Cost and Scalability Analysis of Mobility Management Entities of NEMO

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Abstract

To support IP-mobility of networks in motion, IETF proposed Network Mobility (NEMO) protocol that uses various signaling messages to ensure connectivity of the mobile nodes with the Internet and to maintain security of ongoing sessions by protecting the binding updates. As the next-generation wireless / mobile network is supposed to be a unified network based on all-IP technology, compounded by the fact that the number of mobile nodes requiring mobility support has increased significantly, the cost analysis of mobility protocols and the underlying mobility management entities have become essential to avoid 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 NEMO. We have presented numerical results to demonstrate the impact of network size, mobility rate, traffic rate and data volume on these costs. Our results show that a significant amount of resources (bandwidth, processing power, transmission power) are required by the mobility entities for transmission, processing of various signaling messages, as well as searching location database. Our cost analysis will thus help network engineers in estimating actual resource requirements for the key entities of the network in future design while optimizing network performance.

Index Terms

NEMO, mathematical modeling, cost analysis, mobility management entities, computer networks.

I. Introduction

To ensure continuous Internet connectivity of networks in motion, IETF proposed NEtwork MObility Basic Support Protocol (NEMO BSP) [1] which is an extension of IETF host-mobility protocol, Mobile IPv6 [2]. NEMO BSP requires different mobility agents to exchange various signaling messages to maintain continuous connectivity and security of ongoing sessions between mobile nodes and Internet nodes.

In a mobile computing environment, a number of *network parameters* (such as, network size, mobility rate, traffic rate) influence the cost arising from mobility protocols. These cost include costs related to query messages, updating Home Agents about the change of location of the mobile entity, sending updates to hosts with ongoing communication, and processing and lookup costs by various mobility agents. As the next-generation wireless/mobile network will be a unified network based on all-IP technology, and the number of mobile nodes requiring mobility support has increased significantly, the cost analysis of mobility protocols as well as the underlying *mobility management entities* (e.g., home agents, mobile router, etc.) have become essential to avoid performance degradation of the mobility protocol.

There has been earlier attempts for signaling cost analysis ([3]–[6]) of mobility protocols. Xie et al. [3] performed cost analysis of Mobile IP to minimize the signaling cost while introducing a novel regional location management scheme. Fu et al. [4] analyzed the signaling costs of SIGMA [7] and HMIPv6. Makaya et al. [6] presented an analytical model for the performance and cost analysis of IPv6-based mobility protocols. Reaz et al. [5] performed the signaling cost analysis of SINEMO [8]. However, these analysis did not consider all possible costs (e.g. costs for sending query message by CN, securing location updates, obtaining IP address by MH, etc.) 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 mobility management entities of NEMO. *The authors are not aware of any such work*.

The *objective* of this work is to analyze the total cost (including data delivery cost) of various mobility entities of NEMO basic 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 NEMO: home agent for mobile router, home agent for mobile host, mobile router, and complete network and (ii) analyzing the impact of network size, mobility rate, traffic rate, and data volume on these costs.

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 in order to maintain continuous connectivity with remote Internet hosts and securing the ongoing session.

The rest of the paper is organized as follows. In Section II, NEMO architecture and BSP are briefly explained. In Section III, analytical cost models of various entities of NEMO are presented. Section IV analyzes the results. Finally, Section V has the concluding remarks.

II. Network Mobility

In this section, we explain briefly NEMO architecture and NEMO BSP. This will aid in understanding the cost analysis of NEMO in Section III.

A. NEMO Architecture

Fig. 1 shows the architecture of a Mobile Network (MN). Mobile Router (MR) act as gateways for the nodes inside the MN, each of the nodes are called a Mobile Network Node (MNN). Different types of MNNs are: Local Fixed Nodes (LFN) that do not move with respect to MN, Local Mobile Nodes (LMN) that usually reside in MN and can move to other networks, and Visiting Mobile Nodes (VMN) that get attached to the MN from another network. LMNs and VMNs are MIPv6 capable, and we refer them as *mobile nodes*. The MR attaches to the Internet through Access Routers (ARs). An MN is usually connected to a network called the home network where an MR is registered with a router called the Home Agent (HA). The HA is notified the location of the MR, and re-directs packets, sent by the Correspondent Node (CN) to MNNs.

B. NEMO BSP

In NEMO BSP [1], the MR ensures connectivity of all hosts inside the MN when the MR changes its point of attachment to the Internet while moving from a home network to a foreign network. An MR has its unique IP address and one or more MN Prefixes (MNP) that it advertises to the hosts attached to it. MR establishes a bidirectional tunnel with the HA of Mobile Hosts (HA-MH) to pass all the traffic between its MHs and the CNs. When MR changes its point of attachment, it acquires a new care-of-address from the visited foreign network. It then sends a Binding Update (BU) to its HA which creates a cache entry, binding MRs home address with its care-of-address, and creates a bidirectional tunnel between HA and MR. When a CN sends a packet to a host, the packet is routed to the HA of the corresponding MR. HA looks at its cache entry and forwards the packet to the MR using the bidirectional tunnel. Finally, MR receives the packet, decapsulates it, and forwards it to the host inside the MN.

III. Cost Analysis

We compute below the mobility management cost on NEMO's key entities, such as, Home Agent, Mobile Router (MR) and the complete network.

A. Notations

The notations that are used the cost analysis are listed below.

N_f Number of LFNs in the mobile network,
N_m Total mobile nodes (LMNs and VMNs) in the mobile network,
N_c Average number of CNs communicating with the nodes inside the mobile network,

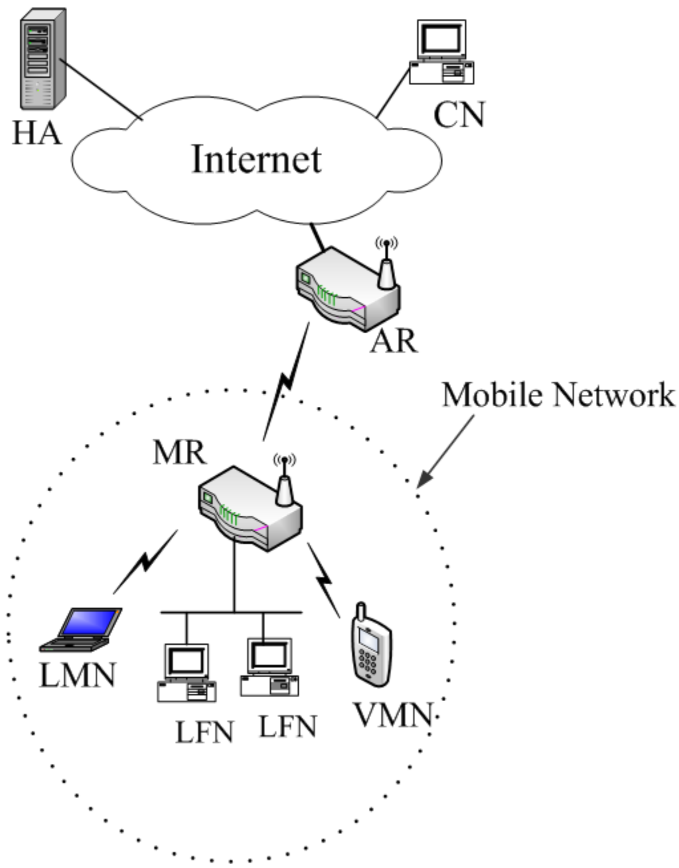


Fig. 1. NEMO Architecture

δ_L	Per hop transmission cost for Location Update (LU) message,
δ_B	Per hop transmission cost for Binding Update (BU) message,
δ_Q	Per hop transmission cost for query message,
δ_{DT}	Per hop transmission cost for each data packet,
δ_{DA}	Per hop transmission cost for each (data) Ack packet,
δ_{RR}	Per hop transmission cost for Return Routability (RR) message,
δ_{DH}	Per hop transmission cost for DHCPv6 message,
δ_{TH}	Transmission cost for extra IP header used in tunneling,
γ_t	processing cost for tunneled packet,
γ_r	processing cost at MR,
σ	Proportionality constant (for transmission cost) of wireless link over wired link,
ψ	Linear coefficient for lookup cost,
T_r	Subnet residence time,
λ_s	Average session arrival rate,
h_p	average number of hops between Internet to arbitrary CN, HA or AR,
h_{in}	average number of hops in the Internet,
κ	Maximum transmission unit,
α	Average session size.

B. Assumptions

Following are the assumptions of the model:

- HA has been considered to be HA of all the LFNs, LMNs, VMNs and MRs of the mobile network under consideration.

- Session arrival rate for each mobile host is equal.
- The data (file) size in each session is equal.
- Each CN has, on the average, one ongoing session with a MNN.
- Binary search is used to search location database.

C. Home Agent

In NEMO, the HA keeps the location database of the mobile network. In fact, the location information of MR, LFNs and LMNs are kept in the HA whereas that of VMNs are kept in corresponding HAs since they belong to some other networks. The main tasks of HA are processing 1) query messages from CNs, 2) LU messages from MRs, 3) RR test messages, 4) BU messages to CNs, and 5) data delivery cost.

1) Query message: Every CN send query message to the HA at the beginning of every session. This requires a lookup at the HA which is proportional to the logarithm of the number of entries in the lookup table. So the lookup cost at HA is $\Psi_{HA}^{LK} = \psi \log_2(N_f + N_m)$. In addition, transmission cost is incurred for query-reply messages at the HA. Hence, the cost relating to query messages at HA are given by the following equation:

$$\Lambda_{HA-MR}^{QR} = N_c \lambda_s \Big[2\delta_Q + \Psi_{HA}^{LK} \Big] \quad (1)$$

2) Location update messages: When the mobile network crosses subnets, MR sends LU message to the HA and the location database is modified by the HA which sends back acknowledgement to LU message. This happens in every T_r seconds. In addition, MRs and mobile nodes send periodic refreshing updates to the HA so that the entries are not removed from the the location database after the binding lifetime. Let the lifetime of the entries in the location database be T_e. Therefore, $\lfloor \frac{T_r}{T_e} \rfloor$ refreshing updates will be sent to HA within the time T_r. Thus, the frequency of sending periodic refreshing updates are $\eta_r = \lfloor \frac{T_r}{T_e} \rfloor / T_r$, and total frequency of sending LU and refreshing LU is $\eta_t = \Big(1 + \lfloor \frac{T_r}{T_e} \rfloor \Big) / T_r$,

Each LU and corresponding Acknowledgement messages exchanged with HA incurs transmission and processing cost. The LU messages from mobile nodes go through one level of encapsulation which cost additional transmission cost of δ_{TH} and a processing cost of γ_t whereas the LU messages from the MR goes without encapsulation. In both cases, a lookup cost of Ψ_{HA}^{LK} is required. So the cost related to the LU and refreshing LU messages can be computed as follows:

$$\Lambda_{HA}^{LU} = \eta_t \Big[2\delta_L + \Psi_{HA}^{LK} \Big] + \eta_r \Big[2(\delta_L + \delta_{TH} + \gamma_t) + \Psi_{HA}^{LK} \Big] \quad (2)$$

3) Return routability messages: NEMO employs RR test before sending BU to the HA similar to the mechanism employed in route optimization of MIPv6 [2]. Before each BU message, RR messages are exchanged among the MR, HA and CN. The HA receives the Home Test Init (HoTI) message sent by the MR and forwards it to the CN. HA also receives the Home Test (HoT) message from the CN and sends it back to MR. This happens for every T_r seconds. The HA receives these RR messages for all CNs that are communicating with LMN. Therefore, the cost on HA for RR messages are as follows:

$$\Lambda_{HA-MR}^{RR} = N_c \frac{4\delta_{RR}}{T_r} \quad (3)$$

4) Binding updates to CNs: To continue ongoing sessions with the CNs, mobile nodes inside the mobile network sends refreshing Binding Updates (BU) to the CNs by tunneling through the HA. The HA has to lookup the table, tunnel and transmit those BUs. Hence, cost incurred on HA-MR due these BUs are given by,

$$\Lambda_{HA}^{BU} = 2N_c \eta_r \Big[\delta_B + \delta_{TH} + \gamma_t + \Psi_{HA}^{LK} \Big] \quad (4)$$

5) Data delivery cost: In NEMO BSP, all data traffic to the mobile network goes through the HA.

In each session between the CN and MNN, an average of $\lceil \frac{\alpha}{\kappa} \rceil$ data packets are sent from the CN to MNN or vice versa. The successful reception of each data packet is confirmed by a corresponding ACK packet from the receiver. Therefore, the packet arrival rate is $\lambda_p = \lambda_s \lceil \frac{\alpha}{\kappa} \rceil$. As all the data traffic goes through the HA, it costs transmission cost data and ACK packets, extra IP-header processing and transmission cost as well as lookup cost. Therefore, the data delivery cost on the HA is given by,

$$\Lambda_{HA}^{DD} = N_c \lambda_p \Bigg[\delta_{DT} + \delta_{DA} + 2\Big(\delta_{TH} + \gamma_t + \Psi_{HA}^{LK} \Big) \Bigg] \quad (5)$$

6) Total cost: Thus, the total cost of the HA can be obtained by adding Eqns. (1), (2), (3) (4), and (5):

$$\Lambda_{HA} \quad = \quad \Lambda_{HA}^{QR} + \Lambda_{HA}^{LU} + +\Lambda_{HA}^{RR} + \Lambda_{HA}^{BU} + \Lambda_{HA}^{DD} \tag{6}$$

D. Mobile Router

In NEMO, the main tasks of the MRs are 1) IP address and prefix acquisition, 2) sending LU messages to HA, 3) sending binding updates to the CNs, 4)processing RR messages, and 5) processing data (ACK) packets to and from MNNs,

1) Acquiring IP address and prefixes: MRs acquire IP address from access router in the foreign network during each handoff by exchanging DHCPv6 request-reply messages through the wireless media.

$$\Lambda_{MR}^{Acq} \quad = \quad \frac{2\sigma\delta_{DH}}{T_r} \tag{7}$$

2) Location updates: After each handoff, each MR sends a LU message to the HA. In addition, periodic refreshing updates are also sent by the MRs and the mobile nodes through MR. Thus the cost on the MRs due to LU messages is,

$$\Lambda_{MR}^{LU} \quad = \quad 2\sigma\eta_t\delta_L + 2\eta_r N_m\Big(\sigma(\delta_L + \delta_{TH}) + \gamma_t\Big) \tag{8}$$

3) Binding updates to CNs: Mobile nodes send periodic refreshing BUs to the CNs through the MR updating the current address to continue ongoing sessions. This requires transmission of BU message through the wireless media with extra IP-header (encapsulation), and processing cost due to tunneling. Thus the cost on the MRs for these BU messages are

$$\Lambda_{MR}^{BU} \quad = \quad 2\eta_r N_c(N_m + N_f)\Big(\sigma(\delta_B + \delta_{TH}) + \gamma_t\Big) \tag{9}$$

4) Return routability messages: To ensure that the ongoing session is not hijacked by some malicious agent, before sending binding updates to the HA, it is essential to perform RR test to verify that the node can actually respond to packets sent to a given CoA [2]. Thus the MR will have to process and transmit RR messages on behalf of the mobile nodes under its domain.

$$\Lambda_{MR}^{RR} \quad = \quad \frac{4\sigma N_m\delta_{RR}}{T_r} \tag{10}$$

5) Data delivery cost: Data packet delivery incurs transmission cost through the wireless media (with extra IP-header), and processing cost for the MR. Therefore, the data delivery cost at the MRs is given by,

$$\Lambda_{MR}^{DD} \quad = \quad \lambda_p N_c\Big(\sigma(\delta_{DT} + \delta_{DA} + \delta_{TH}) + \gamma_t\Big) \tag{11}$$

6) Total cost: Therefore, total cost of each MR can be obtained by adding Eqns. (7), (8), (9), (10), and (11),

$$\Lambda_{MR} = \Lambda_{MR}^{Acq} + \Lambda_{MR}^{LU} + \Lambda_{MR}^{BU} + \Lambda_{MR}^{RR} + \Lambda_{MR}^{DD} \tag{12}$$

E. Complete Network

In order to compute the signaling load on the network as a whole, we consider all the resources (such as, bandwidth, processing power, etc.) consumed in all network entities. The cost of the network due to the operation of NEMO BSP include query messages exchanged between HA and CN, RR messages, location update messages, binding updates to CNs, and data delivery to CN.

1) Query message: At the beginning of each session between a MNN and a CN, query messages are exchanged between CN and HA. As the session arrival rates for each MNN are assumed to be equal (λ_s), the transmission cost for all the query and reply messages towards the HA is $2N_c(h_p + h_{in} + h_p)\delta_Q\lambda_s$. The searching cost in the HA is $N_c\psi\lambda_s\log_2(N_m + N_f)$. Hence, the cost of the network for the query messages from the CNs is,

$$\Lambda_{Net}^{QR} = \lambda_s N_c\Big[2\delta_Q(2h_p + h_{in}) + \psi\log_2(N_m + N_f)\Big] \tag{13}$$

2) Return routability messages: The RR messages are sent every T_r second by the MRs (on behalf of the MNNs) to HA which forwards them to CN. The HoTI message follow the path between MR and HA which consists of $(h_p + h_{in} + h_p)$ wired hops with one wireless hop (between the MR and the AR). The path between HA and CN contains $(h_p + h_{in} + h_p)$ wired hops. Similar cost is incurred for each HoT message. Each CoTI message is sent directly to CN from the MR which uses $(h_p + h_{in} + h_p)$ wired hops and one wireless hop. Therefore, cost on the network for RR messages are as follows:

$$\Lambda_{Net}^{RR} = \frac{N_c}{T_r} \times 2\delta_{rr}\Big((h_p + h_{in} + h_p + \sigma) + (h_p + h_{in} + h_p) + (h_p + h_{in} + h_p + \sigma)\Big) \tag{14}$$

3) Location updates: After each handoff, the MRs and the mobile nodes send LU to the HA informing the newly acquired IP address and prefixes. As the HA is $(h_p + h_{in} + h_p + 1)$ hops (including h_p wireless hop) away from the MR, each LU from MR (and corresponding Ack) message incurs a transmission cost of $\delta_L(h_p + h_{in} + h_p + \sigma)$, and a lookup cost of Ψ_{HA}^{LK} at the HA. The LU messages from LMNs (or VMNs) travels one more wireless hop than the MR with additional transmission cost for tunneling header and tunnel processing cost. Thus, the cost of LU message on the network is given by,

$$\begin{aligned}\Lambda_{Net}^{LU} &= 2\delta_L\eta_t(h_p + h_{in} + h_p + \sigma) + 2N_m\eta_r\Big((\delta_L + \delta_{TH})(h_p + h_{in} + h_p + 2\sigma) + \gamma_t\Big) \\ &\quad + (\eta_t + \eta_r N_m)\Psi_{HA}^{LK} +\end{aligned} \tag{15}$$

4) Binding updates to CNs: To maintain continuous connectivity with the CNs that are communicating with the mobile nodes, binding updates informing the care-of-address are sent to the CNs. These BU messages goes through and $(h_p + h_{in} + h_p)$ wired hops and two wireless hop, on the average, to reach a CN. Thus cost required to send BU to CNs are given by,

$$\Lambda_{Net}^{BU} \quad = \quad 2N_c(N_m + N_f)\eta_r\Big[(h_p + h_{in} + h_p + 2\sigma)(\delta_B + \delta_{TH}) + \gamma_t\Big] \tag{16}$$

5) Data delivery cost: All the data and corresponding Ack) packets, that is, goes through HA. The path between a MNN and the HA contains $(h_p + h_{in} + h_p)$ wired links and 2 wireless links whereas the path between HA and CN contains $(h_p + h_{in} + h_p)$ wired links. In addition, data packets incur table lookup in the HA. Thus, the costs related to data delivery and processing by the network are given by

$$\Lambda_{Net}^{DD} = \lambda_p N_c\Bigg[\Big((h_p + h_{in} + h_p + 2\sigma) + (2h_p + h_{in})\Big)(\delta_{DT} + \delta_{DA} + 2\delta_{TH}) + 2\gamma_t + 2\Psi_{HA}^{LK}\Bigg] \tag{17}$$

6) Total cost of the network: Therefore, the total cost of the complete network due to NEMO protocol can be obtained by adding Eqns. (13), (14), (15), (16), and (17),

$$\Lambda_{Net} = \Lambda_{Net}^{QR} + \Lambda_{Net}^{RR} + \Lambda_{Net}^{LU} + \Lambda_{Net}^{BU} + \Lambda_{Net}^{DD} \tag{18}$$

F. 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. In NEMO BSP, 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:

$$\Lambda^{DD} = N_c\lambda_s\left\lceil\frac{\alpha}{\kappa}\right\rceil\Big((h_p + h_{in} + h_p + 2\sigma)\Big)\delta_{DT} \tag{19}$$

Therefore, efficiency of NEMO BSP can be obtained using the following equation:

$$\zeta^N = \frac{\Lambda^{DD}}{\Lambda_{Net}} \tag{20}$$

G. Scalability Analysis

Here, we analyze the scalability of NEMO BSP based on the cost analysis performed in Section III.

a) Definition: According to Santivanez et al. [9], scalability is the ability of a network to support the increase of its limiting parameters without degrading the network performance. Examples of such limiting parameters are network size (number of mobile hosts, routers, etc.), mobility rate, traffic rate, and number of correspondent nodes. Mobility protocol's scalability can be defined as the ability to support continuous increase of network parameter values without degrading the performance of various network entities that are responsible for mobility management.

Let $\Gamma^X(\lambda_1,\ \lambda_2,\ ...)$ be the total overhead induced by mobility protocol X, dependent on parameters $\lambda_1,\ \lambda_2$,.. (such as, network size, mobility rate, traffic rate etc). So the protocol X's mobility scalability factor with respect to a parameter λ_i is defined to be

$$\rho^X_{\lambda_i} = \lim_{\lambda_i \to \infty} \frac{\log \Gamma^X(\lambda_1, \lambda_2, ...)}{\log \lambda_i} \tag{21}$$

Protocol X is said to be more scalable than protocol Y with respect to parameter λ_i if $\rho^X_{\lambda_i} \leq \rho^Y_{\lambda_i}$.

b) Home Agent: From Eqn. (6), we get the asymptotic cost expression of NEMO for HA using the Θ notation [1] as follows:

$$\Lambda_{HA} = \Lambda^{QR}_{HA} + \Lambda^{LU}_{HA} + +\Lambda^{RR}_{HA} + \Lambda^{BU}_{HA} + \Lambda^{DD}_{HA} \quad = \Theta((V + \lambda_p)N_c \log(N_m + N_f)) \tag{22}$$

So NEMO's mobility scalability factors for the HA with respect to N_m, N_f, λ_p, V, and N_c can be computed as follows:

$$\rho^{HA}_{N_m} = \lim_{N_m \to \infty} \frac{\log((V + \lambda_p)N_c \log(N_m + N_f))}{\log N_m} = 0$$

$$\rho^{HA}_{N_f} = \lim_{N_f \to \infty} \frac{\log((V + \lambda_p)N_c \log(N_m + N_f))}{\log N_f} = 0$$

$$\rho^{HA}_{\lambda_p} = \lim_{\lambda_p \to \infty} \frac{\log((V + \lambda_p)N_c \log(N_m + N_f))}{\log \lambda_p} = 1$$

$$\rho^{HA}_{V} = \lim_{V \to \infty} \frac{\log((V + \lambda_p)N_c \log(N_m + N_f))}{\log V} = 1$$

$$\rho^{HA}_{N_c} = \lim_{N_c \to \infty} \frac{\log((V + \lambda_p)N_c \log(N_m + N_f))}{\log N_c} = 1$$

c) Mobile Router: From Eqn. (12), we get the asymptotic cost expression for MR as follows:

$$\begin{aligned}\Lambda_{MR} &= \Lambda^{Acq}_{MR} + \Lambda^{LU}_{MR} + \Lambda^{BU}_{MR} + \Lambda^{RR}_{MR} + \Lambda^{DD}_{MR} \\ &= \Theta(VN_c(N_m + N_f) + \lambda_p N_c)\end{aligned} \tag{23}$$

Hence, NEMO's mobility scalability factors for the MRs with respect to N_m, N_f, λ_p, V, and N_c are $\rho^{MR}_{N_m} = 1$, $\rho^{MR}_{N_f} = 1$, $\rho^{MR}_{\lambda_p} = 1$, $\rho^{MR}_{V} = 1$ and $\rho^{MR}_{N_c} = 1$.

TABLE I
ASYMPTOTIC COST EXPRESSIONS FOR NEMO.

Entity	Mobility Signaling Overhead
HA	$\Theta((V+\lambda_p)N_c \log(N_m+N_f))$
MR	$\Theta(VN_c(N_m+N_f)+\lambda_p N_c)$
Complete Net.	$\Theta(VN_c(N_m+N_f)+\lambda_p N_c)$

TABLE II
MOBILITY SCALABILITY FACTORS OF NEMO.

$\rho^X_{N_m}$	$\rho^X_{N_f}$	$\rho^X_{\lambda_p}$	ρ^X_V	$\rho^X_{N_c}$	Entity
0	0	1	1	1	HA
1	1	1	1	1	MR
1	1	1	1	1	Complete Network

d) Complete Network: From Equation (18), we get the asymptotic cost expression of NEMO for the complete network as follows:

$$\begin{aligned}\Lambda_{Net} &= \Lambda^{QR}_{Net} + \Lambda^{RR}_{Net} + \Lambda^{LU}_{Net} + \Lambda^{BU}_{Net} + \Lambda^{DD}_{Net} \\ &= \Theta(VN_c(N_m+N_f)+\lambda_p N_c)\end{aligned} \tag{24}$$

Hence, NEMO's mobility scalability factors for the complete network with respect to N_m, N_f, λ_p, V, and N_c are $\rho^N_{N_m}=1$, $\rho^N_{N_f}=1$, $\rho^N_{\lambda_p}=1$, $\rho^N_V=1$ and $\rho^N_{N_c}=1$.

Table I summarizes the asymptotic expression for the total cost of key mobility management entities of NEMO. In Table II, the scalability factors of NEMO entities are listed with respect to N_m, N_f, λ_p, V and N_c.

IV. RESULTS

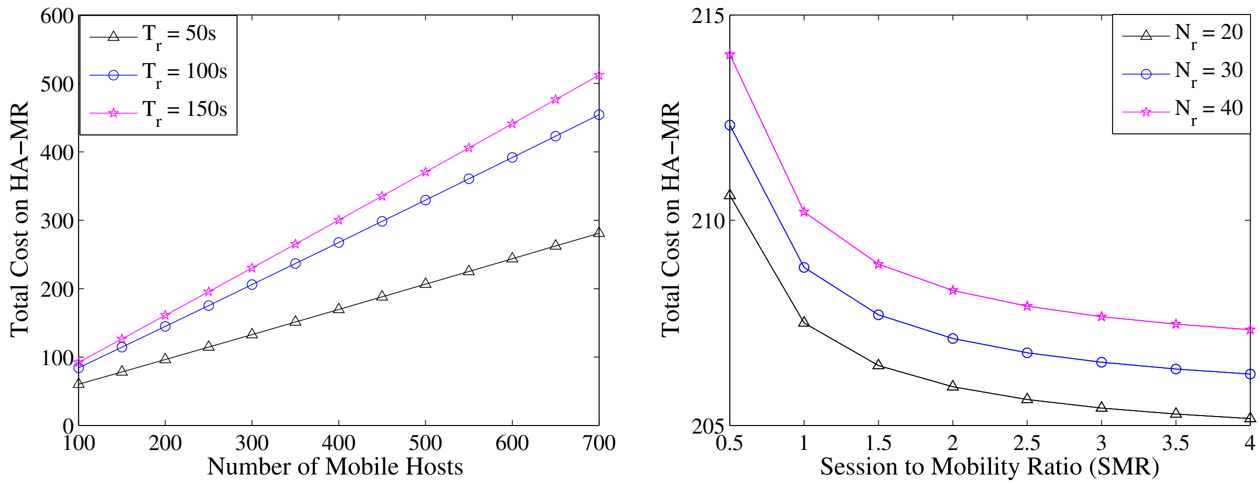
In this section, we present numerical results to demonstrate the impact of network size, mobility rate, traffic rate and data volume on the total cost of various mobility management entities. The values for the system parameters have been taken from the previous works [5], [10]: δ_L = 0.6, δ_B = 0.6, δ_Q = 0.6, δ_{DH} = 1.4, δ_{RR} = 0.6, δ_{DT} = 5.72, δ_{DA} = 0.60, δ_{TH} = 0.40, σ = 10, λ_s = 0.01, γ_t = 10, h_{in}= 5, h_p= 1, T_r = 70s, T_e = 60s, ψ = 0.3, α = 10Kb, and κ = 576b, N_f = 70, N_m = 200;

A. HA

In Fig. 2(a), the total cost of the HA is shown for varying number of mobile hosts and different subnet residence times. It is found that total cost of HA increases for higher number of mobile hosts and higher residence times. For NEMO, when the subnet residence time increases the refreshing binding cost increases although the cost related to handoff reduces due to less handoff frequency. Other costs, such as, query and data delivery cost remains unchanged. The net result is increase of total cost. It can be noted that refreshing BU is dependent on the values of T_r and T_e. For T_e = 60 sec and T_r = 50 sec, there will be no need of refreshing BU, whereas for T_r = 100 and T_r = 150, the number of times RBU sent by mobile hosts (while residing in a subnet) are 1 and 2, respectively.

In Fig. 2(b), the total cost of the HA is shown as a function of Session to Mobility Ratio (SMR) which is defined as $\lambda_s \times T_r$. We keep λ_s constant while varying the value of T_r between 50 to 400 sec. Increase of SMR value implies higher subnet residence times of the mobile network, producing less signaling relating to location updates and refreshing binding updates. In addition, the presence of higher number of MRs results in more LUs, thus increasing the total cost of HA.

[1]Standard asymptotic notation has been used. A function $f(n) = \Theta(g(n))$ if there exists some positive constants c_1, c_2, and n_0 such that $c_1 g(n) \leq f(n) \leq c_2 g(n)$ for all $n \geq n_o$.

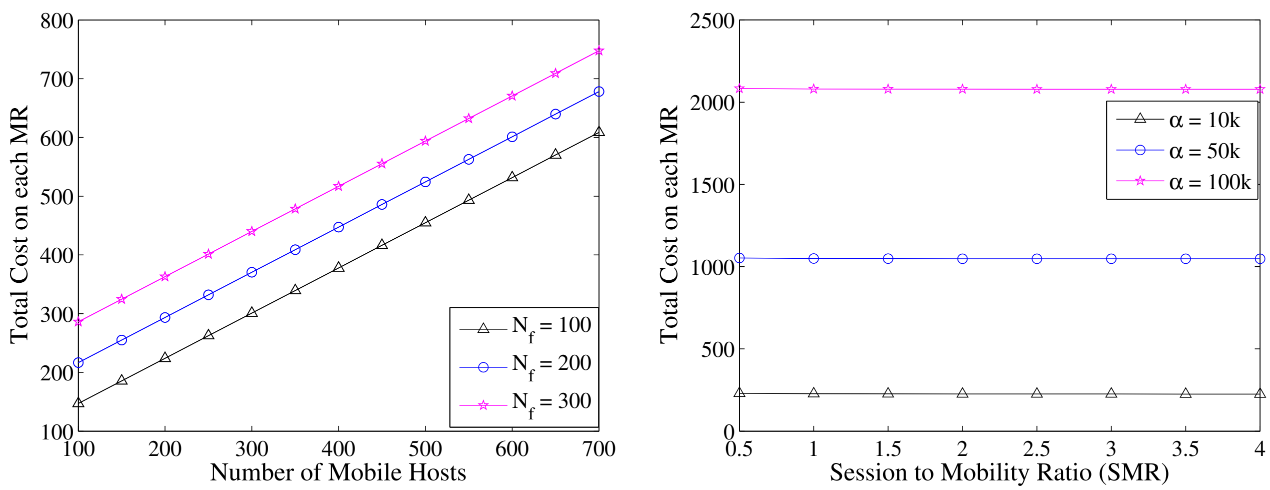


(a) (b)

Fig. 2. (a) Impact of number of mobile hosts on the total cost on the HA for different subnet residence times and (b) Impact of SMR on the total cost of the HA for different number of MRs.

B. MR

In Fig. 3(a), the total cost of each MR is shown for varying number of mobile hosts and LFNs. Increase in LFNs results in constant shifting of the total cost graph due to the increase in query message cost and data delivery cost. In Fig. 3(b), the impact of SMR on the total cost of each MR is shown for varying session lengths. Higher session



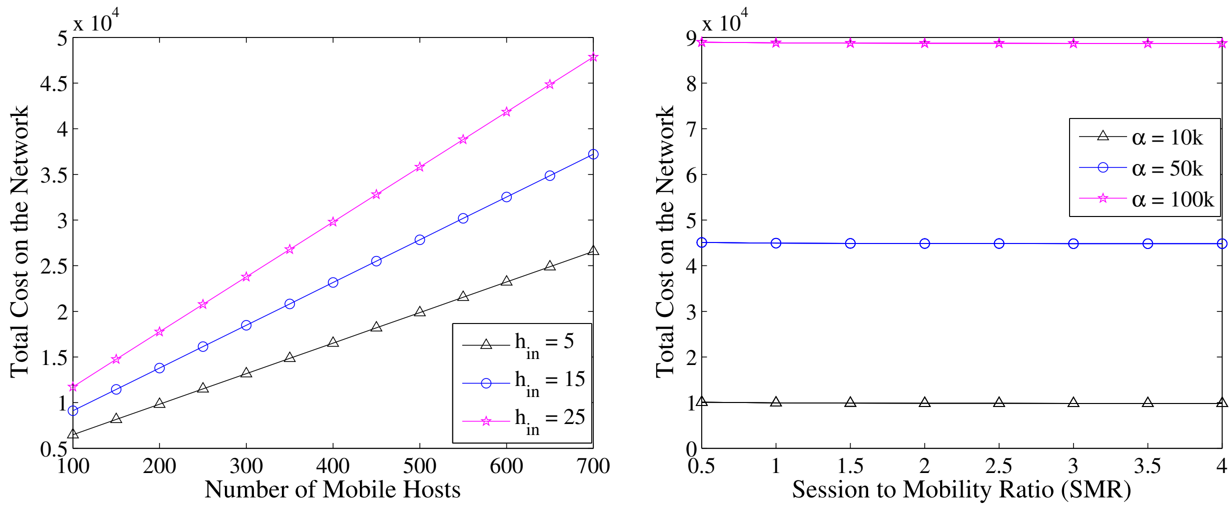
(a) (b)

Fig. 3. (a) Impact of number of mobile hosts on the total cost of each MR for different number of LFNs, (b) Impact of SMR on the total cost of each MR for different session lengths.

length causes more data packets to be routed through each MR, resulting in higher cost. The total cost is found to be invariant of SMR due to the dominance of data delivery cost.

C. Complete Network

Fig. 4(a), the total cost of the complete network is shown as function of number of mobile hosts. We have used equal number of LMN and VMNs for this graph. Increased number of mobile hosts sends higher number of location updates, binding updates; in addition, query for the mobile hosts are also increased for higher number of mobile hosts in the MN. The total cost is also shown for different number of hops in the Internet (such as, h_{in} = 5, 15 and 25). The slope of the total cost graph rises for higher values of h_{in} since its value of influences all the costs of the network.



(a) (b)

Fig. 4. (a) Impact of number of mobile hosts on the total cost of the network for different number of hops in Internet, (b) Impact of SMR on the total cost of the network for different session lengths.

In Fig. 4(b), total cost of the network is shown as a function of SMR for different session length. It is found that the total cost does not vary much (around 1%) with respect to SMR. This implies that data delivery cost (through optimized and unoptimized route) dominates the total cost.

V. Conclusion

In this paper, we have developed a mathematical model to estimate the total cost of various mobility management entities of NEMO BSP considering all possible costs that influence their operation. We have presented numerical results to show the impact of network size, mobility rate, and traffic rate on those mobility entities. It is found that total cost on various entities increases for smaller session length as there is more signaling traffic compared to data traffic. In addition, the cost on various entities does not vary much with respect to session to mobility ratio due to the dominance of data delivery cost over signaling costs. The cost analysis presented in this paper will help network engineers in estimating actual resource requirements for the key entities of the network in future design while optimizing network performance.

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