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On Achieving Seamless IP Communications in Heterogeneous Vehicular Networks

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***Abstract*—The supporting infrastructure and communications technologies for vehicular networking contexts are heterogeneous by nature. Large coverage access networks, such as 3G/4G, coexist with wireless local area networks (WLAN) and dedicated short range communications (DSRC). In such a scenario, we investigate the seamless provision of Mobile Internet access and general IP services over the heterogeneous network, in particular for loosely coupling architectures. We propose a hybrid global mobility scheme that allows for the on-going IP sessions to be transferred across dissimilar radio access networks that may belong to different administrative domains. In order to achieve the global mobility, our scheme combines host-based and network-based mobility. The solution focuses on urban vehicular scenarios and enables seamless communications for in-vehicle networks, passengers with mobile devices, and users of public transportation commuting along the system. By means of analytical evaluations and simulations of realistic urban vehicular scenarios, we show that our hybrid scheme can achieve seamless IP communications for Mobile Internet access over the heterogeneous vehicular network.**

***Index Terms*—IP Mobility, Heterogeneous Vehicular Networks, Host Identity Protocol, Mobile Internet, Proxy Mobile IP.**

I. Introduction

URBAN vehicular communication networks are mobile environments that involve from computers and entertainment systems installed in moving vehicles, buses, or trains, to mobile devices being used by passengers or by people commuting across public transportation vehicles, bus stops, and terminal stations. All these mobile devices are employed for accessing a wide range of Internet services and applications. In such a mobile environment, the demand for data has grown significantly over the recent years and will continue growing even faster. If a single access network were to be used for Mobile Internet access, it would likely be overloaded and congested in the near future [1]. Hence, two different heterogeneous network architectures have been proposed to meet the capacity requirements: i) a heterogeneous cellular network, in which different areas of coverage are created by adapting transmission power, network density, and data rate depending on the intended area of coverage. In this way, the cellular network becomes a combination of macrocells, microcells, and femtocells; and ii) the heterogeneous radio access network, which requires the interworking of different radio access technologies such as LTE, WLAN, and WiMAX [2]. It is the second heterogeneous architecture that we are concerned in this paper, motivated by the need to ensure unrestricted mobility as well as proper data capacity to nodes in the vehicular network.

One of the major challenges in our heterogeneous network scenario is to enable the continuity of communications when the Internet connection is changed, not only between dissimilar radio access networks, but also between different administrative domains (i.e., from network operator A to network operator B). A mobility management solution is the mechanism that addresses this specific challenge. The requirements for such a mechanism depend on the extension of the area where the mobile node is moving and the mobility profile of the node (i.e., high, medium, or low mobility) [3], [4]. First, if nodes are moving within the same administrative domain, QoS capabilities and fast handovers are expected. Second, when the users move among different administrative domains, the global mobility scheme should adapt to support dissimilar types of access networks and different administrative policies. In such a case, a centralized mobility management scheme such as the one proposed for heterogeneous networks in 3GPP (HetNet) is difficult to realize, considering that the infrastructure networks may belong to separated administrative entities [2], [5].

The mobility protocols introduced by the IETF, such as the recently Mobility Support in IPv6 (MIP) [6], NEMO Basic Support (NEMO BS) [7], and Proxy Mobile IPv6 (PMIP) [8], are not designed specifically for urban vehicular scenarios. MIP and NEMO BS provide global mobility support, but they tend to use suboptimal routes and to introduce a longer end-to-end delay that severely affects real-time applications [9]. In a similar way, it has been shown that PMIP requires adaptations for the protocol to be usable in vehicular environments [10]; nevertheless, the protocol is still limited to mobility within a single administrative domain.

Therefore, in this paper we discuss the design of a hybrid scheme for seamless IP communications in urban heterogeneous vehicular networks. The scheme enables the interworking between host-based and network-based mobility support, by means of the interaction between PMIP and the Host Identity Protocol (HIP). Although HIP by itself allows for global mobility, our proposed scheme aims at taking advantage of the reduced signalling overhead when the localized mobility is managed by PMIP (i.e., when the node is moving within the same administrative domain). In our proposed scheme, the two protocols not only "coexist", but we also define the

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mechanisms to extend mobility from single nodes to mobile networks, which includes the identification of the capabilities of each node, the handling of communications from devices traveling within a vehicle, and the transferring of IP sessions across different administrative domains.

Furthermore, our proposed interworking scheme intends to benefit two types of users: legacy nodes that depend on the vehicle's router to support mobility, and mobility-enabled nodes that are able to manage their own end-to-end IP mobility. The first type of users correspond to devices traveling within a vehicle, which constitute the so-called in-vehicle network. Such nodes rely on the vehicle's mobile router (MR) for external connectivity. The second type represents end devices from passengers (or pedestrians) that have IP mobility support by means of HIP. Accordingly, mobility-enabled nodes may for example switch the connection from the MR in a train, to the WiFi access router at the train station. Another example is a passenger switching between two different bus routes, and transferring the active IP sessions in his/her tablet, from the WiFi network in the first bus to the WiFi network in a second bus. The main contributions of this work are described as follows:

- A global IP mobility scheme is proposed, which is dedicated for nodes and mobile networks (e.g., pedestrians, commuters, and vehicles) interacting in vehicular environments.
- The required signaling is specified to identify legacy, mobility-enable nodes, and in-vehicle networks, and the specific mechanisms are devised for the transferring of active IP sessions for each type of node. The scheme supports intra-domain and inter-domain handovers in combination with heterogeneous radio access networks.
- Extensive simulation results are provided to verify the analytical results and evaluate the effectiveness of the proposed scheme in a realistic urban vehicular scenario.

Therefore, in this paper we extend our preliminary results presented in [11]. In this work, we clarify the proposed signalling for all types of nodes and the different stages of the global mobility communication scheme. The analyses introduced in [11] only consider the handover latency and packets dropped from a mobile node perspective, so we introduce a new analysis from the mobile network perspective. In addition, we present new experimental results from simulations in a realistic urban vehicular scenario, in which we combine pedestrian and vehicular traces that recreate a commuters journey. The simulations consider different coupling levels among the network operators, as well as different radio access technologies.

The remainder of this paper is organized as follows. In Section II, we provide a brief survey of previous work that addresses the problem of global IP mobility in vehicular networks. Then, we describe our system model in Section III, and introduce the hybrid global mobility scheme in Section IV. After that, we provide performance analysis in Section V and simulation results in Section VI. Concluding remarks are presented in Section VII.

II. Previous work

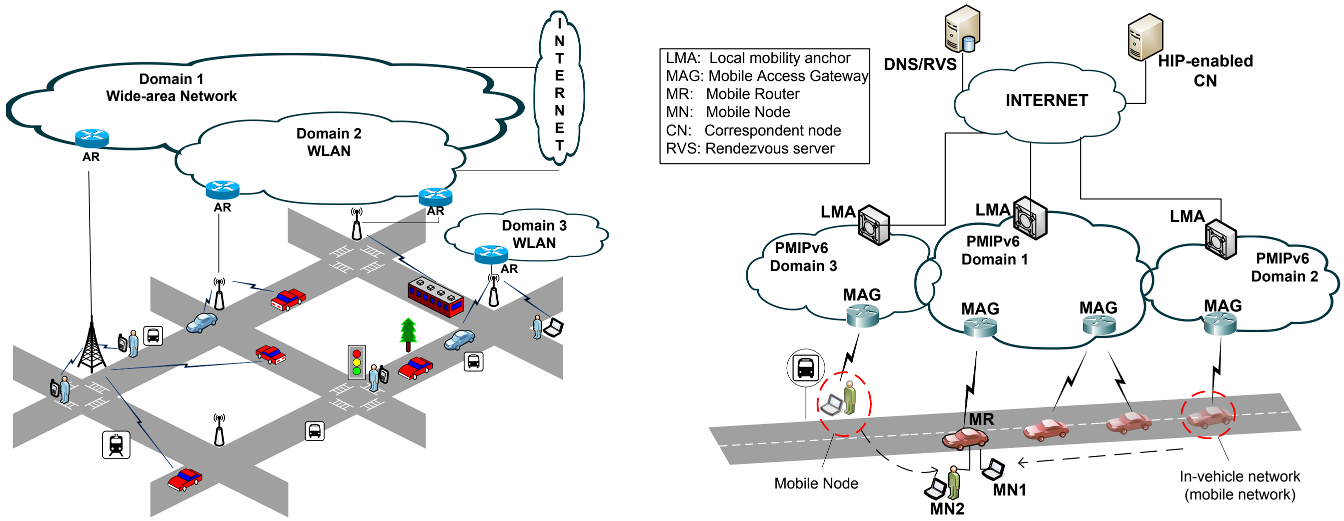
This section provides a brief review of the two major mobility support standards related to our proposed scheme, and describes some solutions that apply or extend well-known mobility management protocols for vehicular scenarios.

Proxy Mobile IPv6 [8] is a network-based mobility approach in which the network, on behalf of the mobile node (MN), performs all the signalling required to provide IP mobility. An entity named the Mobile Access Gateway (MAG) detects new connections and exchanges Proxy Binding Updates and Proxy Binding Acknowledgements (PBU/PBA) with a centralized entity known as the Local Mobility Anchor (LMA). The LMA is a manager for network prefixes assigned to nodes inside the administrative domain. When a handover occurs, the new MAG notifies the new connection to the LMA (i.e., it sends a PBU). Then, the LMA identifies the MN and assigns the same network prefix to it (i.e., it replies with a PBA).

Conversely, Host Identity Protocol (HIP) is a host-based mobility approach [12] that follows in the category of ID/locator separation architectures [13]. Such architectures are being widely adopted to provide support to the Future Internet [14]. HIP defines a Host Identity, which is cryptographic by nature, to identify the nodes in a way that it separates the location and identification functions of IP addresses. When two nodes want to communicate using HIP, each peer establishes a pair of Security Associations (SA), which are later used for the encryption/decryption of data packets. If the IP address changes in one (or both) side of the communication, HIP allows for the continuation of data packets transmission, because neither the transport layer sessions nor the SAs are related to the IP addresses (i.e., they are related to the Host Identity).

Numerous studies, based on adaptations to MIP, NEMO BS, and PMIP, are proposed to support global mobility for nodes that may eventually leave the mobile network. In [15], a network-based mobility protocol is proposed to handle vertical handovers in heterogeneous networks. It defines an interaction between Layers 2 and 3 to accelerate the handover control procedures. This network-based solution is limited to intra-domain handovers.

A solution for enabling inter-domain handovers with PMIP is proposed in [16]. This solution introduces a new element, the iMAG, which is a normal MAG located between the two different PMIP domains. This iMAG performs a layer 3 inter-domain procedure before the layer 2 inter-domain handover is completed. Hence, by the time the mobile node completes the new L2 connection, the information has already been updated in the new domain. A similar solution that uses a tunnel between LMA's of different domains is presented in [17]. Although the two solutions enable global mobility based on PMIP, they require some pre-agreement between the administrative domains for putting in place the domain-connecting elements. Furthermore, they do not define a mechanism for clustering the mobility signalling when a number of mobile nodes travel together in a mobile network. The latter problem is addressed in [18], where the authors propose an adaptation to PMIP for the support of mobile networks. The solution focuses on automotive scenarios, and reduces the signalling



(a) System architecture

(b) Network elements, mobile nodes, and in-vehicle networks

Fig. 1. Global mobility scheme system model.

overhead caused by a number of mobility-enabled nodes of the in-vehicle network. However, N-PMIP does not consider the handover of nodes across different administrative domains.

Since HIP provides a mechanism to maintain the communications independently of changes in the IP address, it has been also considered as a global mobility management protocol. A solution to reduce the signalling overhead of HIP in a micro-mobility scenario is presented by Novaczki *et al.* [19]. The authors introduce the Local Rendezvous Servers (LRVS), which are located in every administrative domain and have to translate the mobile node's local IP address to a globally-routable IP address. The mobile node notifies the change of local IP address to the LRVS during an intra-domain handover. Since the global IP address remains the same, no other notifications are required to be sent to correspondent nodes. Conversely, during inter-domain handovers the mobile node first registers with the LRVS in the new domain; in this way the old LRVS can temporarily redirect the packets to the new location. In the meantime, the new LRVS sends notifications to the correspondent nodes updating the location of the mobile node.

There are also proposals that combine protocols from different layers, whether to improve the performance of intra-domain handovers or to enable efficient inter-domain handovers [20]–[22]. The proposed protocols show different combinations of HIP with a network layer mobility management protocol. On the one hand, the scheme in [21] enables a micro-mobility solution with less signalling overhead through the combination of HIP and PMIP. However, it is specifically designed for an emergency system, and it does not provide IP mobility for moving networks. On the other hand, HarMoNy [22] provides a global mobility solution that extends HIP to support mobile networks by means of NEMO BS. Since both HIP and NEMO BS enable global mobility, the solution in [22] may be subject to a large signaling overhead. Another line of research explores the distribution of mobility anchors, in what is known as Distributed Mobility Management [23]. In [24], a host-based distributed mobility scheme is proposed to provide global IP mobility and it enables selective offloading of data traffic at the same time.

III. System Model

We consider in-vehicle networks and mobile nodes moving in the heterogeneous access network illustrated in Fig. 1a. An in-vehicle network is formed by devices (e.g., internal computer, entertainment system, and passenger's mobile devices) traveling within a vehicle and employing the vehicle's mobile router (MR) for external connectivity, including Internet access. The mobile router has one or more wireless interfaces for connecting to access networks, and a WLAN interface to serve as the MR for devices in the in-vehicle network. The mobile nodes correspond to terminal devices that connect to Internet in a direct way (e.g., a mobile phone with cellular Internet access while on-the-move or at a terminal station), or through the vehicle's MR (e.g., a mobile phone using WLAN Internet access available on a bus). The mobile nodes can have multiple wireless interfaces, although we consider only one active interface in this paper. Some of the mobile nodes support IP mobility by means of HIP.

A heterogeneous access network consists of different radio access technologies that provide varied areas of coverage and may belong to different administrative domains (i.e., different network operators). In our urban vehicular scenario, wide area wireless networks (WWAN), such as 3G/4G, provide extended coverage, whereas WLAN coverage for specific areas is provided by technologies such as 802.11n and 802.11p/WAVE [25]. Each access network enables Internet connectivity. The radio access networks may be tightly connected or may follow a loose coupling architecture [26]. In a loose coupling architecture, the WLAN networks do not connect directly to the WWAN; thus, communications between overlapping WLAN and WWAN happen indirectly through a third party network (e.g., the Internet).

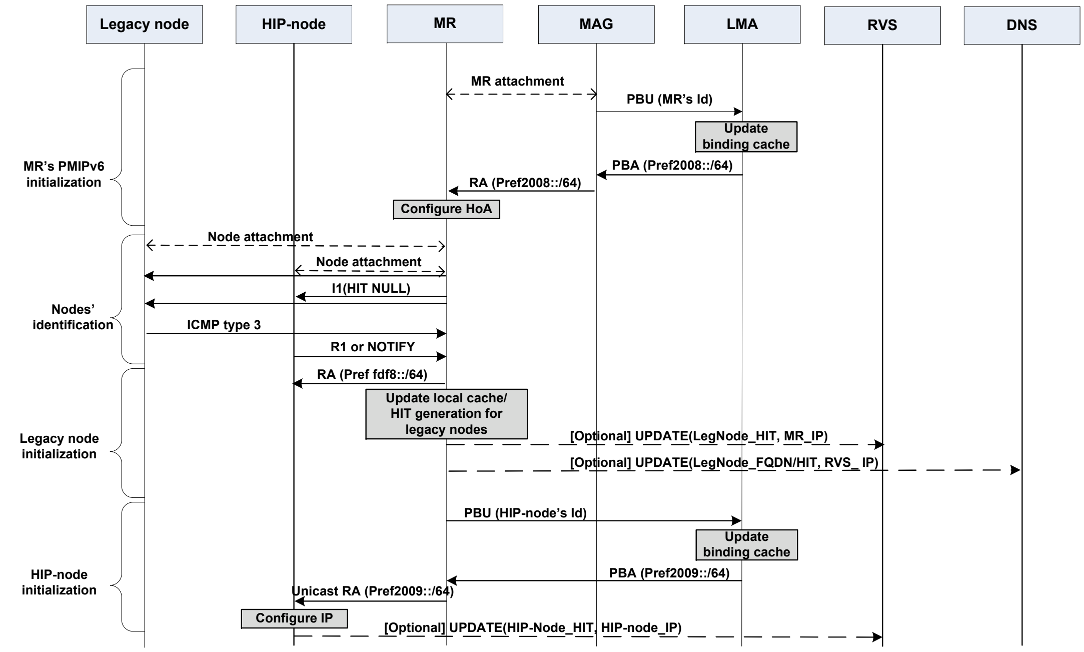


Fig. 2. Initialization phase in the proposed hybrid scheme.

It is assumed that network operators provide PMIP support to handle intra-domain handovers, as illustrated in Fig. 1b. If users move inside the same administrative domain all the time, our scheme can provide the means to enable IP mobility for single hosts or for mobile networks, as the standard PMIP does not provide support for mobile networks. On the contrary, users moving across different administrative domains require the full features of our proposed hybrid mobility scheme to achieve IP mobility. No other policy-related requirements are assumed from the operator. The terminal devices define their own policies that trigger handovers to a different access networks (e.g., lower cost, availability, quality of reception, etc.)

Access Routers (ARs) are available for mobile devices and vehicles to access the Internet. We consider one single LMA per domain, and fixed tunnels from the LMA to each MAG (i.e., the AR), so that they remain active even when there are no active connections in a given MAG. Nodes obtain access across different administrative domains after an authentication method grants them with such an access. This authentication is performed while the node is establishing the layer 2 connection in a new domain.

Nodes in the vehicular network communicate with correspondent nodes (CN) arbitrarily located in the Internet. These CNs are HIP-enabled or located behind a proxy HIP. Domain name servers (DNS) are available for translating Full Qualified Domain Names (FQDN) to host identities, and from host identities to IP addresses [27]. Rendezvous servers (RVS) are available for redirecting initial solicitations of HIP associations when the mobile node's location is unknown by the correspondent node. The two servers may be co-located, although this is not strictly necessary. The aforementioned network elements, mobile nodes, and in-vehicle networks are illustrated in Fig. 1b.

IV. Proposed Hybrid Global Mobility Scheme

A. *Initialization*

An illustration of the initialization phase of our hybrid global mobility scheme is depicted in Fig. 2. When an MR enters to a PMIP domain for the first time, it initially follows the regular steps for new associations defined in the standard PMIP [8]. During the layer 2 connection to the serving MAG, the MR completes the authentication procedures in the new network. Next, the MAG notifies the detection of a new connection to the LMA, by means of a PBU message. The PBU includes the MR's unique identifier, which is in turn used by the LMA to detect whether it corresponds to a new node in the network.

Once the LMA finds that this is the first time the MR registers in the domain, it proceeds to assign it a home network prefix, and to send a PBA back to the MAG. The MAG then advertises the network prefix to the MR in a Router Advertisement (RA) message, and the MR configures an address based on the received home network prefix. In parallel, the MR continuously sends RA messages to nodes in the in-vehicle network. The RAs announce a unique local IPv6 unicast prefix, which allows the nodes to configure globally unique addresses that are intended for local communications [28]. All nodes in the in-vehicle network configure addresses from the local unicast prefix.

After the initialization is completed, the MR identifies if there are HIP-enabled nodes in the in-vehicle network. In order to do this identification, the MR sends I1 messages in opportunistic mode (i.e., an I1 with a NULL destination HIT). Only the HIP-enabled nodes will respond to that message, whether with an R1 or a NOTIFY packet [1]. Nodes that

[1]A NOTIFY reply is sent when the node does not allow for opportunistic mode.

are not HIP-enabled will reply with an ICMP destination protocol unreachable packet. Subsequently, the MR completes the initialization in a different way, depending on whether or not mobile node support HIP. The procedures are described as follows.

1) Initialization for legacy nodes: The MR acts as a proxy HIP for the identified legacy nodes. The proxy HIP generates a Host Identity Tag (HIT) for each legacy node, and places this information in a local cache. The cache relates the HIT to the unique local IPv6 address of the legacy node. At this point, the legacy nodes may initialize access to the Internet. As an optional step, the MR may send an UPDATE message to the RVS (`[LegNode_HIT→MR_IP]`), and to the DNS (`[LegNode_FQDN→LegNode_HIT→RVS_IP]`), on behalf of each legacy node. In this way, incoming communications from correspondent nodes to legacy nodes are also enabled.

2) Initialization for HIP-enabled nodes: The MR acts as a mobile MAG (mMAG) for mobile nodes that have been identified as HIP-enabled [18]. A PBU is sent from the MR to the LMA indicating the unique identifier of the HIP-enabled node, and the LMA sends back a PBA with the IP prefix assigned to the mobile node. The information about the HIP-enabled node is stored in the LMA's binding cache. The stored entry includes the node's identifier, the assigned IP prefix, the serving MAG (i.e., the mMAG), and a flag to indicate the serving MAG is mobile. This flag is necessary to perform recursive lookups when there is incoming traffic directed to the HIP-enabled node, as we later explain in Section IV-B2.

After completing the PMIP signalling, the MR announces the network prefix in a unicast RA message to the HIP-enabled node [29]. Upon receiving the RA, the node configures an IP address from the new prefix and selects it as the source address for external communications [30]. However, the node also keeps the address initially configured from the local unicast prefix. At this point, HIP-enabled nodes may initialize access to the Internet. An additional UPDATE message, `[HIP-node_HIT→HIP-node_IP]`, can be sent from the HIP-enabled node to the RVS, in order to enable incoming communications. No updates need to be sent to the DNS.

B. End-to-end communications

Data packets to/from the Internet are forwarded in a different way depending on the type of node that is transmitting/receiving the packets in the vehicular network. The two procedures are explained as follows.

1) Communications from/to legacy nodes: When the legacy node communicates with a correspondent node in an external network, it first sends a DNS query to translate the correspondent node's FQDN to an IP address. The proxy HIP in the MR then intercepts this query, and replaces the packet's source address with its own IP [31]. Once the MR receives a reply from the DNS, it inspects the packet and stores the correspondent node's information (i.e., the HIT and IP address). The reply packet is then forwarded to the legacy node. Upon receiving the first legacy node's data packet to be forwarded outside the in-vehicle network, the MR starts an HIP base exchange with the correspondent node. This is a four-way handshake in which the MR and correspondent node establish the required HIP security associations. Consequently, the MR removes the IP header of each packet received from a legacy node, and generates a new header using the Encapsulating Security Payload (ESP) transport format. This new header includes the MR's IP as the packet's source address. When packets arrive from the infrastructure, the MR looks for the correspondent security association, and once it locates the HIT-IP association in its local cache, it removes the packet's ESP encapsulation and forwards it to the legacy node.

2) Communications from/to HIP-enabled nodes: The end-to-end communication between an HIP-enabled mobile node and a correspondent node is illustrated in Fig. 3. Since HIP-enabled nodes manage their communications autonomously, they do not require any action from the MR other than the forwarding of packets. Before transmitting the first data packet, the HIP-node performs the HIP base exchange with the correspondent node. It then encapsulates the packets using the ESP format and forwards them through the outgoing security association. As for the MR, when it receives an ESP-protected packet, it simply forwards the packet in the proper direction after identifying the packet's destination address.

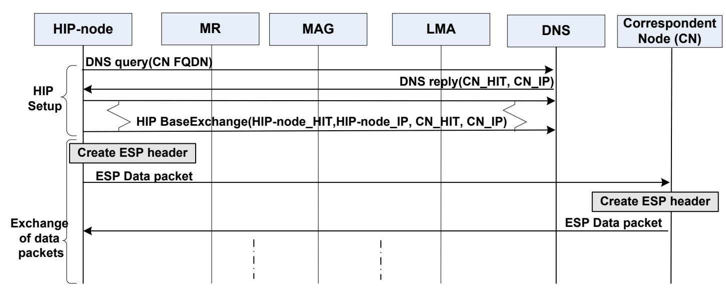
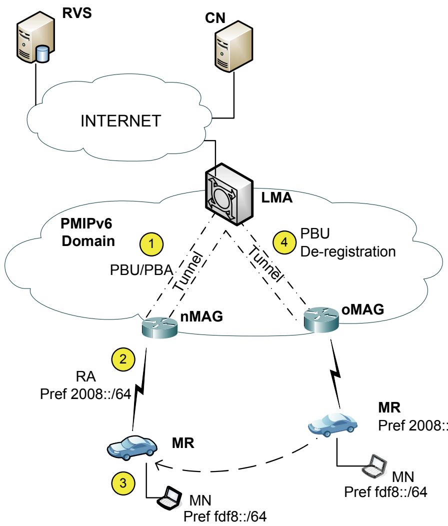


Fig. 3. End-to-end communications between HIP-enabled nodes and correspondent nodes.

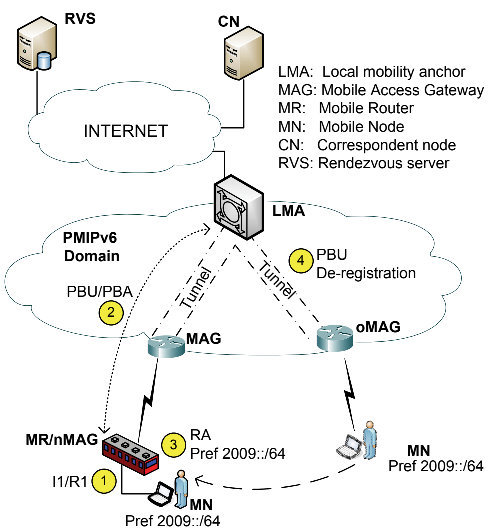
C. Intra-domain handovers

Intra-domain handovers involve the change of connection to another AR/MR located in the same administrative domain (i.e., inside the PMIP domain). The procedures for intra-domain handovers for both types of mobile nodes are depicted in Fig. 4 and described as follows:

1) Intra-domain handovers for legacy nodes: The process of intra-domain handovers for legacy nodes is illustrated in Fig. 4a. An intra-domain handover should be the result of a movement of the MR (the one serving the legacy node) to a new AR in the same domain. When this movement occurs, the PMIP functionalities are activated, so that the new MAG detects the new connection and proceeds with the notification to the LMA (Fig. 4a-1). Once the LMA receives the PBU sent by the MAG, it recognizes the MR has been already registered in the domain, and it maintains the same home network prefix assignment. When the new MAG receives the PBA, it announces the same network prefix to the MR (Fig. 4a-2). Thus, the MR does not perceive any changes at the network layer. As for the legacy node, the local unicast prefix announced by the MR does not changes (Fig. 4a-3), the intra-domain handover is transparent to the node. Given that



(a) Legacy node intra-domain handover



(b) HIP-enabled node intra-domain handover to a MR

Fig. 4. Intra-domain handover in the proposed hybrid scheme.

the MR's IP remains the same, the MR does not need to update any of the active HIP sessions. This involves no notifications to correspondent nodes, nor to the RVS or DNS.

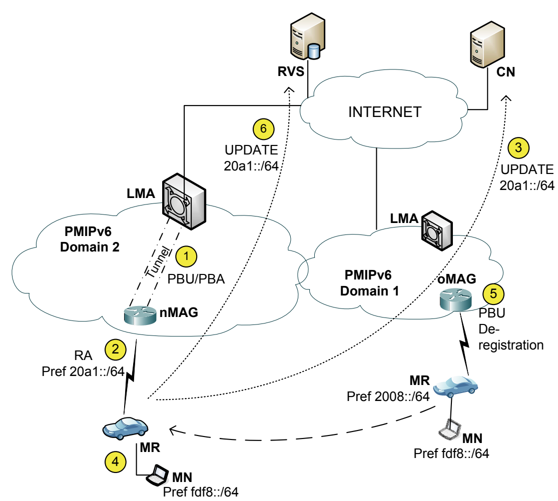
2) Intra-domain handovers for HIP-enabled nodes: There are several cases in which an HIP-enabled node may experience an intra-domain handover. The least complex cases are: a) when the vehicle where the HIP-node is located moves the connection to a new AR; and b) when the HIP-node itself moves its connection to a new AR (e.g., a passenger leaving a train and joining the network at the train station). In these cases, the signalling is the same as for the intra-domain handover of a legacy node (Fig. 4a). A more complex situation appears when the HIP-enabled node switches the connection to another MR (e.g., a passenger switching between two bus routes). This process is illustrated in Fig. 4b. When the HIP-node joins the network of the new MR, the MR first performs the identification process described in Section IV-A. Once the R1 or NOTIFY packets are received as a response from the node (Fig. 4b-1), the new MR exchanges the PMIP signalling with the LMA (Fig. 4b-2). Since the node has been already registered in the domain, the LMA assigns the same network prefix to it, and the MR proceeds to advertise such a prefix to the node (Fig. 4b-3). Once again, none of the active HIP sessions have to be updated, since the HIP-enabled node does not perceive any changes at the network layer.

D. Inter-domain handovers

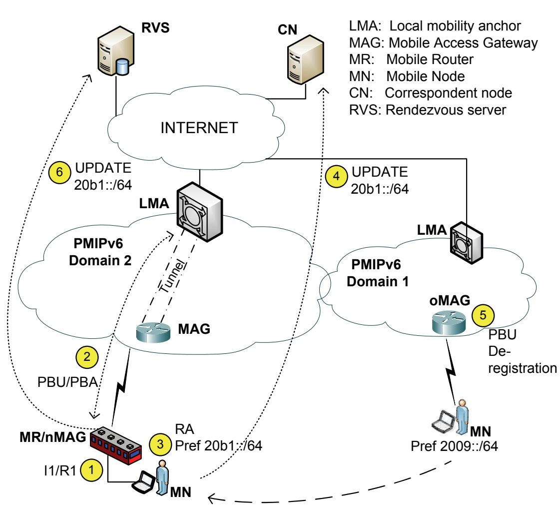
Inter-domain handovers involve the change of connection, whether from the node or the MR, to a point of attachment that belongs to a different PMIP domain. The procedures for inter-domain handovers are depicted in Fig. 5 and described below.

1) Inter-domain handovers for legacy nodes: The process of inter-domain handovers for legacy nodes is illustrated in Fig. 5a. An inter-domain handover is the result of the MR (the one serving the legacy node) roaming to a new PMIP domain. When this occurs, the new MAG and LMA exchange the standard PMIP signalling (Fig. 5a-1).

The LMA registers the MR upon reception of the PBU, and proceeds to assign a home network prefix to it (Fig. 5a-



(a) Legacy node inter-domain handover



(b) HIP-enabled node inter-domain handover to a MR

Fig. 5. Inter-domain handover in the proposed hybrid scheme.

1). Next, the MAG announces the prefix to the MR (Fig. 5a-2). At this point, the MR detects the change of IP network, and starts updating the active HIP communications. Thus, the MR sends UPDATE message to correspondent nodes for which active security associations exist. The UPDATE indicates the newly acquired IP address as the new locator (Fig. 5a-3). In the meantime, the legacy node keeps the same local IP address; hence, it does not detect any changes at the network layer (Fig. 5a-4). The MR may also send an UPDATE message to the RVS, on behalf of each legacy node, in order to enable incoming communications at the new location (Fig. 5a-6).

We employ the Credit-Based Authorization mechanism [32], which allows the correspondent node to securely use the new locator as soon as it receives the UPDATE message. Although the peer's reachability at the address embedded in the locator has not yet been verified, with such an authorization both sides can immediately start using the new address for active communications. Nonetheless, the verification of the new address is later completed with two more UPDATE packets exchanged between the MR and correspondent node, but this verification does not affect the continuity of current communications.

2) Inter-domain handovers for HIP-enabled nodes: The scenarios considered in Section IV-C2 are also applicable for inter-domain handovers of HIP-enabled nodes. However, the difference here is that the new point of attachment belongs to a different administrative domain.

If a node transfers its connection from an AR in one domain, to an AR in another domain, the signalling is exactly the same as the one described for inter-domain handovers of a legacy node; except that the update of active sessions is done by the node itself. On the other hand, if the connection is transferred to an MR in a different domain, the MR then advertises the new IP prefix to the HIP-enabled node, and the HIP-enabled node updates its IP address accordingly (Fig. 5b-3). Subsequently, the node sends UDPATE messages for each active security associations established with correspondent nodes (Fig. 5b-4). The node may also send an UPDATE message to the RVS, in order to enable new incoming communications (Fig. 5b-6).

V. Performance Analysis

We evaluate the proposed scheme from the point of view of the in-vehicle network, the legacy nodes and mobility-enabled nodes, respectively. In the mobile network case, we calculate the crossing probability across subnets and administrative domains, and quantify the generated signalling load as the *location update cost* and the *packet delivery overhead cost*. In the mobile node case, the performance is evaluated based on two different criteria: *handover delay* and *expected number of dropped packets*. The latter refers to the expected number of packets the MN is unable to transmit due to the handover process.

A. Mobile network analysis

The in-vehicle network mobility is described according to a fluid flow model [33]. Using the model, we then calculate the crossing rate at which a vehicle transitions across different ARs (i.e., intra-domain handovers), and across different PMIP domains (i.e., inter-domain handovers). The mobile network performance of our proposed global mobility scheme is compared to the global IP mobility protocol for mobile networks NEMO BS. The notations employed for the analysis are defined in Table I.

TABLE I
Notations employed in Mobile Network analysis

Notation	Meaning
N	Number of subnets that form the PMIP domain
P_s	Perimeter of region covered by AP (square-shaped)
A_s	Area of region covered by AP (square-shaped)
v	Average velocity of mobile network
μ_{intra}	Intra-domain crossing rate for a single mobile network
μ_{inter}	Inter-domain crossing rate for a single mobile network
$f_{intra}(s)$	Subnet residence time distribution with mean $1/\mu_{intra}$
$f_{inter}(s)$	Domain residence time distribution with mean $1/\mu_{inter}$
$f^*_{intra}(s)$	Laplace transform of $f_{intra}(s)$
$f^*_{inter}(s)$	Laplace transform of $f_{inter}(s)$
λ_I	Inter-session arrival rate
$P(N_{intra}=i)$	Probability of i subnet crossings during an inter-session arrival time
$P(N_{inter}=j)$	Probability of j domain crossings during an inter-session arrival time
L	Average length (packets) of incoming session
ω	Cost weight factor of wireless links
S_{BU}	Size of BU/BA (PBU/PBA) message in NEMO BS (PMIP)
S_{HI}	Size of IP tunnel header
S_{HS}	Size of IPSec header in transport format
S_U	Size of UPDATE message in HIP

The fluid flow model considerations specified in [33] are summarized in the following equations:

$$\mu_{intra} = \frac{vP_s}{\pi A_s}, \mu_{inter} = \frac{\mu_{intra}}{\sqrt{N}} \tag{1}$$

$$P(N_{intra}=i) = \begin{cases} 1 - \frac{1}{\rho_{intra}}[1 - f^*_{intra}(\lambda_I)], & \text{if } i = 0 \\ \frac{1}{\rho_{intra}}[1 - f^*_{intra}(\lambda_I)]^2[f^*_{intra}(\lambda_I)]^{i-1}, & \text{if } i > 0 \end{cases} \tag{2}$$

$$P(N_{inter}=j) = \begin{cases} 1 - \frac{1}{\rho_{inter}}[1 - f^*_{inter}(\lambda_I)], & \text{if } j = 0 \\ \frac{1}{\rho_{inter}}[1 - f^*_{inter}(\lambda_I)]^2[f^*_{inter}(\lambda_I)]^{j-1}, & \text{if } j > 0, \end{cases} \tag{3}$$

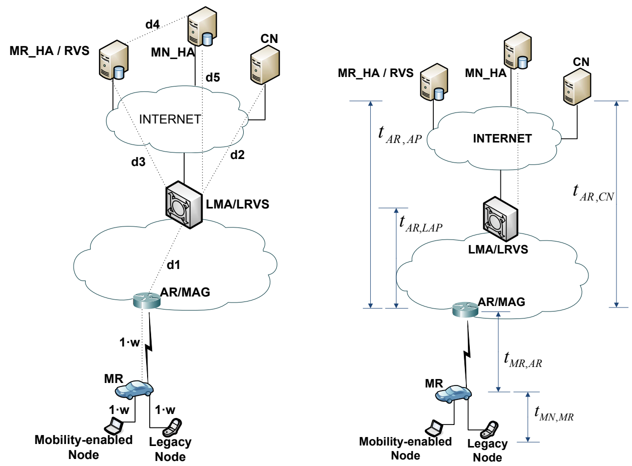
where $\rho_{intra} = \lambda_I/\mu_{intra}$ and $\rho_{inter} = \lambda_I/\mu_{inter}$.

The distances between network elements (i.e., number of intermediate hops) are represented in Fig. 6a by $d_1, d_2, d_3, d_4,$ and d_5. Given m legacy nodes and n mobility-enabled nodes in the mobile network, the total signalling cost is calculated as:

$$C_T(m,n) = C_{BU}(m,n) + C_{PD}(m,n), \tag{4}$$

where $C_{BU}(m,n)$ is the average signalling cost of location updates for handovers during an inter-session arrival time, and $C_{PD}(m,n)$ is the total packet delivery overhead incurred during the same period. Different from [33], in our analysis we need to consider the mix between legacy and mobility-enabled nodes traveling together in the in-vehicle network. If $P(N_{intra} = i) = \alpha(i)$ and $P(N_{inter} = j) = \beta(j)$, then $C_{BU}(m,n)$ is calculated as:

$$C_{BU}(m,n) = \sum_j \sum_i C_{BU}(m,n|i,j) \cdot \alpha(i) \cdot \beta(j). \tag{5}$$



(a) Mobile network analysis (b) Mobile node analysis

Fig. 6. Proposed Global Mobility scheme performance analysis.

In NEMO BS, two types of nodes are defined: Local Fixed Nodes (LFN) and Visitor Mobile Nodes (VMN). LFN rely on the MR for the support of mobility, whereas VMN employ a Home Agent to register the changes of location.

1) Location updates in NEMO BS: According to the signalling defined in the standard NEMO BS [33], the location udpate cost is calculated as:

$$C_{BU}^{\text{NEMO}}(m,n) = \sum_i C_{BU}^{\text{NEMO}}(m,n|i)\cdot\alpha(i), \tag{6}$$

$$C_{BU}^{\text{NEMO}}(m,n|i) = i\cdot B^{\text{MR-HA}}, \tag{7}$$

where $B^{\text{MR-HA}} = S_{BU}\cdot(w+d_1+d_3)$. Note that NEMO BS does not have the concept of domains. Moreover, when the MR performs a handover, only its own care-of-address changes. Therefore, none of the local nodes have to update their location, and there is no cost added from LFNs or VMNs.

2) Location updates in the proposed hybrid scheme: When the in-vehicle network performs an intra-domain handover, there is an exchange of PBU/PBA messages to maintain the IP prefix assignment of the MR. Conversely, when an inter-domain handover occurs, the MR has to additionally notify, on behalf of legacy nodes, the change of address to the correspondent nodes. Similarly, mobility-enabled nodes also inform the correspondent nodes about the new location. Given that i subnets and j domains are crossed, the location update cost for our hybrid global scheme is calculated as follows:

$$C_{BU}^{\text{HYBRID}}(m,n|i,j) = i\cdot B^{\text{MAG-LMA}} + j\cdot(B^{\text{MAG-LMA}} + m\cdot(B^{\text{MR-CN}} + B^{\text{MR-RVS}})) + n\cdot j\cdot(B^{\text{MR-LMA}} + B^{\text{MN-CN}} + B^{\text{MN-RVS}}), \tag{8}$$

where $B^{\text{MAG-LMA}} = S_{BU}\cdot d_1$, $B^{\text{MR-CN}} = S_U\cdot(w+d_1+d_2)$, $B^{\text{MR-RVS}} = S_U\cdot(w+d_1+d_3)$, $B^{\text{MR-LMA}} = S_{BU}\cdot(w+d_1)$, $B^{\text{MN-CN}} = S_U\cdot(2\cdot w+d_1+d_2)$, and $B^{\text{MN-RVS}} = S_U\cdot(2\cdot w+d_1+d_3)$. Note also that we have included the optional updates to the RVS to enable incoming communications to the mobile network after a handover occurs.

3) Packet delivery overhead in NEMO BS: According to [33], the packet delivery cost of NEMO BS is calculated as:

TABLE II
PARAMETERS FOR MOBILE NETWORK ANALYSIS

Parameter	Value	Parameter	Value
m	3	P_s	2800m
n	2	A_s	490Km^2
$1/\lambda_I$	400s–900s	N_{intra}	20
L	22000 packets	N_{inter}	4
d_1	3 hops	Packet size	512 bytes
d_2	8 hops	S_{BU}	124 bytes
d_3	4 hops	S_{HI}	40 bytes
d_4	8 hops	S_{HS}	20 bytes
d_5	4 hops	S_U	80 bytes
w	2	v	30Km/h–65Km/h

$$C_{PD}^{\text{NEMO}}(m,n) = L\cdot\left(\frac{m}{m+n}\cdot C^{\text{LFN-PD}} + \frac{n}{m+n}\cdot C^{\text{VMN-PD}}\right), \tag{9}$$

where $C^{\text{LFN-PD}} = S_{HI}\cdot(d_3+d_1+w)$ and $C^{\text{VMN-PD}} = S_{HI}\cdot d_5 + 2S_{HI}\cdot(d_3+d_1+w) + S_{HI}\cdot w$. Packets destined to a VMN require an extra tunnel from the MR's home agent and the MR.

4) Packet delivery overhead in the proposed hybrid scheme: The packet delivery overhead of our scheme is derived as follows:

$$C_{PD}^{\text{HYBRID}}(m,n) = L\cdot\left(\frac{m}{m+n}\cdot C^{\text{LegNode-PD}} + \frac{n}{m+n}\cdot C^{\text{HipNode-PD}}\right), \tag{10}$$

where $C^{\text{LegNode-PD}} = S_{HS}\cdot d_2 + (S_{HS}+S_{HI})\cdot d_1 + S_{HS}\cdot w$. Packets destined to legacy nodes travel directly from the correspondent node to the PMIP domain, with an extra tunnel added between the LMA and the serving MAG. When the MR receives a packet, it removes the ESP encapsulation and forwards a normal IP packet to the legacy node. The packet delivery overhead for a mobility-enabled node is $C^{\text{HipNode-PD}} = S_{HS}\cdot d_2 + (S_{HS}+2S_{HI})\cdot d_1 + (S_{HS}+S_{HI})\cdot w + S_{HS}\cdot w$. In this case, an extra IP tunnel is employed to forward packets to the mobile MAG. Also, the ESP encapsulation is removed only when the packet arrives to the mobility-enabled node.

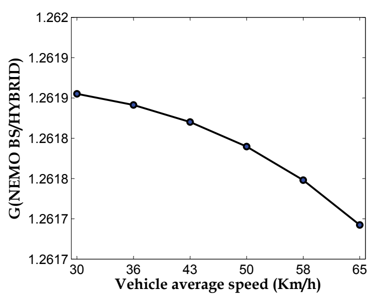
5) Mobile network analysis results: The values employed to quantify the equations for the mobile network analysis are specified in Table II. To calculate $C_T^{\text{NEMO}}(m,n)$, we substitute equations (6) and (9) in (4). In a similar way, $C_T^{\text{HYBRID}}(m,n)$ is obtained by plugging equations (8) and (10) in (4).

To compare both schemes, the gain G is defined as the total relative cost gain:

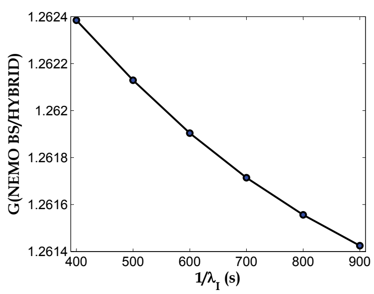
$$G = \frac{C_T^{\text{NEMO}}(m,n)}{C_T^{\text{HYBRID}}(m,n)}. \tag{11}$$

Fig. 7a and Fig. 7b show the impact of different average speeds and different session lengths, respectively. The average speeds are set according to speeds registered for urban scenarios [34]. Due to limitations in the fluid flow model, it is not possible to describe "stop-and-go" patterns caused by traffic lights in urban roads. However, the analysis helps understand the advantages of using our hybrid scheme instead of the standard NEMO BS.

As observed in both figures, although the gain decreases for increasing speeds or inter-session arrival time, the decrease is small, which helps our scheme outperform NEMO BS almost with a constant gain. The decreasing gain observed in Fig. 7a is caused by the increased vehicular mobility, which triggers more inter-domain handovers. Our hybrid scheme, in comparison to NEMO BS, has a costly location update process because it involves updates to each correspondent node. A similar effect is observed in Fig. 7b by considering longer session lengths. However, the high location update cost of our hybrid scheme is compensated by the low overhead packet delivery cost. In our scheme, packets go directly between correspondent node and LMA, as opposed to the packet delivery in NEMO BS. Therefore, on average, packets traverse less hops in the hybrid scheme than in NEMO BS.



(a) G for different urban average speeds



(b) G for different inter-session arrival times

Fig. 7. Cost gain analysis of NEMO BS vs. Proposed hybrid scheme

B. Mobile nodes analysis

In this analysis we employ the *handover delay* as the metric for comparison, which is derived separately as for legacy and mobility-enabled nodes. The notations employed for the analysis are illustrated in Fig. 6b and defined in Table III. Moreover, in this analysis we compare our hybrid scheme with four additional protocols that also provide global mobility support: MIPv6 [6], NEMO BS [7], HIP [12], and Novaczki's micro-mobility solution for HIP [19].

The bases of our mobile node analysis are described as follows:

- All wireless links are symmetric.
- For simplicity, we consider the mobile node is communicating with one correspondent node at the moment of handover.
- The layer 2 handover delay is the same value for all the compared protocols.
- The movement detection at the network side is triggered by the reception of a Router Solicitation message. Nodes detect a change of network when they receive Router Advertisement messages as a response to the solicitation.
- Delay related to the Duplicate Address Detection (DAD) mechanism is not considered in any of the compared schemes.
- In the HIP-related protocols, including our hybrid scheme, we do not perform rekeying of the security associations after a change of IP address.
- It is assumed the mobility-enabled nodes are able to obtain IP addresses directly from the infrastructure. This means that, if the node is connected through an MR, the MR forwards the RS/RA messages between the MN and the AR to allow for IP address configuration. This assumption holds for MIPv6, HIP, and Novackzi's scheme, but it does not hold for our proposed scheme, since the mobile MAG already allows for this configuration.

TABLE III
NOTATIONS AND VALUES EMPLOYED IN MOBILE NODE ANALYSIS

Notation	Meaning	Value
T_{L2HD}	Layer 2 handover delay. The time between the node's disconnection from the AR and the layer 2 connection to a new point of attachment. It includes AAA authentication delay	50ms
$t_{\text{MR,AR}}$	Time required to transmit a packet from the MR to the road-side AR	10ms
$t_{\text{MN,MR}}$	Time required to transmit a packet from the MN to the MR	5ms
$t_{\text{AR,LAP}}$	Time required to transmit a packet from the road-side AR to the Local Anchor Point (for instance an LMA or LRVS) located in the same domain	2ms
$t_{\text{AR,CN}}$	Time required to transmit a packet from the road-side AR to a node in the Internet	40ms
$t_{\text{AR,AP}}$	Time required to transmit a packet from the road-side AR to an Anchor Point (for instance a HA)	40ms
a	Processing time due to the updating of a local binding cache	0.5ms

In general, the handover delay T_{HD} comprises the layer 2 handover delay, the movement detection delay, the IP addressing configuration, and the location update delay. The derivation of this metric is explained below.

1) Handover delay in MIPv6/NEMO BS: MIPv6 and NEMO BS work in a similar manner. The former supports single nodes, whereas the latter supports mobile networks. Consequently, NEMO BS is employed for legacy nodes of the in-vehicle network, whereas MIPv6 is employed by mobility-enabled nodes. NEMO BS requires an update to be sent to the home agent every time the MR experiences a handover. We consider the HA to be arbitrarily located in the Internet, hence T_{HD}^{NEMO} is expressed as follows:

$$T_{HD}^{\text{NEMO}} = T_{\text{L2HD}} + 2t_{\text{MR,AR}} + 2(t_{\text{MR,AR}} + t_{\text{AR,HA}}) + a_{\text{HA}}. \quad (12)$$

Similarly, MIPv6 requires the node to update the home agent whenever it acquires a new care-of-address. Moreover, MIPv6 defines an optimized version in which the node is able to notify the change directly to the correspondent node. Therefore, we calculate T_{HD}^{MIPv6} as follows:

$$T_{HD}^{\text{MIPv6}} = T_{\text{L2HD}} + 2(t_{\text{MN,MR}} + t_{\text{MR,AR}}) + 2(t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{CN}}. \quad (13)$$

Since NEMO BS and MIPv6 are not limited to domains, there is no separated calculation for intra and inter-domain handovers.

2) Handover delay in standard HIP: When an HIP node travels in the in-vehicle network, it expects the MR to announce the change of IP addresses every time the vehicle roams to a different IP network. Thus, after the node reconfigures its address, it has to send an UPDATE to the correspondent node. As a result, $T_{\text{HIP-a}}$ is calculated as follows:

$$T_{HD}^{\text{HIP-a}} = T_{\text{L2HD}} + 2t_{\text{MR,AR}} + t_{\text{MN,MR}} + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{CN}}. \quad (14)$$

On the other hand, when the HIP node transfers a connection to an MR, it updates the correspondent node right after acquiring the new IP address. Thus, $T_{HDI}^{\text{HIP-b}}$ is calculated as follows:

$$T_{HD}^{\text{HIP-b}} = T_{\text{L2HD}} + 2(t_{\text{MN,MR}} + t_{\text{MR,AR}}) + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{CN}}. \quad (15)$$

Since the standard HIP is not limited to domains, there is no separated calculation for intra and inter-domain handovers.

3) Handover delay in Novaczki's scheme: In this scheme, when the node performs an intra-domain handover, it updates the new location only with the LRVS [19]. The improvement to the normal HIP is given by the fact that no updates have to be sent to correspondent nodes. As a result, the calculations for handover delay differ from (14) and (15) only in the destination for the UPDATE message, as indicated below:

$$\begin{aligned} T_{HD-\text{intra}}^{\text{NOV-a}} &= T_{\text{L2HD}} + 2t_{\text{MR,AR}} + t_{\text{MN,MR}} \\ &\quad + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,LRVS}}) + a_{\text{LRVS}}, \quad (16) \\ T_{HD-\text{intra}}^{\text{NOV-b}} &= T_{\text{L2HD}} + 2(t_{\text{MN,MR}} + t_{\text{MR,AR}}) \\ &\quad + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,LRVS}}) + a_{\text{LRVS}}. \quad (17) \end{aligned}$$

Novaczki's scheme is more complex for inter-domain handovers. Given that the LRVS operates as the anchor point and address translator for mobile nodes, every time a node moves to a different domain, it has to register with a new LRVS. A registration with the LRVS is an HIP base exchange (i.e., a four-way handshake). Additionally, once the MN finishes the registration at the new domain, it updates the previous LRVS with the information of its new location. In this way, the old LRVS can redirect the incoming packets to the new domain. The old LRVS is used as a temporary relay only when the new LRVS completes the updates to the correspondent nodes.

When the mobile node sends the UPDATE message to the old LRVS, we consider the old LRVS to be arbitrarily located in the Internet. As a result, the inter-domain handover for Novaczki's scheme is calculated as follows:

$$\begin{aligned} T_{HD-\text{inter}}^{\text{NOV-a}} &= T_{\text{L2HD}} + 2t_{\text{MR,AR}} + t_{\text{MN,MR}} + 4(t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,nLRVS}}) \\ &\quad + a_{\text{nLRVS}} + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{oLRVS}}, \quad (18) \\ T_{HD-\text{inter}}^{\text{NOV-b}} &= T_{\text{L2HD}} + 2(t_{\text{MN,MR}} + t_{\text{MR,AR}}) + 4(t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,nLRVS}}) \\ &\quad + a_{\text{nLRVS}} + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{oLRVS}}. \quad (19) \end{aligned}$$

4) Handover delay in the proposed hybrid global scheme: Intra-domain handovers of legacy nodes are managed by the MR. When the in-vehicle network handovers, a regular PMIP location update is performed as soon as the new MAG receives the router solicitation. As a result, $T_{HD-\text{intra}}^{\text{HYBRID-a}}$ follows the signalling presented in Fig. 4a, given by:

$$T_{HD-\text{intra}}^{\text{HYBRID-LegNode}} = T_{\text{L2HD}} + t_{\text{MR,AR}} + 2t_{\text{AR,LMA}} + a_{\text{LMA}} \quad (20)$$

Conversely, the intra-domain handover of a mobility-enabled node involves additional identification signalling, given that the connection is transferred to an MR. The intra-domain handover in such a case follows the signalling presented in Fig. 4b, and the delay is calculated as follows:

$$\begin{aligned} T_{HD-\text{intra}}^{\text{HYBRID-HipNode}} &= T_{\text{L2HD}} + 2t_{\text{MN,MR}} + 2(t_{\text{MR,AR}} + t_{\text{AR,LMA}}) \\ &\quad + a_{\text{LMA}} + t_{\text{MN,MR}}. \quad (21) \end{aligned}$$

Likewise, two different calculations are provided for inter-domain handover delay. When a legacy node moves to a different administrative domain, that means the serving MR has moved. The only difference with the intra-domain handover is that the MR has to notify the correspondent node about the change of location. The handover follows the signalling presented in Fig. 5a, and its delay is expressed by:

$$\begin{aligned} T_{HD-\text{inter}}^{\text{HYBRID-LegNode}} &= T_{\text{L2HD}} + t_{\text{MR,AR}} + 2t_{\text{AR,LMA}} + a_{\text{LMA}} \\ &\quad + (t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{CN}}. \quad (22) \end{aligned}$$

When a mobility-enabled node transfers its connection to an MR in a different domain, the calculations are similar to the ones for intra-domain handover, except that the UPDATE notification is delivered to the correspondent node. In such a case, the handover signalling is depicted in Fig. 5b, and the delay is calculated as follows:

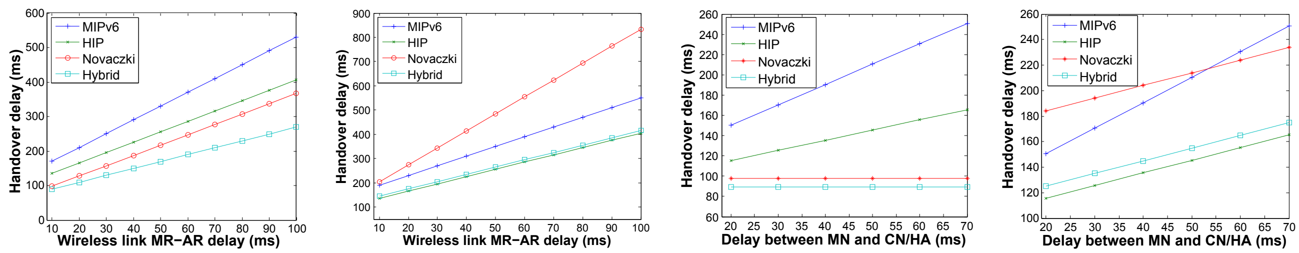
$$\begin{aligned} T_{HD-\text{inter}}^{\text{HYBRID-HipNode}} &= T_{\text{L2HD}} + 2t_{\text{MN,MR}} + 2(t_{\text{MR,AR}} + t_{\text{AR,LMA}}) + a_{\text{LMA}} \\ &\quad + t_{\text{MN,MR}} + (t_{\text{MN,MR}} + t_{\text{MR,AR}} + t_{\text{AR,CN}}) + a_{\text{CN}}. \quad (23) \end{aligned}$$

5) Mobile node analysis results: The parameters employed for mobile node analysis are presented in Table III.

We analyze the results for the case of a mobility-enabled node transferring a connection to an MR, since that is the worst case signalling load scenario in our scheme. Fig. 8a and Fig. 8b show the impact of wireless access delays during inter- and intra-domain handovers. The handover delay is indeed sensitive to a high-delay access network; however, in the intra-handover case our proposed scheme is observed to outperform the other schemes. The reduced delay is due to assigning the same network prefix when the node (or the MR) is moving inside the PMIP domain. The high delay experienced by the other reported schemes is the result of changing the network prefix (or care-of-address) in every handover.

As for the inter-domain handover, it is observed that only Novaczki's and our hybrid schemes present a different behaviour compared with the results in Fig. 8a. The temporary use of old LRVS for redirection of packets in Novaczki's scheme increases the handover delay to the point that makes it impractical during inter-domain handovers. In the case of our hybrid scheme, it presents a performance comparable to that of HIP. The increased delay observed by mobility-enabled nodes is due to the MR's exchange of PMIP signalling before being able to advertise the new prefix to the node.

Fig. 8c and Fig. 8d show the impact of different end-to-end delays between the mobile node and the correspondent



(a) Access delay vs. intra-domain (b) Access delay vs. inter-domain (c) End-to-end delay vs. intra-domain (d) End-to-end delay vs. inter-domain

Fig. 8. Impact of access and end-to-end delays on handover delay.

node (or the home agent in the case of NEMO BS). It is observed that, when the correspondent node or home agent are located far away from the vehicular network, the delay for end-to-end communications increases. In addition, the handover performance degrades if the location update takes longer. Such a behavior severly affects NEMO BS and MIPv6 schemes. Furthermore, during inter-domain handovers we observe an increased delay of our hybrid scheme compared with HIP (Fig. 8d). Despite of the increased delay the hybrid scheme has the advantage of supporting legacy mobile nodes, whereas the standard HIP requires all the nodes to be HIP-enabled.

Our analysis highlights the following advantages: 1) the hybrid scheme achieves a reduced handover delay, which is the result of using PMIP for the localized mobility; 2) by clustering the signalling overhead from mobile nodes, even for those that are mobility-enabled, the hybrid scheme reduces the load over the MR→AR link; and 3) our interworking scheme allows for seamless communications of legacy and mobility-enabled nodes in the heterogeneous network.

VI. Simulation Results

In order to evaluate the performance of the proposed hybrid global mobility scheme, we have performed simulations in a realistic urban scenario. A typical commuter is simulated traveling to his/her workplace. The commuter has a mobility-enabled device, which is employed for Internet access during the journey. Initially, the commuter walks toward the nearest bus station, and from there, he/she takes a bus ride toward the destination bus stop. In the last segment, the commuter walks from the bus stop to the workplace. The total commuting time has been set to 26 minutes, according to the average travel times that Canadian commuters take for going to work on a typical day [35].

To recreate the city scenario, the commuter and the bus move according to the Manhattan Grid mobility model, on a grid of 4000 Km^2 and with 100m×100m-blocks that emulate the city blocks. The mobility traces are generated with the BonnMotion tool [36]. We have employed the ChainScenario, provided by BonnMotion, in order to concatenate the different mobility patterns (i.e., walking – bus riding – walking) in a single 26-minute trip. During both pedestrian and vehicular movements, the node stops at random time instants to simulate the red traffic lights it may encounter during the journey. Details of the parameters employed in pedestrian and vehicular traces are presented in Table IV.

TABLE IV
Simulation Parameters

Scenario	Parameter	Value
Pedestrian Mobility	Minimum speed	0.7m/s
	Mean speed	1 m/s
	Speed standard deviation	0.1 m/s
	Max. pause time	10s
	Pause probability	0.15
	Speed change probability	0.1
	Turn probability	0.25
Vehicular Mobility	Minimum speed	7m/s
	Mean speed	13 m/s
	Speed standard deviation	1 m/s
	Max. pause time	20s
	Pause probability	0.15
	Speed change probability	0.1
	Turn probability	0.3
Intra-domain Set #1	p^{w-c}	0.3
	p^{w-w}	0.3
	p^{c-w}	0.3
	p^{c-c}	0.9
Intra-domain Set #2	p^{w-c}	0.7
	p^{w-w}	0.7
	p^{c-w}	0.7
	p^{c-c}	0.9
Handover delay (HD)	HD^{c-w}_{intra}, HD^{w-w}_{intra}	98ms
	HD^{c-c}_{intra}, HD^{w-c}_{intra}	290ms
	HD^{c-w}_{inter}, HD^{w-w}_{inter}	150ms
	HD^{c-c}_{inter}, HD^{w-c}_{inter}	450ms

Then, we have calculated the residence times in every 50m×50m-cell along the path employed by the node during the simulation. The residence times are illustrated in Fig. 9. The figure indicates the two areas where the commuter is walking, and the rest of the movements happen during the bus ride. Note that, although the randomness in direction's selection of the Manhattan Grid model causes a few loops in the path, in general this does not affect the results obtained for dwell times.

Based on this information, we have proceeded to simulate our hybrid scheme in Matlab. A 3G network is assumed to cover all the simulated area, whereas WiFi hotspots provide limited coverage. The ratio of coverage of WiFi to 3G in the simulated area is indicated by Δ, which varies from 0 (only 3G coverage available) to 1 (double coverage always available). When roaming through the cells along the path, the node decides with a probability $1-\Delta$ to switch between networks. If a switching occurs, the type of intra-domain handover is determined by the transition probabilities $p^{w-w}, p^{w-c}, p^{c-w}$, and p^{c-c}, where p^{a-b} indicates a handover from technology a to technology b, w indicates WiFi, and c indicates 3G cellular network. An inter-domain handover in each case occurs with probability $1-p^{a-b}$. Once the type of handover has been determined, in the simulation we calculate the throughput per cell considering the residence time (i.e., time available for receiving data) and the handover delay (i.e., time unavailable for receiving data). Note we have not considered unavailability due to link layer collisions or weak channel conditions.

Two sets of probabilities have been used during simulations (see Table IV). The Set #1 represents a loosely coupled architecture, where inter-domains handovers happen frequently, except for cellular-to-cellular transitions. The 90% of the time, a cellular-to-cellular transition result in intra-domain handover, because a single cellular operator typically provides a large coverage. The Set #2 represents an architecture in which more access networks belong to the same provider, resulting in intra-domain handovers happening more frequently than in Set #1. The delays caused by intra- and inter-domain handovers, to WiFi and 3G technologies, have been calculated from the analysis presented in Section V-B4. In addition, the node is actively receiving data from the Internet during the whole journey, at a rate γ=50 packets/s.

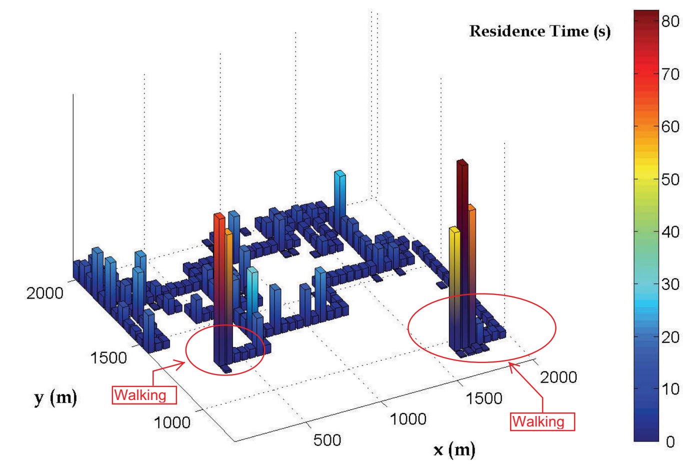


Fig. 9. Residence times of a commuter during a journey to work

In order to verify the behavior of our scheme for different ratios of coverage, we have run both sets 30 times for each Δ value. The results are plotted in Fig. 10 with the 95% confidence interval. It is observed that Set #2 suffers from less packet losses than Set #1. This is expected since the inter-domain handover delay is higher compared with the intra-domain handover. Therefore, the more loosely-coupled the architecture is (Set #1), the more inter-domain handovers the commuter's mobile device has to experienced. Nevertheless, for both scenarios the performance of our hybrid scheme achieves throughputs ranging from 90% to 98% of the total packets sent.

In Section V we have shown the analytical performance in terms of handover delay, and the preliminary results presented in [11] have shown the performance in terms of packet drops for all the compared schemes. Both analyses are consistent to results presented in this section: a reduced handover delay leads to less packet drops, hence an increased throughput. Since our scheme outperforms the other schemes presented in Section V, it is expected a similar result in terms of throughput. The results are promising considering that we have employed the highest handover delays (i.e., the worst-case scenario) found for mobility-enabled nodes in our hybrid scheme analysis.

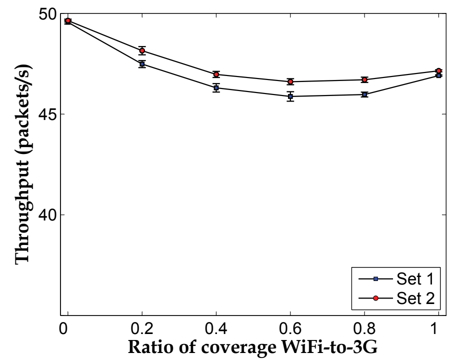


Fig. 10. Hybrid Scheme throughput in a city scenario

VII. Conclusions

In this paper, we have proposed a novel hybrid interworking scheme, which enables access to Mobile Internet and general IP services through a global mobility management mechanism. The scheme is designed for urban vehicular scenarios with a heterogeneous radio access network. In our proposed scheme, we have considered in-vehicle networks, passengers with mobile devices traveling within a vehicle, and also users that commute between vehicles and terminal stations. The scheme has been defined to allow for intra and inter-domain handovers of nodes, as well as intra and inter-technology handovers over loose coupling architectures. That means that nodes employing the proposed scheme could be able to maintain seamless communications regardless of roaming agreements between network operators.

Our performance analysis has shown that the proposed scheme outperforms other protocols, such as the optimized version of MIPv6, NEMO BS, the standard HIP, and Novaczki's micro-mobility scheme for HIP. Furthermore, we have carried out simulations in a realistic urban vehicular scenario, in which pedestrian and vehicular mobility traces are combined to recreate a commuter's journey to his/her workplace. The results have demonstrated that the proposed hybrid scheme allows for a seamless transferring of IP sessions, despite of different patterns of mobility and the heterogeneity of the supporting radio access technologies. In our future work, we will exploit the network diversity in a heterogeneous vehicular network for designing a dissemination mechanism suitable for traffic efficiency applications.

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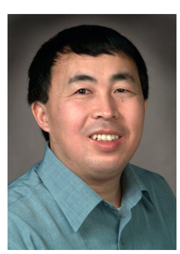

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