by the European Commission I (636537-H2020).

This work was supported in part by the Cisco University Research Program Fund, Grant # 2019-199458 (3696), and by ANID Chile Basal Project FB0008.

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