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802.21-Assisted Distributed Mobility Management Solution in Vehicular Networks

MOHAMMED BALFAQIH[1], MAHAMOD ISMAIL[1], (Senior Member, IEEE), ROSDIADEE NORDIN[1], (Senior Member, IEEE), AND ZAIN A. BALFAQIH[2]
[1]Department of Electrical, Electronic and System Engineering, Faculty of Engineering, UKM, Bangi 43600, Malaysia
[2]Department of Information Systems, Faculty of Engineering, Effat University, Jeddah 22332, Saudi Arabia

Corresponding author: Mohammed Balfaqih (m_balfageh@hotmail.com)

ABSTRACT Recently, distributed mobility management (DMM) solutions have been proposed to address the drawbacks of centralized mobility management (CMM) solutions. The Internet engineering task force (IETF) has stated that extending and reusing CMM protocols are one of the considerations for DMM solutions design, where it is less faulty and more effective. Therefore, IETF has proposed a network-based DMM solution based on the well-known network-based CMM protocol: Proxy Mobile IPv6 (PMIPv6). However, network-based DMM has marginal improvements over the handover latency and packet loss of PMIPv6. Thus, this paper enhances the handover procedure of network-based DMM using the HO-initiate process and the IEEE 802.21 media-independent handover services. We tackle the issue of binding registration latency by performing the HO-initiate process proactively. Moreover, we mitigate the latency of discovering next access network and candidate mobile anchor access routers (MAARs) with the support of the lower three layers' information of the mobile user and surrounded MAARs. A neighbors network information container is introduced to store and retrieve the link and network layers' information of neighboring networks. A candidate access networks cache is defined at the serving-MAAR to decrease the prediction time. Furthermore, we propose a candidate access network selector to facilitate smart handover decision making by using the information of required and available resources in the candidate networks. We derive an analytical expression to evaluate the proposed solution compared with DMM and fast handover for DMM mechanisms. Simulation is also performed to verify the analytical results, where we consider realistic urban and highway environments. Numerical and simulation results prove that the proposed solution decreases 74.61% of the overall handover latency in DMM.

INDEX TERMS Distributed mobility management, PMIPv6, fast handover, IP mobility in VANET, V2I.

I. INTRODUCTION

Internet access in automotive scenarios has rapidly become an important aspect of Intelligent Transportation Systems (ITS), especially with the evolution of infotainment applications. Vehicle-to-Infrastructure (V2I) communication provides a communication gateway for vehicles to exchange data via a wireless connection with roadside infrastructure. Various IP-based wireless network technologies could offer Internet service in vehicular networks (e.g., 802.11p, WiMAX, Wi-Fi, and LTE-Advanced) for which the vehicle most likely will roam between them. To eliminate connection interruption and Quality of Service (QoS) degradation during the handovers, several IP-based mobility management solutions have been proposed and discussed by the Internet Engineering Task Force (IETF). One of these solutions is Proxy Mobile IPv6 (PMIPv6), which has been widely accepted in the industry and academia [1]. However, PMIPv6, like other Centralized Mobility Management (CMM) solutions, manages the mobility and routing functionalities by a logical single mobility anchor, i.e., Local Mobility Anchor (LMA). This anchor is responsible for sending all data traffic and management messages toward their final destination. Consequently, overall reliability (i.e., single-node failure) and system scalability will be degraded.

Few proposals have been reported to overcome the scalability and reliability issues in PMIPv6 [2]–[5]. One of the promising proposals is presented in [6] by the IETF, where a network-based Distributed Mobility Management (DMM) solution has been proposed. DMM basically distributes the functionalities of LMA between the routers, which are named Mobile Anchor Access Routers (MAARs). It employs the concept of a flatter system where the anchor entity is placed dynamically closer to the Mobile User (MU). The LMA functionalities could be distributed partially or fully. The data plane of LMA is distributed and handled by the MAARs in the partially distributed approach, while the control plane is handled by a Centralized Mobility Database (CMD). Every MAAR has its own global IPv6 prefixes, named Local Network Prefixes (LNPs), where the MAAR allocates one LNP to an MU upon attachment. A Local BCE (LBCE) at the MAAR is used to store the information of attached MUs. The CMD exchanges Proxy Binding Update (PBU) and Proxy Binding Acknowledgment (PBA) messages with MAARs to maintain mobility session management. Alternately, control and data planes are placed at the MAAR in a fully distributed approach. However, network-based DMM still suffers from high handover latency and packet loss similar to PMIPv6. This is because network-based DMM initiates the handover process reactively once the MU joins the new Mobile Anchor and Access Router (nMAAR).

This paper proposes a proactive handover management solution for DMM using IEEE 802.21 Media Independent Handover (MIH) services. This paper is built on top of our previous work [7], which presents the first core idea of the HO-Initiate process. In this paper, we continue further and address the issues of discovering the next access network and candidate MAARs with the support of the lower three layers' information of the MU and surrounded MAARs. We present a Neighbors Network Information (NNI) Container to save the candidate access networks information, including the static and dynamic Layer 2 (*L2*) and Layer 3 (*L3*) information. Moreover, Serving-MAAR (S-MAAR) employs a cache to store the information received from NNI to decrease the prediction time in DMM. Last but not least, we propose a Candidate Access Network Selector (ANS) to assist in smart handover decision-making using the lower-layer information of the surrounding networks. Analytical expressions are derived to evaluate the proposed solution compared to network-based DMM. Simulation is also performed to verify the analytical results where we consider realistic urban and highway environments. Numerical and simulation results show that our proposed solution reduces the overall handover latency in DMM significantly. Note that, throughout the paper, the terms MU and vehicle are used interchangeably because a vehicle may carry multiple MUs. At the end of the paper, Table 1 lists the definition of acronyms used throughout the paper.

TABLE 1. List of Acronyms

Acronym	Quantity
A-MAAR	Anchor-Mobile Anchor Access Router
AN	Access Network
ANS	Access Network Selector
BCE	Binding Cache Entry
CAN	Candidate Access Networks
CMD	Centralized Mobility Database
CMM	Centralized Mobility Management
CN	Corresponding Node
CSM	City Section Model
DMIPA	Dynamic Mobile IP Anchoring
DMM	Distributed Mobility Management
FDMM	Fast Handover for DMM
HAck	Handover Acknowledgment
HI	Handover Initiate
HL	Handover Latency
HO-Initiate	Handover-Initiate
IDM	Intelligent Driving Model
IE	Information Element
IETF	Internet Engineering Task Force
IS	Information Server
ITS	Intelligent Transportation Management
L2	Layer 2
L3	Layer 3
LBCE	Local Binding Cache Entry
LMA	Local Mobility Anchor
LNP	Local Network Prefix
MAAR	Mobile Anchor Access Router
MAC	Media Access Control
MICS	Media Independent Command Service
MIES	Media Independent Event Service
MIH	Media Independent Handover
MIHF	MIH Function
MIIS	Media Independent Information Service
MIPv6	Mobile IPv6
MU	Mobile User
NIST	National Institute of Standards and Technology
nLNP	new LNP
nMAAR	new MAAR
NNI	Neighbor Networks Information
PBA	Proxy Binding Acknowledgment
PBU	Proxy Binding Update
PFMIPv6	Fast Handover for proxy MIPv6
PL	Packet Loss
pLNP	previous LNP
PMIPv6	Proxy Mobile IPv6
PoA	Point of Attachment
PF	Handover Failure Probability
QoS	Quality of Service
RA	Router Advertisement
RS	Router Solicitation
RSSI	Received Signal Strength Indicator
S-MAAR	Serving-MAAR
SR	Session Recovery Time
TLV	Type-Length-Value
V2I	Vehicular-to-Infrastructure
WME	WAVE Management Entity

The remainder of the paper is organized as follows. Section II critically discusses the related works on handover management schemes for DMM in vehicular networks. Section III briefly explains the network-based DMM operation, including the initial registration and the handover management procedures. In Section IV, the IEEE 802.21 MIH protocol and its services are presented. The 802.21-Assisted DMM solution is detailed in Section V, including services, messages and the handover procedures. Section VI presents the evaluation of the proposed solution, in which the performance models and the simulation settings are presented. In Section VII, the numerical and simulation results are discussed, and important observations are obtained. Finally, Section VIII provides conclusions and direction for future works.

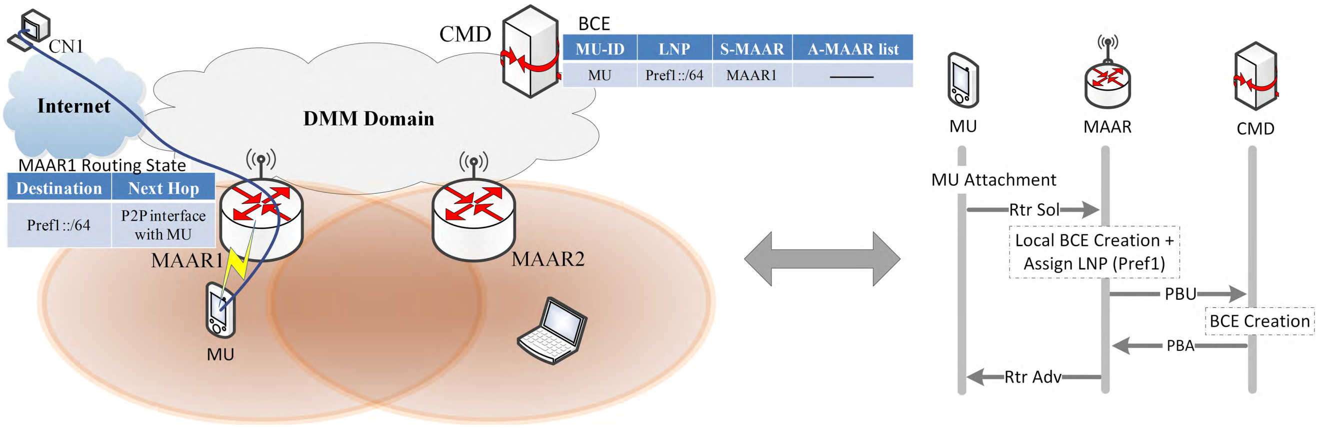

FIGURE 1. **DMM Initial Registration Operation [6].**

II. RELATED WORKS

This section critically explores the related works on handover management schemes for DMM in vehicular networks. The effects of speed and number of vehicles on host-based DMM compared to Mobile IPv6 (MIPv6) have been investigated in [8]. Alternately, the authors in [9] have analyzed the vehicle speed effect on network-based DMM compared to PMIPv6. The results show that DMM schemes outperform CMM schemes in terms of data loss and binding update latency.

The authors in [10] have proposed an extension to the host-based DMM scheme: Dynamic Mobile IP Anchoring (DMIPA). The purpose of the extension is to enable DMIPA to work in vehicular networks with IEEE 802.11p technology. First, a Router Advertisement (RA) message is sent periodically to the MU to initiate the handover when needed. Second, WAVE Management Entity (WME) messages are used to discover the available networks and services. Third, a very simple connection manager is integrated to connect to the network with the highest Received Signal Strength Indication (RSSI). Although the results have shown that the proposed extension of DMIPA is suitable for vehicular networks, it carries various limitations, such as the additional signaling overhead and the complexity of the MU stack. Moreover, it is insufficient in fast and abrupt MU movement scenarios, which may pose additional complexities for the MU.

In our previous work [7], Fast handover for DMM (FDMM) in vehicular networks was proposed based on Fast handover for PMIPv6 (PFMIPv6). Reactive and predictive modes have been defined as operation modes of FDMM. In the former, the handover process starts upon the MU attachment with the nMAAR, while in the latter, the handover process starts proactively before the MU detachment with S-MAAR. The main idea of FDMM is to decrease the latency of movement detection and binding registration processes to reduce the handover latency. Moreover, a buffering mechanism has been utilized to mitigate the packet loss throughout the handover. However, FDMM concentrates on the IP mobility management operation only, and the issues of how to discover the candidate MAARs are not considered. Probing all the channels of the surrounding networks is insufficient and takes a long time. As a result, the connectivity of the MU will probably be dropped before sending and receiving all FDMM messages. Thereby, FDMM will operate in a reactive mode where the handover latency is high. Thus, the latency of discovering the next MAAR must be reduced.

III. DMM OPERATION

Our proposed solution, 802.21-Assisted DMM, relies on an IETF network-based DMM proposal that is still in the early stage of standardization [6]. Fig. 1 shows the architecture of the network-based DMM and the initial registration operation. Subsequent sub-sections describe the initial registration and handover processes in the network-based DMM operation.

A. INITIAL REGISTRATION

Upon link layer establishment, the MU sends a Router Solicitation (RS) message to the MAAR in charge (MAAR1 in Fig. 1). The MAAR, in turn, allocates a unique LNP (pref1::MU1/64) for the MU and creates LBCE to store the MU's information, including the MU-ID and LNP. Then, the CMD creates BCE for the MU upon exchanging PBU/PBA messages with the MAAR and starts a new mobility session. Finally, the MAAR informs the MU of the assigned LNP through an RA message to configure an IPv6 address. The MAAR in which the MU is attached is called S-MAAR.

B. HANDOVER MANAGEMENT

The handover management operation of DMM is shown in Fig. 2. The handover procedures are triggered upon the attachment of the MU to a nMAAR, i.e., MAAR2 in Fig. 2. The nMAAR, upon receiving the RS message from the MU, reserves a new LNP from its unique set of LNPs and stores it in its temporal LBCE. Thereafter, the nMAAR will send a PBU message to the CMD to register the MU. The CMD, in turn, updates the S-MAAR's address and the

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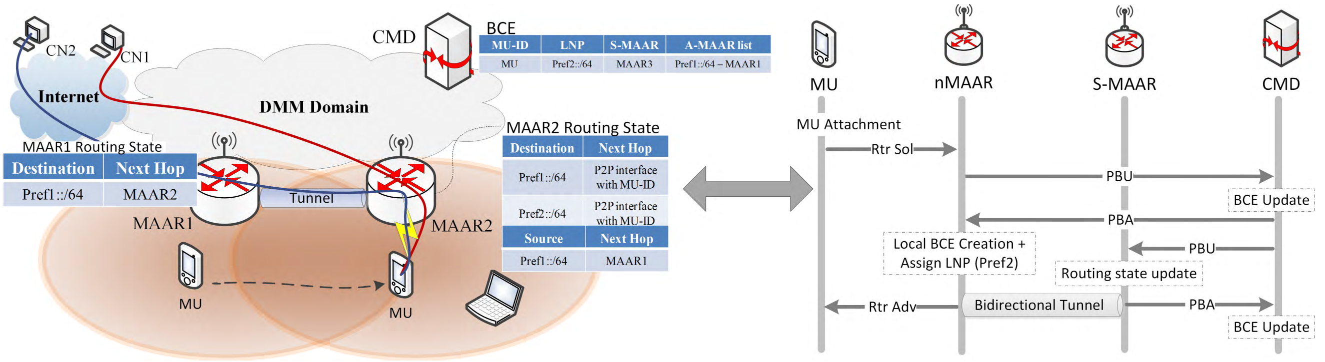

FIGURE 2. DMM Handover Management Operation [6].

Anchor-MAAR (A-MAAR) list fields in the BCE with MAAR2's address and MAAR1's address, respectively. Then, the CMD sends an extended PBA to the nMAAR containing the A-MAAR's address and its corresponding previous LNP (pLNP). Upon receiving the PBA, the nMAAR, through an RA message, advertises the new LNP (nLNP) allocated to the MU, which will configure its new IP address (Pref2::MU1/64). In addition, the nMAAR will establish a tunnel with all A-MAARs to handle the traffic of pLNPs (Pref1::/64 in our example). Simultaneously, the CMD will notify the active A-MAARs (only MAAR1 in our example) about the new MU location by exchanging PBU and PBA messages. The A-MAARs in turn update their LBCE and establish a tunnel towards nMAAR. Hereafter, the nMAAR will send the new flows that use nLNP to the MU directly, while the previous active IP flows that use pLNP will be forwarded to MAAR1. Network-based DMM is considered to be a dynamic mobility solution where the aforementioned handover procedures occur if the session continuity of the old IP flows is necessary. In such a scenario, the MU may have a number of IP flows anchored at different MAARs.

IV. IEEE 802.21 MIH

The IEEE 802.21 MIH standard specifies mechanisms to exchange information between various link types and handover decision-makers to maintain service continuity during the handover among heterogamous wireless technologies [11]. To achieve this, a logical entity between the link layer and the network layer named MIH Functions (MIHF) is defined. The MIHF provides services to the upper layers through a unified interface known as a media-independent Service Access Point (i.e., MIH_SAP), while it provides services to the lower layers through a media-dependent SAP (i.e., Link_SAP).

The MIHF provides three main services to support handovers between heterogamous and homologous networks. The services, as shown in the MIH general architecture in Fig. 3, are the following:

1) MEDIA INDEPENDENT EVENT SERVICE (MIES)

It provides local and remote event reports about the dynamic changes in link characteristics to the upper layers.

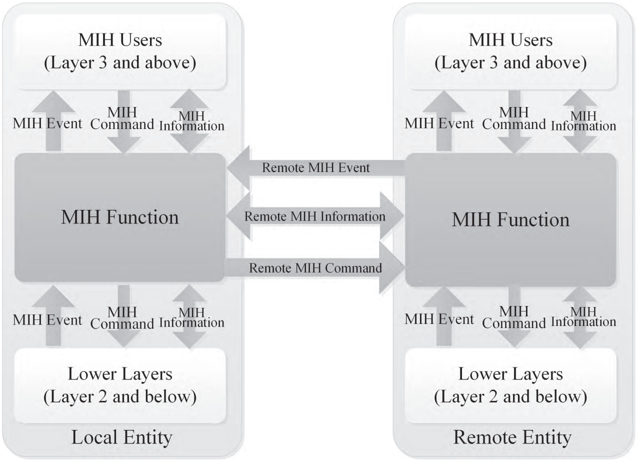

FIGURE 3. IEEE 802.21 MIH General Architecture [11].

Consequently, the upper layers protocols can use these events, along with the application QoS requirements, to make smart handover decisions. Examples of the events that can be reported are Link_Up, Link_Down, Link_Parameters_Report and Link_Going_Down.

2) MEDIA INDEPENDENT COMMAND SERVICE (MICS)

It enables the upper layers (e.g., Mobility Management protocols) to control and manage local and remote lower layers through a set of commands. Determining the status of connected links and executing the handover decisions are done using MICS commands. Examples of these commands are MIH_Net_HO_Candidate_Query and MIH_MN_HO_Candidate_Query.

3) MEDIA INDEPENDENT INFORMATION SERVICE (MIIS)

It allows the upper and lower layers to collect static and dynamic information about the available networks in range to facilitate the handover process. Such information could be used to make preparations before the handover and to select the appropriate handover target. Examples of static information are link type, operator identifier, Medium Access Control (MAC) addresses, and channel information. Alternately, examples of dynamic information are link layer parameters, such as throughput and data rate. A certain query/response mechanism must be invoked to obtain the static and dynamic information.

MIIS deploys various Information Elements (IEs), and each IE provides specific information. These IEs are presented in containers where each container has a certain group of information. The containers are represented in Type-Length-Value (TLV) format. The upper and lower layers can get information about the neighboring heterogeneous networks either by requesting individual IEs from the Information Server (IS) or by requesting IE containers.

V. 802.21-ASSISTED DMM SOLUTION

This section details the 802.21-Assisted DMM solution including services, messages and the handover procedures. In 802.21-Assisted DMM, the IS serves as a data reservoir to store and manage the knowledge of neighboring networks. To support both partially and fully distributed approaches, the IS location could be varied depending on the deployed approach. In partial distribution, the IS could be located at CMD, which manages the control plane centrally, while in full distribution approaches, the IS would be standalone since data and control planes are completely distributed between MAARs. However, this paper considers partial distribution because IETF has detailed the operation of partially distributed only [6].

One of PMIPv6's objectives, and accordingly one of network-based DMM's, is to eliminate the MU involvement in the IP mobility process [1], [6]. This is to avoid upgrading or modifying the mobility stack in the MU, which increases the operation expense and complexity [1]. To keep such an objective in the 802.21-Assisted DMM as well, we adopt a network-initiated handover process where the S-MAAR selects the handover target. In this manner, the MU is not involved in IP mobility signaling. It is relieved from the burden of discovering and selecting the next MAAR.

A. 802.21-ASSISTED DMM SERVICES AND MESSAGES

Fig. 4 shows the architecture of the 802.21-Assisted DMM solution on the MAAR side. We address the issues of network-based DMM handover performance with the following main amendments:

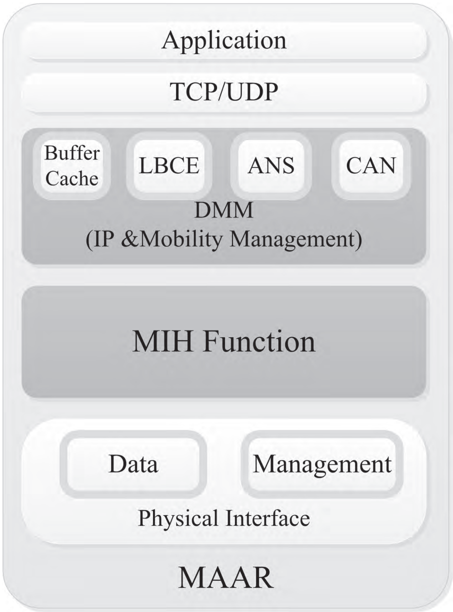

FIGURE 4. 802.21-Assisted DMM Architecture on the MAAR Side.

1) To perform the DMM handover in a proactive manner, the new Access Network (nAN) and nMAAR must be known before the MU detachment from the S-MAAR. To achieve this, we define a new information element container, located at CMD, named the NNI Container. The NNI facilitates the storing and retrieval of the dynamic and static link and network layers information of neighboring networks that are collected from IS through MIIS. In the current 802.21 specifications, three information element containers are defined: (i) List of neighboring access network container, (ii) Access network container and (iii) Point of Attachment (PoA) container [11]. These containers include many IEs, which may not be useful for our proposed solution. Consequently, this may increase signaling overheads and processing time. Thus, we utilize a single container having all the IEs that can enhance our solution instead of including all IEs. The handover latency caused by discovering neighbor ANs in DMM will be removed using the *L2* layer information obtained from the IS. In addition, with the network layer information of the corresponding nAN, the S-MAAR will obtain the nMAAR's address, which is used to reduce the *L3* handover latency in DMM.
2) We also define a Candidate Access Networks (CAN) cache at the MAAR to store and maintain the NNI report received from IS. The MAAR receives the NNI report through an MIH_Get_Information message. Having the CAN cache will help to decrease the number of signaling messages during the prediction interval and therefore the overall prediction latency. Consequently, this will reduce the nLNP configuration interval and thereby the *L3* handover latency.
3) We deploy MICS to obtain the required and available resources for each neighbor network. We use the extension proposed in [12] on MIH_Net_HO_Candidate_Query and MIH_Net_N2N_Candidate_Query messages. To facilitate the decision of the nAN, the messages will query the following parameters: Signal-to-Noise Ratio (SNR), available data rate, number of associated users, throughput, packet loss rate, and average packet transfer delay.
4) We deploy our proposed HO-Initiate process in FDMM [6] to obtain the MU's context for registering the MU and restoring old sessions. Different than FDMM, the S-MAAR is the entity that exchanges Handover Initiate (HI) and Handover Acknowledge (HAck) messages with the nMAAR for the context information transfer. In addition, the HI message is delivered to the

nMAAR and A-MAARs (if any). The context information includes the MU-ID, MU's LNPS, S-MAAR address, CMD and Routing state table. HI and HAck messages may include one or more mobility options based on the required information. Please refer to [7] for more details regarding HI/HAck messages and the defined mobility options.

5) We propose an Access Network Selector (ANS) module in the MAAR to select the appropriate AN based on the obtained information using MICS extended messages. The ANS module compares the dynamic link layer parameters and selects the best AN. The details of how to select the best AN are out of the scope of our solution. A complicated and sophisticated algorithm to make a smart decision can be utilized.
6) To avoid packet loss during the handover, a buffering technique is utilized at the nMAAR to buffer the packets destined for the MU. Once the S-MAAR successfully establishes a bidirectional tunnel with the nMAAR, it starts forwarding the packets meant for the MU to the nMAAR, which in turn will start buffering. Deploying the buffering mechanism will reduce the packet loss during the MU detachment period. The buffering size is determined by the network administrator.

B. HANDOVER PROCEDURE OF 802.21-ASSISTED DMM

The handover procedure of the 802.21-Assisted DMM solution in the first roaming scenario is shown in Fig. 5. The handover procedure starts upon successful MU association with the S-MAAR (i.e., MAAR1 in Fig. 5). The S-MAAR, using MICS, sends an MIH_Get_Information request message with an Info query binary data list option to the Information Server/Central Mobility Database (IS/CMD). Here, we locate the IS at the CMD since we consider a partially distributed approach. The RPT_TEMPL parameter will be presented in the request to include the neighbor network information container (IE_Container_NNI) in the information response. The IS/CMD replies with an MIH_Get_Information response message containing IE_Container_NNI and its IEs. Then, the S-MAAR will process the content of the response and store it in the CAN cache.

Once the link layer connectivity is anticipated to be dropped within a certain time, the MU using MIES sends an MIH_Link_Going_Down indication message to S-MAAR. Because our solution is a network-initiated handover, the S-MAAR triggers the handover and requests the dynamic link layer parameters of the listed access networks in its CAN cache from the MU by sending the extended MIH_Net_HO_Candidate_Query request message. The MU replies with the MIH_Net_HO_Candidate_Query response message including the requested information regarding the candidate networks and the MU's preferred list.

Thereafter, the S-MAAR sends the MIH_N2N_HO_Query_Resource request message to the candidate MAARs to inquire about the resource availability at candidate networks. The candidate MAARs in turn will send an MIH_N2N_HO_Query_Resource response message to the S-MAAR. After receiving the response, the ANS module in the S-MAAR compares the dynamic link layer parameters and selects the best AN.

Once the S-MAAR selects the nAN, it will execute the predictive mode of the HO-Initiate process with the nMAAR, as detailed in [7]. Upon completing the HO-Initiate process, the nMAAR will receive the traffic destined for any of the MU's prefixes (i.e., more than one handover) and start the buffering. Meanwhile, the S-MAAR triggers the MU to roam to the selected MAAR (nMAAR) through an MIH_Net_HO_Commit request message. As a response, the MU will inform the S-MAAR as to the result of the handover commitment through an MIH_Net_HO_Commit response message. Then, it will establish a physical-layer connection with the nAN and send an RS message to the nMAAR, which will reply with an RA message advertising the allocated nLNP. Using the nLNP, the MU configures a new IP address (Pref2::/64). At this step, the handover process is completed; the nMAAR (MAAR2) now starts forwarding the new flows that use nLNP to the MU directly, while the previous active IP flows that use pLNP will be forwarded to MAAR1, as shown in Fig. 5. However, the nMAAR exchanges PBU/PBA messages with the CMD to update it with the new MU location. Fig. 6 shows the signaling for the next MU's movements where the process is repeated while taking into consideration the number of pLNPs (old IP flows) that the MU wishes to maintain.

VI. HANDOVER PERFORMANCE EVALUATION

This section explains the executed simulation and analysis evaluation to investigate the performance of 802.21-Assisted DMM with respect to DMM [6] and FDMM [7] mechanisms. The considered aspects are handover latency, handover failure probability, session recovery time, packet loss and signaling cost. The deployed system, user mobility and traffic models in the analysis are detailed in [7]. The City Section Mobility (CSM) model [13], [14] is utilized as a mobility model. The traffic model presented in [15] is extended and utilized as a traffic model. Alternately, the simulation is carried out using Simulation of Urban Mobility (SUMO) and Network Simulator-2 (NS-2) simulators. The first simulates the mobility traffic in the vehicular environment, while NS-2 simulates the network. New modules implementing DMM and 802.21-Assisted DMM are developed. The proposed mechanism has been evaluated in urban and highway environments.

A. ANALYSIS OF THE HANDOVER LATENCY

The Handover Latency (HL) is the time from the last moment the MU is enabled to exchange packets through S-MAAR to the first moment it is enabled to exchange packets through the nMAAR [15], [16]. Once an MU moves from one MAAR to another, it initiates the handover process by performing Layer 2 link establishment and authentication processes. The interval time to establish a new Layer 2 link is T_{L2},

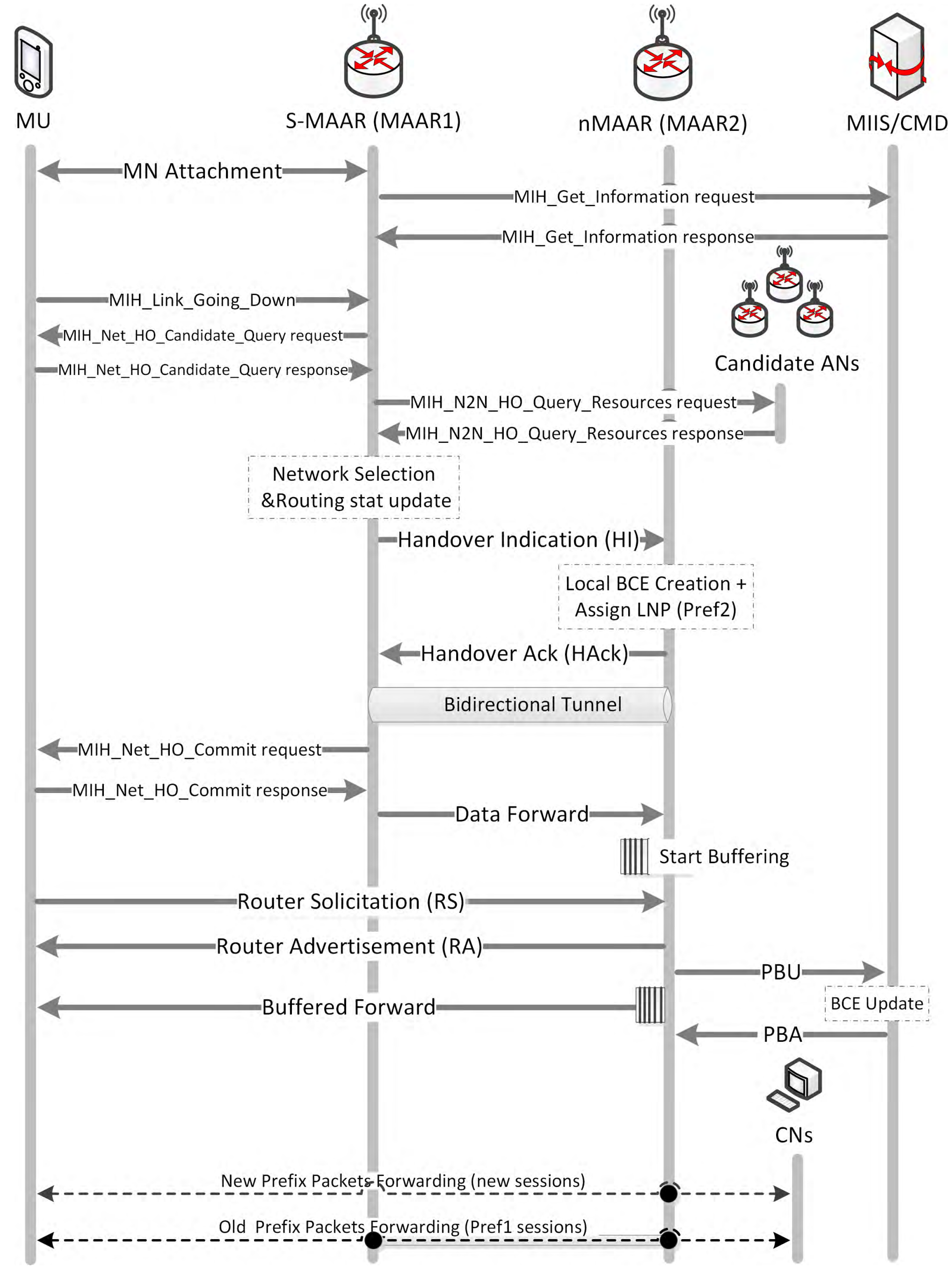

FIGURE 5. **802.21-Assisted DMM Handover Management Operation in First Roaming.**

while the interval time to authorize an MU is T_{Auth}. Both T_{L2} and T_{Auth} are considered constant in all examined mechanisms. Fig. 7 shows the timeline of the DMM handover operation. $d_{x,y}(p)$, shown in the figure, is the symmetric delay of a packet of size p sent from x to y, while T_{PC}^{X} is the processing time by node x.

The handover procedure of DMM includes three main phases as follows (see Fig. 7):

$$T_{HL}^{DMM} = T_{L2} + T_{Auth} + T_{Binding}^{DMM} \tag{1}$$

$T_{Binding}^{DMM}$ is the time interval to accomplish the binding registration phase. The aims of the binding phase are updating the MU location and recovering the ongoing IP flows. $T_{Binding}^{DMM}$ is given by

$$T_{Binding}^{DMM} = T_{MD}^{DMM} + T_{LU}^{DMM} \tag{2}$$

T_{MD}^{DMM} is the movement detection latency. It is the time elapsed to exchange router solicitation and router advertisement messages. It is calculated as

$$T_{MD}^{DMM} = 2d_{MU-MAAR}\,(c) \tag{3}$$

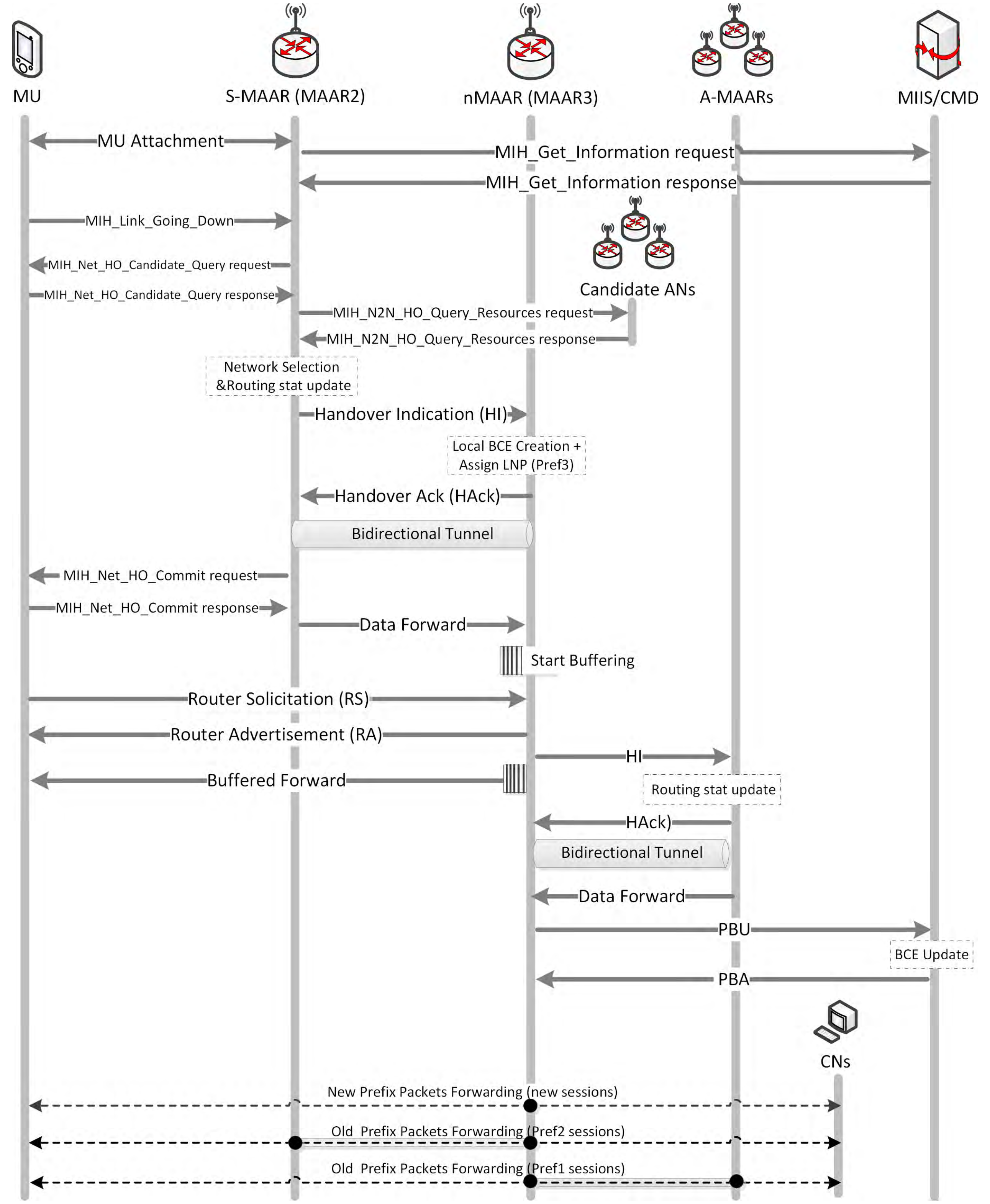

FIGURE 6. 802.21-Assisted DMM Handover Management Operation in Second Roaming.

where $d_{MN-MAAR}(c)$ is:

$$d_{MU-MAAR}(c) = \left(\frac{L_c}{BW_w} + l_w\right)\left(\frac{1}{1-P_f}\right) h_{MU-MAAR} \quad (4)$$

L_c is the average size of control packets, BW_w is the bandwidth of the wireless link, l_w is the wireless propagation latency and P_f is the wireless link failure probability. T_{LU}^{DMM} includes exchanging PBU/PBA messages and the processing

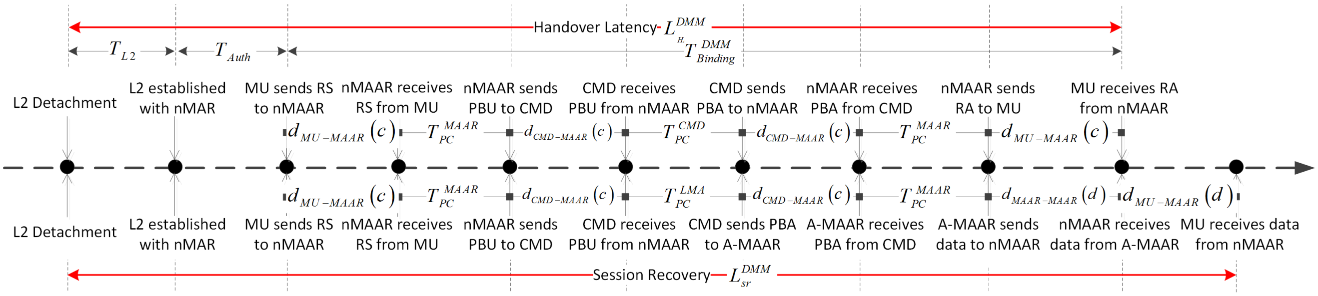

FIGURE 7. **DMM Handover Operation Timeline.**

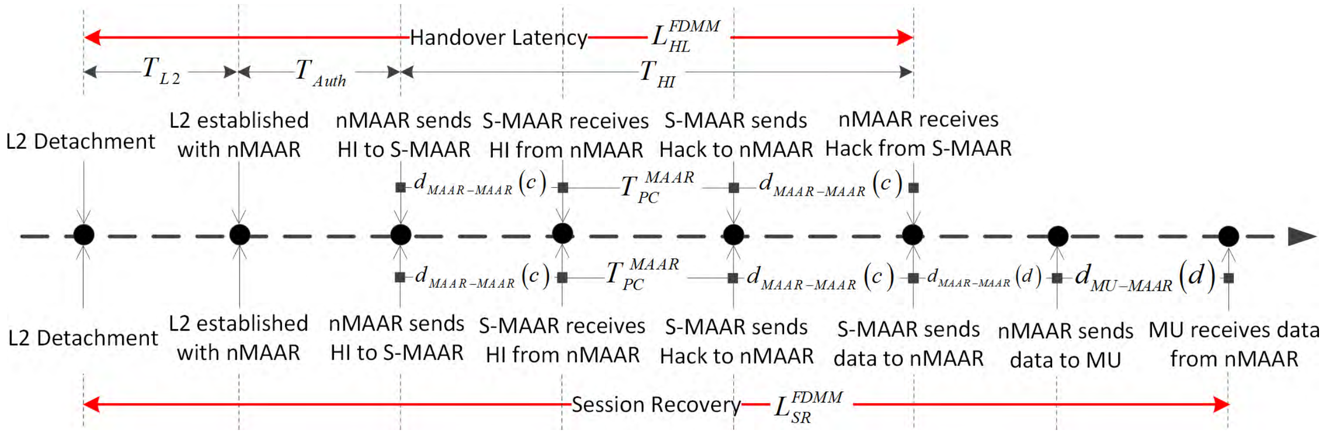

FIGURE 8. **FDMM Handover Operation Timeline.**

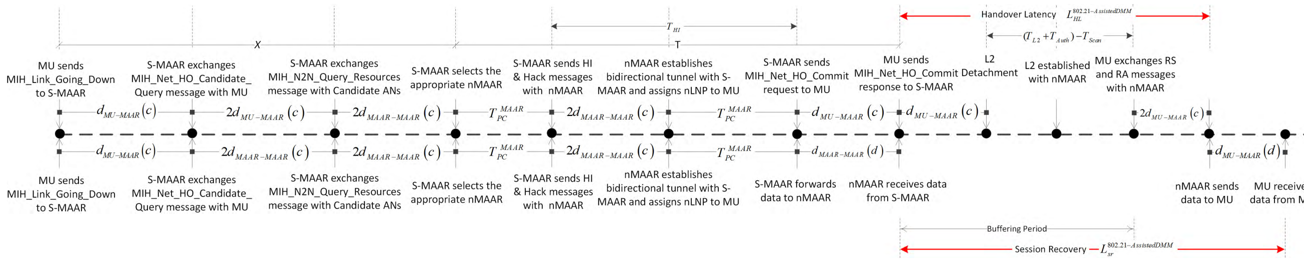

FIGURE 9. **802.21-Assisted DMM Handover Operation Timeline.**

time taken to update the MU location and establish the tunnel.

$$T^{DMM}_{LU} = 2d_{CMD-MAAR}(c) + T^{CMD}_{PC} + 2T^{MAAR}_{PC} \tag{5}$$

where $d_{CMD-MAAR}(c)$ is:

$$d_{CMD-MAAR}(c) = \left(\frac{L_c}{BW} + l\right) h_{CMD-MAAR} \tag{6}$$

BW represents the wired link bandwidth, and l represents the wire link propagation latency. Fig. 8 shows the FDMM handover operation timeline, where the handover latency can be expressed as

$$T^{FDMM}_{HL} = T_{L2} + T_{Auth} + T_{HI} \tag{7}$$

The T_{HI} is the period for executing the HO-Initiate process and calculated as

$$T_{HI} = 2d_{MAAR-MAAR}(c) + T^{MAAR}_{PC} \tag{8}$$

where $d_{MAAR-MAAR}(c)$ is:

$$d_{MAAR-MAAR}(c) = \left(\frac{L_c}{BW} + l\right) h_{MAAR-MAAR} \tag{9}$$

Alternately, 802.21-Assisted DMM requires extra signaling due to the handover preparation for the MU compared to DMM. Fig. 9 shows the 802.21-Assisted DMM handover operation timeline. The following parameters are used for 802.21-Assisted DMM performance analysis:

x : The elapsed time between the MU's RSS reaching the threshold and the S-MAAR collecting the information about neighbor ANs.

T : The period from when the S-MAAR selects the nAN to when the MU receives the MIH_Net_HO_Commit request from the S-MAAR.

$$T_{HL}^{802.21-\text{Assisted DMM}} = \begin{pmatrix} \left(\left(4d_{MU-MAAR}(c)+2Nd_{MAAR-MAAR}(c)+T_{PC}^{MAAR}+T_{HI}\right)-\emptyset\right) \\ +3d_{MU-MAAR}(c)+\left(\left(T_{L2}+T_{Auth}\right)-T_{Scan}\right) \end{pmatrix} \tag{10}$$

$\emptyset$: The elapsed time between sending the MIH_Link_Going_Down indication message to the S-MAAR and when the *L2* link goes down, where $\emptyset \leq x + T$

The handover latency of 802.21-Assisted DMM may differ by the time point at which the *L2* link goes down. Thus, two possible cases may occur. If $\emptyset = x + T$, the MU's *L2* link with the S-MAAR goes down after receiving the MIH_Net_HO_Commit request message. In such a case, the nMAAR has already completed the pre-handover process and established a tunnel with S-MAAR. Alternately, if $\emptyset < x + T$, the MU's *L2* link with the S-MAAR goes down before receiving the MIH_Net_HO_Commit request message. Thus, the pre-handover process and tunnel-establishing time between the nMAAR and S-MAAR must be included in the handover latency. As indicated in the timeline, x equals $3d_{MU-MAAR}(c) + 2Nd_{MAAR-MAAR}(c)$, where N is the number of candidate ANs, which is assumed to be 2 throughout the analysis. Moreover, T equals $d_{MU-MAAR}(c) + T_{PC}^{MAAR} + T_{HI}$. The handover latency of 802.21-Assisted DMM can be expressed as in (10), shown at the top this page.

The MU in 802.21-Assisted DMM already knows the nAN through the MIH_Net_HO_Commit request message, and thus we do not consider scanning time during the *L2* link establishment and authentication phases.

B. ANALYSIS OF THE HANDOVER FAILURE PROBABILITY

We define the Handover Failure Probability (PF) as the probability that the handover latency exceeds the subnet residence time [15]. The general expression for the handover failure probability is [16]

$$\begin{aligned} PF(.) &= Prob\{T_{SN} < HL(.)\} \\ &= \int_0^{HL(.)} \mu_{SN} e^{-\mu_{SN}x} dx = 1 - e^{-\mu_{SN}HL(.)} \end{aligned} \tag{11}$$

μ_{SN} is the subnet crossing rate and is expressed as $1/T_{SN}$. T_{SN} is the mean subnet residence time, which is defined as

$$T_{SN} = \left(\frac{E(T) + 2E(P)}{E(C)}\right) \tag{12}$$

$E(T)$ is the expected epoch time, $E(P)$ is the expected pause time, and $E(C)$ is the expected number of crossed cells. Theses parameters are defined and calculated in [7].

C. ANALYSIS OF THE SESSION RECOVERY TIME

Session Recovery Time (SR) represents the time between receiving the last data packet of a session by the MU before the handover and receiving the first packet of the same session after the handover [15]. The session recovery time is equal to the handover latency with the addition of the elapsed time to receive the first data packet by the MU. Thus, the session recovery time of DMM, as shown in Fig. 7, is calculated as:

$$\begin{aligned} T_{SR}^{DMM} = &\left(T_{HL}^{DMM} - d_{MU-MAAR}(c)\right) + d_{MAAR-MAAR}(d) \\ &+ d_{MU-MAAR}(d) \end{aligned} \tag{13}$$

where $d_{MAAR-MAAR}(d)$ is

$$d_{MAAR-MAAR}(d) = \left(\frac{L_d}{BW} + l\right) h_{MAAR-MAAR} \tag{14}$$

The session recovery time of FDMM shown in Fig. 8 is expressed as follows:

$$T_{SR}^{FDMM} = T_{HL}^{FDMM} + d_{MAAR-MAAR}(d) + d_{MU-MAAR}(d) \tag{15}$$

Similar to DMM and FDMM, the session recovery time in 802.21-Assisted DMM equals the handover latency plus the interval for the first data packet to travel from the S-MAAR to the nMAAR and from the nMAAR to the MU. The session recovery time in 802.21-Assisted DMM is

$$\begin{aligned} &T_{SR}^{802.21-\text{Assisted DMM}} \\ &= \begin{pmatrix} \max\left\{\left(4d_{MU-MAAR}(c)+2Nd_{MAAR-MAAR}(c)+T_{HI}\right)-\emptyset, 0\right\} \\ +3d_{MU-MAAR}(c)+\left(\left(T_{L2}+T_{Auth}\right)-T_{Scan}\right)+d_{MU-MAAR}(d) \end{pmatrix} \end{aligned} \tag{16}$$

As shown in Fig. 9, $(3d_{MU-MAAR}(c) + ((T_{L2} + T_{Auth}) - T_{Scan})) > d_{MAAR-MAAR}(d)$, and thus the time to switch between ANs is considered only in the session recovery time. In addition, the S-MAAR starts forwarding the data traffic to the nMAAR once it receives the Hack message and before sending the MIH_Net_HO_Commit request message. At that time, the MU can still receive and send data through the S-MAAR until it receives the MIH_Net_HO_Commit request message. Thus, the interval to send the MIH_Net_HO_Commit request message is not included in the session recovery time.

D. ANALYSIS OF THE PACKET LOSS

The Packet Loss (PL) represents the total amount of data packet traffic lost or dropped throughout the handover. It is proportional to the session recovery interval and to the packet arrival rate λ if no buffering mechanism is used during the handover [15]. If packet buffering is employed, the packet loss will be proportional to the tunnel-establishing time and to buffering overflow at the nMAAR [17], [18].

The packet arrival rate is considered to be $\lambda = \lambda_p \bar{N}_{PR}$ packets/second to and from the MU, where λ_p is the packet rate per active prefix. Because there is no buffering in DMM and FDMM, the packet loss will be expressed as follows:

$$PL_{DMM} = \lambda L_d T_{SR}^{DMM} \tag{17}$$

$$PL_{FDMM} = \lambda L_d T_{SR}^{FDMM} \tag{18}$$

In 802.21-Assisted DMM, the buffer technique is used at the nMAAR (see Fig. 9). Hence, the packet loss is expressed as the total packets transferred before initiating the buffering and the packets that exceed the buffering size, as follows:

$$T_{Buffering}^{802.21-\text{Assisted DMM}} = (3d_{MU-MAAR}(c) + ((T_{L2} + T_{Auth}) - T_{Scan})) - (d_{MAAR-MAAR}(d)) \tag{19}$$

$$PL_{802.21-\text{Assisted DMM}} = \left(\begin{array}{l} \lambda L_d \left(max\left\{\left(d_{MU-MAAR}(c) + T_{PC}^{MAAR} + T_{HI}\right) - \emptyset, 0\right\}\right) \\ + \left(max\left\{\lambda L_d T_{Buffering}^{FDMM} - B, 0\right\}\right) \end{array} \right) \tag{20}$$

where B is the buffer size.

E. ANALYSIS OF THE SIGNALING COST

Signaling Cost (C) is an accumulation of the handover-related signaling messages and expressed as the multiplication of the size of the mobility signaling message and the hop distance [19]–[21]. The signaling cost in DMM is an accumulation of the following messages: RS/RA messages, PBU/PBA messages exchanged between the nMAAR and the CMD to register nLNP, and PBU/PBA messages exchanged between each A-MAAR and the CMD. Therefore, the signaling cost of DMM is expressed as

$$C_{sig}^{DMM} = 2\mu_{sn} L_c \left(h_{MU-MAAR} + h_{CMD-MAAR}\left(\bar{N}_{PR} + 1\right)\right) \tag{21}$$

In FDMM, there are no RS and RA messages exchanged between the MU and the nMAAR because the handover operation starts after attachment to the nMAAR. The signaling cost of FDMM is

$$C_{sig}^{FDMM} = 2\mu_{sn} L_c \left(h_{CMD-MAAR} + \sum_{n=1}^{\bar{N}_{PR}} N h_{MAAR-MAAR} \right) \tag{22}$$

where N is the number of candidate ANs.

The signaling cost of 802.21-Assisted DMM contains, in addition to the DMM signaling, extra signaling messages exchanged between MAARs. The 802.21-Assisted DMM signaling cost includes RS and RA messages and is expressed as follows:

$$C_{sig}^{802.21-\text{Assisted DMM}} = \mu_{sn} L_c \left(\begin{array}{l} 4h_{CMD-MAAR} + 7h_{MU-MAAR} \\ + N(2h_{MAAR-MAAR}) + \sum_{n=1}^{\bar{N}_{PR}} N h_{MAAR-MAAR} \end{array} \right) \tag{23}$$

F. SIMULATION SCENARIO

This sub-section discusses the simulation configuration and the tested environments. The simulation setup is shown in Fig. 10. The simulation is performed using NS-2.29 combined with the National Institute of Standards and Technology (NIST) mobility package [22] and our developed modules implementing network-based DMM, FDMM and 802.21-Assisted DMM. The NIST mobility package includes 802.21 information, command and event services. The employed radio communication technology is IEEE 802.11p [23] with 10 Mbps bandwidth and a 1 km transmission range. The vehicle in the simulation communicates with a static Corresponding Node (CN) transmitting CBR data traffic with a 512 byte packet size and 0.01 s interval. The wired link rate between the CN and the router is 10 Mbps, while the link delay is 1 ms. The link between the router and MAAR1 is set to a 100 Mbps link rate and 100 ms link delay. In addition, the link rate between the MAARs and CMD is 100 Mbps with a 10 ms link delay. The simulation time is 70 seconds.

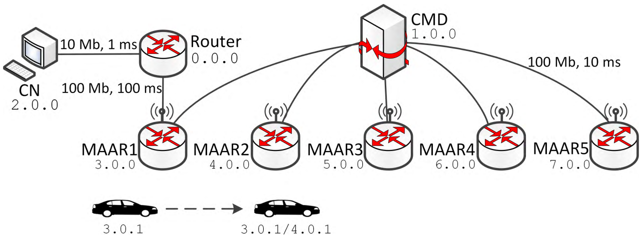

FIGURE 10. **Simulation Setup.**

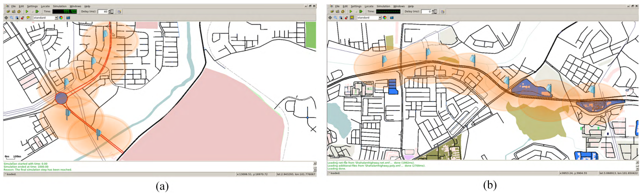
(a)
(b)

FIGURE 11. **SUMO Simulator for Vehicular Traffic Simulation (a) Bangi City (b) Shah Alam Highway.**

For vehicle mobility, the urban area around a campus area, known as Universiti Kebangsaan Malaysia (UKM), located in Bangi, central Malaysia, has been taken from OSM to represent an urban environment. For a highway environment, Shah Alam highway is considered. SUMO is used to simulate the vehicle mobility as shown in Fig. 11. The mobility pattern is set to Random Waypoint Mobility with Obstacle Avoidance, while the driving model is set to Intelligent Driving Model (IDM) with Intersection Management and Lane Changing. In the urban environment, the length of the selected area is approximately 5 km, with one roundabout and two traffic lights. The area is covered with 5 MAARs having both *L2* and *L3* capabilities and the ability to handle handovers. The speed of vehicles is changed over the range of (35-95 km/h). Alternately, the selected area in Shah Alam highway is approximately 6 km and covered by 6 MAARs. The range of the vehicle's speed is between 95 and 155 km/h.

VII. RESULTS AND DISCUSSION

This section presents and discusses the obtained simulation and numerical results based on the conducted evaluation as explained in the previous section. In the analytical evaluation, the default parameter values defined in [7] are utilized.

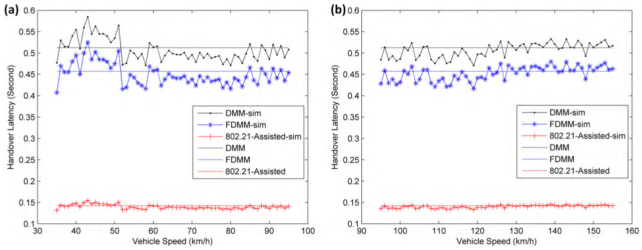

FIGURE 12. **Vehicle speed effect on handover latency (a) urban environment (b) highway environment.**

However, the impacts of several parameters have been studied by changing their values.

We start by investigating the handover latency performance with different network parameter values. Fig. 12 shows the simulation and analytical results of vehicle speed impact on handover latency in urban and highway environments. The handover latency stays fixed over various vehicle speeds in both environments. This is because the interval to exchange handover signaling is independent of the vehicle speed. In an urban environment, the range of handover latency in DMM is between 471 and 584 ms, while in in FDMM is between 407 and 525 ms. The range of handover latency in 802.21-Assisted is between 131 and 154 ms. Alternately, in the highway environment, the handover latency values are between 470 and 533 ms in DMM and between 416 and 480 ms in FDMM. The handover latency values are between 133 and 145 ms in 802.21-Assisted DMM. The handover latency in the analytical results approximately equals the average of the simulation's handover latency. The average handover latencies in DMM and 802.21-Assisted DMM are 512 and 142 ms, respectively.

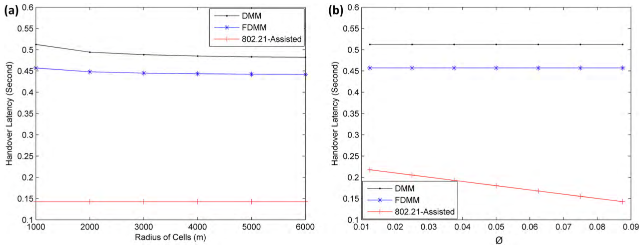

FIGURE 13. **Handover latency with the increase of (a) the radius of cells and (b) the elapsed time between receiving the MIH_Link_Going_Down message and the link being dropped.**

In Fig. 13, the handover latency behavior is investigated with increasing radius of cells and changing of the interval between receiving the *L2* link report and the link being dropped. Fig. 13a illustrates that increasing the radius of cells reduces the handover latency of DMM and FDMM slightly, with no effect on 802.21-Assisted DMM. Increasing the radius of cells decreases the number of cells required to cover a certain area. With respect to our analyzed area dimensions of 36x24 km [7], the required number of cells is between 285 and 4 with a radius of 1000 to 6000 m, respectively. Hence, the number of hops between MAARs is reduced, as is the required interval to exchange HO-initiate process messages as a consequence. However, the handover latency of 802.21-Assisted DMM remains constant since there are no exchanged messages between MAARs during the handover. Fig. 13b shows that, once the parameter Ø increases, the handover latency of the 802.21-Assisted DMM mechanism decreases. Increasing this interval raises the chance of performing the pre-handover process completely. In DMM and FDMM, there is no process prior to link dropping being triggered; hence, the handover latency remains constant.

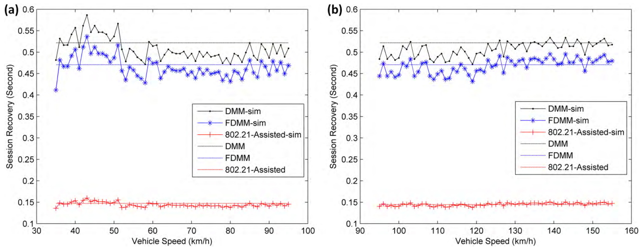

FIGURE 14. **Vehicle speed effect on session recovery time (a) urban environment (b) highway environment.**

Similar to handover latency, the impact of vehicle velocity on the session recovery time has been studied, as shown in Fig. 14. The session recovery time has the same trends as the handover latency with a slight increment in the value due to the time for forwarding the packets to the vehicle. The average session recovery time in DMM is 521 ms, and it is 470 ms in FDMM. The average session recovery time in 802.21-Assisted DMM is 147 ms with an approximately 71.8% reduction with respect to DMM.

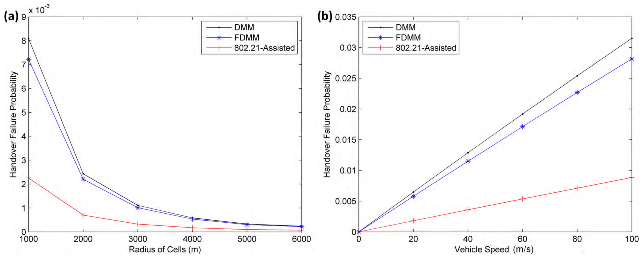

FIGURE 15. **Handover failure probability with the increase of (a) the radius of cells and (b) the vehicle speed.**

Through the analysis, Fig. 15 illustrates the impact of the radius of cells and vehicle speed on the handover failure probability. As shown in equation (11), the main factors having an effect on handover failure probability are handover latency and subnet crossing rate. Thus, as the radius of cells decreases or vehicle speed increases, the subnet crossing rate increases, and consequently the handover failure probability increases. The amount of time required to perform the handover process in DMM and FDMM are higher than in 802.21-Assisted DMM, and hence the probability that the vehicle fails to complete the handover process is higher.

Considering the simulation scenario explained in the previous section, the number of MAARs in the urban environment is 5, while in the highway environment is 6. Fig. 16 shows

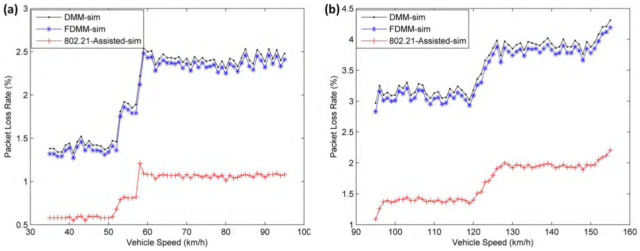

FIGURE 16. **Vehicle speed effect on packet loss (a) urban environment (b) highway environment.**

the simulation results of the packet loss rate throughout the handover. As the speed of the vehicle increases, the packet loss rate increases. This is because once the vehicle speed increases, the number of handover events occurring within the same simulation time increases, and subsequently the total packet loss during the simulation does as well.

In an urban environment as shown in Fig. 16a, the handover occurs twice once the vehicle speed is between 35 and 51 km/h. The handover occurs three times once the vehicle speed is 52 km/h and four times once the vehicle speed is 57 km/h and above. Fig. 16b displays the highway environment case. At a speed of 95 km/h, the handover occurs four times, while at a speed of 122 km/h, it occurs five times. This explains the reason behind the increment in the packet loss rate in Fig. 16.

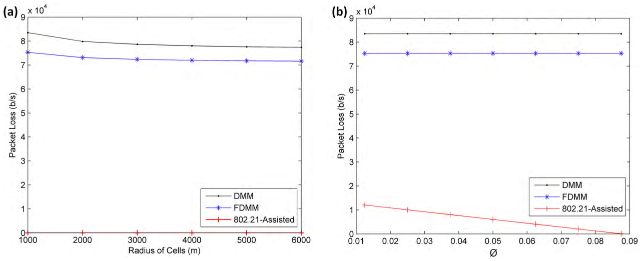

FIGURE 17. **Packet loss with the increase of the (a) radius of cells and (b) the elapsed time between receiving the MIH_Link_Going_Down message and the link being dropped.**

The packet loss during the handover has the same trend as the handover latency. Thus, similar to Fig. 13, Fig. 17 clarifies the packet loss manner for increasing radius of cells and interval between receiving the MIH_Link_Going_Down message and the link being dropped. As the radius of cells increases, the handover latency of DMM and FDMM decrease, and consequently, the packet loss rate decreases as shown in Fig. 17a. However, the 802.21 mechanism eliminates the packet loss during the handover by deploying the buffering at the nMAAR. The packet loss remains zero as long as the buffered packets do not exceed the buffering size. Fig. 17b shows that packet loss occurs once the connectivity is dropped before completing the pre-handover process.

Finally, we study the signaling cost according to the radius of cells, vehicle speed and network scale. The DMM protocol is basically designed as a flow-based protocol, where the number of active prefixes increases as the subnet crossing rate increases. Once the radius of cells is small and/or the vehicle speed is high, the subnet crossing rate increases, and subsequently the number of active prefixes does as well. Thus, the leftmost of Fig. 18a and the rightmost of Fig. 18b denote the highest signaling cost, where the amount of exchanged signaling is high. Recall that it is assumed that the vehicle moves away from home MAARs, increasing the cost of exchanging signaling between MAARs. In FDMM and 802.21-Assisted DMM, the number of handover management messages exchanged between MAARs increases exponentially as the number of active prefixes increases. Unlike FDMM and 802.21-Assisted DMM, most of DMM's handover management messages are exchanged between MAARs and the CMD. Therefore, it has the lowest signaling cost.

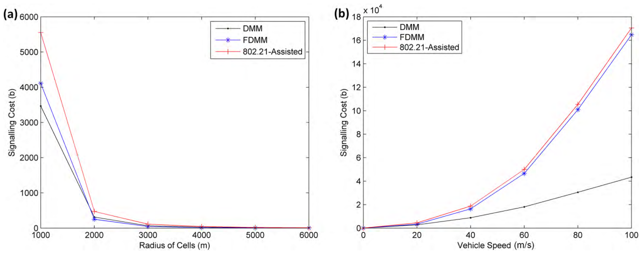

FIGURE 18. **Signaling cost with the increase of the (a) radius of cells and (b) the vehicle speed.**

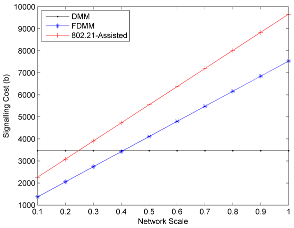

FIGURE 19. **Effect of network scale on the signaling cost.**

To show a more suitable scale for deploying the 802.21-Assisted DMM mechanism, we present in Fig. 19 the signaling cost pattern according to the network scale. As defined in [7], the network scale is the ratio of the number of hops between two MAARs and number of hops between the CMD and MAARs. It is assumed that all MAARs are the same number of hops from the CMD. In addition, the network scale is increased by increasing the number of hops between MAARs. As a result, the cost of exchanging signaling between MAARs increases when increasing the network scale. In FDMM and 802.21-Assisted DMM schemes, because there are messages exchanged between MAARs during the handover process, the signaling cost increases steadily as the network scale increases. Differently, the signaling cost in DMM remains fixed since there are no messages exchanged between MAARs during the handover.

We can summarize the findings of the simulation and the analysis results as follows. (i) The 802.21-Assisted mechanism reduces the handover latency significantly with respect to the DMM protocol. As a consequence, the performance metrics that are mainly affected by handover latency are enhanced, including session recovery time, packet loss and handover failure probability. (ii) The 802.21-Assisted DMM mechanism is more appropriate for low- to medium-speed scenarios where the signaling cost remains at an acceptable level. Although the handover latency of the 802.21-Assisted DMM mechanism is low, deploying it in high-speed scenarios has high signaling costs compared to DMM. (iii) Large-scale networks are more suitable for deployment of the 802.21-Assisted DMM mechanism where the distances between MAARs are high with respect to the distance between MAARs and the CMD. The high signaling in such a network is mitigated as shown in the results.

VIII. CONCLUSION AND FUTURE WORK

This paper proposed a fast handover solution for network-based DMM named the IEEE 802.21-Assisted DMM mechanism. The proposed solution enhances the handover procedure of DMM using the HO-Initiate process and IEEE 802.21 MIH services. The binding registration latency is eliminated by performing the registration process prior to the handover. In addition, the scanning for candidate access network latency is mitigated by predicting the next access network proactively. We developed an NNI container and ANS selector to facilitate the discovery of the next access network. Evaluation has been conducted through analysis and simulation in Bangi city and Shah Alam highway. The results have proven that the 802.21-Assisted DMM mechanism reduces the handover latency by 72.3% with respect to DMM. Subsequently, the packet loss, throughput and handover failure probability are enhanced. However, the signaling cost of the proposed solution is higher than DMM, especially in high-speed scenarios and/or small-scale networks. Therefore, our future work will be in the trend of developing a solution that implements the 802.21-Assisted DMM mechanism once the limitation of signaling cost is at an acceptable level and otherwise implements the default handover process. Certain criteria could be considered, such as vehicle speeds, network scale and the average session period.

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MOHAMMED BALFAQIH received the M.S. degree in communication engineering from International Islamic University Malaysia. He is currently pursuing the Ph.D. degree with Universiti Kebangsaan Malaysia. He was a Research Assistant with the Malaysian Institute of Microelectronics Systems. His principal research interests are in the field of mobility in wireless communication. He also has research experience and is interested in other fields, such as cooperative communications, self-organization in wireless networks, image processing, and computer vision.

MAHAMOD ISMAIL received the B.Sc. degree in electrical and electronics engineering from the University of Strathclyde, U.K., in 1985, the M.Sc. degree in communications engineering and digital electronics from UMIST, Manchester, U.K., in 1987, and the Ph.D. degree from the University of Bradford, U.K., in 1996. He is currently a Professor in communications engineering and the Head of the Department of the Electrical, Electronic, and Systems, Universiti Kebangsaan Malaysia. His current research interests include mobile communications and wireless networking. He is an Executive Member of the Communications/Vehicular Technology Society, the IEEE Malaysia chapter.

ROSDIADEE NORDIN received the B.Eng. degree from Universiti Kebangsaan Malaysia (UKM) in 2001 and the Ph.D. degree from the University of Bristol, U.K., in 2011. He is currently a Senior Lecturer with the Department of Electrical, Electronic, and Systems Engineering, UKM. His research interests include peer-to-peer routing protocol, resource allocation, multiple-input multiple-output, orthogonal frequency-division multiple access, green radio, and indoor wireless localization.

ZAIN A. BALFAQIH received the M.S. degrees in information technology from International Islamic University, Malaysia, and the Ph.D. degree in software engineering from Universiti Teknologi Petronas, Malaysia. He is currently an Assistant Professor with the Information System Department, Effat University, Saudi Arabia. His principal research interests lie in the field of service-oriented architecture and cloud computing from a networking perspective. He is currently involved in automating service level agreements management using agent technology and VANET applications. He has authored several research papers and book chapters and registered patents in these fields.

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