Cost and Efficiency Analysis of NEMO Protocol Entities

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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 and 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 NEMO 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 defined a metric to compute the efficiency of mobility protocol as well as the mobility entities to find out the percentage of resources used for data (payload) delivery. We have presented numerical results to demonstrate the impact of network size, mobility rate, traffic rate and data volume on the total costs and the efficiency of the NEMO protocol and its key entities. 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 analyzing the data transmission efficiencies of these entities.**

***Index Terms*—NEMO, mathematical modeling, cost analysis, mobility management entities, mobility protocol.**

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, data volume) influence the cost arising from mobility protocols. The total cost includes cost 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 have been earlier attempts for signaling cost analysis ([3]–[10]) of host-mobility protocols, such as, Mobile IPv6 [2], Hierarchical Mobile IPv6 (HMIPv6) [11]. However, these cost analysis are not adequate for NEMO protocols since NEMO has more parameters and cost components and different types of nodes in the mobile network unlike host-mobility protocols.

There have been a few works [12]–[14] on the cost analysis of NEMO protocols. However, these cost analysis ignored major cost components relating to mobility management, e.g., cost related to securing location updates, query messages by CN, obtaining IP address by MH, refreshing binding updates, costs of registration messages, etc. Hence, those analysis are incomplete. Moreover, the entity-wise evaluation of costs has not been performed to obtain the load on various mobility entities of the network required for the operation of NEMO protocol. Such analysis is very essential as resource limitations exist for all network entities and this entity-wise evaluation can aid in estimating actual resource requirement of these entities.

The main *differences* of this work are that we have considered all possible costs required for mobility management and have computed total costs of various mobility management entities of NEMO. We have also defined a metric to compute the data transmission efficiency of NEMO protocol as well as its key entities. *The authors are not aware of any such work.*

The *objective* of this work is to analyze the total cost (including data delivery cost) and data transmission efficiency of various mobility entities of NEMO 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, correspondent

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node, mobile host, and complete network and (ii) defining a novel metric to compute the data (payload) transmission efficacy of NEMO protocol and its key entities (iii) analyzing the impact of network size, mobility rate, traffic rate, and data volume on these costs and efficiency.

The analytical cost models 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. Moreover, the efficiency metric can be used to compare the NEMO protocol and its mobility entities with other related protocols.

The rest of the paper is organized as follows. In Section II, we present a literature review of the existing cost models of different mobility protocols. In Section III, NEMO architecture and BSP are briefly explained. In Section IV, analytical models for total cost and efficiency of various entities of NEMO are presented. Section V analyzes the results. Finally, Section VI has the concluding remarks.

II. Literature Review

In this section, we present some of earlier attempts for cost analysis of mobility protocols. Xie et al. [3] perform the cost analysis of Mobile IP to minimize the signaling cost while introducing a novel regional location management scheme. Fu et al. [4] analyze the signaling costs of Seamless IP-diversity based Generalized Mobility Architecture (SIGMA) [15] and Hierarchical Mobile IPv6 (HMIPv6) [11]. 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). Diab et al. [8] propose a generic mathematical model for fast and simple cost estimation that 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. Galli et al. [6] 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 [7] 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). These cost analysis on host mobility protocols are not adequate for NEMO protocols since NEMO has more parameters and cost components and different types of nodes in the mobile network unlike host-mobility protocols.

Munasinghe et al. [16] 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. [17] 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. Narayanan et al. [9] 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. Lee et al. [10] 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. Again, these works mainly focus on host-mobility protocols.

There have been a few works on the cost analysis of NEMO protocols. Reaz et al. [12] perform the signaling cost analysis of NEMO and SINEMO [18], seamless IP-diversity based network mobility protocol. Jalil et al. [13] perform a signaling cost analysis of NEMO using the similar models developed in [12]. Lim et al. [14] perform the cost analysis of NEMO route optimization schemes. Shahriar et al. [19] presents a cost analysis framework for NEMO prefix delegation-based schemes. However, the cost analysis performed earlier ignored some major costs relating to mobility management, e.g., cost related to securing location updates, costs related to query messages by CN, costs of refreshing binding updates, and costs of registration messages, and data acknowledgement messages, etc. These are regular and essential messages exchanged during the operation of a mobility protocol and have significant impact on NEMO and its mobility entities. Hence, the analysis found in the literature are incomplete. Moreover, the entity-wise evaluation of costs has not been performed to obtain the load on various mobility entities of the network due to the operation of NEMO protocol.

We have developed an analytical model that takes into account all possible costs for mobility management. Unlike previous works, we have also performed the entity-wise analysis to compute the actual costs and efficiencies of various key mobility entities involved in mobility management. Such analysis is very essential as resource limitations exist for all the entities responsible for mobility management in the network. This work is an extension of our earlier work [20]. We have added analysis and corresponding results for other network entities, such as on mobile hosts, correspondent nodes. We have defined a new metric called efficiency of mobility protocol to estimate the data transmission efficacy of NEMO protocol and its key entities. We have also presented results showing efficiency of NEMO protocol and all its entities. Therefore, this work is a complete cost and efficiency analysis of NEMO.

III. 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 IV.

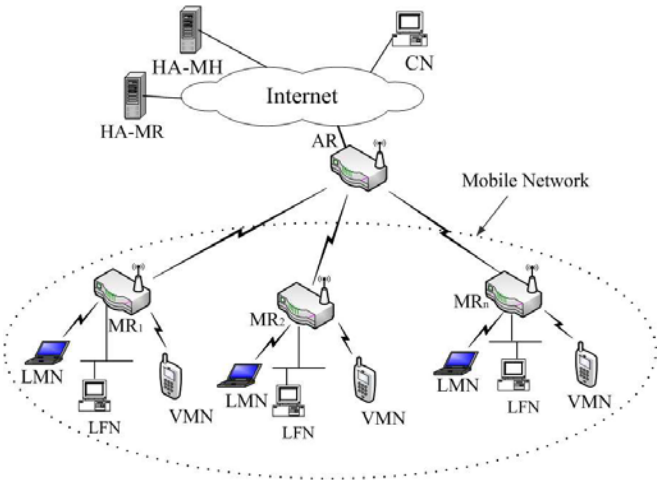


Fig. 1. NEMO Architecture

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 notiŒed 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 PreŒxes (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 trafŒc 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-MR). HA-MR 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.

IV. Cost Analysis

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

A. Notations

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

- N_r Number of mobile routers in the mobile network,
- N_f Number of LFNs in the mobile network,
- N_l Number of LMNs in the mobile network,
- N_v Number of VMNs in the mobile network,
- N_{mnn} Total MNNs in the mobile network, i.e., $N_{mnn} = N_f + N_l + N_v$,
- N_m Total mobile nodes in the mobile network, i.e., $N_m = N_l + N_v$,
- N_c Average number of CNs communicating with the nodes inside the mobile network,
- 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_R Per hop transmission cost for MH registration,
- 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 coefŒcient 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,
- ω_l Ratio of number of LMNs to total MNNs in the MN,
- ω_f Ratio of number of LFNs to total MNNs in the MN,
- ω_v Ratio of number of VMNs to total MNNs in the MN,
- κ Maximum transmission unit,
- α Average session size.

B. Assumptions

Following are the assumptions of the model:

- All the MRs have the same HA which is HA-MR.
- HA-MR is the HA for LFNs and LMNs of the mobile network under consideration.
- HA-MH has been considered to be HA of all the VMNs of the mobile network under consideration. That is, HA-MH serves as the location manager of N_f mobile hosts.
- 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. User Mobility Model

Most of the cost analysis ([3], [4], [12]) used random waypoint model as the user mobility model though the mobility pattern simulated by the RWP model is not realistic. We have used city section mobility model, a realistic street movement model, as the mobility model. The stochastic properties of CSM model has been analyzed in [21] and we use the expression of subnet residence time in Section V for numerical analysis.

D. 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 (file size) is assumed to be α.

E. HA-MR

In NEMO, the HA-MR keeps the location database of the mobile network. In fact, the location information of MR, LFNs and LMNs are kept in the HA-MR whereas that of VMNs are kept in corresponding HAs since they belong to some other networks. The main tasks of HA-MR 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: The fraction of CNs that communicate with either with a LMN or a LFN are $(\omega_l + \omega_f)N_c$. These CNs send query message to the HA-MR at the beginning of every session. This requires a lookup at the HA-MR which is proportional to the logarithm of the number of entries in the lookup table. As the HA-MR contains location information for all the MRs, LFNs and LMNs (see the assumption above), the lookup cost at HA-MR is $\Psi^{LK}_{HA-MR} = \psi \log_2(N_r + N_f + N_l)$. In addition, transmission cost is incurred for query-reply messages at the HA-MR. Hence, the cost relating to query messages at HA-MR are given by the following equation:

$$\Lambda^{QR}_{HA-MR} = (\omega_l + \omega_f)N_c\lambda_s\Big[2\delta_Q + \Psi^{LK}_{HA-MR}\Big] \quad (2)$$

2) Location update messages: When the mobile network crosses subnets, MR sends LU message to the HA-MR and the location database is modified by the HA-MR 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-MR 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-MR 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-MR incurs transmission and processing cost. The LU messages from LMNs goes 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^{LK}_{HA-MR} is required. So the cost related to the LU and refreshing LU messages can be computed as follows:

$$\begin{aligned}\Lambda^{LU}_{HA-MR} &= \eta_t N_r\Big[2\delta_L + \Psi^{LK}_{HA-MR}\Big] \\ &\quad + \eta_r N_l\Big[2(\delta_L + \delta_{TH} + \gamma_t) + \Psi^{LK}_{HA-MR}\Big]\end{aligned} \quad (3)$$

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-MR receives the Home Test Init (HoTI) message sent by the MR and forwards it to the CN. HA-MR 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-MR receives these RR messages for all CNs that are communicating with LMN. Therefore, the cost on HA-MR for RR messages are as follows:

$$\Lambda^{RR}_{HA-MR} = N_l\left(\frac{N_c}{N_{mnn}}\right)\frac{4\delta_{RR}}{T_r} \quad (4)$$

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

$$\Lambda^{BU}_{HA-MR} = 2\omega_l N_c\eta_r\Big[\delta_B + \delta_{TH} + \gamma_t + \Psi^{LK}_{HA-MR}\Big] \quad (5)$$

5) Data delivery cost: In every session, the first data packet is sent through the HA and all other packets are transmitted through direct path to the MR [2]. This is also true for VMNs. Data packets (first one of each session) are routed though the HA-MR. This 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-MR is given by,

$$\Lambda^{DD}_{HA-MR} = N_c\lambda_s\left[\delta_{DT} + \delta_{DA} + 2\Big(\delta_{TH} + \gamma_t + \Psi^{LK}_{HA-MR}\Big)\right] \quad (6)$$

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

$$\Lambda_{HA-MR} = \Lambda^{QR}_{HA-MR} + \Lambda^{LU}_{HA-MR} + \Lambda^{RR}_{HA-MR} + \Lambda^{BU}_{HA-MR} + \Lambda^{DD}_{HA-MR} \quad (7)$$

F. HA-MH

The HA-MH serves as the location manager of the VMNs of the mobile network. The main tasks of the HA-MH are 1) processing the query message sent by the CNs, 2) processing the LU messages, 3) RR messages of the VMNs, and 4) data delivery cost.

1) Query message: The fraction of CNs that communicate with the VMN are $\omega_v N_c$ and they send query message to the HA-MH at the beginning of every session. This incurs transmission and lookup cost for HA-MH. Thus, cost on HA-MH for query messages is

$$\Lambda^{QR}_{HA-MH} = \omega_v N_c \lambda_s \Big[2\delta_Q + \psi \log_2 N_v\Big] \quad (8)$$

2) Location update messages: Each VMN sends LU message after each handoff and periodic refreshing updates to the HA-MH which incurs transmission, and lookup cost. Thus the cost on HA-MH is

$$\Lambda^{LU}_{HA-MH} = N_v \eta_t \Big(2(\delta_L + \delta_{TH} + \gamma_t) + \psi \log_2 N_v\Big) \quad (9)$$

3) Return routability messages: Each VMN sends RR messages involving the HA-MH which costs the following:

$$\Lambda^{RR}_{HA-MH} = N_v \left(\frac{N_c}{N_{mnn}}\right) \frac{4\delta_{RR}}{T_r} \quad (10)$$

4) Data delivery cost: The first data packet from the CN travel through the HA-MH, and then through the HA-MR to reach the VMN. This requires transmission, extra IP-header processing and lookup cost at HA-MH. Therefore, the data delivery cost on the HA-MH is given by

$$\Lambda^{DD}_{HA-MH} = \omega_v N_c \lambda_s \Bigg[\delta_{DT} + \delta_{DA} + 2\Big(\delta_{TH} + \gamma_t + \psi \log_2 N_v\Big)\Bigg] \quad (11)$$

5) Total cost: Thus, the total cost of the HA-MR can be obtained by adding Eqns. (8), (9), (10), and (11):

$$\Lambda_{HA-MH} = \Lambda^{QR}_{HA-MH} + \Lambda^{LU}_{HA-MH} + \Lambda^{RR}_{HA-MH} + \Lambda^{DD}_{HA-MH} \quad (12)$$

G. Mobile Router

In NEMO, the main tasks of each MR are 1)IP address and prefix acquisition, 2) sending LU messages to HA-MR, 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.

$$\Lambda^{DHCP}_{MR} = \frac{2\sigma\delta_{DH}}{T_r} \quad (13)$$

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

$$\Lambda^{LU}_{MR} = 2\sigma\eta_t\delta_L + 2\eta_r \left(\frac{N_m}{N_r}\right)\Big(\sigma(\delta_L + \delta_{TH}) + \gamma_t\Big) \quad (14)$$

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. Number of CNs that communicates with the mobile nodes are $N_c(\omega_l + \omega_v)$. 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 each MR for these BU messages are

$$\Lambda^{BU}_{MR} = 2\eta_r \left(\frac{N_c}{N_r}\right)(\omega_l + \omega_v)\Big(\sigma(\delta_B + \delta_{TH}) + \gamma_t\Big) \quad (15)$$

4) MH's local registration messages: Every subnet crossing by the MH (in every T_l sec from a MR region) triggers a local registration message to be sent to the MR. This involves transmission cost over the wireless link and processing cost at MR.

$$\Lambda^{LR}_{MR} = \frac{N_m}{N_r} \times \frac{2\sigma\delta_R + \gamma_r}{T_l} \quad (16)$$

5) Return routability messages: To ensure that the ongoing session is not hijacked by some malicious agent, before sending binding updates to the HA-MR, 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.

$$\Lambda^{RR}_{MR} = \frac{4\sigma(N_m/N_r)\delta_{RR}}{T_r} \quad (17)$$

6) Data delivery cost: 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. As each MR manages the ongoing communication of N_c/N_r sessions, total data / ACK packet arrival rate to the MR is $\lambda_p = (N_c/N_r)\lambda_s\lceil \frac{\alpha}{\kappa} \rceil$. 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,

$$\Lambda^{DD}_{MR} = \lambda_p \Big(\sigma(\delta_{DT} + \delta_{DA} + \delta_{TH}) + \gamma_t\Big) \quad (18)$$

7) Total cost: Therefore, total cost of each MR can be obtained by adding Eqns. (13), (14), (15), (17), and (18),

$$\Lambda_{MR} = \Lambda_{MR}^{DHCP} + \Lambda_{MR}^{LU} + \Lambda_{MR}^{BU} + \Lambda_{MR}^{LR} + \Lambda_{MR}^{RR} + \Lambda_{MR}^{DD} \quad (19)$$

H. Mobile Host

As the mobile nodes inside a mobile network can move within the network, they can be attached to a new MR leaving the domain of a previous mobile network. As the mobile nodes inside the network do not have to send binding updates to the CNs, rather the MR does so on their (MHs) behalf, reducing the signaling load on the MHs. In fact, the MRs analyzes the sessions between the MHs and the CNs, and updates the sessions table which is used to send binding updates to the CNs. Thus, the cost on each MH is for registration with the MR and data delivery directly to the CN through the MR.

1) Registration messages: When a MH enters into a MR domain, it receives router advertisements, and registers with the MR sending (receiving) registration request (reply). Let the time duration that a MH reside within a MR be T_l. So the subnet change frequency for the MH (micro-mobility inside the MN) is $1/T_l$. Therefore, the overhead on each MH associated with the registration event is given by

$$\Lambda_{MH}^{RG} = \frac{2\sigma\delta_R}{T_l} \quad (20)$$

2) Data delivery cost: We have assumed a total of N_c CNs for all the $(N_f + N_m)$ MNNs. Therefore, on the average, number of correspondent node per MNN or MH is $N_c/(N_f + N_m) = N_c^m$ (let). Thus, Each MH communicates with N_c^m correspondent nodes through MRs. Since average session length is α, total number of packets in a session is $\left\lceil \frac{\alpha}{\kappa} \right\rceil$. Therefore, the packet delivery costs for each MH per second is as follows:

$$\Lambda_{MH}^{DD} = N_c^m \left\lceil \frac{\alpha}{\kappa} \right\rceil \sigma\lambda_s(\delta_{DT} + \delta_{DA}) \quad (21)$$

3) Total cost of each MH: Thus, the total signaling overhead on each HA can be obtained by adding Eqns. (20), and (21) as

$$\Lambda_{MH} = \Lambda_{MH}^{RG} + \Lambda_{MH}^{DD} \quad (22)$$

I. Correspondent Node

The total cost of each CN are due to the query message exchanged with CLM, RR messages and data delivery cost.

1) Query message: Each CN sends query messages to the HA for each association with the MH. Since the session arrival rate is λ_s, the transmission cost per second on CN for this query message is

$$\Lambda_{CN}^{QR} = 2\delta_Q\lambda_s \quad (23)$$

2) Return routability messages: Every CN processes return routability messages sent by the MH so that malicious hosts cannot steal a session. So the cost on CN is given by,

$$\Lambda_{CN}^{RR} = \frac{4\delta_{RR}}{T_r} \quad (24)$$

3) Data delivery cost: In each session, a file of size α is transferred from the CN to the MH. Since session arrival rate is λ_s, then packet delivery cost on CN per unit time can be obtained as

$$\gamma_{CN}^{DD} = \lambda_s \left\lceil \frac{\alpha}{\kappa} \right\rceil (\delta_{DT} + \delta_{DA}) \quad (25)$$

4) Total Cost on each CN: Therefore, the total cost on each CN can be obtained by adding Eqns. (23), (24) and (25):

$$\Lambda_{CN} = \Lambda_{CN}^{QR} + \Lambda_{CN}^{RR} + \Lambda_{CN}^{DD} \quad (26)$$

J. 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, local registration of MHs, 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 (HA-MR or HA-MH). 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-MR or HA-MH is $2N_c(h_p + h_{in} + h_p)\delta_Q\lambda_s$. The searching cost in the HA-MR is $(\omega_l + \omega_f)N_c\psi\lambda_s \log_2(N_r + N_l + N_f)$ and that in HA-MH is $\omega_v N_c \psi\lambda_s \log_2 N_v$. Hence, the cost of the network for the query messages from the CNs is,

$$\Lambda_{Net}^{QR} = \lambda_s N_c \Big[2\delta_Q(2h_p + h_{in}) + \psi(\omega_l + \omega_f) \times \log_2(N_r + N_l + N_f) + \psi\omega_v \log_2 N_v \Big] \quad (27)$$

2) Local registration messages: Every subnet crossing by the MH (in every T_l sec) within a MR region, triggers a local registration message to be sent to the MR. This involves transmission cost in one wireless hop. In addition, processing cost is incurred at the MR for updating the local location database.

$$\Lambda_{Net}^{LR} = N_m \frac{2\sigma\delta_R + \gamma_r}{T_l} \quad (28)$$

3) Return routability messages: The RR messages are sent every T_r second by the MRs (on behalf of the MNNs) to HA (either HA-MR or HA-MH) 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:

$$\Lambda_{Net}^{RR} = 2\delta_{RR}\Big((h_p + h_{in} + h_p + \sigma) + (h_p + h_{in} + h_p) + (h_p + h_{in} + h_p + \sigma)\Big) \times \frac{N_c}{T_r} \quad (29)$$

4) Location updates: After each handoff, each MRs and LMNs send LU to the HA-MR and VMNs send LU to HA-MH 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-MR}^{LK} at the HA-MR. 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,

$$\Lambda_{Net}^{LU} = 2N_r\delta_L\eta_t(h_p + h_{in} + h_p + \sigma) + 2(N_l + N_v)\eta_r \times \Big((\delta_L + \delta_{TH})(h_p + h_{in} + h_p + 2\sigma) + \gamma_t\Big) + (\eta_t N_r + \eta_r N_l)\Psi_{HA-MR}^{LK} + \eta_t N_v \psi \log_2 N_v \quad (30)$$

5) 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,

$$\Lambda_{Net}^{BU} = 2N_c\eta_r(\omega_l + \omega_v)\Big[(h_p + h_{in} + h_p + 2\sigma) \times (\delta_B + \delta_{TH}) + \gamma_t\Big] \quad (31)$$

6) Data delivery cost: The first data packet in a session goes through the HA (with tunneling) whereas the rest of the packets, that is, $\left(\left\lceil \frac{\alpha}{\kappa} \right\rceil - 1\right)$ packets use direct route (without tunneling). 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 HA-MR and HA-MH. Thus, the costs related to data delivery and processing by the network are given by

$$\Lambda_{Net}^{DD} = \lambda_s N_c\Big[\Big((h_p + h_{in} + h_p + 2\sigma) + (2h_p + h_{in})\Big) \times (\delta_{DT} + \delta_{DA} + 2\delta_{TH}) + 2\gamma_t + 2\omega_v\psi\log_2 N_v + 2\Psi_{HA-MR}^{LK}\Big] + N_c\lambda_s\left(\left\lceil\frac{\alpha}{\kappa}\right\rceil - 1\right)\Big[\Big((h_p + h_{in} + h_p + 2\sigma)\Big)(\delta_{DT} + \delta_{DA})\Big] \quad (32)$$

7) Total cost of the network: Therefore, the total cost of the complete network due to NEMO protocol can be obtained by adding Eqns. (27), (28), (29), (30), (31), and (32),

$$\Lambda_{Net} = \Lambda_{Net}^{QR} + \Lambda_{Net}^{LR} + \Lambda_{Net}^{RR} + \Lambda_{Net}^{LU} + \Lambda_{Net}^{BU} + \Lambda_{Net}^{DD} \quad (33)$$

K. Efficiency

In this section, we define a new metric (efficiency) for the mobility protocol as well as the entities of the network.

a) NEMO protocol: Efficiency of a NEMO 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:

$$\Lambda^{DD} = N_c\lambda_s\left\lceil\frac{\alpha}{\kappa}\right\rceil(h_p + h_{in} + h_p + 2\sigma)\delta_{DT} \quad (34)$$

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

$$\zeta^{NEMO} = \frac{\Lambda^{DD}}{\Lambda_{Net}} \quad (35)$$

b) Mobility entities: We define efficiency of an entity as the percentage of usage of its resources due to the transmission of payload (data). Thus the efficiency of HA-MR can be obtained as follows:

$$\zeta^{HA-MR} = \frac{N_c\lambda_s\delta_{DT}}{\Lambda_{HA-MR}} \quad (36)$$

Similarly, we can compute the efficiencies of HA-MH, MR, MH and CN using the following equations:

$$\zeta^{HA-MH} = \frac{\omega_v N_c\lambda_s\delta_{DT}}{\Lambda_{HA-MH}} \quad (37)$$

$$\zeta^{MR} = \frac{\sigma\lambda_p\delta_{DT}}{\Lambda_{MR}} \quad (38)$$

$$\zeta^{MH} = \frac{N_c^m\sigma\lambda_s\left\lceil\frac{\alpha}{\kappa}\right\rceil\delta_{DT}}{\Lambda_{MH}} \quad (39)$$

$$\zeta^{CN} = \frac{\lambda_s\left\lceil\frac{\alpha}{\kappa}\right\rceil\delta_{DT}}{\Lambda_{CN}} \quad (40)$$

V. 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 default values of the parameters used to obtain the numerical results are shown in Table ???. We have considered a large mobile network with the number of MNNs around 270 which is common onboard a train or ship. Values of the parameters related to the file-size, packet-size, session arrival rates and the proportionality constant for the wireless network are taken from [12], [22]. Transmission costs are relative and determined based on the packet size assuming unit cost per 100 bytes. Similarly, processing costs are determined assuming unit cost per 100 bytes. The transmission and processing costs are determined following the technique used in [19], [32]. For the lookup cost, we assume a logarithmic time for the lookup with the proportionality constant as the processing cost per entry.

The values for the system parameters have been taken from the previous works [12], [22]: δ_L = 0.6, δ_B = 0.6, δ_Q = 0.6, δ_R = 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, $N_c = N_{mnn}$, h_{in}= 5, h_p= 1, T_r = 70s, T_e = 60s, ψ = 0.3, α = 10Kb, and κ = 576b, N_r = 20, N_f = 70, N_l = 100, N_v = 100; N_m = 200;

A. Total cost on HA-MR

In Fig. 2(a), the total cost of the HA-MR is shown for varying number of mobile hosts and different subnet residence times. Here we have used equal number of LMNs and VMNs, that is, $N_v = N_l = \frac{1}{2}N_m$. and the values used for N_f and N_r are 100 and 20, respectively. It is found that total cost of HA-MR 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-MR 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-MR.

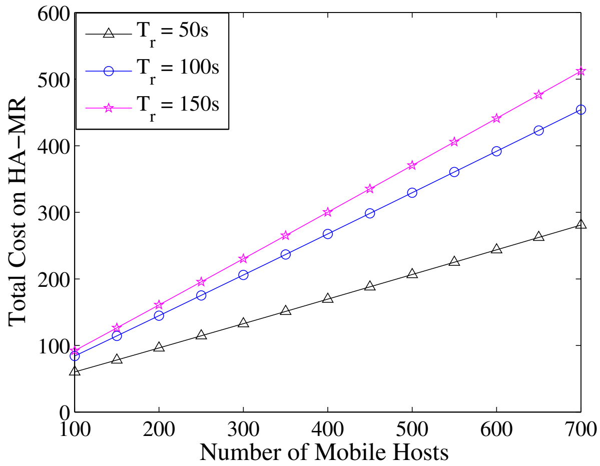
B. Total cost on HA-MH

Fig. 3(a) shows the impact of number of VMNs on the total cost of HA-MH. We have varied total number of CNs communicating with the MNNs for this graph. As number of VMNs increases in the mobile network, data packets are sent through the HA-MH along with higher number of LU and RR messages. In addition, higher number of CNs implies in higher query messages exchanged between HA-MH and CN, thus producing higher cost for HA-MH.

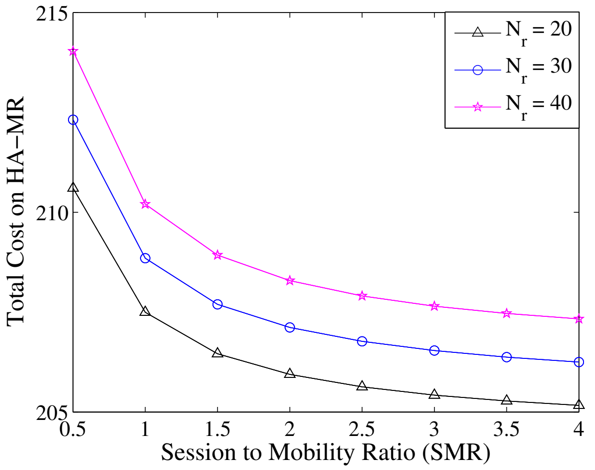
Fig. 3(b) shows the impact of SMR on the total cost of the HA-MH for different number of VMNs. Total cost decreases with higher SMR values (that is, when mobility rate of MN is low). The changes of total cost is very small as the total cost is dominated by the data delivery cost which is independent of subnet residence time.

C. Total cost on each MR

In Fig. 4(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. 4(b),



(a)



(b)

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

the impact of SMR on the total cost of each MR is shown for varying session lengths. Higher session 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.

D. Total cost on each MH

In Fig. 5(a), the total cost of each MH is shown for varying number of CNs communicating with it and for different session lengths. Increase in number of CNs per MH results in higher data delivery cost, thereby producing more cost on the MH. Similar thing happens for higher values session lengths. In Fig. 5(b), the impact of SMR on the total cost of each MH is shown for various T_l, i.e, the subnet residence time of a MH under a MR-region in the mobile network. Higher values of T_l produces less registration messages, thereby reducing the total cost. The total cost is found to be invariant of SMR due to the dominance of data delivery cost in each MH.

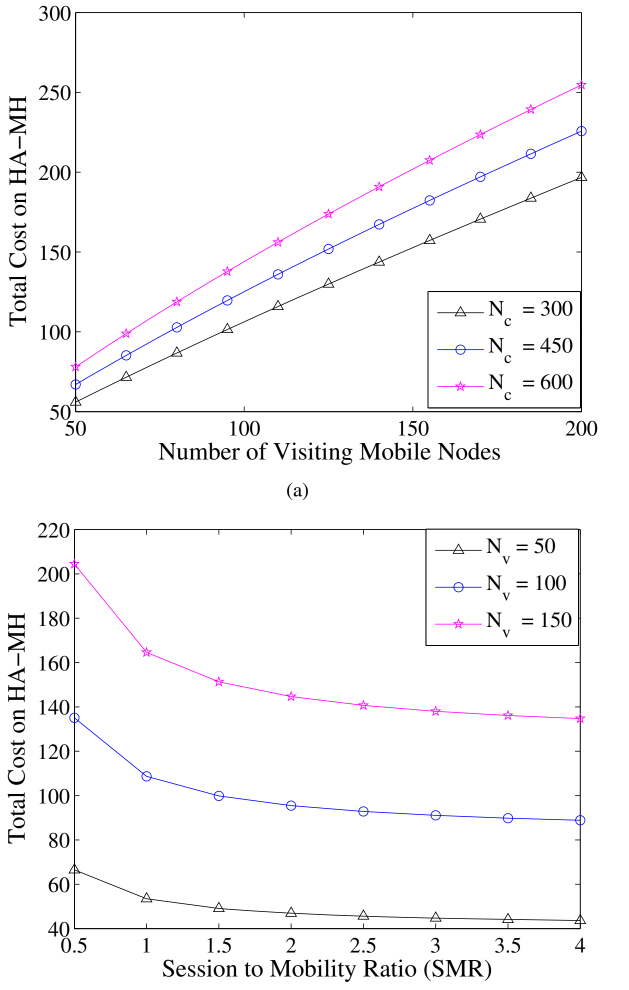


Fig. 3. (a) Impact of number of VMNs on the total cost of the HA-MH for different number of CNs, (b) Impact of SMR on the total cost of the HA-MH for different number of VMNs.

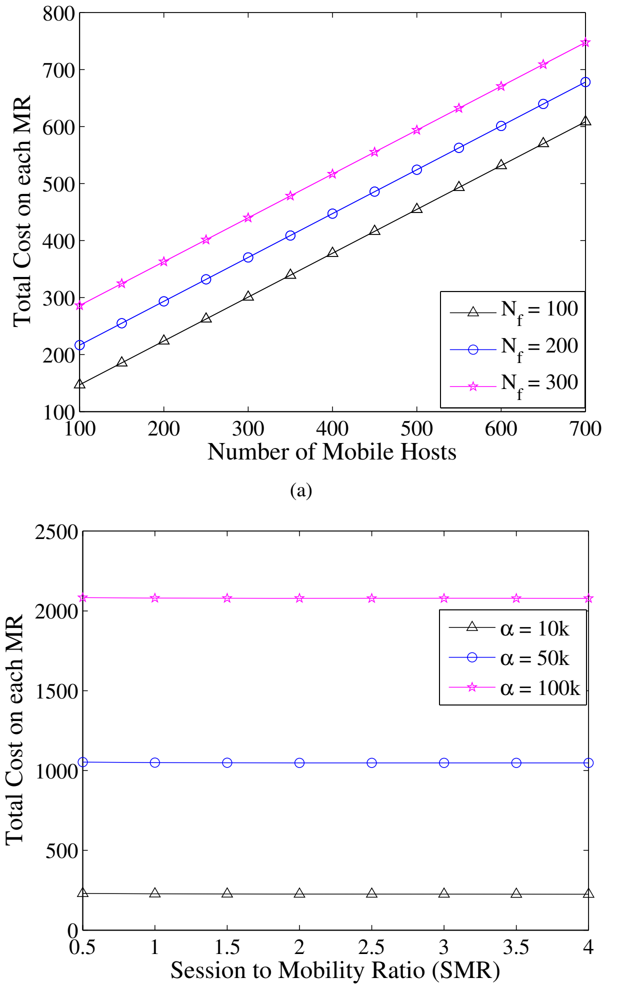


Fig. 4. (a) Impact of number of mobile hosts on the total cost of each MR for different number of LFNs, (b) Impact of SMR on the total cost of each MR for different session lengths.

E. Total cost on each CN

In Fig. 6(a), the total cost of each CN is shown for varying session arrival rates and session lengths. Higher session arrival rates causes more query messages to be sent to the CN, resulting in the increase of total cost on each CN. Higher session lengths causes higher packet delivery costs, thereby generating higher cost on each CN.

In Fig. 6(b), the total cost of each CN is shown for varying subnet residence times and session arrival rates. The total cost increases for higher session arrival rates, as the CN sends more query messages to the HA, in addition to the higher data delivery cost. However, the total cost on each CN reduces very slowly with higher subnet residence times, as the magnitude of lower return routability cost is not quite visible due to the more dominant data delivery cost.

F. Cost on Complete Network

Fig. 7(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 inœuences all the costs of the network.

In Fig. 7(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.

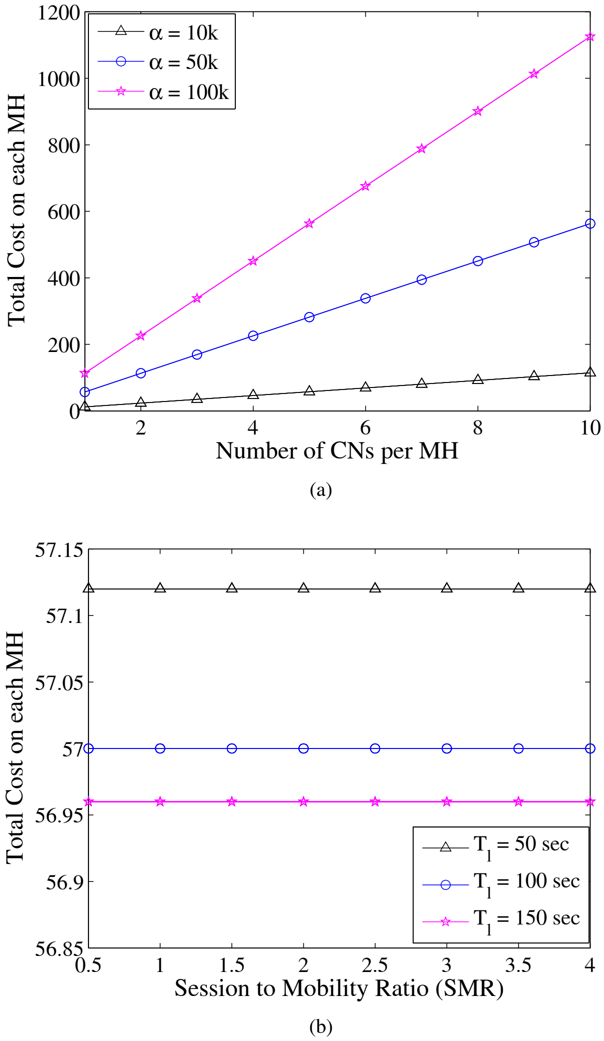


Fig. 5. (a) Impact of number of CNs per MH on the total cost of each MH for different session lengths, (b) Impact of SMR on the total cost of each MH for subnet residence times inside a MR-region.

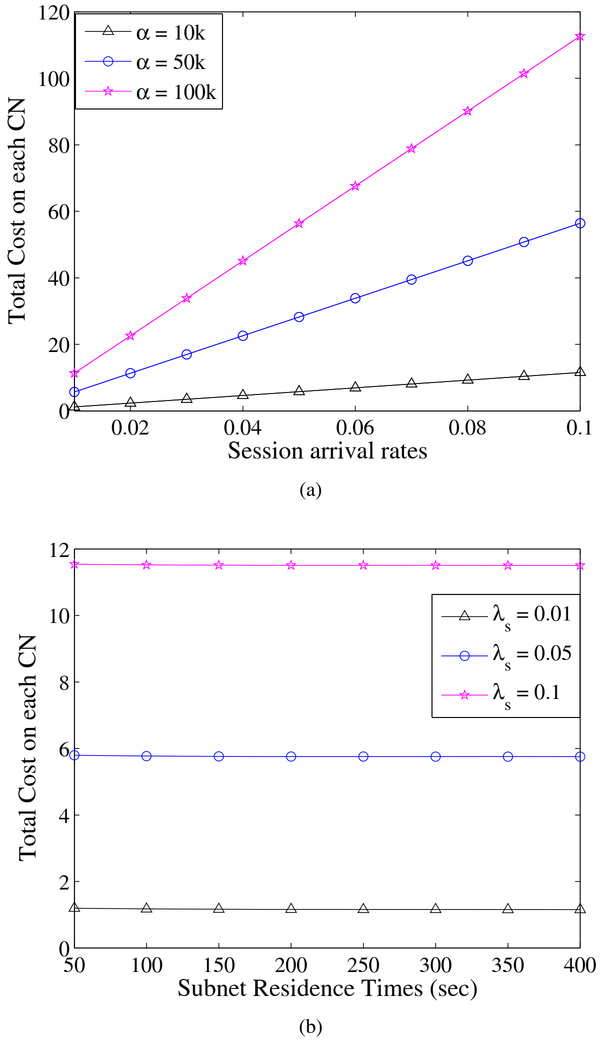


Fig. 6. (a) Impact of session arrival rates on the total cost of each CN for different session lengths, (b) Impact of subnet residence times on the total cost of each CN for different session arrival rates.

G. Efficiency of NEMO

Fig. 8(a), the efficiency of NEMO is shown for varying number of mobile hosts in the network with different number of hops in the Internet. Increased number of mobile hosts causes higher signaling costs, such as, location updates, binding updates, query cost. Hence the efficiency drops for higher number of nodes. Moreover, with more number of Internet hops, these signaling costs increases, thereby producing lower efficiency of NEMO.

In Fig. 8(b), the efficiency of NEMO is shown as a function of SMR for different session lengths. Higher session lengths causes higher efficiency of NEMO due to higher data volume. On the other hand, higher SMR (i.e., lower speed of MN) causes less signaling traffic, thereby causing higher efficiency.

H. Efficiency of HA-MR

Fig 9(a) shows the efficiency of HA-MR as a function of number of MHs for various subnet residence times. As we can see that the efficiency of HA-MR is much less than that of the NEMO protocol (see Fig. 8(a)) since HA-MR is highly involved in signaling which makes its (data) efficiency much less than the network. The pattern of this graph is similar to Fig. 8(a).

In Fig. 9(b), the efficiency of HA-MR as a function of SMR for different number of MRs in the network. Higher number of MRs produces more binding updates and refreshing binding updates, thereby reducing the efficiency. Moreover, the higher SMR value produces higher efficiency due to lower signaling traffic.

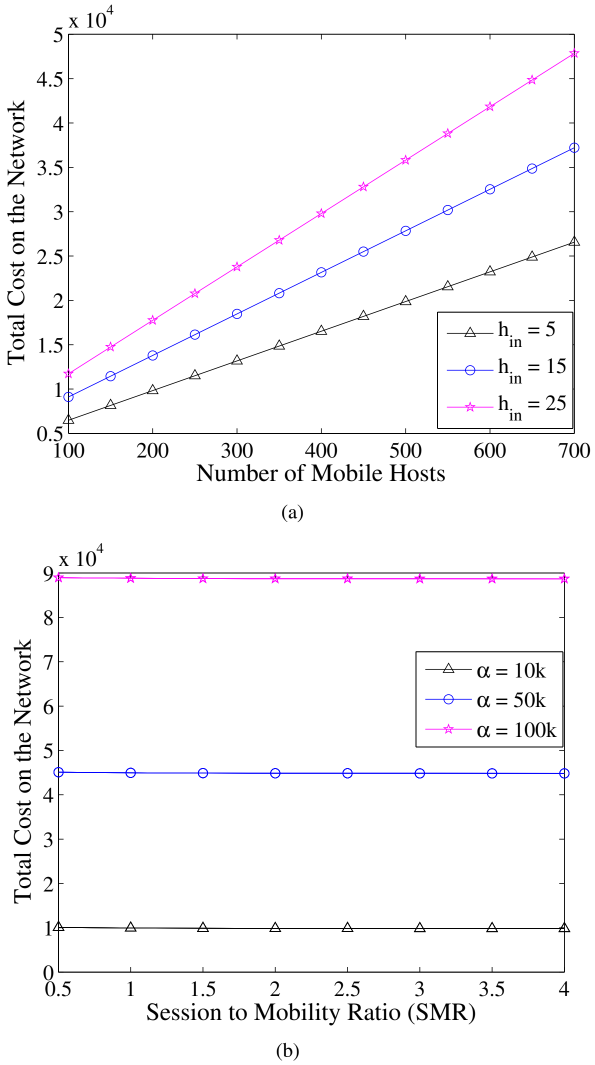


Fig. 7. (a) Impact of number of mobile hosts on the total cost of the network for different number of hops in Internet, (b) Impact of SMR on the total cost of the network for different session lengths.

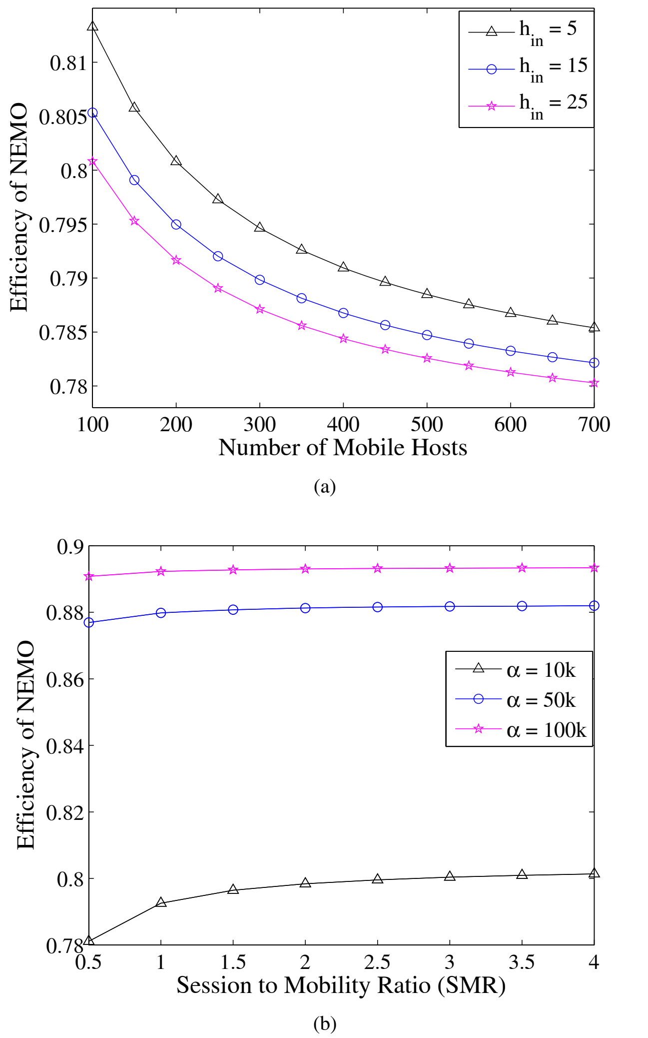


Fig. 8. (a) Efficiency of NEMO vs. number of MHs for different number of hops in Internet, (b) Efficiency of NEMO vs. SMR for different session lengths.

I. Efficiency of HA-MH

Fig. 10 shows the efficiency of HA-MH as a function of VMNs for different number of CNs. Higher values of N_c more query messages, and return routability message, thereby reducing the efficiency. With the increase of number of VMNs, the magnitude of signaling cost rises at a higher rate than the data delivery cost, producing lower efficiency of HA-MH. It can be noted that the efficiency of HA-MH is somewhat closer to that HA-MR as both serve as the HA of the nodes inside the mobile netowrk.

J. Efficiency of each MR

Fig. 11 shows the efficiency of each MR as a function of SMR for different session lengths. Higher session lengths produce higher (data) efficiency. In addition, the higher value of SMR (less mobility) causes efficiency to increase due to less signaling

K. Efficiency of each MH

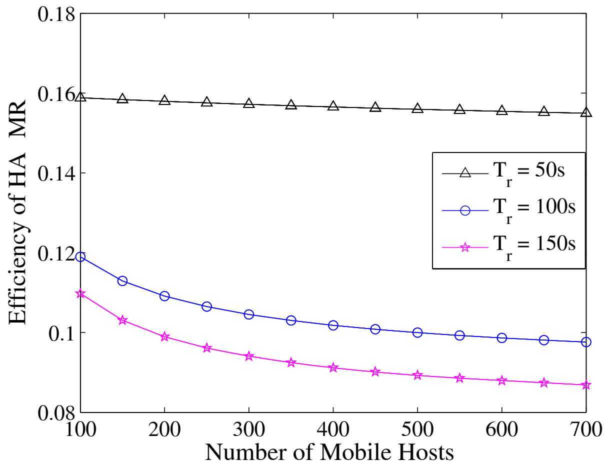
Fig. 12 shows the efficiency of each MH as a function of number of CNs (per MH) for different session lengths. Higher values of CNs and higher session lengths causes more data traffic in the network, thereby increasing the efficiency.

L. Efficiency of each CN

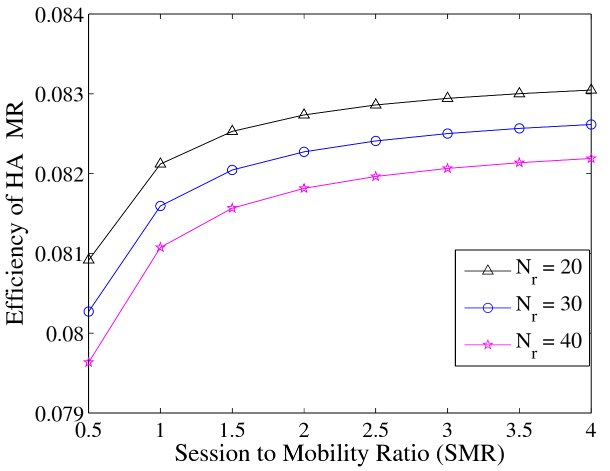
In Fig. 13, the efficiency of each CN is shown as a function of subnet residence times for various session arrival rates. Higher subnet residence times cause less signaling traffic, thereby producing higher efficiency. For λ_s, the opposite is true.

M. Discussion on Results

We have analyzed the impact of network size (number of MHs, LFNs, MRs), mobility rate (subnet residence times,



(a)



(b)

Fig. 9. (a) Efficiency of HA-MR vs. number of MHs for different subnet residence times, (b) Efficiency of NEMO vs. SMR for different number of MRs.

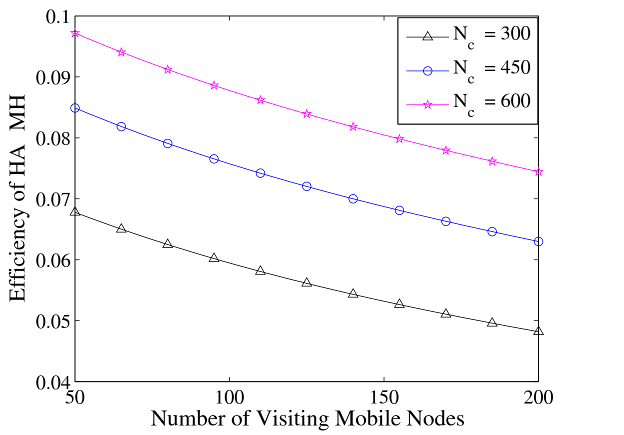


Fig. 10. Efficiency of HA-MH vs. number of VMNs for different number of CNs.

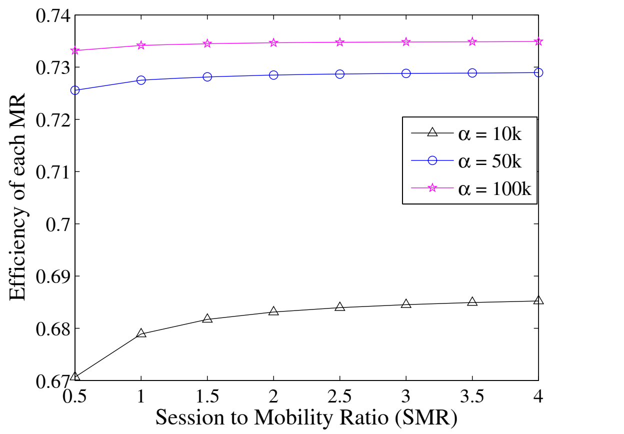


Fig. 11. Efficiency of MR vs. SMR for different session lengths.

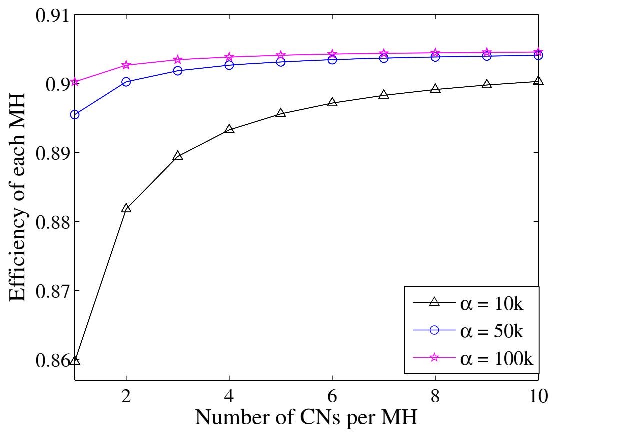


Fig. 12. Efficiency of MH vs. number of CNs for different session lengths.

SMR), traffic rate (session arrival rate), and data volume (session length) on the total costs and efficiencies of various mobility entities of NEMO protocol. 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 efficiency of the NEMO protocol is found to be much higher than that of home agents (HA-MR and HA-MH) as these entities manage most of the mobility signaling whereas the efficiencies of mobile hosts and correspondent nodes are much higher due to their less involvement in signaling.

VI. Conclusion

In this paper, we have developed mathematical models to estimate the total costs and data transmission efficiencies

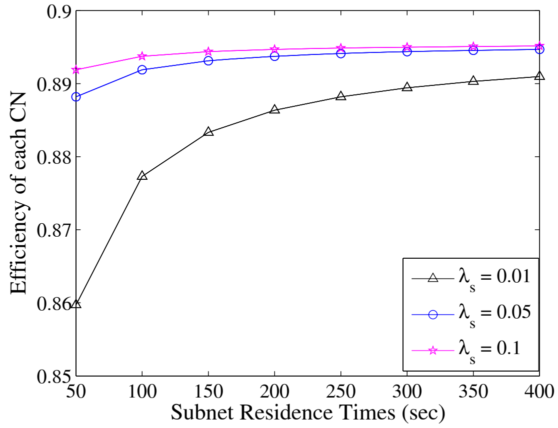


Fig. 13. EfŒciency of CN vs. subnet residence times for different session arrival rates.

of various mobility management entities of NEMO BSP, considering all possible costs that inœuence their operation. We have presented numerical results to show the impact of network size, mobility rate, trafŒc rate, and data volume on the total costs and efŒciencies of these mobility entities as well as the NEMO protocol. 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 and can be used to compare with other mobility protocols.

REFERENCES

[1] V. Devarapalli, R. Wakikawa, A. Petrescu, and P. Thubert, NEtwork MObility (NEMO) basic support protocol,ƒ RFC 3963, Jan 2005.
[2] D. Johnson, C. E. Perkins, and J. Arkko, Mobility support in IPv6,ƒ IETF RFC 3775, Jun 2004.
[3] J. Xie and I. Akyildiz, A novel distributed dynamic location management scheme for minimizing signaling costs in Mobile IP,ƒ *IEEE Transactions on Mobile Computing*, vol. 1, no. 3, pp. 163˘175, Jul 2002.
[4] S. Fu and M. Atiquzzaman, Signaling cost and performance of SIGMA: A seamless handover scheme for data networks,ƒ *Wireless Communication and Mobile Computing*, vol. 5, no. 7, pp. 825˘845, Nov 2005.
[5] C. Makaya and S. Pierre, An analytical framework for performance evaluation of IPv6-based mobility management protocols,ƒ *IEEE Transactions on Wireless Communications*, vol. 7, no. 3, pp. 972˘983, Mar 2008.
[6] S. Galli, A. McAuley, and R. Morera, An analytical approach to the performance evaluation of mobility protocols: The overall mobility cost case,ƒ in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Barcelona, Spain, Sept 5-8, 2004.
[7] B. Singh, Signaling cost analysis in mobile IP networks,ƒ in *IET Conference on Wireless, Mobile and Multimedia Networks*, Mumbai, India, Jan 11-12, 2008.
[8] A. Diab, A. Mitschele-Thiel, and F. Liers, Estimation of the cost resulting from mobility management protocols using a generic mathematical model,ƒ in *ACM International Conference on Modeling, Analysis, and Simulation of Wireless and Mobile Systems*, Vancouver, BC, Canada, Oct 27-31, 2008.
[9] J. Xie and U. Narayanan, Performance analysis of mobility support in IPv4/IPv6 mixed wireless networks,ƒ *IEEE Transactions on Vehicular Technology*, vol. 59, no. 2, Feb 2010.
[10] J.-H. Lee, T. Ernst, and T.-M. Chung, Cost analysis of IP mobility management protocols for consumer mobile devices,ƒ *IEEE Transactions on Consumer Electronics*, vol. 56, no. 2, May 2010.
[11] H. Soliman, C. Castelluccia, K. E. Malki, and L. Bellier, Hierarchical Mobile IPv6 mobility management (HMIPv6),ƒ IETF RFC 5380, Oct 2008.
[12] A. S. Reaz, P. K. Chowdhury, and M. Atiquzzaman, Signaling cost analysis of SINEMO: Seamless End-to-End Network Mobility,ƒ in *First ACM/IEEE International Workshop on Mobility in the Evolving Internet Architecture*, San Francisco, CA, Dec 1, 2006.
[13] K. A. Jalil and J. Dunlop, Signaling cost analysis of PDE-NEMO,ƒ in *World Congress on Science, Engineering and Technology*, Penang, Malaysia, Feb 25-27, 2009.
[14] H. Lim, D. Lee, T. Kim, and T. Chung, A model and evaluation of route optimization in nested NEMO environment,ƒ *IEICE Transaction on Communications*, vol. E88-B, no. 7, pp. 2765˘2776, Jul 2005.
[15] S. Fu and M. Atiquzzaman, SIGMA: A Transport Layer Handover Protocol for Mobile Terrestrial and Space Networks,ƒ *e-Business and Telecommunication Networks, Springer*, pp. 41˘52, 2006.
[16] K. S. Munasinghe and A. Jamalipour, Analysis of signaling cost for a roaming user in a heterogeneous mobile data network,ƒ in *IEEE Globecom*, New Orleans, LA, Nov 26-30, 2008.
[17] J.-H. Lee, S. Gundavelli, and T.-M. Chung, A performance analysis on route optimization for Proxy Mobile IPv6,ƒ in *IEEE International Conference on Communications, ICC 2009*, Dresden, Germany, Jun 14-18, 2009.
[18] P. Chowdhury, M. Atiquzzaman, and W. Ivancic, SINEMO: An IP-diversity based approach for network mobility in space,ƒ in *Second IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)*, Pasadena, CA, Jul 17-21, 2006.
[19] A. Z. M. Shahriar, M. S. Hossain, and M. Atiquzzaman, A cost analysis framework for NEMO preŒx delegation-based schemes,ƒ University of Oklahoma, Technical report, TR-OU-TNRL-10-101, January 2010, http://cs.ou.edu/∼netlab/.
[20] M. S. Hossain, M. Atiquzzaman, and W. Ivancic, Cost analysis of NEMO protocol entities,ƒ in *International Conference on Computer and Information Technology*, Dhaka, Bangladesh, Dec 23-25, 2010.
[21] M. S. Hossain and M. Atiquzzaman, Stochastic properties and application of city section mobility model,ƒ in *IEEE Global Communications Conference (GLOBECOM)*, Honolulu, HI, Nov 30- Dec 4, 2009.
[22] P. Chowdhury, A. Reaz, M. Atiquzzaman, and W. Ivancic, Performance analysis of SINEMO: Seamless IP-diversity based Network Mobility,ƒ in *IEEE ICC 2007*, Glasgow, Scotland, Jun 24-28, 2007.

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William Ivancic has over twenty-Œve years experience in network and system engineering for communication applications, communication networking research, state-of-the-art digital, analog and RF hardware design and testing. He currently is a senior research engineer at NASA s Glenn Research Center where he directs the hybrid satellite/terrestrial networking, space-based Internet, and aeronautical Internet research. He has lead research efforts to deploy commercial-off-the-shelf (COTS) technology into NASA missions including the International Space Station and Shuttle. Mr. Ivancic is also performing joint research with Cisco System on advance routing research for space-based and aeronautic-based networks. Of particular interest is large scale, secure deployment of mobile networks including mobile-ip and mobile router technology. Recent accomplishments include being Œrst to demonstrate and deploy secure mobile networks in an operational government network, the US Coast Guard, Œrst to deploy Mobile-IP Mobile networking on a space-based asset, the Cisco router in Low Earth Orbit (CLEO, Œrst to deploy Internet Protocol security (IPsec) and Internet Protocol version 6 on a space-base asset, and Œrst to deploy delay/disruption network technology bundling protocol in space.

Mr. Ivancic is also the principal of Syzygy Engineering, a small consulting company specializing in communications systems and networking as well as advanced technology risk assessment. Mr. Ivancic is currently performing research and development on Identity-based security and key and policy management and distribution for tactical networks - particularly mobile networks.