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Cost analysis of mobility protocols

M. Shohrab Hossain · Mohammed Atiquzzaman

Abstract Increasing demand for mobility in wireless data network has given rise to various mobility management schemes. Most of the analysis on mobility protocols used Random Waypoint mobility model However, the analysis done earlier ignored some major costs, resulting in an incomplete estimation and used random waypoint model which fails to represent realistic movement pattern. In this paper, we have developed an analytical cost model considering all possible costs related to mobility management, and have used city section mobility model, a realistic mobility model, to compute the total costs of two mobility protocols: HIMPv6 and SIGMA. We have defined two novel performance metrics, normalized overhead and efficiency, for mobility protocols based on the signaling costs and used them to evaluate the performance of SIGMA and HMIPv6 protocols varying network size, mobility rate and traffic rate. Results show that the total cost of SIGMA is much less than HMIPv6 due to the higher cost of packet tunneling, even though the mobility signaling cost of SIGMA is higher than HMIPv6. Moreover, mobility signaling costs of both the protocols using city model and random waypoint model are found to be much different, demonstrating the fact that random waypoint model cannot be used as an approximation to a realistic scenario. The analytical framework presented in this paper can be used by the network professionals to estimate amount of load on the network due to mobility protocols and compare them based on the proposed performance metrics to select the best protocol.

Keywords Mobility protocols · Analytical modeling · Signaling cost · Mobility model · Mobile IPv6

1 Introduction

Increasing demand for mobility in wireless data networks has given rise to various mobility management schemes. IETF proposed Mobile IPv6 [1] and Hierarchical Mobile IPv6 (HMIPv6) [2] to support node mobility. But these protocols have a number of drawbacks, such as, high handover latency, packet loss, inefficient routing path, and high signaling cost. To address these drawbacks, SIGMA [3], an IP-diversity based seamless handover protocol, has been proposed. SIGMA uses direct efficient routes to send/receive packets whereas HMIPv6 uses tunneling through home agents.

Mobility management protocols require signaling messages to be exchanged among various entities of the network, such as, home agent, correspondent nodes, mobile hosts, etc to maintain continuity in data transfer while in motion. These include costs that are dependent on mobility rate (referred to as *mobility signaling costs*) and other types of costs, such as data delivery costs. All these costs constitute *total cost* for mobility protocols. Protocols having high signaling traffic consume wireless bandwidth, resulting in inefficient throughput and increased packet delivery time.

In order to simulate movement of mobile nodes, mobility models are used. Choice of the mobility model can significantly affect the performance evaluation of mobility protocols [4]. Examples of various mobility models are

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M.S. Hossain · M. Atiquzzaman (✉)
School of Computer Science, University of Oklahoma, Norman, OK 73019, USA
e-mail: atiq@ou.edu

M.S. Hossain
e-mail: shohrab@ou.edu

Random Walk, Random WayPoint (RWP), Random Direction, Gauss-Markov, and City Section. Among these models, RWP model is the most common and frequently used model due to its simplicity. But it has a number of drawbacks as follows. In RWP model, a mobile node picks up a random speed and direction, resulting in sharp turns and sudden stops frequently which is very unusual in real scenarios. Moreover, the assumption of straight line movement is not always valid; there may be obstructions in its path. In contrast, City Section Mobility (CSM) model, introduced by Davies et al. [4, 5] represents a movement behavior that is influenced by constraints of the environment. In real life scenarios, mobile nodes do not have the ability to travel freely; rather they have to follow traffic regulations, avoid obstacles, buildings, etc. Thus CSM model is a realistic movement pattern for vehicles in a city.

There has been a number of cost analysis of mobility protocols [6–17] . However, the analysis done earlier did not consider all possible costs e.g. costs related to query messages by CN, costs of refreshing binding updates, and costs of registration messages, and data acknowledgement messages, etc. Hence, the cost estimation analysis are incomplete. In addition, many of the signaling cost analysis, such as [7, 8] used random waypoint mobility model which is not a realistic mobility model. Therefore, those work cannot accurately estimate the amount of resources required by the mobility protocols with the increased network size, mobility rate and traffic rate. The main *differences* of this work from previous works are that we have considered all possible costs related to mobility management, and have used city section mobility model to compute the total costs and costs related to mobility. We have defined two novel performance metrics (normalized overhead and efficiency) in terms of signaling cost and used them to evaluate the performance of the mobility protocols.

The *objective* of this paper is to perform a comprehensive cost analysis of mobility protocols using a realistic mobility model, figure out how those costs are affected by various parameters and to evaluate the performance of these protocols using proposed metrics.

Our *contribution* in this paper are: (i) developing an analytical framework for signaling cost analysis of SIGMA and HMIPv6, (ii) defining two novel performance metrics, viz. normalized overhead and efficiency of mobility protocols based on the signaling costs, (iii) evaluating and comparing normalized overhead, efficiency, and signaling costs of the two mobility protocols in terms of network size, mobility rate and traffic rate using CSM and RWP model.

We have developed analytical models to compute the total costs related to SIGMA and HMIPv6 protocols, taken into account all possible costs and proposed metrics for performance evaluation of these protocols. Results show that even though the mobility signaling cost of SIGMA is higher than HMIPv6, the total cost is much less for SIGMA than that of HMIPv6 due to the higher cost of packet tunneling. In addition, the mobility signaling costs of both the protocols using CSM and RWP model are found to be much different, demonstrating the fact that RWP model cannot be used as an approximation to a realistic scenario. The analytical framework presented in this paper can be used for the performance comparison of other mobility protocols and will help network professionals to choose the best one.

The rest of the paper is organized as follows. In Sect. 2, previous works on cost analysis of mobility protocols are listed. In Sect. 3, the analysis on city section mobility model is presented to compute the subnet residence time. In Sect. 4, a brief description of mobility protocols is given. In Sect. 5, the cost analysis of SIGMA and HMIPv6 protocols is performed. In Sect. 6, the performance metrics of mobility protocols have been defined for SIGMA and HMIPv6 protocols. Section 7 presents and explains the numerical results. Finally, Sect. 8 has the concluding remarks.

2 Literature review

In this section, we present some of earlier attempts for cost analysis of mobility protocols. Xie et al. [6] perform the cost analysis of Mobile IP to minimize the signaling cost while introducing a novel regional location management scheme. Fu et al. [7] analyze the signaling costs of SIGMA and HMIPv6. Reaz et al. [8] perform the signaling cost analysis of NEMO and SINEMO, seamless IP-diversity based network mobility protocol. These work ignored some major costs relating to mobility management and used random waypoint model as the underlying mobility model.

Makaya et al. [9] present an analytical model for the performance and cost analysis of IPv6-based mobility protocols (i.e., MIPv6, HMIPv6, FMIPv6 and F-HMIPv6). Diab et al. [11] propose a generic mathematical model for fast, simple and accurate cost estimation and it can be used for a wide range of mobility management protocols and the parameters of the generic model are chosen to reflect the characteristics of the studied protocols, mobility patterns and network topologies.

Munasinghe et al. [12] present an analytical signaling cost model in a heterogeneous mobile networking environment for vertical handoffs at the core network level for a roaming user. The numerical analysis and evaluation is based on a framework designed for interworking between UMTS, CDMA2000 technology, and mobile WiMAX networks. Lee et al. [13] analyze the performance of recently proposed route optimization of Proxy Mobile IPv6, a network-based mobility support protocol proposed by the IETF, in terms of signaling cost and packet delivery cost. They demonstrate that route optimization solves the ineffective routing path problem improving the scalability of

Proxy Mobile IPv6 architecture. Narayanan et al. [14] have analyzed various handoff scenarios for a dual stack mobile node roaming in a mixed IPv4/IPv6 environment. They also present an analytical model for the handoff signaling cost for dual stack scenario.

Galli et al. [15] propose an analytical model for the comparative analysis of mobility protocols by decomposing existing protocols into their building blocks, and obtaining the general cost functions. to identify network and topology conditions under which a certain protocol performs better than another. Singh [16] analyze the signaling cost of MIPv6 and HMIPv6 using random walk and fluid flow model. They use two cost components: location update cost and packet delivery cost which are computed as a function of session to mobility ratio (SMR). Lee et al. [17] present an analytical cost model to evaluate the performance of the existing IP mobility protocols, such as Mobile IPv6, HMIPv6 and the recently proposed Proxy Mobile IPv6 and compare them with respect to signaling cost, packet delivery cost, tunneling cost, and total cost. They argue that the performance of mobility management protocols largely affects consumers' experiences and the results can be used to facilitate decision-making for consumer network design.

However, the cost analysis performed earlier did not consider all possible costs, e.g. costs related to query messages by CN, costs of refreshing binding updates, and costs of registration messages, and data acknowledgement messages, etc. Hence, those analysis are incomplete. Moreover, the mobility model used in those works are not a realistic one. Hence, we develop an analytical model that takes into account all possible costs for mobility management and uses a realistic movement pattern for the cost estimation.

3 City section mobility model

In this section, we explain the City Section Mobility (CSM) model that is used to simulate the movement pattern of the mobile hosts. The simulation area used in CSM model [4, 5] is represented by a grid of streets forming a particular section of a city. The model sets the speed limit of each street. Each mobile host starts at a predefined intersection of two streets. It then randomly chooses a destination, also represented by intersection of two streets. Moving to this destination involves (at most) one horizontal and one vertical movement. Upon reaching the destination, it pauses for some random time and the same process is repeated. Each such cycle is termed as an *epoch*. The stochastic properties of CSM model has been analyzed in [18] and we present some results here that will be used in Sect. 5 to obtain the residence time of the mobile hosts roaming in the environment. Following are the assumptions of CSM model:

- Roads are parallel to axes.

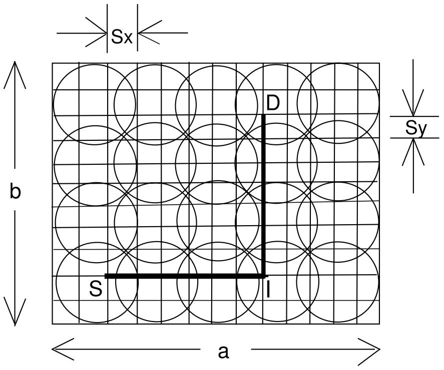

Fig. 1 Road network in CSM model

- Starting point and each destination point are assumed to be road intersections.

Let the environment be a rectangular area of dimension $a \times b$ as shown in Fig. 1. Let there be N_s horizontal roads (*streets*) and N_a vertical roads (*avenues*) and streets be S_y distance apart and avenues be S_x distance apart. So number of streets and number of avenues are

$$N_a = \frac{a}{S_x} + 1, \tag{1}$$

$$N_s = \frac{b}{S_y} + 1 \tag{2}$$

Let us consider that in epoch i, MN moves from point S^i to point D^i via intermediate point I^i, involving (at most) one horizontal and one vertical movement.

3.1 Expected epoch length

Let us first find out the expected length that a mobile host travels in horizontal direction in an epoch. Let L_x be the length of one instance. The values of L_x can be found from the $N_a \times N_a$ matrix below. Each entry of the matrix is given by,

$$M(i, j) = S_x \mid i - j \mid, \quad \text{where } 1 \le i, j \le N_a \tag{3}$$

The values of L_x can be 0, $S_x, 2S_x, \ldots, (N_a - 1)S_x$ depending on the location of points S and I. So the expected value of L_x is given by,

$$\begin{aligned} E(L_x) &= \frac{1}{{N_a}^2}[N_a \times 0 + 2\{(N_a - 1)S_x + (N_a - 2)2S_x \\ &\quad + \cdots + 2(N_a - 2)S_x + 1(N_a - 1)S_x\}] \\ &= \frac{2S_x}{{N_a}^2} \sum_{i=1}^{N_a - 1} (N_a - i)i \\ &= \frac{S_x({N_a}^2 - 1)}{3N_a} \end{aligned}$$

Substituting $a = S_x(N_a - 1)$, we get

$$E(L_x) = \frac{a(N_a + 1)}{3N_a} \tag{4}$$

Similarly, for vertical movement

$$E(L_y) = \frac{b(N_s + 1)}{3N_s} \tag{5}$$

Now adding (4) and (5), the expected epoch length can be obtained as

$$E(L) = \frac{a(N_a + 1)}{3N_a} + \frac{b(N_s + 1)}{3N_s} \tag{6}$$

For large values of N_a and N_s, (6) reduces to

$$E(L) = \frac{a}{3} + \frac{b}{3} \tag{7}$$

For a square grid of size $a \times a$, $E(L) = 2a/3$. This expected epoch length of CSM model gives a measure of the distance covered by a mobile node in an epoch on the average.

3.2 Epoch time

Let the speed of the MN vary between V_x^{min} to V_x^{max} for some horizontal road segment. So for uniform speed distribution, the probability density function of MN's speed in horizontal direction can be given by

$$f_V(v_x) = \frac{1}{V_x^{max} - V_x^{min}} \tag{8}$$

The expected time required for movement on horizontal road segment in an epoch is thus,

$$\begin{aligned} E(T_x) &= E(L_x) \int_{V_x^{min}}^{V_x^{max}} \frac{1}{v_x} f_V(v_x) dv_x \\ &= E(L_x) \frac{\ln(V_x^{max}/V_x^{min})}{V_x^{max} - V_x^{min}} \end{aligned} \tag{9}$$

Similarly, for movement on vertical road segment

$$E(T_y) = E(L_y) \frac{\ln(V_y^{max}/V_y^{min})}{V_y^{max} - V_y^{min}} \tag{10}$$

Adding (9) and (10), the expected epoch time can be obtained as follows:

$$\begin{aligned} E(T) &= \frac{a(N_a + 1)\ln(V_x^{max}/V_x^{min})}{3N_a(V_x^{max} - V_x^{min})} \\ &\quad + \frac{b(N_s + 1)\ln(V_y^{max}/V_y^{min})}{3N_s(V_y^{max} - V_y^{min})} \end{aligned} \tag{11}$$

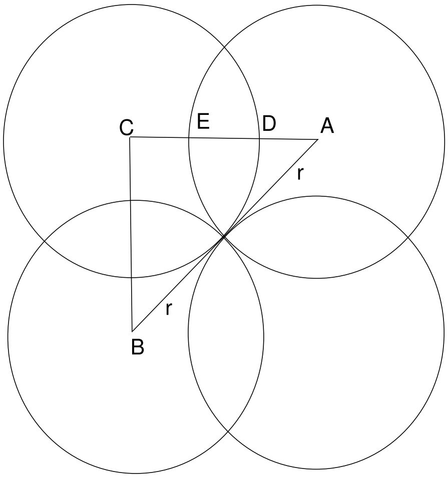

Fig. 2 Subnet overlapping in CSM model

3.3 Pause time

For safety at each road intersection, there is a random pause time between 0 to U_{max} in order to avoid collisions. The expected pause time is thus

$$E(U) = \int_0^{U_{max}} \frac{udu}{U_{max}} = \frac{U_{max}}{2} \tag{12}$$

3.4 Number of subnet crossing

Let us consider that the road network of dimensions $a \times b$ (Fig. 1) is covered by Access Points (AP); let there be n rows of APs and m APs in each row. In total, there will be mn APs to cover the rectangular area. Let the radio coverage area of each AP be a circular region of radius r and two successive APs overlap at a maximum length of l along its diameter. So

$$a = 2rm - (m-1)l, \tag{13}$$

$$b = 2rn - (n-1)l \tag{14}$$

Let the radius r of each subnet be greater than the inter-road spacing, i.e., $r > S_x$ and $r > S_y$. Let us assume that $2r = K_1 S_x = K_2 S_y$. In Fig. 2, the length of $AB = 2r$, and let $AC = x = BC$, $DE = l$. Since the cells are parallel to axes, we find that $x = \sqrt{2}r = r + r - l$. Hence,

$$l = (2 - \sqrt{2})r \tag{15}$$

Now putting the value of l in (13), we get,

$$m = \left\lceil \frac{\sqrt{2}a - 2(\sqrt{2} - 1)r}{2r} \right\rceil \tag{16}$$

Similarly, we can have

$$n = \left\lceil \frac{\sqrt{2}b - 2(\sqrt{2}-1)r}{2r} \right\rceil \tag{17}$$

For $a = 36$ km, $b = 24$ km, and $r = 0.5$ km, we have, $m = 51$, $n = 34$. Let us now consider the movement along horizontal direction. If the distance between the two endpoints is less than the diameter of an AP's coverage area i.e., between 0 to $(K_1 - 1)S_x$, there will be at most one subnet crossing. For any distance between $K_1 S_x$ to $(2K_1 - 1)S_x$, there will be at most two subnet crossings, and so on. Thus, if the point S is at first avenue and point I is at N_ath avenue, then the distance of the road segment will be $(N_a - 1)S_x$ and there will be at most m subnet crossings. Thus we can find out the expected number of subnet crossings in an epoch for movement along horizontal direction as,

$$\begin{aligned}
E(C_x) = {} & \frac{2}{{N_a}^2}[(N_a - 1) + (N_a - 2) + \cdots + N_a - (K_1 - 1) \\
& + 2\{(N_a - K_1) + (N_a - K_1 - 1) + \cdots \\
& + (N_a - 2K_1 + 1)\} + \cdots + m\{(N_a - (m-1)K_1) \\
& + (N_a - (m-1)K_1 - 1) + \cdots \\
& + (N_a - mK_1 + 1)\}] \\
= {} & \frac{2}{{N_a}^2}\Bigg[K_1 N_a \sum_{i=1}^{m} i - K_1^2 \sum_{i=2}^{m} i(i-1) \\
& - \sum_{i=1}^{K_1-1} i \sum_{j=1}^{m} j\Bigg] \\
= {} & \frac{m(m+1)K_1}{6{N_a}^2}(6N_a - 4mK_1 + K_1 + 3)
\end{aligned}$$

Similarly, for movement along vertical direction

$$E(C_y) = \frac{n(n+1)K_2}{6{N_s}^2}(6N_s - 4nK_2 + K_2 + 3) \tag{18}$$

The expected number of subnet crossing in an epoch is thus

$$E(C) = E(C_x) + E(C_y) \tag{19}$$

3.5 Subnet residence time

Since in each epoch, the MN pauses at two different points, the average residence time of a MN in a subnet can be estimated as follows:

$$T_r = \frac{E(T) + 2E(U)}{E(C)} \tag{20}$$

A similar analysis on RWP model is done in [19] whose results will be used to compute the signaling costs in Sect. 7.

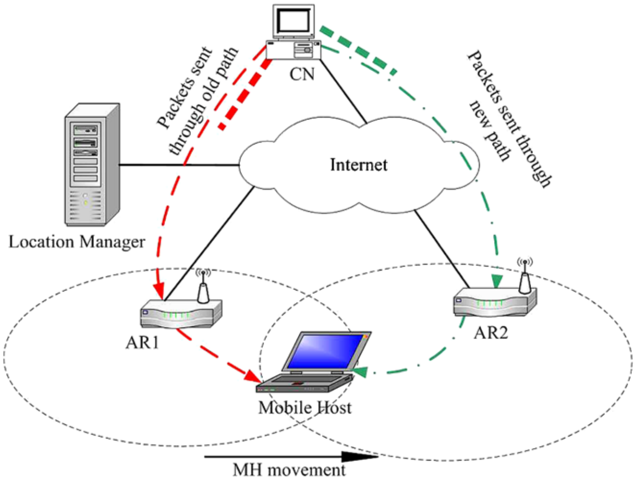

Fig. 3 SIGMA architecture [3]

4 Mobility protocols

In this section, we give a brief description of two mobility protocols: SIGMA and HMIPv6.

4.1 SIGMA

SIGMA [3] utilizes IP-diversity to achieve a seamless handover of a Mobile Host (MH), and is designed to solve the drawbacks of Mobile IP. The architecture of SIGMA is shown in Fig. 3. The Location Manager (LM) is responsible for keeping location database of mobile hosts. Whenever any Correspondent Node (CN) wants to send data to a MH, it must first send a query message to the LM to obtain its current IP address. Hence, every MH must send its new IP address in a network it has moved to the LM; these are termed as Location Updates. Moreover, every subnet crossing triggers binding updates; after handover each MH needs to send a binding update to every CN it is communicating with. As shown in Fig. 3, the communication occurs through Access Router 1 (AR1) before handover, and after handover, it is through AR2. SIGMA achieves seamless handover by using the multi-homing feature of Stream Control Transport Protocol (STCP).

4.2 Hierarchical mobile IPv6

Enhancement to MIPv6 [1] has resulted in Hierarchical MIPv6 (HMIPv6) [2] where a new network element, called Mobility Anchor Point (MAP), is used to introduce hierarchy in mobility management. The architecture of HMIPv6 is shown in Fig. 4. A MAP, essentially a local Home Agent (HA), covers several subnets under its domain, called a region. A Mobile Host (MH) entering a MAP domain receives Router Advertisements containing information on

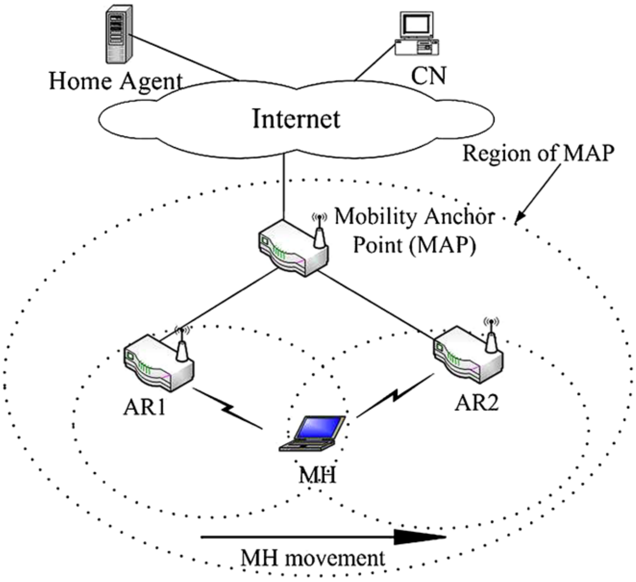

Fig. 4 HMIPv6 architecture

one or more local MAPs. The MH updates Home Agent with an address assigned by the MAP, called Regional Care-of-Address, as its current location. The MAP intercepts all packets sent to the MH, encapsulates, and forwards them to the MH's current address. Upon arrival in a new network, the mobile host discovers the global address of the MAP which is stored in the Access Routers (AR) and communicated to the mobile node via router advertisements.

5 Signaling cost analysis

In this section, we discuss the signaling costs of SIGMA and HMIPv6. In order to compute the total cost on the network as a whole, we will consider resources (such as, bandwidth, processing power etc.) consumed due to the mobility protocols.

5.1 Notations

The notations to be used in this paper are explained in this section. They are divided into three categories, depending whether they are required only for SIGMA, HMIPv6 or both.

5.1.1 Notations that apply to both protocols

N_m	Number of Mobile Hosts,
N_c	Average number of CNs with which a MH is communicating,
δ_L	Per hop transmission cost for location update message,
δ_B	Per hop transmission cost for binding update message,
δ_Q	Per hop transmission cost for query message,
δ_R	Per hop transmission cost for router discovery messages
δ_D	Per hop transmission cost for average data packet,
δ_A	Per hop transmission cost for acknowledgement (data) packet,
σ	Proportionality constant of signaling cost over wired and wireless link,
ψ	Linear coefficient for lookup cost,
T_r	Subnet residence time,
λ_s	Average session arrival rate,
ζ	linear coefficient for IP routing table lookup,
τ	encapsulation cost,
κ	Maximum transmission unit,
α	Filesize,
T_{be}	Lifetime of binding entry.

5.1.2 Notations that apply only to SIGMA

l_{la}	Average number of hops between LM and AR,
l_{lc}	Average number of hops between LM and CN,
l_{ac}	Average number of hops between AR and CN,
γ_l	Processing cost at LM,
γ_a	Processing cost at AR,
γ_c	Processing cost at CN for binding update message from MH.

5.1.3 Notations that apply only to HMIPv6

l_{mh}	Average distance between MAP and HA (in hops),
l_{ma}	Average distance between MAP and AR (in hops),
l_{mc}	Average number of hops between MAP and CN,
l_{hc}	Average distance between HA and CN (in hops),
δ_{rr}	Per hop transmission cost for RCoA registration request-reply message,
δ_{lr}	Per hop transmission cost for LCoA registration request-reply message,
γ_{rr}	Processing cost for each RCoA registration request at MAP,
γ_{lr}	Processing cost for each LCoA registration request at MAP,
γ_h	Processing cost for each location update at HA,
m	Number of access routers in a row,
n	Number of access routers a column,
k	Number of subnets under an MAP,
M	Expected number of moves for a MAP domain move-out.

5.2 Assumptions

Following are assumptions for signaling cost analysis:

- Session arrival rate for each mobile host is equal.
- While considering load on various mobility agents, ignore costs relating to standard IP switching is ignored.

- The data (file) size in each session is equal.
- Uniform distribution of mobile hosts over the region of the network.
- The database of mobile hosts' current location is stored in such a way that binary search can be used while searching the location database.
- Lifetime of binding entries are equal in LM, HA, MAP and CN.

5.3 Signaling cost of SIGMA

The signaling cost of SIGMA consists of five major components. They are costs related to query messages (Ψ^S_{QR}), router discovery messages (Ψ^S_{RD}), location update messages (Ψ^S_{LU}), binding update messages (Ψ^S_{BU}), refreshing binding update messages (Ψ^S_{RB}), and packet delivery (Ψ^S_{PD}).

5.3.1 Query messages

For each association between MH and CN, query messages are exchanged between CN and LM. Each MH has an average of N_c number of correspondent nodes; therefore, total number of correspondent nodes for all the mobile hosts are $N_m N_c$. As the session arrival rates for each MH are assumed to be equal (λ_s), the transmission cost for all the query messages towards the LM is $N_c N_m(2l_{lc}\delta_Q)\lambda_s$. The searching costs for the query messages are $N_c N_m(\psi\lambda_s \log_2 N_m)$. Hence, the cost of the network for the query messages from the CNs is,

$$\Psi^S_{QR} = N_m N_c \lambda_s (2\delta_Q l_{lc} + \psi \log_2 N_m) \tag{21}$$

5.3.2 Router discovery messages

Whenever a MH comes within the coverage area of a new AR, discovery of that new AR is done exchanging router solicitation and router advertisement messages. The costs associated with these messages are

$$\Psi^S_{RD} = N_m \frac{2\sigma\delta_R + \gamma_a}{T_r} \tag{22}$$

5.3.3 Location update messages

Each subnet crossing by the MH triggers location update message to be sent to LM which processes the message and sends back acknowledgement to MH. The location update cost is proportional to the distance (in hops) between the MH and LM (note that there is one wireless link, and transmission cost in wireless link is higher than that of wired link by a factor of σ). So the resources (bandwidth and processing cost) used in the network for location updates are

$$\Psi^S_{LU} = N_m \frac{2(l_{la} + \sigma)\delta_L + \gamma_l}{T_r} \tag{23}$$

5.3.4 Binding update messages

After each subnet crossing of each MH, binding updates (ASCONF message with Add IP, Set primary, Delete IP messages) are sent to all the correspondent nodes. The binding update is proportional to the distance (in hops) between the MH and CN.

$$\Psi^S_{BU} = N_m N_c \frac{6(l_{ac} + \sigma)\delta_B + \gamma_c}{T_r} \tag{24}$$

5.3.5 Refreshing binding update messages

During the subnet residence time, each MH sends refreshing binding update to the LM and all the CNs so that the binding entry is not expired. If the lifetime of each binding entry is T_{be}, then there will be ω ($= \lfloor \frac{T_r}{T_{be}} \rfloor$) refreshing binding updates sent to LM and CN within the time T_r. So the cost related to the refreshing binding update messages can be computed as follows:

$$\Psi^S_{RB} = \frac{\omega N_m}{T_r} \times \Big(2(l_{la} + \sigma)\delta_L + 2N_c(l_{ac} + \sigma)\delta_B\Big) \tag{25}$$

5.3.6 Packet delivery cost

After getting the IP address of the MH from the LM, the CN send data packets directly to the MH through l_{ac} wired hops and one wireless hop. The corresponding ACK packet uses the reverse path. The transmission cost for each data packet is $(l_{ac} + \sigma)\delta_D$, and a transmission cost of $(l_{ac} + \sigma)\delta_A$ for each acknowledgement packet. Hence the packet delivery cost for all the communications in the network can be obtained using the following equation:

$$\begin{aligned} \Psi^S_{PD} &= \Psi^S_{DP} + \Psi^S_{AP} \\ &= N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil (\delta_D + \delta_A)(l_{ac} + \sigma) \end{aligned} \tag{26}$$

where Ψ^S_{DP} denotes the costs related to data packets and Ψ^S_{AP} denotes the costs related to ACK packets.

Thus, the total cost on the complete network due to SIGMA protocol can be obtained by adding (21), (22), (23), (24), (25) and (26):

$$\Psi^S = \Psi^S_{QR} + \Psi^S_{RD} + \Psi^S_{LU} + \Psi^S_{BU} + \Psi^S_{RB} + \Psi^S_{PD} \tag{27}$$

5.4 Signaling cost of HMIPv6

Before deriving the cost expressions for HMIPv6 protocol, we compute the expected number of moves that causes a MH to move out of a MAP region that results in regional registration as the number of regional registration influence the signaling costs. In the considered topology, there are n rows of ARs and each row has m ARs. So in total, there mn

ARs in the network. In city section mobility model, the MH can move from the coverage area of one AR to the coverage area of any other AR in one move. As each MAP covers k ARs, the probability that the mobile host will be within the coverage area of the previous MAP after a movement in city section mobility model is $p = \frac{k}{mn}$. Conversely, the probability that MH will reach a new AR after the movement is $q = 1 - p = \frac{mn-k}{mn}$. So the probability that the MH moves out of a MAP domain in i movement is given by the following equation:

$$P_i = p^{i-1} q \tag{28}$$

Hence, the expected number of moves for a MAP domain move-out can be obtained as follows:

$$\begin{aligned} M &= \sum_{i=1}^{\infty} i P_i = q + 2pq + 3p^2 q + 4p^3 q + \cdots \\ &= q(1 + 2p + 3p^2 + 4p^3 + \cdots) \\ &= q(1-p)^{-2} = \frac{1}{1-p} \\ &= \frac{mn}{mn-k} \end{aligned} \tag{29}$$

The mobility signaling overheads on the network are due to exchange of Location Query/reply messages between HAs with CNs, exchange of RCoA and LCoA registration request/reply messages among MH, MAP and HA, and tunneling of data and ACK packets. Thus the signaling cost of HMIPv6 consists of four components. They are costs associated with query messages (Ψ^H_{QR}), LCoA registration messages (Ψ^H_{LR}), RCoA registration messages (Ψ^H_{RR}), and tunneling (Ψ^H_{PT}).

5.4.1 Query message

For each association between MH and CN, query messages are exchanged between CN and HA which is similar to that for SIGMA.

The transmission cost for all the query and reply messages towards the HA is $N_c N_m (2 l_{hc} \delta_Q) \lambda_s$. The searching cost in the HA is $N_c N_m (\psi \lambda_s \log_2 N_m)$. Hence, the cost of the network for the query messages from the CNs is,

$$\Psi^H_{QR} = N_m N_c \lambda_s (2 \delta_Q l_{hc} + \psi \log_2 N_m) \tag{30}$$

5.4.2 LCoA registration messages

Every subnet crossing by the MH (in every T_r sec) within a MAP region, triggers a LCoA registration message to be sent to the MAP. This involves transmission cost of $2\delta_{lr}$ in each of the l_{ma} wired hops and one wireless hops. In addition, processing cost is incurred at MAP for updating the location database.

$$\Psi^H_{LR} = N_m \frac{2\delta_{lr}(l_{ma} + \sigma) + \gamma_{lr}}{T_r} \tag{31}$$

5.4.3 RCoA registration messages

For every region crossing (happens every MT_r seconds), MH needs to register the RCoA with HA. MH sends RCoA registration request to the MAP. The MAP processes the request and assigns a Regional Care of Address (RCoA) to the MH. As the MAP is l_{mm} hops (that include one wireless hop) away from the MH, this RCoA registration incurs a transmission cost of $2\delta_{rr}(l_{ma} + \sigma)$, and a processing cost γ_{rr} at the MAP. The MAP informs the HA about this new RCoA registration. Since HA is l_{mh} hops away from the MAP, this involves a transmission cost of $2\delta_{rr} l_{mh}$, and a processing cost of γ_h at the HA. Thus the RCoA registration requires costs given by the following equation.

$$\Psi^H_{RR} = N_m \frac{2\delta_{rr}(l_{ma} + \sigma) + \gamma_{rr}}{MT_r} + N_m \frac{2\delta_{rr} l_{mh} + \gamma_h}{MT_r} \tag{32}$$

5.4.4 Refreshing binding update messages

Each MH sends refreshing binding update to the HA, MAP and all the CNs so that the binding entry is not expired. Since the subnet occupancy in a MAP domain is MT_r, $M\lfloor \frac{T_r}{T_{be}} \rfloor$ ($= M\omega$)refreshing binding updates will be sent to the HA during the time MT_r. And there will be ω ($= \lfloor \frac{T_r}{T_{be}} \rfloor$) refreshing binding updates sent to MAP and CNs within the time T_r. So the cost related to the refreshing binding update messages can be computed as follows:

$$\begin{aligned} \Psi^H_{RB} &= \frac{\omega M N_m}{MT_r} 2(l_{mh} + l_{ma} + \sigma)\delta_L + \frac{\omega N_m}{T_r} 2N_c \\ &\quad \times (l_{mc} + l_{ma} + \sigma)\delta_B + \frac{\omega N_m}{T_r} 2(l_{ma} + \sigma)\delta_L \\ &= \frac{2\omega N_m}{T_r} \Big((l_{mh} + 2l_{ma} + 2\sigma)\delta_L \\ &\quad + N_c (l_{mc} + l_{ma} + \sigma)\delta_B \Big) \end{aligned} \tag{33}$$

5.4.5 Packet tunneling cost

In HMIPv6, CN sends every data packet to MH through HA and then MAP. The cost required for the data packet to reach HA is $\delta_D l_{hc}$. Similar cost of $\delta_A l_{hc}$ is required for each ACK packet to reach CN from HA. So tunneling each data packet and corresponding ACK packet from CN to the HA costs $(\delta_D + \delta_A) l_{hc}$.

The HA of the MH receives the data packets, encapsulates it using the RCoA address of the MH, and sends it to the MAP. Thus a transmission cost of $\delta_D l_{mh}$, and encapsulation cost of ξ for each data packet. Similar cost of $\delta_A l_{mh} + \xi$ for each ACK packet. So tunneling each data packet and corresponding ACK packet from HA to the MAP cost $(\delta_D + \delta_A)l_{mh} + 2\xi$.

Since total number of MH in the network is N_m and we have assumed uniform distribution of MH in the network, the number of MH under a MAP will be $\frac{N_m k}{xy}$. MAP receives the data packet on behalf of the MH from the HA, decapsulates the packet, and then encapsulates it to forward it to MH's current location using the translation table of RCoA to LCoA. Hence it costs $\delta_D(l_{ma} + \sigma) + 2\xi$ for each data packet and $\delta_A(l_{ma} + \sigma) + 2\xi$ for each ACK packet. In addition, visitor list lookup at MAP costs $\psi \log_2(\frac{N_m k}{xy})$, and IP routing table lookup for the k ARs under MAP costs another $\zeta \log_2 k$. So tunneling each data packet and corresponding ACK packet from MAP to the MH costs $(\delta_D + \delta_A)(l_{ma} + \sigma) + 4\xi + \psi \log_2(\frac{N_m k}{xy}) + \zeta \log_2 k$.

Thus, the costs related to packet tunneling are given by

$$\begin{aligned}\Psi^H_{PT} &= N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \Bigg(\bigg((\delta_D + \delta_A) l_{hc} + (\delta_D + \delta_A) l_{mh} \\ &\quad + 2\tau + (\delta_D + \delta_A)(l_{ma} + \sigma)\bigg) + 4\tau \\ &\quad + \psi \log_2\left(\frac{N_m k}{mn}\right) + \zeta \log_2 k\Bigg) \\ &= N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \bigg((l_{hc} + l_{mh} + l_{ma} + \sigma) \\ &\quad \times (\delta_D + \delta_A) + 6\tau + \psi \log_2\left(\frac{N_m k}{mn}\right) + \zeta \log_2 k\bigg)\end{aligned} \tag{34}$$

5.4.6 *Total overhead on the network*

Therefore, the total cost on the complete network due to HMIPv6 protocol can be obtained by adding (30), (31), (32), (33) and (34):

$$\Psi^H = \Psi^H_{QR} + \Psi^H_{LR} + \Psi^H_{RR} + \Psi^H_{RB} + \Psi^H_{PT} \tag{35}$$

6 Performance metrics

Since no performance metrics of mobility protocols exists in terms of signaling costs, we define two performance metrics to evaluate the effectiveness of the protocols. They are normalized signaling overhead and efficiency.

6.1 Normalized overhead

Normalized overhead is defined as the overhead on the network per unit size of data transmission, that is, the ratio of total signaling overhead to the total data transmitted.

6.1.1 *SIGMA*

For SIGMA protocol, the total signaling cost can be obtained by adding the cost for query messages, router discovery, location update, binding update, refreshing binding update and costs required for ACK packets. On the other hand, the amount of data transmission per second is $N_m N_c \lambda_s \alpha$. Hence the normalized overhead of SIGMA can be obtained using the following equation:

$$\rho^S = \frac{\Psi^S_{QR} + \Psi^S_{RD} + \Psi^S_{LU} + \Psi^S_{BU} + \Psi^S_{RB} + \Psi^S_{AP}}{N_m N_c \lambda_s \alpha} \tag{36}$$

6.1.2 *HMIPv6*

For HMIPv6 protocol, the total signaling cost can be obtained by adding the cost for query messages, LCoA registration messages, RCoA registration messages, refreshing binding update and costs required tunneling and transmission costs of ACK packets. The costs of tunneling and ACK packet transmissions can be obtained from (37) by considering only related terms as follows:

$$\begin{aligned}\Psi^H_{AT} &= N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \bigg((l_{hc} + l_{mh} + l_{ma} + \sigma)\delta_A \\ &\quad + 6\tau + \psi \log_2\left(\frac{N_m k}{mn}\right) + \zeta \log_2 k\bigg)\end{aligned} \tag{37}$$

The amount of data transmission per second is $N_m N_c \lambda_s \alpha$ which is same as SIGMA. Hence the normalized overhead of HMIPv6 can be obtained using the following equation:

$$\rho^H = \frac{\Psi^H_{QR} + \Psi^H_{LR} + \Psi^H_{RR} + \Psi^H_{RB} + \Psi^H_{AT}}{N_m N_c \lambda_s \alpha} \tag{38}$$

6.2 Efficiency

Efficiency of a mobility protocol is defined as the ratio of data delivery cost (when an optimal route is used) to the total cost (that includes signaling and data delivery costs) required for the mobility protocol.

6.2.1 *SIGMA*

Since SIGMA uses optimal route for data delivery from CN to MH, the data delivery cost Ψ^S_{DP} can be obtained from (39) by considering only term related to data packets as follows:

$$\Psi^S_{DP} = N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \delta_D (l_{ac} + \sigma) \tag{39}$$

Hence, efficiency of SIGMA protocol can be obtained using the following equation:

$$\eta^S = \frac{\Psi^S_{DP}}{\Psi^S_{QR} + \Psi^S_{RD} + \Psi^S_{LU} + \Psi^S_{BU} + \Psi^S_{RB} + \Psi^S_{PD}} \tag{40}$$

Table 1 Parameter values related to mobility model

Parameter	Value	Parameter	Value
a	36 km	b	24 km
S_x	200 m	S_y	200 m
K_1	5	K_2	5
V_x^{max}	120 km/hr	V_x^{max}	120 km/hr
V_x^{min}	120 km/hr	V_x^{min}	120 km/hr
$E(u)$	4 s		

6.2.2 HMIPv6

In HMIPv6, the data packets are sent through the HA even though it is not the optimal route. The cost to send data from CN to MH in the optimal route can be obtained as follows:

$$\Psi_{DP}^{H} = N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \delta_D (l_{mc} + l_{ma} + \sigma) \tag{41}$$

Therefore, efficiency of HMIPv6 protocol can be obtained using the following equation:

$$\eta^H = \frac{\Psi_{DP}^{H}}{\Psi_{QR}^{H} + \Psi_{LR}^{H} + \Psi_{RR}^{H} + \Psi_{RB}^{H} + \Psi_{PT}^{H}} \tag{42}$$

7 Numeric results

In this section, numerical results are presented for the comparison of SIGMA and HMIPv6 protocols using CSM and RWP model. The parameters that affect the total cost are number and speed of mobile hosts, number of correspondent nodes, session arrival rate, file (data) size of the session, session to mobility ratio (defined as $T_r \times \lambda_s$). Results on normalized overhead and efficiency of mobility protocols are explained in Sects. 7.1 and 7.2, respectively. Total costs and cost related to mobility are presented as functions of number of MHs, speed of MHs and session to mobility ratio in Sects. 7.3, 7.4, and 7.5, respectively.

The comparison with RWP model is based on the analysis presented in [19] which assumes that the coverage area of each AP is square-shaped that is not realistic. For the sake of comparison, we are assuming the dimensions of each AP's coverage area of RWP model to be $2r \times 2r$. Values of the parameters relating to the CSM model are listed in Table 1 which are similar to the previous work [18]. Using these values, number of ARs in a row (or column), subnet residence times of MHs are computed using (16), (17) and (20), respectively in Sect. 3.

Parameters relating to mobility protocols are listed in Table 2, some of which are similar to that in [6–8]. However, we have considered the IPv6 header while considering all transmission costs.

Table 2 Values of parameters used in the numerical analysis

Parameter	Value	Parameter	Value
N_m	40000	N_c	5
δ_L	0.6	δ_B	0.6
δ_Q	0.6	δ_R	1.4
δ_D	5.72	δ_A	0.6
δ_{rr}	0.6	δ_{lr}	0.6
σ	10	ψ	0.3
T_r	70 s	T_{be}	90 s
α	10 Kb	κ	576 b
l_{la}	35	l_{lc}	35
l_{ac}	35	l_{mh}	35
l_{ma}	1	l_{mc}	35
l_{hc}	35	τ	0.5
γ_l	30	γ_a	30
γ_c	30	γ_h	30
γ_{rr}	30	γ_{lr}	30
λ_s	0.01	k	12
m	51	n	34

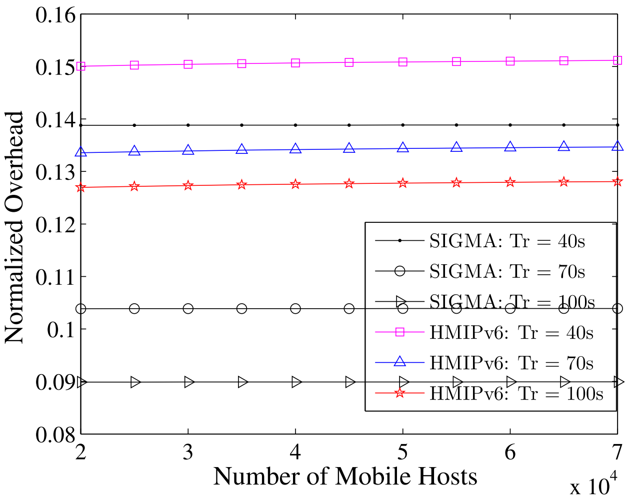

Fig. 5 Normalized overhead of SIGMA and HMIPv6 vs. number of MHs for various residence time

7.1 Normalized overhead

Here we present the results of the normalized overhead of SIGMA and HMIPv6 protocol varying various system parameters. The normalized overhead of HMIPv6 protocol is found to be higher than that of SIGMA in all the cases.

In Fig. 5, normalized overheads of SIGMA and HMIPv6 are shown for varying number of MHs and various subnet residence time. The overhead increases as mobile hosts move faster (with lower residence time) resulting in more handover traffic. However, the normalized overhead does

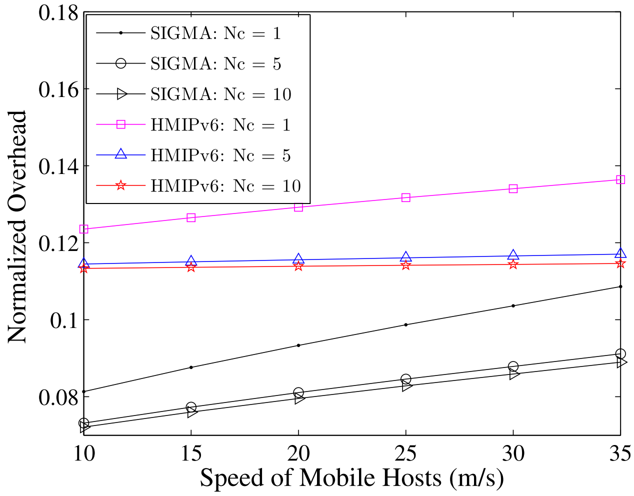

Fig. 6 Normalized overhead of SIGMA and HMIPv6 vs. speed of MHs for various number of CNs

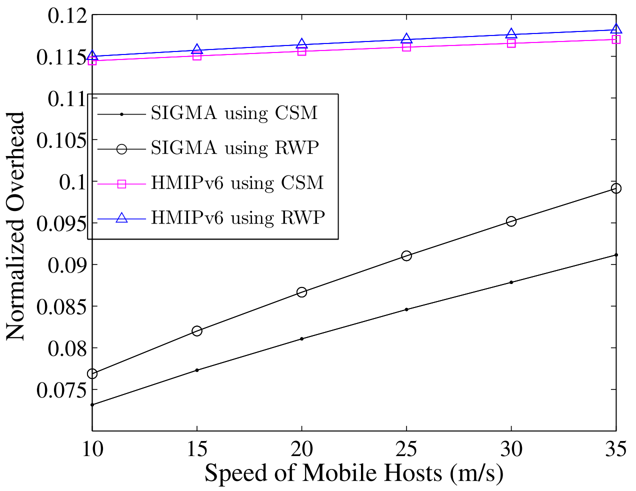

Fig. 7 Normalized overhead of SIGMA and HMIPv6 vs. speed of MHs for CSM and RWP model

not vary much with the increase of number of mobile hosts as the N_m terms are cancelled out due to the ratio.

Figure 6, normalized overheads of SIGMA and HMIPv6 are shown as a function of MH speeds for various number of CNs. The normalized overhead rises for increased number of CNs and higher MH speed. This is because increased number of CNs means more data traffic, and as the data traffic in HMIPv6 is routed through the HA, the normalized overhead for HMIPv6 is always much higher than that of SIGMA. On the other hand, higher movement speed causes the more signaling traffic, resulting in higher overhead.

Figure 7, normalized overheads of SIGMA and HMIPv6 are shown as a function of speed of MH for CSM and RWP model. They are found to be different for CSM and RWP model. This is because the movement pattern in CSM and RWP are quite different. In RWP model, the user may move in an unrestricted way whereas the in CSM model, movement is restricted according to the model parameters, such as, speed limit, road networks, etc.

In Fig. 8, normalized overheads of SIGMA and HMIPv6 are shown as a function of session to mobility ratio (SMR) for various data file size. The higher SMR value implies lower mobility rate resulting in lower signaling overhead. Thus the higher SMR value causes lower normalized overhead. The normalized overhead reduces for larger session size (data files). This is because for larger session size means less normalized overhead for a session or less signaling per unit of data.

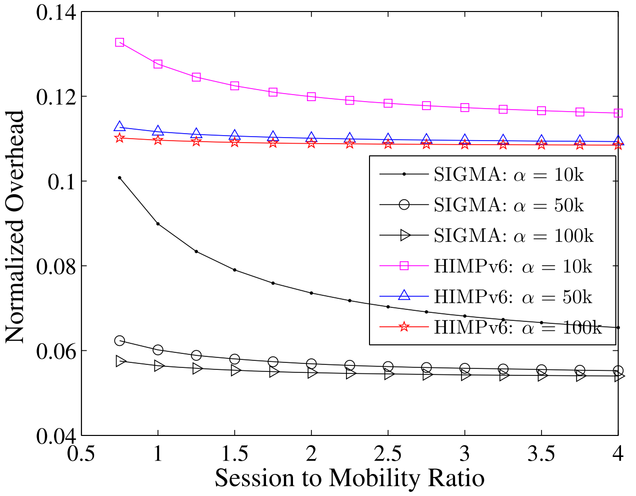

Fig. 8 Normalized overhead of SIGMA and HMIPv6 vs. number of MHs for various residence time

7.2 Efficiency

In Fig. 9, efficiency of SIGMA and HMIPv6 are shown for varying number of MHs for different subnet residence times. The efficiency of HMIPv6 is found to be around 50% whereas SIGMA has an efficiency of more than 78% since SIGMA uses optimal route to send/receive data packets between MH and CN. The efficiency of SIGMA increases for higher subnet residence times as the costs related to mobility signaling reduces, making the ratio (efficiency) higher, and it is 85% when $T_r = 100$ sec.

Figure 10 shows the efficiency for various MH speed and different number of CNs. The efficiency of HMIPv6 does not change much for various speeds of MH since the data packet delivery costs dominates the total cost of HMIPv6. Also it does not vary much for different values of N_c as the effect of N_c is canceled out due to the ratio.

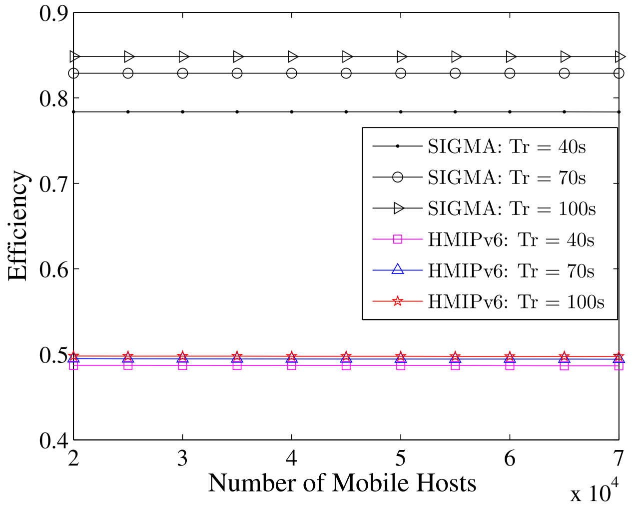

Fig. 9 Efficiency of SIGMA and HMIPv6 vs. number of MHs for various residence time

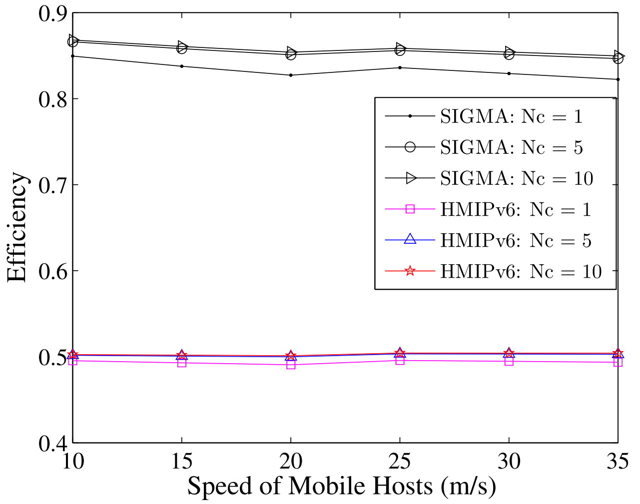

Fig. 10 Efficiency of SIGMA and HMIPv6 vs. number of MHs for various residence time

7.3 Cost as a function of number of MHs

In Fig. 11, the total costs of SIGMA and HMIPv6 are shown as a function of number of MHs for RWP and CSM model. The total cost of HMIPv6 is higher than that of SIGMA though the total cost for two mobility model (CSM and RWP) are almost equal. This is because there are several cost terms that are independent of mobility protocols, such as query message cost, packet delivery cost for SIGMA and query message cost, packet tunneling cost for HMIPv6 (see Sect. 5). These cost terms are dominant terms and they make the total cost almost equal for both the mobility model as shown in Fig. 11.

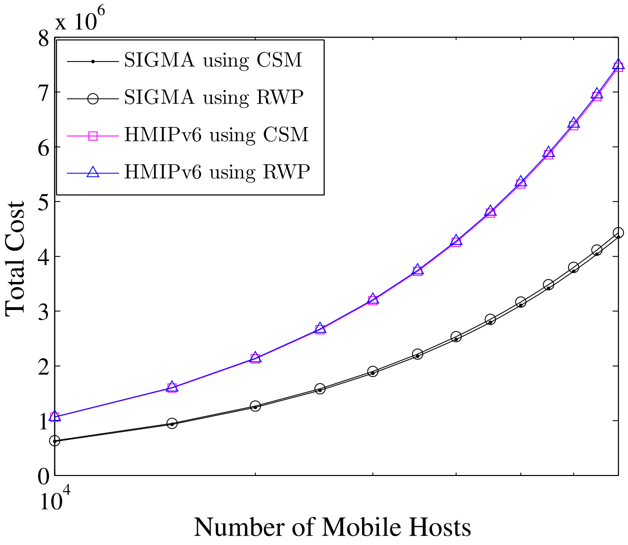

Fig. 11 Total cost of HMIPv6 and SIGMA vs. number of MHs using RWP and CSM model

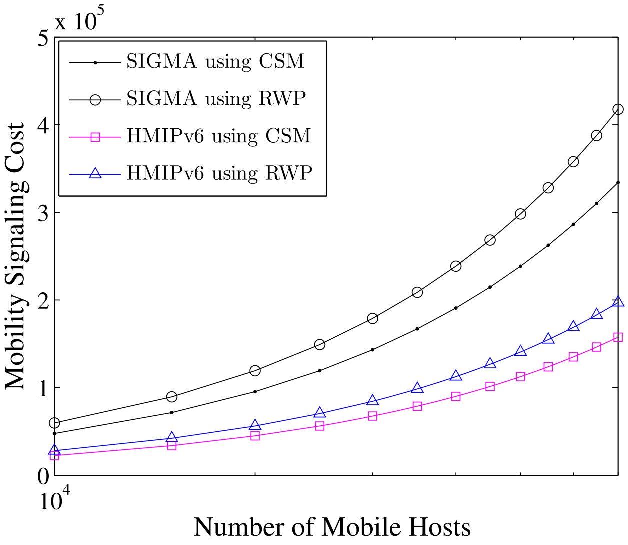

Fig. 12 Mobility signaling cost of HMIPv6 and SIGMA vs. number of MHs using RWP and CSM model

But apart from these above mentioned cost, other costs are related to mobility model. We refer these costs as *mobility signaling cost*. In Fig. 12, the mobility signaling costs of SIGMA and HMIPv6 are shown as a function of number of MHs for RWP and CSM model and we find that this cost is different for two mobility models. It should be noted that mobility signaling cost of SIGMA is higher than that of HMIPv6 but the total cost of SIGMA is much less than that of HMIPv6 since SIGMA uses binding updates to CN to maintain direct route between MH and MH unlike HMIPv6.

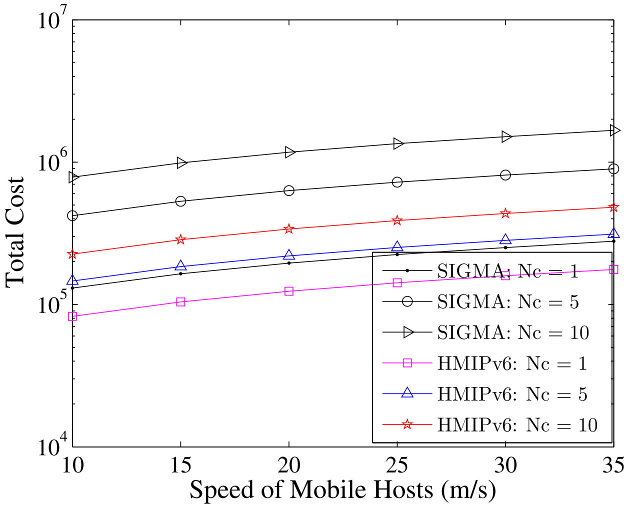

Fig. 13 Total cost of HMIPv6 and SIGMA vs. speed of MHs for various number of CNs

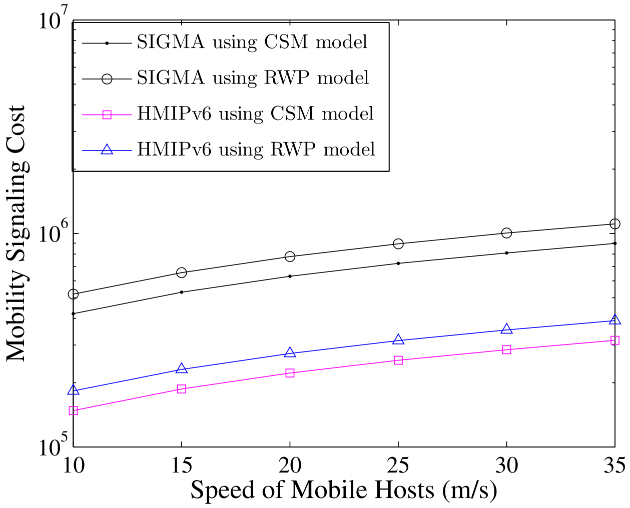

Fig. 14 Mobility signaling cost of HMIPv6 and SIGMA vs. speed of MHs using CSM and RWP model

7.4 Cost as a function of speed of MHs

Figure 13 shows the impact of MH speed on total costs of SIGMA and HMIPv6 for different number of CNs. Results show that the total cost increases with higher mobility rate and for higher number of CNs. Higher mobility rate causes more frequent handover resulting in more signaling traffic in the network; thus, the total cost rises. For higher number of CNs, the binding update costs are higher, thus increasing the total cost.

In Fig. 14, the mobility signaling costs of SIGMA and HMIPv6 are shown as function MH speed using CSM and RWP model, and it increases with increased speed as expected.

7.5 Cost as a function of session to mobility ratio

Figure 15 shows the impact of SMR on total costs of SIGMA and HMIPv6 for various file size. It is found that the total cost is higher for larger data file size. For HMIPv6, for larger session size more tunneling cost is incurred which increases the total cost unlike HMIPv6. However, the total costs are invariant of SMR due to dominance of data packet delivery cost.

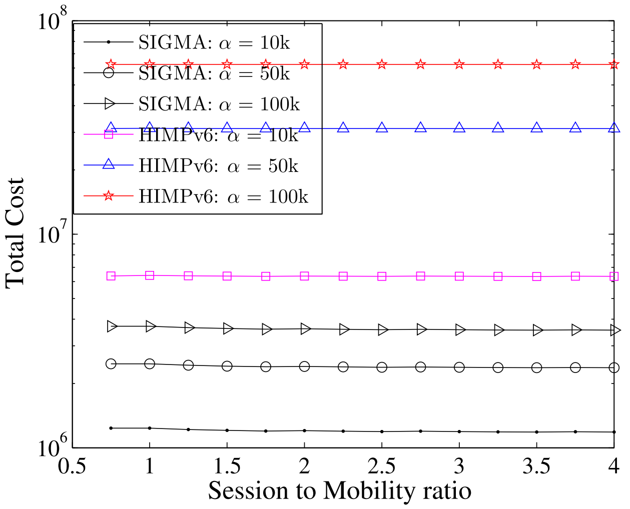

Fig. 15 Total cost of HMIPv6 and SIGMA vs. SMR for various file size

7.6 Summary of the results

The summary of the results are as follows:

- The total cost is much less for SIGMA than that of HMIPv6.
- The mobility signaling cost of SIGMA is higher than HMIPv6 due to binding updates sent to correspondent nodes to maintain direct (optimal) data path.
- The efficiency of SIGMA (85%) is higher than that of HMIPv6 (50%).
- The normalized overhead of SIGMA is less than that of HMIPv6.
- The mobility signaling costs are much different for CSM and RWP model.

8 Conclusion

In this paper, we have developed an analytical model to estimate the total costs of two mobility protocols: SIGMA and HMIPv6 covering all possible ones. We have used the city section mobility model, a realistic street mobility model, for the cost analysis instead of the random waypoint model. Two performance metrics have been proposed based on the signaling costs to evaluate the percentage overhead and efficacy of the mobility protocols.

We have presented numerical results to find out the impact of various network parameters, such as network size, mobility rate, traffic rate, and data volume on total cost, mobility signaling cost, overhead and efficiency of the mobility protocols. Results show that the total cost is much less for SIGMA than that of HMIPv6 due to the higher cost of packet tunneling, even though the mobility signaling cost of SIGMA is higher than HMIPv6. The efficiency of SIGMA protocol is found to be much higher than that of HMIIPv6, and the normalized overhead is less for SIGMA than HMIPv6.

The analytical framework presented in this paper can be used in estimating cost of other mobility protocols, such as Proxy Mobile IPv6, Dual-stack MIPv6, etc. Network professionals can use it to estimate amount of load on the network due to mobility protocols and compare them based on the proposed performance metrics, thus facilitating decision-making in future network. In addition, the cost analysis can be used for scalability analysis of these mobility protocols in future research.

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M. Shohrab Hossain received his B.Sc. and M.Sc. in Computer Science and Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in the year 2003 and 2007, respectively. Currently he is a Research Assistant, and working towards his Ph.D. in the School of Computer Science at University of Oklahoma. His research interests include mobility of IPv6 networks, mobility models, security, scalability and survivability of wireless and mobile networks.

Mohammed Atiquzzaman obtained his M.S. and Ph.D. in Electrical Engineering and Electronics from the University of Manchester. He is currently a professor in the School of Computer Science at the University of Oklahoma, and a senior member of IEEE.

Dr. Atiquzzaman is the editor-in-chief of *Journal of Networks and Computer Applications*, co-editor-in-chief of *Computer Communications* journal and serves on the editorial boards of *IEEE Communications Magazine*, *International Journal on Wireless and Optical Communications*, *Real Time Imaging* journal, *Journal of Communication Systems, Communication Networks and Distributed Systems* and *Journal of Sensor Networks*.

Dr. Atiquzzaman has received Edith Kinney Gaylord Presidential Professorship for meeting the highest standards of excellence in scholarship and teaching at University of Oklahoma. In recognition of his contribution to NASA research, he received the NASA Group Achievement Award for “outstanding work to further NASA Glenn Research Center’s effort in the area of Advanced Communications/Air Traffic Management’s Fiber Optic Signal Distribution for Aeronautical Communications” project. He is the co-author of the book “Performance of TCP/IP over ATM networks” and has over 220 refereed publications, available at www.cs.ou.edu/~atiq.

His research interests are in wireless and mobile networks, ad hoc networks, and satellite networks. His research has been funded by National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), U.S. Air Force, and Cisco through grants totaling over $3.8M.