Cost Analysis of Mobility Entities of Hierarchical Mobile IPv6

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***Abstract*—IETF proposed Hierarchical Mobile IPv6 (HMIPv6) to support host mobility and mobility management involves signaling costs at various mobility entities of the network. Widespread use of IP-enabled mobile devices have resulted in increase in number of mobile users and the signaling cost on underlying mobility entities have increased significantly, which will result in their performance degradation. However, there has been no comprehensive cost analysis of mobility protocol entities that considers all possible costs. In this paper, we have developed analytical models to estimate total costs of key mobility management entities of HMIPv6. We have presented numerical results to demonstrate the impact of network size, mobility rate, traffic rate and data volume on these costs and the percentage overhead on the mobility entities. Our results show that a significant amount of resources are required by the mobility entities for transmission, processing of various signaling messages, as well as searching location database. Our cost analysis will thus be helpful for military applications in estimating actual resource requirements for on-board IP-enabled devices in military vans, tanks, helicopters that require mobility management especially while in operation.**

***Index Terms*—Mobility Protocols, Analytical Modeling, Signaling cost, Mobile IPv6**

I. Introduction

To manage Internet connectivity of mobile hosts, such as soldiers (with IP-enabled devices) in a battle field, various mobility management schemes have been proposed. Internet Engineering Task Force (IETF) proposed Mobile IPv6 (MIPv6) [1] and Hierarchical Mobile IPv6 (HMIPv6) [2] to support host mobility and facilitate seamless connectivity at remote locations.

In a mobile computing environment, a number of *network parameters* (such as, network size, mobility rate, traffic rate) influence signaling overheads relating to mobility. These signaling costs include cost related to query messages, location updates, binding updates, local and regional care-of-address registration, return routability messages, packet tunneling, etc. Increase in the number of mobile users have resulted in more signaling load on different *mobility management entities* (e.g., home agents) many of which were not designed to handle such enormous load. Hence, mobility protocols must be analyzed with respect to the overheads on various mobility management entities to ensure their smooth operation with increased load.

There has been earlier attempts for signaling cost analysis [3]–[6] of mobility protocols. Fu et al. [3] analyze the signaling costs of SIGMA and HMIPv6. Xie et al. [4] perform cost analysis of Mobile IP to minimize the signaling cost while introducing a novel regional location management scheme. Makaya et al. [5] present an analytical model for the performance and cost analysis of IPv6-based mobility protocols (i.e., MIPv6, HMIPv6, FMIPv6 and F-HMIPv6). Reaz et al. [6] perform the signaling cost analysis of SINEMO and NEMO BSP. However, these analysis did not consider all possible costs and they did not compute the signaling costs on various mobility entities.

The main *differences* of this work are that we have considered all possible costs required for mobility management and have computed total costs on various entities of HMIPv6. The authors are not aware of any such work.

The *objective* of this work is to analyze the signaling costs of various mobility management entities of Hierarchical Mobile IPv6 protocol and figure out how those costs are affected by various network parameters, such as network size, mobility rate, traffic rate, and data volume.

The *contributions* of this work are: (i) developing mathematical models to estimate total costs of various mobility management entities of HMIPv6: home agent, mobility anchor point, mobile host, correspondent node, and complete network and (ii) analyzing the impact of network size, mobility rate, traffic rate, and data volume on these costs and percentage overhead on the mobility entities.

The analytical cost model developed in this paper covers all possible costs required for mobility management and will help in estimating the actual resources (bandwidth, processing power, transmission power) required by key entities of the network while in operation in the battle field in order to maintain continuous connectivity with the military base or head quarters avoiding loss of connection.

The rest of the paper is organized as follows. In Section II, a brief description of HMIPv6 protocol is given. In Section III, analytical models for the cost analysis of various entities of HMIPv6 are presented. Section IV analyzes the results. Finally, Section V has the concluding remarks.

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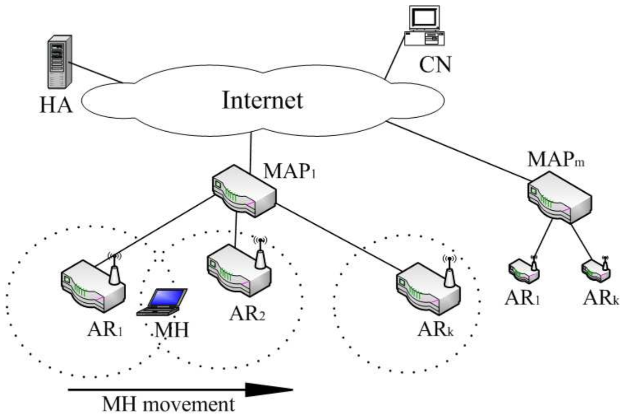

Fig. 1. HMIPv6 Architecture.

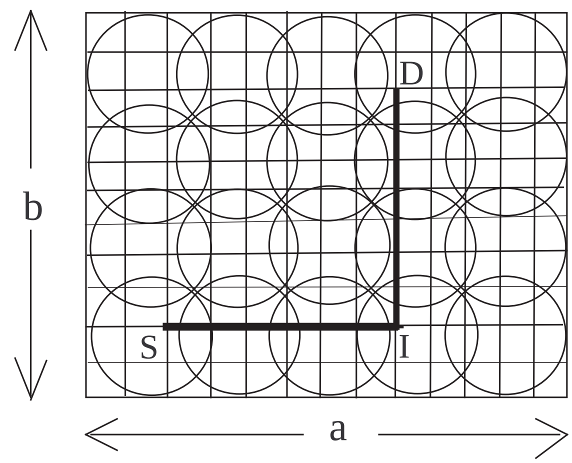

Fig. 2. Layout of access routers in the foreign network.

II. 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. 1. 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 one or more local MAPs. The MH updates HA with an address assigned by the MAP, called Regional Care-of-Address (RCoA), 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.

III. Analytical Modeling

First, the assumptions and the notations of the model are listed in section III-A, and III-B, respectively. The user mobility, traffic and error models are discussed in section III-C. Finally, the cost model is presented in section III-D.

A. Assumptions

Following are assumptions for cost analysis.

- Session arrival rate for each mobile host is equal.
- The average file size in each session is equal.
- Costs relating to standard IP switching are ignored.
- Uniform distribution of mobile hosts in the network.
- Location database is searched by binary search.

B. Notations

The notations used in this paper are listed in this section.

N_m Number of Mobile Hosts,
N_c Average number of CNs per MH,
β_q Per hop transmission cost for query message,
β_{dp} Per hop transmission cost for average data packet,
β_{da} Per hop transmission cost for data Ack packet,
β_{rr} Per hop transmission cost for Return Routability (RR) message,
β_{rc} Per hop transmission cost for RCoA registration request /reply message,
β_{lc} Per hop transmission cost for LCoA registration request /reply message,
Φ_{mh} Average distance between MAP and HA (in hops),
Φ_{mm} Average distance between MH and MAP (in hops),
Φ_{hc} Average distance between HA and CN (in hops),
Φ_{mc} Average distance between MH and CN (in hops),
σ Proportionality constant of wireless link over wired link,
η Linear coefficient for lookup cost,
T_r Subnet residence time,
λ_s Average session arrival rate for each mobile host,
x, y Number of access routers in a row or column
k Number of access routers under a MAP,
m Number of MAPs, where $m = xy/k$,
κ Maximum transmission unit,
α Average session size,
δ_{rc} Processing cost for each RCoA registration at MAP,
δ_{lc} Processing cost for each LCoA registration at MAP,
δ_h Processing cost for Location Update (LU) at HA,
ζ Linear coefficient for IP routing table lookup,
ξ Encapsulation cost.

C. Traffic Model

We have used city section mobility model [7], in our analysis. Session arrival follows Poisson process with the following probability distribution function:

$$f_{sa}(n) = \frac{e^{-\lambda_s}\lambda_s^n}{n!} \tag{1}$$

In other words, the inter-arrival times are exponentially distributed. The session length process that denotes size of data (file) in each session follows Pareto distribution. The mean session length is assumed to be α.

D. Cost Model

The cost terms for HMIPv6 protocol is influenced by the number of regional registration that happens in every move out of a MAP region. In the topology (shown in Fig. 2), there are xy ARs in the foreign network. The MH can move from the coverage area of one AR to any other 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 is $p = \frac{k}{xy}$. Conversely, the probability that MH will reach a new AR is $q = 1 - p = \frac{xy-k}{xy}$. So the probability that the MH moves out of a MAP domain in i movement is $P_i = p^{i-1}q$. Hence, the expected number of moves for a MAP domain move-out can be obtained as follows:

$$\begin{aligned} M &= \sum_{i=1}^{\infty} iP_i = q(1 + 2p + 3p^2 + 4p^3 + ...) \\ &= \frac{1}{1-p} = \frac{xy}{xy-k} \end{aligned} \tag{2}$$

We now derive the expressions for total cost on the MAP, the HA, and the complete network for HMIPv6.

1) Mobility Anchor Point: The total cost on the MAP are due to exchange of RCoA and LCoA registration messages, RR messages and tunneling of packets from HA to MH, and vice versa.

a) LCoA Registration Messages: Every subnet crossing by the MH (happens every T_r sec) within a MAP region, triggers a (on-link CoA) LCoA registration message to the MAP. This involves transmission cost of $2\beta_{lc}$ and processing cost of δ_{lc} for each MH.

$$\Lambda_{MAP}^{LC} = \frac{N_m}{m} \times \frac{2\beta_{lc} + \delta_{lc}}{T_r} \tag{3}$$

b) Return Routability Messages: In order to ensure that binding update message are authentic and is not originated from malicious MH, RR procedure is performed before each BU. This process makes use of four messages: Home Test Init (HoTI), Home Test (HoT), Care-of Test Init (CoTI) and Care-of Test (CoT) [1].

$$\Lambda_{MAP}^{RR} = \frac{N_m}{m} \times \frac{4\beta_{rr}N_c}{MT_r} \tag{4}$$

c) RCoA Registration Messages: The MAP receives registration requests from every MH entering the MAP domain. Since there are m MAPs and the MHs are uniformly distributed, there will be N_m/m MHs under an MAP on the average. The MAP processes the request and assigns a RCoA to the MH. This involves transmission cost of $2\beta_{rc}$ and processing cost of δ_{rc} for each MH at an MAP. Each MH sends such RCoA registration requests in every MT_r seconds.

$$\Lambda_{MAP}^{RC} = \frac{N_m}{m} \times \frac{2\beta_{rc} + \delta_{rc}}{MT_r} \tag{5}$$

d) Packet Tunneling Cost: MAP acts as a local HA for the MH, receives all packets 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. Thus, for every packet sent from CN to MH, transmission cost and processing costs are incurred at the MAP. As the average session length is α, and maximum transmission unit is κ, there will be $\lceil \frac{\alpha}{\kappa} \rceil$ number of packets, and the packet rate can be obtained by $\lceil \frac{\alpha}{\kappa} \rceil \times \lambda_s$. The transmission cost for each packet is $(\beta_{dp} + \beta_{da})$ due to the data packet and corresponding acknowledgement. As we have assumed uniform distribution of MH in the network, the number of MH under a MAP is $\frac{N_m k}{xy}$. The cost for IP routing table (with entries of k ARs) lookup is proportional to $\log k$. Thus, the packet tunneling cost at MAP is given by

$$\begin{aligned} \Lambda_{MAP}^{PT} = \quad & \frac{N_m}{m} \times N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \Bigg((\beta_{dp} + \beta_{da}) + \\ & \eta \log_2 \left(\frac{N_m k}{xy} \right) + \zeta \log_2 k + 2\xi \Bigg) \end{aligned} \tag{6}$$

e) Total Overhead on MAP: Thus, the total cost on each MAP can be obtained by adding Eqns. (3), (4), (5), and (6):

$$\Lambda_{MAP} = \Lambda_{MAP}^{LC} + \Lambda_{MAP}^{RR} + \Lambda_{MAP}^{RC} + \Lambda_{MAP}^{PT} \tag{7}$$

2) Home Agent: The total cost on the HA are due to exchange of location query messages with CNs, RR messages, RCoA registration messages with MH and MAP, and tunneling of packets from CN to MAP, and vice versa.

a) Query Messages: For each association between MH and CN, query and reply messages are exchanged between CN and HA. The HA has to search a database of size proportional to number of mobile hosts under its domain and the lookup cost is $\eta \lambda_s \log_2(cN_m)$. Here we assume that the HA has a total of cN_m number of hosts under its domain. Hence, the cost on HA for query messages is

$$\Lambda_{HA}^{Q} = N_m N_c (2\beta_q \lambda_s + \eta \lambda_s \log_2(cN_m)) \tag{8}$$

b) Return Routability Messages: Before each BU message, RR messages are exchanged among the MH, HA and CN. The HA receives the Home Test Init (HoTI) message sent by the MH and forwards it to the CN. It also receives the Home Test (HoT) message sent by the CN and sends it back to MH. This happens for every MT_r seconds and for every MH-CN pair under the HA. Therefore, the cost on HA for RR messages are as follows:

$$\Lambda_{HA}^{RR} = N_m N_c \times \frac{4\beta_{rr}}{MT_r} \tag{9}$$

c) RCoA Registration Messages: For every region crossing between MAPs (happens every MT_r seconds), MH needs to register the RCoA with HA. Therefore,

$$\Lambda_{HA}^{RC} = N_m \frac{2\beta_{rc} + \delta_h}{MT_r} \tag{10}$$

d) Packet Tunneling Cost: For every packet sent from CN to MH, transmission and processing costs (for location database lookup, and encapsulation) are incurred at the HA. This costs are similar to that incurred at MAP, except that HA does not have to decapsualte the packet from the CN. Thus cost on the HA due to packet tunneling is,

$$\Lambda_{HA}^{PT} = N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \Big((\beta_{dp} + \beta_{da}) + \eta \log_2(cN_m) + \xi \Big) \quad (11)$$

e) Total Overhead on HA: Thus, the total cost on each HA can be obtained by adding Eqns. (8), (9), (10), and (11):

$$\Lambda_{HA} = \Lambda_{HA}^{Q} + \Lambda_{HA}^{RR} + \Lambda_{HA}^{RC} + \Lambda_{HA}^{PT}$$

3) Complete Network: In order to compute the total cost on the network, we will consider resources (bandwidth, processing power, etc.) consumed due to HMIPv6 protocol.

a) Query Message: As each MH has an average of N_c CNs, total CNs for all the MHs are $N_m N_c$. The transmission cost for all the query and reply messages towards the HA is $N_c N_m (2\Phi_{hc}\beta_q)\lambda_s$. The searching cost in the HA is $N_c N_m (\eta \lambda_s \log_2(cN_m))$. Hence, the cost of the network for the query messages from the CNs is,

$$\Lambda_{Net}^{Q} = N_m N_c \lambda_s (2\beta_q \Phi_{hc} + \eta(\log_2 cN_m)) \quad (12)$$

b) LCoA Registration Messages: Every subnet crossing by the MH within a MAP region, triggers a LCoA registration message to be sent to the MAP. This involves transmission cost of $2\beta_{lc}$ in each of the $\Phi_{mm} - 1$ wired hops and one wireless hops. In addition, processing cost is incurred at MAP for updating the location database. So

$$\Lambda_{Net}^{LC} = N_m \frac{2\beta_{lc}(\Phi_{mm} - 1 + \sigma) + \delta_{lc}}{T_r} \quad (13)$$

c) Return Routability Messages: The RR messages are sent every MT_r second by the MH to HA which forwards them to CN. The HoTI message follow the path between MH and HA which is of $(\phi_{mh} + \phi_{mm})$ hops with one wireless hop and the path between HA and CN which is of ϕ_{hc} hops. Similar cost is incurred for each HoT message. Each CoTI message is sent directly to CN from the MH which uses ϕ_{mc} hops. Therefore, cost on the network for RR messages are:

$$\Lambda_{Net}^{RR} = \frac{N_m N_c}{MT_r} 2\beta_{rr} \Big(\phi_{mh} + \phi_{mm} + \phi_{hc} + \phi_{mc-2+2\sigma} \Big) \quad (14)$$

d) RCoA Registration Messages: The MAP processes the RCoA request and assigns a RCoA to the MH. As the MAP is Φ_{mm} hops (that include one wireless hop) away from the MH, this RCoA registration incurs a transmission cost of $2\beta_{rc}(\Phi_{mm} - 1 + \sigma)$, and a processing cost δ_{rc} at the MAP. The MAP informs the HA about this new RCoA registration that requires a transmission cost of $2\beta_{rc}\Phi_{mh}$, and a processing cost of δ_h at the HA. Thus the RCoA registration cost for the network is

$$\Lambda_{Net}^{RC} = N_m \frac{2\beta_{rc}(\Phi_{mm} - 1 + \sigma) + \delta_{rc}}{MT_r} + N_m \frac{2\beta_{rc}\Phi_{mh} + \delta_h}{MT_r} \quad (15)$$

e) Packet Tunneling Cost: CN sends every data packet to MH through HA and then MAP. The cost required for the data packet to reach HA is $\beta_{dp}\Phi_{hc}$. Similar cost of $\beta_{da}\Phi_{hc}$ is required for each ACK packet. The HA receives the data packets, encapsulates it and sends it to the MAP. Thus a cost of $(\beta_{dp} + \beta_{da})\Phi_{mh} + 2\xi$ is required. The 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 $(\beta_{dp} + \beta_{da})(\Phi_{mm} - 1 + \sigma) + 4\xi$ for each data and Ack packet. In addition, visitor list lookup at MAP costs $\eta \log_2 \frac{N_m k}{xy}$, and IP routing table lookup costs another $\zeta \log_2 k$. So tunneling each data packet and corresponding ACK packet from MAP to the MH costs $(\beta_{dp} + \beta_{da})(\Phi_{mm} - 1 + \sigma) + 4\xi + \eta \log_2 \frac{N_m k}{xy} + \zeta \log_2 k$. 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 $\frac{N_m k}{xy}$. Thus, the costs related to packet tunneling are given by

$$\Lambda_{Net}^{PT} = N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil \Bigg(\Big((\beta_{dp} + \beta_{da})\Phi_{hc} + (\beta_{dp} + \beta_{da})\Phi_{mh} + 2\xi + (\beta_{dp} + \beta_{da})(\Phi_{mm} - 1 + \sigma) \Big) + 4\xi + \eta \log_2 \frac{N_m k}{xy} + \zeta \log_2 k \Bigg) \quad (16)$$

f) Total Overhead on the Network: Therefore, the total cost on the complete network due to HMIPv6 protocol can be obtained by adding Eqns. (12), (13), (14), (15), and (16):

$$\Lambda_{Net} = \Lambda_{Net}^{Q} + \Lambda_{Net}^{LC} + \Lambda_{Net}^{RR} + \Lambda_{Net}^{RC} + \Lambda_{Net}^{PT} \quad (17)$$

4) Efficiency of HMIPv6: We define a new metric called *efficiency* to measure the performance of mobility management protocols. It is defined as the ratio of net data delivery cost (excluding all overheads along the optimal route) to the total cost (that includes signaling and data delivery costs) required for the mobility protocol. If direct route is used for deliver data and Ack packets, then the net data delivery cost would be as follows:

$$\Lambda_{Net}^{DD} = N_m N_c \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil (\beta_{dp} + \beta_{da})(\Phi_{mc} - 1 + \sigma) \quad (18)$$

Therefore, the efficiency HMIPv6 protocol can be computed as follows:

$$\xi^{HMIPv6} = \frac{\Lambda_{Net}^{DD}}{\Lambda_{Net}} \quad (19)$$

IV. Numerical Results

In this section, the expressions derived in the cost analysis section are used to find out total cost on various entities of HMIPv6 protocols: HA, MAP, and complete network. We have also computed the percentage overhead on various entities per unit data as:

$$\%\ \text{Overhead} = \frac{\text{Total cost} - \text{Cost for data traffic}}{\text{Cost for data traffic}} \times 100$$

The parameters that affect the total cost and percentage overhead are number and speed of MHs, number of CNs, session arrival rate, session size, session to mobility ratio (defined as $T_r \times \lambda_s$). We varied number of MHs between 20,000 to 70,000; number of CNs per MH between 1 to 10; session arrival rate between 0.01 to 0.1; average session size between 10Kb to 100Kb; session to mobility ratio (SMR) between 0.75 to 400. For computation of SMR, λ_s was kept constant while T_r was varied.

We are assuming a foreign network (shown in Fig. 2) in an area of 36 km $\times$ 24 km and covered by 51 $\times$ 34 ARs, having the transmission range of 0.5 km (similar to [7]). This means the average density of MHs (e.g., soldiers or military vans) per square kilometer is assumed to be between 23 to 81. Parameters relating to mobility protocols are: N_c = 1, N_m =

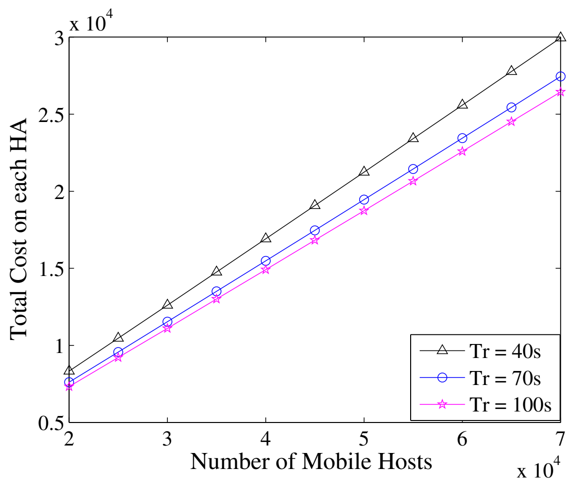

Fig. 3. Total cost on each HA vs. number of mobile hosts for different residence times.

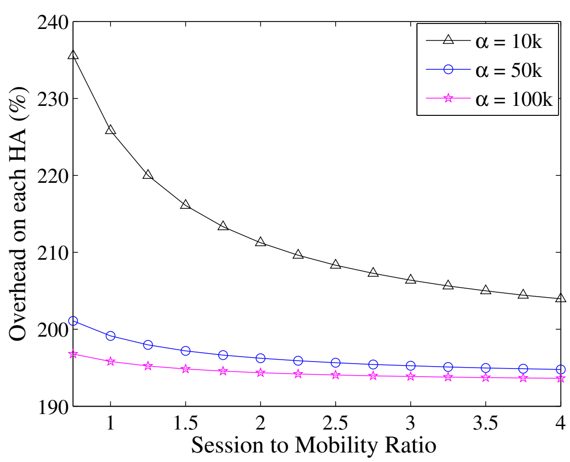

Fig. 4. Percentage overhead on each HA vs. session to mobility ratio for different session size.

40000, β_q = 0.6, β_{dp} = 5.72, β_{da} = 0.60, β_{rr} = 0.6, β_{rc} = 0.6, β_{lc} = 0.6, Φ_{mm} = 35, Φ_{mh} = 35, Φ_{mc} = 35, Φ_{hc} = 35, σ = 10, η = 0.3, T_r = 70, λ_s = 0.01, x = 51, y = 34, k = 12, $\delta_{l}c$ = 30, $\delta_{r}c$ = 5, δ_h = 30, κ = 512, α = 10240, χ = 3, ζ = 0.3,

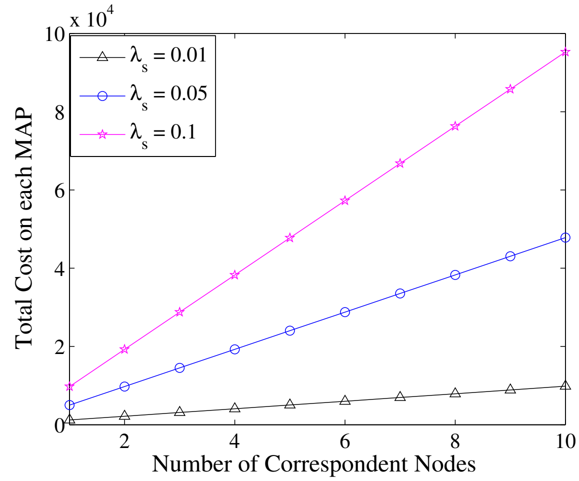

Fig. 5. Total cost on each MAP vs. number of CNs for different session arrival rates.

ξ = 0.5. Some of these parameter values are similar to that in [4], [3], [6].

A. HA

In Fig. 3, the impact of number of MHs on the total cost of each HA are shown for T_r = 40, 70, 100 sec. It is found that total cost increases for higher number of MHs and lower residence time as more LUs are sent to the HA.

Fig. 4 shows the impact on the percentage overhead on each HA per unit size of data transmitted for different session size. Results show that overhead on the HA is higher for smaller session length as there is more signaling traffic compared to data traffic. Moreover, the overhead reduces with higher SMR value as the MHs tend to move slowly producing less LUs.

B. MAP

In Fig. 5, total cost of each MAP are shown as a function of number of CNs for different session arrival rates. Results show that total cost for each MAP increases with higher session arrival rates as more data are processed by the MAP. The total cost also rises with higher number of CNs for similar reason.

In Fig. 6, the percentage overhead per unit data on each MAP are shown as a function of number of MHs for various subnet residence time. It is found that percentage overhead is higher for smaller residence time as MHs tend to move faster producing more signaling overhead. In addition, the percentage overhead does not increase significantly with the increase of number of MHs as more data make the ratio almost similar.

C. Complete Network

In Fig. 7, the impact of number of MHs on the total cost of each MAP are shown for various values of Φ_{mm}, Φ_{mh}, Φ_{mc}, Φ_{hc}. It is found that when all the average distance are 25, the total cost on the network is the lowest and this does not change when we increase the value of Φ_{mc} to 35. On the other hand, when either of Φ_{mm}, Φ_{mh}, Φ_{hc} is 35, the total costs on the network are rises for all of them.

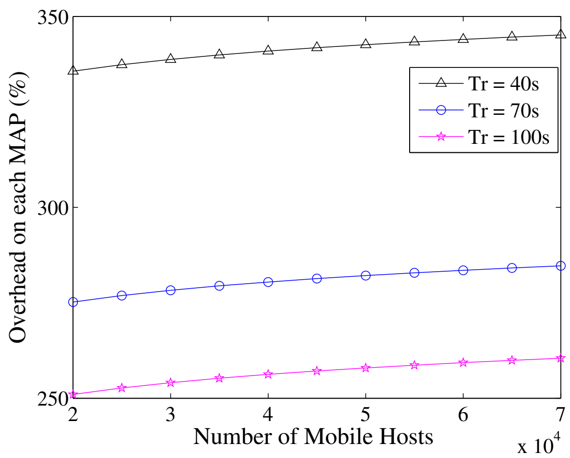

Fig. 6. Percentage overhead on each MAP vs. number of mobile hosts for different residence times.

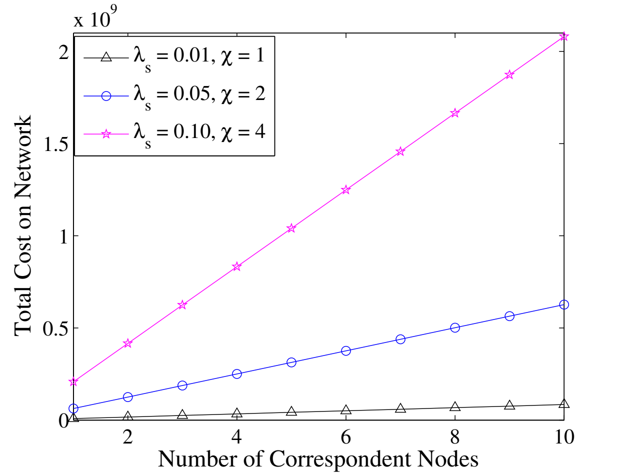

Fig. 8. Total cost on the network vs. number of CNs for different values of λ_s and χ.

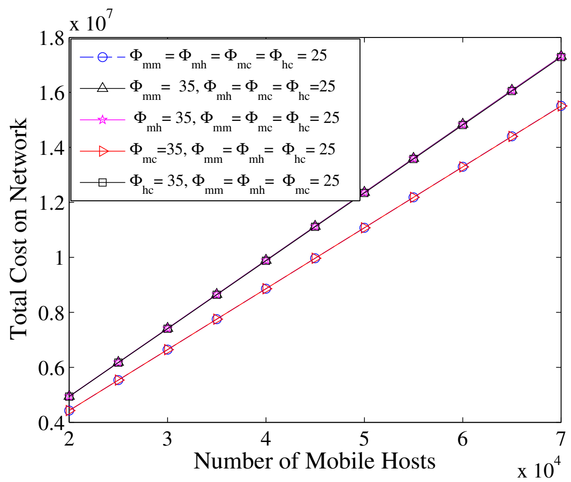

Fig. 7. Total cost on the network vs. number of mobile hosts for different values of Φ_{mm}, Φ_{mh}, Φ_{mc}, Φ_{hc}.

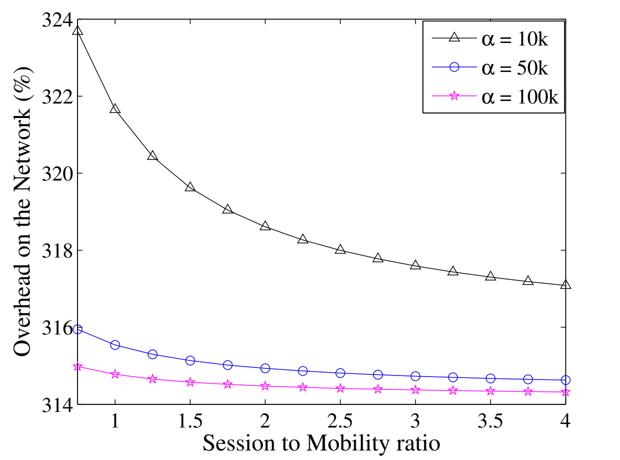

Fig. 9. Percentage overhead on the network vs. session to mobility ratio for different residence times.

Fig. 8 shows the effect of number of CNs on the total cost of the network for different session arrival rates and number of retransmissions. Results show that total cost increases with higher session arrival rates and higher number of CNs as there are more data in the network.

Fig. 9 shows the impact on the percentage of overhead on the network per data unit for different session length. Results show that overhead on the network increases for smaller session length as there is more signaling traffic compared to data traffic. Moreover, the overhead reduces with higher SMR value as the MHs tend to move slowly producing less LUs.

V. Conclusion

In this paper, we have developed analytical models to compute the mobility signaling costs on various entities of Hierarchical Mobile IPv6. We have also shown the numerical results of the growth of those overhead with the increase of network size, mobility rate, traffic rate, and data volume. Results show that overhead on various mobility management entities, such as home agent, mobile host increases for smaller session length as there is more signaling traffic compared to data traffic. Moreover, the overhead reduces with higher SMR value as the MHs tend to move slowly producing less LUs.

Our analytical model can be used by network engineers to estimate the resource (bandwidth, processing power, transmission power) requirement of the IP-enabled devices used by soldiers, military vans, tanks, helicopters in the battle field facilitating seamless communication with the commanders in military bases and headquarters.

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