Signaling Cost Evaluation of SIGMA

Shaojian Fu, Mohammed Atiquzzaman, William Ivancic

TR-OU-TNRL-05-102
January 2005

Telecommunication & Network Research Lab

School of Computer Science

THE UNIVERSITY OF OKLAHOMA

200 Felgar Street, Room 159, Norman, Oklahoma 73019-6151
(405)-325-4042, atiq@ou.edu, www.cs.ou.edu/~atiq

Signaling Cost Evaluation of SIGMA

Shaojian Fu
Mohammed Atiquzzaman
School of Computer Science
University of Oklahoma,
Norman, OK 73019-6151.

William Ivancic
Satellite Networks & Architectures Branch
NASA Glenn Research Center
21000 Brookpark Rd. MS 54-8,
Cleveland, OH 44135.

Abstract— **In our earlier study, we proposed SIGMA, a Transport Layer Seamless Handover solution to mobility. SIGMA utilizes multihoming to achieve a seamless handover of a mobile host, and is designed to solve many of the drawbacks of Mobile IP. In this paper, we evaluate the signaling cost of SIGMA by using an analytical model. The signaling cost of SIGMA is also compared with Hierarchical Mobile IPv6 (HMIPv6) by using the proposed model. Various aspects affecting signaling cost are considered such as mobile host moving speed, number of mobile host, number of correspondent node, per-hop transmission cost, and Session to Mobility Ratio.**

I. Introduction

Mobile IP (MIP) [1] is the standard proposed by IETF to handle mobility of Internet hosts for mobile data communication. Several drawbacks exist when using MIP in a mobile computing environment, the most important issues of MIP identified to date are high handover latency, and high packet loss rate [2]. Even with various recent proposed enhancements [2], [3], [4], [5], Mobile IP still can not completely remove the latency associated handover, and the resulting packet loss rate is still high [6].

As the percentage 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. A transport layer mobility solution would be a natural candidate for an alternative approach, since most of the applications in the Internet are end-to-end. A number of transport layer mobility protocols have been proposed in the context of TCP: MSOCKS [7] and connection migration solution [8]. These protocols tried to implement mobility as an end-to-end service without the requirement on the network layer infrastructures; they are not aimed at reducing the high latency and packet loss resulted from handovers. The handover latency for these schemes is in the scale of seconds.

The research reported in this paper was funded by NASA Grant NAG3-2922.

We designed a new scheme for supporting low latency, low packet loss mobility called Transport Layer Seamless Handover (SIGMA) [9]. It can also cooperate with normal IPv4 or IPv6 infrastructure without the support of Mobile IP. Similar in principle to a number of recent transport layer handover schemes [10], [11], [12], the basic idea of SIGMA is to exploit multihoming to keep the old path alive during the process of setting up the new path to achieve a seamless handover. SIGMA relies on the signaling message exchange between the MH, correspondent node (CN), and location manager (LM). For every handover, MH need to send binding update and location update to CN and LM, respectively. For SIGMA to be useful in real world wireless system, all these signaling messages should not cost too much network bandwidth to leave no space for payload data transmission.

The signaling cost analysis for MIP protocols are presented earlier in [13], [14], but there is no much work done in analyzing the signaling cost of transport layer mobility solutions. The *objective* of this paper is to look into the signaling cost required by SIGMA. Similar to paper [9], we illustrate SIGMA using SCTP since multihoming is a built-in feature of SCTP.

The *contributions* of our paper can be outlined as follows:

- Developed a analytical model for SIGMA signaling cost.
- Evaluate the signaling cost of SIGMA under various input parameters such as mobile host moving speed, number of mobile host, number of correspondent node, and per-hop transmission cost.

The rest of this paper is structured as follows: Sec. II outlines the handover signalling procedures, timing diagram of SIGMA. The analytical model for SIGMA signaling cost is presented in Sec. III and Sec. IV. Then we evaluate the signaling cost of SIGMA by the model under various input parameters in Sec. V-C. Finally, concluding remarks are presented in Sec. VI.

II. ARCHITECTURE OF SIGMA

A typical mobile handover in SIGMA using SCTP as an illustration is shown in Fig. 1, where the Mobile Host (MH) is multi-homed node connected through two wireless access networks. Correspondent node (CN) is a single-homed node sending traffic to MH, which corresponds to the services like file download or web browse by the mobile users.

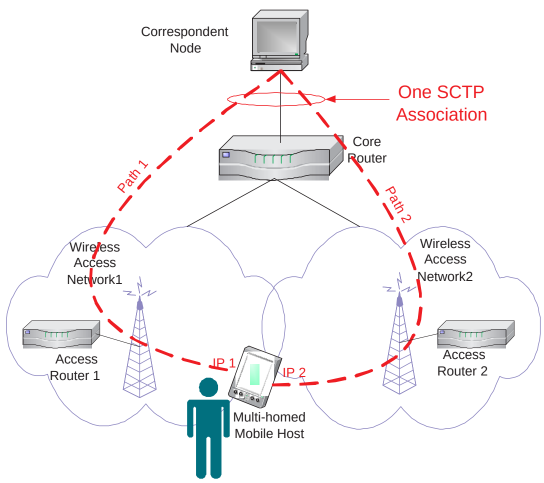

Fig. 1. An SCTP association with multi-homed mobile host.

A. Handover Process

The handover process of SIGMA can be described by the following five steps.

STEP 1: Obtain new IP address

Refer to Fig. 1 as an example, the handover preparation procedure begins when MH moves into the overlapping radio coverage area of two adjacent subnets. Once the MH receives the router advertisement from the new access router (AR2), it should begin to obtain a new IP address (IP2 in Fig. 1). This can be accomplished through several methods: DHCP, DHCPv6, or IPv6 stateless address autoconfiguration (SAA) [15].

STEP 2: Add IP addresses into the association

After the MH obtained the IP address IP2 by STEP 1, MH should notify CN about the availability of the new IP address through SCTP Address Dynamic Reconfiguration option [16]. This option defines two new chunk types (ASCONF and ASCONF-ACK) and several parameter types (Add IP Address, Delete IP address, and Set Primary Address etc.).

STEP 3: Redirect data packets to new IP address

When MH moves further into the coverage area of wireless access network2, CN can redirect data traffic to new IP address IP2 to increase the possibility that data can be delivered successfully to the MH. This task can be accomplished by sending an ASCONF from MH to CN, through which CN set its primary destination address to MH's IP2. At the same time, MH need to modify its local routing table to make sure the future outgoing packets to CN using new path through AR2.

STEP 4: Update location manager (LM)

SIGMA supports location management by employing a location manager which maintains a database recording the correspondence between MH's identity and MH's current primary IP address. MH can use any unique information as its identity such as home address like MIP, or domain name, or a public key defined in Public Key Infrastructure (PKI).

Following our example, once MH decides to handover, it should update the LM's relevant entry with new IP address IP2. The purpose of this procedure is to ensure that after MH moves from wireless access network1 into network2, further association setup requests can be routed to MH's new IP address IP2. This update has no impact on the existing active associations.

We can observe an important difference between SIGMA and MIP: the location management and data traffic forwarding functions are coupled together in MIP, while in SIGMA they are decoupled to speedup handover and make the deployment more flexible.

STEP 5: Delete or deactivate obsolete IP address

When MH moves out of the coverage of wireless access network1, no *new* or *retransmitted* data should be directed to address IP1. In SIGMA, MH notifies CN that IP1 is out of service for data transmission by sending an ASCONF chunk to CN to delete IP1 from CN's available destination IP list.

A less aggressive way to prevent CN from sending data to IP1 is MH advertising a zero receiver window (corresponding to IP1) to CN. This will give CN an impression that the interface (on which IP1 is bound) buffer is full and can not receive data any more. By deactivating, instead of deleting, the IP address, SIGMA can adapt more gracefully to MH's zigzag movement patterns and reuse the previous obtained IP address (IP1) as long as the IP1's lifetime is not expired. This will reduce the latency and signalling traffic caused by obtaining a new IP address.

B. Timing diagram of SIGMA

The numbers before the events correspond to the step numbers in Sec. II-A. Fig. 2 summarizes the signalling sequences involved in SIGMA. Here we assume IPv6 SAA is used for MH to get new IP address. It should be noted that before the old IP is deleted at CN, it can always receive data packets (not shown in the figure) in parallel with the exchange of signalling packets.

III. MODELLING PREPARATION

In this section, we describe some necessary preparation work for developing an analytical model for SIGMA signaling cost. First, the network structure we are considering and model's assumptions and notations are presented in Secs. III-A, III-B and III-C respectively. Then the MH mobility model and traffic arrival model used by signaling cost analysis are set up in Secs. III-D and III-E respectively. After these modeling foundations are ready, Sec. IV develops the signaling cost for location update, binding update and packet delivery in SIGMA.

A. Network structure

In this section, we describe the network structure that will be used in our analytical model, which is shown in Fig. 3. In the figure, a two dimensional subnet arrangement is assumed for modeling MH movement. $\mathrm{AR}_{1,1}, \cdots \mathrm{AR}_{m,n}$ stand for the access routers. There are one location manager and a number of CNs connected into the topology by Internet. The MHs are roaming around in the subnets covered by $\mathrm{AR}_{1,1}, \cdots \mathrm{AR}_{m,n}$, and each of them are communicating with one or more of the CNs. Between a pair of MH and CN, intermittent file transfers occur caused by mobile user request information from CNs using protocols like HTTP. We call each active transferring period during the whole MH-CN interactivity as one session.

B. Model assumptions

The assumptions we have made for developing our analytical model of SIGMA signaling cost are described below.

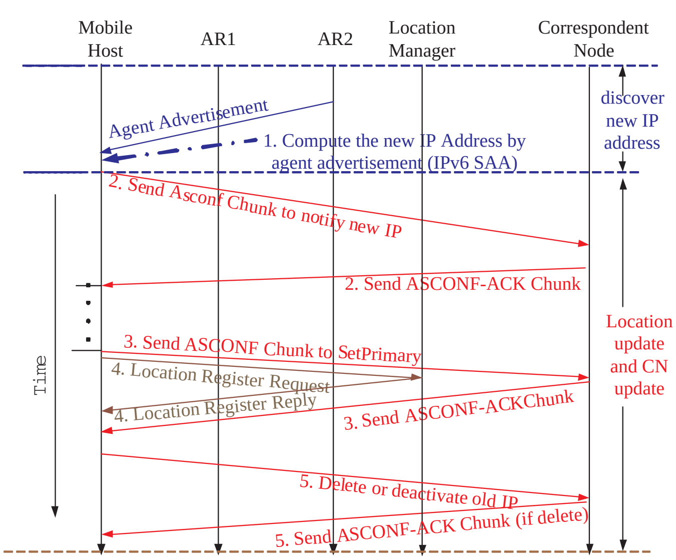

Fig. 2. Timing diagram of SIGMA

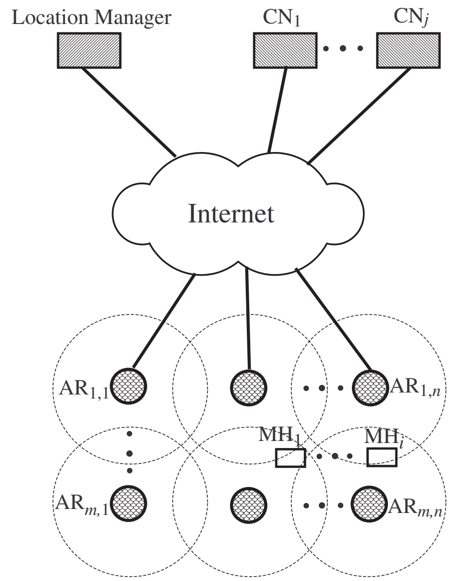

Fig. 3. Network structure considered.

- In the previous study of P-MIP signaling cost analytical model [14], 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 [17], [18], 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 (κ), and a heavy-tailness factor (σ).
- Mobile host moves according to Random Waypoint model [19], which is the most frequently used model in recent 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 [13], [14], [20].

C. Notations

The notations used in this paper are given below.

- l_{ml} average distance between MH and location manager in hops.
- l_{mc} average distance between MH and CN in hops.
- N_{mh} total number of MHs.
- N_{cn} average number of CNs with which a MH is communicating.
- LU_{ml} transmission cost of a location update from MH to location manager.
- γ_l processing cost at location manager for each location update.
- υ_l location database lookup cost per second for each transport layer association at LM.
- Ψ_{LU} location update cost per second for the whole system, including transmission cost and processing cost incurred by location update of all MHs, $\Psi_{LU} = N_{mh}\frac{LU_{ml}+\gamma_l}{T_r}$.
- BU_{mc} transmission cost of a binding update between MH and CN.
- Ψ_{BU} binding update cost per second between MHs and CNs for the whole system, $\Psi_{BU} = N_{mh}N_{cn}\frac{BU_{mc}}{T_r}$.
- Ψ_{PD} packet delivery cost per second from CNs to MHs for the whole system.
- Ψ_{TOT} total signaling cost per second for the whole system including location update cost, binding update cost and packet delivery cost, $\Psi_{TOT} = \Psi_{LU} + \Psi_{BU} + \Psi_{PD}$.
- 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 session time.
- T_i session interval time.
- κ_s minimum session time.
- σ_s heavy-tailness factor for session time.
- BW_{mc} bottleneck bandwidth between CN and MH.
- κ_i minimum session interval time.
- σ_i heavy-tailness factor for session interval time.
- λ_a average session arrival rate.

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 LM 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:

$$E(T) = E(L/v) = E(L)E(1/v) \tag{2}$$

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

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

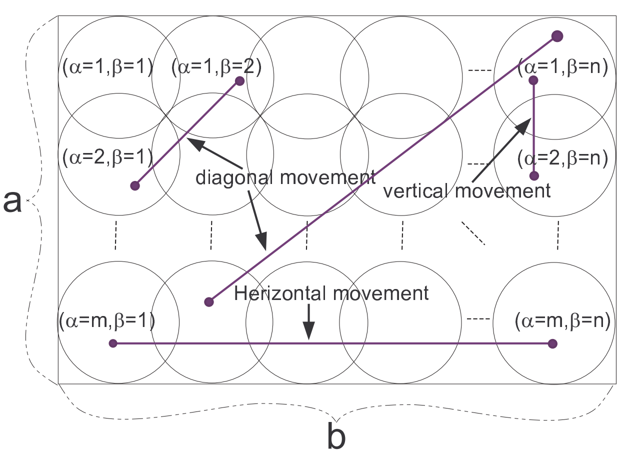

Fig. 4. Arrangement of subnets in a rectangular topology

In order to determine $E(L)$ and $E(C)$, we assume an arrangement of circular subnets in a rectangular topology as shown in Fig. 4, and m, n are the number of vertically and horizontally arranged subnets in the topology, respectively. From [19], 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 uniform distribution between (0, P_{max}), we have:

$$E(P) = \int_0^{P_{max}} \frac{P}{P_{max}} dP = P_{max}/2 \quad (5)$$

Next, we need to find $E(C)$, the general form of which can be expressed as [19]:

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

The value $C \begin{pmatrix} (\alpha_i, \beta_i) \\ (\alpha_j, \beta_j) \end{pmatrix}$ is the number of subnet crossing caused by a movement between subnet (α_i, β_i) to (α_j, β_j), which depends on the actual subnet shape and arrangement. Consider the circular subnet arrangement as shown in Fig. 4, 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:

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

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

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

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 (λ_a). As discussed in Sec. III-B, both session time and session interval time are of *Pareto* distribution. The PDF function of session time's distribution is [17]:

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

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

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

Also from [17], we know session interval time has a PDF function of:

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

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. 5, the total time for k sessions can be calculated as:

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

So, the session arrival rate is:

$$\lambda_a = \frac{k}{E(T_{tot})} = \frac{1}{E(T_s) + E(T_i)} \quad (13)$$

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

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

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

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

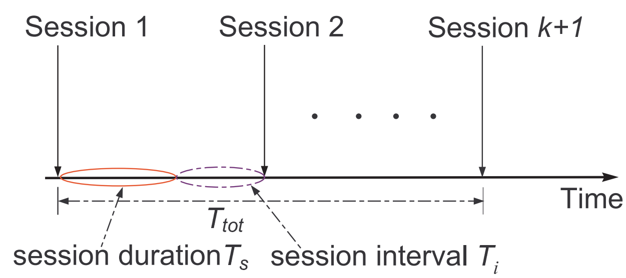

Fig. 5. Session arrival illustration.

IV. SIGNALING COST ANALYSIS OF `SIGMA`

In this section, the signaling cost of `SIGMA` 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 `SIGMA`.

A. Location update cost

In `SIGMA`, every subnet crossing (happens every T_r seconds) by an MH will trigger a location update, which incurs a transmission cost (LU_{ml}) and processing cost (γ) for the location update message. 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, divided by the average subnet residence time:

$$\Psi_{LU}^{T} = N_{mh}\frac{LU_{ml}+\gamma_l}{T_r} \quad (16)$$

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, ρ. Let the per-hop location update transmission cost be δ_U, for a round trip, LU_{ml} can be calculated as:

$$LU_{ml} = 2(l_{ml}-1+\rho)\delta_U \quad (17)$$

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

$$\Psi_{LU}^{T} = N_{mh}\frac{2(l_{ml}-1+\rho)\delta_U+\gamma_l}{T_r} \quad (18)$$

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 [13], [14], [20].

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:

$$\Psi_{BU}^{T} = N_{mh}N_{cn}\frac{BU_{mc}}{T_r} \quad (19)$$

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

$$BU_{mc} = 2(l_{mc}-1+\rho)\delta_B \quad (20)$$

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:

$$\Psi_{BU}^{T} = N_{mh}N_{cn}\frac{2(l_{mc}-1+\rho)\delta_B}{T_r} \quad (21)$$

C. Packet delivery cost

Unlike the analysis of packet delivery cost in [13], 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 LM. 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 `SIGMA`, a location database lookup at LM 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/λ_{sa} seconds. If we assume the database lookup cost has a linear relationship with N_{mh}, and φ_l and ψ be the per location database lookup cost and the linear coefficient at LM, then the per-second per-association lookup cost υ_l can be calculated as:

$$\upsilon_l = \frac{\varphi_l\lambda_{sa}}{S} = \frac{\psi N_{mh}\lambda_{sa}}{S} \quad (22)$$

Since `SIGMA` 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:

$$\begin{aligned}\Psi_{PD}^{T} &= N_{mh}N_{cn}\upsilon_l \\ &= N_{mh}^2 N_{cn}\tfrac{\psi\lambda_{sa}}{S}\end{aligned} \quad (23)$$

D. Total signaling cost of `SIGMA`

Based on above analysis on the location update cost, binding update cost, and packet delivery cost shown in Eqns. (18), (21), and (23), we can get the total signaling cost of `SIGMA` as:

$$\Psi_{TOT}^{T} = \Psi_{LU}^{T} + \Psi_{BU}^{T} + \Psi_{PD}^{T} \quad (24)$$

V. RESULTS FROM PROPOSED ANALYTICAL MODEL

In this section, we present comparison results showing the effect of various input parameters on `SIGMA`'s total signaling cost. we also compare the signaling cost of `SIGMA` with HMIPv6. We, therefore, briefly describe the HMIPv6 first in this section.

A. Hierarchical Mobile IPv6 (HMIPv6)

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. Signaling cost of HMIPv6

The detailed signaling cost analysis of HMIPv6 using the mobility and traffic model described in Sec. III is not presented here in this paper due to space limits. Readers can refer to [21] for more details.

C. Results and signalling cost comparison of SIGMA *and HMIPv6*

In this section, we present results showing the effect of various input parameters on SIGMA's total signaling cost. In all the numerical examples, using the following parameter values, which are obtained from previous work [13] and our calculation based on user traffic and mobility models [19], [17]: $\gamma_l = 30$, $\psi = 0.3$, $F = 10$Kbytes, $PMTU = 576$bytes, $S = 10$, $\rho = 10$, $l_{ml} = 35$, $l_{mc} = 35$, $m = 10$, $n = 8$, $R = 10$, $\gamma_h = 30$, $\gamma_m = 20$, $\tau = 0.5$, $\lambda_{sa} = 0.01$, $l_{mh} = 25$, and $l_{mm} = 10$.

D. Impact of number of MHs under different maximum MH moving speeds

1) Impact of number of MHs for different moving speeds: The impact of number of MHs on total signaling cost of SIGMA and HMIPv6 for different MH moving speed is shown in Fig. 6. Here, the values used for other parameters are: $N_{cn} = 1$ and $\delta_U = \delta_B = 0.2$. From the figure, we can see that under different moving speeds, the signaling cost of both SIGMA and HMIPv6 increases with the increase of the number of MHs. When the moving speed is higher, the subnet residence time T_r decreases (see Eqns. (1) , (2), and (3)), resulting in a increase of the location update and binding update costs per second (see Eqns. (18) and (21)). We can also observe that the total signaling cost of SIGMA is less than HMIPv6 in this scenario; this is because when δ_U and δ_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 SIGMA.

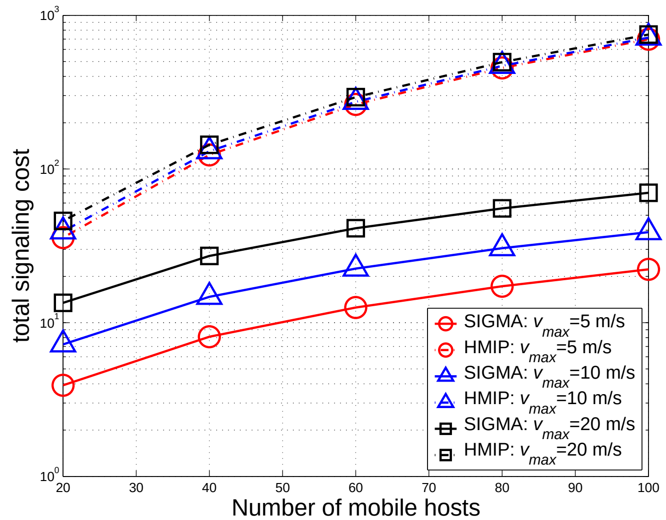

Fig. 6. Impact of number of MHs on total signaling cost of SIGMA and HMIPv6 under different moving speeds.

2) 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 (δ_U) is shown in Fig. 7. It can be observed from this figure that when the average number of communicating CNs increases, the total signaling cost increases (see Eqns.(18), (21) and (23)). Also, when δ_U increases, the location update cost per second will increase as indicated by Eqn. (17), which will result in the increase of the total signaling cost of both SIGMA and HMIPv6. However, we can see that the impact of δ_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 SIGMA when $\delta_U = 0.4$ or 1.6. However, when $\delta_U = 6.4$, SIGMA requires a higher signaling cost due to frequent location update for each subnet crossing (compared to HMIPv6's hierarchical mobility management policy).

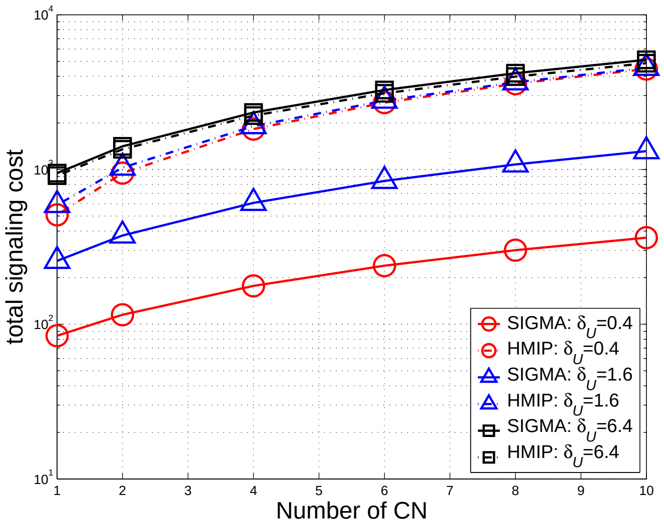

Fig. 7. Impact of number of CNs and per-hop binding update transmission cost

3) 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 λ_{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. 8. We can observe that a higher *SMR* results in lower signaling cost in both SIGMA and HMIPv6. This is mainly because high *SMR* means lower mobility, and thus lower signaling cost due to less location update and binding update. Also, we can see that the decrease of HMIPv6's signaling cost as a function of *SMR* is not as fast as that of SIGMA. This again is because HMIPv6's hierarchy structure reduces the impact of mobility on the signaling cost. The signaling cost, therefore, decreases slower than that of SIGMA when MH's mobility decreases.

4) Relative signaling cost of SIGMA *to HMIPv6:* Fig. 9 shows the impact of (location update transmission cost) / (packet tunnelling cost) ratio (δ_U/τ) on the relative signaling cost between SIGMA and HMIPv6. A higher δ_U/τ 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 as long as $\delta_U/\tau < 12$, the signaling cost of SIGMA is less than that of HMIPv6 due to the advantage of no

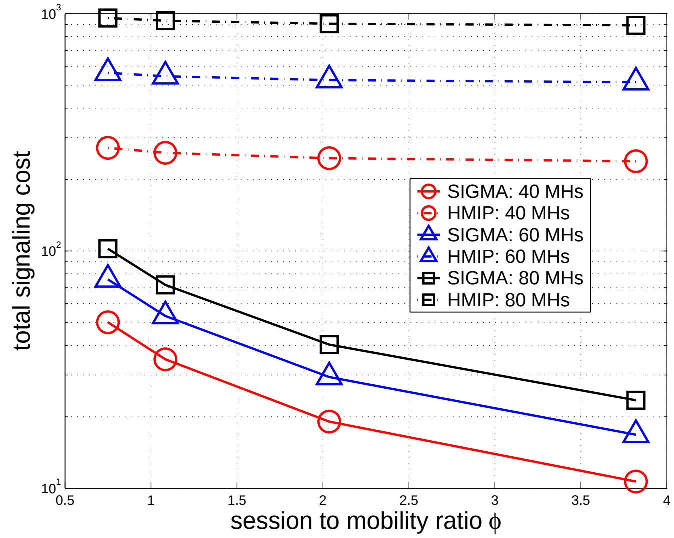

Fig. 8. Impact of *SMR* on total signaling cost for different N_{mh}

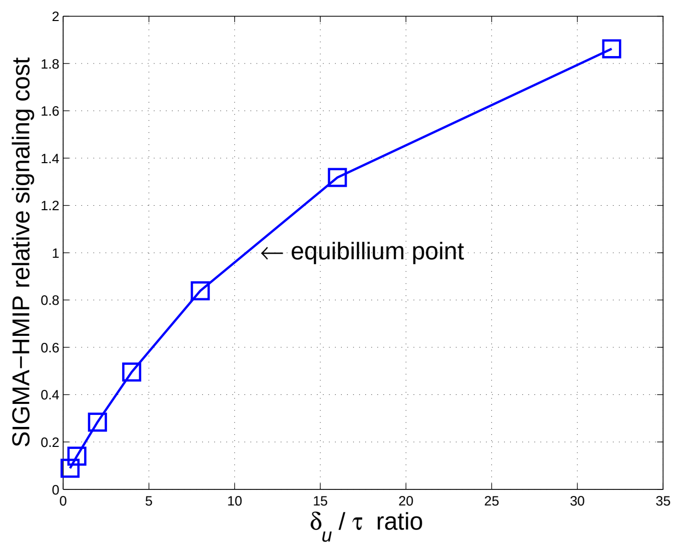

Fig. 9. Impact of δ_U/τ ratio on SIGMA to HMIPv6 relative signaling cost

tunnelling required. After that equilibrium point, the cost of location update will take dominance, and the signaling cost of SIGMA will become higher than that of HMIPv6.

VI. Conclusions

This paper evaluates the signaling cost of SIGMAby using an analytical model. Various aspects affecting SIGMA's signaling cost are considered such as mobile host moving speed, number of mobile host, number of correspondent node, per-hop transmission cost, and session to mobility ratio. we also compared the signaling cost of SIGMA with that of HMIPv6. Numerical results show that, in most scenarios, the signaling cost of

SIGMA is lower than HMIPv6. However, there is a tradeoff between location update transmission cost (δ_U) and packet tunnelling cost (τ); very high δ_U/τ ratio results in the signaling cost of SIGMA being higher than that of HMIPv6.

References

[1] C.E. Perkins (editor), "IP Mobility Support." IETF RFC 3344, August 2002.

[2] K.E. Malki (editor), "Low latency handoffs in Mobile IPv4." IETF DRAFT, draft-ietf-mobileip-lowlatency-handoffs-v4-07.txt, October 2003.

[3] X. Zhang, J. G. Castellanos, and A. T. Campbell, "P-MIP: paging extensions for Mobile IP," *Mobile Networks and Applications*, vol. 7, no. 2, pp. 127–141, April 2002.

[4] R. Koodli (editor), "Fast handovers for Mobile IPv6." IETF DRAFT, draft-ietf-mipshop-fast-mipv6-03.txt, October 2004.

[5] H. Soliman, C. Catelluccia, and K.E. Malki et al., "Hierarchical Mobile IPv6 mobility management (HMIPv6)." IETF DRAFT, draft-ietf-mipshop-hmipv6-04.txt, December 2004.

[6] R. Hsieh and A. Seneviratne, "A comparison of mechanisms for improving Mobile IP handoff latency for end-to-end TCP," *ACM MobiCom*, San Diego, USA, pp. 29–41, September 2003.

[7] D. A. Maltz and P. Bhagwat, "MSOCKS: An architecture for transport layer mobility," *INFOCOM*, San Francisco, USA, pp. 1037–1045, March 1998.

[8] A. C. Snoeren and H. Balakrishnan, "An end-to-end approach to host mobility," *ACM MobiCom*, Boston, MA, pp. 155–166, August 2000.

[9] S. Fu, L. Ma, M. Atiquzzaman, and Y. Lee, "Architecture and performance of SIGMA: Seamless IP diversity based Generalized Mobility Architecture," *Accepted for publication by ICC*, Seoul, Korea, May 2005.

[10] S. J. Koh, M. J. Lee, M. L. Ma, and M. Tuexen, *Mobile SCTP for Transport Layer Mobility*. draft-sjkoh-sctp-mobility-03.txt, February 2004.

[11] W. Xing, H. Karl, and A. Wolisz, "M-SCTP: Design and prototypical implementation of an end-to-end mobility concept," *5th Intl. Workshop on the Internet Challenge: Technology and Applications*, Berlin, Germany, October 2002.

[12] L. Li, "PKI based end-to-end mobility using SCTP," *MobiCom 2002*, Atlanta, Georgia, USA, September 2002.

[13] J. Xie and I. F. Akyildiz, "An optimal location management scheme for minimizing signaling cost in Mobile IP," *IEEE International Conference on Communications (ICC)*, New York, pp. 3313–3317, April 2002.

[14] Y.W. Chung, D.K. Sun, and A.H. Aghvami, "Steady state analysis of P-MIP mobility management," *IEEE Communication Letters*, vol. 7, no. 6, pp. 278–280, June 2003.

[15] S. Thomson and T. Narten, "IPv6 stateless address autoconfiguration." IETF RFC 2462, December 1998.

[16] R. Stewart, M. Ramalho, and Q. Xie et. al., "Stream control transmission protocol (SCTP) dynamic address reconfiguration." IETF DRAFT, draft-ietf-tsvwg-addip-sctp-09.txt, June 2004.

[17] M.E. Crovella and A. Bestavros, "Self-similarity in world wide web traffic: evidence and possible causes," *IEEE/ACM Transactions on Networking*, vol. 5, no. 6, pp. 835–846, Dec 1997.

[18] V. Paxson and S. Floyd, "Wide area traffic: the failure of Poisson modeling," *IEEE/ACM Transactions on Networking*, vol. 3, no. 3, pp. 226–244, June 1995.

[19] C. Bettstetter, H. Hartenstein, and X. Perez-Costa, "Stochastic properties of the random waypoint mobility model: epoch length, direction distribution, and cell change rate," *5th ACM International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems*, pp. 7–14, September 2002.

[20] J. Xie and I. F. Akyildiz, "A novel distributed dynamic location management scheme for minimizing signaling costs in Mobile IP," *IEEE Transactions on Mobile Computing*, vol. 1, no. 3, pp. 163–175, July 2002.

[21] S. Fu, M. Atiquzzaman, L. Ma, and Y. Lee, "Signaling cost and performance of SIGMA: A seamless handover scheme for data networks," *Accepted by Journal of Wireless Communications and Mobile Computing*.