Performance Modeling on Handover Latency in Mobile IP Regional Registration

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***Abstract*—The *Authentication, Authorization, Accounting* (AAA) infrastructure in Mobile IP network is designed to distribute keys to network entities for signaling message protection. In Mobile IP network, Regional Registration is employed to migrate the high signaling delay when a mobile user moves between network agents within the same visited domain. How to distribute keys in Mobile IP Regional Registration is still an open issue and adopting AAA infrastructure may be a suitable solution. However, in the literature, no work has a sound analytical study on Regional Registration in Mobile IP network with AAA infrastructure. In this paper, we develop a complete analytical model to investigate handover delay of Mobile IP network with and without Regional Registration. The accuracy of this model is validated by the developed simulations. From the proposed model, this paper precisely justifies performance improvement of Regional Registration in Mobile IP network.**

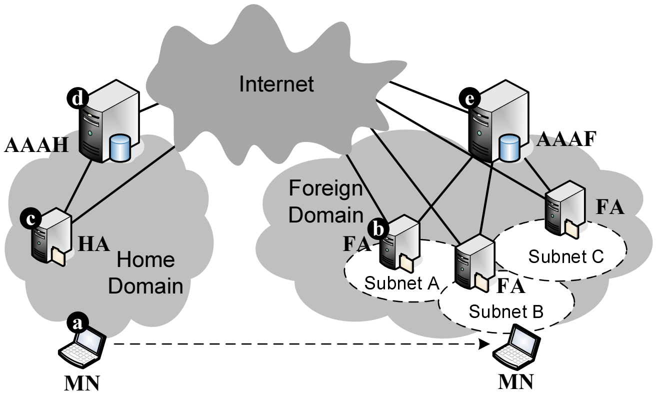

Fig. 1. The AAA infrastructure in MIP network

I. Introduction

In the recently years, the development of wireless networks towards All-IP networks and numerous mobile users can access Internet service anytime and anywhere through these networks. While mobile users moving and changing their points of attachment to the Internet, the network should provide users seamless and continuous services. Thus, how to manage user mobility in wireless networks to maintain the quality of service (QoS) is always an important issue.

In these networks, an IP address is always assigned to a mobile user to identify user's point of attachment to the Internet, and packets for that user are routed to it according to its address. Mobile IP version 4 (MIPv4) [1] and version 6 (MIPv6) [2] present the standard solution for user mobility. With MIP, when a *Mobile Node* (MN; Figure 1 (a)) moves into a new domain served by a *Foreign Agent* (FA; Figure 1 (b)), it obtains a new *Care-of-Address* (CoA) from the FA and registers the CoA with its *Home Agent* (HA; Figure 1 (c)). Then HA associates the CoA of the MN with MN's permanent IP address and tunnels the packets to the MN's CoA.

However, MIP can not satisfy highly mobile MNs due to that MN must notify HA through a registration procedure whenever MN moves from one domain to another. The long signaling delay associated with the registration procedure may result in significant packet loss for delay-sensitive and real-time services during MN changes the points of attachment. To resolve this problem, several approaches have been proposed to support local (micro) mobility, such as MIPv4 Regional Registration (MIP-RR) [3], Hierarchical Mobile IPv6 (HMIP) [4], IDMP [5], Cellular IP [6], and HAWAII [7]. In this paper, we focus on MIP-RR, where a visited domain consists of two hierarchy levels of FAs is introduced. A new entity, Gateway FA (GFA), is defined to locate at the top of the hierarchy. Beneath a GFA, there are one or more FAs. When a MN first arrives at a visited domain, it performs a home registration procedure where the GFA address is registered at the HA as the CoA of the MN. When a MN moves from one FA to another within the same domain, the MN only needs to make a regional registration to the GFA and thus the number of registration messages to the home domain and delay are both minimized.

In order to protect MIP signaling messages from being modified or eavesdropped, keys are shared between MN and HA (denoted as k_{MN-HA}), between MN and FA (denoted as k_{MN-FA}), as well as between FA and HA (denoted as k_{FA-HA}) for *Mobile Security Association* (MSA) establishment. MSA is used to calculate authenticator needed by authentication extensions used in MIP control message. With the authentication, the legitimacy of sender and message integrity are guaranteed.

A global *Authentication, Authorization, Accounting* (AAA) infrastructure is proposed [8] to enable AAA servers located in the home domain (AAAH; Figure 1 (d)) and the foreign

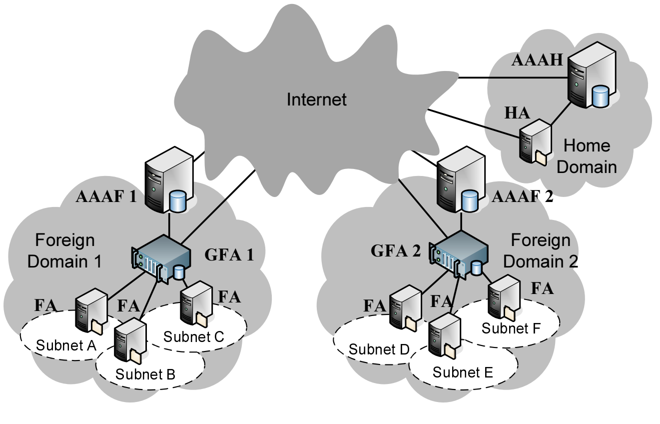

Fig. 2. Network architecture of AAA infrastructure in MIP-RR

domain (AAAF; Figure 1 (e)) to authenticate and authorize network access requests from MN and to supervise session key distribution. When the network is initially configured, AAAH creates an authentication credential for each MN. Each time MN changes the points of attachment, it executes a modified registration procedure [9] where AAAH and AAAF are involved. In this procedure, AAAH authenticates the identity of MN, generates a key set containing k_{MN-FA}, k_{MN-HA}, and k_{FA-HA}, and distributes keys to MN, FA, and HA for authentication of following MIP signaling messages among them. Note that the lifetime of the key set is limited to avoid being cracked by malicious attackers and each time the key set is expired, the registration procedure must be executed to distribute a fresh key set.

However, for micro-mobility solution (such as MIP-RR), how to distribute keys to network entities is not considered [3] and one may adopt AAA infrastructure where keys are distributed through the home registration. Moreover, although it is obvious that signaling delay during handover in MIP-RR outperforms that in Mobile IP, no previous work has conducted a sound analytical model to analyze the performance of MIP-RR where key distribution is considered. In this paper, we develop a general analytical model to study the handover latency in MIP AAA network with and without Regional Registration. Note that the key distribution is considered in both cases, which means, the handover latency includes authentication delay. Particularly, we model the expected number of the registration procedure executed for a MN within a domain, and thus the corresponding delay caused by the registration procedure during handover can be derived. The accuracy of our model is validated by the proposed simulations. The results show that our model can precisely measure the benefits of MIP-RR regarding handover delay.

The rest of this paper is organized as follows: Section II describes the registration procedure of MIP-RR in AAA infrastructure. Section III proposes a general analytical model to evaluate handover delay in MIP-RR and MIP. In Section IV Simulation experiments are proposed to validate the correctness of analytical model and numerical results are studied. Finally, we conclude this work in Section V.

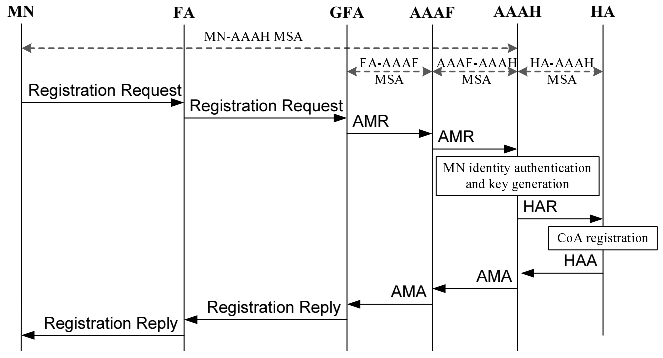

Fig. 3. The message flow for home registration in MIP-RR

II. REGISTRATION PROCEDURES IN MIP-RR WITH AAA INFRASTRUCTURE

MIP-RR suggests that GFA takes the role of FAs in the same domain with regard to MSAs in the home registrations. This means that GFA and HA share K_{FA-HA} to protect MIP control messages transmitted between them. Equally, regional registration messages transmitted between MN and GFA are authenticated by K_{MN-FA} shared between MN and GFA. With AAA infrastructure, key distribution is executed as part of the home registration in MIP-RR. Figure 2 shows the network architecture of AAA framework supporting MIP-RR. In this architecture, we assume that the serving domain of a GFA is equal to that of a AAA server. The domain served by a AAA server may cover one or more subnets served by a agent. In the following, we describe the operations of AAA framework in MIP-RR.

Home registration. When a MN moves into a new foreign domain, it registers using home registration as depicted in Figure 3. The MN sends the discovered FA a Registration Request message where advertised GFA address is inserted in the CoA field. The FA adds its own address to the Registration Request, and relays it to the GFA. Then the GFA sends the AAAF of this domain a Diameter message, AA-Mobile-Node-Request (AMR), which encapsulates the Registration Request message. AAAF in turn forwards this message to the AAAH. AAAH checks whether the MN is a legal user by using the MSA between the MN and the AAAH. Then AAAH generates keys (k_{FA-MN}, k_{HA-MN}, and k_{FA-HA}) and two key generation nonces (n_{MN-FA} and n_{MN-HA}). The AAAH sends the HA a Home-Agent-MIP-Request (HAR) message containing keys (k_{HA-MN} and k_{FA-HA}), nonces (n_{MN-FA} and n_{MN-HA}), and the Registration Request message.
The HA extracts the keys and the Registration Request message and registers the GFA's address as CoA of the MN. The HA generates Registration Reply message and encapsulates the two nonces (n_{MN-FA} and n_{MN-HA}) in this message. Then the HA send a Home-Agent-MIP-Answer (HAR) message to the AAAH, where the Registration Reply message is inserted in this message.

AAAH builds a AA-Mobile-Node-Answer (AMA) message containing the Registration Reply message and the keys (k_{FA-MN} and k_{FA-HA}). Then the AAAH forwards this message to the AAAF, which relays it to the GFA. The GFA extracts Registration Reply message and keys (k_{FA-MN} and k_{FA-HA}) from received AMA and sends Registration Reply message to the FA, which forwards it to the MN. The MN in turn uses nonces (n_{MN-FA} and n_{MN-HA}) to derive keys (k_{MN-FA} and k_{MN-HA}).

Regional registration. If the MN moves to a FA located in the same domain the previous FA belongs to, it registers itself by the GFA using regional registration. The regional registration message is authenticated using the MSA between the GFA and the MN established in home registration. In regional registration, the address of local FA is registered to the GFA and the GFA updates the MN's current point of attachment in its visitor list.

Re-authentication. When the validation timer of a key set expires, the MN executes home registration to retrieve a fresh key set.

Obviously, MIP-RR can decrease the number of signaling messages to the home network, and reduce the signaling delay when a MN moves between FAs within the same visited domain. However, the quantified performance improvement enabled by MIP-RR should to be constructed. However, most of existing works comparing the performance of MIP-RR and MIP did not utilize AAA infrastructure and may not be suitable for the real situation. Wa and Fang [10] introduced a novel Dynamic Hierarchical mobility management strategy for MIP networks (named DHMIP), where GFAs are dynamically selected for different users and an analytical model is proposed to investigate the performance of DHMIP and MIP. However, this work only considers legacy MIP-RR network where no AAA servers are involved. Diab and his college proposed a MIP Fast Authentication (MIFA) protocol [11] and developed an analytical model to investigate the performance of MIFA, MIP, and MIP-RR. However, this work did not consider key distribution, either. Diab et al. enhanced MIFA in [12] by adopting AAA infrastructure to manage key distribution in MIP-RR. Although the authors elaborated the registration procedure of MIFA for MIP-RR but no analytical model was introduced. To conclude, no research activities developed model to evaluate the performance improvement of MIP-RR when key expiration is considered. In the next section, we propose an analytical model to investigate the performance of handover latency in MIP and MIP-RR.

III. ANALYTICAL MODEL

Suppose that the validation time of a key set, t_v, is exponentially distributed with the density function $f_v(t_v) = \mu_v e^{-\mu_v t_v}$ and the mean $E[t_v] = \frac{1}{\mu_v}$. Let $t_{a,i}$ be the residence time for an MN at subnet i. $t_{a,i}$ are assumed to be exponential i.i.d. random variables with the density function $f_a(t_{a,i}) = \eta_a e^{-\eta_a t_{a,i}}$ and the mean $E[t_{a,i}] = \frac{1}{\eta_a}$. For a homogeneous MIP network, we have for $i \neq j$, $f_a(t_{a,i}) = f_a(t_{a,j}) = f_a(t_a)$.

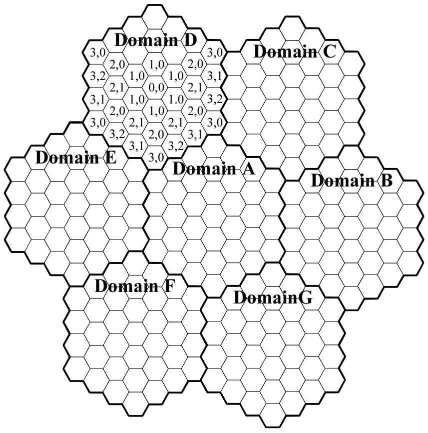

Fig. 4. The topology of network domains and subnets

Let t_A denote the time period when an MN resides in a domain. Suppose that during $t_A^{(m)}$, the MN changes m subnets. Then, $t_A^{(m)} = t_{a,1} + t_{a,2} + \cdots + t_{a,m}$ has the density function

$$f_A^{(m)}(t_A^{(m)})=\int_{t_{a,1}=0}^{t_A^{(m)}}\int_{t_{a,2}=0}^{t_A^{(m)}-t_{a,1}}\cdots\int_{t_{a,m-1}=0}^{t_A^{(m)}-t_{a,1}-\cdots-t_{a,m-2}} \times\left(\prod_{i=1}^{m-1}\eta_a e^{-\eta_a t_{a,i}}\right) \times\eta_a e^{-\eta_a(t_A^{(m)}-t_{a,1}-\cdots-t_{a,m-1})}dt_{a,m-1}\cdots dt_{a,1}. \tag{1}$$

Our analytical model considers a uniform random walk model for the MN's movement, which follows a regular domain/subnet overlay structure as shown in Figure 4. This structure has been widely adopted to simulate the wireless mobile networks in several studies [13], [14]. In this configuration, a r-layer domain is grouped by $3r^2 - 3r + 1$ subnets and Figure 4 shows seven 4-layer domains. The subnet at the center of the domain is called layer 0 subnet. The subnets that surround layer $x - 1$ subnets are called layer x subnets. An r-layer domain overlays subnet from layer 0 to layer $r - 1$.

Based on the assumption that MN moves to each of the neighboring subnets with probability 1/6, the subnets in one domain can be classified into different types [13]. The type format of an subnet is $\langle x, y\rangle$ where "x" indicates that the subnet is in layer x, and "y" represents the $y + 1$st type in layer x. In the model, the state (x, y) represents that the MN is in one of the subnets of type $\langle x, y\rangle$ where $0 \leq x < r$ and $0 \leq y \leq x - 1$. The state (r, j) represents that MN leaves the domain from state $(r - 1, j)$ where $0 \leq j < r - 1$.

Let $p_{(x,y),(x',y')}$ be the one-step transition probability from state (x, y) to state (x', y'), i.e., the probability that the MN moves from a $\langle x, y\rangle$ subnet to a $\langle x', y'\rangle$ subnet in one step. Let $\mathbf{P} = (p_{(x,y),(x',y')})$ be the transition matrix of this random walk model. We use the Chapman-Kolmogorov equation [15] to compute the probability for the number of steps that an MN moves from a domain to another. For $m \geq 1$, let

$$\mathbf{P}^{(m)} = \begin{cases}\mathbf{P}, & \text{if } m = 1,\\ \mathbf{P}\times\mathbf{P}^{(m-1)}, & \text{if } m > 1.\end{cases} \tag{2}$$

An element $p^{(m)}_{(x,y),(x',y')}$ in $\mathbf{P}^{(m)}$ is the probability that the random walk moves from state (x, y) to state (x', y') with exact m steps. Define $p_{m,(x,y),(r,j)}$ as the probability that an MN initially resides at a $\langle x, y\rangle$ subnet, moves into a $\langle r-1, j\rangle$ subnet at the $m-1$st step, and then leaves the domain at the mth step. Then $p_{m,(x,y),(r,j)}$ can be expressed as: for $0 \leq j < r-1$,

$$p_{m,(x,y),(r,j)} = \begin{cases} p_{(x,y),(r,j)}, & \text{for } m = 1, \\ p^{(m)}_{(x,y),(r,j)} - p^{(m-1)}_{(x,y),(r,j)}, & \text{for } m > 1. \end{cases} \tag{3}$$

Equation (3) can be solved using the transition probability matrix $\mathbf{P}$ and equation (2). Let $q_{(r-1,j)}$ be the probability that an MN enters the domain through a $\langle r-1, j\rangle$ subnet at the first step. The $q_{(r-1,j)}$ can be computed from $p_{m,(x,y),(r,j)}$ and readers may refer to [14] for more details. The $q_{(r-1,y)}p_{m,(r-1,y),(r,j)}$ is the probability that an MN enters a domain through a $\langle r-1, y\rangle$ subnet at the first step, moves into a $\langle r-1, j\rangle$ subnet at the $m-1$st step, and then leaves the domain at the mth step. Thus, by using (2), the density function $f_A(t_A)$ for the MN residence time in an r-layer domain is

$$f_A(t_A) = \sum_{m=1}^{\infty}\sum_{y=0}^{r-2}\sum_{j=0}^{r-2} q_{(r-1,y)}p_{m,(r-1,y),(r,j)} f_A^{(m)}(t_A^{(m)}). \tag{4}$$

Let $f_a^*(s)$ be the Laplace transform of $f_a(t_a)$. Then from (2) and the Laplace transform convolution rule, the Laplace transform $f_A^{(m)*}(s)$ for $f_A^{(m)}(\cdot)$ can be computed as follows:

$$f_A^{(m)*}(s) = \left[f_a^*(s)\right]^m. \tag{5}$$

From (4) and (5), the Laplace transform of $f_A(t_A)$ is

$$f_A^*(s) = \sum_{m=1}^{\infty}\sum_{y=0}^{r-2}\sum_{j=0}^{r-2} q_{(r-1,y)}p_{m,(r-1,y),(r,j)} \left[f_a^*(s)\right]^m. \tag{6}$$

Since t_a is exponentially distributed, the Laplace transform of $f_a^*(s)$ is $\frac{\eta_a}{\eta_a+s}$, and then (6) is rewritten as

$$f_A^*(s) = \sum_{m=1}^{\infty}\sum_{y=0}^{r-2}\sum_{j=0}^{r-2} q_{(r-1,y)}p_{m,(r-1,y),(r,j)} \left(\frac{\eta_a}{\eta_a+s}\right)^m \tag{7}$$

In the following, we consider the handover latency in regular MIP. In this case, MN requests a new key set when it enters an subnet or when the validation timer of the old key set expires. Let t_l be the life time of a key set. If the validation timer of this key set expires after the MN moves to another subnet (i.e., $t_v > t_a$), then t_l of this key set is equal to the subnet residence time (i.e., $t_l = t_a$). If not, $t_l = t_v$. The remaining residence time in this subset after the MN retrieves a new key set is defined as τ_a. Thus, the life time of the next key is $min(t_v, \tau_a)$. From [16], the density function $r_a(\tau_a)$ for the distribution of τ_a can be obtained as follows:

$$r_a(\tau_a) = \eta_a \int_{t_a=\tau_a}^{\infty} f_a(t_a) = \eta_a\left[1 - F_a(t_a)\right]\Big|_{t_a=\tau_a},$$

where F_a is the distribution function of t_a. Since t_a is exponentially distributed, τ_a and t_a have the same distribution, and thus $t_l = \min(t_v, t_a)$. Then from [17], the density function $f_l(t_l)$ of t_l is

$$f_l(t_l) = (\mu_v + \eta_a)e^{-(\mu_v+\eta_a)t_l}.$$

Let N_M be the number of key-set retrievals from AAAH while the MN resides in a domain, and $\Pr[N_M = n]$ be the probability that there are n key-set retrievals from AAAH. $\Pr[N_M = n]$ can be derived as follows:

$$\begin{aligned}\Pr[N_M = n] &= \int_{t_A=0}^{\infty}\left\{\frac{[(\mu_v+\eta_a)t_A]^n}{n!}\right\} e^{-(\mu_v+\eta_a)t_A} f_A(t_A)dt_A \\ &= \left[\frac{(\mu_v+\eta_a)^n}{n!}\right]\int_{t_A=0}^{\infty} t_A^n f_A(t_A) e^{-(\mu_v+\eta_a)t_A}dt_A \\ &= \left[\frac{(\mu_v+\eta_a)^n}{n!}\right](-1)^n\left[\frac{d^n f_A^*(s)}{ds^n}\right]\Bigg|_{s=\mu_v+\eta_a}.\end{aligned} \tag{8}$$

From 7, $\frac{d^n f_A^*(s)}{ds^n}$ can be calculated as follows:

$$\begin{aligned}\frac{d^n f_A^*(s)}{ds^n} &= \sum_{m=1}^{\infty}\sum_{y=0}^{r-2}\sum_{j=0}^{r-2} q_{(r-1,y)}p_{m,(r-1,y),(r,j)} \\ &\quad \times\left[\frac{(-1)^n\eta_a^m(m+n-1)!}{(\eta_a+s)^{m+n}(m-1)!}\right].\end{aligned} \tag{9}$$

Applying 9 to 8, 8 can be rewritten as:

$$\begin{aligned}\Pr[N_M = n] &= \sum_{m=1}^{\infty}\sum_{y=0}^{r-2}\sum_{j=0}^{r-2} q_{(r-1,y)}p_{m,(r-1,y),(r,j)} \\ &\quad \times\left[\frac{(m+n-1)!}{n!(m-1)!}\right]\left[\frac{\eta_a^m(\mu_v+\eta_a)^n}{(\mu_v+2\eta_a)^{m+n}}\right].\end{aligned} \tag{10}$$

Then the expected number of N_M for MIP can be obtained by using $E[N_M] = \sum_{n=1}^{\infty} n\Pr[N_M = n]$.

On the other hand, with MIP-RR, if the MN moves to a subnet located in the same domain the previous subnet belongs to, no key set update is needed. The key set is only updated when the MN enters a new domain or the key set expires. In MIP-RR, let $N_{R,hr}$ and $N_{R,rr}$ be the number of key-set retrievals from AAAH and the number of region registration executed locally while the MN resides in a domain, respectively. In the random walk model, the expected number of subnets crossed $E[N_s]$ by a MN within a domain is calculated as follows:

$$E[N_s] = \sum_{m=1}^{\infty}\sum_{y=0}^{r-2}\sum_{j=0}^{r-2} m \times q_{(r-1,y)}p_{m,(r-1,y),(r,j)}.$$

Then $E[N_{R,rr}] = E[N_s] - 1$ since when the MN moves into a new domain at first time, the MN executes home registration in MIP-RR. Obviously, $E[N_{R,hr}] = E[N_M] - E[N_{R,rr}]$.

For simplification, we denote t_{x-y} be the time required to transmit a MIP control message from node x to node y. Let t_M, $t_{R,hr}$, and $t_{R,rr}$ denote the control message transmission time for traditional MIP, home registration in MIP-RR, and regional registration in MIP-RR, respectively. Obviously, $t_M = 2(t_{MN-FA} + t_{FA-AAAF} +$

TABLE I
PARAMETERS SETUP

Parameter	Value	Parameter	Value
t_{MN-FA}	$3ms$	t_{FA-GFA}	$2ms$
$t_{GFA-AAAF}$	$5ms$	$t_{FA-AAAF}$	$5ms$
$t_{AAAF-AAAH}$	$30ms$	$t_{AAAH-HA}$	$5ms$
t_M	$86ms$	$t_{R,hr}$	$10ms$
$t_{R,rr}$	$90ms$		

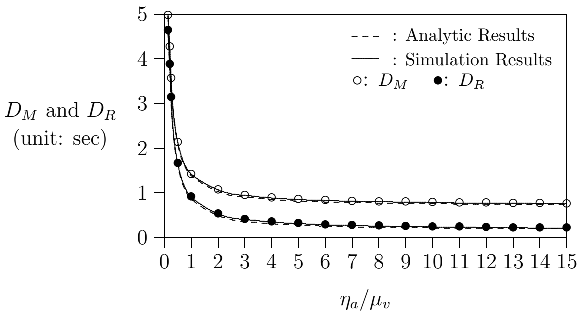

Fig. 5. Effects of η_a/μ_v on D_M and D_R

$t_{AAAF-AAAH} + t_{AAAH-HA})$, $t_{R,hr} = 2(t_{MN-FA} + t_{FA-GFA} + t_{GFA-AAAF} + t_{AAAF-AAAH} + t_{AAAH-HA})$, and $t_{R,rr} = 2(t_{MN-FA} + t_{FA-GFA})$. Then the handover latency D_M and D_R for MIP and MIP-RR respectively while the MN resides in a domain can be calculated as follows:

$$D_M = E[N_M]t_M \tag{11}$$

$$D_R = E[N_{R,hr}]t_{R,hr} + E[N_{R,rr}]t_{R,rr} \tag{12}$$

IV. NUMERICAL AND SIMULATION RESULTS

In this section, we develop simulation experiments to validate the correctness of the proposed model. The simulation technique used in this paper is the event-driven approach, which has been widely used in many wireless network studies [14], [18]. The experiments simulate the movement of an MN on the hexagonal plane, where the MIP network consists of two-layer subnets and domains. In the experiments, the MN starts from an arbitrary subnet, resides in this subnet for a period, then moves to one of its neighbors with probability $1/6$. We calculate the handover latency for intra-domain mobility and adopt MIP to support inter-domain mobility. The parameters setup for this simulation is shown in Table I. Figure 5 plots D_M and D_R in terms of η_a/μ_v for the analytical model and simulation experiment. This figure indicates that the simulation result and analytical result are consistent.

This figure shows that both D_M and D_R decrease when η_a/μ_v increases. It is due to that when η_a/μ_v increases, a MN has more chance to leave a domain and thus the number of handover occurred during the period the MN stays in a domain decreases, thus the handover delay decreases. Another observation is that the improvement ratio from MIP to MIP-RR (denoted as D_R/D_M) increases as η_a/μ_v increases.

When η_a is larger, a MN has higher micro mobility. With MIP, each time the MN changes subnets, the regular registration procedure is executed and the corresponding handover delay is large. On the other hand, with MIP-RR, the benefits of regional registration is leveraged, and thus the handover delay is small. The improvement ratio is approximately 3.30 when $\eta_a/\mu_v = 10$. When μ_v is larger, the MN remains static and may stay in a subnet for a long time. In this case, both MIP-RR and mobile IP retrieve key from AAAH (caused by re-authentication in most cases), and thus D_R/D_M becomes small (equals to 1.10 when $\eta_a/\mu_v = 0.2$).

V. CONCLUSION

This paper proposed a complete analytical model and conducted simulation experiments to study the performance of registration procedure for MIP and MIP-RR with AAA infrastructure in terms of handover delay D_M and D_R while the MN resides in a domain. Our study on handover delay improvement from MIP-RR demonstrates that when η_a increases, D_R/D_M increases. The complete performance analysis for MIP-RR with AAA infrastructure has never been treated in the previous studies. This study can be considered as the first one providing such analysis and simulation validates its correctness.

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