# Hierarchical Location Management for Transport Layer Mobility

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# Hierarchical Location Management for Transport Layer Mobility

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*Abstract*— **IP mobility can be handled at different layers of the protocol stack. Mobile IP has been developed to handle mobility of Internet hosts at the network layer. As an alternative solution, a number of transport layer mobility protocols have been proposed, for example, MSOCKS and TCP connection migration solution in the context of TCP, and M-SCTP and mobile SCTP in the context of SCTP. More recently, a new protocol called Seamless IP diversity based Generalized Mobility Architecture (`SIGMA`) was proposed to support low latency, low packet loss IP mobility. The location management schemes used in these transport layer solutions are not suitable for frequent mobile handovers due to user's high mobility. In this paper, we propose `HiSIGMA`, a hierarchical location management scheme for transport layer mobility schemes. We develop an analytical model to evaluate `HiSIGMA` using signaling cost as the performance measure, followed by comparison of the signalling cost of `HiSIGMA` and Hierarchical Mobile IPv6 (an enhancement of Mobile IP). Numerical results have shown that signaling cost of `HiSIGMA` is lower than that of HMIPv6.**

## I. INTRODUCTION

There are solutions to IP mobility at different layers of the protocol stack. Mobile IP (MIP) [1] is designed to handle mobility of Internet hosts at the network layer. Several drawbacks exist when using MIP in a mobile computing environment, the most important ones identified to date are high handover latency, high packet loss rate [2], and requirement for change in infrastructure. Mobile IP is based on the concept of Home Agent (HA) and Foreign Agent (FA) (which requires modification to existing routers in Internet) for routing packets from previous point of attachment to the new one.

As the amount of real-time traffic over wireless networks keeps growing, the deficiencies of the network layer based Mobile IP, in terms of high latency and packet loss, becomes more obvious. Since most of the applications in the Internet are end-to-end, a transport layer mobility solution would be a natural candidate for an alternative approach. A number of transport layer mobility protocols have been proposed, for example, MSOCKS [3] and connection migration solution [4] in the context of TCP, and M-SCTP [5] and mobile SCTP [6] in the context of SCTP [7]. More recently, the authors in [8] described the architecture of a new scheme for supporting low latency, low packet loss mobility scheme called Seamless IP diversity based Generalized Mobility Architecture (`SIGMA`), and evaluated its handover performance compared with MIPv6 enhancements. These protocols implement mobility as an end-to-end service without the requirement to change the network layer infrastructures; they, however, did not thoroughly studied the location management scheme can be used in transport layer mobility solutions. These previous studies mainly focuses on how to provide the mobility support in an end-to-end architecture [3], [4], [5], [6] or reduce the mobile handover latency utilizing IP diversity [8]. They only briefly outlined the some simple form of location management method. Transport layer mobility solutions proposed in [4], [5], [6], [8] needs to setup a location manager for maintaining a database of the correspondence between MH's identity and its current active IP address. If domain name is used as MH's identity, the functionality of location manager can be merged into a DNS server. The idea of using a DNS server to locate mobile users can be traced back to [9]. The advantage of this approach is its transparency to existing network applications that use domain name to IP address mapping. An Internet administrative domain can allocate one or more location servers for its registered mobile users.

Take `SIGMA` proposed in [8] as an example, the basic form of location management in transport layer mobility schemes can be done in the following sequence as shown in Fig. 1: (1) MH updates the location manager with the current primary IP address. (2) When CN wants to setup

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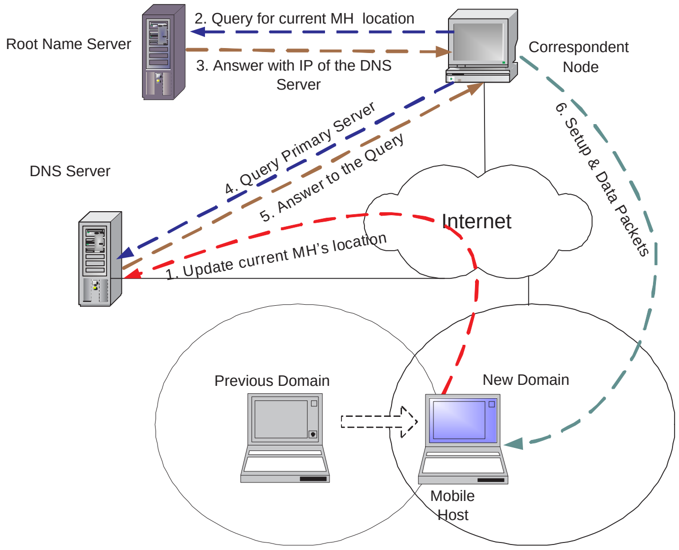

Fig. 1. Basic form of location management in SIGMA

a new association with MH, CN sends a query to the root name server with MH's domain name. (3) Root name server replies to CN with the IP address of the name server managing the DNS zone to which MH belongs. (4) CN query the name server referred by the root name server. (5) Name server replies with the current primary IP address of MH. (6) CN initiates the handshake sequence with MH's new primary IP address to setup the association. The location management schemes used in [3], [4], [8] are not suitable for frequent mobile handovers due to user's high mobility. The reasons are as follows:

- There is a race condition between (Location Manager) LM database update caused by the change of MH's point of attachment and the arrival of association setup request from CN. The higher the Round Trip Time (RTT) between MH and LM is, the larger probability that CN get a stale information from the database at LM, which will result in MH being inaccessible from CN.
- Performing location update on LM whenever MH changes its location may be too costly and time-consuming for LM to process. Too many signaling messages exchanged in the network wastes network bandwidth and may result in unnecessary congestions.
- DNS servers commonly cache DNS replies to reduce the signaling load on network and response time to CN. Each DNS reply is associated with a Time-To-Live (TTL) field indicating the valid period of the cached DNS reply. During the TTL period, the DNS server with cache could answer additional requests for the MH's location from its local cache instead of querying LM again. Thus, even after MH has updated its location with LM, the CN's DNS server could still reply with the old location until the cached entry's TTL expire. This will also lead to MH being inaccessible from CN.

The *objective* of this paper is to propose a hierarchical location management scheme for transport layer mobility solutions to reduce the possibility that MH is inaccessible from CNs and the processing load on LM. The contributions of our paper can be outlined as follows:

- Propose and develop a hierarchical location management scheme for transport layer mobility protocols.
- Evaluate and compare the signaling cost of proposed the hierarchical management scheme with that of HMIPv6 [10] using analytical models. We choose HMIPv6 as the benchmark protocol for signaling cost comparison because HMIPv6 is designed to reduce the signaling cost of base MIPv6, and it has the lowest signaling cost in all versions of MIPv6 enhancements.

The authors are not aware of any *previous studies for hierarchical location management for transport layer mobility solutions*. For instance, the signaling cost, which is a very important performance measures for a location management scheme, is not investigated by the authors of [3], [4], [5], [6], [8]. The rest of this paper is structured as follows: Sec. II describes the hierarchical location management scheme including its architecture, timeline, and state machine. The network structure, mobility model, and arrival traffic model for signaling cost evaluation is presented in Sec. III. The full analytical models for HiSIGMA and HMIPv6 are presented in Secs. IV and V, respectively. The results of signaling cost comparison of HiSIGMA and HMIPv6 is presented in Sec. III. Finally, concluding remarks are presented in Sec. VII.

## II. HIERARCHICAL LOCATION MANAGEMENT OF TRANSPORT LAYER MOBILITY

In this section, we introduce hierarchical location management for transport layer mobility. Since we use SIGMA as the base architecture for introducing hierarchical location management, we call the proposed scheme as HiSIGMA. However, the principle of HiSIGMA also applies to other transport layer mobility solutions such as [3], [4].

### A. *Architecture of* HiSIGMA

A new entity called Anchor Zone Server needs to be introduced in HiSIGMA as shown in Fig. 2. MH

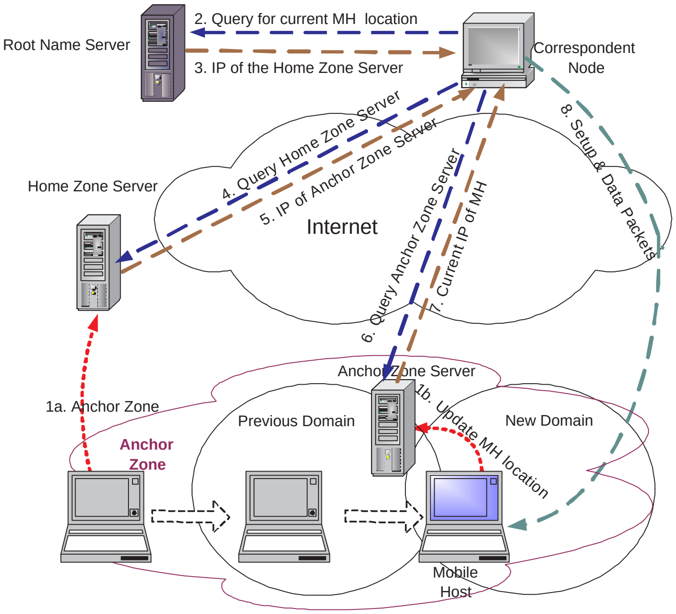

Fig. 2. Hierarchical location management in HiSIGMA

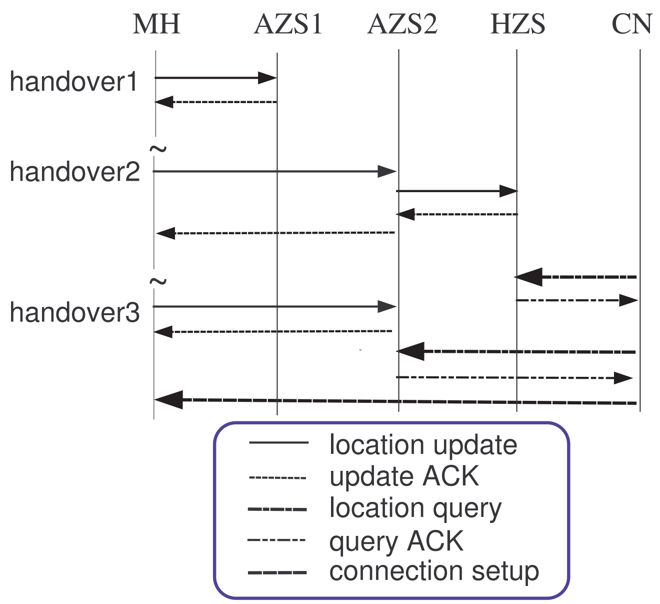

Fig. 3. Time line of HiSIGMA

only needs to update the Home Zone Server when it enters a new Anchor Zone. Otherwise, MH need only to update the Anchor Zone Server with its current location. Whenever Home Zone Server receives a location query for MH, it will answer with the registered Anchor Zone Server's IP address. This approach will reduce the location update latency and signaling cost while improve the accuracy of the location management. The hierarchical location management can be done in the following sequence as shown in Fig. 2:

1) a. When MH enters into a new DNS zone, MH updates the HZS with the IP address of new attached AZS. b. When MH moves between IP domains within the region managed by a specific AZS, MH only updates AZS.
2) When CN wants to setup a new association with MH, CN sends a query to the root name server with MH's domain name.
3) Root name server replies to CN with the IP address of the HZS.
4) CN query the HZS referred by the root name server.
5) HZS replies with the IP address of current AZS where MH resides.
6) CN query the AZS referred by the HZS.
7) AZS replies with the current IP address(es) of MH.
8) CN initiates the handshake sequence with MH's current IP address to setup the association.

The timeline for three handovers in HiSIGMA is shown in Fig. 3, where handover1 and handover3 are intra-AZS handovers within AZS1 and AZS2, respectively. And handover2 is an inter-AZS handover which requires an update to HZS server. The signaling messages for CN querying MH's location and setting up a connection with MH are also shown in Fig. 3.

### B. State machine at AZS

During the movement of MH, the IP address used by MH keeps changing. Furthermore, in schemes like SIGMA, the number of IP addresses that MH have also varies, sometimes one and sometimes two [8]. MH may also have its preference on which IP should be used at a particular time based on application characteristics (e.g. VoIP or data) and cost constraints (e.g. satellite links are generally more expensive than WLAN). To support this kind of desirable flexibility and optimize the performance of location management for transport layer mobility solutions that support IP diversity like SIGMA, a state machine is introduced at AZS. For the schemes in which mobile hosts do not support IP diversity, the hierarchical location management is still useful, but the lack of this state machine may result in non-optimal results.

It is necessary for AZS to have a clear idea on which IP address(es) should be used and which one has priority when multiple IP are available. In HiSIGMA, this goal is achieved by multicasting the IP reconfiguration information of MH to CN and AZS. When MH send IP reconfiguration signaling messages to CN, MH should also send a copy to AZS. These messages could include [8]:

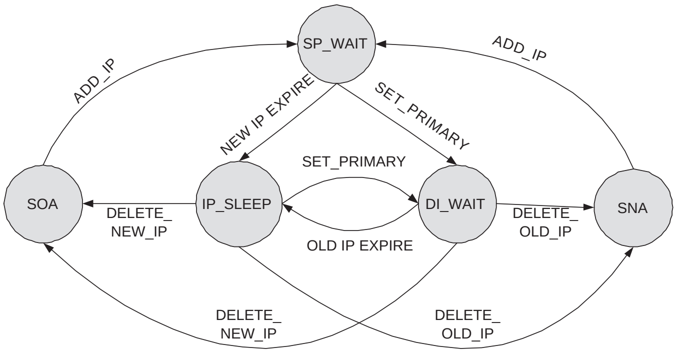

Fig. 4. State machine at AZS

- Add new IP into association between MH and CN (ADD_IP).
- Designate one of the available IP addresses as the primary destination address (SET_PRIMARY).
- Delete obsolete IP address (DELETE_IP).

. These signaling messages are used to construct a state machine at AZS to better reflect the current location status of MH.

The state machine at AZS is shown in Fig. 4. The state machine works as follows:

- If MH has only one IP address assigned from the old domain or new domain, the AZS is in `SOA` (Single Old Address) or `SNA` (Single New Address) state, respectively.
- If current state is `SOA` or `SNA`, an `ADD_IP` message received from MH will trigger the machine to transfer into `SP_WAIT` state, which means that AZS is waiting for a `SET_PRIMARY` message.
- If current state is `SP_WAIT` or `IP_SLEEP`, a `SET_PRIMARY` message received from MH will trigger the machine to transfer into `DI_WAIT` state, which means that AZS is waiting for a `DELETE_IP` message.
- If current state is `SP_WAIT`, and the timer associated with the new IP just added into the association expires before a `SET_PRIMARY` message is received, the machine transfer into `IP_SLEEP` state, which means that the IP is marked as inactive and should not be advertised to CN.
- If current state is `DI_WAIT` or `IP_SLEEP`, and a `DELETE_IP` message is received from MH with the old IP address as the target IP being deleted, it will trigger the machine to transfer into `SNA` state. Similarly, if a `DELETE_IP` message is received with the new IP address as the target IP being deleted, it will trigger the machine to transfer into `SOA` state.
- If current state is `DI_WAIT`, and the timer associated with the old IP waiting to be deleted expires before a `DELETE_IP` message is received, the machine transfer into `IP_SLEEP` state, which means that the old IP is marked as inactive and should not be advertised to CN.

### *C. Location query replies sent to CN by AZS*

One of the most important objectives of location management is to accurately pointer CN to the current location of MH. We utilize the sate machine at AZS to improve this accuracy. The reply sent by AZS to CN depends on the current state of AZS as described below.

- *SOA or SNA*: Only one IP available at MH, just send MH's IP to CN.
- *SP_WAIT*: Send both MH's new and old IP to CN, old IP has higher priority.
- *DI_WAIT*: Send both MH's new and old IP to CN, new IP has higher priority.
- *IP_SLEEP*: Only one IP active at MH, send current MH's active IP to CN.

When CN receives a location reply with multiple entries of MH's IP address, it will first try the first entry. If the association setup using first entry fails, CN will automatically try the second entry.

## III. MODELLING PREPARATION

In this section, we lay down the ground for signaling cost analysis of mobility protocols. First, the network structure being considered, assumptions, and the notations to be used in the model are presented in Secs. III-A, III-B and III-C, respectively. Then the mobility model and arrival traffic model that will be used in this paper are described in Secs. III-D and III-E, respectively.

### *A. Network structure*

Fig. 5 shows a two dimensional subnet arrangement for modeling MH movement, where $\mathrm{AR}_{1,1}, \cdots \mathrm{AR}_{m,n}$ represent access routers. There are $k$ AZSs, each of which covers $R$ subnets. There are also one HZS (same as HA in the case of HMIPv6) and a number of CNs connected to the Internet. The MHs are roaming in the subnets covered by $\mathrm{AR}_{1,1}, \cdots \mathrm{AR}_{m,n}$, and each MH communicates with one or more of the CNs. Between a pair of MH and CN, intermittent file transfers occur caused by mobile users requesting information from CNs using protocols like HTTP. We call each active transfer period during the whole MH-CN interactivity as a session.

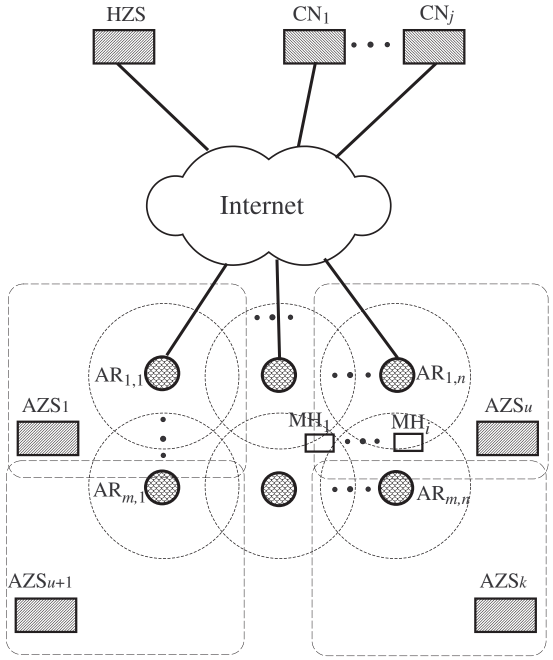

Fig. 5. Network structure considered.

### B. Model assumptions

We make the following assumptions for developing the analytical model of `HiSIGMA` signaling cost:

- In the previous study of P-MIP signaling cost analytical model [11], the session time is assumed to be Pareto distribution and the session arrival is assumed to be *Poisson* distribution. In our modeling process, Both session time and session interval time are of *Pareto* distribution to better model HTTP traffic [12], [13], which is dominant in current Internet traffic load. The *Pareto* distribution is a heavy-tailed distribution, and it can be characterized with two parameters: minimum possible value ($\kappa$), and a heavy-tailness factor ($\sigma$).
- Mobile host moves according to Random Waypoint model [14], which is the most frequently used model in mobile networking research. In this mobility model, a MH randomly selects a destination point in the topology area according to uniform distribution, then moves towards this point at a random speed again uniformly selected between ($v_{min}$, $v_{max}$). This one movement is called an *epoch*, and the elapsed time and the moved distance during an epoch are called *epoch time* and *epoch length*, respectively. At destination point, the MH will stay stationary for a period of time, called *pause time*, after that a new epoch starts.
- Processing costs at the endpoints (MH and CN) are not counted into the total signaling cost since these costs stand for the load that can be scattered into user terminals. Because we are more concerned about the load on the network elements, this assumption enables us to concentrate on the impact of protocol on the network performance. This same assumption was also made by other previous works [15], [11], [16].

### C. Notations

The notations to be used for developing the analytical models of `HiSIGMA` and HMIPv6 are given below. They are divided into three categories depending on whether they are required for `HiSIGMA`, HMIPv6 or both. For the sake of consistency, the notations for HMIPv6 modeling are similar to those used in [15].

*1) Notations that apply to both* `HiSIGMA` *and HMIPv6 signaling cost models:*

| | |
|---|---|
| $N_{mh}$ | total number of MHs. |
| $N_{cn}$ | average number of CNs with which a MH is communicating. |
| $D_{pq}$ | average propagation and queuing delay per hop. |
| $E[T]$ | expected value of *epoch time*. |
| $E[P]$ | expected value of MH pause time between movements. |
| $E[L]$ | expected value of *epoch length*. |
| $E[C]$ | expected number of subnet crossings per *epoch*. |
| $v$ | moving speed of MH. |
| $T_r$ | MH residence time in a subnet. |
| $T_s$, $T_i$ | session time and session interval time. |
| $S$ | number of sessions during an MH-CN transport layer association (connection) time. |
| $\kappa_s$, $\kappa_i$ | minimum session time and session interval time. |
| $\sigma_s$, $\sigma_i$ | heavy-tailness factor for session time and session interval time. |
| $BW_{mc}$ | bottleneck bandwidth between CN and MH. |
| $\lambda_{sa}$, $\lambda_{pa}$ | average session arrival rate and packet arrival rate |
| $\phi$ | session-mobility ratio defined as $\lambda_{sa} \times T_r$. |

*2) Notations that apply only to* `HiSIGMA` *signaling cost modeling:*

| | |
|---|---|
| $l_{ma}$, $l_{mc}$ | average distance from MH to AZS and CN in hops. |
| $l_{al}$ | average distance from AZS to HZS in hops. |
| $LU_{ml}$, $LU_{ma}$ | transmission cost of one location update from MH to HZS and AZS. |
| $AU_{ma}$ | transmission cost of dynamic address reconfiguration messages from MH to AZS. |
| $\gamma_l$, $\gamma_a$ | processing cost at location manager and AZS for each location update, respectively. |

| | |
|---|---|
| $v_l$, $v_a$ | location database lookup cost per second for each transport layer association at HZS and AZS, respectively. |
| $C_{ml}$ | registration cost of one location update from MH to HZS, including transmission cost and processing cost: $C_{ml} = 2LU_{ml} + \gamma_l + 2\gamma_a$. |
| $C_{ma}$ | registration cost of one location update from MH to AZS, including transmission cost and processing cost: $C_{ma} = 2LU_{ma} + \gamma_a$. |
| $M^T$ | threshold of subnet crossings below which a local registration is performed in `HiSIGMA`. |
| $R^T$ | number of subnets managed by an AZS. |
| $\Psi^T_{LU}$ | `HiSIGMA` location update cost per second for the whole system, including transmission cost and processing cost incurred by location update of all MHs. |
| $BU_{mc}$ | transmission cost of one binding update between MH and CN. |
| $\Psi^T_{BU}$ | `HiSIGMA` binding update cost per second between MHs and CNs for the whole system, $\Psi^T_{BU} = N_{mh}N_{cn}\frac{BU_{mc}}{T_r}$. |
| $\Psi^T_{PD}$ | `HiSIGMA` packet delivery cost per second from CNs to MHs for the whole system. |
| $\Psi^T_{TOT}$ | `HiSIGMA` total signaling cost per second for the whole system including location update cost, binding update cost and packet delivery cost, $\Psi^T_{TOT} = \Psi^T_{LU} + \Psi^T_{BU} + \Psi^T_{PD}$. |

*3) Notations that apply only to HMIPv6 signaling cost modeling:*

| | |
|---|---|
| $l_{mh}$ | average distance between MAP and HA in hops. |
| $l_{mm}$ | average distance between MH and MAP in hops. |
| $LU_{mh}$ | transmission cost of one location update from MH to HA. |
| $LU_{mm}$ | transmission cost of one location update from MH to MAP. |
| $\gamma_h$, $\gamma_m$ | processing cost for each location update at HA and MAP, respectively. |
| $v_h$, $v_m$ | processing cost for each data packet at HA and MAP, respectively. |
| $C_{mh}$ | registration cost of one location update from MH to HA, including transmission cost and processing cost: $C_{mh} = 2LU_{mh} + \gamma_h + 2\gamma_m$. |
| $C_{mm}$ | registration cost of one location update from MH to MAP, including transmission cost and processing cost: $C_{mm} = 2LU_{mm} + \gamma_m$. |
| $M^H$ | threshold of subnet crossings below which a local registration is performed in HMIPv6. |
| $R^H$ | number of subnets under a MAP. |
| $\Psi^H_{LU}$ | HMIPv6 location update cost per second for the whole system which includes transmission cost and processing cost incurred by location update of all MHs to their HA and/or MAP, $\Psi^H_{LU} = N_{mh}\frac{MC_{mm}+C_{mh}}{MT_r}$. |
| $\Psi^H_{PD}$ | HMIPv6 packet delivery cost per second for the whole system from CNs to MHs, including the encapsulation/decapsulation processing cost at mobile agents. |
| $\Psi^H_{TOT}$ | total HMIPv6 signaling cost per second for the whole system including location update cost, binding update cost and packet delivery cost, $\Psi^H_{TOT} = \Psi^H_{LU} + \Psi^H_{PD}$. |

### D. Mobility model

The objective of this section is to find the average residence time ($T_r$) for MH in a subnet. With this parameter, we know the frequency for MH to change the point of attachment, therefore the frequency of updating HZS, AZS and CN. $T_r$ can be estimated by the time between two successive movements (*epoch time* plus *pause time*) divided by the number of subnet crossing during this epoch, as shown in Eqn. (1):

$$T_r = \frac{E[T] + E[P]}{E[C]} \tag{1}$$

We first compute $E(T)$, since *epoch length* $L$ and movement speed $v$ are independent:

$$E[T] = E\left[L/v\right] = E[L]E[1/v] \tag{2}$$

Since the moving speed is of uniform distribution between ($v_{min}$, $v_{max}$), we have:

$$\begin{aligned} E[1/v] &= \int_{v_{min}}^{v_{max}} (1/v)\frac{1}{v_{max} - v_{min}}dv \\ &= \frac{ln(v_{max}/v_{min})}{v_{max} - v_{min}} \end{aligned} \tag{3}$$

In order to determine $E[L]$ and $E[C]$, we assume an arrangement of circular subnets in a rectangular topology as shown in Fig. 6, where $m$, $n$ are the number of vertically and horizontally arranged subnets in the topology, respectively. From [14], we know that $E[L]$ for a rectangular area of size $a \times b$ can be estimated as:

$$\begin{aligned} E[L] &= \frac{1}{15}\left[\frac{a^3}{b^2} + \frac{b^3}{a^2} + \sqrt{a^2+b^2}\left(3 - \frac{a^2}{b^2} - \frac{b^2}{a^2}\right)\right] \\ &+ \frac{1}{6}\left[\frac{b^2}{a}\Phi\left(\frac{\sqrt{a^2+b^2}}{b}\right) + \frac{a^2}{b}\Phi\left(\frac{\sqrt{a^2+b^2}}{a}\right)\right] \end{aligned} \tag{4}$$

where $\Phi(\cdot) = \ln\left(\cdot + \sqrt{(\cdot)^2 - 1}\right)$.

Now we can get $E[T]$ by combining Eqns. (2), (3) and (4). Since pause time has been assumed to be uniformly distributed between (0, $P_{max}$), we have:

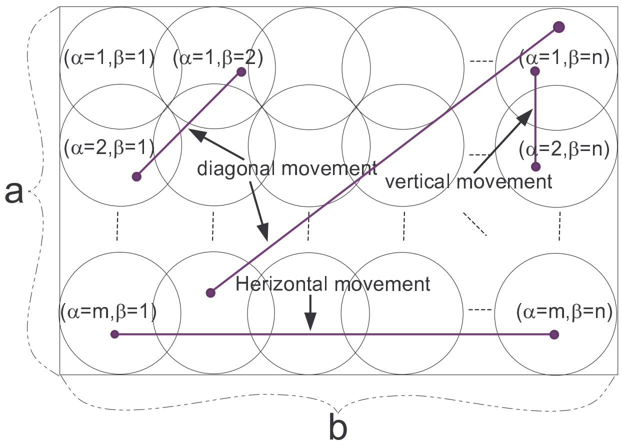

Fig. 6. Arrangement of subnets in a rectangular topology

$$E[P] = \int_0^{P_{max}} \frac{P}{P_{max}} dP = P_{max}/2 \tag{5}$$

Next, we need to find $E(C)$, the general form of which can be expressed as [14]:

$$E[C] = \frac{1}{m^2n^2} \sum_{\alpha_j=1}^{m} \sum_{\beta_j=1}^{n} \sum_{\alpha_i=1}^{m} \sum_{\beta_i=1}^{n} C\begin{pmatrix} (\alpha_i, \beta_i) \\ (\alpha_j, \beta_j) \end{pmatrix} \tag{6}$$

The value $C\begin{pmatrix} (\alpha_i, \beta_i) \\ (\alpha_j, \beta_j) \end{pmatrix}$ is the number of subnet crossings caused by one movement between subnet $(\alpha_i, \beta_i)$ to $(\alpha_j, \beta_j)$, which depends on the actual subnet shape and arrangement. Consider the circular subnet arrangement as shown in Fig. 6, we can observe three kind of movements: horizontal, vertical and diagonal. $C\begin{pmatrix} (\alpha_i, \beta_i) \\ (\alpha_j, \beta_j) \end{pmatrix}$ can be generalized by the following Manhattan distance metric:

$$C\begin{pmatrix} (\alpha_i, \beta_i) \\ (\alpha_j, \beta_j) \end{pmatrix} = |\alpha_i - \alpha_j| + |\beta_i - \beta_j| \tag{7}$$

By substituting Eqn. (7) into Eqn. (6), we can get the expression for $E[C]$:

$$E[C] = \frac{1}{m^2n^2} \sum_{\alpha_j=1}^{m} \sum_{\beta_j=1}^{n} \sum_{\alpha_i=1}^{m} \sum_{\beta_i=1}^{n} (|\alpha_i - \alpha_j| + |\beta_i - \beta_j|) \tag{8}$$

Substituting Eqns. (2), (5) and (8) into Eqn. (1), we can get the expression for $T_r$.

### *E. Arrival traffic model*

The objective of this section is to find the average session arrival rate ($\lambda_{sa}$) and packet arrival rate ($\lambda_{pa}$). As discussed in Sec. III-B, both session time and session interval time are of *Pareto* distribution. The PDF function of session time distribution is [12]:

$$f_{T_s}(t) = \frac{\sigma_s \kappa_s^{\sigma_s}}{t^{(\sigma_s+1)}} \tag{9}$$

where $\sigma_s = 1.2$, and $\kappa_s$ can be estimated as:

$$\kappa_s = \frac{10\text{KB}}{BW_{mc}} + l_{mc}D_{pq} \tag{10}$$

Also from [12], we know session interval time has a PDF function of:

$$f_{T_i}(t) = \frac{\sigma_i \kappa_i^{\sigma_i}}{t^{(\sigma_i+1)}} \tag{11}$$

where $\sigma_i = 1.5$, and $\kappa_i = 30s$.

Consider $k$ ($k > 0$) consecutive user session arrivals (the start of the session $k+1$ means the end of the session $k$ plus an interval time) as shown in Fig. 7, the total time for $k$ sessions can be calculated as:

$$T_{tot} = k(T_s + T_i) \tag{12}$$

So, the session arrival rate is:

$$\lambda_{sa} = \frac{k}{E(T_{tot})} = \frac{1}{E(T_s) + E(T_i)} \tag{13}$$

From probability theory, since $T_s > 1$ and $T_i > 1$, the expected value of $T_s$ and $T_i$ are:

$$E[T_s] = \int_0^{\infty} t f_{T_s}(t)dt = \frac{\kappa_s\sigma_s}{\sigma_s - 1} \tag{14}$$

$$E[T_i] = \int_0^{\infty} t f_{T_i}(t)dt = \frac{\kappa_i\sigma_i}{\sigma_i - 1} \tag{15}$$

By substituting Eqns. (14) and (15) into Eqn. (13), we can get the average session arrival rate.

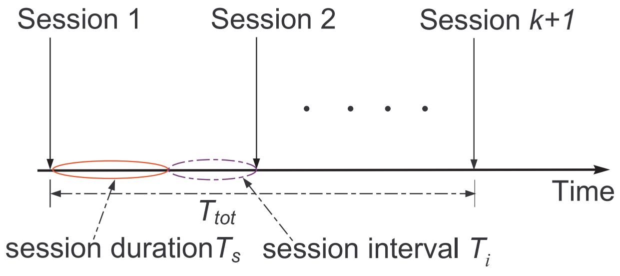

Fig. 7. Session arrival illustration.

## IV. SIGNALING COST ANALYSIS OF `HiSIGMA`

In this section, the signaling cost of `HiSIGMA` will be analyzed. Subsections IV-A, IV-B, and IV-C develop the cost for location update, binding update and packet delivery, respectively. Finally, subsection IV-D gives the total signaling cost of `HiSIGMA`.

### A. Location update cost

In `HiSIGMA`, an MH does not need to register with the HZS until the MH moves out of the region covered by an AZS, instead it only registers with the AZS. Therefore, every subnet crossing within a AZS (happens every $T_r$ seconds) will trigger a registration to the AZS, which incurs a transmission cost to AZS ($LU_{ma}$) and processing cost at AZS ($\gamma_a$) of the location update message. Also, MH needs to update its current AZS with its dynamic address configuration messages to maintain the state machine at the AZS. Therefore, $C_{ma} = LU_{ma} + \gamma_a + AU_{ma}$.

For every region crossing between AZSs (happens every $M \times T_r$ seconds), MH needs to register with HZS, which incurs a transmission cost to HZS ($LU_{ml}$), processing cost at HZS ($\gamma_l$), and processing cost at AZS ($2\gamma_a$, since AZS needs to process both registration request and reply messages). Therefore, $C_{ml} = LU_{ml} + \gamma_l + 2\gamma_a$.

Since there is only one location update per subnet crossing, no matter how many CNs an MH is communicating with, the number of CNs does not have any impact on the location update cost. Therefore, the average location update cost per second in the whole system can be estimated as the number of MHs multiplied by the location update cost for each MH:

$$\Psi_{LU}^{T} = N_{mh} \frac{M^T C_{ma} + C_{ml}}{M^T T_r} \tag{16}$$

$M^T$ can be calculated from the total number of subnets ($m \times n$) and the number of subnets beneath a AZS ($R^T$): [15]:

$$M^T = 1 + \frac{mn - 1}{mn - R^T} \tag{17}$$

Due to frame retransmissions and medium access contentions at the data link layer of wireless links, transmission cost of a wireless hop is higher than that of a wired hop; we denote this effect by a proportionality constant, $\rho$. Let the per-hop location update and dynamic address reconfiguration transmission cost be $\delta_U$ and $\delta_A$, respectively. For a round trip, $LU_{ma}$, $AU_{ma}$ and $LU_{ml}$ can be calculated as:

$$LU_{ma} = 2(l_{ma} - 1 + \rho)\delta_U \tag{18}$$

$$AU_{ma} = 2(l_{ma} - 1 + \rho)\delta_A \tag{19}$$

$$LU_{ml} = 2(l_{ma} + l_{al} - 1 + \rho)\delta_U \tag{20}$$

Where $(l_{ml} - 1)$ represents the number of wired hops. Therefore,

$$\Psi_{LU}^{T} = N_{mh} \Big[ \tfrac{2(l_{ma} - 1 + \rho)(\delta_U + \delta_A) + \gamma_a}{T_r} + \tfrac{2(l_{ma} + l_{al} - 1 + \rho)\delta_U + \gamma_l + 2\gamma_a}{T_r} \times \tfrac{mn - R^T}{2mn - R^T - 1} \Big] \tag{21}$$

### B. Binding update cost

In the analysis of binding update cost, processing costs at the endpoints (MH and CN) are not counted into the total signaling cost, since these costs stand for the load that can be scattered into user terminals and hence do not contribute to the network load. Because we are more concerned about the load on the network elements, this assumption enables us to concentrate on the impact of the handover protocol on network performance. This same assumption was also made by other previous works [15], [11], [16].

Similar to the analysis in Sec. IV-A, every subnet crossing will trigger a binding update to CN, which incurs a transmission cost ($BU_{mc}$) due to the binding update message. For each CN communicating with an MH, the MH need to send a binding update after each handover. Therefore, the average binding update cost can be estimated as:

$$\Psi_{BU}^{T} = N_{mh} N_{cn} \frac{BU_{mc}}{T_r} \tag{22}$$

Let the per-hop binding update transmission cost be $\delta_B$. The $BU_{mc}$ can be calculated as:

$$BU_{mc} = 2(l_{mc} - 1 + \rho)\delta_B \tag{23}$$

Therefore, the binding update cost per second in the whole system can be calculated by multiplying the number of MHs, the average number of communicating CNs, and the average cost per binding update:

$$\Psi_{BU}^{T} = N_{mh} N_{cn} \frac{2(l_{mc} - 1 + \rho)\delta_B}{T_r} \tag{24}$$

### C. Packet delivery cost

Unlike the analysis of packet delivery cost in [15], we do not consider the data packet transmission cost, IP routing table searching cost, and bandwidth allocation cost since these costs are incurred by standard IP switching, which are not particularly related to mobility protocols. Instead, we only consider the location database lookup cost at HZS and AZS. Moreover we take into account the processing cost caused by packet tunnelling to better reflect the impact of mobility protocol on overall network load.

For `HiSIGMA`, a location database lookup at HZS is required when an association is being setup between CN and MH. If each session duration time is independent from each other, the association setup event happens every $S/\lambda_{sa}$ seconds. If we assume the database lookup cost has a linear relationship with $N_{mh}$, and $\varphi_l$ and $\psi$ be the per location database lookup cost and the linear coefficient at HZS, then the per-second per-association lookup cost $\upsilon_l$ can be calculated as:

$$\upsilon_l = \frac{\varphi_l \lambda_{sa}}{S} = \frac{\psi N_{mh} \lambda_{sa}}{S} \tag{25}$$

Let $\varphi_a$ and $\psi$ be the per location database lookup cost and the linear coefficient at AZS, then the per-second per-association lookup cost $\upsilon_a$ can be calculated as:

$$\upsilon_a = \frac{\varphi_a \lambda_{sa}}{S} = \frac{\psi N_{mh} R^T \lambda_{sa}}{mnS} \tag{26}$$

Since `HiSIGMA` is free of packet encapsulation or decapsulation, there is no processing cost incurred at intermediate routers. So the packet delivery cost from CN to MH can be calculated by only counting the location database lookup cost. This cost can be expressed as:

$$\begin{aligned} \Psi^T_{PD} = & \quad N_{mh} N_{cn} (\upsilon_l + \upsilon_a) \\ = & \quad N^2_{mh} N_{cn} \tfrac{\psi \lambda_{sa}}{S} (1 + \tfrac{R^T}{mn}) \end{aligned} \tag{27}$$

### D. *Total signaling cost of* `HiSIGMA`

Based on above analysis on the location update cost, binding update cost, and packet delivery cost shown in Eqns. (21), (24), and (27), we can get the total signaling cost of `HiSIGMA` as:

$$\Psi^T_{TOT} = \Psi^T_{LU} + \Psi^T_{BU} + \Psi^T_{PD} \tag{28}$$

## V. SIGNALING COST ANALYSIS OF HMIPv6

The analysis in this section follow a logic which is similar to the previous work on HMIP signaling cost analysis [15]. However, *our analysis differs from [15] in three ways*: (i) we do not consider the packet delivery costs incurred by standard IP switching, since they are not particularly related to mobility protocols; (ii) the tunnelling costs at HA and MAP are considered explicitly; (iii) we removed the processing costs at FAs to match the operation of HMIPv6. These modifications to the analysis of [15] enables us to compare the signaling cost of `HiSIGMA` and HMIPv6 more consistently. In HMIPv6, there is no binding update cost since the MH will not send a binding update to CN (if we consider HMIPv6 operating at the *bidirectional tunnelling mode* [17]). First, Secs. V-A gives an overview of the basic idea of HMIPv6, then Secs. V-B and V-C develop the cost for location update and packet delivery respectively, and Sec. V-D gives the total signaling cost of HMIPv6.

### A. *Overview of HMIPv6*

One of the objectives of this paper is to compare the performance of hierarchical transport layer mobility protocol with HMIPv6. We, therefore, briefly describe the protocols of the MIPv6 enhancements in this section.

The objective of HMIPv6 is to reduce the frequency and delay of location updates caused by MH's mobility. In HMIPv6, operation of the correspondent node and HA are the same as MIPv6. A new network element, called the Mobility Anchor Point (MAP), is used to introduce hierarchy in mobility management. A MAP covers several subnets under its domain, called a *region* in this paper. A MAP is essentially a local Home Agent. The introduction of MAP can limit the amount of MIPv6 signalling cost outside its region as follows:

- When an MH roams between the subnets within a region (covered by a MAP), it only sends location updates to the local MAP rather than the HA (that is typically further away and has a higher load).
- The HA is updated only when the MH moves out of the region.

HMIPv6 operates as follows. An MH entering a MAP domain receives Router Advertisements containing information on one or more local MAPs. The MH updates the HA with an address assigned by the MAP, called Regional COA (RCoA), as its current location. The MAP intercepts all packets sent to the MH, encapsulates, and forwards them to the MH's current address. If the MH changes its point of attachment within a MAP domain, it gets a new local CoA (LCoA) from the AR serving it; the MH only needs to register the LCoA with the MAP. MH's mobility (change of the LCoA) is transparent to the HA, and the RCoA remains unchanged (thus no need to update HA) as long as the MH stays within a MAP's region.

### B. *Location update cost*

In HMIPv6, an MH does not need to register with the HA until the MH moves out of the region covered by a MAP, instead it only registers with the MAP. Therefore, every subnet crossing within a MAP (happens every $T_r$ seconds) will trigger a registration to the MAP, which incurs a transmission cost to MAP ($LU_{mm}$) and processing cost at MAP ($\gamma_m$) of the location update message. Therefore, $C_{mm} = LU_{mm} + \gamma_m$.

For every *region* crossing between MAPs (happens every $M \times T_r$ seconds), MH needs to register with HA, which incurs a transmission cost to HA ($LU_{mh}$), processing cost at HA ($\gamma_h$), and processing cost at MAP ($2\gamma_m$, since MAP needs to process both registration request and reply messages). Therefore, $C_{mh} = LU_{mh} + \gamma_h + 2\gamma_m$.

Similar to HiSIGMA, the number of CNs that an MH is communicating with have no impact on the location update. Therefore, the average location update cost per second in the whole system can be estimated as the number of MHs multiplied by the location update cost for each MH, then divided by the average subnet residence time:

$$\Psi_{LU}^{H} = N_{mh} \frac{M^{H} C_{mm} + C_{mh}}{M^{H} T_r} \tag{29}$$

Similar to Eqn. (20), for a round trip, $LU_{mh}$ and $LU_{mm}$ can be calculated as:

$$LU_{mh} = 2(l_{mm} + l_{mh} - 1 + \rho)\delta_U \tag{30}$$

$$LU_{mm} = 2(l_{mm} - 1 + \rho)\delta_U \tag{31}$$

Similar to Eqn. (17), $M^H$ can be calculated as:

$$M^{H} = 1 + \frac{mn - 1}{mn - R^{H}} \tag{32}$$

Therefore,

$$\begin{aligned} \Psi_{LU}^{H} = N_{mh} \Big[ &\tfrac{2(l_{mm}-1+\rho)\delta_U + \gamma_m}{T_r} + \\ &\tfrac{2(l_{mm}+l_{mh}-1+\rho)\delta_U + \gamma_h + 2\gamma_m}{T_r} \times \tfrac{mn - R^{H}}{2mn - R^{H} - 1} \Big] \end{aligned} \tag{33}$$

### C. Packet delivery cost

Similar to the analysis of Sec. IV-C, for packet delivery cost analysis, we only consider the location database lookup cost and tunnelling-related costs at HA and MAP. For each packet sent from CN to MH, processing costs incurred in sequence are: one location database lookup and one encapsulation at HA; one location database lookup, one decapsulation and one encapsulation at MAP.

Let $\varphi_h$, $\varphi_m$ be the per location database lookup costs at HA, MAP, respectively; let $\tau$ be the per encapsulation/decapsulation cost at HA or MAP; and let $\psi$ be the linear constant for location database lookup as defined in Eqn. (25); then we have:

$$\upsilon_h = \varphi_h + \tau = (\psi N_{mh}) + \tau \tag{34}$$

$$\upsilon_m = \varphi_m + 2\tau = \left( \psi \frac{N_{mh} R^{H}}{mn} \right) + 2\tau \tag{35}$$

So the packet delivery cost from CN to MH can be calculated by summing up the processing cost due to database lookup and tunnelling in the system, as shown in Eqns. (34) and (35). This cost can be expressed as:

$$\begin{aligned} \Psi_{PD}^{H} &= N_{mh} N_{cn} \lambda_{pa} (\upsilon_h + \upsilon_m) \\ &= N_{mh} N_{cn} \lambda_{pa} (\psi N_{mh} \tfrac{mn + R^{H}}{mn} + 3\tau) \end{aligned} \tag{36}$$

Where packet arrival rate ($\lambda_{pa}$) can be calculated from the session arrival rate and packet size. Let $F$ be the file size being transferred by the session, and $PMTU$ be the path MTU between CN and MH, then the packet arrival rate can be calculated as:

$$\lambda_{pa} = \lambda_{sa} \frac{F}{PMTU} \tag{37}$$

### D. Total HMIPv6 signaling cost

Based on above analysis of the location update cost and packet delivery cost shown in Eqns. (33) and (36), we can get the total signaling cost of HMIPv6 as:

$$\Psi_{TOT}^{H} = \Psi_{LU}^{H} + \Psi_{PD}^{H} \tag{38}$$

## VI. RESULTS AND SIGNALLING COST COMPARISON OF HiSIGMA AND HMIPV6

In this section, we present results showing the effect of various input parameters on HiSIGMA's total signaling cost. In all the numerical examples, using the following parameter values, which are obtained from previous work [15] and our calculation based on user traffic and mobility models [14], [12]: $\gamma_l = \gamma_h = 30$, $\gamma_a = \gamma_m = 20$, $\psi = 0.3$, $F = 10$Kbytes, $PMTU = 576$bytes, $S = 10$, $\rho = 10$, $l_{al} = l_{mh} = 25$, $l_{ma} = l_{mm} = 10$, $l_{mc} = 35$, $m = 10$, $n = 8$, $R^T = R^H = 10$, $\tau = 0.5$, and $\lambda_{sa} = 0.01$.

### A. Impact of number of MHs for different subnet residence times

The impact of number of MHs on total signaling cost of HiSIGMA and HMIPv6 for different subnet residence times is shown in Fig. 8. Here, the values used for other parameters are: $N_{cn} = 1$ and $\delta_U = \delta_B = \delta_A = 0.2$. From the figure, we can see that under different residence time, the signaling cost of both HiSIGMA and HMIPv6 increases with the increase of the number of MHs. When the moving speed is higher, the subnet residence time $T_r$ decreases, resulting in a increase of the location update and binding update costs per second (see Eqns. (21), (24) and (33)). We can also observe that the total signaling cost of HiSIGMA is less than HMIPv6 in this scenario; this is because when $\delta_U$ and $\delta_B$ are small, the location update and binding update costs are not high, and the high packet delivery cost will make the signaling cost of HMIPv6 much higher than that of HiSIGMA.

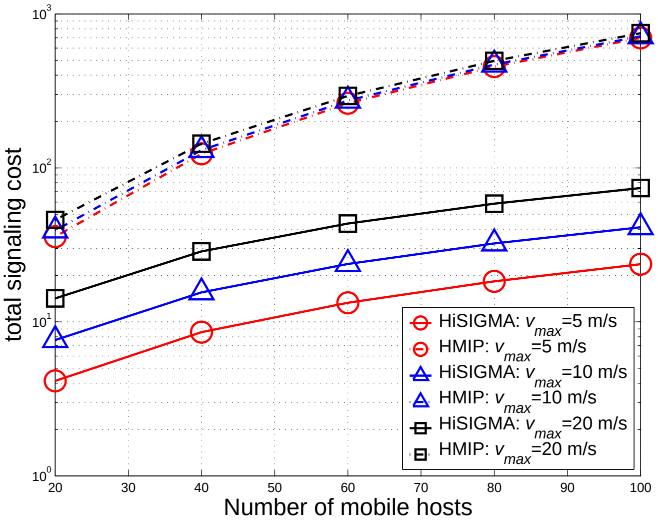

Fig. 8. Impact of number of MHs on total signaling cost of `HiSIGMA` and HMIPv6 under different moving speeds.

### *B. Impact of average number of communicating CN and location update transmission cost*

Next, we set subnet residence time $T_r = 60s$, and number of MHs $N_{mh} = 80$. The impact of the number of average CNs with which an MH communicates with for different per-hop transmission cost for location update cost ($\delta_U$) is shown in Fig. 9. It can be observed from this figure that when the average number of communicating CNs increases, the total signaling cost increases (see Eqns.(21), (24) (27), (33) and (36)). Also, when $\delta_U$ increases, the location update cost per second will increase as indicated by Eqn. (20), (30) and (31), which will result in the increase of the total signaling cost of both `HiSIGMA` and HMIPv6. However, we can see that the impact of $\delta_U$ is much smaller in HMIPv6; this is because HMIPv6's signaling cost is less sensitive to location update cost due to its hierarchical structure. In this scenario, signaling cost of HMIPv6 is higher than that of `HiSIGMA` when $\delta_U = 0.4$ or 1.6. However, when $\delta_U = 6.4$, `HiSIGMA` requires a higher signaling cost due to frequent location update for each subnet crossing (compared to HMIPv6's hierarchical mobility management policy).

### *C. Session to Mobility Ratio*

Session to Mobility Ratio (*SMR*) is a mobile packet network's counterpart of Call to Mobility Ratio (*CMR*) in PCS networks. We vary $T_r$ from 75 to 375 seconds with $\lambda_{sa}$ fixed to 0.01, which yields a *SMR* of 0.75 to 3.75. The impact of *SMR* on total signaling cost for different $N_{mh}$ is shown in Fig. 10. We can observe that a higher *SMR* results in lower signaling cost in both `HiSIGMA` and HMIPv6. This is mainly because high *SMR* means lower mobility, and thus lower signaling cost due to less location update and binding update.

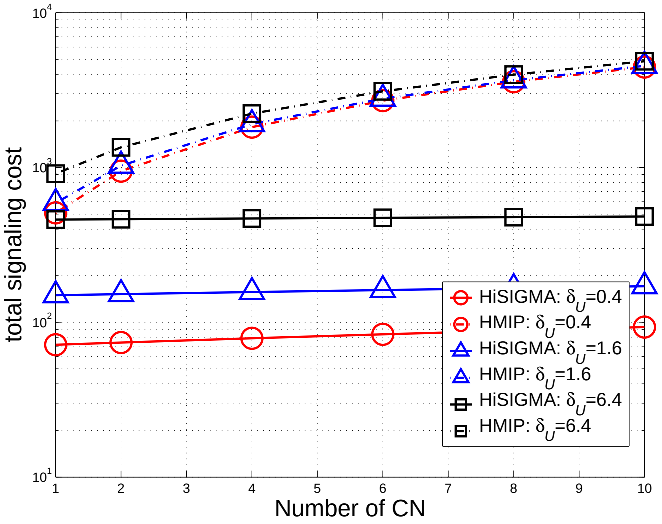

Fig. 9. Impact of number of CNs and per-hop binding update transmission cost

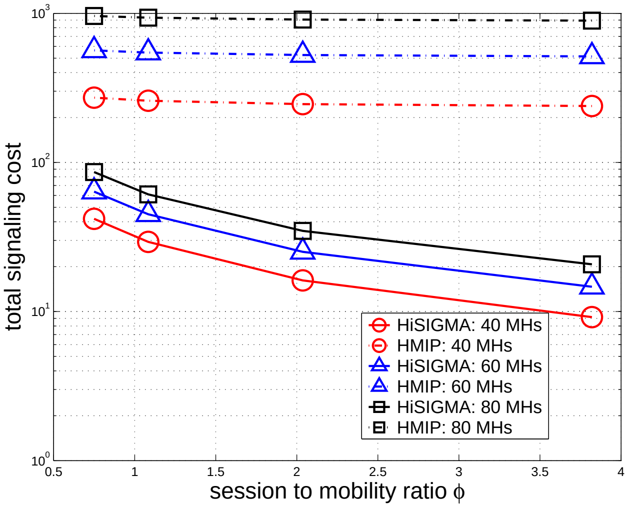

Fig. 10. Impact of *SMR* on total signaling cost for different $N_{mh}$

### *D. Relative signaling cost of `HiSIGMA` to HMIPv6*

Fig. 11 shows the impact of (location update transmission cost) / (packet tunnelling cost) ratio ($\delta_U/\tau$) on the relative signaling cost between `HiSIGMA` and HMIPv6. A higher $\delta_U/\tau$ ratio means that the location update requires more cost while packet encapsulation/decapsulation costs less. This ratio depends on the implementation of the intermediate routers. We can see that the signaling cost of `HiSIGMA` is less than that of

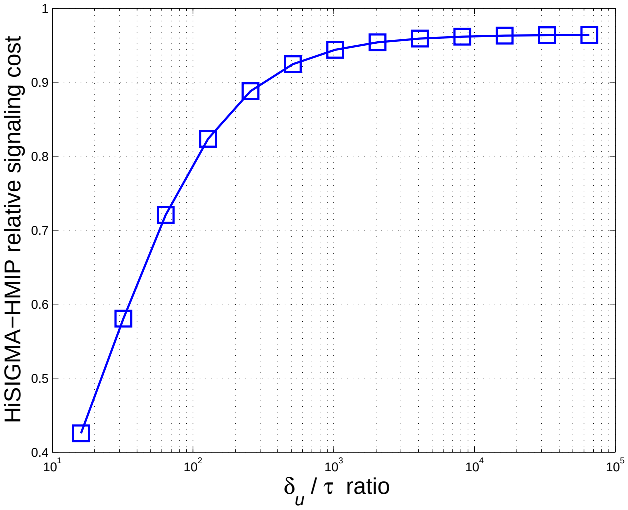

Fig. 11. Impact of $\delta_U/\tau$ ratio on `HiSIGMA` to HMIPv6 relative signaling cost

HMIPv6 in the possible range of $\delta_U/\tau$ since the relative cost between `HiSIGMA` and HMIPv6 is always less than one.

## VII. CONCLUSIONS

In this paper, we presented the hierarchical location management scheme for transport layer mobility protocols. We developed an analytical model to evaluate `HiSIGMA` using signaling cost as the performance measure, followed by a comparison of the signalling cost of `HiSIGMA` and Hierarchical Mobile IPv6. Numerical results show that, by introducing the concept of Anchor Zone Server into location management of mobile hosts, the signaling cost of `HiSIGMA` can be greatly reduced and is lower than that of HMIPv6.

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