On the Efficiency of IPv6-based Network Mobility

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***Abstract*—Mobile networks can be formed in vehicles, ships, satellites with a wide variety of on-board IP-enable devices. In spite of the fact that the connection configuration of the components inside the mobile network can influence its total cost and performance regarding mobility management, there exists no standard topological configuration of the mobile network. In this paper, we have performed a cost analysis of the key components of the nested mobile network considering all possible costs. We have chosen several topological configurations to evaluate their cost and performance. Our analysis will help in selecting a mobile network configuration that minimizes the total costs while maximizing efficiency for data communication.**

***Index Terms*—Network Mobility, mobility and handoff management, network architecture, nested mobile network.**

I. Introduction

To efficiently manage the mobility of multiple IP-enabled hosts moving together, Internet Engineering Task Force proposed NEtwork MObility Basic Support Protocol (NEMO BSP) [1]. A mobile network can have one or more mobile routers that acts as the gateways for all the nodes inside the mobile network. On behalf of all the nodes inside NEMO, the mobile router–the key component of NEMO–always updates its current location to a special router in its home network known as home agent. Hence, the signaling load on these entities can be enormous and they may become performance bottleneck, thereby disrupting the communication. Therefore, it is crucial to design a mobile network that incurs least loads on these key entities to ensure better performance.

The internal configuration of the mobile network may be dynamic; there might be new visiting nodes or even another visiting mobile network joining the base mobile network forming nested mobile network. For example, a ship can have a large mobile network, and a helicopter (with a visiting mobile network) can land on the ship and get attached to the ship's mobile network. There is no standard topological configuration for the nested NEMO [2] in spite of the fact that the connection configuration of the components inside a nested mobile network can influence the signaling loads and performance of nested NEMO. Therefore, it is essential to investigate the performance of NEMO by varying the organization and hierarchy of mobile routers.

There have been a few works that deal with NEMO architecture. Qun et al. [3] propose a new mobile network architecture based on vector network that aims at designing an architecture to separate the name address and the switching address of the mobile nodes. There have been several works on the cost analysis of IPv6-based host mobility protocols [4]–[6], such as, Mobile IPv6 [7]. However, these cost analysis are not adequate for mobile network since NEMO has more complex scenario than MIPv6. On the other hand, earlier attempts for cost and performance analysis of NEMO or similar protocols [8], [9] did not consider all possible costs for mobility management in a nested NEMO architecture. Our work *differs* from the previous works in the sense that we have focused on a generalized nested NEMO architecture considering all possible costs. In addition, we have evaluated the cost and efficiency of the key mobility management entities of nested NEMO using different topological scenarios.

The organization of the mobile routers, mobile and fixed nodes, and their hierarchy in a nested NEMO can result in significant variation in total costs incurred for mobility management. Our *objective* of this work is to investigate this variation by using different topological scenarios.

The *contributions* of our work are: (i) developing an analytical model to estimate total cost and efficiency of key mobility management entities of nested NEMO, and (ii) evaluating the cost and performance of these entities through several topological scenarios, thereby obtaining the optimal structure of mobile networks.

Our analysis presented in this paper will help network engineers in comparing the performance of critical mobility management entities in nested NEMO scenario.

The rest of the paper is organized as follows. In Section II, NEMO architecture and basic protocol are explained in brief. In Section III, we evaluate the total costs of two key mobility management entities of NEMO. In Section IV, the possible connection topologies of the mobile network are explained, followed by the numerical results in Section V. Finally, Section VI has the concluding remarks.

II. Network Mobility

Fig. 1 shows the architecture of a Mobile Network (MN). The root-Mobile Router (root-MR) acts as the gateway for all the Mobile Network Nodes (MNN). MNNs are of different types: Local Fixed Nodes (LFN), Local Mobile Nodes (LMN) and Visiting Mobile Nodes (VMN). LFNs do not move with respect to MN. LMNs usually reside in MN and can move to other networks, whereas VMNs can get attached to the

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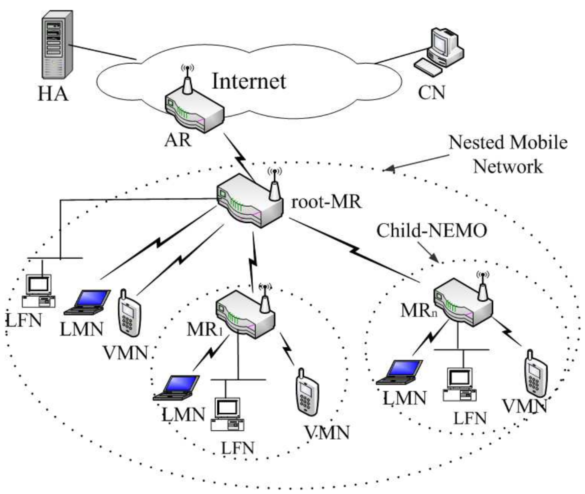

Fig. 1. Nested NEMO architecture.

MN from another network. In fact, a smaller mobile network can get attached to another larger mobile network, and if so, the former is known as child-NEMO, the latter as parent-NEMO. All mobile nodes (LMNs and VMNs, MRs) are MIPv6 capable. The root-MR attaches to the Internet through Access Routers (ARs). A mobile network 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 about the location of the MR, and redirects packets sent by the Correspondent Node (CN) to MNNs.

In NEMO BSP [1], 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 (which is the mapping of MRs home address to 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 which 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 MNN.

III. Analysis

In this section, we derive the cost and efficiency expressions for the key mobility management entities of nested NEMO: Home Agent and the root-MR(s).

A. Notations

The notations used in this paper are listed below.

N_f	Number of LFNs in the MN,
N_m	Total mobile nodes (LMN and VMN) in the MN,
N_{mnn}	Total MNNs, i.e., $N_{mnn} = N_f + N_m$,
K	Nesting levels in the mobile network,
N_c	Average number of CNs per MNN,
δ_L	Per hop transmission cost for Location Update (LU),
δ_B	Per hop transmission cost for 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 (tunneling) header,
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,
κ	Maximum transmission unit,
α	Average session size.

$N_r^{(k)}$ denotes number of MRs at level k. Similar notations are used for LFNs, and mobile nodes at different levels.

B. Assumptions

The assumptions of the model are as follows:

- Number of nodes registered with an HA are higher than the number of nodes in the MN (by a factor β).
- Binary search is used to search location database.
- Each CN has one ongoing session with a MNN.

C. Traffic Model

Session arrival follows Poisson process with the following probability distribution function:

$$f_s(n) = \frac{e^{-\lambda_s}\lambda_s^n}{n!} \quad (1)$$

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. Home Agent

The Home Agent is an crucial mobility management entity for NEMO and too much load on this key component may result in unavailability of several MNNs or the whole network. The various costs incurred at the HA are listed below.

1) Query message: Any CN that wants to communicate with any MNN, sends query message to the HA at the beginning of each session. This requires a lookup at the HA which is proportional to the logarithm of the number of entries in the lookup table. Therefore, the lookup cost at HA is $\Psi_H = \psi \log_2(\beta(N_r + N_{mnn}))$. In addition, transmission cost is incurred for query-reply messages at the HA. Hence, the cost relating to query messages at HA are as follows:

$$\Lambda^{QR} = N_c\lambda_s\Big(2\delta_Q + \Psi_H\Big) \quad (2)$$

2) Location updates: After each handoff, the root-MR(s) sends LU message to the HA which modifies the location database. In addition, root-MR(s) and mobile nodes send periodic refreshing updates to HA to avoid removal of binding entries after its lifetime. Let the lifetime of binding entries be T_e. Therefore, $\left\lfloor \frac{T_r}{T_e} \right\rfloor$ refreshing updates are sent to HA within time T_r. So the frequency of sending periodic refreshing updates is $\eta_r = \left\lfloor \frac{T_r}{T_e} \right\rfloor / T_r$, and total frequency of sending LU and refreshing LU is $\eta_t = \left(1 + \lfloor \frac{T_r}{T_e} \rfloor\right)/T_r$. Each LU and corresponding acknowledgement message (exchanged with HA) incur transmission and processing cost. In addition, the LU messages from MRs and the mobile nodes go through several levels of encapsulation depending on the level they belong to. This results in additional header overhead of δ_{TH} and a processing cost of γ_t at each level whereas the LU messages from the root-MR(s) go without encapsulation. In both cases, a lookup cost of Ψ_H is required. So cost related to LU and refreshing LU messages can be computed as follows:

$$\Lambda^{LU} = \eta_t N_r^{(0)} \Big[2\delta_L + \Psi_H\Big] + \eta_r \sum_{j=1}^{K} (N_r^{(j)} + N_m^{(j)}) \times \Big(2(\delta_L + j\delta_{TH} + \gamma_t) + \Psi_H\Big) \tag{3}$$

3) Return routability: In order to prevent session hijacking, NEMO employs RR test before sending BU similar to the mechanism employed in MIPv6 [7]. Before each BU message, RR messages are exchanged among the MR, HA and CN. Therefore, the cost on HA for RR messages is as follows:

$$\Lambda^{RR} = \frac{N_c}{T_r} \sum_{j=1}^{K} N_m^{(j)} 2(\delta_{RR} + j\delta_{TH} + \gamma_t) \tag{4}$$

4) Binding updates: To continue ongoing sessions with the CNs, mobile nodes inside the mobile network sends refreshing BU to the CNs by tunneling through the HA. The HA has to lookup the table, tunnel and transmit those BUs. Therefore,

$$\Lambda^{BU} = \eta_r N_c \sum_{j=1}^{K} N_m^{(j)} \Big(2(\delta_B + j\delta_{TH} + \gamma_t) + \Psi_H\Big) \tag{5}$$

5) Data delivery cost: In every session, the first data packet is sent through the HA [7] which incurs transmission cost (for data and ACK packets), extra IP-header processing and lookup cost. Therefore, the data delivery cost on the HA is given by,

$$\Lambda^{DD} = N_c \lambda_s \sum_{j=1}^{K} \Big(N_m^{(j)} + N_f^{(j)}\Big) \Big(\delta_{DT} + \delta_{DA} + 2(j\delta_{TH} + \gamma_t) + \Psi_H\Big) \tag{6}$$

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

$$\Lambda^{Total} = \Lambda^{QR} + \Lambda^{LU} + \Lambda^{RR} + \Lambda^{BU} + \Lambda^{DD} \tag{7}$$

E. root-MR

For a nested NEMO, the root-MR is the most important entity as all essential mobility management signaling goes through it. Therefore, we evaluate the total cost of root-MR(s).

1) Acquiring IP address and prefixes: The root-MR(s) acquire IP address from the AR during each handoff by exchanging DHCPv6 request-reply messages. Hence,

$$\Gamma^{Acq} = \frac{2\sigma\delta_{DH}}{T_r} \tag{8}$$

2) Location updates: After each handoff, the root-MR(s) sends LU message(s) to the HA. Periodic refreshing updates are also sent by the MRs and the mobile nodes through root-MR(s). Thus, the cost on each MR due to LU messages is,

$$\Gamma^{LU} = 2\sigma\eta_t\delta_L + 2\eta_r \sum_{j=1}^{K} \Big(N_r^{(j)} + N_m^{(j)}\Big) \times \Big(\sigma(\delta_L + j\delta_{TH}) + \gamma_r\Big) \tag{9}$$

3) Binding updates to CNs: In order to maintain session continuity, mobile nodes send periodic refreshing BUs to the CNs through the root-MR(s), thereby updating their current addresses. This requires transmission of BU message through the wireless media with extra IP-header, and processing due to tunneling. Thus,

$$\Gamma^{BU} = 2N_c\eta_r \sum_{j=1}^{K} N_m^{(j)} \Big(\sigma(\delta_B + j\delta_{TH}) + \gamma_r\Big) \tag{10}$$

4) Return routability messages: To prevent possible hijacking of ongoing session, it is essential to perform RR test [7]. The root-MR(s), therefore, processes and transmits RR messages on behalf of the mobile nodes under its domain.

$$\Gamma^{RR} = \frac{2\sigma N_c}{T_r} \sum_{j=1}^{K} N_m^{(j)} (\delta_{RR} + j\delta_{TH} + \gamma_r) \tag{11}$$

5) Data delivery cost: In each session between the CN and an MNN, an average of $\lceil \frac{\alpha}{\kappa} \rceil$ data packets are sent. So the packet arrival rate to each MNN is $\lambda_p = \lambda_s \lceil \frac{\alpha}{\kappa} \rceil$. 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 each MR is given by,

$$\Gamma^{DD} = \lambda_p N_c \sum_{j=1}^{K} \big(N_m^{(j)} + N_f^{(j)}\big) \Big(\sigma(\delta_{DT} + \delta_{DA} + j\delta_{TH}) + \gamma_r\Big) \tag{12}$$

6) Total cost: Therefore, total cost of each MR can be obtained by adding Eqns. (8), (9), (10), (11), and (12),

$$\Gamma^{Total} = \Gamma^{Acq} + \Gamma^{LU} + \Gamma^{BU} + \Gamma^{RR} + \Gamma^{DD} \tag{13}$$

F. Efficiency

We define the *efficiency* metric for mobility entities as the ratio of data delivery cost (without any tunneling and extra header) to the total cost (that includes signaling and data delivery costs) required for the mobility protocol.

a) Home Agent: Data delivery cost incurred at HA can be obtained as:

$$\Lambda^{DD}_{HA} = N_c\lambda_s \sum_{j=1}^{K} \Big(N_m^{(j)} + N_f^{(j)}\Big)(\delta_{DT} + \delta_{DA}) \tag{14}$$

Therefore, efficiency of the HA is given by:

$$\xi^{HA} = \frac{\Lambda^{DD}_{HA}}{\Lambda^{Total}} \tag{15}$$

b) root-MR: The net cost incurred at the root-MR for data delivery between CNs and MNNs can be obtained as:

$$\Gamma^{DD}_{rMR} = \sigma\lambda_p N_c \sum_{j=1}^{K} \big(N_m^{(j)} + N_f^{(j)}\big)(\delta_{DT} + \delta_{DA}) \tag{16}$$

Therefore, efficiency of root-MR is given by:

$$\xi^{rMR} = \frac{\Gamma^{DD}_{rMR}}{\Gamma^{Total}} \tag{17}$$

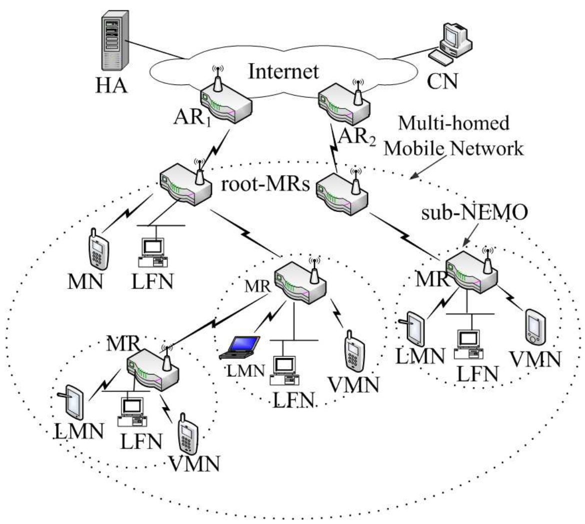

Fig. 2. Topology 2: a multi-homed nested NEMO with two root-MRs.

IV. CONNECTION TOPOLOGY

For comparative analysis, we have chosen three representative connection topologies of nested NEMO with equal number of fixed and mobile nodes (total 600 MNNs of which 480 are mobile and 120 are fixed nodes). The first topology has least nesting level while third one has the highest among the three. We could have further considered more topologies; however, the topologies considered here are general enough for our comparative analysis as they represent possible extreme cases.

A. Topology 1

The first topology shown in Fig. 1 is a 3-layer nested NEMO with a single root-MR in layer 0. The root-MR is connected to all the 14 MRs in layer 1. The LFNs and mobile nodes are equally distributed in layer 1 and layer 2. That is, there are 60 LFNs and 240 mobile nodes in each of the layers.

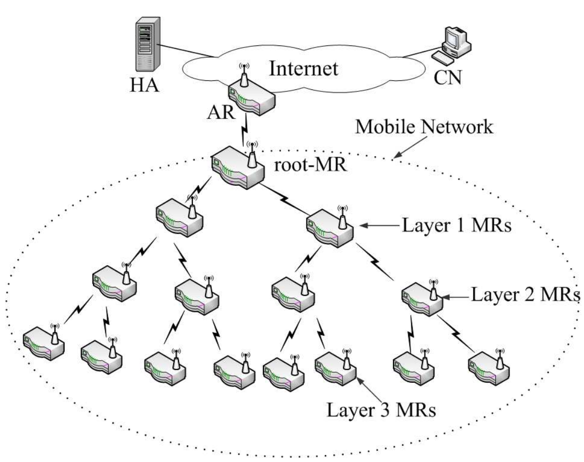

Fig. 3. Topology 3: only connections among the MRs are shown.

B. Topology 2

The second topology (Fig. 2) is a 4-layer nested NEMO with two root-MRs (for improved availability and robustness). The root-MRs are connected to layer 1 MRs (6 MRs in layer 1, though not shown for simplicity). Another 6 MRs are in layer 2 and none in layer 3. Again, the LFNs and mobile nodes are equally distributed among the layers 1, 2, and 3 (having 160 mobile nodes and 40 LFNs each).

C. Topology 3

The third topology shown is a 5-layer nested NEMO. The connection topology of the MRs (tree-structure) is only shown in Fig. 3. For simplicity, the LFNs and mobile nodes are not shown. Layer 0 through layer 3 has 1, 2, 4, and 8 MR(s). The LFNs and mobile nodes in layer 1 through 4 are all equal, that is, 30 LFNs and 120 mobile nodes in each layer.

V. NUMERICAL RESULTS

In this section, we present the numerical results showing the impact of mobility rate, session arrival rate, and number of CNs on the total cost and efficiency of the HA and root-MR(s) for the above mentioned topologies. The values for the system parameters are consistant with the previous works [8], [9]: 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 = 0.50, γ_r = 0.50, β =5, T_r = 70s, T_e = 120s, ψ = 0.3, α = 10Kb, κ = 576b, N_c = 1, N_f = 120, N_m = 480, N_{mnn} = 600. All the costs are relative terms (unitless). The transmission and processing costs are relative and determined based on the packet size assuming unit cost per 100 bytes [6]. For the lookup cost, we assume a logarithmic time for the processing cost per entry.

First, we present results for the total cost of the HA as a function of number of CNs (Fig. 4). It is found that cost on the HA increases with increased CNs since more query requests have to be processed by the HA, in addition to the RR message and binding updates. Among the three topologies, topology 3 has the highest cost on the HA since it has a five-layer configuration, producing more encapsulation costs for extra headers.

In Fig. 5, the efficiency of HA is shown as a function of session arrival rates (λ_s). It is found that the efficiency of the HA is the least for the third configuration of the mobile network since more signaling cost is incurred at the HA with this topology compared to the other topology for higher lengths of tunneling header as well as higher processing cost.

In Fig. 6, the efficiency of HA is shown as a function of subnet residence time of the nested mobile network. This graph shows interesting behavior; it has sudden drops around 120 sec and 240 sec. This is due to the refreshing update messages. As the value of binding entry lifetime is assumed to be 120 sec, no refreshing update is sent if the subnet residence time is less than 120 sec. However, if the mobile network moves slowly and resides in the subnet longer than 120 sec, the root-MR has to send refreshing updates so that the binding cache remains active. Other than that, the efficiency for the first topology is found to be highest due to its less nesting levels which produces smaller headers and requires less processing cost.

Fig. 7 shows the total cost of the root-MR(s) as a function of Session-to-Mobility Ratio (SMR). We have computed SMR by multiplying T_r with session arrival rate (λ_s). We have used a fixed value (0.01) for λ_s and varied the value of T_r. The total cost of the root-MR(s) reduces when the mobile

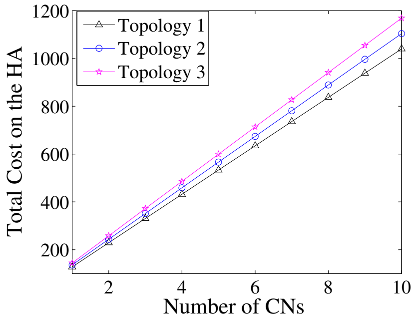

Fig. 4. Total cost at the HA vs. number of CNs per MNN.

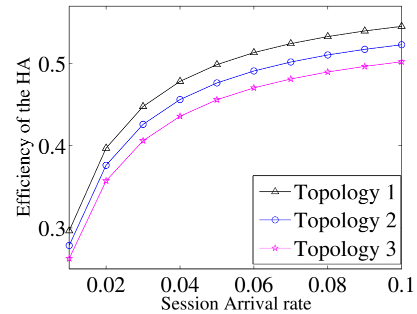

Fig. 5. Efficiency of the HA vs. session arrival rates.

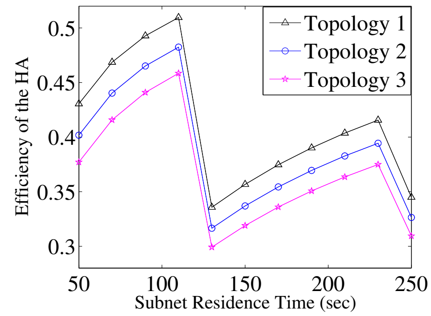

Fig. 6. Efficiency of the HA vs. subnet residence time.

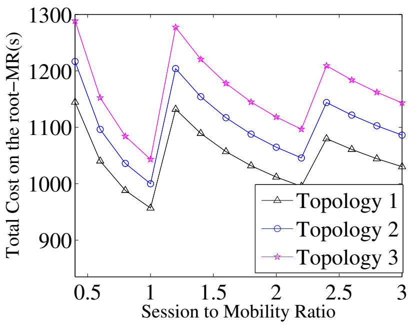

Fig. 7. Total cost at the root-MR(s) as a function of SMR.

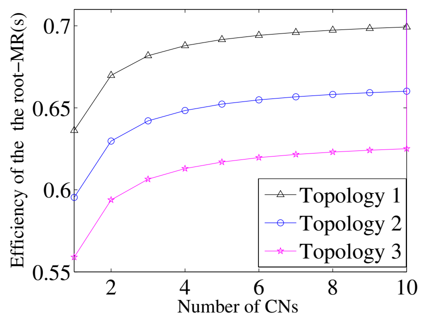

Fig. 8. Efficiency of the root-MR(s) as a function of number of CNs.

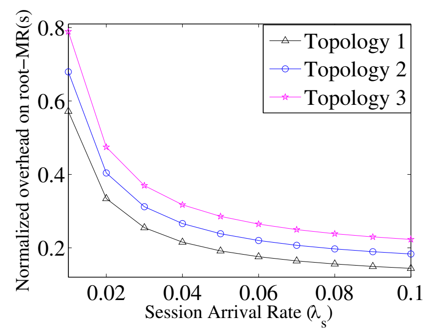

Fig. 9. Overhead of the root-MR(s) vs. session arrival rate.

network moves slowly, thereby producing less signaling traffic (e.g., location and binding updates to the HA and the CNs). However, we have similar kind of behavior (spikes) due to the refreshing update traffic explained earlier (for Fig. 6).

Fig. 8 shows the efficiency of the root-MR(s) as a function of number of CNs for different configurations of the mobile network. As found earlier, the third configuration has the least efficiency. However, the efficiency curves become saturated with higher values of N_c due to the dominance of data delivery costs over the signaling costs (e.g., location updates, binding updates and RR costs).

In Fig. 9, we have computed the normalized overhead on the root-MR(s) for different configurations of the mobile network. First, the overhead on the root-MR(s) was computed by subtracting the net data delivery cost from the total cost; then normalization was done by dividing the result with the net data delivery cost. As shown in Fig. 9, the normalized overhead for the first configuration is the least whereas that of the third configuration is the highest. The overhead of each topology decreases with higher session arrival rates as data delivery cost increases, thereby reducing the normalized results.

From the above graphs, it is clear that the third nested NEMO configuration incurs highest signaling cost on the root-MR(s) as well as the HA. On the other hand, with respect to efficiency, the first one is the best configuration. Therefore, reducing the nesting levels can improve the performance of the mobility management entities though it is not always possible to use a flat topology where separate stand-alone units (such as, child-NEMO) might be a necessity.

VI. Conclusion

In this paper, we have presented analytical model that estimates the costs and efficiency for key mobility management entities of nested NEMO architecture. We have used several topological configurations to find out the configuration that requires least cost yet best performance. Our results also reveal interesting relationships among various network parameters. Our analysis presented in this paper will help in selecting a nested NEMO configuration that minimizes the total costs of key mobility management entities.

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