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RESEARCH ARTICLE

A Localized Forwarding Scheme for the Shared-Prefix Model-Based Vehicular Mobility Management Over IEEE WAVE IPv6 Networks

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ABSTRACT IETF IP Wireless Access in Vehicular Environments Working Group proposes a shared-prefix model, where multiple RSUs share a common prefix. In the same prefix domain, a WAVE wireless interface does not need to reconfigure its IPv6 address even if its serving RSU is changed. We had proposed a vehicular mobility management scheme for a shared prefix model over IEEE WAVE IPv6 networks. However, when two vehicles communicate with each other, the data path between two vehicles can be sub-optimal. In the scheme, all incoming packets having a specific prefix are forwarded by a Link Border Router, which manages the prefix, to the serving RSU of the destination vehicle. It causes the triangular data path. To eliminate this triangular data path, we propose a localized forwarding scheme for the vehicular mobility management scheme. This scheme allows that two vehicles within direct communication distance can communicate directly or serving RSUs of two vehicles can communicate directly for intra-vehicular traffic within the WAVE network. It eliminates the triangular data path between two vehicles within the WAVE network. It also reduces the workload of Link Border Routers, which are the hotspot of the vehicular mobility management scheme.

INDEX TERMS Localized forwarding, WAVE, IPWAVE, shared prefix model, vehicular mobility management.

I. INTRODUCTION

IETF IP Wireless Access in Vehicular Environments (IPWAVE) working group is developing an IPv6-based solution to establish direct and secure connectivity for V2V and V2I communication [1]. It proposes a shared-prefix model, where multiple Road Side Units (RSUs) share a common prefix. A main advantage of the shared-prefix model is that the IPv6 address of the WAVE interface of the vehicle within the shared-prefix domain is not changed.

In the shared-prefix model, a single prefix domain consists of multi-link subnets of RSUs that share the same prefix [2]. A prefix domain is managed by a Mobility Anchor (MA) in the Traffic Control Center (TCC). Vehicle movement within the prefix domain is not visible at the outside of the prefix domain, but it requires a local mobility management within the prefix domain to route traffic to the right RSU to which a destination vehicle is attached. IETF IPWAVE working group proposed a Vehicular Mobility Management (VMM) [2] based on Proxy Mobile IPv6 (PMIPv6) [3].

Our previous work proposed an Enhanced-VMM (E-VMM) scheme for a shared-prefix model over IEEE WAVE IPv6 networks [4]. In E-VMM scheme, a virtual link replaces a single prefix domain. The shared-prefix is assigned to the virtual link, which is attached to the Link Border Router (LBR) instead of the MA in the TCC. The virtual link consists of multiple sub-links, with each sub-link representing a wireless link covered by an RSU included in

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the virtual link. Vehicle movement within the virtual link is handled locally and is not visible outside of the virtual link. Therefore, its Correspondent Node (CN) does not need to be aware of the vehicle's movement.

However, E-VMM scheme has a triangular data path problem. Because all incoming packets having a shared-prefix are handled by the LBR, which manages the shared-prefix assigned to one of its virtual links. Fig.1 illustrates the triangular data path problem. In the event that Vehicle1(V1) communicates with Vehicle2(V2), data packets from V1 to V2 are handled by LBR2, and the reverse data packets are handled by LBR1. The data path between the two vehicles takes on a triangular shape, consisting of the source RSU, destination LBR, and destination RSU. If data packets are forwarded through the triangular path, it can be suboptimal, and result in increased the end-to-end delay and traffic load at the LBRs. To overcome this problem, the triangular path can be shortened to a direct path from the source RSU to the destination RSU.

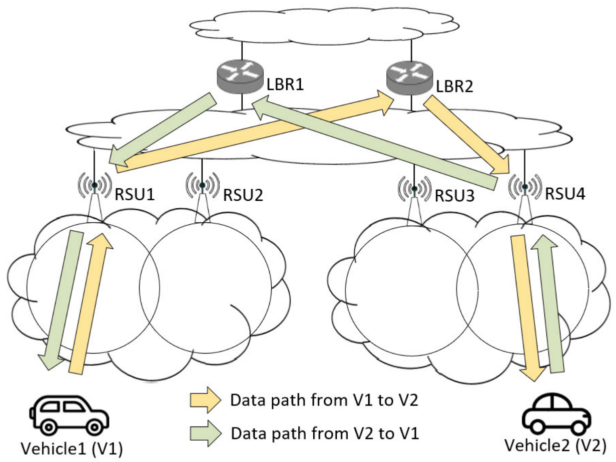


FIGURE 1. Triangular data path.

In this paper, we propose a Localized Forwarding (LF) scheme to eliminate the triangular data path in E-VMM scheme. The LF scheme allows two vehicles within direct communication distance to communicate directly or the serving RSUs of two vehicles to communicate directly within the WAVE network. To support localized forwarding, the scheme extends VMM-Neighbor Discovery Protocol (NDP) defined in [4]. It uses a UDP-Redirect message based on the standard NDP Redirect message [5] to carry local forwarding information between an LBR and an RSU. As the two vehicles can communicate through the optimal path, it eliminates the triangular data path between the two vehicles within the WAVE network and reduces the end-to-end delay. It also reduces the workload of LBRs, which are the hotspot of the E-VMM scheme, because all down-link data packets do not go through LBR with localized forwarding. According to our analysis, when applied our LF scheme, the workload of the LBR is decreased by nearly 50% if the vehicle sends 0.1 message per second. If the vehicle sends 1 message per second, the workload of the LBR is decreased by nearly 95%. Additionally, according to our simulation, the end-to-end delay is reduced by half of the total delay because the source RSU does not forward the UDP packets to LBR and LBR does not reflect the packets to the destination RSU.

The rest of this paper is organized as follows. Section II presents related work. Section III lists all abbreviations and acronyms used in this paper. Section IV briefly describes E-VMM scheme to aid understanding of the proposed LF scheme. Section V describes the network architecture of the proposed LF scheme. Section VI presents the procedure of proposed LF scheme in detail. Section VII describes the proposed scheme analysis. Section VIII presents the simulation results. Finally, Section IX concludes this paper.

II. RELATED WORK

IPv4 and IPv6 mobility schemes define their own route optimization schemes. In Mobile IPv4 (MIPv4) [6], there are two different approaches for route optimization: one is defined in a [7] and the other is a standard [8]. In Mobile IPv6 (MIPv6) [9], localized routing is defined as "Route Optimization" and it must be supported by all IPv6 nodes which support route optimization. In PMIPv6 [3], localized routing is defined in another standard [10].

There is a specialized route optimization scheme for routers to optimize the forwarding path among them, called "Asymmetric Extended Route Optimization (AERO) [11]". As the NDP Redirect message cannot be used between IPv6 routers, AERO defines a new Redirect message between routers. It also defines a security mechanism for messages and uses User Datagram Protocol (UDP) [12] encapsulation instead of Internet Control Message Protocol version 6 (ICMPv6) [13] to distinguish the new Redirect messages from NDP Redirect message. It is applied to our proposed localized forwarding scheme.

A. ROUTE OPTIMIZATION IN MOBILE IPV4

The basic framework for Route Optimization in MIPv4 is described in [7]. The scheme includes CN in the mobility scheme. If a CN supports route optimization, it maintains a Binding Cache Entry (BCE). A entry of the BCE is created when a Home Agent (HA) sends a Binding Update (BU) to notify the current location of a Mobile Node (MN), with which it is communicating. The BU is also sent when the MN changes its location. When the CN sends a packet to the MN, it encapsulates the packet into another IP (IP-in-IP encapsulation). Then the CN sends the encapsulated packet directly to the MN. The Route Optimization in MIPv6 is a kind of the enhanced version of this scheme. In MIPv6, the BU for Route Optimization is sent by the MN instead of the HA. It means that the decision for Route Optimization is done by MN, not HA.

The another Route Optimization scheme is a home agent-assisted route optimization functionality for MIPv4 [8].

The scheme is proposed to optimize routes between networks behind Mobile Routers (MRs), as defined by Network Mobility (NEMO) [14]. To use this scheme, all nodes must be connected to a single HA. In the scheme, the HA sends eligible peer nodes' information to discover their network prefixes and to establish a direct tunnel between peer nodes.

B. LOCALIZED ROUTING FOR PROXY MOBILE IPV6

A Localized Routing scheme for PMIPv6 is defined in [10]. In PMIPv6, Local Mobility Anchors (LMAs) and Mobile Access Gateways (MAGs) establish a bi-directional tunnel for forwarding all data packets belonging to the MNs. All up-stream data packets are forwarded from MAGs to LMAs and all down-stream data packets are handled by LMAs and forwarded to MAGs via the bi-directional tunnels between them. If both up-stream data packets and down-stream data packets may pass the common LMA or the common MAG, these packets traverse sub-optimal data path.

The Localized Routing scheme [10] identifiers three sub-optimal cases: 1) the common LMA with different MAGs, 2) the common MAG with different LMAs, and 3) the common LMA with common MAGs. It presents the local routing scheme for each case. However, the scheme does not consider the case where MNs are attached to the different MAGs and anchored at different LMAs. Also, it does not specified about the exact traffic identification mechanism and how to detect the possibility of Localized Routing.

III. ABBREVIATIONS AND ACRONYMS

In this section, the definitions of abbreviations and acronyms used in the paper are summarized in Table 1. Each abbreviation and acronym is ordered from A to Z.

TABLE 1. Abbreviations and acronyms.

Abbreviation	Full Form
ACK	Acknowledgement
AERO	Asymmetric Extended Route Optimization
BCE	Binding Cache Entry
BSM	Basic Safety Message
BU	Binding Update
CCH	Control Channel
CN	Correspondent Node
DC	Destination Cache
DCE	Destination Cache Entry
E-VMM	Enhanced-Vehicular Mobility Management
HA	Home Agent
ICMPv6	Internet Control Message Protocol version 6
ILNPv6	Identifier-Locator Network Protocol for IPv6
ILPL	Inter Link Prefix List
IP-WAVE	IP Wireless Access in Vehicular Environments
LBR	Link Border Router
LF	Localized Forwarding
LFA	Localized Forwarding Acknowledgement
LFI	Localized Forwarding Initiation
LFT	Localized Forwarding Table
LLA	Link Layer Address
LMA	Local Mobiity Anchor
MA	Mobility Anchor
MAG	Mobile Access Gateway
MIPv4	Mobile IPv4
MIPv6	Mobile IPv6
MN	Mobile Node
MR	Mobile Router
NA	Neighbor Advertisement
NC	Neighbor Cache
NCE	Neighbor Cache Entry
NDP	Neighbor Discovery Protocol
NEMO	Network Mobility
NS	Neighbor Solicitation
PMIPv6	Proxy Mobile IPv6
RSU	Road Side Unit
RVL	Registered Vehicle List
SCH	Service Channel
SDN	Software-Defined Network
SLFT	Suppress Localized Forwarding Table
SLLAO	Source Link Layer Address Option
TCC	Traffic Control Center
TLLAO	Target Link Layer Address Option
UDP	User Datagram Protocol
VMM	Vehicular Mobility Management
WRA	Wave Routing Advertisement
WSA	WAVE Service Advertisement

IV. THE ENHANCED VEHICULAR MOBILITY MANAGEMENT FOR THE SHARED-PREFIX MODEL

We explain briefly about the network attachment procedure and the handover procedure of the enhanced vehicular mobility management [4] to aid understanding the proposed localized forwarding scheme.

A. NETWORK ATTACHMENT

When a vehicle first enters the WAVE network or moves to another RSU which belongs to another virtual link, the vehicle performs the network attachment procedure. This network attachment procedure is performed by the IPv6 configuration module in the vehicle and the VMM-NDP module in the vehicle, the RSU and the LBR as follows:

Step 1) When a vehicle receives a WAVE Service Advertisement (WSA) from the first RSU or another RSU which belongs to another virtual link, the received WSA is forwarded to the IPv6 configuration module.

Step 2) The IPv6 configuration module adds a Destination Cache Entry (DCE) and a Neighbor Cache Entry (NCE) for the RSU's link-local IPv6 address using the information in the WSA. It prevents the Neighbor Solicitation (NS)/Neighbor Advertisement (NA) exchange for the RSU's link-local IPv6 address.

Step 3) The IPv6 configuration module performs the following address registration procedure:

- It generates IPv6 addresses according to [4].
- It requests address registration for newly generated IPv6 addresses to the VMM-NDP module.
- The VMM-NDP module creates NS messages for newly generated IPv6 addresses. These NS messages include the Stateless Link Layer Address Option (SLLAO) [5]. Then, it encapsulates NS messages into an UDP message and sends the UDP-NS message to the default gateway (RSU)'s link-local address.

Step 4) The VMM-NDP module in the RSU forwards the UDP-NS message to the LBR.

Step 5) The VMM-NDP module in the LBR registers IPv6 addresses in the NS messages in the the UDP-NS message and sends the NA messages to the vehicle via the RSU.

B. HANDOVER PROCEDURE

When the vehicle moves to another RSU, the vehicle performs the following handover procedure.

Step 1) When the vehicle receives a WSA sent by another RSU, the IPv6 configuration module requests for the VMM-NDP module to notify the change of the point of attachment for each public IPv6 address to the RSU using an UDP-NS message which consists of NS messages with 'H' flag set. Note that a public IPv6 address currently used at on-going connection may use another prefix which is assigned to the previous virtual link.

Step 2) When the VMM-NDP module in the RSU receives the UDP-NS message, the VMM-NDP module forwards each NS message in the UDP-NS message to the LBR which manages the prefix of the public IPv6 address in the NS message.

Step 3) The VMM-NDP module in the LBR updates the serving RSU of the public IPv6 address in each NS message in the the UDP-NS message, and sends NA messages to the vehicle via the RSU.

V. THE NETWORK ARCHITECTURE FOR THE PROPOSED LOCALIZED FORWARDING SCHEME

The proposed LF scheme is based on E-VMM scheme [4]. Fig.2 shows the network architecture of both E-VMM scheme and proposed LF scheme.

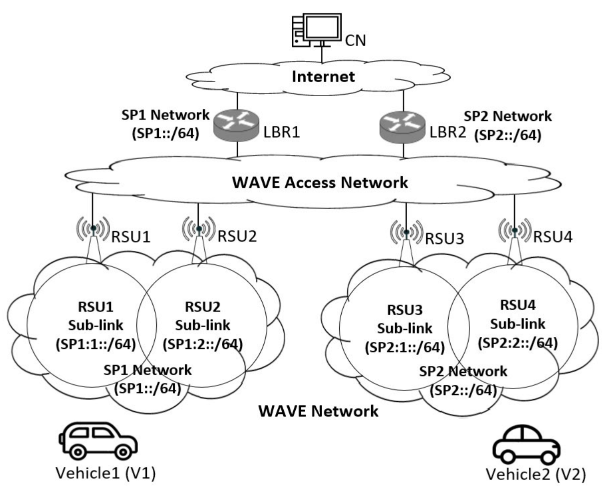


FIGURE 2. The network architecture of proposed LF scheme.

In this LF scheme, CN becomes a vehicle in the WAVE network instead of an IPv6 node in the Internet. Therefore, data packets travel from the RSU to which a source vehicle (V1) is currently attached to the RSU to which a destination vehicle (V2) is currently attached. The former RSU is called the source RSU and the latter RSU is called the destination RSU. In the reverse direction, the role of the source RSU and the destination RSU is also reversed. These RSUs are also changed frequently, as V1 and V2 are rapidly moving within the WAVE network. The proposed LF scheme tries to shorten the data path between two communication vehicles.

The architecture uses the shared-prefix model. E-VMM scheme defines a virtual IPv6 link, which consists of multiple sub-links. Each sub-link in the virtual link represents a wireless link of an RSU. A shared prefix is assigned to the virtual link and it conforms the ICMP Locator Update Message for the Identifier-Locator Network Protocol for IPv6 (ILNPv6) address architecture [15] as well as the standard IPv6 address architecture [16]. Each sub-link has its own prefix derived from the shared prefix. The shared prefix consists of a 48-bit global routing prefix and a 16-bit subnet identifier. The subnet identifier of the shared prefix is zero, while the subnet identifier of sub-links are non zero. In Fig.2, there are two virtual links. A virtual link is managed by an LBR1. The virtual link has two sub-links. A shared prefix (SP1::/64) is assigned to the virtual link. Sub-links of the virtual link represent wireless links of RSU1 and RSU2. Their subnet prefixes are SP1:1::/64 and SP1:2::/64, respectively.

The major components of the proposed scheme are as follows:

- Vehicle
- Road Side Unit (RSU)
- The WAVE access network
- Link Border Router (LBR)

A. VEHICLE

A vehicle is a MN or a CN which wants to communicate with another vehicle in the WAVE network. A vehicle periodically broadcasts Basic Safety Messages (BSMs) via the control channel (CCH) into the WAVE network. However, the vehicle uses the service channel (SCH), indicated at the Wave Routing Advertisement (WRA) for the IPv6 routing service, to access Internet services. When the CCH and the SCH use different WAVE interfaceslink, two link-layer addresses (LLAs), CCH LLA and SCH LLA, of the WAVE interfaces are different. In this case, neighbors' SCH LLAs may not be used to identify neighboring vehicles, as neighboring vehicles are usually identified by neighbors' CCH LLAs. We assume that the IPv6 module in a vehicle includes conceptual data structures (a Destination Cache (DC) and a Neighbor Cache (NC)) and follows the conceptual sending algorithm, defined in [5]. Fig.3(a) and Fig.3(b) shows the entry of the DC and NC, respectively.

A vehicle also includes an IPv6 configuration module and a VMM-NDP module, defined in [4]. The IPv6 configuration module configures new IPv6 addresses for the WAVE interface, tuned to SCH, to use the Internet. The VMM-NDP module performs the network attachment procedure and the handover procedure. A vehicle sends all IPv6 packets to

Destination IPv6 address	Next Hop IPv6 address

(a) Vehicle Destination Cache (DC)

IPv6 address	Link-Layer address

(b) Vehicle Neighbor Cache (NC)

FIGURE 3. Entry of the table at vehicle.

its default gateway due to the wireless link property, called the undetermined link-level connectivity property [17]. The link-local address and the link-layer address of the default gateway are included in the WRA of the IPv6 routing service.

B. ROAD SIDE UNIT (RSU)

An RSU is an IPv6 router which connects the WAVE network to the WAVE access network. It broadcasts WSAs into the WAVE network. A WSA for the IPv6 routing service includes the WRA.

Vehicle's IPv6 address	Vehicele link-layer address	Status

(a) RSU-Registered Vehicle List (RSU-RVL)

Shared prefix	LBR's IPv6 address

(b) RSU-Inter Link Prefix List (RSU-ILPL)

Vehicle's IPv6 address	Prefix of the RSU's sub-link

(c) RSU-Localized Forwarding Table (RSU-LFT)

Src vehicle's IPv6 address	Dst vehicle's IPv6 address

(d) RSU-Suppress Localized Forwarding Table (RSU-SLFT)

FIGURE 4. Entry of the table at RSU.

An RSU includes a VMM-NDP module for the network attachment procedure and the handover procedure. The VMM-NDP module maintains two lists defined in [4]:

- Registered Vehicle List (RSU-RVL)
  The RSU-RVL entry is shown in Fig.4(a). It is used to determine whether an IPv6 packet is an intra-RSU packet. If the destination IPv6 addresses of a packet are registered at its RSU-RVL, the packet is an intra-RSU packet.
- Inter Link Prefix List (RSU-ILPL)
  The ILPL entry is shown in Fig.4(b). It is used to determine whether an IPv6 packet is an inter-RSU packet with the WAVE network. If the prefix of the destination IPv6 addresses of a packet is included in the ILPL, the packet is an inter-RSU packet with the WAVE network.

An RSU can optionally support the proposed LF scheme. The LF scheme introduces two tables as follows:

- Localized Forwarding Table (RSU-LFT)
  The RSU-LFT entry is shown in Fig.4(c). It is used by the inter-RSU LF.
- Suppress Localized Forwarding Table (RSU-SLFT)
  The RSU-SLFT entry is shown in Fig.4(d). It is used to suppress the LF scheme for specific destination IPv6 addresses. For the intra-RSU case, an RSU-SLFT entry is created when the VMM-NDP module in a source vehicle indicates that it cannot communicate with the destination vehicle directly due to the destination vehicle is not its one-hop neighbor. For the inter-RSU, an RSU-SLFT entry is created when the destination LBR indicates for the source RSU not to support the LF scheme for a specific destination address of an IPv6 packet. The destination LBR is an LBR which manages the shared prefix which matches the prefix of the destination IPv6 address of an IPv6 packet.

C. THE WAVE ACCESS NETWORK

The WAVE access network is an IPv6 network and it connects RSUs and LBRs in the proposed scheme.

D. LINK BORDER ROUTER (LBR)

An LBR is a router which manages a virtual link. It includes a VMM-NDP module to perform the network attachment procedure and the handover procedure. The VMM-NDP module maintains an LBR-RVL [4]. Fig.5(a) shows the entry of the LBR-RVL. The LBR-RVL tracks the current serving RSU of an IPv6 address. The IPv6 address is assigned to the WAVE interface of a vehicle, which is attached to the serving RSU.

Vehicle's IPv6 address	RSU's IPv6 address	Prefix of the RSU's sub-link

(a) LBR-Registered Vehicle List (LBR-RVL)

RSU's IPv6 address	Vehicle's IPv6 address

(b) LBR-Localized Forwarding Table (LBR-LFT)

FIGURE 5. Entry of the table at LBR.

The proposed LF scheme introduces a Localized Forwarding Table (LBR-LFT). Fig.5(b) shows the entry of the LBR-LFT. An LBR-LFT entry is created when the source RSU of a packet indicates that it wants to perform the LF scheme with the LBR. The LBR-LFT entry is used to notify the change of the serving RSU of an destination IPv6 address of a packet to the source RSU of the IPv6 packet.

VI. THE PROPOSED LOCALIZED FORWARDING SCHEME

The proposed LF scheme introduces three new messages and a new flag as follows:

- UDP-Redirect message

- UDP-Localized Forwarding Initiation (UDP-LFI) message
- UDP-Localized Forwarding Acknowledgement (UDP-LFA) message
- 'C' flag at the UDP-NS/NA message

The format of three message follows the format defined in the NDP standard [5]. They also use the UDP encapsulation instead of ICMPv6 to separate them from the standard NDP message.

Type(8)	Code(8)	Checksum(16)
T | H | Reserved(30)		
Target Address(128)		
Destination Address(128)		
Target Link-Layer Address Option(TLLAO)		

(a) UDP-Redirect

Type(8)	Code(8)	Checksum(16)
Reserved(32)		
Sequence(16)		Lifetime(16)
Destination Address(128)		

(b) UDP-LFI and UDP-LFA

Type(8)	Code(8)	Checksum(16)
H | C | Reserved(30)		
Target Address(128)		
Source Link-Layer Address Option(SLLAO)		

(c) UDP-NS

Type(8)	Code(8)	Checksum(16)
R | S | O | H | D | C | Reserved(27)		
Target Address(128)		
Source Link-Layer Address Option(SLLAO)		

(d) UDP-NA

FIGURE 6. Proposed message formats.

The UDP-Redirect message format is shown in Fig. 6(a). It defines two new flags: a 'Termination (T)' flag and a 'Handover (H)' flag in the first two bits of the reserved field in the NDP Redirect message. The 'T' flag indicates that the localized forwarding for the destination address should be terminated. The 'H' flag indicates that the target address for the destination address is changed.

The UDP-LFI message format and the UDP-LFA message format are shown in Fig.6(b). They use the same message format. The UDP-LFI message is used to request the localized forwarding to the LBR which manages the prefix of the destination IPv6 address of an IPv6 packet. The UDP-LFA message is used to notify that the LBR refuses the localized forwarding request. When the localized forwarding is acceptable, the LBR sends an UDP-Redirect message.

In addition, we also define new flags in the UDP-NS/NA messages. the UDP-NS/NA messages' formats are shown at Fig.6(c) and Fig.6(d). The 'C' flag is used to request the link layer address of the CCH interface at the vehicle which owns the destination address in the NS message. The 'C' flag in the UDP-NA message indicates that the link-layer address in the SLLAO is the link-layer address of the CCH interface.

The localized forwarding is always applied to up-stream traffic only at the source RSU of an uni-directional IP flow. For bi-directional communication, the localized forwarding of each direction is handled independently by the source RSU of each direction.

The localized forwarding can occur in two cases depending on locations of source and destination vehicles in the WAVE network:

- The intra-RSU localized forwarding
  - Two vehicles are attached to the same RSU
- The inter-RSU localized forwarding
  - Two vehicles are attached to different RSUs, but the prefixes of vehicles' public IPv6 addresses are pre-configured to support the localized forwarding.

A. OVERVIEW OF THE LOCALIZED FORWARDING

An RSU must be configured to support the localized forwarding. We assume that the prefix of the destination IPv6 address of an IPv6 packet has an match entry at the ILPL. Each ILPL entry indicates that the LBR which manages the prefix of the entry can be cooperative with the RSU. The destination LBR is defined as the LBR which manages the prefix of the destination IPv6 address. Fig.7 shows the localized forwarding procedure when an IPv6 packet is arrived at the RSU.

Step 1) A source vehicle (V1) wants to send IPv6 packets to another destination vehicle (V2). The IPv6 module in V1 follows the conceptual sending algorithm defined in [5]. The IPv6 module creates an DCE for the destination address of an IPv6 packet. Since the prefix list is empty due to undetermined link-level connectivity property, the on-link determination of the next-hop determination procedure determine the prefix of the destination address of the packet is "off-link". As a result, the next-hop field of the created DCE becomes the default gateway (the current RSU). The packet is sent the default gateway and the NCE for the default gateway is already created by the IPv6 configuration module using the WRA information. No NS/NA exchange is occurred.

Step 2) When the source RSU receives the IPv6 packet, the VMM-NDP module in the RSU looks up both RSU-RVL and S-LFT with the destination IPv6 address of the packet.

Depending on the matching result of the RSU-RVL and S-LFT, there are 4 cases in Table 2:

TABLE 2. Each case according to the matching result.

	S-LFT found	S-LFT not found
RSU-RVL found	Case 1	Case 2
RSU-RVL not found	Case 3	Case 4

Case 1) Intra-RSU without the localized forwarding

The matching entry of the RSU-RVL table indicates V2 is attached at the RSU, and the matching entry of the S-LFT table indicates that V1 suppresses the localized forwarding with V2 since V1 cannot communicate with V2 directly. As a result, the RSU forwards the IPv6 packets to V2 and does not send UDP-Redirect messages to V1.

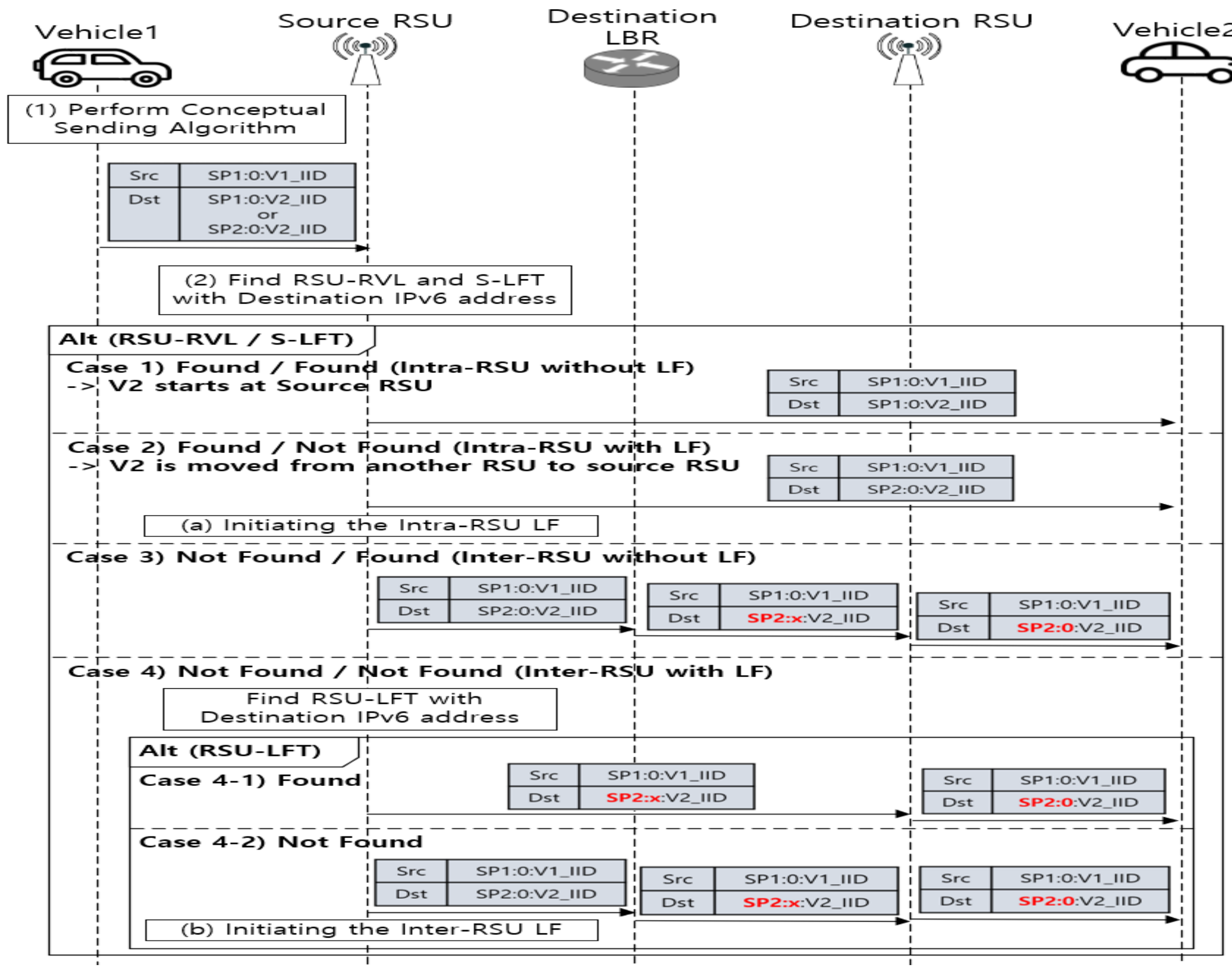


FIGURE 7. Overview of localized forwarding.

Case 2) Intra-RSU with the localized forwarding

Both V1 and V2 are attached the RSU and V1 does not suppress the LF yet. This case is happened when both V1 and V2 starts communication at the same RSU or the destination vehicle is attached to the same RSU when their communication is ongoing. Firstly, the RSU forwards the packet to V2. Then it starts the intra-RSU LF procedure (Fig.8) by sending an UDP-Redirect message to V1. The UDP-Redirect message is a hit to V1 that V1 may communicate with V2 directly. If V1 cannot communicates with V2 directly, V1 sends the UDP-LFA message to suppress the intra-RSU LF. It creates an S-LFT entry for the destination IPv6 address (V2). The same operation is also done to V2, as the RSU becomes the source RSU for both forward and reverse directions.

Case 3) Inter-RSU without the localized forwarding

V2 is attached at another RSU, and the matching entry of the S-LFT table indicates that the destination LBR suppresses the localized forwarding for the destination IPv6 address. The RSU handles the IPv6 packet according the the IPv6 standards.

Case 4) Inter-RSU with the localized forwarding

Both V1 and V2 are attached the RSU, and the destination LBR does not suppress the LF yet. The RSU looks up the RSU-LFT with the destination IPv6 address of the IPv6 packet.

- **Case 4-1)** If there is a matching RSU-LFT entry, the RSU replaces the prefix of the destination address of the packet with the prefix of the matching entry. Then the RSU handles the modified IPv6 packet according the the IPv6 standards.
- **Case 4-2)** Otherwise, the RSU forwards the packet according the the IPv6 standards. Then the RSU starts the inter-RSU LF procedure (Fig. 9) by sending an UDP-LFI message to the destination LBR. The destination LBR may send an UDP-LFA message if it wants to suppress the inter-RSU LF. The RSU creates an S-LFT entry for the destination IPv6 address of the packet when the RSU receives the UDP-LFA message.

B. THE INTRA-RSU LOCALIZED FORWARDING

Even if both V1 and V2 are registered at the same RSU, V2 may not be one-hop neighbor of V1. Therefore, the source RSU notifies that V1 may communicate with V2 directly. V1 must determine whether it communicates with V2 directly.

The intra-RSU LF procedure is performed as follows (Fig.7 Case 2 (a)):

Step 1) The RSU sends an UDP-Redirect message to V1. The target address field and the destination address field of the UDP-Redirect message contains the destination IPv6 address of the received packet. The UDP-Redirect message also contains the SCH LLA of the destination IPv6 address in the Target Link Layer Address Option (TLLAO). The LLA is taken from the RSU-RVL table entry of the destination IPv6 address.

Step 2) When V1 receives the UDP-Redirect message, the VMM-NDP module sends an unicast UDP-NS message with the 'C' flag set to V2. V1 can detect the existence of V2 with the BSM set by V2. Because the SCH LLA in the TLLAO and the CCH's LLA taken from BSMs sent by V2 can be different, V1 has to obtain the CCH's LLA from V2. The unicast UDP-NS message also determines whether V2 is really V1's one-hop neighbor.

Step 3) When V2 receives the UDP-NS message with 'C' flag set, it sends the unicast UDP-NA message to V1. The SLLAO in the unicast NA message contains the CCH LLA of V2.

Step 4) When the VMM-NDP module receives the UDP-NA message with 'C' flag set, it updates the next-hop field of the corresponding DCE of the destination IPv6 address to the target IPv6 address. It also creates an NCE for the target IPv6 address with the SCH LLA in the TLLAO of the UDP-Redirect message to avoid standard NS/NA exchange. The VMM-NDP module also subscribes the event "Delete V2 CCH LLA". The event indicates that V2 is no longer its one-hop neighbor. If the VMM-NDP module does not receive any unicast NA message or it is notified the subscribed event, the VMM-NDP module reverts the next-hop field of the corresponding DCE to the default gateway and sends an UDP-LFA message to the RSU to suppress the intra-RSU LF for V2.

Step 5) As the next-hop field of the corresponding DCE of IPv6 packets destined to V2 is the destination IPv6 address itself, these IPv6 packets are forwarded to V2 directly.

Fig.8 shows an example of the intra-RSU case. V1 and V2 are attached to the RSU1. When RSU1 receives an IPv6 packet dested to V2, it sends an UDP-Redirect message to V1. The message contains the V2's IPv6 address (SP1:0:V2_IID) at the target address field and the destination field, and V2's SCH LLA at the TLLAO.

C. THE INTER-RSU LOCALIZED FORWARDING

The inter-RSU LF procedure is performed as follows:

Step 1) The VMM-NDP module at the RSU is requested to perform the inter-RSU LF procedure by its IPv6 LF forwarding module (Fig.7 Case 4-2 (b)).

Step 2) The VMM-NDP module at the RSU sends an UDP-LFI message to the destination LBR. The destination address field of the LFI is set to the destination IPv6 address of the packet.

Step 3) When the VMM-NDP module at the destination LBR receives the UDP-LFI message, it processes the message as follows:

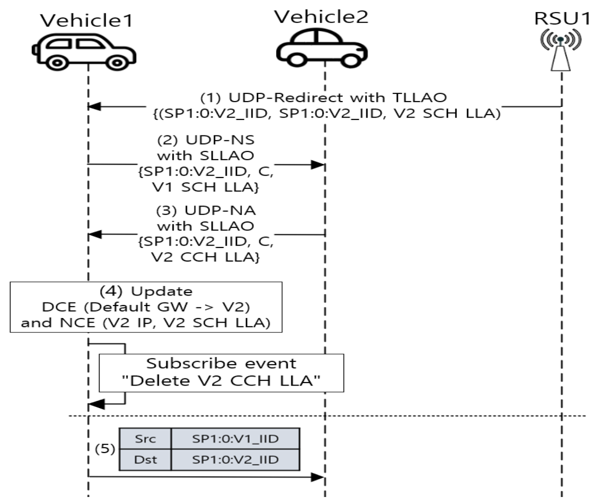


FIGURE 8. Intra-RSU localized forwarding.

- The VMM-NDP module looks up its LBR-RVL with the IPv6 address in the destination IPv6 address field of the UDP-LFI message.
- If there is the matching LBR-RVL entry, it creates the LBR-LFT entry with the source address of the UDP-LFI message and the destination address field of the UDP-LFI message. If the LBR-LFT entry for the destination address is already existed, it updates the RSU IP field to the source address of the UDP-LFI message.
  Then, it sends an UDP-Redirect message to the RSU. The destination address field of the UDP-Redirect message is set to the destination address field of the UDP-LFI message, and the target address field is set to the 64-bit sub-link prefix of the matched entry.
- Otherwise, it sends an UDP-LFA message to the RSU to suppress the LF request.

Step 4) When the RSU receives the UDP-Redirect message, it creates an RSU-LFT entry for the destination IPv6 address. The RSU-LFT entry contains the destination IPv6 address and the target IPv6 address in the UDP-Redirect message. The target IPv6 address indicates the IPv6 address of the current destination RSU.

Fig.9 shows an example of this case. V1 is attached to RSU1 and V2 is attached to RSU3. RSU1 and RSU3 may belong to the same LBR or different LBRs. In this example, RSU1 belongs to the LBR1 and RSU3 belongs to the LBR2. When RSU1 receives an IPv6 data packet destined to V2, it sends an UDP-LFI message to LBR2. V2's IPv6 address (SP2:0:V2_IID) is set to the destination address field of the UDP-LFI message. When LBR2 receives the UDP-LFI message, it finds its LBR-RVL using the address at the destination address field of the UDP-LFI message. It creates an LBR-LFT entry with the destination address and the source address of the UDP-LFI message. Then it sends an UDP-Redirect message to RSU1. The target address field of the UDP-Redirect message is set to the sub-link prefix (SP2:1::/64) of the RSU3's address.

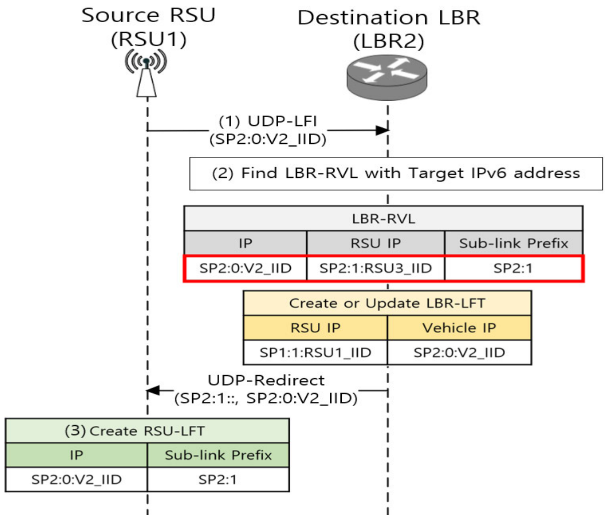


FIGURE 9. Inter-RSU localized forwarding.

D. HANDLING THE DESTINATION VEHICLE'S MOVEMENT

When V2 changes its point of attachment to another RSU, V2 notifies the destination LBR by sending an UDP-NS message with 'H' flag set as explained at the section IV-B.

Then the destination LBR notifies the source RSU as follows:

Step 1) The VMM-NDP module at the LBR looks up its LBR-LFT with the target IPv6 address contained in the UDP-NS message. If there is no matching entry, stop this procedure.

Step 2) The VMM-NDP module creates an UDP-Redirect message. The target address field of the UDP-Redirect message is set to the source address of the UDP-NS message (new RSU address). The destination address field of the UDP-Redirect message is set to the target address field of the UDP-NS message. The 'H' flag of the UDP-Redirect message must be set to notify the change of the destination RSU. The UDP-Redirect message is sent to the RSU address field in the matching LBR-LFT entry.

Step 3) When the VMM-NDP module at the source RSU receives the UDP-Redirect message, it looks up its RSU-LFT using the IPv6 address at the destination address field of the UDP-redirect message.

Step 4) If there is a matching entry, it updates the sub-link prefix field of the matching RSU-LFT entry with the prefix of the target address field of the UDP-Redirect message.

Step 5) Otherwise, the VMM-NDP module at the source RSU ignores the UDP-Redirect message and creates an S-LFT entry to suppress the inter-RSU LF for the address contained at the destination address field of the UDP-Redirect message.

Fig.10 shows an example of this case. V2 moves from RSU3 to RSU4. When LBR2 receives the UDP-NS message with 'H' flag from RSU4, it creates an UDP-Redirect message with the 'H' flag set. The target address field is set to

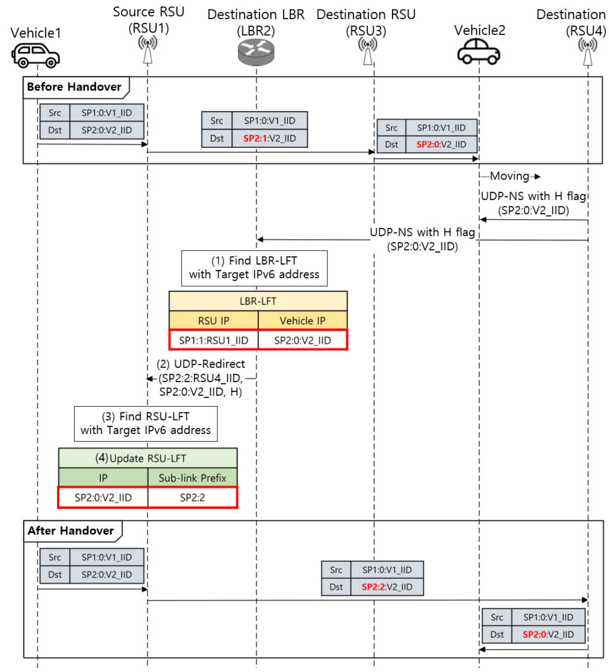


FIGURE 10. Handover with localized forwarding.

TABLE 3. Symbols for the scheme analysis.

D_{rsu}	Diameter of an RSU coverage (m)
H_v	Frequency at which a vehicle handover per second
Sig_v	Number of signalling messages per second that are sent to LBR
N_{lbr}	Total number of messages that LBR has to process per second
v	Speed of vehicle (m/s)
x	Number of UDP data messages sent by a vehicle per second
$\alpha_{(x)}$	Decrease rate in messages that LBR has to process per second

SP2:2:RSU4_IID (RSU2's IPv6 address) and the destination address field is set to SP2:0:V2_IID (V2's IPv6 address). It sends the message to RSU1. RSU1 looks up the matching RSU-LFT with SP2:0:V2_IID. It updates the sub-link prefix field of the corresponding RSU-LFT with SP2:2/64 (the prefix of the target address field). After handling the UDP-Redirect message, the prefix of the destination address of IPv6 packets destined to V2 at RSU1 is changed from SP2:1/64 to SP2:2/64.

VII. THE PROPOSED SCHEME ANALYSIS

In this section, we analyze the decrease rate of LBR's workload. Table 3 lists symbols used for our analysis.

$$H_v = \frac{v}{D_{rsu}} \tag{1}$$

The frequency at which a vehicle handover per second is equal to dividing the vehicle's speed by the coverage that RSU can communicate with, as shown in "(1)". According to [18], a reliable communication radius of an RSU coverage should be 370m if there is no obstruction. We assume that D_{rsu} is 740m in the following analysis.

$$Sig_v = 3\frac{v}{D_{rsu}} \tag{2}$$

When a vehicle handovers, 3 signalling messages are exchanged between the vehicle and the destination LBR: UDP-NS, UDP-NA and UDP-Redirect messages. As a result, the number of signalling messages per second sent to LBR is equal to "(2)".

$$N_{lbr} = Sig_v + x = 3\frac{v}{D_{rsu}} + x \quad (3)$$

The total number of messages to be processed by the LBR is equal to the sum of signalling messages and UDP data messages sent by the vehicle, as shown in "(3)".

$$\alpha_{(x)} = \frac{x}{N_{lbr}} = \frac{x}{3\frac{v}{D_{rsu}} + x} \quad (4)$$

If the proposed LF scheme is applied, UDP data messages are not forwarded to LBR. Therefore, the number of messages to be processed by LBR is reduced by x per second. As a result, the decrease rate of messages that LBR has to process per second is as shown in "(4)".

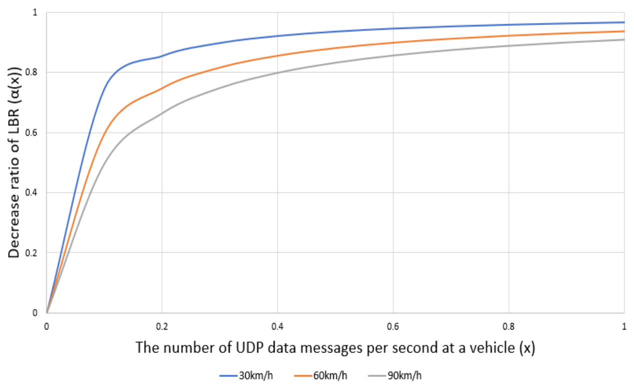


FIGURE 11. Decrease rate in messages that LBR has to process.

Fig.11 shows the decrease rate of messages that LBR has to process per second according to vehicle speed. In the analysis, we assume that D_{rsu} is 740m in advance. As the number of UDP messages transmitted by the vehicle per second increases, the decrease rate of messages that the LBR has to process per second approaches 1. Also, the faster the vehicle is, the lower the decrease rate of LBR. This is because the vehicle stays less time in one RSU. In addition, it can be inferred that the number of signalling messages exchanged between the vehicle and the LBR in each handover does not significantly affect the workload of the LBR. Furthermore, the graph illustrates the case where two vehicles communicate with each other.

VIII. SIMULATION

The proposed localized forwarding scheme is simulated with the ns-3 network simulator (version 3.32 [19]) and its WAVE model library.

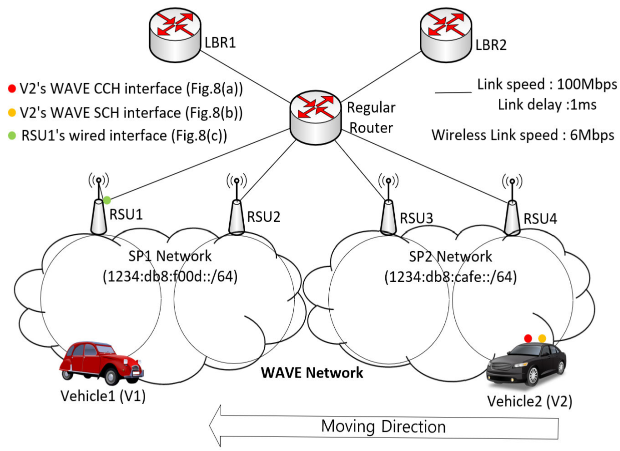


FIGURE 12. Simulation topology.

Fig.12 shows the network topology used in the simulation. There are two vehicles, V1 and V2. They have two WAVE interfaces. One WAVE interface is tuned to the CCH and the other is tuned to the SCH. V1 is stationary and attached to RSU1, while V2 moves from RSU4 to RSU1 at a constant velocity (60km/h). An RSU broadcasts the IPv6 routing serving using WSAs at a rate of 10 times per second. RSU1 and RSU2 belong to the same virtual link managed by LBR1, and RSU3 and RSU4 belongs to another virtual link managed by LBR2. In the simulation, V1's IPv6 address is set to 1234:db8:f00d:0:e470:8687:d7a3:8f9b and V2's IPv6 address is set to 1234:db8:cafe:0:0683:3b54:e665:f78b.

According to [18], the reliable communication radius of an RSU is measured to be under 370 meters. The distance between two adjacent RSUs is 740m in the simulation. A regular IPv6 router connects RSUs and LBRs. The source vehicle (V1) sends UDP packets to the destination vehicle (V2) at a rate of 4.96Kbps (62 octets per packet, 10Hz) after V1 perform the initial network attachment procedure.

We have programmed the Wireshark's [20] decoding module to aid the analysis of the control message flow of proposed scheme using lua language [21]. In Wireshark's captured packet screens, the control packets used at the proposed scheme are marked UDP-Redirect, UDP-NS/NA, or UDP-LFI/LFA. We filter out irrelevant packets such as 802.11 Acknowledgement (ACK) from the captured packets to aid visibility.

Fig.13(a) shows BSM and WSA messages at V2's WAVE CCH interface. WSA messages are highlighted to separate them from BSM messages. Packet#1 is an BSM sent by V2 and packet#2 is an WSA sent by RSU4. Packet#400, packet#1197, and packet#2027 are WSAs sent by RSU3, RSU2, and RSU1, respectively. Packet#2028 is an BSM sent by V1. As a result, V2 recognizes that V1 is its one-hop neighbor.

Fig.13(b) shows IPv6 packets exchanged between V2 and RSUs (RSU4, RSU3, RSU2 and RSU1) via WAVE SCH interface. Fig.13(c) shows IPv6 packets shown at RSU1's

No.	Time	Source	Destination	Proto	Info
1	00:00:00.000058	00:00:00_00:00:02	Broadcast	WSMP	WAVE Short Message Protocol IEEE P1609.3
2	00:00:00.136009	00:00:00_00:00:06	Broadcast	WSMP	WAVE Short Message Protocol IEEE P1609.3
...	...	...	...	...	...
400	00:00:22.691876	00:00:00_00:00:05	Broadcast	WSMP	WAVE Short Message Protocol IEEE P1609.3
...	...	...	...	...	...
1197	00:01:07.773047	00:00:00_00:00:04	Broadcast	WSMP	WAVE Short Message Protocol IEEE P1609.3
...	...	...	...	...	...
2027	00:01:52.695720	00:00:00_00:00:03	Broadcast	WSMP	WAVE Short Message Protocol IEEE P1609.3
2028	00:01:52.706802	00:00:00_00:00:01	Broadcast	WSMP	WAVE Short Message Protocol IEEE P1609.3
...	...	...	...	...	...

(a) Packet trace at V2's WAVE CCH interface

No.	Time	Source	Destination	Proto	Info
4	00:00:00.136473	::	fe80::200:ff:fe00:c	UDP-NS	UDP-NS-H:0 (Registration)
6	00:00:00.141010	fe80::200:ff:fe00:c	ff02::1	UDP-NA	UDP-NA-Success, H:0, D:0 (Registration)
8	00:00:00.504378	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:cafe:0:68e:3b54:e665:f78b	UDP	5421 -> 54321 Len=12
10	00:00:00.504584	1234:db8:cafe:0:68e:3b54:e665:f78b	1234:db8:f00d:0:e470:8687:d7a3:8f9b	UDP	5421 -> 54321 Len=12
...	...	...	...	...	...
896	00:00:22.691885	fe80::46d:76ca:21fb:ee4	fe80::200:ff:fe00:b	UDP-NS	UDP-NS-H:1 (Handover)
898	00:00:22.696344	fe80::200:ff:fe00:b	fe80::46d:76ca:21fb:ee4	UDP-NA	UDP-NA-Success, H:1, D:0 (Handover)
...	...	...	...	...	...
2704	00:01:07.773059	::	fe80::200:ff:fe00:a	UDP-NS	UDP-NS-H:0 (Registration)
2706	00:01:07.777598	fe80::200:ff:fe00:a	ff02::1	UDP-NA	UDP-NA-Success, H:1, D:0 (Handover)
2708	00:01:07.778120	fe80::200:ff:fe00:a	ff02::1	UDP-NA	UDP-NA-Success, H:0, D:0 (Registration)
...	...	...	...	...	...
4706	00:01:52.695733	fe80::e1d6:e5b1:e55c:44a	fe80::200:ff:fe00:9	UDP-NS	UDP-NS-H:1 (Handover)
4710	00:01:52.700693	fe80::200:ff:fe00:9	ff02::1	UDP-NA	UDP-NA-Success, H:1, D:0 (Handover)
4712	00:01:52.701265	fe80::200:ff:fe00:9	ff02::1	UDP-NA	UDP-NA-Success, H:1, D:0 (Handover)
4714	00:01:52.701854	1234:db8:f00d:1::1	1234:db8:f00d:0:e470:8687:d7a3:8f9b	UDP-Redirect	UDP-Redirect-T:0, H:1 (Handover LF)
4716	00:01:52.702268	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:cafe:0:68e:3b54:e665:f78b	UDP-NS	UDP-NS-C:1 (CCH Mac Request)
4718	00:01:52.702474	1234:db8:f00d:0:fcb2:99c9:63d7:3f9a	1234:db8:f00d:0:e470:8687:d7a3:8f9b	UDP-NA	UDP-NA-Success, C:1 (CCH Mac Response)
...	...	...	...	...	...
4724	00:01:52.801004	1234:db8:f00d:1::1	1234:db8:f00d:0:fcb2:99c9:63d7:3f9a	UDP-Redirect	UDP-Redirect-T:0, H:1 (Handover LF)
4726	00:01:52.801249	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:f00d:0:e470:8687:d7a3:8f9b	UDP-NS	UDP-NS-C:1 (CCH Mac Request)
4728	00:01:52.801873	1234:db8:f00d:0:fcb2:99c9:63d7:3f9a	1234:db8:f00d:0:fcb2:99c9:63d7:3f9a	UDP-NA	UDP-NA-Success, C:1 (CCH Mac Response)
...	...	...		...	...

(b) Packet trace at V2's WAVE SCH interface

No.	Time	Source	Destination	Proto	Info
1	00:00:00.117624	1234:db8:f00d:1::1	1234:db8:f00d:ffff:200:ff:fe00:15	UDP-NS	UDP-NS-H:0 (Registration)
2	00:00:00.121660	1234:db8:f00d:ffff:200:ff:fe00:15	1234:db8:f00d:1::1	UDP-NA	UDP-NA-Success, H:0, D:0 (Registration)
3	00:00:00.500179	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:cafe:0:68e:3b54:e665:f78b	UDP	5421 -> 54321 Len=12
4	00:00:00.500184	1234:db8:f00d:1::1	1234:db8:cafe:ffff:200:ff:fe00:17	UDP-LFI	UDP-LFI
5	00:00:00.504211	1234:db8:cafe:ffff:200:ff:fe00:17	1234:db8:f00d:1::1	UDP-Redirect	UDP-Redirect, T:0 H:0 (New LF)
6	00:00:00.508780	1234:db8:cafe:0:68e:3b54:e665:f78b	1234:db8:f00d:1:e470:8687:d7a3:8f9b	UDP	5421 -> 54321 Len=12
7	00:00:00.600185	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:cafe:2:68e:3b54:e665:f78b	UDP	5421 -> 54321 Len=12
...	...	...	...	...	...
449	00:00:22.696128	1234:db8:cafe:ffff:200:ff:fe00:17	1234:db8:f00d:1::1	UDP-Redirect	UDP-Redirect, T:0 H:1 (LF Handover)
450	00:00:22.700186	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:cafe:1:68e:3b54:e665:f78b	UDP	5421 -> 54321 Len=12
...	...	...	...	...	...
1352	00:01:07.777382	1234:db8:cafe:ffff:200:ff:fe00:17	1234:db8:f00d:1::1	UDP-Redirect	UDP-Redirect, T:0 H:1 (LF Handover)
1353	00:01:07.800179	1234:db8:f00d:0:e470:8687:d7a3:8f9b	1234:db8:f00d:2:68e:3b54:e665:f78b	UDP	5421 -> 54321 Len=12
...	...	...	...	...	...
2251	00:01:52.695982	1234:db8:f00d:1::1	1234:db8:f00d:ffff:200:ff:fe00:17	UDP-NS	UDP-NS-H:1 (Handover)
2252	00:01:52.695989	1234:db8:f00d:1::1	1234:db8:f00d:ffff:200:ff:fe00:15	UDP-NS	UDP-NS-H:1 (Handover)
2253	00:01:52.700017	234:db8:cafe:ffff:200:ff:fe00:17	1234:db8:f00d:1::1	UDP-Redirect	UDP-Redirect, T:0 H:1 (LF Handover)
2254	00:01:52.700023	1234:db8:f00d:ffff:200:ff:fe00:15	1234:db8:f00d:1::1	UDP-NA	UDP-NA-Success, H:1, D:0 (Handover)
2255	00:01:52.700030	1234:db8:f00d:ffff:200:ff:fe00:17	1234:db8:f00d:1::1	UDP-NA	UDP-NA-Success, H:1, D:0 (Handover)

(c) Packet trace at RSU1's wired interface

FIGURE 13. Captured packet trace.

wired interface connected to the WAVE access network. When V2 enters RSU4's coverage, V2 performs the network attachment procedure (section IV-A). Packet#4 and packet#6 in Fig.13(b) show the UDP-NS/NA messages exchanged between V2 and RSU4. Packet#1 and packet#2 in Fig.13(c) show the UDP-NS/NA messages exchanged between RSU1 and LBR1 for V1's network attachment procedure.

There are two data paths between V1 and V2. We focus on the data path from V1 to V2. The action of each component in the proposed LF scheme to the reverse path is exactly the same as those of the V1 to V2 path except the role of source RSU, destination LBR and destination RSU are changed from RSU1, LBR2 and RSU4/RSU3/RSU2 to RSU4/RSU3/RSU2, LBR1, and RSU1, respectively.

```
▸ Frame 4: 78 bytes on wire (624 bits), 78 bytes captured (624 bits)
▸ Point-to-Point Protocol
▸ Internet Protocol Version 6, Src: 1234:db8:f00d:1::1, Dst: 1234:db8:cafe:ffff:200:ff:fe00:17
▸ User Datagram Protocol, Src Port: 12345, Dst Port: 12345
▾ UDP-LR
  ▾ UDP-ND Element
      Type: 138 (UDP-LFI)
      Code: 0 (Code)
      Checksum: 0
      Reserved: 0
      Sequence: 0
      LifetimeLri: 65535
      Target IP: 1234:0db8:cafe:0000:068e:3b54:e665:f78b
```

(a) UDP-LFI Message (Packet #4 in Fig.13(c)

```
▸ Frame 5: 90 bytes on wire (720 bits), 90 bytes captured (720 bits)
▸ Point-to-Point Protocol
▸ Internet Protocol Version 6, Src: 1234:db8:cafe:ffff:200:ff:fe00:17, Dst: 1234:db8:f00d:1::1
▸ User Datagram Protocol, Src Port: 12345, Dst Port: 12345
▾ UDP-LR
  ▾ UDP-ND Element
      Type: 137 (UDP-Redirect)
      Code: 0 (Code)
      Checksum: 0
      Flags: T:0, H:0
      Target IP: 1234:0db8:cafe:0002:0000:0000:0000:0000
      Destination IP: 1234:0db8:cafe:0000:068e:3b54:e665:f78b
```

(b) UDP-Redirect Message (Packet #5 in Fig.13(c)

```
▸ Frame 449: 90 bytes on wire (720 bits), 90 bytes captured (720 bits)
▸ Point-to-Point Protocol
▸ Internet Protocol Version 6, Src: 1234:db8:cafe:ffff:200:ff:fe00:17, Dst: 1234:db8:f00d:1::1
▸ User Datagram Protocol, Src Port: 12345, Dst Port: 12345
▾ UDP-LR
  ▾ UDP-ND Element
      Type: 137 (UDP-Redirect)
      Code: 0 (Code)
      Checksum: 0
      Flags: T:0, H:1
      Target IP: 1234:0db8:cafe:0001:0000:0000:0000:0000
      Destination IP: 1234:0db8:cafe:0000:068e:3b54:e665:f78b
```

(c) UDP-Redirect Message (Packet #449 in Fig.13(c)

FIGURE 14. Captured packet.

The procedure according to the simulation result is as follows:

1) V1 belongs to RSU1 and V2 belongs to RSU4

When RSU1 receives the data packet from V1 (Packet#3 in Fig.13(c)), it forwards the packet and sends an UDP-LFI message to LBR2 (Packet#4 in Fig.13(c) and Fig.14(a)). The target IP field of the UDP-LFI message is the destination address of the data packet (1234:db8:**cafe:0**:0683:3b54:e665:f78b). The destination LBR (LBR2) of the UDP-LFI message is taken from the matching entry of the ILPL list with the prefix of the destination IPv6 address (1234:db8:**cafe:0**::/64).

When LBR2 receives the UDP-LFI message, it sends UDP-Redirect message to RSU1 (Packet#5 in Fig.13(c) and Fig.14(b)). The destination IP field of the UDP-Redirect message is V2's IPv6 address and the target IP field of the UDP-Redirect message is RSU4's sub-link prefix (1234:db8:**cafe:2**::/64). RSU1 creates an entry of the RSU-LFT table for the V2's destination address.

After this exchange, the V2's destination address has the matching entry in the the RSU-LFT table. The prefix of the destination address (1234:db8:**cafe:0**::/64) is replaces the prefix field of the RSU-LFT matching entry (1234:db8:**cafe:2**::/64). Packet#7 in Fig.13(c) show the operation result. Packet#6 in Fig.13(c) also shows that the same operation is done at RSU4 for the reverse path.

2) V1 belongs to RSU1 and V2 moves to RSU3

When V2 moves from RSU4 to RSU3, it receives a new WSA from RSU3 (Packet#400 in Fig. 13(b)). V2 performs the handover procedure (section IV-B). It exchanges an UDP-NS/NA message with 'H' flag set with RSU3 (Packet#896 and packet#898 in Fig.13(b)).

When LBR2 receives the UDP-NS message with 'H' flag set, it sends UDP-Redirect message to RSU1 (Packet#449 in Fig.13(c) and Fig.14(b)). The destination IP field of the UDP-Redirect message is V2's IPv6 address and the target IP field of the UDP-Redirect message is RSU3's sub-link prefix (1234:db8:**cafe:1**::/64). RSU1 updates the prefix field of the RSU-LFT entry with the target IP field of the UDP-Redirect message.

After processing the Redirect message, the prefix of the IPv6 packet destined to the V2 (1234:db8:**cafe:0**::/64) is replaced to the prefix field of the RSU-LFT entry (1234:db8:**cafe:1**::/64). Packet#452 show the operation result.

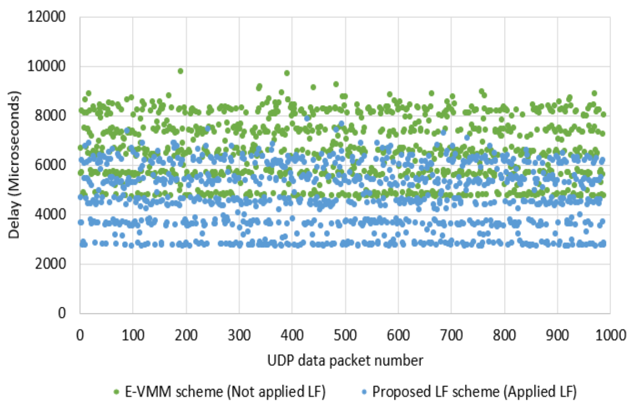
3) V1 belongs to RSU1 and V2 moves to RSU2

When V2 moves from RSU3 to RSU2, it receives a new WSA from RSU2 (Packet#1197 in Fig. 13(a)). V2 performs the handover procedure (section IV-B). LBR2 sends another UDP-Redirect message to RSU1 (Packet#1352 in Fig.13(c). RSU1 replaces the prefix field of the RSU-LFT entry. The prefix of the IPv6 packet destined to the V2 (1234:db8:**cafe:0**::/64) is replaced to the prefix of RSU2 (1234:db8:**f00d:2**::/64). Packet#1353 in Fig.13(c) show the operation result.

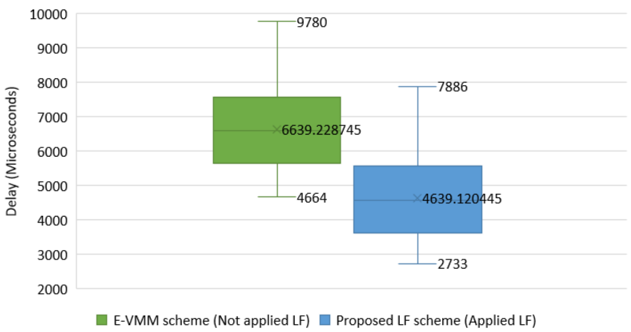
4) V1 belongs to RSU1 and V2 moves to RSU1

When V2 moves from RSU2 to RSU1, it receives a new WSA from RSU1 (Packet#2027 in Fig. 13(a)). V2 performs the handover procedure (section IV-B). It exchanges an UDP-NS/NA message with 'H' flag set with RSU1 (Packet#4706 and packet#4710, #4712 in Fig.13(b)). LBR2 sends another UDP-Redirect message to RSU1 (Packet#449 in Fig.13(c) and Fig.14(b)). RSU1 replaces the prefix field of the RSU-LFT entry, and RSU1 recognizes that both V1 and V2 are belong to it. It also creates an entry of the S-LFT for V2's destination address. RSU1 performs the intra-RSU localized forwarding (section VI-B) by sending an UDP-Redirect message to V1 (Packet#4714 in Fig.13(b)). The destination IP field and the target IP field of the UDP-Redirect message is V2's IPv6 address.

When V1 receives the UDP-Redirect message, it sends an UDP-NS message with 'C' flag to obtain V2's CCH link-layer address (Packet#4716 in Fig.13(b)). Then, the V2 responds to the UDP-NS message by sending an UDP-NA message including its CCH link-layer address in the SLLAO (Packet#4718 in Fig.13(b)). V1 subscribes the delete V2's CCH link-layer address to detect the departure of V2 from its one-hop neighbors. After this exchange, V1 sends UDP packets to V2 directly (Packet#4720 in Fig.13(b)). Note that the same intra-RSU localized forwarding is performed for V2.



(a) Delay of each UDP data packet



(b) Summary about delay of each UDP data packet

FIGURE 15. Delay of each UDP data packet in the E-VMM scheme and proposed LF scheme.

In order to compare the delay of UDP data packets between the case where the proposed LF scheme is applied and the case where it is not applied, we simulate by increasing the number of vehicles. There are a total of 20 vehicles from vehicle1 to vehicle20, 10 vehicles (vehicle1 to vehicle10) belong to RSU1 and the remaining 10 (vehicle11 to vehicle20) belong to RSU4. A total of 10 pairs of vehicles communicate with each other (e.g. vehicle1 communicates with vehicle11, vehicle2 communicates with vehicle12, and vehicle10 communicates with vehicle20.) Vehicles belonging to RSU1 move from RSU1 to RSU4 at a constant velocity (60km/h), while vehicles belonging to RSU4 are stationary.

Fig.15(a) shows the delay of each UDP data packet in the E-VMM scheme without applying LF and in the proposed LF scheme at vehicle2. Fig.15(b) shows that summarizes the minimum, maximum, and average delay of the values in Fig.15(a). In the E-VMM scheme to which LF is not applied, the maximum delay is 9780 milliseconds, the minimum delay is 4664 milliseconds, and the average delay is 6639 milliseconds. On the other hand, in the proposed LF scheme, the maximum delay is 7886 milliseconds, the minimum delay is 2733 milliseconds, and the average delay is 4639 milliseconds. It can be seen that when LF is applied, the delay of UDP data packets is reduced on average by about 2000 microseconds compared to when LF is not applied.

IX. CONCLUSION AND FUTURE WORKS

In this paper, we propose a localized forwarding scheme for the vehicular mobility management scheme for a shared-prefix model over IEEE WAVE IPv6 networks [4]. It shortens the data paths between two vehicles in the WAVE network and reduces the workload of LBRs and end-to-end delay. It extends a VMM-NDP module to supports the localized forwarding procedure.

In the base VMM and proposed LF scheme, LBRs are still hotspot. They have to handle all control messages and all down-link data packets, of which the destination IPv6 address includes its shared-prefix. This hotspot problem can be mitigated if the Software-Defined Network (SDN) is applied to the WAVE access network. The SDN controller handles the control messages instead of LBRs. It also eliminates the need of the prefix replacement done at LBRs and RSUs. The SDN switch handles packets based on SDN flows. Therefore, RSUs' unique link-layer addresses can be used at SDN flows instead of the IPv6 prefixes. We are going to implement this strategy to the base VMM and proposed LF scheme.

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