

Network Working Group
Internet-Draft
Intended status: Standards Track
Expires: May 4, 2017

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Survey on IP-based Vehicular Networking for Intelligent Transportation
Systems
draft-jeong-ipwave-vehicular-networking-survey-00

Abstract

This document surveys the IP-based vehicular networks, which are considered a key component of Intelligent Transportation Systems (ITS). The main topics of vehicular networking are vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) networking. This document deals with some critical aspects in vehicular networking, such as IP address autoconfiguration, vehicular network architecture, routing, mobility management, and security. This document summarizes and analyzes the previous research activities that use IPv4 or IPv6 for vehicular networking.

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1. Introduction

Nowadays vehicular networks have been focused on the driving safety, driving efficiency, and infotainment in road networks. For the driving safety, IEEE has standardized Wireless Access in Vehicular Environments (WAVE) standards, such as IEEE 802.11p, IEEE 1609.3, and IEEE 1609.4 [VIP-WAVE]. Along with these WAVE standards, IPv6 and Mobile IP protocols (e.g., MIPv4 and MIPv6) can be extended to vehicular networks.

This document surveys the IP-based vehicular networking for Intelligent Transportation Systems (ITS), such as IP address autoconfiguration, vehicular network architecture, vehicular network routing (for multi-hop V2V, V2I, and V2V), mobility management, and security. This document summarizes and analyzes the previous research activities using IPv4 or IPv6 for vehicular networking.

Based on the survey of this document, we can specify the requirements for vehicular networks for the intended purposes, such as the driving safety, driving efficiency, and infotainment. As a consequence, this will make it possible to design the network architecture and protocols for vehicular networking.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

3. Terminology

This document defines the following new terms:

- o Road-Side Unit (RSU): A node that has Dedicated Short-Range Communications (DSRC) device for wireless communications with vehicles and is connected to the Internet. An RSU is usually deployed at an intersection.
- o Vehicle: A node that has DSRC device for wireless communications with vehicles and RSUs. A vehicle may also have a GPS-navigation system for efficient driving.
- o Traffic Control Center (TCC): A node that maintains road infrastructure information (e.g., RSUs and traffic signals), 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 included in a

vehicular cloud for vehicular networks.

4. IP Address Autoconfiguration

This section surveys IP address autoconfiguration schemes for vehicular networks.

4.1. Automatic IP Address Configuration in VANETs

Fazio et al. proposed a vehicular address configuration called VAC for automatic IP address configuration in Vehicular Ad Hoc Networks (VANET) [Address-Autoconf]. VAC uses a distributed dynamic host configuration protocol (DHCP). This scheme uses a leader playing a role of a DHCP server within a cluster having connected vehicles within a VANET. In a connected VANET, vehicles are connected with each other with the communication range. In this VANET, VAC dynamically elects a leader-vehicle to quickly provide vehicles with unique IP addresses. The leader-vehicle maintains updated information on configured addresses in its connected VANET. It aims at the reduction of the frequency of IP address reconfiguration due to mobility.

VAC defines the concept of SCOPE as a delimited geographic area where IP addresses are guaranteed to be unique. When it is allocated an IP address from a leader-vehicle with a scope, a vehicle is guaranteed to have a unique IP address while moving within the scope of the leader-vehicle. If it moves out of the scope of the leader vehicle, it needs to ask for another IP address from another leader-vehicle so that its IP address can be unique within the scope of the new leader-vehicle. This approach may allow for less frequent change of an IP address than the address allocation from a fixed Internet gateway.

Thus, VAC can support a feasible address autoconfiguration for V2V scenarios, but the overhead to guarantee the uniqueness of IP addresses is not ignorable under high-speed mobility.

4.2. Routing and Address Assignment using Lane/Position Information in a Vehicular Ad-hoc Network

Kato et al. proposed an IPv6 address assignment scheme using lane and position information [Address-Assignment]. In this addressing scheme, each lane of a road segment has a unique IPv6 prefix. When it moves in a lane in a road segment, a vehicle autoconfigures its IPv6 address with its MAC address and the prefix assigned to the lane. A group of vehicles constructs a connected VANET within the same subnet such that their IPv6 addresses have the same prefix. Whenever it moves to another lane, a vehicle updates its IPv6 address with the prefix corresponding to the new lane and also joins the

group corresponding to the lane.

However, this address autoconfiguration scheme may have much overhead in the case where vehicles change their lanes frequently in highway.

4.3. GeoSAC: Scalable Address Autoconfiguration for VANET Using Geographic Networking Concepts

Baldessari et al. proposed an IPv6 scalable address autoconfiguration scheme called GeoSAC for vehicular networks [GeoSAC]. GeoSAC uses geographic networking concepts such that it combines the standard IPv6 ND and geographic routing functionality. It matches geographically-scoped network partitions to individual IPv6 multicast-capable links. In the standard IPv6, all nodes within the same link must communicate with each other, but due to the characteristics of wireless links, this concept of a link is not clear in vehicular networks. GeoSAC defines a link as a geographic area having a network partition. This geographic area can have a connected VANET. Thus, vehicles within the same VANET in a specific geographic area are regarded as staying in the same link, that is, an IPv6 multicast link.

This paper identifies four key requirements of IPv6 address autoconfiguration for vehicular networks: (i) the configuration of globally valid addresses, (ii) a low complexity for address autoconfiguration, (iii) a minimum signaling overhead of address autoconfiguration, (iv) the support of network mobility through movement detection, (v) an efficient gateway selection from multiple RSUs, (vi) a fully distributed address autoconfiguration for network security, (vii) the authentication and integrity of signaling messages, and (viii) the privacy protection of vehicles' users.

To support the proposed link concept, GeoSAC performs ad hoc routing for geographic networking in a sub-IP layer called Car-to-Car (C2C) NET. Vehicles within the same link can receive an IPv6 router advertisement (RA) message transmitted by an RSU as a router, so they can autoconfigure their IPv6 address based on the IPv6 prefix contained in the RA and perform Duplicate Address Detection (DAD) to verify the uniqueness of the autoconfigured IP address by the help of the geographic routing within the link.

For location-based applications, to translate between a geographic area and an IPv6 prefix belonging to an RSU, this paper takes advantage of an extended DNS service, using GPS-based addressing and routing along with geographic IPv6 prefix format [GeoSAC].

Thus, GeoSAC can support the IPv6 link concept through geographic routing within a specific geographic area.

4.4. Key Observations

High-speed mobility should be considered for a light-overhead address autoconfiguration. A cluster leader can have an IPv6 prefix [Address-Autoconf]. Each lane in a road segment can have an IPv6 prefix [Address-Assignment]. A geographic region under the communication range of an RSU can have an IPv6 prefix [GeoSAC].

IPv6 Neighbor Discovery (ND) should be extended to support the concept of a link for an IPv6 prefix in terms of multicast. Ad Hoc routing is required for the multicast in a connected VANET with the same IPv6 prefix [GeoSAC]. A rapid DAD should be supported to prevent or reduce IPv6 address conflicts.

5. Vehicular Network Architecture

This section surveys vehicular network architectures based on IP along with various radio technologies.

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

Céspedes et al. proposed a vehicular IP in WAVE called VIP-WAVE for I2V and V2I networking [VIP-WAVE]. IEEE 1609.4 specified a WAVE stack of protocols and includes IPv6 as a network layer protocol in data plane. The standard WAVE does not support DAD, seamless communications for Internet services, and multi-hop communications between a vehicle and an infrastructure node (e.g., RSU). To overcome these limitations of the standard WAVE for IP-based networking, VIP-WAVE enhances the standard WAVE by the following three schemes: (i) an efficient mechanism for the IPv6 address assignment and DAD, (ii) on-demand IP mobility based on Proxy Mobile IPv6 (PMIPv6), and (iii) one-hop and two-hop communications for I2V and V2I networking.

In WAVE, IPv6 neighbor discovery (ND) protocol is not recommended due to the overhead of ND against the timely and prompt communications in vehicular networking. By WAVE service advertisement (WAS) management frame, an RSU can provide vehicles with IP configuration information (e.g., IPv6 prefix, prefix length, gateway, router lifetime, and DNS server) without using ND. However, WAVE devices may support readdressing to provide pseudonymity, so a MAC address of a vehicle may be changed or randomly generated. This update of the MAC address may lead to the collision of an IPv6 address based on a MAC address, so VIP-WAVE includes a light-weight, on-demand ND to perform DAD.

For IP-based Internet services, VIP-WAVE adopts PMIPv6 for network-based mobility management in vehicular networks. In VIP-WAVE, RSU

plays a role of mobile anchor gateway (MAG) of PMIPv6, which performs the detection of a vehicle as a mobile node in a PMIPv6 domain and registers it into the PMIPv6 domain. For PMIPv6 operations, VIP-WAVE requires a central node called local mobility anchor (LMA), which assigns IPv6 prefixes to vehicles as mobile nodes and forwards data packets to the vehicles moving in the coverage of RSUs under its control through tunnels between MAGs and itself.

For two-hop communications between a vehicle and an RSU, VIP-WAVE allows an intermediate vehicle between the vehicle and the RSU to play a role of a packet relay for the vehicle. When it becomes out of the communication range of an RSU, a vehicle searches for another vehicle as a packet relay by sending a relay service announcement. When it receives this relay service announcement and is within the communication range of an RSU, another vehicle registers itself into the RSU as a relay and notifies the relay-requester vehicle of a relay maintenance announcement.

Thus, VIP-WAVE is a good candidate for I2V and V2I networking, supporting an enhanced ND, handover, and two-hop communications through a relay.

5.2. IPv6 Operation for WAVE - Wireless Access in Vehicular Environments

Baccelli et al. provided an analysis of the operation of IPv6 as it has been described by the IEEE WAVE standards 1609 [IPv6-WAVE]. Although the main focus of WAVE has been the timely delivery of safety related information, the deployment of IP-based infotainment applications is also considered. Thus, in order to support infotainment traffic, WAVE supports IPv6 and transport protocols such as TCP and UDP.

In the analysis provided in [IPv6-WAVE], it is identified that the IEEE 1609.3 standard's recommendations for IPv6 operation over WAVE are rather minimal. Protocols on which the operation of IPv6 relies for IP address configuration and IP-to-link-layer address translation (e.g., IPv6 NP protocol) are not recommended in the standard. Additionally, IPv6 works under certain assumptions for the link model that do not necessarily hold in WAVE. For instance, IPv6 assumes symmetry in the connectivity among neighboring interfaces. However, interference and different levels of transmission power may cause unidirectional links to appear in a WAVE link model. Also, in an IPv6 link, it is assumed that all interfaces which are configured with the same subnet prefix are on the same IP link. Hence, there is a relationship between link and prefix, besides the different scopes that are expected from the link-local and global types of IPv6 addresses. Such a relationship does not hold in a WAVE link model

due to node mobility and highly dynamic topology.

Baccellii et al. concluded that the use of the standard IPv6 protocol stack, as the IEEE 1609 family of specifications stipulate, is not sufficient. Instead, the addressing assignment should follow considerations for ad-hoc link models, defined in [RFC5889], which are similar to the characteristics of the WAVE link model. In terms of the supporting protocols for IPv6, such as ND, DHCP, or stateless auto-configuration, which rely largely on multicast, do not operate as expected in the case where the WAVE link model does not have the same behavior expected for multicast IPv6 traffic due to nodes' mobility and link variability. Additional challenges such as the support of pseudonymity through MAC address change along with the suitability of traditional TCP applications are discussed by the authors since they require the design of appropriate solutions.

5.3. A Framework for IP and non-IP Multicast Services for Vehicular Networks

Jemaa et al. presented a framework that enables deploying multicast services for vehicular networks in Infrastructure-based scenarios [Vehicular-Network-Framework]. This framework deals with two phases: (i) Initialization or bootstrapping phase that includes a geographic multicast auto-configuration process and a group membership building method and (ii) Multicast traffic dissemination phase that includes a network selecting mechanism on the transmission side and a receiver-based multicast delivery in the reception side. To this end, authors define a distributed mechanism that allows the vehicles to configure a common multicast address: Geographic Multicast Address Auto-configuration (GMAA), which allows a vehicle to configure its own address without signaling. A vehicle may also be able to change the multicast address to which it is subscribed when it changes its location.

This framework suggests a network selecting approach that allows IP and non-IP multicast data delivery in the sender side. Then, to meet the challenges of multicast address auto-configuration, the authors propose a distributed geographic multicast auto-addressing mechanism for multicast groups of vehicles, and a simple multicast data delivery scheme in hybrid networks from a server to the group of moving vehicles. However, this study lacks simulations related to performance assessment.

5.4. Joint IP Networking and Radio Architecture for Vehicular Networks

Petrescu et al. defined the joined IP networking and radio architecture for V2V and V2I communication in [Joint-IP-Networking]. The paper proposes to consider an IP topology in a similar way as a

radio link topology, in the sense that an IP subnet would correspond to the range of 1-hop vehicular communication. The paper defines three types of vehicles: Leaf Vehicle (LV), Range Extending Vehicle (REV), and Internet Vehicle (IV). The first class corresponds to the largest set of communicating vehicles (or network nodes within a vehicle), while the role of the second class is to build an IP relay between two IP-subnet and two sub-IP networks. Finally, the last class corresponds to vehicles being connected to Internet. Based on these three classes, the paper defines six types of IP topologies corresponding to V2V communication between two LVs in direct range, or two LVs over a range extending vehicle, or V2I communication again either directly via an IV, via another vehicles being IV, or via an REV connecting to an IV.

Considering a toy example of a vehicular train, where LV would be in-wagon communicating nodes, REV would be inter-wagon relays, and IV would be one node (e.g., train head) connected to Internet. Petrescu et al. defined the required mechanisms to build subnetworks, and evaluated the protocol time that is required to build such networks. Although no simulation-based evaluation is conducted, the initial analysis shows a long initial connection overhead, which should be alleviated once the multi-wagon remains stable. However, this approach does not describe what would happen in the case of a dynamic multi-hop vehicular network, where such overhead would end up being too high for V2V/V2I IP-based vehicular applications.

One other aspect described in this paper is to join the IP-layer relaying with radio-link channels. This paper suggests to separate different subnetworks in different WiFi/ITS-G5 channels, which could be advertised by the REV. Accordingly, the overall interference could be controlled within each subnetwork. This statement is similar to multi-channel topology management proposals in multi-hop sensor networks, yet adapted to an IP topology.

In conclusion, this paper proposes to classify an IP multi-hop vehicular network in three classes of vehicles: Leaf Vehicle (LV), Range Extending Vehicle (REV), and Internet Vehicle (IV). It suggests that the generally complex multi-hop IP vehicular topology could be represented by only six different topologies, which could be further analyzed and optimized. A prefix dissemination protocol is proposed for one of the topologies.

5.5. Mobile Internet Access in FleetNet

Bechler et al. described the FleetNet project approach to integrate Internet Access in future vehicular networks [FleetNet]. The paper is most probably one of the first paper to address this aspect, and in many ways, introduces concepts that will be later used in MIPv6 or

other subsequent IP mobility management schemes. The paper describes a V2I architecture consisting of Vehicles, Internet Gateways (IGW), Proxy, and Corresponding Nodes (CN). Considering that vehicular networks are required to use IPv6 addresses and also the new wireless access technology ITS-G5 (new at that time), one of the challenges is to bridge the two different networks (i.e., VANET and IP4/IPv6 Internet). Accordingly, the paper introduces a Fleetnet Gateway (FGW), which allows vehicles in IPv6 to access the IPv4 Internet and to bridge two types of networks and radio access technologies. Another challenge is to keep the active addressing and flows while vehicles move between FGWs. Accordingly, the paper introduces a proxy node, a cranked-up MIP Home Agent, which can re-route flows to the new FGW as well as acting as a local IPv4-IPv6 NAT.

The authors from the paper mostly observed two issues that VANET brings into the traditional IP mobility. First, VANET vehicles must mostly be addressed from the Internet directly, and do not specifically have a Home Network. Accordingly, VANET vehicles require a globally (predefined) unique IPv6 address, while an IPv6 co-located care-of address (CCoA) is a newly allocated IPv6 address every time a vehicle would enter a new IGW radio range. Second, VANET links are known to be unreliable and short, and the extensive use of IP tunneling on-the-air was judged not efficient. Accordingly, the first major architecture innovation proposed in this paper is to re-introduce a foreign agent (FA) in MIP located at the IGW, so that the IP-tunneling would be kept in the back-end (between a Proxy and an IGW) and not on the air. Second, the proxy has been extended to build an IP tunnel and be connected to the right FA/IGW for an IP flow using a global IPv6 address.

This is a pioneer paper, which contributed to changing MIP and led to the new IPv6 architecture currently known as Proxy-MIP and the subsequent DMM-PMIP. Three key messages can be yet kept in mind. First, unlike the Internet, vehicles can be more prominently directly addressed than the Internet traffic, and do not have a Home Network in the traditional MIP sense. Second, IP tunneling should be avoided as much as possible over the air. Third, the protocol-based mobility (induced by the physical mobility) must be kept hidden to both the vehicle and the correspondent node (CN).

5.6. A Layered Architecture for Vehicular Delay-Tolerant Networks

Soares et al. addressed the case of delay tolerant vehicular network [Vehicular-DTN]. For delay tolerant or disruption tolerant networks, rather than building a complex VANET-IP multi-hop route, vehicles may also be used to carry packets closer to the destination or directly at the destination. The authors built the well-accepted DTN Bundle architecture and protocol to propose a VANET extension. They

introduced three types of VANET nodes: (i) terminal nodes (requiring data), (ii) mobile nodes (carrying data along their routes), and (iii) relay nodes (storing data at cross-roads of mobile nodes as data hotspot).

The major innovation in this paper is to propose a DTN VANET architecture separating a Control plane and a Data plane. The authors claimed it to be designed to allow full freedom to select the most appropriate technology, as well as allow to use out-of-band communication for small Control plane packets and use DTN in-band for the Data plane. The paper then further describes the different layers from the Control and the Data planes. One interesting aspect is the positioning of the Bundle layer between L2 and L3, rather than above TCP/IP as for the DTN Bundle architecture. The authors claimed this to be required first to keep bundle aggregation/disaggregation transparent to IP, as well as to allow bundle transmission over multiple access technologies (described as MAC/PHY layers in the paper).

Although the DTN architectures evolved since the paper has been written, this paper addresses IP mobility management from a different approach. The innovative aspect is an early proposal to separate the Control from the Data plane to allow a large flexibility in a Control plane to coordinate a heterogeneous radio access technology (RAT) Data plane.

5.7. Key Observations

Unidirectional links exist and must be considered. Control Plane must be separated from Data Plane. ID/Pseudonym change requires a lightweight DAD. IP tunneling should be avoided. Vehicles do not have a Home Network. Protocol-based mobility must be kept hidden to both the vehicle and the correspondent node (CN). An ITS architecture may be composed of three types of vehicles: Leaf Vehicle, Range Extending Vehicle, and Internet Vehicle.

6. Vehicular Network Routing

This section surveys routing in vehicular networks.

6.1. An IP Passing Protocol for Vehicular Ad Hoc Networks with Network Fragmentation

Chen et al. tackled the issue of network fragmentation in VANET environments [IP-Passing-Protocol]. The paper proposes a protocol that can postpone the time to release IP addresses to the DHCP server and select a faster way to get the vehicle's new IP address, when the vehicle density is low or the speeds of vehicles are varied. In such

circumstances, the vehicle may not be able to communicate with the intended vehicle either directly or through multi-hop relays as a consequence of network fragmentation.

The paper claims that although the existing IP passing and mobility solutions may reduce handoff delay, but they cannot work properly on VANET especially with network fragmentation. This is due to the fact that messages cannot be transmitted to the intended vehicles. When network fragmentation occurs, it may incur longer handoff latency and higher packet loss rate. The main goal of this study is to improve existing works by proposing an IP passing protocol for VANET with network fragmentation.

The paper makes the assumption that on the highway, when a vehicle moves to a new subnet, the vehicle will receive broadcast packet from the target Base Station (BS), and then perform the handoff procedure. The handoff procedure includes two parts, such as the layer-2 handoff (new frequency channel) and the layer-3 handover (a new IP address). The handoff procedure contains movement detection, DAD procedure, and registration. In the case of IPv6, the DAD procedure is time consuming and may cause the link to be disconnected.

This paper proposes another handoff mechanism. The handoff procedure contains the following phases. The first is the information collecting phase, where each mobile node (vehicle) will broadcast its own and its neighboring vehicles' locations, moving speeds, and directions periodically. The remaining phases are, the fast IP acquiring phase, the cooperation of vehicle phase, the make before break phase, and the route redirection phase.

Simulation results show that for the proposed protocol, network fragmentation ratio incurs less impact. Vehicle speed and density has great impact on the performance of the IP passing protocol because vehicle speed and vehicle density will affect network fragmentation ratio. A longer IP lifetime can provide a vehicle with more chances to acquire its IP address through IP passing. Simulation results show that the proposed scheme can reduce IP acquisition time and packet loss rate, so extend IP lifetime with extra message overhead.

6.2. Experimental Evaluation for IPv6 over VANET Geographic Routing

Tsukada et al. presented a work that aims at combining IPv6 networking and a Car-to-Car Network routing protocol (called C2CNet) proposed by the Car2Car Communication Consortium (C2C-CC), which is an architecture using a geographic routing protocol [VANET-Geo-Routing]. In C2C-CC architecture, C2CNet layer is located between IPv6 and link layers. Thus, an IPv6 packet is delivered with

outer C2CNet header, which introduces the challenge of how to support the communication types defined in C2CNet in IPv6 layer.

The main goal of GeoNet is to enhance these specifications and create a prototype software implementation interfacing with IPv6. C2CNet is specified in C2C-CC as a geographic routing protocol.

In order to assess the performance of this protocol, the authors measured the network performance with UDP and ICMPv6 traffic using iperf and ping6. The test results show that IPv6 over C2CNet does not have too much delay (less than 4ms with a single hop) and is feasible for vehicle communication. In the outdoor testbed, they developed AnaVANET to enable hop-by-hop performance measurement and position trace of the vehicles.

The combination of IPv6 multicast and GeoBroadcast was implemented, however, the authors did not evaluate the performance with such a scenario. One of the reasons is that a sufficiently high number of receivers are necessary to properly evaluate multicast but experimental evaluation is limited in the number of vehicles (4 in this study).

6.3. Key Observations

IP address autoconfiguration should be manipulated to support the efficient networking. Due to network fragmentation, vehicles cannot communicate with each other temporarily. IPv6 ND should consider the temporary network fragmentation. IPv6 link concept can be supported by Geographic routing to connect vehicles with the same IPv6 prefix.

7. Mobility Management in Vehicular Networks

This section surveys mobility management schemes in vehicular networks to support handover.

7.1. A Hybrid Centralized-Distributed Mobility Management for Supporting Highly Mobile Users

Nguyen et al. proposed a hybrid centralized-distributed mobility management called H-DMM to support highly mobile vehicles [H-DMM]. The legacy DMM is not suitable for high-speed scenarios because it requires additional registration delay proportional to the distance between a vehicle and its anchor network. H-DMM is designed to satisfy a set of requirements, such as service disruption time, end-to-end delay, packet delivery cost, and tunneling cost.

H-DMM adopts a central node called central mobility anchor (CMA), which plays the role of a local mobility anchor (LMA) in PMIPv6.

When it enters a mobile access router (MAR) as an access router, a vehicle obtains a prefix from the MAR (called MAR-prefix) according to the legacy DMM protocol. In addition, it obtains another prefix from the CMA (called LMA-prefix) for a PMIPv6 domain. Whenever it performs a handover between the subnets for two adjacent MARs, a vehicle keeps the LMA-prefix while obtaining a new prefix from the new MAR. For a new data exchange with a new CN, the vehicle can select the MAR-prefix or the LMA-prefix for its own source IPv6 address. If the number of active prefixes is greater than a threshold, the vehicle uses the LMA-prefix-based IPv6 address as its source address. In addition, it can continue receiving data packets with the destination IPv6 addresses based on the previous prefixes through the legacy DMM protocol.

Thus, H-DMM can support an efficient tunneling for a high-speed vehicle that moves fast across the subnets of two adjacent MARs. However, when H-DMM asks a vehicle to perform DAD for the uniqueness test of its configured IPv6 address in the subnet of the next MAR, the activation of the configured IPv6 address for networking will take a delay. This indicates that a proactive DAD by a network component (i.e., MAR and LMA) can shorten the address configuration delay of the current DAD triggered by a vehicle.

7.2. A Hybrid Centralized-Distributed Mobility Management Architecture for Network Mobility

Nguyen et al. proposed H-NEMO, a hybrid centralized-distributed mobility management scheme to handle IP mobility of moving vehicles [H-NEMO]. The standard Network Mobility (NEMO) basic support, which is a centralized scheme for network mobility, provides IP mobility for a group of users in a moving vehicle, but also inherits the drawbacks from Mobile IPv6, such as suboptimal routing and signaling overhead in nested scenarios as well as reliability and scalability issues. On the contrary, distributed schemes such as the recently proposed Distributed Mobility Management (DMM) locates the mobility anchor at the network edge and enables mobility support only to traffic flows that require such support. However, in high speed moving vehicles, DMM may suffer from high signaling cost and high handover latency.

The proposed H-NEMO architecture is not designed for a specific wireless technology. Instead, it defines a general architecture and signaling protocol so that a mobile node can obtain mobility from fixed locations or mobile platforms, and also allows the use of DMM or Proxy Mobile IPv6 (PMIPv6), depending on flow characteristics and mobility patterns of the node. For IP addressing allocation, a mobile router (MR) or the mobile node (MN) connected to an MR in a NEMO obtain two sets of prefixes: one from the central mobility

anchor and one from the mobile access router (MAR). In this way, the MR/MN may choose a more stable prefix for long-lived flows to be routed via the central mobility anchor and the MAR-prefix for short-lived flows to be routed following the DMM concept. The multi-hop scenario is considered under the concept of a nested-NEMO.

Nguyen et al. did not provide simulation-based evaluations, but they provided an analytical evaluation that considered signaling and packet delivery costs, and showed that H-NEMO outperforms the previous proposals, which are either centralized or distributed ones with NEMO support. In particular cases, such as the signaling cost, H-NEMO is more costly than centralized schemes when the velocity of the node is increasing, but behaves better in terms of packet delivery cost and handover delay.

7.3. NEMO-Enabled Localized Mobility Support for Internet Access in Automotive Scenarios

In [NEMO-LMS], authors proposed an architecture to enable IP mobility for moving networks in a network-based mobility scheme based on PMIPv6. In PMIPv6, only mobile terminals are provided with IP mobility. Different from host-based mobility, PMIPv6 shifts the signaling to the network side, so that the mobile access gateway (MAG) is in charge of detecting connection/disconnection of the mobile node, upon which the signaling to the Local Mobility Anchor (LMA) is triggered to guarantee a stable IP addressing assignment when the mobile node performs handover to a new MAG.

Soto et al. proposed NEMO support in PMIPv6 (N-PMIP). In this scheme, the functionality of the MAG is extended to the mobile router (MR), also called a mobile MAG (mMAG). The functionality of the mobile terminal remains unchanged, but it can receive an IPv6 prefix belonging to the PMIPv6 domain through the new functionality of the mMAG. Therefore, in N-PMIP, the mobile terminal connects to the MR as if it is connecting to a fixed MAG, and the MR connects to the fixed MAG with the standardized signaling of PMIPv6. When the mobile terminal roams to a new MAG or a new MR, the network forwards the packets through the LMA. Hence, N-PMIP defines an extended functionality in the LMA that enables a recursive lookup. First, it locates the binding entry corresponding to the mMAGr. Next, it locates the entry corresponding to the fixed MAG, after which the LMA can encapsulate packets to the mMAG to which the mobile terminal is currently connected.

The performance of N-PMIP was evaluated through simulations and compared to a NEMO+MIPv6+PMIPv6 scheme, with better results obtained in N-PMIP. The work did not consider the case of multi-hop connectivity in the vehicular scenario. In addition, since the MR

should be a trusted entity in the PMIP domain, it requires specific security associations that were not addressed in [NEMO-LMS].

7.4. Network Mobility Protocol for Vehicular Ad Hoc Networks

Chen et al. proposed a network mobility protocol to reduce handoff delay and maintain Internet connectivity to moving vehicles in a highway [NEMO-VANET]. In this work, vehicles can acquire IP addresses from other vehicles through V2V communications. At the time the vehicle goes out of the coverage of the base station, another vehicle may assist the roaming car to acquire a new IP address. Also, cars on the same or opposite lane are entitled to assist the vehicle to perform a pre-handoff.

Authors assumed that the wireless connectivity is provided by WiFi and WiMAX access networks. Also, they considered scenarios in which a single vehicle, i.e., a bus, may need two mobile routers in order to have an effective pre-handoff procedure. Evaluations are performed through simulations and the comparison schemes are the standard NEMO Basic Support protocol and the fast NEMO Basic Support protocol. Authors did not mention applicability of the scheme in other scenarios such as in urban transport schemes.

7.5. Performance Analysis of PMIPv6-Based Network Mobility for Intelligent Transportation Systems

Lee et al. proposed P-NEMO, which is an IP mobility management scheme to maintain the Internet connectivity at the vehicle as a mobile network, and provides a make-before-break mechanism when vehicles switch to a new access network [PMIPv6-NEMO-Analysis]. Since the standard PMIPv6 only supports mobility for a single node, the solution in [PMIPv6-NEMO-Analysis] adapts the protocol to reduce the signaling when a local network is to be served by the in-vehicle mobile router. To achieve this, P-NEMO extends the binding update lists at both MAG and LMA, so that the mobile router (MR) can receive a home network prefix (HNP) and a mobile network prefix (MNP). The latter prefix enables mobility for the moving network, instead of a single node as in the standard PMIPv6.

An additional feature is proposed by Lee et al. named fast P-NEMO (FP-NEMO). It adopts the fast handover approach standardized for PMIPv6 in [RFC5949] with both predictive and reactive modes. The difference of the proposed feature with the standard version is that by using the extensions provided by P-NEMO, the predictive transferring of the context from the old MAG to the new MAG also includes information for the moving network, i.e., the MNP, so that mobility support can be achieved not only for the mobile router, but also for mobile nodes traveling with the vehicle.

The performance of P-NEMO and F-NEMO is only evaluated through an analytical model that is compared to the standard NEMO-BS. No comparison was provided to other schemes that enable network mobility in PMIPv6 domains, such as the one presented in [NEMO-LMS].

7.6. A Novel Mobility Management Scheme for Integration of Vehicular Ad Hoc Networks and Fixed IP Networks

Peng et al. proposed a novel mobility management scheme for integration of VANET and fixed IP networks [Vehicular-Network-MM]. The proposed scheme deals with mobility of vehicles based on a street layout instead of a general two dimensional ad hoc network. This scheme makes use of the information provided by vehicular networks to reduce mobility management overhead. It allows multiple base stations that are close to a destination vehicle to discover the connection to the vehicle simultaneously, which leads to an improvement of the connectivity and data delivery ratio without redundant messages. The performance was assessed by using a road traffic simulator called SUMO (Simulation of Urban Mobility).

7.7. SDN-based Distributed Mobility Management for 5G Networks

Nguyen et al. extended their previous works on a vehicular adapted DMM considering a Software-Defined Networking (SDN) architecture [SDN-DMM]. On one hand, in their previous work, Nguyen et al. proposed DMM-PMIP and DMM-MIP architectures for VANET. The major innovation behind DMM is to distribute the Mobility Functions (MF) through the network instead of concentrating them in one bottleneck MF, or in a hierarchically organized backbone of MF. Highly mobile vehicular networks impose frequent IP route optimizations that lead to suboptimal routes (detours) between CN and vehicles. The suboptimality critically increases by nested or hierarchical MF nodes. Therefore, flattening the IP mobility architecture significantly reduces detours, as it is the role of the last MF to get the closest next MF (in most cases nearby). Yet, with an MF being distributed throughout the network, a Control plane becomes necessary in order to provide a solution for CN to address vehicles. The various solutions developed by Nguyen et al. not only showed the large benefit of a DMM approach for IPv6 mobility management, but also emphasized the critical role of an efficient Control plane.

On the other hand, SDN recently appeared and gained a big attention from the Internet Networking community due to its capacity to provide a significantly higher scalability of highly dynamic flows, which is required by future 5G dynamic networks. In particular, SDN also suggests a strict separation between a Control plane (SDN-Controller) and a Data plane (OpenFlow Switches) based on the OpenFlow standard. Such an architecture has two advantages that are critical for IP

mobility management in VANET. First, unlike traditional routing mechanisms, OpenFlow focuses on flows rather than optimized routes. Accordingly, they can optimize routing based on flows (grouping multiple flows in one route, or allowing one flow to have different routes), and can detect broken flows much earlier than the traditional networking solutions. Second, SDN controllers may dynamically reprogram (reconfigure) OpenFlow Switches (OFS) to always keep an optimal route between CN and a vehicular node.

Nguyen et. al observed the mutual benefits IPv6 DMM could obtain from an SDN architecture, and then proposed an SDN-based DMM for VANET. In their proposed architecture, a PMIP-DMM is used, where MF is OFS for the Data plane, and one or more SDN controllers handle the Control plane. The evaluation and prototype in the paper prove that the proposed architecture can provide a higher scalability than the standard DMM.

This paper makes several observations leading to a strong suggestions that IP mobility management should be based on an SDN architecture. First, SDN will be integrated into future Internet and 5G in a near future. Second, after separating the Identity and Routing addressing, IP mobility management further requires to separate the Control from the Data plane if it needs to remain scalable for VANET. Finally, Flow-based routing (in particular OpenFlow standard) will be required in future heterogeneous vehicular networks (e.g., multi-RAT and multi-protocol) and the SDN coupled with DMM provides a double benefit of dynamic flow detection/reconfiguration and short(-er) route optimizations.

7.8. IP Mobility Management for Vehicular Communication Networks: Challenges and Solutions

Cespedes et al. provided a survey of the challenges for NEMO Basic Support for VANET [Vehicular-IP-MM]. NEMO allows the management of a group of nodes (a mobile network) rather than a single node. However, although a vehicle and even a platoon of vehicles could be seen as a group of nodes, NEMO has not been designed considering the particularities of VANET. For example, NEMO builds a tunnel between an MR (on board of a vehicle) and its HA, which in a VANET context is suboptimal, for instance due to over-the-air tunneling cost, the detour taken to pass by the MR's HA even if the CN is nearby, or the route optimization when the MR moves to a new AR.

Cespedes et al. first summarize the requirements of IP mobility management, such as reduced power at end-device, reduced handover event, reduced complexity, or reduced bandwidth consumption. VANET adds the following requirements, such as minimum signaling for route optimization (RO), per-flow separability, security and binding

privacy protection, multi-homing, and switching HA. As observed, these provide several challenges to IP mobility and NEMO BS for VANET.

Cespedes et al. then describe various optimization schemes available for NEMO BS. Considering a single hop connection to CN, one major optimization direction is to avoid the HA detour and reach the CN directly. In that direction, a few optimizations are proposed, such as creating an IP tunnel between the MR and the CR directly, creating an IP tunnel between the MR and a CR (rather than the HA), a delegation mechanism allowing Visiting Nodes to use MIPv6 directly rather than NEMO or finally intra-NEMO optimization for a direct path within NEMO bypassing HAS.

Specific to VANET, multi-hop connection is possible to the fixed network. In that case, NEMO BS must be enhanced to avoid that the path to immediate neighbors must pass by the respective HAS instead of directly. More specifically, two approaches are proposed to rely on VANET sub-IP multi-hop routing to hide a NEMO complex topology (e.g., Nested NEMO) and provide a direct route between two VANET nodes. Generally, one major challenge is security and privacy when opening a multi-hop route between a VANET and a CN. Heterogeneous multi-hop in a VANET (e.g., relying on various access technologies) corresponds to another challenge for NEMO BS as well.

Cespedes et al. conclude their paper with an overview of critical research challenges, such as Anchor Point location, the optimized usage of geographic information at the subIP as well as at the IP level to improve NEMO BS, security and privacy, and the addressing allocation schema for NEMO.

In summary, this paper illustrates that NEMO BS for VANET should avoid the HA detour as well as opening IP tunnels over the air. Also, NEMO BS could use geographic information for subIP routing when a direct link between vehicles is required to reach an AR, but also anticipate handovers and optimize ROs. From an addressing perspective, dynamic MNP assignments should be preferred, but should be secured in particular during binding update (BU).

7.9. Key Observations

Mobility Management (MM) solution design varies, depending on scenarios: highway vs. urban roadway. Hybrid schemes (NEMO + PMIP, PMIP + DMM, etc.) usually show better performance than pure schemes. Most schemes assume that IP address configuration is already set up. Most schemes have been tested only at either simulation or analytical level. SDN can be considered as a player in the MM solution.

8. Vehicular Network Security

This section surveys security in vehicular networks.

8.1. Securing Vehicular IPv6 Communications

Fernandez et al. proposed a secure vehicular IPv6 communication scheme using Internet Key Exchange version 2 (IKEv2) and Internet Protocol Security (IPsec) [Securing-VCOMM]. This scheme aims at the security support for IPv6 Network Mobility (NEMO) for in-vehicle devices inside a vehicle via a Mobile Router (MR). An MR has multiple wireless interfaces, such as 3G, IEEE 802.11p, WiFi, and WiMAX. The proposed architecture consists of Vehicle ITS Station (Vehicle ITS-S), Roadside ITS Station (Roadside ITS-S), and Central ITS Station (Central ITS-S). Vehicle ITS-S is a vehicle having a mobile Network along with an MR. Roadside ITS-S is an RSU as a gateway to connect vehicular networks to the Internet. Central ITS-S is a TCC as a Home Agent (HA) for the location management of vehicles having their MR.

The proposed secure vehicular IPv6 communication scheme sets up IPsec secure sessions for control and data traffic between the MR in a Vehicle ITS-S and the HA in a Central ITS-S. Roadside ITS-S plays a role of an Access Router (AR) for Vehicle ITS-S's MR to provide the Internet connectivity for Vehicle ITS-S via wireless interfaces, such as IEEE 802.11p, WiFi, and WiMAX. In the case where Roadside ITS-S is not available to Vehicle ITS-S, Vehicle ITS-S communicates with Central ITS-S via cellular networks (e.g., 3G). The secure communication scheme enhances the NEMO protocol that interworks with IKEv2 and IPsec in network mobility in vehicular networks.

The authors implemented their scheme and evaluated its performance in a real testbed. This testbed supports two wireless networks, such as IEEE 802.11p and 3G. The in-vehicle devices (or hosts) in Vehicle ITS-S are connected to an MR of Vehicle ITS-S via IEEE 802.11g. The test results show that their scheme supports promising secure IPv6 communications with a low impact on communication performance.

8.2. Providing Authentication and Access Control in Vehicular Network Environment

Moustafa et al. proposed a security scheme providing authentication, authorization, and accounting (AAA) services in vehicular networks [VNET-AAA]. This security scheme aims at the support of safe and reliable data services in vehicular networks. It authenticates vehicles as mobile clients to use the network access and various services that are provided by service providers. Also, it ensures a confidential data transfer between communicating parties (e.g.,

vehicle and infrastructure node) by using IEEE 802.11i (i.e., WPA2) for secure layer-2 links.

The authors proposed a vehicular network architecture consisting of three entities, such as Access network, Wireless mobile ad hoc networks (MANETs), and Access Points (APs). Access network is the fixed network infrastructure forming the back-end of the architecture. Wireless MANETs are constructed by moving vehicles forming the front-end of the architecture. APs is the IEEE 802.11 WLAN infrastructure forming the interface between the front-end and back-end of the architecture.

For AAA services, the proposed architecture uses a Kerberos authentication model that authenticates vehicles at the entry point with the AP and also authorizes them to the access of various services. Since vehicles are authenticated by a Kerberos Authentication Server (AS) only once, the proposed security scheme can minimize the load on the AS and reduce the delay imposed by layer 2 using IEEE 802.11i.

8.3. Key Observations

The security for vehicular networks should provide vehicles with AAA services in an efficient way. It should consider not only horizontal handover, but also vertical handover since vehicles have multiple wireless interfaces.

9. Summary and Analysis

This document surveyed state-of-the-arts technologies for IP-based vehicular networks, such as IP address autoconfiguration, vehicular network architecture, vehicular network routing, and mobility management.

Through this survey, it is learned that IPv6-based vehicular networking can be well-aligned with IEEE WAVE standards for various vehicular network applications, such as driving safety, efficient driving, and infotainment. However, since the IEEE WAVE standards do not recommend to use the IPv6 neighbor discovery (ND) protocol for the communication efficiency under high-speed mobility, it is necessary to adapt the ND for vehicular networks with such high-speed mobility.

The concept of a link in IPv6 does not match that of a link in VANET because of the physical separation of communication ranges of vehicles in a connected VANET. That is, in a linear topology of three vehicles (Vehicle-1, Vehicle-2, and Vehicle-3), Vehicle-1 and Vehicle-2 can communicate directly with each other. Vehicle-2 and

Vehicle-3 can communicate directly with each other. However, Vehicle-1 and Vehicle-3 cannot communicate directly with each other due to the out-of-communication range. For the link in IPv6, all of three vehicles are on a link, so they can communicate directly with each other. On the other hand, in VANET, this on-link communication concept is not valid in VANET. Thus, the IPv6 ND should be extended to support this multi-link subnet of a connected VANET through either ND proxy or VANET routing.

For IP-based networking, IP address autoconfiguration is a prerequisite function. Since vehicles can communicate intermittently with TCC via RSUs through V2I communications, TCC can play a role of a DHCP server to allocate unique IPv6 addresses to the vehicles. This centralized address allocation can remove the delay of the DAD procedure for testing the uniqueness of IPv6 addresses.

For routing and mobility management, most of vehicles are equipped with a GPS navigator as a dedicated navigation system or a smartphone App. With this GPS navigator, vehicles can share their current position and trajectory (i.e., navigation path) with TCC. TCC can predict the future positions of the vehicles with their mobility information (i.e., the current position, speed, direction, and trajectory). With the prediction of the vehicle mobility, TCC supports RSUs to perform data packet routing and handover proactively.

10. Security Considerations

Security and privacy are important aspects in vehicular networks. Only valid vehicles should be allowed to participate in vehicular networking. Vehicle Identification Number (VIN) and user certificate can be used to authenticate a vehicle and user through road infrastructure, such as Road-Side Unit (RSU) connected to an authentication server in Traffic Control Center (TCC).

11. Acknowledgements

This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No.R-20160222-002755, Cloud based Security Intelligence Technology Development for the Customized Security Service Provisioning). This work was supported in part by ICT R&D program of MSIP/IITP (14-824-09-013, Resilient Cyber-Physical Systems Research) and the DGIST Research and Development Program (CPS Global Center) funded by the Ministry of Science, ICT & Future Planning. 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).

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Appendix A. Changes from draft-jeong-its-vehicular-networking-survey-01

The following changes were made from draft-jeong-its-vehicular-networking-survey-01:

- o Vehicular Network Security section is added.
- o Key Observations subsection is added for each section.
- o The editorial corrections are made.

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