An Efficient PMIPv6-Based Handoff Scheme for Urban Vehicular Networks

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***Abstract*—In urban vehicular networks, traveling users can enjoy Internet multimedia services through various mobile devices, such as smart phones and laptops. To maintain seamless and ubiquitous Internet connectivity, an efficient handoff scheme has to be employed when mobile users travel across different access networks. However, in the urban vehicular environment, the high velocity of vehicles and the random mobility of users impose great challenges to the design of an effective handoff scheme. In this paper, we propose an Efficient Proxy Mobile IPv6 (E-PMIPv6)-based handoff scheme that guarantees session continuity for urban mobile users. In the registration process, E-PMIPv6 enables mobile users to obtain seamless Internet connectivity either from fixed roadside units or mobile routers and improves cache utilization at the local mobility anchor by merging the binding cache entries of the mobile users. In the handoff process, E-PMIPv6 comprehensively considers various handoff scenarios in the urban vehicular environment and provides transparent network-based mobility support to individual mobile users or a group of users in the same mobile network without disrupting ongoing sessions. In addition, E-PMIPv6 eliminates packet loss by either packet buffering or packet tunneling to improve handoff performance in each handoff scenario. Finally, a detailed analytical model is developed to study the performance of E-PMIPv6 in terms of handoff latency, signaling overhead, buffering cost, and tunneling cost. Analysis and simulation results demonstrate that the proposed E-PMIPv6 successfully extends the scalability of user mobility and greatly improves handoff efficiency in urban vehicular networks.**

***Index Terms*—Urban vehicular networks, Proxy Mobile IPv6, network mobility, local mobility anchor, mobile router.**

I. Introduction

NOWADAYS, people in cities spend much more time in vehicles than ever before. With the rapid development of wireless communication technologies, there is an increasing number of traveling users to access Internet through IP-enabled smart devices. They are eager to enjoy continuous and ubiquitous Internet multimedia services, e.g., video streaming, web browsing, and file downloading, etc., even though vehicles may roam across different access networks (e.g., WiFi, WiMAX, LTE/3G) in the urban transportation environment [1]–[3]. In order to meet diverse Quality of Service (QoS) requirements of these multimedia services, vehicular networks have to support seamless wireless communications with low handoff latency, low packet loss, reduced signaling overhead, etc.

Whereas, different from the highway scenario where mobile users usually obtain wireless connectivity to Internet through fixed RSUs, in the urban environment public transportation vehicles (e.g., city bus, subway train) may be equipped with MRs and provide wireless access to mobile users with smart devices. As a result, the complex user mobility in the urban environment usually induces frequent handoffs when mobile users travel from one access network to another access network (e.g., a mobile user may get off a public transportation vehicle at a station and switch its wireless connection from an MR to a fixed RSU), which greatly degrades the communication performance. Consequently, an efficient mobility management scheme has to be designed to support seamless handoff when mobile users traverse different access networks, and improve handoff performance by reducing handoff latency, packet loss, and signaling overhead, etc., in each handoff scenario.

Mobile IPv6 (MIPv6) [4] is a widely accepted standard to support global mobility for Mobile Hosts (MHs). The extensions of MIPv6 such as Fast-Handovers for Mobile IPv6 (FMIPv6) [5], Hierarchical MIPv6 (HMIPv6) [6], [7], Fast Handover for Hierarchical MIPv6 (FHMIPv6) [8], etc., have been standardized by Internet Engineering Task Force (IETF) to improve handoff performance. However, the MIPv6 extensions only provide host-based mobility support for individual MHs, and demand MHs to involve in the handoff signaling. As a network-based handoff protocol, PMIPv6 enables network entities to transparently conduct mobility management on behalf of MHs [9], [10], and exempts them from involving in any mobility related signaling. Fast Handover for PMIPv6 (PFMIPv6) [11] in the predictive mode establishes a bidirectional tunnel between the previous Mobile Access Gateway (p-MAG) and the new Mobile Access Gateway (n-MAG) to reduce packet loss by exchanging the Handover Initiate (HI) and Handover Acknowledge (HAck) messages [12]. Nevertheless, both PMIPv6 and PFMIPv6 provide mobility management to individual MHs, and suffer from heavy signaling overhead with the increasing number of MHs in vehicular networks.

IETF has standardized NEtwork MObility Basic Support (NEMO-BS) [13] that is dedicated to provide mobility management to an entire mobile network. NEMO-BS has been

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considered as an indispensable part of several Intelligent Transport Systems (ITS) projects, such as Communication Architecture for Land Mobile (CALM) [14], Cooperative Vehicle Infrastructure Systems (CVIS) [15], GeoNetworking [16], etc. Although the handoff performance in NEMO-BS has been improved in terms of reduced signaling overhead and scalability, the handoff process of an MR is still based on MIPv6, and thus suffers from long handoff delay. Furthermore, NEMO-BS lacks mobility support for individual MHs roaming across various access networks.

In order to improve handoff performance and support NEMO, we propose an enhanced PMIPv6 based handoff scheme E-PMIPv6 to provide seamless and transparent mobility management to MHs in urban vehicular networks. In the initial registration process, E-PMIPv6 enables individual MHs to obtain connectivity from either fixed MAGs or MRs, and supports Home Network Prefix (HNP) allocations for a group of MHs within the same mobile network that only occupies one BCE at the LMA, which is different from existing schemes where each MH occupies a separate BCE at the LMA, and significantly improves buffer resource utilization. In the handoff process, E-PMIPv6 comprehensively considers four handoff scenarios to provide transparent mobility support to MHs roaming across various access networks, and flexibly utilizes packet buffering and tunneling mechanisms in each handoff scenario, which reduces handoff delay and prevents packet loss.

Accordingly, the contributions of this paper are summarized as follows.

1) E-PMIPv6 efficiently utilizes cache resources at the LMA by merging the BCEs of MHs within the same mobile network in the urban transportation system, where the LMA is usually in charge of mobility management for tens of thousands of MHs.
2) E-PMIPv6 jointly considers different handoff scenarios by providing efficient mobility support to MHs when they roam across different access networks in the urban vehicular environment (e.g., from a fixed RSU to another RSU, from an MR to another MR, or between a fixed RSU and an MR), and improves handoff performance by eliminating packet loss, reducing handoff latency and signaling overhead, etc., in each handoff scenario.
3) We present a detailed analytical model to study the performance of E-PMIPv6 in terms of handoff latency, signaling overhead, buffering cost, and tunneling cost, etc., and validate the analytical results by extensive simulations.

The remainder of this paper is organized as follows. We briefly describe the base protocol PMIPv6 and review some related works in Section II. The system model is presented in Section III. The proposed E-PMIPv6 is explicitly illustrated in Section IV. An analytical model is developed to study the performance of the proposed scheme in Section V. Numerical results are given in Section VI, followed by concluding remarks in Section VII.

II. Related Works

PMIPv6 has been standardized by IETF to provide network-based mobility support to MHs in a localized PMIPv6 domain without requiring MHs to involve in any handoff signaling. In PMIPv6, the core functional entities in IP networks are MAG and LMA. An MAG usually runs on an access router and forwards packets between the LMA and MHs, and it emulates the home network of MHs by sending Router Advertisement (RA) messages with HNP information. Different from the Home Agent (HA) in MIPv6, the LMA in PMIPv6 has some extended capabilities to provide transparent mobility support, for example, besides forwarding packets between the registered MHs and their Correspondent Nodes (CNs), the LMA also allocates HNPs to these MHs and maintains their binding information. The handoff procedure is triggered when an MH travels from the p-MAG to the n-MAG, and accordingly the LMA updates the MH's BCE to keep track of the new attached MAG. PMIPv6 migrates the mobility functionality residing in MHs to network entities, and provides transparent mobility management to MHs without changing their IP addresses. However, PMIPv6 suffers from long handoff delay and high packet loss [17], and lacks mobility support for NEMO.

In order to shorten handoff delay, a fast handoff scheme is proposed to improve PMIPv6 in IEEE 802.11 networks [18]. The scheme suggests to exchange authentication information and HNPs of MHs between neighboring access points, and reduces the total handoff latency by eliminating context acquisition delay. However, it still experiences heavy packet loss during the handoff process. In PFMIPv6, the p-MAG obtains the n-MAG information of an MH before the MH detaches from the current access network, and establishes a tunnel to the n-MAG. The buffered packets at the p-MAG are delivered to the n-MAG along the pre-established tunnel when the MH begins to perform the handoff process, which achieves to alleviate packet loss. In [19], EBR-PMIPv6 is proposed to support fast handoff in vehicular networks. By utilizing the Global Positioning Systems (GPS) coordinate information and the movement direction of an MH, the p-MAG can identify the exact n-MAG from its neighboring MAG table in advance, which shortens the handoff delay. A similar handoff proposal [20] also utilizes GPS information to accurately identify the n-MAG, and pre-establishes a tunnel between the p-MAG and the n-MAG for delivering buffered packets in vehicular networks. In [21], the proposed MHVA completes the network layer handoff operations before the link layer handoff operations, and a vehicle keeps its link layer connection during the advanced mobility handover process, which greatly reduces packet loss. In [22], VIP-WAVE adopts PMIPv6 based mobility management to support IP services in 802.11p/WAVE networks. The proposals in [18]–[22] extend PMIPv6 to improve handoff performance by either shortening handoff delay or reducing packet loss in mobility support for individual MHs.

NEMO-BS [13] has been standardized to support NEMO for a group of MHs within a public transportation vehicle. In NEMO-BS, an MR fixed on a vehicle is responsible for maintaining Internet connectivity and session continuity for a group of MHs attached to it. The MR is required to configure a Home Address (HoA) for its egress interface at its home network, and obtains a Care of Address (CoA) as soon as it moves into a new access network. Then the MR sends a binding update message to its HA, which is used to bind its CoA to its HoA in the BCE at the HA. Consequently, a bidirectional tunnel between the MR and the HA is established through the binding update procedure. In NEMO-BS, an MR conducts the handoff process for a group of MHs instead of each MH handling mobility independently, which significantly reduces signaling overhead. However, the handoff process of an MR is still based on MIPv6, for example, location update signaling has to be exchanged between an MR and its HA, and the Duplicate Address Detection (DAD) process needs to be performed after a CoA is acquired, which induces a long handoff delay. P-NEMO [23] proposes to accommodate NEMO in PMIPv6 to provide transparent handoff for an entire mobile network in intelligent transportation systems. In addition, as an extension to P-NEMO, FP-NEMO pre-establishes a bi-directional tunnel between the p-MAG and the n-MAG to exchange downlink or uplink packets during the handoff process, which successfully reduces packet loss. However, P-NEMO and FP-NEMO only support NEMO for a mobile network. In [24], an enhanced fast handover scheme EfNEMO is proposed for NEMO, and an MR conducts a tentative binding update to register a new CoA before the Layer-2 (L2) handoff. As a result, packets destined to MHs are forwarded via the path between the HA and the n-MAG, and packet tunneling between the p-MAG and the n-MAG is eliminated.

In [25], the NEMO-enabled PMIPv6 (N-PMIPv6) is presented to extend a PMIPv6 domain to support mobile networks, and it provides transparent handoff when an MH switches its wireless connection from an MR to a fixed MAG. In intra-domain handovers in [26], the handoff between two MAGs and the handoff from an MAG to an MR are considered. In [27], three handoff scenarios are considered to provide transparent mobility support to mobile networks or MHs. In [28], N-NEMO directly adopts PMIPv6 to provide transparent handoff to MHs under various handoff scenarios. However, packet loss is neglected in the proposals [25]–[28] when MHs roam across different access networks in the urban vehicular environment, which degrades the handoff performance. In order to efficiently address the aforementioned issues, this paper presents E-PMIPv6 to provide seamless handoff under different handoff scenarios in urban vehicular networks, and enhance handoff performance by eliminating packet loss, reducing handoff delay and signaling overhead, and improving buffer utilization.

III. System Model

This paper considers an infrastructure-based vehicular network in a localized E-PMIPv6 domain which consists of the LMA, multiple RSUs/MAGs, and traveling MHs in vehicles as shown in Fig. 1. RSUs are deployed along city roads, and function as MAGs to provide MHs with wireless access to Internet. They connect to the LMA by multi-hop wireline links. Vehicles are classified into two categories depending on whether they are equipped with MRs, for example, usually a private car is not equipped with an MR, and an MH in the car has to obtain wireless access from roadside MAGs; while a city bus may install an MR to provide wireless access to MHs within the bus. An MR has two communication interfaces: i) the egress interface is used for vehicle-to-infrastructure communications

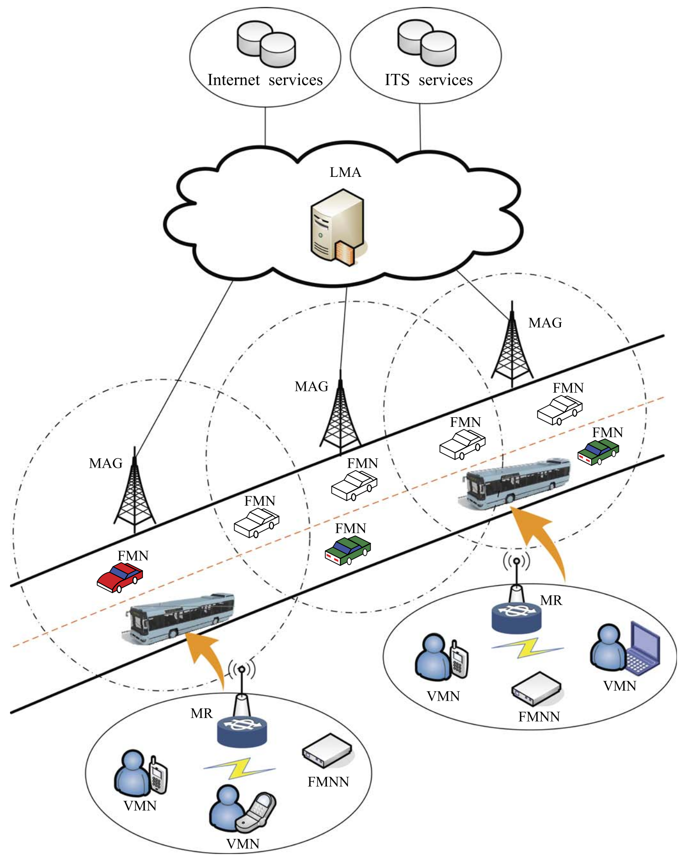

Fig. 1. Architecture of a localized E-PMIPv6 domain.

with an MAG, and ii) the ingress interface communicates with the MHs that form a mobile network in the vehicle. There are three types of MHs in E-PMIPv6:

1) Fixed Mobile Node (FMN)—a FMN is an embedded communication device fixed on a vehicle, and it needs to attach to a roadside MAG since there is no MR installed on the vehicle (e.g., a private car).
2) Fixed Mobile Network Node (FMNN)—a FMNN is a fixed communication device that has to attach to the MR installed on the same vehicle (e.g., city bus), and it cannot change its point of attachment.
3) Visiting Mobile Node (VMN)—a VMN is a handheld smart device, and it may temporarily attach to either an MR on the same vehicle or a roadside MAG.

Note that, a VMN may initially attach to an MR when the passenger gets on an MR enabled vehicle, and hands over to another MR when the passenger transfers to an MR enabled vehicle at a station (***MR-MR*** handoff). In addition, the VMN may also hand over to an MAG when the passenger gets off the MR enabled vehicle but waits for another vehicle at the station (***MR-MAG*** handoff). A VMN may also initially attach to an MAG, and hands over to an MR when the passenger gets on an MR enabled vehicle (***MAG-MR*** handoff), or switches to another MAG when the passenger travels in an MR disabled vehicle (***MAG-MAG*** handoff). As a result, there are totally four handoff scenarios in E-PMIPv6.

TABLE I
SUMMARY OF ACRONYMS

Acronym	Definition	Acronym	Definition
HA	Home Agent	BCE	Binding Cache Entry
CN	Correspondent Node	HNP	Home Network Prefix
MH	Mobile Host	HI	Handover Initiate
LMA	Local Mobility Anchor	HAck	Handover Acknowledge
MAG	Mobile Access Gateway	HoA	Home Address
p-MAG	previous Mobile Access Gateway	CoA	Care of Address
n-MAG	new Mobile Access Gateway	DAD	Duplicate Address Detection
MR	Mobile Router	RS	Router Solicitation
p-MR	previous Mobile Router	RA	Router Advertisement
n-MR	new Mobile Router	BULE	Binding Update List Entry
FMN	Fixed Mobile Node	PBU	Proxy Binding Update
FMNN	Fixed Mobile Network Node	PBA	Proxy Binding Acknowledgement
VMN	Visiting Mobile Node	Dereg RS	Deregistration Router Solicitation

IV. THE PROPOSED E-PMIPV6

This section presents a novel mobility support protocol E-PMIPv6 which provides transparent handoff to either an MH or a mobile network in a localized E-PMIPv6 domain. E-PMIPv6 considers the same network entities (e.g., LMA, MAG) as PMIPv6 in the wireline network. But it extends PMIPv6 to include MRs in the wireless network that is also supported by NEMO-BS where an MR conducts the handoff process for a number of MHs instead of each MH handling mobility independently. However, different from NEMO-BS that only considers MR's handoff across neighboring MAGs, E-PMIPv6 supports MHs to obtain HNPs either from an MR or an MAG, which enables MHs to roam between fixed MAGs, between MRs, or between fixed MAGs and MRs without changing their IP configurations.

In E-PMIPv6, in order to establish an end-to-end connection with the CN, an MH or MR has to conduct the initial binding registration to obtain HNPs from an access network, and then it can configure its IP address and access Internet services. However, when it travels from the current access network to a new one (e.g., from an MAG to another MAG, from an MR to another MR, or between an MAG and an MR) in the urban environment, it needs to conduct one of the four handoffs introduced in Section III to maintain the end-to-end connection depending on the handoff scenario. In the following subsections, we explicitly describe the operations of the initial binding registration and the four handoffs. Some important acronyms used in the protocol description are summarized in Table I.

A. Initial Binding Registration

When an MR enabled vehicle moves into the E-PMIPv6 domain, the MR initially sends a Router Solicitation (RS) message to the attached MAG to solicit HNPs for VMNs and FMNNs in the MR enabled vehicle. On receiving the RS message, the MAG creates a Binding Update List Entry (BULE) to keep the registration information for the MR. Then, it initializes a registration Proxy Binding Update (PBU) message, and delivers it to the LMA. In order to comply with PMIPv6, E-PMIPv6 needs to allocate a HNP to each VMN or FMNN that is attached to the MR. Therefore, the customized RS message is extended to carry the number of requested prefixes. Similarly, there are multiple HNP options in the PBU message, and the number of HNP options indicates the amount of requested prefixes. The Prefix field of each HNP option is set to *ALL_ZERO*.

After receiving the PBU message from the MAG, the LMA finds that it's a new binding registration, and then creates a BCE for the MR. If there is no bi-directional tunnel between the LMA and the MAG, the LMA establishes a bi-directional tunnel to the MAG. Thereafter, the LMA allocates a number of available prefixes and fills them into a Proxy Binding Acknowledgement (PBA) message, and then returns the message to the MAG as a response to the registration PBU. On receiving the PBA message, the MAG updates the corresponding BULE of the MR to keep the allocated prefix information. The MR then receives an RA message with the allocated prefixes from the MAG, and distributes them to the VMNs and FMNNs as their HNPs. Finally, the VMNs and FMNNs configure their IPv6 addresses according to the assigned HNPs. After obtaining the IPv6 addresses, VMNs and FMNNs are able to access Internet through the attached MR.

Different from PMIPv6 and N-PMIPv6 that each MH occupies a corresponding BCE at the LMA, in E-PMIPv6 only one BCE is created for an MR, and the HNP field of the BCE keeps a list of allocated HNPs to the VMNs and FMNNs attached to the MR. Similarly, only one BULE is established for an MR at its attached MAG. For example, VMN_1, VMN_2, and $FMNN_1$ are attached to MR_1. When MAG_1 sends a registration PBU message to the LMA after receiving an RS message from MR_1, the LMA only creates one BCE for MR_1. As shown in Fig. 2(a), the allocated prefixes $pref_0 \sim pref_3$ to MR_1, VMN_1, VMN_2, and $FMNN_1$ are maintained in the HNP field of the BCE. In the similar way, only one BULE is established for MR_1 at MAG_1 as shown in Fig. 2(b). The description of each field in data structures BCE and BULE is illustrated in [9].

It is possible that a new VMN on an MR enabled vehicle starts to access Internet after the MR has already finished its initial binding registration. As a result, the VMN has to separately conduct its initial binding registration through the attached MR to acquire its HNP. After the VMN's L2 attachment to the MR, the MR delivers an updated RS message to the attached MAG. After receiving a PBU message from the MAG, the LMA allocates a new HNP to the VMN. Since there is already a BCE for the VMN's attached MR, the LMA only keeps the new prefix information in the HNP field of the MR's BCE, but does not create a new BCE for the VMN. Then, the LMA

Proxy_flag	MN_ID	MN_IF_ID	MAG_Addr	HNP	Tunnel-IF-ID	Access_Tech	Timestamp
1	MR_1	$MR_1\_IF\_ID$	MAG_1_addr	$pref_0$ $pref_1$ $pref_2$ $pref_3$	$Tun_1\_IF\_ID$	IEEE 802.11	t_1

(a)

MN_ID	MN_IF_ID	HNP	L_L_Addr	LMA_Addr	MAG_IF_ID	Tunnel-IF-ID
MR_1	$MR_1\_IF\_ID$	$pref_0$ $pref_1$ $pref_2$ $pref_3$	$L\_L\_addr_1$	LMAA	$MAG_1\_IF\_ID$	$Tun_1\_IF\_ID$

(b)

Proxy_flag	MN_ID	MN_IF_ID	MAG_Addr	HNP	Tunnel-IF-ID	Access_Tech	Timestamp
1	MR_1	$MR_1\_IF\_ID$	MAG_1_addr	$pref_0$ $pref_1$ $pref_2$ $pref_3$ $pref_4$	$Tun_1\_IF\_ID$	IEEE 802.11	t_2
1	VMN_4	$VMN_4\_IF\_ID$	MAG_1_addr	$pref_5$	$Tun_1\_IF\_ID$	IEEE 802.11	t_3

(c)

MN_ID	MN_IF_ID	HNP	L_L_Addr	LMA_Addr	MAG_IF_ID	Tunnel-IF-ID
MR_1	$MR_1\_IF\_ID$	$pref_0$ $pref_1$ $pref_2$ $pref_3$ $pref_4$	$L\_L\_addr_1$	LMAA	$MAG_1\_IF\_ID$	$Tun_1\_IF\_ID$
VMN_4	$VMN_4\_IF\_ID$	$pref_5$	$L\_L\_addr_1$	LMAA	$MAG_1\_IF\_ID$	$Tun_1\_IF\_ID$

(d)

Fig. 2. Initial binding registrations. (a) BCE of an MR at the LMA. (b) BULE of an MR at the MAG. (c) Updated BCE of an MR at the LMA. (d) Updated BULE of an MR at the MAG.

replies a PBA message to the MAG, and similarly the MAG only keeps the VMN's binding information in the BULE of its attached MR. Thereafter, the MAG returns an RA message to the MR, and then the MR delivers the allocated HNP to the VMN. After configuring the IPv6 address based on the allocated HNP, the VMN is able to access Internet through its attached MR. However, a VMN on an MR disabled vehicle has to attach to a roadside MAG directly, and its registration process has no difference with that in PMIPv6. The LMA needs to create a separate BCE for the VMN, and the MAG also creates a separate BULE for the VMN.

For instance, VMN_3 attaches to MR_1 and requests HNP allocation from the LMA. Then, the LMA allocates $pref_4$ to VMN_3, and adds $pref_4$ into the HNP field of MR_1's BCE as shown in the first item of Fig. 2(c). However, on an MR disabled vehicle, VMN_4 has to attach to MAG_1 directly, and the LMA needs to create a separate BCE for VMN_4 as shown in the second item of Fig. 2(c). Similarly, MAG_1 keeps VMN_3's registration information in the BULE of MR_1 as shown in the first item of Fig. 2(d), but creates a new BULE to keep VMN_4's registration information as shown in the second item of Fig. 2(d).

After obtaining HNPs and configuring IPv6 addresses, MHs are able to access Internet through their access networks. When IPv6 packets are delivered from wireline networks to an MH, they are firstly routed to the LMA. On receiving an IPv6 packet, the LMA searches for the matching HNP from its binding cache according to the destination IPv6 address. Then, the LMA finds the corresponding MAG, and forwards the packet to it. After receiving the IPv6 packet, the MAG forwards it to the destination MH if the MH is attached to the MAG directly. Otherwise, the MAG forwards it to the corresponding MR, and then the packet is delivered to the destination MH. For uplink IPv6 packets destined to wireline networks, they are first transmitted to the corresponding MR or MAG depending on where the MH is attached, and then routed to the LMA along the established bi-directional tunnel.

In E-PMIPv6, an MR requests HNPs for a group of MHs by one initial binding registration when they move into the E-PMIPv6 domain together, which prevents the MHs from conducting their initial binding registrations individually and thus greatly reduces signaling overhead. Furthermore, instead of creating one BCE for each MH, the binding information of MHs attached to the same MR is kept in one BCE at the LMA. Similarly, only one BULE is created for MHs attached to the same MR at the MAG. Therefore, E-PMIPv6 prevents redundant information from occupying limited cache resource at the LMA and MAGs, which significantly improves their cache resource utilization in urban vehicular networks where the LMA is usually responsible for maintaining binding information for tens of thousands of MHs.

B. Handoff Process

The handoff process is triggered when an MR or MH is moving out of its current access network. As mentioned in Section III, E-PMIPv6 comprehensively considers four handoff scenarios in urban vehicular networks. For example, a VMN may experience any of the four handoff scenarios, an MR/VMN/FMN needs to conduct the ***MAG-MAG*** handoff when they roam across different MAGs, but a FMNN is not required to conduct handoff since it permanently attaches to a fixed MR on the vehicle. The detailed operations of each kind of handoffs are illustrated as follows.

MR-MR handoff—When a VMN gets off an MR enabled vehicle and immediately transfers to another MR enabled vehicle, its wireless connection should be handed over to the new MR (n-MR) from the previous MR (p-MR). Assuming the p-MR and the n-MR attach to the same serving MAG, E-PMIPv6 performs the following operations as shown in Fig. 3(a).

- On detecting a L2 detachment event, the VMN sends a L2 report to the p-MR with its MN_ID and the n-MR identifier information. Note that, before delivering the report, the n-MR identifier is usually known to the VMN by L2 scanning in the predictive mode handoff [11], [12].
- After receiving the report, the p-MR sends a Deregistration RS (Dereg RS) message including the VMN's HNP and n-MR identifier to the serving MAG, and a flag field is added to differentiate a RS message and a Dereg RS message.
- On receiving the Dereg RS message, the MAG finds that the n-MR currently attaches to it, and then it stops forwarding downlink packets destined to the VMN through the p-MR, and temporarily keeps them in its buffer.

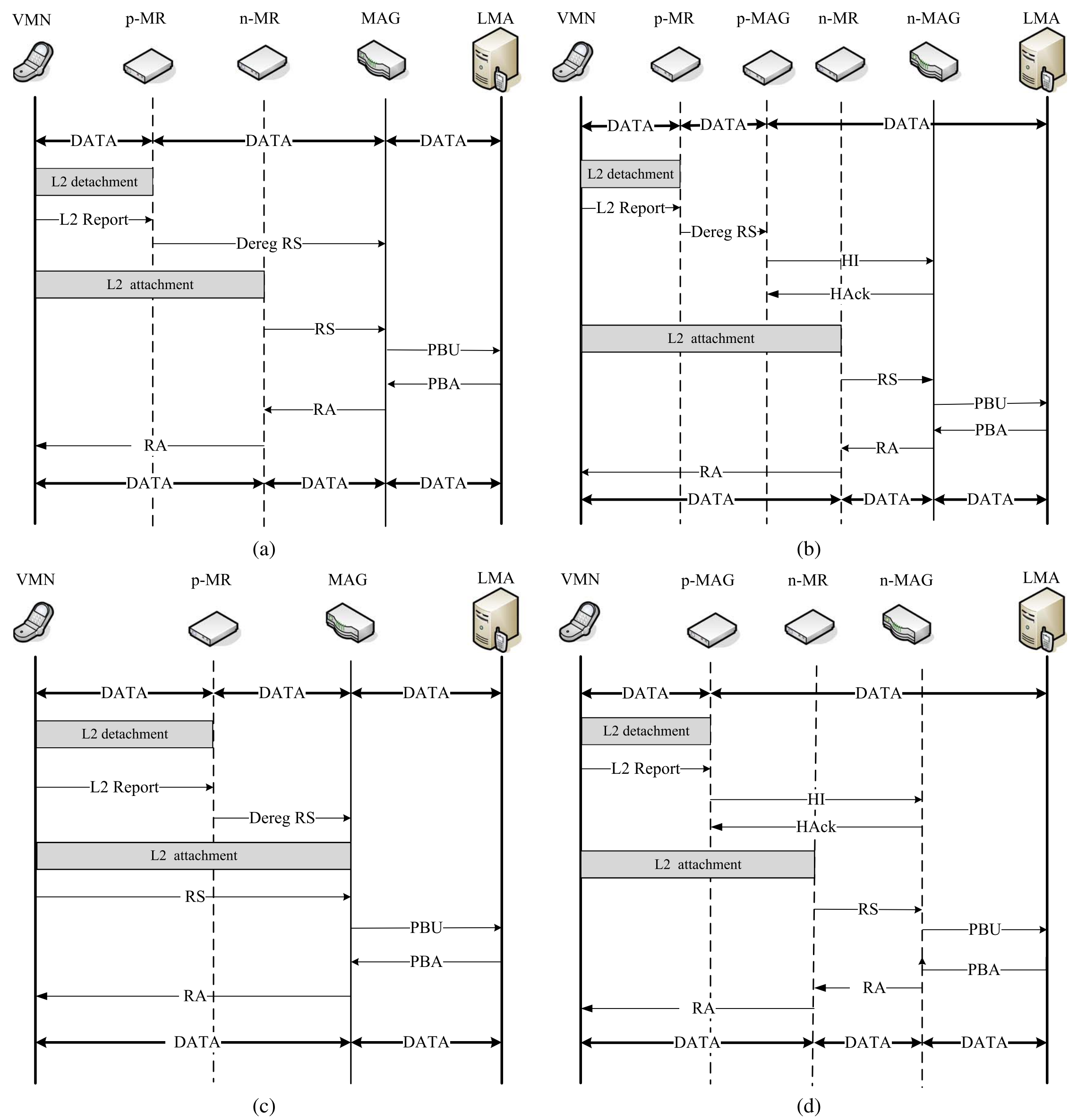

Fig. 3. Different kinds of handoffs. (a) MR–MR handoff within the same MAG. (b) MR–MR handoff across different MAGs. (c) MR–MAG handoff. (d) MAG–MR handoff.

- After the VMN's L2 attachment to the n-MR, the n-MR delivers an RS message including the VMN's HNP and n-MR identifier to the MAG.
- The MAG delivers a PBU message to the LMA.
- The LMA identifies the BCE of the p-MR based on the received HNP in its binding cache, and then removes the VMN's HNP from the BCE of the p-MR to the BCE of the n-MR. Then the LMA returns a PBA message to the MAG to confirm the binding update of the VMN.
- The MAG receives the PBA message from the LMA, and then removes the VMN's binding information from the BULE of the p-MR to the BULE of the n-MR. Thereafter, the MAG delivers an RA message to the n-MR. Then the downlink packets destined to the VMN can be delivered to the n-MR.
- The n-MR forwards the RA message to the VMN.
- On receiving the RA message, the VMN successfully attaches to the n-MR, and immediately resumes its data communications without changing its IP address.

Even though the p-MR and the n-MR probably attach to the same MAG, it is still possible that they locate at the boundary of two neighboring MAGs. In case of the p-MR and the n-MR attaching to different MAGs, the serving MAG (p-MAG) cannot find the n-MR binding information in its binding update list. As a result, the p-MAG establishes a bidirectional tunnel with the n-MAG by exchanging HI and HAck messages as the operations in [11] as shown in Fig. 3(b), by which the buffered packets destined to the VMN at the P-MAG could be forwarded to the n-MAG during the handoff process. Thereafter, the p-MAG removes the VMN's binding information from the BULE of the p-MR. After the VMN's L2 attachment, the n-MR delivers an RS message to the n-MAG. On receiving the RS message, the n-MAG adds the binding information of the VMN into the BULE of the n-MR, and then sends a PBU message to the LMA which immediately removes the VMN's HNP from the BCE of the p-MR to the BCE of the n-MR.

MR-MAG handoff—A VMN may get off an MR enabled vehicle, and then transfers to an MR disabled vehicle or wait at the station. As a result, it has to detach from the p-MR and immediately attach to a roadside MAG to maintain ongoing sessions. Assuming the VMN attaches to the current serving MAG, the following operations are conducted as shown in Fig. 3(c).

- On detecting a L2 detachment event, the VMN delivers a L2 report to the p-MR with its MN_ID and the new MAG's identifier that is acquired by L2 scanning.
- The p-MR sends a Dereg RS message to the serving MAG with the VMN'S MN_ID and the new MAG's identifier after receiving the report.
- The serving MAG finds that it is the new MAG, and then temporarily keeps the downlink packets destined to the VMN in its buffer.
- After the VMN's L2 attachment to the MAG, it sends an RS message including its MN_ID and HNP to the MAG.
- The MAG delivers a PBU message to the LMA.
- The LMA identifies the BCE of the p-MR based on the VMN's HNP in its binding cache, and then deletes the HNP from the corresponding BCE of the p-MR. In the meantime, the LMA creates a separate BCE for the VMN and returns a PBA message to the MAG.
- On receiving the PBA message from the LMA, the MAG deletes the VMN's binding information from the BULE of the p-MR, and creates a separate BULE for the VMN in its binding update list. Then the MAG returns an RA message to the VMN.
- After directly attaching to the serving MAG, the VMN resumes its data communications without changing its address configuration.

However, it is possible that the VMN attaches to another MAG. Since the serving MAG (p-MAG) receives the Dereg RS message with the new MAG's identifier, it knows that the VMN will attach to another MAG (n-MAG) if it's not the new MAG. Therefore, the p-MAG establishes a bidirectional tunnel with the n-MAG, and the buffered packets destined to the VMN at the p-MAG are forwarded to the n-MAG. After successfully attaching to the n-MAG, the n-MAG establishes a BULE for the VMN. After receiving a PBU message from the n-MAG, the LMA deletes the VMN's HNP from the BCE of the p-MR, and creates a separate BCE for the VMN. As a result, packets delivered to the VMN are firstly routed to the n-MAG from the LMA, and then are transmitted to the VMN.

MAG-MR handoff—A VMN may initially attaches to an MAG, and then gets on an MR enabled vehicle. Even though the VMN travels on the MR enabled vehicle, its detachment from the serving MAG will not be triggered as long as the vehicle locates in the coverage of the MAG. However, if the vehicle is moving out of the serving MAG (p-MAG), the VMN may detach from the p-MAG and then attach to the MR (n-MR), which introduces a ***MAG-MR*** handoff. As a result, the following operations are conducted as shown in Fig. 3(d).

- On detecting a L2 detachment event, the VMN transmits a L2 report with its MN_ID and the n-MR's identifier information to the p-MAG.
- The p-MAG establishes a bidirectional tunnel with the n-MAG by exchanging HI and HAck messages, and downlink packets destined to the VMN at the P-MAG will be forwarded to the n-MAG during the handoff process.
- After the VMN's L2 attachment, the n-MR sends an RS message including the VMN'S MN_ID and HNP to the n-MAG.
- The n-MAG sends a PBU message to the LMA.
- The LMA deletes the BCE of the VMN, and then adds its HNP into the BCE of the n-MR in its binding cache. Thereafter, the LMA returns a PBA message to the n-MAG to confirm the binding update of the VMN.
- On receiving the PBA message, the n-MAG adds the HNP of the VMN into the BULE of the n-MR, and sends an RA message to the n-MR.
- The n-MR forwards the RA message to the VMN.
- After receiving the RA message, the VMN resumes communications without changing its address configuration.

MAG-MAG handoff—A VMN or FMN on an MR disabled vehicle may move out of the serving MAG, and travel into another MAG. As a result, they have to conduct the ***MAG-MAG*** handoff to maintain their ongoing sessions. Similarly, on an MR enabled vehicle, the MR needs to conduct the ***MAG-MAG*** handoff transparently to avoid session interruptions of the MHs when the vehicle roams across neighboring MAGs. As a result, when the p-MAG receives a L2 report from a VMN/FMN/MR, it establishes a bidirectional tunnel with the n-MAG by exchanging HI and HAck messages. After the VMN/FMN/MR's L2 attachment, the n-MAG sends a PBU message to the LMA to update the VMN/FMN/MR's binding information at the LMA. Thereafter, the n-MAG creates a BULE for the VMN/FMN/MR after receiving a PBA message from the LMA, and then returns an RA message to the VMN/FMN/MR. After receiving the RA message from the n-MAG, the VMN/FMN/MR restarts data communications without changing its address configuration.

V. Performance Analysis

In this section, we develop an analytical model to study the performance of the proposed E-PMIPv6 in terms of handoff latency, signaling overhead, buffering cost, and tunneling cost [29]. The notations used in the performance analysis are listed in Table II. The coverage of an MAG overlaps with those of its neighboring MAGs, and the distance between two neighboring MAGs is d. An MR enabled vehicle has to pause for VMNs getting on or getting off the vehicle at a station, and the distance between two neighboring stations is represented by D ($D > d$). The VMNs and FMNs on an MR disabled vehicle conduct the ***MAG-MAG*** handoff when the vehicle travels across neighboring MAGs, and consequently the average ***MAG-MAG*** handoff rate for an MR disabled vehicle is expressed as

$$\mu^*_{\text{MAG-MAG}} = \frac{v}{d}. \tag{1}$$

TABLE II
NOTATIONS AND SETTINGS

Notation	Description	Default Value
d	The distance between neighboring MAGs	500 m
D	The distance between neighboring stations	2.5 km
v	The moving speed of a vehicle	10 m/s
T_p	The pause time at a station for an MR enabled vehicle	60 s
B_{MR}	The bandwidth in wireless communications between an MH and an MR	11 M
B_{MAG}	The bandwidth in wireless communications between an MH and an MAG	11 M
B_{wd}	The bandwidth in wired communications	100 M
L_{X}	The length of message X	N/A
H_{X-Y}	the hop distance between node X to node Y	N/A
ϖ_{MR}, ϖ_{wd}	The average queueing delays at an MR and a wireline router	0.1 s, 0.1 s
ω_{LMA}, ω_{MAG}	The average processing delays at the LMA and the n-MAG	0.5 ms, 0.5 ms
p_{MR}	The loss probability in wireless communications between an MH and an MR	0.05
p_{MAG}	The loss probability in wireless communications between an MH and an MAG	0.1
$\Delta t'_{\mathrm{MR-MR}}$	The duration from the reception of a Dereg RS message to MR-MR L2 handoff	0
$\Delta t''_{\mathrm{MR-MR}}$	The duration from the reception of a HAck message to MR-MR L2 handoff	0
$\Delta t_{\mathrm{MR-MAG}}$	The duration from the reception of a Dereg RS message to MR-MAG L2 handoff	0
$\Delta t_{\mathrm{MAG-MR}}$	The duration from the reception of a HAck message to MAG-MR L2 handoff	0
$\Delta t_{\mathrm{MAG-MAG}}$	The duration from the reception of a HAck message to MAG-MAG L2 handoff	0
$T^{l2}_{\mathrm{X-Y}}$	The average L2 switching delay in $X-Y$ handoff	N/A
ρ_{mr}, ρ_{mag}, ρ_{wd}	The signaling factors in communications with an MR, an MAG, a wired router	0.3, 0.6, 0.1
ϵ_{lma}, ϵ_{mag}	The buffering factors at the LMA and an MAG	0.5, 0.5
λ	The arrival rate of packets destined to an MH	10 packets/s
λ_t	The tunneling rate of packets from the p-MAG to the n-MAG for a VMN	10 packets/s
τ	The tunneling factor for data transmissions between the p-MAG and the n-MAG	1
n_{VMN}	The numbers of VMNs on an MR enabled vehicle	20
n^*_{VMN}	The number of the VMNs and FMNs on an MR disabled vehicle	4
$n_{\mathrm{X-Y}}$	The number of VMNs conducting the $X-Y$ handoff on an MR enabled vehicle	N/A
$N_{\mathrm{MR\in MAG}}$, $N^*_{\mathrm{MR\in MAG}}$	The numbers of MR enabled vehicles and MR disabled vehicles within an MAG	5, 5
$N_{\mathrm{MR\in LMA}}$, $N^*_{\mathrm{MR\in LMA}}$	The numbers of MR enabled vehicles and MR disabled vehicles within the LMA	20, 20

Similarly, the MR on an MR enabled vehicle also performs the ***MAG-MAG*** handoff when the vehicle travels from one MAG to another neighboring MAG. However, when the MR enabled vehicle arrives at a station and pauses for T_p, some VMNs may get off the vehicle, and conduct the ***MR-MR*** handoff or the ***MR-MAG*** handoff. On the other hand, some VMNs that have started end-to-end sessions through the serving MAG may get on the vehicle during the pause time T_p, and conduct the ***MAG-MR*** handoff when the vehicle is moving out of the serving MAG. As a result, the ***MAG-MAG*** handoff rate for an MR enabled vehicle is denoted as

$$\mu_{\mathrm{MAG-MAG}} = \frac{1}{d/v + T_p \cdot d/D}. \quad (2)$$

In addition, an MR enabled vehicle has the same ***MR-MR***, ***MR-MAG***, and ***MAG-MR*** handoff rate since these handoffs only occur when the vehicle passes a station, and we have the handoff rates

$$\mu_{\mathrm{MR-MR}} = \mu_{\mathrm{MR-MAG}} = \mu_{\mathrm{MAG-MR}} = \frac{1}{d/v + T_p}. \quad (3)$$

In the following subsections, we analyze each performance metric of E-PMIPv6 separately.

A. Handoff Latency

The handoff latency is defined as the interval from the trigger of the L2 report to the successful reception of the RA message as shown in Fig. 3. In an ***MR-MR*** handoff, the p-MR and the n-MR probably attach to the same MAG, but it is still possible that they locate at the boundary of two neighboring MAGs and attach to different MAGs, which induces the HI/HAck handshake between the p-MAG and the n-MAG. Denote $T'_{\mathrm{MR-MR}}$ as the ***MR-MR*** handoff latency when p-MR and the n-MR attach to the same MAG, $T''_{\mathrm{MR-MR}}$ as the ***MR-MR*** handoff latency when p-MR and the n-MR attach to different MAGs, and B_{MR} and B_{MAG} as the bandwidths in wireless communications between a VMN and an MR and wireless communications between a VMN and an MAG, respectively. Consequently, the ***MR-MR*** handoff latencies $T'_{\mathrm{MR-MR}}$ and $T''_{\mathrm{MR-MR}}$ are expressed as

$$\begin{aligned} T'_{\mathrm{MR-MR}} &= 2\varpi_{\mathrm{MR}} + \Delta t'_{\mathrm{MR-MR}} + T^{l2}_{\mathrm{MR-MR}} + \omega_{\mathrm{LMA}} \\ &\quad + \frac{L_{l2} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MR}}) \cdot B_{\mathrm{MR}}} + \frac{L_{\mathrm{D-RS}} + L_{\mathrm{RS}} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MAG}}) \cdot B_{\mathrm{MAG}}} \\ &\quad + H_{\mathrm{MAG-LMA}} \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{PBU}} + L_{\mathrm{PBA}}}{B_{\mathrm{wd}}}\right) \end{aligned} \quad (4)$$

$$\begin{aligned} T''_{\mathrm{MR-MR}} &= 2\varpi_{\mathrm{MR}} + \Delta t''_{\mathrm{MR-MR}} + T^{l2}_{\mathrm{MR-MR}} + \omega_{\mathrm{MAG}} + \omega_{\mathrm{LMA}} \\ &\quad + \frac{L_{l2} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MR}}) \cdot B_{\mathrm{MR}}} + \frac{L_{\mathrm{D-RS}} + L_{\mathrm{RS}} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MAG}}) \cdot B_{\mathrm{MAG}}} \\ &\quad + H_{\mathrm{MAG-MAG}} \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{HI}} + L_{\mathrm{HAck}}}{B_{\mathrm{wd}}}\right) \\ &\quad + H_{\mathrm{MAG-LMA}} \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{PBU}} + L_{\mathrm{PBA}}}{B_{\mathrm{wd}}}\right) \end{aligned} \quad (5)$$

where L_{l2}, $L_{\mathrm{D-RS}}$, L_{RS}, L_{PBU}, L_{PBA}, L_{RA}, L_{HI}, and L_{HAck} are the lengths of messages L2 report, Dereg RS, RS, PBU, PBA, RA, HI and HAck, receptively; ϖ_{MR} and ϖ_{wd} are the average queueing delays at an MR and a wireline router; ω_{LMA} and ω_{MAG} are the average processing delays at the LMA and a

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n-MAG, receptively; p_{MR} and p_{MAG} are the failure probability in wireless communications between an MH and an MR and the failure probability in wireless communications between an MH and an MAG, receptively; $\Delta t'_{\mathrm{MR-MR}}$ and $\Delta t''_{\mathrm{MR-MR}}$ are the duration from the reception of a Dereg RS message to the beginning of the L2 handoff and the duration from the reception of a HAck message to the beginning of the L2 handoff, receptively; $T^{l2}_{\mathrm{MR-MR}}$ is the average ***MR-MR*** L2 handoff delay; $H_{\mathrm{MAG-LMA}}$ and $H_{\mathrm{MAG-MAG}}$ are the hop distance from the MAG to the LMA in wireline networks and the hop distance between the p-MAG and the n-MAG, receptively. Similarly, we can obtain the ***MR-MAG***, ***MAG-MR***, and ***MAG-MAG*** handoff latencies

$$\begin{aligned} T_{\mathrm{MR-MAG}} &= \varpi_{\mathrm{MR}} + \Delta t_{\mathrm{MR-MAG}} + T^{l2}_{\mathrm{MR-MAG}} + \omega_{\mathrm{LMA}} \\ &\quad + \frac{L_{l2}}{(1-p_{\mathrm{MR}})\cdot B_{\mathrm{MR}}} + \frac{L_{\mathrm{D-RS}} + L_{\mathrm{RS}} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MAG}})\cdot B_{\mathrm{MAG}}} \\ &\quad + H_{\mathrm{MAG-LMA}} \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{PBU}} + L_{\mathrm{PBA}}}{B_{\mathrm{wd}}}\right) \end{aligned} \tag{6}$$

$$\begin{aligned} T_{\mathrm{MAG-MR}} &= \varpi_{\mathrm{MR}} + \omega_{\mathrm{MAG}} + \Delta t_{\mathrm{MAG-MR}} + \omega_{\mathrm{LMA}} \\ &\quad + T^{l2}_{\mathrm{MAG-MR}} + \frac{L_{\mathrm{RA}}}{(1-p_{\mathrm{MR}})\cdot B_{\mathrm{MR}}} \\ &\quad + \frac{L_{l2} + L_{\mathrm{RS}} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MAG}})\cdot B_{\mathrm{MAG}}} + H_{\mathrm{MAG-MAG}} \\ &\quad \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{HI}} + L_{\mathrm{HAck}}}{B_{\mathrm{wd}}}\right) + H_{\mathrm{MAG-LMA}} \\ &\quad \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{PBU}} + L_{\mathrm{PBA}}}{B_{\mathrm{wd}}}\right) \end{aligned} \tag{7}$$

$$\begin{aligned} T_{\mathrm{MAG-MAG}} &= \omega_{\mathrm{MAG}} + \Delta t_{\mathrm{MAG-MAG}} + T^{l2}_{\mathrm{MAG-MAG}} + \omega_{\mathrm{LMA}} \\ &\quad + H_{\mathrm{MAG-MAG}} \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{HI}} + L_{\mathrm{HAck}}}{B_{\mathrm{wd}}}\right) \\ &\quad + H_{\mathrm{MAG-LMA}} \cdot \left(2\varpi_{\mathrm{wd}} + \frac{L_{\mathrm{PBU}} + L_{\mathrm{PBA}}}{B_{\mathrm{wd}}}\right) \\ &\quad + \frac{L_{l2} + L_{\mathrm{RS}} + L_{\mathrm{RA}}}{(1-p_{\mathrm{MAG}})} \end{aligned} \tag{8}$$

where $\Delta t_{\mathrm{MR-MAG}}$, $\Delta t_{\mathrm{MAG-MR}}$, and $\Delta t_{\mathrm{MAG-MAG}}$ are the duration from the reception of a Dereg RS message to the beginning of the ***MR-MAG*** L2 handoff, the duration from the reception of a HAck message to the beginning of the ***MAG-MR*** L2 handoff, and the duration from the reception of a HAck message to the beginning of the ***MAG-MAG*** L2 handoff, receptively; $T^{l2}_{\mathrm{MR-MAG}}$, $T^{l2}_{\mathrm{MAG-MR}}$, and $T^{l2}_{\mathrm{MAG-MAG}}$ are the ***MR-MAG*** L2 handoff delay, the ***MAG-MR*** L2 handoff delay, and the ***MAG-MAG*** L2 handoff delay, respectively. Consequently, the handoff delay in each kind of handoffs is obtained.

B. Signaling Overhead

When a VMN/FMN/MR travels across different access networks, signaling messages will be exchanged in the handoff process. Therefore, signaling overhead is calculated by the sum of the signaling messages incurred during the handoff process. As shown in Fig. 3(a) and (b), there are two different signaling flows in the ***MR-MR*** handoff. Denote $S'_{\mathrm{MR-MR}}$ as the signaling overhead when the p-MR and the n-MR attach to the same MAG, and $S''_{\mathrm{MR-MR}}$ as the signaling overhead when the p-MR and the n-MR attach to different MAGs. Consequently, $S'_{\mathrm{MR-MR}}$ and $S''_{\mathrm{MR-MR}}$ are expressed as

$$\begin{aligned} S'_{\mathrm{MR-MR}} &= \frac{\rho_{\mathrm{mr}}\cdot(L_{l2}+L_{\mathrm{RA}})}{1-p_{\mathrm{MR}}} + \frac{\rho_{\mathrm{mag}}\cdot(L_{\mathrm{D-RS}}+L_{\mathrm{RA}}+L_{\mathrm{RS}})}{1-p_{\mathrm{MAG}}} \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-LMA}} \cdot (L_{\mathrm{PBU}} + L_{\mathrm{PBA}}) \end{aligned} \tag{9}$$

$$\begin{aligned} S''_{\mathrm{MR-MR}} &= \frac{\rho_{\mathrm{mr}}\cdot(L_{l2}+L_{\mathrm{RA}})}{1-p_{\mathrm{MR}}} + \frac{\rho_{\mathrm{mag}}\cdot(L_{\mathrm{D-RS}}+L_{\mathrm{RA}}+L_{\mathrm{RS}})}{1-p_{\mathrm{MAG}}} \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-MAG}} \cdot (L_{\mathrm{HI}} + L_{\mathrm{HAck}}) \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-LMA}} \cdot (L_{\mathrm{PBU}} + L_{\mathrm{PBA}}) \end{aligned} \tag{10}$$

where ρ_{mr}, ρ_{mag}, and ρ_{wd} are the signaling factors for the wireless communications with an MR, the wireless communications with an MAG, and the wireline communications, respectively. Note that the signaling cost in wireless communications is much more expensive than that in wireline communications [30]. The signaling overheads in the ***MR-MAG***, ***MAG-MR***, and ***MAG-MAG*** handoffs are expressed as

$$\begin{aligned} S_{\mathrm{MR-MAG}} &= \frac{\rho_{\mathrm{mr}}\cdot L_{l2}}{1-p_{\mathrm{MR}}} + \frac{\rho_{\mathrm{mag}}\cdot(L_{\mathrm{D-RS}}+L_{\mathrm{RA}}+L_{\mathrm{RS}})}{1-p_{\mathrm{MAG}}} \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-LMA}} \cdot (L_{\mathrm{PBU}} + L_{\mathrm{PBA}}) \end{aligned} \tag{11}$$

$$\begin{aligned} S_{\mathrm{MAG-MR}} &= \frac{\rho_{\mathrm{mr}}\cdot L_{\mathrm{RA}}}{1-p_{\mathrm{MR}}} + \frac{\rho_{\mathrm{mag}}\cdot(L_{l2}+L_{\mathrm{RA}}+L_{\mathrm{RS}})}{1-p_{\mathrm{MAG}}} \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-MAG}} \cdot (L_{\mathrm{HI}} + L_{\mathrm{HAck}}) \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-LMA}} \cdot (L_{\mathrm{PBU}} + L_{\mathrm{PBA}}) \end{aligned} \tag{12}$$

$$\begin{aligned} S_{\mathrm{MAG-MAG}} &= \frac{\rho_{\mathrm{mag}}\cdot(L_{l2}+L_{\mathrm{RA}}+L_{\mathrm{RS}})}{1-p_{\mathrm{MAG}}} \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-MAG}} \cdot (L_{\mathrm{HI}} + L_{\mathrm{HAck}}) \\ &\quad + \rho_{\mathrm{wd}} \cdot H_{\mathrm{MAG-LMA}} \cdot (L_{\mathrm{PBU}} + L_{\mathrm{PBA}}). \end{aligned} \tag{13}$$

C. Buffering Cost

The utilization of buffer resources is an important performance metric since buffer resources are limited. In an E-PMIPv6 domain, the LMA keeps the binding information for a number of MHs. As shown in Fig. 2(c), one BCE keeps either the binding information of a VMN or the binding information of an MR. Denote L_{BCE} as length of the BCE of a VMN and L_{HNP} as the length of one HNP. Consequently, the buffering cost for keeping BCEs at the LMA is expressed as

$$\begin{aligned} \mathcal{B}^{\mathrm{BCE}}_{\mathrm{LMA}} &= \epsilon_{\mathrm{lma}} \cdot N_{\mathrm{MR}\in\mathrm{LMA}} \cdot (L_{\mathrm{BCE}} + n_{\mathrm{VMN}} \cdot L_{\mathrm{HNP}}) \\ &\quad + \epsilon_{\mathrm{lma}} \cdot N^{*}_{\mathrm{MR}\in\mathrm{LMA}} \cdot n^{*}_{\mathrm{VMN}} \cdot L_{\mathrm{BCE}} \end{aligned} \tag{14}$$

where ϵ_{lma} is the buffering factor at the LMA, $N_{\mathrm{MR}\in\mathrm{LMA}}$ and $N^{*}_{\mathrm{MR}\in\mathrm{LMA}}$ are the numbers of MR enabled vehicles and MR disabled vehicles within the E-PMIPv6 domain, n_{VMN} and n^{*}_{VMN} are the average number of VMNs on an MR enabled vehicle and the average number of VMNs on an MR disabled vehicle, respectively. Similarly, an MAG needs to maintain the binding update information for the MHs attaching to it. Denote $L_{\rm BULE}$ as the length of the BULE of a VMN at an MAG, and the buffering cost for maintaining BULEs at an MAG is

$$\mathcal{B}_{\rm MAG}^{\rm BUL} = \epsilon_{\rm mag} \cdot N_{\rm MR\in MAG} \cdot (L_{\rm BULE} + n_{\rm VMN} \cdot L_{\rm HNP}) + \epsilon_{\rm mag} \cdot N^{*}_{\rm MR\in MAG} \cdot n^{*}_{\rm VMN} \cdot L_{\rm BULE} \quad (15)$$

where $\epsilon_{\rm mag}$ is the buffering factor at an MAG, $N_{\rm MR\in MAG}$ and $N^{*}_{\rm MR\in MAG}$ are the average numbers of MR enabled vehicles and MR disabled vehicles attaching to an MAG, respectively.

In addition, an MAG may need to temporarily keep packets during a handoff process. For example, when a VMN on an MR enabled vehicle conducts the ***MR-MR*** handoff, the serving MAG needs to keep the packets destined to the VMN if the p-MR and the n-MR attach to the same MAG. Consequently, the buffering cost of the MR enabled vehicle at the MAG is

$$\mathcal{B}'_{\rm MR-MR} = \epsilon_{\rm mag} \cdot \mu_{\rm MR-MR} \cdot n'_{\rm MR-MR} \cdot \lambda \cdot L_{\rm DATA} \cdot \left(T'_{\rm MR-MR} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}} - \varpi_{\rm MR} - \frac{L_{\rm D-RS}}{(1-p_{\rm MAG}) \cdot B_{\rm MAG}}\right) \quad (16)$$

where $L_{\rm DATA}$ is the length of a data packet, and λ is the average packet arrival rate to a VMN. When the p-MR and the n-MR attach to different MAGs, packets are buffered at the p-MAG before the tunnel between the p-MAG and the n-MAG is established, or at the n-MAG after the establishment of the tunnel, and the buffering cost of the MR enabled vehicle is

$$\mathcal{B}''_{\rm MR-MR} = \epsilon_{\rm mag} \cdot \mu_{\rm MR-MR} \cdot n''_{\rm MR-MR} \cdot \lambda \cdot L_{\rm DATA} \cdot \left(T''_{\rm MR-MR} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}} - \varpi_{\rm MR} - \frac{L_{\rm D-RS}}{(1-p_{\rm MAG}) \cdot B_{\rm MAG}}\right). \quad (17)$$

Similarly, the buffering cost of the MR enabled vehicle in the ***MR-MAG*** handoff is

$$\mathcal{B}_{\rm MR-MAG} = \epsilon_{\rm mag} \cdot \mu_{\rm MR-MAG} \cdot n_{\rm MR-MAG} \cdot \lambda \cdot L_{\rm DATA} \cdot \left(T_{\rm MR-MAG} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}} - \varpi_{\rm MR} - \frac{L_{\rm D-RS}}{(1-p_{\rm MAG}) \cdot B_{\rm MAG}}\right) \quad (18)$$

and the buffering cost of the MR enabled vehicle in the ***MAG-MR*** handoff is represented as

$$\mathcal{B}_{\rm MAG-MR} = \epsilon_{\rm mag} \cdot \mu_{\rm MAG-MR} \cdot n_{\rm MAG-MR} \cdot \lambda \cdot L_{\rm DATA} \cdot \left(T_{\rm MAG-MR} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}}\right). \quad (19)$$

However, for an MR enabled vehicle only the MR conducts the ***MAG-MAG*** handoff, and its buffering cost is represented as

$$\mathcal{B}_{\rm MAG-MAG} = \epsilon_{\rm mag} \cdot \mu_{\rm MAG-MAG} \cdot n_{\rm VMN} \cdot \lambda \cdot L_{\rm DATA} \cdot \left(T_{\rm MAG-MAG} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}}\right). \quad (20)$$

Since the VMNs and FMNs on an MR disabled vehicle need to conduct the ***MAG-MAG*** handoff separately, the buffering cost of the vehicle is represented as

$$\mathcal{B}^{*}_{\rm MAG-MAG} = \epsilon_{\rm mag} \cdot \mu^{*}_{\rm MAG-MAG} \cdot n^{*}_{\rm VMN} \cdot \lambda \cdot L_{\rm DATA} \cdot \left(T_{\rm MAG-MAG} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}}\right). \quad (21)$$

D. Tunneling Cost

In an ***MR-MR*** handoff, when the p-MR and the n-MR attach to different MAGs, DATA packets should be tunneled to the n-MAG from the p-MAG during the handoff process, which consumes the bandwidth resources of intermediate routers and induces tunneling cost [31]. As a result, the tunneling cost of an MR enabled vehicle in the ***MR-MR*** handoff is represented as

$$C^{\rm tun}_{\rm MR-MR} = \tau \cdot \mu_{\rm MR-MR} \cdot n''_{\rm MR-MR} \cdot \lambda_t \cdot L_{\rm DATA} \cdot \left(T''_{\rm MR-MR} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}} - \frac{L_{\rm D-RS}}{(1-p_{\rm MAG}) \cdot B_{\rm MAG}} - \varpi_{\rm MR} - H_{\rm MAG-MAG} \cdot \left(\varpi_{\rm wd} + \frac{L_{\rm HI}}{B_{\rm wd}}\right) - \omega_{\rm MAG} - H_{\rm MAG-MAG} \cdot \left(\varpi_{\rm wd} + \frac{L_{\rm HAck}}{B_{\rm wd}}\right)\right) \quad (22)$$

where τ is the tunneling factor for DATA transmissions between the p-MAG and the n-MAG, and λ_t is the average sending rate of packets destined to a VMN from the p-MAG to the n-MAG. When VMNs on an MR enabled vehicle conduct the ***MAG-MR*** handoff, packets should be tunneled to the n-MAG from the p-MAG, and the tunneling cost is represented as

$$C^{\rm tun}_{\rm MAG-MR} = \tau \cdot \mu_{\rm MAG-MR} \cdot n_{\rm MAG-MR} \cdot \lambda_t \cdot L_{\rm DATA} \cdot \left(T_{\rm MAG-MR} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}} - H_{\rm MAG-MAG} \cdot \left(\varpi_{\rm wd} + \frac{L_{\rm HI}}{B_{\rm wd}}\right) - \omega_{\rm MAG} - H_{\rm MAG-MAG} \cdot \left(\varpi_{\rm wd} + \frac{L_{\rm HAck}}{B_{\rm wd}}\right)\right). \quad (23)$$

For an MR conducting the ***MAG-MAG*** handoff, the tunneling cost is expressed as

$$C^{\rm tun}_{\rm MAG-MAG} = \tau \cdot \mu_{\rm MAG-MAG} \cdot n_{\rm VMN} \cdot \lambda_t \cdot L_{\rm DATA} \cdot \left(T_{\rm MAG-MAG} - \frac{L_{l2}}{(1-p_{\rm MR}) \cdot B_{\rm MR}} - H_{\rm MAG-MAG} \cdot \left(\varpi_{\rm wd} + \frac{L_{\rm HI}}{B_{\rm wd}}\right) - \omega_{\rm MAG} - H_{\rm MAG-MAG} \cdot \left(\varpi_{\rm wd} + \frac{L_{\rm HAck}}{B_{\rm wd}}\right)\right). \quad (24)$$

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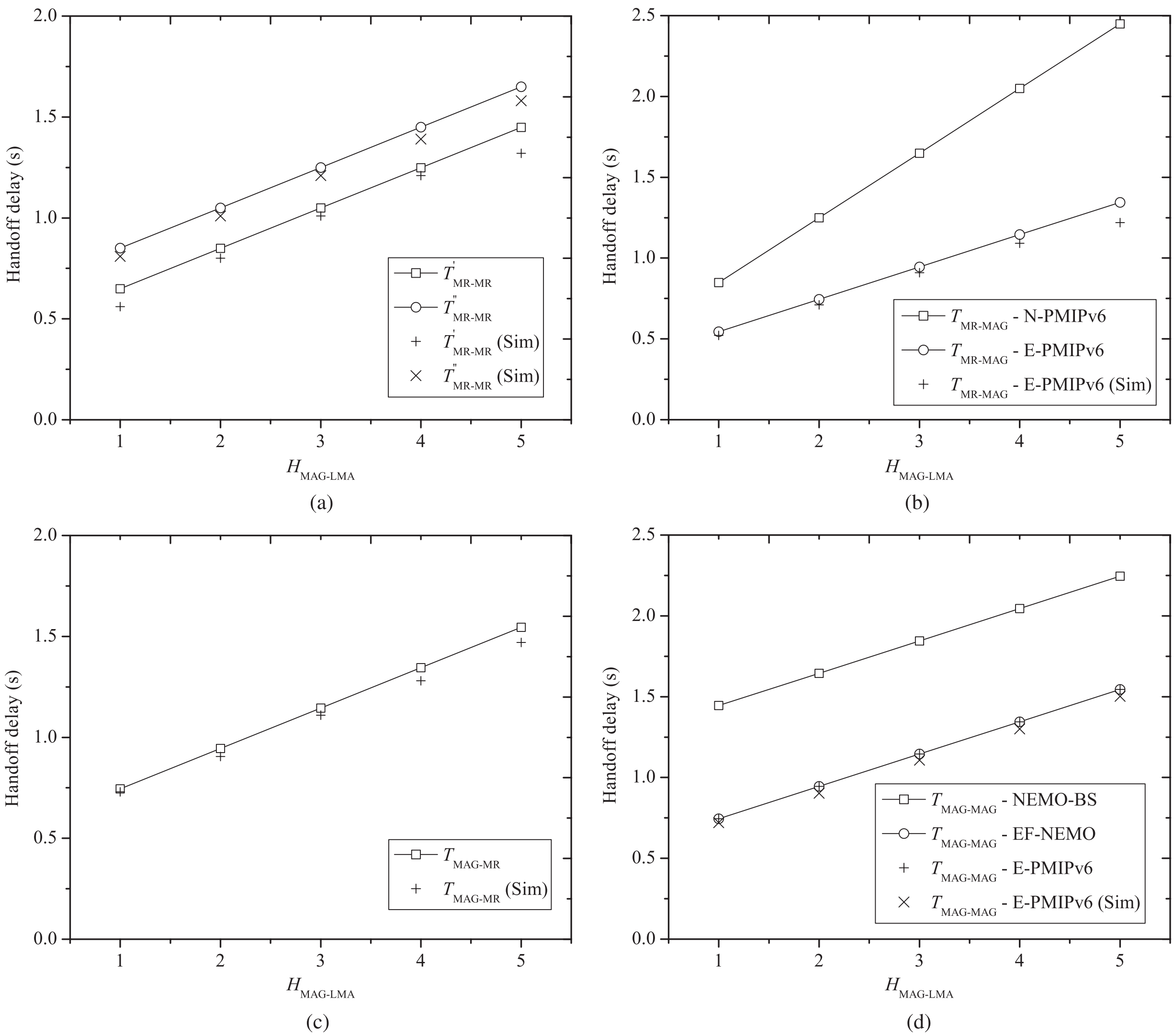

Fig. 4. Handoff delay in different kinds of handoffs. (a) MR–MR handoff delay. (b) MR–MAG handoff delay. (c) MAG–MR handoff delay. (d) MAG–MAG handoff delay.

Whereas, the tunneling cost of an MR disabled vehicle due to VMNs and FMNs conducting the ***MAG-MAG*** handoff is expressed as

$$\begin{aligned} C^{\text{tun}\cdot *}_{\text{MAG-MAG}} = {} & \tau \cdot \mu^{*}_{\text{MAG-MAG}} \cdot n^{*}_{\text{VMN}} \cdot \lambda_t \cdot L_{\text{DATA}} \\ & \cdot \Bigg(T_{\text{MAG-MAG}} - \frac{L_{l2}}{(1-p_{\text{MR}}) \cdot B_{\text{MR}}} \\ & - H_{\text{MAG-MAG}} \cdot \left(\varpi_{\text{wd}} + \frac{L_{\text{HI}}}{B_{\text{wd}}} \right) - \omega_{\text{MAG}} \\ & - H_{\text{MAG-MAG}} \cdot \left(\varpi_{\text{wd}} + \frac{L_{\text{HAck}}}{B_{\text{wd}}} \right) \Bigg). \end{aligned} \tag{25}$$

Finally, the tunneling cost in each kind of handoffs is obtained.

VI. Simulation Results

In order to evaluate the performance of the proposed E-PMIPv6, we downloaded the NS-2 based PMIPv6 package [32], and extended the package to implement E-PMIPv6 in Network Simulator-2 (NS-2) [33]. We conducted performance comparisons among E-PMIPv6, NEMO-BS, FP-NEMO, and N-PMIPv6 in terms of handoff latency, signaling overhead, buffering cost, and tunneling cost. In the simulated environment, vehicles are traveling on straight roads of the urban transportation system, and multiple MAGs are distributed along the roads. The transmission range of an MAG overlaps with those of its neighboring MAGs on two opposite sides. Some important parameter settings in the simulations are tabulated in Table II, and other parameters without explicit settings in the table are listed as follows: $L_{l2} = 52$ bytes, $L_{\text{D-RS}} = 52$ bytes, $L_{\text{RS}} = 52$ bytes, $L_{\text{PBU}} = 72$ bytes, $L_{\text{PBA}} = 72$ bytes, $L_{\text{RA}} = 92$ bytes, $L_{\text{HI}} = 52$ bytes, and $L_{\text{HAck}} = 52$ bytes, $L_{\text{DATA}} = 512$ bytes, $L_{\text{BCE}} = 62$ bytes, $L_{\text{BULE}} = 62$ bytes, $L_{\text{HNP}} = 8$ bytes, $H_{\text{MAG-LMA}} = 2$, $H_{\text{MAG-MAG}} = 1$, $T^{l2}_{\text{MR-MR}} = 244$ ms, $T^{l2}_{\text{MR-MAG}} = 244$ ms, $T^{l2}_{\text{MAG-MR}} = 244$ ms, $T^{l2}_{\text{MAG-MAG}} = 244$ ms, $n_{\text{MR-MAG}} = 5$, $n_{\text{MAG-MR}} = 5$, $n'_{\text{MR-MR}} = 5$, $n''_{\text{MR-MR}} = 5$. Some existing analytical models have been developed to study the performances of NEMO-BS, FP-NEMO, and N-PMIPv6 in [13], [23], and [25], by which we obtain analysis results for performance comparisons with E-PMIPv6.

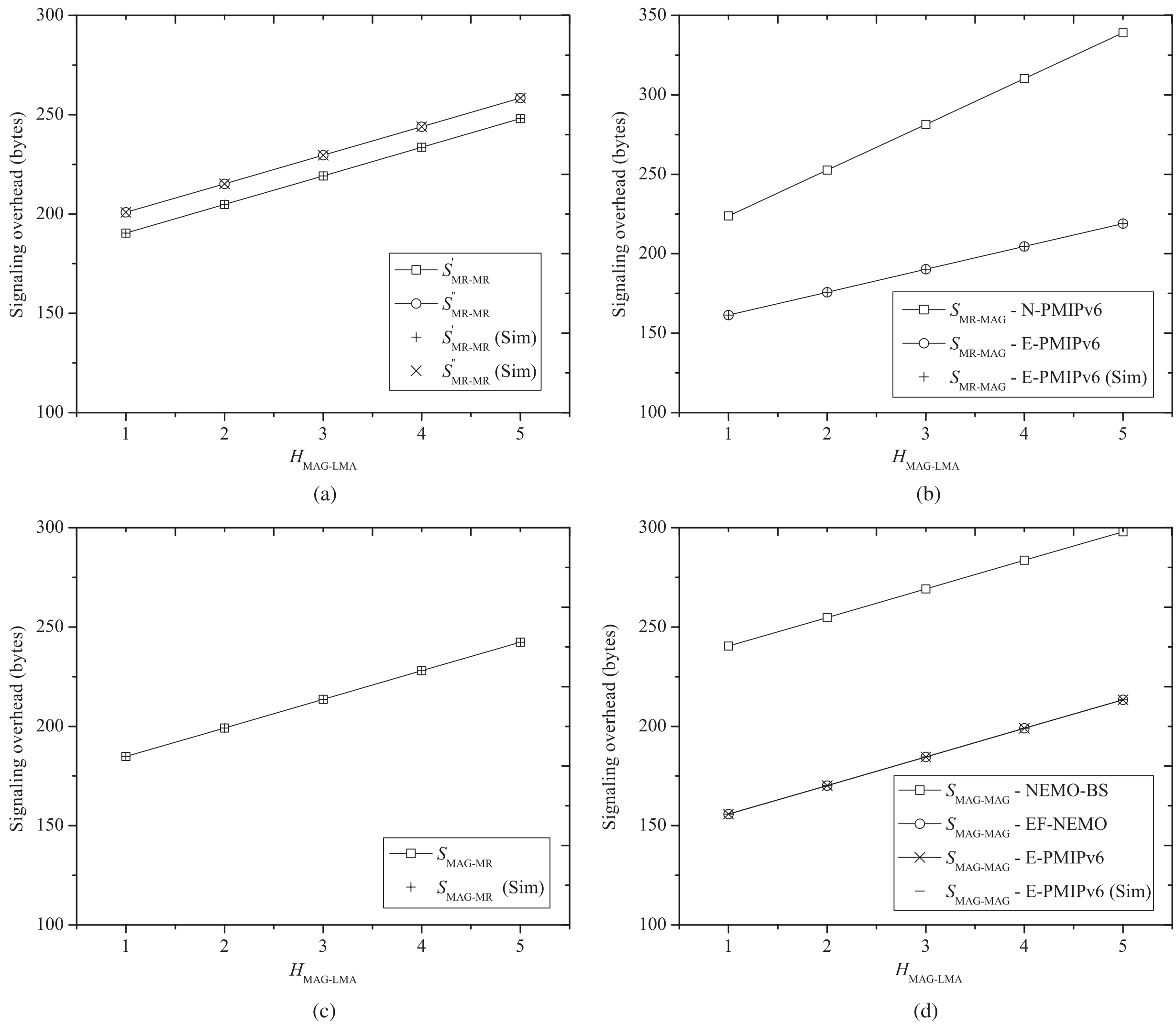

Fig. 5. Signaling overhead in different kinds of handoffs. (a) Signaling overhead in the MR–MR handoff. (b) Signaling overhead in the MR–MAG handoff. (c) Signaling overhead in the MAG–MR handoff. (d) Signaling overhead in the MAG–MAG handoff.

A. Handoff Latency

Handoff latency is an important performance metric for a handoff protocol, and it critically affects the throughput of the network. For example, for a traveling MH, if the handoff latency is prolonged, the remaining time for its data communications within an MAG will be decreased. Fig. 4 shows the handoff delay performance with the increase of hop distance between an MAG and the LMA in each kind of handoffs. Since the comparative protocols do not support the ***MR-MR*** and the ***MAG-MR*** handoffs, Fig. 4(a) and (c) only show the handoff delays in E-PMIPv6. Whereas, Fig. 4(b) shows the handoff delay comparisons between N-PMIPv6 and E-PMIPv6, and we can observe that the delays in N-PMIPv6 are much larger than those in E-PMIPv6. In N-PMIPv6, after receiving a Dereg RS message, the MAG will notify the LMA of the upcoming departure of an MH before the L2 handoff, and the LMA will buffer packets destined to the MH during the handoff process, which may take much time in the wired domain. However, without notifying the LMA, E-PMIPv6 does not require the above operations and packets will be buffered at the MAG during the handoff process, which greatly reduces the handoff delay.

Fig. 4(d) shows the ***MAG-MAG*** handoff delay comparisons among NEMO-BS, FP-NEMO, and E-PMIPv6. We can observe that FP-NEMO and E-PMIPv6 demonstrate the same handoff delay performance since they adopt the same signaling flow in the ***MAG-MAG*** handoff, but the handoff delays in NEMO-BS are larger than those in FP-NEMO and E-PMIPv6. In the ***MAG-MAG*** handoff, NEMO-BS adopts the same signaling flow as MIPv6 and has to conduct the movement detection (MD) and the DAD operations, which consume much time in the handoff process. However, without changing the CoA configuration, an MR in E-PMIPv6 does not experience the DAD process in the ***MAG-MAG*** handoff, which saves much time in the handoff process. Whereas, with the increase of the hop distance between an MAG and the LMA, the time spent in the wired domain will go up, which prolongs the handoff delay in each kind of handoffs.

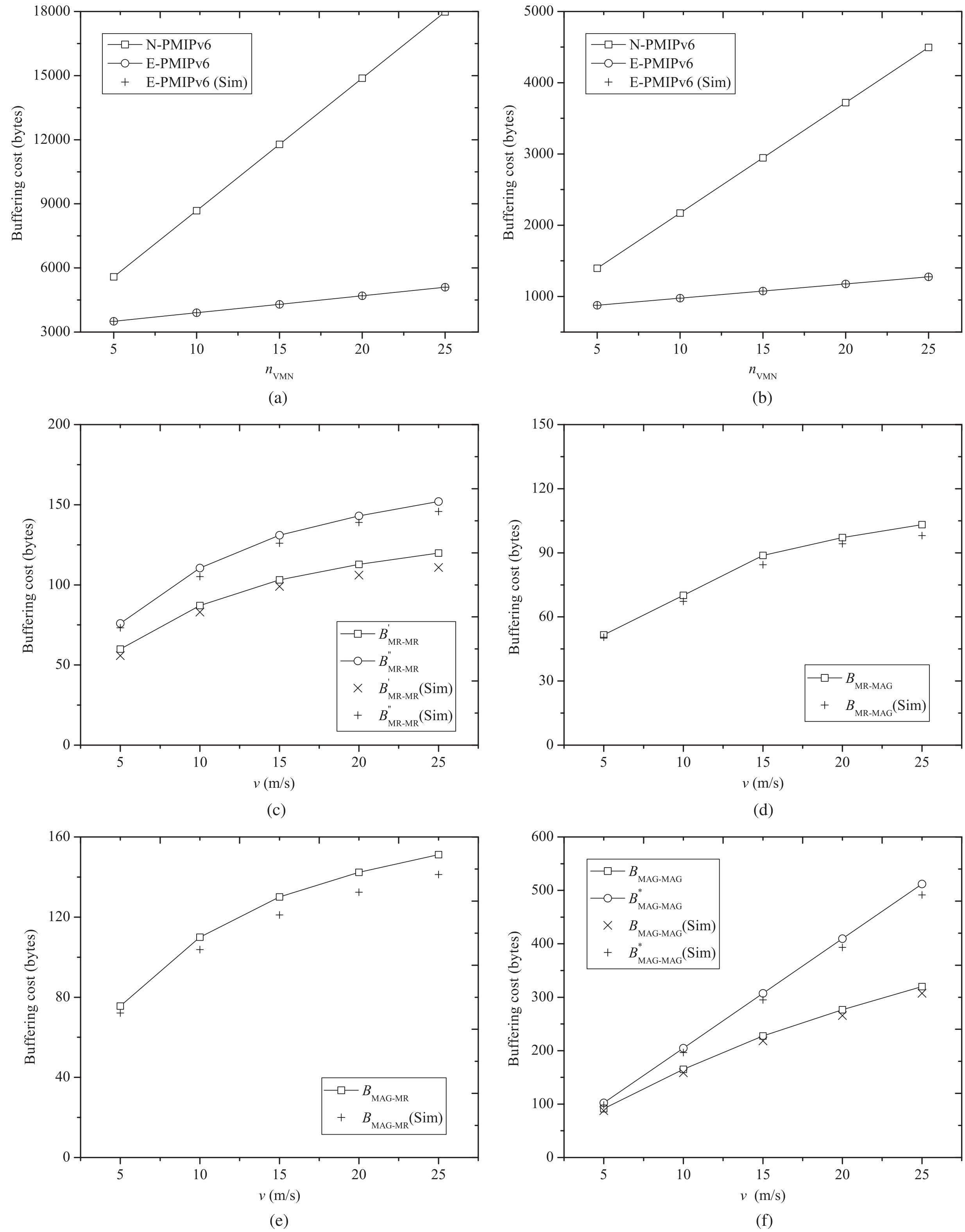

Fig. 6. Buffering cost in different kinds of handoffs. (a) Buffering cost at the LMA. (b) Buffering cost at an MAG. (c) Buffering cost in the MR–MR handoff. (d) Buffering cost in the MR–MAG handoff. (e) Buffering cost in the MAG–MR handoff. (f) Buffering cost in the MAG–MAG handoff.

B. Signaling Overhead

Signaling overhead in the handoff process consumes much bandwidth resource, and should be reduced as much as possible. Fig. 5 shows the signaling overhead in each kind of handoffs. Similarly, Fig. 5(a) and (c) only show the signaling overhead in the ***MR-MR*** and the ***MAG-MR*** handoffs inu E-PMIPv6 since none of the comparative protocols supports such handoffs. Fig. 5(b) shows the signaling overhead comparisons between N-PMIPv6 and E-PMIPv6, and we can observe that N-PMIPv6 induces more signaling overhead than E-PMIPv6. In N-PMIPv6,

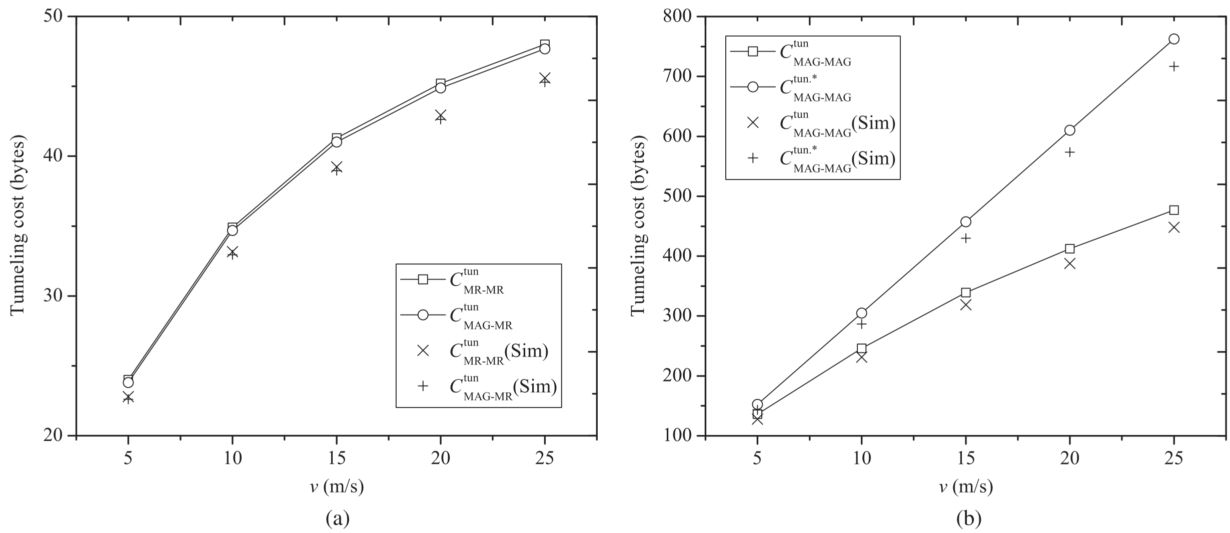

Fig. 7. Tunneling cost in different kinds of handoffs. (a) Tunneling cost in the MR–MR and MAG–MR handoffs. (b) Tunneling cost in the MAG–MAG handoff.

there is a handshake process between the MR and the LMA to notify the upcoming departure of an MH before the L2 handoff, which introduces extra signaling overhead in the ***MR-MAG*** handoff. Fig. 5(d) demonstrates signaling overhead comparisons among NEMO-BS, FP-NEMO, and E-PMIPv6. The figure shows that the signaling overhead in NEMO-BS is larger than those in FP-NEMO and E-PMIPv6 in the ***MAG-MAG*** handoff. As a host-based mobility management protocol, NEMO-BS needs to experience the MD, DAD, and binding update processes, which impose heavy signaling overhead. However, as a network-based handoff protocol, E-PMIPv6 provides transparent mobility support to MHs without complex configurations in the terminals, and greatly reduces signaling overhead in the wireless domain.

C. Buffering Cost

Buffer resources should be efficiently utilized for the entities involved in the handoff process. There are two kinds of buffer resources: i) the buffer to keep binding information for MHs, and such information will always occupy the buffer space until the MHs move out of the management entity, for example, the BCEs kept in the LMA; and ii) the buffer to temporarily keep packets when MHs conduct the handoff process, and the buffer space will be released after MHs complete the handoff process and resume data communications. Fig. 6(a) shows the comparisons of buffering cost at the LMA between N-PMIPv6 and E-PMIPv6. We can observe that the buffering cost in N-PMIPv6 increases faster than that in E-PMIPv6 with the growing number of VMNs in an MR. Similar as PMIPv6, the LMA in N-PMIPv6 creates a separate BCE for each MH to keep track of its binding information, and the number of BCEs in the buffer equals the number of MHs. However, in E-PMIPv6 the MHs within the same MR enabled vehicle only occupy one BCE space at the LMA, and only the HNP field needs to keep the allocated HNPs as shown in Fig. 2(a), which greatly saves buffer resources at the LMA. Fig. 6(b) shows the comparisons of buffering cost at an MAG between N-PMIPv6 and E-PMIPv6, and we have the similar observations that the buffering cost in N-PMIPv6 increases faster than that in E-PMIPv6 with the growth of VMNs in an MR. E-PMIPv6 adopts the similar concept to establish BULEs at an MAG where MHs in the same MR enabled vehicle occupy one BULE, which leads to the superiority of E-PMIPv6 over N-PMIPv6 in buffer utilization.

Since NEMO-BS and N-PMIPv6 are lack of packet buffering support at MAGs, packets will be lost during the handoff process. Even though FP-NEMO supports packet buffering in the ***MAG-MAG*** handoff, it has the same buffering cost performance with E-PMIPv6 since they adopt the same signaling flow. Therefore, we demonstrate the buffering cost due to temporary packet buffering in each kind of handoffs of E-PMIPv6 in Fig. 6(c)–(f). We can observe that the buffering cost in the ***MR-MR*** handoff within the same MAG is less than that across different MAGs in the Fig. 6(c), where $n''_{\mathrm{MR-MR}} = 5$. The main reason is that if the p-MR and the n-MR attach to different MAGs, the p-MAG needs to establish a tunnel to n-MAG before the L2 handoff, which induces longer handoff delay and larger buffering cost than the ***MR-MR*** handoff within the same MAG. Fig. 6(f) shows the buffering cost comparisons between an MR enabled vehicle and an MR disabled vehicle with the same number of VMNs in the ***MAG-MAG*** handoff, where $n_{\mathrm{VMN}} = 4$. We can observe that the buffering cost of an MR enabled vehicle is less than that of an MR disabled vehicle. Since an MR enabled vehicle stops at a station for MHs getting off or getting on the vehicle, it has a lower ***MAG-MAG*** handoff rate than an MR disabled vehicle, and achieves less buffering cost. However, with the growth of the vehicle traveling speed, the handoff rate in each kind of handoff will increase, which leads to a higher buffering cost.

D. Tunneling Cost

Packet tunneling between the p-MAG and the n-MAG consumes wired bandwidth, and thus induces tunneling cost. Since NEMO-BS and N-PMIPv6 do not support packet buffering at MAGs, packets will not be tunneled between the p-MAG and the n-MAG. In addition, FP-NEMO has the same tunneling cost with E-PMIPv6 in the ***MAG-MAG*** handoff. Fig. 7(a) shows the tunneling cost in the ***MR-MR*** handoff across different MAGs and the tunneling cost in the ***MAG-MR*** handoff in E-PMIPv6, where $n''_{\mathrm{MR-MR}} = 5$. As shown in Fig. 3(b) and (d), the ***MR-MR*** handoff and the ***MAG-MR*** handoff have similar signaling flow, and achieve the similar handoff latency as shown in Fig. 4(a) and (c). Therefore, the amount of tunneled packets in the two handoffs are similar as shown in Fig. 7(a). The tunneling cost of an MR enabled vehicle and that of an MR disabled vehicle in the ***MAG-MAG*** handoff are shown in Fig. 7(b), where $n_{\mathrm{VMN}} = 4$. Since an MR disabled vehicle experiences a higher ***MAG-MAG*** handoff rate than an MR enabled vehicle as illustrated in Section VI-C, the tunneling cost of an MR disabled vehicle increases faster than that of an MR enabled vehicle. However, with the growth of vehicle velocity, the tunneling cost in each kind of handoffs increases due to the increased handoff rate.

VII. Conclusion

In this paper, an efficient PMIPv6-based handoff scheme has been presented to provide transparent mobility support to mobile users by inheriting both advantages of PMIPv6 and NEMO-BS in different handoff scenarios in urban vehicular networks. In the initial binding registration process, the proposed E-PMIPv6 has provided flexible prefix allocations to various kinds of users, e.g., an MR with a mobile network, an MH from an MR enabled vehicle, or an MH from an MR disabled vehicle, etc., and merged the BCEs of MHs within the same mobile network into one entry, which efficiently improves cache utilization at the LMA that is usually in charge of mobility management for a large number of MHs. In the handoff process, E-PMIPv6 has utilized network-based mobility management approach to provide seamless and ubiquitous Internet connectivity to MHs when they roam across different access networks, and enhanced handoff performance by eliminating packet loss, reducing handoff delay and signaling overhead, and improving buffer utilization in each kind of handoff scenarios. Finally, numerical results from mathematical analysis and simulations have demonstrated that E-PMIPv6 outperforms NEMO-BS, N-PMIPv6, and FP-NEMO in terms of handoff latency, signaling overhead, buffering cost, and tunneling cost. In our future work, we will investigate more general vehicular networks where an MH may obtain IP addresses from not only MRs but also neighboring MHs, since the feasibility of Device-to-Device (D2D) communications for vehicular networks has been comprehensively investigated for the first time in [34] and [35], where novel and practical D2D-based vehicular networks have been proposed by utilizing channel prediction and interference modeling.

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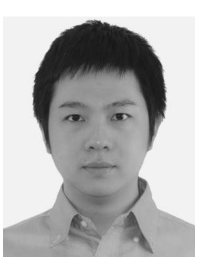

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