A Cost Analysis Framework for NEMO Prefix Delegation-Based Schemes

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Abstract—Network Mobility (NEMO) efficiently manages the mobility of multiple nodes that moves together as a mobile network. A major limitation of the basic protocol in NEMO is the inefficient route between end hosts. A number of prefix delegation-based schemes have been proposed in the literature to solve the route optimization problem in NEMO. Approaches used by the schemes trade off delivery of packets through the partially optimized route with signaling and other processing overheads. Cost of delivering packets through the partially optimized route along with signaling and processing cost need to be measured to find out the gain from tradeoff. However, cost analysis performed so far on NEMO protocols consider only the cost of signaling. In this paper, we have developed analytical framework to measure the costs of the basic protocol for NEMO, and four representative prefix delegation-based schemes. Our results show that cost of packet delivery through the partially optimized route dominates over other costs. Therefore, optimizing the route completely is preferable to reduction of signaling as far as cost of network mobility is concerned. Our cost analysis framework will help in decision making to select the best route optimization scheme depending on the load imposed by the scheme on the infrastructure.

Index Terms—NEMO, route optimization, prefix delegation, cost analysis.

1 Introduction

To efficiently manage the mobility of multiple IP-enabled hosts moving together, such as hosts in a vehicle, Internet Engineering Task Force proposed NEtwork MObility (NEMO) [1]. Hosts, and mobile routers (MRs), managing the mobility of hosts, constitute the mobile network. The basic protocol called NEMO Basic Support Protocol (BSP) enables communication with the mobile network through a bidirectional tunnel between mobile routers and a router called home agent (HA) in the home network [1]. Tunneling results in inefficient routing problem between end hosts [2].

A number of route optimization (RO) schemes [3], [4], [5] have been proposed to solve the inefficient routing problem of NEMO. The schemes have been classified and compared [4] based on the approaches used for route optimization. Among them, prefix delegation (PD)-based schemes have been found to perform better than other schemes in terms of route efficacy and overheads [4]. In prefix delegation-based schemes, the prefix of the foreign network is made available inside the mobile network so that nodes inside the mobile network can obtain addresses from the prefix. Although prefix delegation-based schemes [6], [7], [8], [9], [10], [11], [12], [13], [14] follow a common approach of delegating prefixes, they differ in degree of optimizing route and the amount of signaling depending on the type of nodes, and in the way prefix is delegated. These differences affect the performance as well as the overheads of the schemes.

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In NEMO, *network parameters* (e.g., network size, mobility rate, traffic rate, and distances from mobility agents) influence signaling and routing overheads, resulting from the prefix delegation-based schemes. These overheads include delivery of packets through the partially optimized route, updating home agents about the change of location, sending updates to hosts with ongoing communication, processing and look up by mobility agents, and the delegation of prefix. These overheads cost the transmission and processing power at the network (e.g., routers in the network) between end hosts, and at the *mobility management entities*, such as home agents and mobile routers. We use the term *network mobility cost* to refer to those costs incurred for sending packets to the hosts inside a mobile network. The notion of costs used in this paper refers to the use of resources mentioned in [2], [3], and is a number-only relative measure for the schemes; the higher the number, the higher the cost.

Cost analysis of NEMO protocols has been performed in [15], [16]. They present the signaling cost of NEMO BSP or a similar protocol by constructing analytical models that measure the transmission and processing costs incurred by the signaling packets. Lim et al. [4], [17] performed a cost analysis for the general approaches used for route optimization in terms of the memory consumption and the number of signaling. However, the analysis presented in [4], [15], [16], [17] is unable to show the variations in the costs among the prefix delegation-based schemes adequately. Our *objective* is to perform a cost evaluation of the prefix delegation-based schemes by developing a framework that considers the tradeoff and the differences among the schemes. In addition, unlike any previous work on cost analysis of mobility protocols, we analyze the costs incurred at the mobility entities that are hubs for mobile communications. We believe this to be the *first such work* to evaluate the impact of network parameters on the network and mobility management entities for prefix delegation-based schemes.

In this paper, we have selected four representative prefix delegation-based schemes for evaluation: Simple Prefix Delegation (SPD) [6], Mobile IPv6-based Route Optimization (MIRON) [10], Optimal Path Registration (OPR) [12], and ad hoc protocol-based route optimization (ad-hoc-based) [11]. We have *developed* analytical cost models to measure the network mobility costs on mobility and network entities. Unlike previous works, we have performed entitywise cost evaluation which is essential to show the suitability of a scheme based on the availability of resources since most of the mobility management entities are subject to limited resources. Based on the cost models, we have presented a comparative study of NEMO BSP and the four prefix delegation schemes.

The *contributions* of our work are: 1) developing analytical framework to measure network mobility costs of the prefix delegation-based schemes, and 2) comparative analysis of the schemes based on the network mobility costs. Analytical models developed in this paper will provide useful framework to analyze other route optimization schemes, and can aid in decision making to select the best route optimization scheme depending on the load imposed by the scheme on the infrastructure. Our results lead to the interesting conclusion that optimizing the route completely is preferable to reduction of signaling as far as cost of network mobility is concerned. Results presented in this paper will complement the results of performance evaluation of the schemes in deciding the approach to adopt for route optimization in NEMO.

The rest of the paper is organized as follows. A literature review of cost analysis of NEMO is given in Section 2. NEMO architecture, NEMO BSP and prefix delegation-based route optimization schemes are summarized in Sections 3 and 4. Analytical cost models are presented in Section 5. Section 6 presents the results and comparison among the schemes. Finally, Section 7 has the concluding remarks.

2 Literature Review

A few cost analyses have been performed for the host mobility protocols. Fu and Atiquzzaman [18] present a cost analysis of HMIPv6 and Seamless IP-diversity-based Generalized Mobility Architecture (SIGMA). Xie and Akyildiz [19] perform cost analysis of Mobile IP to minimize the signaling cost while introducing a novel regional location management scheme. Makaya and Pierre [20] present an analytical model for the performance and cost analysis of IPv6-based mobility protocols (i.e., MIPv6, HMIPv6, FMIPv6, and F-HMIPv6). These cost analysis frameworks on host mobility protocols are not adequate for NEMO protocols since NEMO has more parameters and cost components, such as the number and types of nodes in the mobile network, nesting levels, cost of route optimization approaches (e.g., prefix delegation cost).

The load on the infrastructure imposed by NEMO BSP due to tunneling and the consumption of the network resources by the route optimization schemes have been discussed in RFC 4888 [2] and RFC 4889 [3], respectively. There have been a few works on cost analysis of NEMO BSP and similar protocols. Reaz et al. [15] present a cost analysis of a transport layer-based network mobility protocol called SINEMO [21] and NEMO BSP [1]. Their objective was to compare the signaling cost of the protocols by developing analytical models that consider transmission and processing costs incurred at the mobility and network entities. However, the signaling cost presented in [15] does not consider nesting in NEMO. Jalil and Dunlop [16] perform a signaling cost analysis of NEMO using the similar models developed in [15]. Although the cost models presented in [16] considers nesting, they are not general enough in terms of nesting.

Lim et al. [4], [17] perform the cost analysis of NEMO route optimization schemes. They classify the schemes from two different perspective in the two works, and perform the cost analysis which focuses on the general features of each class. The cost metrics used in their analysis are the memory consumption and the amount of signaling. In addition to the cost indicating the resource usage, additional latency for obtaining addresses and sending packets has been computed in [4], [17]. Based on the analysis, comparisons among the classes, and their suitability for particular scenarios has been presented. We provide further analysis of the cost for a selected class of schemes that are a subset of the schemes mentioned as the A&S approach in [4] or TCA-based approach in [17]. We named these schemes as prefix delegation-based schemes in [5].

Prefix delegation-based schemes differ in the degree of route optimization, resulting in the variation in the amount of signaling depending on the node types. In addition, the method of prefix delegation differs among the schemes. Although the analysis presented in [4], [17] show the general cost-characteristics of the PD-based schemes, it is unable to show the differences in the cost resulting from the above-mentioned differences. We have performed a detail analysis of the PD-based schemes to show the differences in their costs. Moreover, unlike previous works, we have performed the entitywise analysis to show the suitability of a scheme based on the availability of resources in various entities that are engaged in mobility management. Such analysis is useful when resource limitations exist in a particular entity rather than in the entire network. A comparative summary of the cost analysis performed so far along with our approach is presented in Table 1. The costs (except memory) mentioned in Table 1 are explained in Section 5.1 where location update and session continuity cost comprise signaling cost.

Performance evaluation of the PD-based schemes have been performed in terms of throughput, end-to-end delay, handoff latency, header overhead, and memory consumption [6], [10], [11], [12], [22], [23]. To achieve better performance, the network mobility cost for the network and mobility entities may increase. Therefore, we present a comprehensive cost analysis of the PD-based schemes by developing cost models that consider nesting, and all types of nodes in the mobile network. Unlike any previous cost analysis for NEMO, we present the costs for mobility entities that are hubs of all communications. Our analysis

TABLE 1
Summary of Cost Analysis-Related Work on NEMO

Paper by citation #	Objective	Cost evaluated				Node type considered?	Entity-wise evaluation	Evaluation of prefix delegation schemes	
		Signaling (BU/BA)	Memory	Prefix delegation	Packet delivery			General feature	Individual scheme
2	Problems and load on the infrastructure due to tunneling	No	No	No	No	No	No	No	No
3	Classification of RO schemes and discuss the issues	No	No	No	No	No	No	No	No
4	Classification of RO schemes and evaluate performance	Yes	Yes	Yes	Yes	No	No	Yes	No
15	Signaling cost evaluation of SINEMO and NEMO	Yes	No	No	No	No	No	No	No
16	Cost evaluation of PDE-NEMO	Yes	No	No	Yes	No	No	No	No
17	Classification of RO schemes and evaluate performance	Yes	Yes	Yes	Yes	No	No	Yes	No
This work	Cost evaluation of PD schemes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes

can be used to measure the cost of achieving the performance gain by the schemes, and provide a framework for analyzing costs of other route optimization schemes.

3 NEMO

In this section, we summarize NEMO architecture and BSP to help the reader in understanding the rest of the paper.

3.1 NEMO Architecture

Fig. 1 shows the architecture of a mobile network [1]. Mobile Routers act as gateways for the nodes inside the mobile network, each called a Mobile Network Node (MNN). Different types of MNNs are—a Local Fixed Node (LFN) that does not move with respect to the mobile network, a Local Mobile Node (LMN) that usually resides in the mobile network and can move to other networks, and a Visiting Mobile Node (VMN) that gets attached to the mobile network from another network. LMNs and VMNs are MIPv6 capable, and we refer them as *mobile nodes* from this point onward. An MR attaches to another MR to form a nested mobile network. The MR, directly attached to the wired network through an Access Router (AR), is called the root-MR while MR1, MR2, etc., are nested under root-MR. Mobile nodes are also nested when they attach under an MR.

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. The HA is notified of the location of the MR, and redirects packets, sent by the Correspondent Node (CN) to MNNs. Although only one HA is shown in Fig. 1, MRs and mobile nodes in a mobile network may be registered to different HAs.

3.2 NEMO BSP

An MR is delegated a prefix [24] in its home network to advertise in its mobile network. MNNs obtain addresses from the advertised mobile network prefix. Packets, sent to that address, reach the HA that forwards the packets to the mobile network in home location. When a mobile network moves to a foreign network, the MR obtains a new address called Care-of-Address (CoA) from the foreign network, and sends a Binding Update (BU) to the HA informing the CoA. The HA intercepts packets sent to MNN's address obtained from the mobile network prefix, and tunnels them to the MR. A (child) mobile network [25], nested under another (parent) mobile network, obtains the CoA from the parent NEMO's prefix. Therefore, packets destined to child NEMO first go to the HA of the child NEMO and then to the HA of parent NEMO. Thus, packets are tunneled through multiple HAs resulting in inefficient route and header overhead. The route is inefficient due to the requirement of traversing through the HAs, resulting in a longer route than direct route between end hosts. Moreover, the HA has the load of forwarding all packets for mobile networks and nodes. Therefore, several route optimization schemes, based on various approaches, have been proposed. An overview of the PD-based schemes are presented in Section 4.

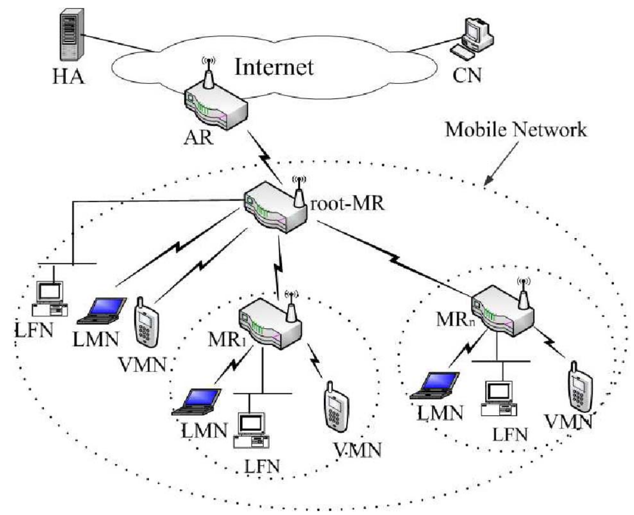

Fig. 1. Architecture of a mobile network.

4 Prefix Delegation-Based Schemes

In PD-based schemes, MNNs (except LFNs) obtain CoAs from the foreign network prefix, and uses MIPv6 [26] like route optimization where LMNs and VMNs send CoAs to CNs through BUs. A BU is sent to the HA and the CN whenever a new CoA is obtained, and periodically for refreshing. CNs use the CoAs to send packets directly (using an optimized tunnel [26]) to the foreign network where the MNNs are in. PD-based schemes vary in prefix delegation or CoA obtention process, and route optimization for MNNs. Four representative PD-based schemes are described in the following sections.

4.1 Simple Prefix Delegation

In this scheme [6], the prefix of the foreign network is hierarchically delegated inside the mobile network by the MRs through router advertisement. A new neighbor discovery option, called Delegated Prefix Option is proposed in this scheme, and is used by the MR to advertise the prefix for delegation. Thus, each MR incurs the overhead of performing functionalities (e.g., authentication, accounting, etc.) related to prefix delegation. Since LFNs are not MIPv6 capable, they are unable to optimize route. Therefore, packets for the LFNs go through a tunnel between the LFNs' MR and its HA.

4.2 MIPv6-Based Route Optimization (MIRON)

In MIRON [10], an MIPv6 capable MNN obtains a CoA from the foreign network using PANA [27] and DHCPv6. When the mobile network moves to a new network, the root-MR obtains a CoA using DHCPv6, and starts PANA reauthentication phase to inform the attached MNNs (except LFNs) that a new CoA has to be obtained. Attached MNNs (excepts LFNs) send DHCPv6 request which is conveyed up along the chain of intermediate MRs to the foreign network. The DHCPv6 reply, containing the CoA, follows the same path in the reverse direction to reach the MNN. To optimize route for attached LFNs, an MR sends BUs to CNs on behalf of LFNs. To send BU to CNs, MR needs to track the CN-LFN communications.

4.3 Optimal Path Registration

Unlike the other PD-based schemes, OPR [12] does not use MIPv6 route optimization. Prefixes of the foreign network are delegated hierarchically to MRs only through multicast router advertisements. After handoff, MRs obtain CoAs from the prefix, and send BUs to their HAs. MNNs other than MRs are transparent to the mobility of the network.

To optimize route for attached MNNs, MRs perform address translation using the delegated prefix. For address translation, MRs maintain a table where the information regarding the translated addresses of MNNs are stored. When a packet from an MNN is received, the MR searches the table for the translated address. If the address is found, the source address is replaced with the translated address, and the source address is put in a header called OPR header [12] which also carries information for the CN to register the translated address in the binding cache. Thus, no BU is required to be sent to CNs for route optimization. If the address is not found a translated address is created using the delegated prefix. For incoming packets from CNs, MRs do the reverse operations.

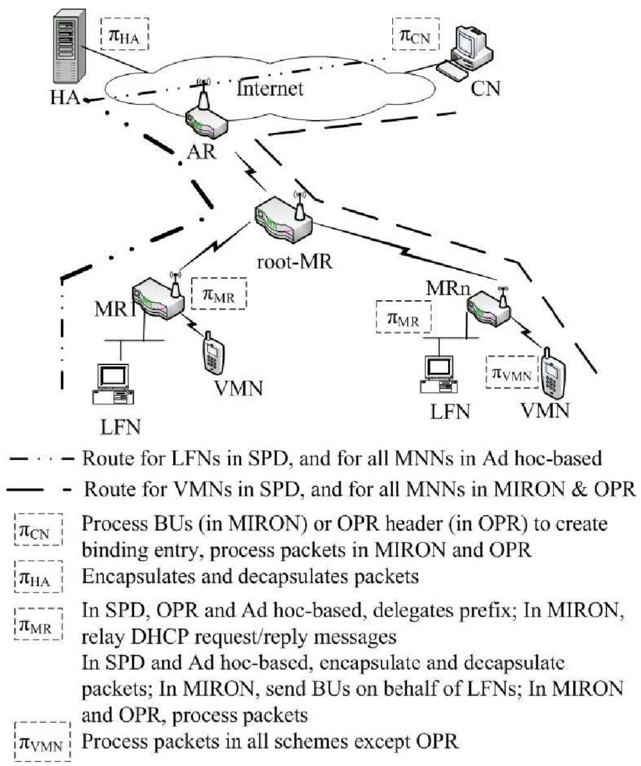

Fig. 2. The routes and major processing requirements for prefix delegation-based schemes.

4.4 Ad Hoc Protocol-Based (Ad-Hoc-Based)

Su et al. [11] proposes a scheme where an ad hoc protocol (e.g., AODV [28]) is used by the MRs to find the AR to use as the gateway to send packets to the wired network. In this scheme, in addition to MR's own router advertisement for its network, the router advertisement of the AR is broadcasted by the MRs to the attached MRs. After handoff, CoAs are obtained by the MRs from the router advertisement, and the route to the AR is discovered using AODV to send BUs. Other MNNs are transparent to the movement of the mobile network, and obtain addresses from the prefix of the mobile network. Therefore, mobile nodes do not need to send BUs due to the handoff of the mobile network. But MNNs' packets undergo one tunnel between the MR above and its HA.

Fig. 2 summarizes the routes used by MNNs and major processing required in the PD-based schemes. The processing at different entities are denoted by Π_{entity}, such as, Π_{HA}, Π_{CN}, etc.

5 Cost Analysis

This section presents costs to support NEMO for the four representative PD-based schemes using analytical models. The costs measure the amount of resources being used by the schemes to support NEMO. Our cost analysis resembles the analysis performed in [15], [18], [19]. Unlike [15], [18], [19], we introduce costs of prefix delegation or CoA obtention, and effects of nesting on costs that are unique for NEMO. We use a general NEMO architecture (as shown in Fig. 1) that includes LFNs, LMNs, VMNs, multiple visiting mobile networks, and multiple levels of nesting. We consider the cost to send refreshing BUs and the cost of packet delivery. In addition to finding costs incurred at the infrastructure including the mobile network, we show a entitywise cost evaluation. The HA and the root-MR have been chosen for the entitywise evaluation because all communications with the mobile network will be through these two entities. Therefore, resource consumptions at these entities are expected to be high, and may become a concern when the resource is limited. For tractability reasons, models were developed based on assumptions. Types of costs analyzed, assumptions, notations, and the models are presented in the following sections.

5.1 Types of Costs

We measure the following costs of the schemes:

- *Location update cost:* To maintain reachability, a node sends BUs to the HA to inform its current location whenever it obtains a CoA. Periodic BUs are sent for refreshing the binding entries. Resources (e.g., transmission and processing power, etc.), consumed by these BUs, comprise the location update cost.
- *Session continuity cost:* To continue session through an optimized route, BUs have to be sent to CNs whenever the mobile network changes the point of attachment. Resources consumed by these BUs, comprise this cost. OPR employs a technique (see Section 4.3) other than sending BUs to continue sessions, and the cost incurred by the technique are also included in this type of cost.
- *Packet delivery cost:* To send a packet to the mobile network, the HA has to perform a lookup to retrieve the CoA for tunneling toward the mobile network. In addition, HA and MR tunnel/detunnel packets. A measure of the processing and transmission power used for lookup and tunneling is given by the packet delivery cost. Moreover, transmission power required by original packets are also included in this cost.
- *Prefix/CoA obtention cost:* After handoff, prefixes/CoAs are obtained from the foreign network. Resources consumed by the control messages required to obtain prefixes/CoAs comprise this cost.

5.2 Assumptions

For tractability reasons, our models are based on the following assumptions:

- We consider the handoff of the mobile network as a whole. Intramobile network movements of MRs, and the movements of the mobile nodes inside the network are not considered. This assumption comply with the type of movement of a nested mobile network in a vehicle that actually motivated NEMO.
- Number of VMNs/LMNs and MRs registered with an HA are assumed to be higher than the number of VMNs/LMNs and MRs in the mobile network (by a factor α).
- We assume the worst possible scenario for the analysis, such as, all MNNs are communicating simultaneously, the CN of each session is different. These assumptions were also made in [15], [18].

TABLE 2
Some Expressions Defined to Simplify Equations

π_{lk}	$= \psi \log_2(\alpha(N_r + N_m))$
π_{bl}	$= \psi \log_2 N_c$ for VMNs and $\psi \log_2(N_f N_c)$ for MRs
λ_{cs}	$= N_c \lambda_s / S$
λ_{cp}	$= N_c \lambda_s F / P$
f_h	$= \left(1 + \lfloor \frac{T_r}{T_{lf}} \rfloor\right) / T_r$
f_r	$= \lfloor \frac{T_r}{T_{lf}} \rfloor / T_r$

5.3 Notations

To denote the cost terms, we have used the superscript X and the subscript Y to indicate the scheme and the type of cost, respectively. X will be replaced by N,S, M, O and A for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based schemes, respectively. Y will be replaced by T, LU, SC, PD, and CO for total, location update, session continuity, packet delivery and prefix/CoA obtention costs, respectively. Some notations are used to denote expressions for simplification of models' representations, and are presented in Table 2.

$\Lambda_Y^X =$ Cost of type Y incurred at network for scheme X,
$\Psi_Y^X =$ Cost of type Y incurred at root-MR for scheme X,
$\Phi_Y^X =$ Cost of type Y incurred at HA for scheme X,
$N_r =$ Number of MRs in mobile network,
$N_r^{(i)} =$ Number of MRs at level i,
$N_m =$ Number of mobile nodes in the mobile network,
$N_f =$ Number of LFNs in mobile network,
$N_m^{(i)} =$ Number of LMNs and VMNs at level i,
$N_f^{(i)} =$ Number of LFNs at level i,
$N_c =$ Number of CNs communicating with each node,
$l =$ Nesting Level (hops to root-MR),
$h_{ah} =$ Average number of hops between AR and HA,
$h_{ac} =$ Average number of hops between AR and CN,
$h_{hc} =$ Average number of hops between HA and CN,
$h_{hh} =$ Average number of hops between HA and HA,
$\tau_l =$ Per hop transmission cost for location update,
$\tau_s =$ Per hop transmission cost for session continuity,
$\tau_{dt} =$ Per hop transmission cost for packets without tunnel header,
$\tau_{ip} =$ Per hop transmission cost for tunnel header,
$\tau_{rh} =$ Per hop transmission cost for home address destination option or routing header type 2,
$\tau_d =$ Average transmission cost of DHCPv6 messages,
$\tau_p =$ Average transmission cost of PANA messages,
$\tau_a =$ Average transmission cost of route request-reply messages of AODV protocol,
$\tau_r =$ Transmission cost for the router advertisement,
$\sigma =$ Proportionality constant of transmission cost over wired and wireless network,
$\pi_{lk} =$ Lookup costs,
$\pi_h =$ BU processing cost,
$\pi_t =$ Tunnel processing costs at HA and MR,
$\pi_{rh} =$ Routing header processing cost,
$\lambda_s =$ Average session arrival rate,
$\lambda_{cs} =$ For an MNN, session arrival rate from all CNs,
$S =$ number of sessions,
$\lambda_{cp} =$ For an MNN, average packet arrival rate from all CNs,

$F =$ File size,
$P =$ Maximum transmission unit,
$T_r =$ Subnet residence time,
$T_{lf} =$ Lifetime of binding entry,
$T_{ra} =$ Interval of sending periodic router advertisement,
$f_h =$ The rate of sending BUs per second for both handoff and refreshing,
$f_r =$ The rate of sending BUs per second for refreshing,
$\phi =$ Fraction of MRs acting as root-MR,
$\alpha =$ Ratio of number of mobile nodes registered to the HA to number of mobile nodes in the mobile network.

The models are developed to show the differences in the costs of the schemes from the viewpoint of total cost rather than that of differential cost. Showing only the differences in costs might give an impression of inflated differences. Therefore, we consider all parameters required to compute the costs. However, following are the parameters that are the keys as far as the differences of the schemes are concerned:

- h_{ah} and h_{hc}: These two represent the distance of the mobile network from the home network, and will affect the differences of the costs depending on the degree of optimization.
- The number and types of MNNs, and CNs: Depending on the number of and types of MNNs and CNs, the signaling and the transmission costs among the schemes may vary.
- λ_{cp}: It represents the amount of data exchanged with the mobile network, and will affect the packet delivery cost.
- T_r: The subnet residence time affects the amount of signaling in a scheme and can make difference among the signaling cost of the schemes depending on the number and types of MNNs.

The key parameters are also discussed in Section 6.

5.4 Cost Models for the Schemes

Analytical models for the costs are presented in the following sections. We have provided detailed description of the cost terms of NEMO BSP to make readers familiar with the cost terms. Detailed description of the cost terms for other schemes (SPD, MIRON, OPR, and ad hoc) can be found at [29].

5.4.1 NEMO BSP

- **Location update cost.** After handoff, TLMR sends a BU to the HA to perform the location update, and receives a BA. Handoff occurs every T_r seconds. In addition to the BU sent after handoff, MRs and mobile nodes send refreshing BU $\lfloor \frac{T_r}{T_{lf}} \rfloor$ times during the period of T_r seconds. Therefore, the frequency of sending BUs including BUs sent during handoff is, $f_h = (1 + \lfloor \frac{T_r}{T_{lf}} \rfloor)/T_r$, and the frequency of sending refreshing BUs is, $f_r = \lfloor \frac{T_r}{T_{lf}} \rfloor / T_r$. BUs sent from MRs and mobile nodes at level i undergoes i number of tunneling resulting in additional transmission cost due to tunnel header. Since all BU/BAs go through the root-MR, the cost at the root-MR is given by

$$\Psi_{LU}^{N} = 2\sigma\tau_l f_h + 2\sigma \sum_{i=1}^{i=l} \left(N_r^{(i)} + N_m^{(i)}\right)(\tau_l + i\tau_{ip} + \pi_t) f_r. \quad (1)$$

To find out the cost incurred at the HA due to the location update, we need to consider the updating of the binding cache in addition to the cost mentioned above. Updating the binding cache is required for each MR and mobile node registered to an HA. In addition, tunneled BUs incur a *lookup cost*. Since $(N_r + N_m)$ nodes are managed by the HA, the lookup is performed in a table of $(N_r + N_m)$ entries and with a lookup key of size equal to the IPv6 address. Assuming a binary search, the lookup cost is $\pi_{lk} = \psi \log_2(N_r + N_m)$, where ψ is the cost of the lookup per operation. Therefore, cost incurred at HA due to location update becomes

$$\Phi_{LU}^{N} = \phi N_r (2\tau_l + \pi_h) f_h + 2 \sum_{i=1}^{l} \left(N_r^{(i)} + N_m^{(i)}\right) \times ((\tau_l + i\tau_{ip} + \pi_t) + \pi_{lk} + 0.5\pi_h) f_r. \quad (2)$$

The cost of location update for the network includes transmission costs at all hops up to the HA including the costs incurred at MRs and the HA. Transmission costs for MRs and mobile nodes at level i are incurred at $h_{ah} + ih_{hh}$ wired hops and $(i+1)$ wireless hops. The transmission cost up to the root-MR increases by τ_{ip} at each level due to tunneling, and at each HA it decreases by the same amount. Also, each BU sent from a node at level i undergoes $2i$ number of tunneling and detunneling. Therefore, location update cost is as follows:

$$\Lambda_{LU}^{N} = (2(h_{ah} + \sigma)\tau_l + \pi_h) f_h + 2 \sum_{i=1}^{l} \left(N_r^{(i)} + N_m^{(i)}\right) \times \Bigg((i+1)\sigma\tau_l + \sigma \sum_{j=1}^{i} j\tau_{ip} + 2i\pi_t + (h_{ah} + ih_{hh})\tau_l + h_{ah} i\tau_{ip} + \sum_{j=0}^{i-1} jh_{hh}\tau_{ip} + i\pi_{lk} + 0.5\pi_h\Bigg) f_r, \quad (3)$$

where, $2(h_{ah} + \sigma)\tau_l + \pi_h$ includes costs incurred due to BUs/BAs sent by root-MR/HAs, $\sum_{i=1}^{l}(N_r^{(i)} + N_m^{(i)})$ includes the number of nodes that send refreshing BUs, $(i+1)\sigma\tau_l + \sigma\sum_{j=1}^{i} j\tau_{ip} + i\pi_t$ includes transmission and tunnel processing costs incurred inside the mobile network and at AR, $i\pi_t + (h_{ah} + ih_{hh})\tau_l + h_{ah} i\tau_{ip} + \sum_{j=0}^{i-1} jh_{hh}\tau_{ip} + i\pi_{lk} + 0.5\pi_h$ includes tunnel processing, transmission, and BU processing costs incurred at hops after AR up to HA.
- **Session continuity cost.** Each mobile node sends BUs to (and receive a BAs from) its CNs for session continuity. Since only root-MR's CoA changes during handoff, mobile nodes send only refreshing BUs. Thus, the cost incurred at the root-MR is

$$\Psi_{SC}^{N} = 2N_c \sum_{i=1}^{l} N_m^{(i)} (\sigma(\tau_s + i\tau_{ip}) + \pi_t) f_r. \quad (4)$$

Since BUs are tunneled through the HA, the cost incurred at the HA includes lookup, tunneling, and transmission costs, and is given as follows:

$$\Phi_{SC}^{N} = 2N_c \sum_{i=1}^{l} N_m^{(i)}(\tau_s + i\tau_{ip} + \pi_t + \pi_{lk}) f_r. \quad (5)$$

The session continuity cost for the network includes the costs at each hop up to CNs, MNNs and at other MRs, and the cost of updating the binding update list incurred per packet at the VMNs in addition to the above cost, and is given by (6)

$$\begin{aligned}\Lambda_{SC}^{N} = 2N_c \sum_{i=1}^{l} N_m^{(i)}\Bigg(&(i+1)\sigma\tau_s + \sigma\sum_{j=1}^{i} j\tau_{ip} \\ &+ 2i\pi_t + (h_{ah} + (i-1)h_{hh} + h_{hc})\tau_s + h_{ah} i\tau_{ip} \\ &+ \sum_{j=0}^{i-1} jh_{hh}\tau_{ip} + i\pi_{lk} + 0.5\pi_h\Bigg) f_r + \lambda_{cp}\pi_{bl}N_m,\end{aligned} \quad (6)$$

where, $N_c \sum_{i=1}^{l} N_m^{(i)}$ is the number of BUs sent to CNs, $(i+1)\sigma\tau_s + \sigma\sum_{j=1}^{i} j\tau_{ip} + i\pi_t$ includes transmission and tunnel processing costs incurred inside the mobile network and at AR, $i\pi_t + (h_{ah} + (i-1)h_{hh} + h_{hc})\tau_s + h_{ah} i\tau_{ip} + \sum_{j=0}^{i-1} jh_{hh}\tau_{ip} + i\pi_{lk} + 0.5\pi_h$ includes tunnel processing, transmission, and BU processing costs incurred at hops after AR up to the CN, and $\lambda_{cp}\pi_{bl}N_m$ is the cost for updating the binding update list at VMNs.

- **Packet delivery cost.** Data packets incurs transmission and tunneling cost which is similar to that of BU packets. For each MNN, costs are incurred at a rate proportional to the packet arrival rate, $\lambda_{cp} = N_c\lambda_s F/P$, from all CNs. For the packets sent to mobile nodes, we assume that only the first packet of a session is sent through the HA before a BU is received at the CN, and additional costs are incurred at a rate, $\lambda_{cs} = N_c\lambda_s/S$ for all CNs. Root-MR needs to detunnel and forward packets to the MNNs at the next level. Additional cost incurred at the root-MR for the first packets sent to mobile nodes is the increased transmission cost for one additional tunnel. Therefore, the cost at the root-MR is

$$\begin{aligned}\Psi_{PD}^{N} = \lambda_{cp}\Bigg(&\sum_{i=1}^{l}\big(N_f^{(i)} + N_m^{(i)}\big)\big(\sigma(\tau_{dt} + (i-1)\tau_{ip}) \\ &+ \pi_t\big) + \sigma\tau_{rh}N_m\Bigg) + \sigma N_m(\tau_{ip} + \tau_{dt})\lambda_{cs}.\end{aligned} \quad (7)$$

In addition to the transmission cost, costs incurred at the HA are due to lookup, tunneling, and the transmission cost for one additional tunnel. Therefore, the packet delivery cost at the HA is as follows:

$$\begin{aligned}\Phi_{PD}^{N} = \lambda_{cp}\Bigg(&\sum_{i=1}^{l}\big(N_f^{(i)} + N_m^{(i)}\big)(\tau_{dt} + i\tau_{ip} + \pi_{lk} + \pi_t) \\ &+ \tau_{rh}N_m\Bigg) + \lambda_{cs}N_m(\tau_{dt} + 2\tau_{ip} + \pi_{lk} + \pi_t).\end{aligned} \quad (8)$$

The packet delivery cost for the network can be obtained at each hop similar to the session continuity cost. Additionally, for the first packet sent through the HA of mobile nodes, costs are incurred due to transmission through h_{hh} hops, tunneling, lookup, and transmission of one additional tunnel header. Therefore, the packet delivery cost for the network is given by (9)

$$\begin{aligned}\Lambda_{PD}^{N} &= \lambda_{cp}(costs\ incurred\ per\ packet) + \lambda_{cs} \\ &\quad (additional\ costs\ incurred\ for\ the\ first\ packet) \\ &= \lambda_{cp}\Bigg(\sum_{i=1}^{l}\big(N_f^{(i)} + N_m^{(i)}\big)\Bigg(i\pi_{lk} + 2i\pi_t + (h_{ah} + h_{hc} \\ &\quad + (i-1)h_{hh})\tau_{dt} + ih_{ah}\tau_{ip} + \sum_{j=0}^{i-1} jh_{hh}\tau_{ip} \\ &\quad + \sigma\sum_{j=1}^{i} j\tau_{ip} + \sigma\tau_{dt}(i+1)\Bigg) + \sum_{i=1}^{l} N_m^{(i)}\big((h_{ah} \\ &\quad + (i-1)h_{hh} + h_{hc} + \sigma(i+1))\tau_{rh} + 2\pi_{rh}\big)\Bigg) \\ &\quad + \lambda_{cs}\sum_{i=1}^{l} N_m^{(i)}\big(\pi_{lk} + 2\pi_t + h_{hh}(\tau_{dt} + \tau_{ip}) \\ &\quad + \sigma i\tau_{ip} + h_{ah}\tau_{ip} + ih_{hh}\tau_{ip}\big).\end{aligned} \quad (9)$$

For the subexpression showing the per packet costs, $i\pi_{lk} + 2i\pi_t + (h_{ah} + (i-1)h_{hh} + h_{hc})(\tau_{dt} + \tau_{rh}) + ih_{ah}\tau_{ip} + \sum_{j=0}^{i-1} jh_{hh}\tau_{ip}$ includes lookup, tunnel processing, transmission costs incurred at hops from the CN until the AR, and $\sigma\sum_{j=1}^{i} j\tau_{ip} + \sigma(\tau_{dt} + \tau_{rh})(i+1)$ includes transmission and tunnel processing costs incurred inside the mobile network for $\sum_{i=1}^{l}(N_f^{(i)} + N_m^{(i)})$ VMNs and LFNs that receive packets from CNs. $(h_{ah} + (i-1)h_{hh} + h_{hc} + \sigma(i+1))\tau_{rh} + 2\pi_{rh}$ includes the additional transmission and processing costs for the home address destination option for VMNs only.

For the subexpression showing the additional costs for the first packet only, $\sum_{i=1}^{l} N_m^{(i)}$ is the number of VMNs that send the first packet through their HA, $h_{hh}(\tau_{dt} + \tau_{ip})$ includes the transmission costs incurred at the hops from the MR's HA up to the VMN's HA, and $\pi_{lk} + 2\pi_t$ includes the lookup and tunnel processing costs in the additional HA, and $\sigma i\tau_{ip} + h_{ah}\tau_{ip} + ih_{hh}\tau_{ip}$ includes the transmission costs at the hops from the VMN up to its MR's HA due to one additional tunnel header.

- **Prefix/CoA obtention cost.** After every handoff, only root-MR obtains a CoA from the foreign network. Therefore, costs incurred due to prefix or CoA obtention are zero.
- **Total cost.** Combining the costs presented above, we find the costs incurred at the root-MR, the HA, and the network given by

$$\Psi_T^N = \Psi_{LU}^N + \Psi_{SC}^N + \Psi_{PD}^N, \quad (10)$$

$$\Phi_T^N = \Phi_{LU}^N + \Phi_{SC}^N + \Phi_{PD}^N, \quad (11)$$

$$\Lambda_T^N = \Lambda_{LU}^N + \Lambda_{SC}^N + \Lambda_{PD}^N. \quad (12)$$

5.4.2 SPD

- **Location update cost.** In SPD, location update after handoff is performed by each MR and mobile node by sending a BU to the HA, and receiving a BA. In addition to the BU sent after handoff, refreshing BUs are sent periodically. Thus, BUs are sent at a rate given by f_h. Since all BU/BAs go through the root-MR, the cost at the root-MR is given by

$$\Psi^S_{LU} = 2\sigma\tau_l(N_r + N_m)f_h. \quad (13)$$

To find the cost incurred at the HA due to the location update, we need to consider the updating of the binding cache in addition to the cost mentioned above. Therefore, cost incurred at HA due to location update becomes

$$\Phi^S_{LU} = (2\tau_l + \pi_h)(N_r + N_m)f_h. \quad (14)$$

The cost of location update for the network includes transmission costs at all hops up to the HA including the costs incurred at the root-MR and the HA. Transmission costs for all MRs and mobile nodes are incurred at h_{ah} wired hops. For nodes at level i, transmission costs are incurred at $i+1$ wireless hops. Therefore, location update cost is given by

$$\Lambda^S_{LU} = \left(2\tau_l\left((N_r + N_m)h_{ah} + \sigma\sum_{i=0}^{l}(i+1) \times \left(N_r^{(i)} + N_m^{(i)}\right)\right) + (N_r + N_m)\pi_h\right)f_h. \quad (15)$$

- **Session continuity cost.** In SPD, each mobile node sends BUs to (and receive BAs from) CNs for session continuity. The cost incurred at the root-MR is thus

$$\Psi^S_{SC} = 2\sigma\tau_s N_m N_c f_h. \quad (16)$$

The session continuity cost for the network also includes costs at each hop up to CNs and at other MRs and VMNs, and is given by

$$\Lambda^S_{SC} = 2\tau_s N_c\left(N_m h_{ac} + \sigma\sum_{i=0}^{l}(i+1)N_m^{(i)} + 0.5\pi_h N_c N_m\right)f_h + \lambda_{cp}\pi_{bl}N_m. \quad (17)$$

- **Packet delivery cost.** For every packet, sent from a CN to an LFN, the HA of the LFN looks up the binding cache to find the CoA to encapsulate the packet for tunneling. Tunneling and lookup costs are incurred at a rate proportional to the packet arrival rate given by λ_{cp}. For the packets sent to mobile nodes, we assume that only the first packet is sent through the HA before a BU is received at the CN while subsequent packets are sent through the optimized route using the home address destination option, and thus, the costs are incurred at a rate given by λ_{cs}. Root-MR needs to detunnel these packets only for attached LFNs. Therefore, the cost at the root-MR is

$$\Psi^S_{PD} = \lambda_{cp}\left(N_f^{(1)}\pi_t + \sigma\tau_{ip}\left(N_f - N_f^{(1)}\right) + \sigma(\tau_{dt}N_f + (\tau_{dt} + \tau_{rh})N_m)\right) + \sigma\tau_{ip}\lambda_{cs}N_m. \quad (18)$$

The HA needs to perform lookup, tunneling, and transmit the packet resulting in a cost as follows:

$$\Phi^S_{PD} = (\lambda_{cp}N_f + \lambda_{cs}N_m)(\pi_{lk} + \tau_{dt} + \tau_{ip} + \pi_t). \quad (19)$$

In addition to the cost incurred at the HA and root-MR, the packet delivery cost for the network have other costs that include the transmission costs at nested MRs and routers up to the CN. For the case of mobile nodes, transmission costs are incurred at each hop between the AR and the CN for all but the first packet. For the case of LFNs and session's first packet of mobile nodes, transmission costs are incurred at each hop from the CN up to the HA, and from the HA up to the AR. For the latter case, additional costs are incurred due to tunnel header at each hop between the HA and the MR for the destination MNN along with the tunneling cost incurred at the MR because it detunnels packets. Therefore, the packet delivery cost for the network is given by

$$\begin{aligned}\Lambda^S_{PD} = \lambda_{cp}\Bigg(&N_f(\pi_{lk} + 2\pi_t + (h_{ah} + h_{hc})\tau_{dt} + h_{ah}\tau_{ip}) \\ &+ N_m(h_{ac}(\tau_{dt} + \tau_{rh}) + 2\pi_{rh}) \\ &+ \sigma\sum_{i=1}^{l}(i+1)\left(\tau_{dt}N_f^{(i)} + (\tau_{dt} + \tau_{rh})N_m^{(i)}\right) \\ &+ \sigma\tau_{ip}\sum_{i=1}^{l}iN_f^{(i)}\Bigg) + \lambda_{cs}\Bigg(N_m(\pi_{lk} + 2\pi_t \\ &+ h_{ah}(\tau_{dt} + \tau_{ip})) + \sigma\tau_{ip}\sum_{i=1}^{l}(i+1)N_m^{(i)}\Bigg).\end{aligned} \quad (20)$$

- **Prefix/CoA obtention cost.** In SPD, prefix and CoAs can be obtained from the MR above using DHCPv6 procedures. This requires a request and a reply message, and some processing at the MR for prefix delegation [30]. Since the root-MR delegates prefixes to attached MRs and provide CoAs to attached mobile nodes, the cost incurred at the root-MR is as follows:

$$\Psi^S_{CO} = \frac{2\sigma\tau_d\left(N_r^{(1)} + N_m^{(1)}\right)}{T_r}. \quad (21)$$

The cost incurred for the entire mobile network is given by

$$\Lambda^S_{CO} = \frac{2\sigma\tau_d(N_r + N_m)}{T_r}. \quad (22)$$

- **Total cost.** Combining the costs presented above, we find the costs of SPD incurred at the root-MR, the HA, and the network given by

$$\Psi_T^S = \Psi_{LU}^S + \Psi_{SC}^S + \Psi_{PD}^S + \Psi_{CO}^S, \tag{23}$$

$$\Phi_T^S = \Phi_{LU}^S + \Phi_{PD}^S, \tag{24}$$

$$\Lambda_T^S = \Lambda_{LU}^S + \Lambda_{SC}^S + \Lambda_{PD}^S + \Lambda_{CO}^S. \tag{25}$$

5.4.3 MIRON

- **Location update cost.** Location update for MIRON is similar to that of SPD. Therefore, location update costs for the root-MR, the HA, and the network is as follows:

$$\Psi_{LU}^M = \Psi_{LU}^S, \tag{26}$$

$$\Phi_{LU}^M = \Phi_{LU}^S, \tag{27}$$

$$\Lambda_{LU}^M = \Lambda_{LU}^S. \tag{28}$$

- **Session continuity cost.** For session continuity, BUs are sent to CNs by mobile nodes, and by MRs on behalf of the attached LFNs. Thus, the costs for MIRON are similar to the costs of SPD except the additional but identical costs for LFNs. Therefore, the costs incurred at the root-MR and at the network are given by

$$\Psi_{SC}^M = 2N_c\big(N_f + N_m\big)\sigma\tau_s f_h + \lambda_{cp}\pi_{bl}N_f^{(1)}, \tag{29}$$

$$\begin{aligned}\Lambda_{SC}^M = 2N_c\Bigg(&(N_f + N_m)(h_{ac}\tau_s + 0.5\pi_h) + \sigma\tau_s \\ &\times \sum_{i=0}^{l}(i+1)\big(N_f^{(i)} + N_m^{(i)}\big)\Bigg)f_h \\ &+ \lambda_{cp}\pi_{bl}(N_f + N_m).\end{aligned} \tag{30}$$

- **Packet delivery cost.** In MIRON, route optimization is performed for all MNNs. Therefore, packet delivery cost for all MNNs are like that for mobile nodes in SPD. Therefore, the costs for the root-MR, the HA, and the network are given by

$$\begin{aligned}\Psi_{PD}^M = \;&\lambda_{cs}\big(N_f^{(1)}\pi_t + \sigma\tau_{ip}\big(N_f - N_f^{(1)} + N_m\big)\big) \\ &+ \sigma\lambda_{cp}(\tau_{dt} + \tau_{rh})(N_f + N_m),\end{aligned} \tag{31}$$

$$\Phi_{PD}^M = \lambda_{cs}\big(N_f + N_m\big)\big(\pi_{lk} + \tau_{dt} + \tau_{ip} + \pi_t\big), \tag{32}$$

$$\begin{aligned}\Lambda_{PD}^M = \lambda_{cs}\Bigg(&(N_f + N_m)\big(\pi_{lk} + 2\pi_t + (h_{ah} + h_{hc}) \times \tau_{dt} \\ &+ h_{ah}\tau_{ip}\big) + \sigma\tau_{ip}\Bigg(\sum_{i=1}^{l} iN_f^{(i)} + \sum_{i=1}^{l}(i+1)N_m^{(i)}\Bigg)\Bigg) \\ &+ \lambda_{cp}\Bigg(\big(h_{ac}(\tau_{dt} + \tau_{rh}) + 2\pi_{rh}\big) \times (N_f + N_m) \\ &+ \sigma\Bigg((\tau_{dt} + \tau_{rh})\sum_{i=1}^{l} i\big(N_f^{(i)} + N_m^{(i)}\big) + \tau_{dt}N_f \\ &+ (\tau_{dt} + \tau_{rh})N_m\Bigg)\Bigg).\end{aligned} \tag{33}$$

- **Prefix/CoA obtention cost.** Two DHCPv6 messages for each MNN (except LFNs) are forwarded by the root-MR along with the transmission of two PANA messages for attached MRs resulting in the cost incurred at the root-MR as follows:

$$\Psi_{CO}^M = \frac{2\sigma}{T_r}\big(\big(N_r^{(1)} + N_m^{(1)}\big)\tau_p + (N_r + N_m)\tau_d\big). \tag{34}$$

For each MNN except the root-MR and LFNs, four PANA messages have to be transmitted, and equal number of replies follow. Moreover, two DHCPv6 messages for each MR and mobile node at level i are transmitted across i number of wireless hops. Therefore, prefix/CoA obtention cost for the network becomes

$$\begin{aligned}\Lambda_{CO}^M = \frac{\sigma}{T_r}\Bigg(&8(N_r - 1 + N_m)\tau_p \\ &+ 2\sum_{i=0}^{l}(i+1)\big(N_r^{(i)} + N_m^{(i)}\big)\tau_d\Bigg).\end{aligned} \tag{35}$$

- **Total cost.** Like SPD, the total costs for MIRON are given by

$$\Psi_T^M = \Psi_{LU}^M + \Psi_{SC}^M + \Psi_{PD}^M + \Psi_{CO}^M, \tag{36}$$

$$\Phi_T^M = \Phi_{LU}^M + \Phi_{PD}^M, \tag{37}$$

$$\Lambda_T^M = \Lambda_{LU}^M + \Lambda_{SC}^M + \Lambda_{PD}^M + \Lambda_{CO}^M. \tag{38}$$

5.4.4 OPR

- **Location update cost.** In OPR, only MRs obtain CoAs after handoff, and perform location update with the HA. Mobile nodes, being transparent to the mobility, send refreshing BUs only. Therefore, we can find the costs like the previous schemes by considering all BUs sent by MRs, and refreshing BUs sent by mobile nodes

$$\Psi_{LU}^O = 2N_r\sigma\tau_l f_h + 2N_m\sigma\tau_l f_r, \tag{39}$$

$$\Phi_{LU}^O = N_r(2\tau_l + \pi_h)f_h + N_m(2\tau_l + \pi_h)f_r, \tag{40}$$

$$\Lambda_{LU}^{O} = \left(2\tau_l\left(N_r h_{ah} + \sigma\sum_{i=0}^{l}(i+1)N_r^{(i)}\right) + N_r\pi_h\right)f_h + \left(2\tau_l\left(N_m h_{ah} + \sigma\sum_{i=0}^{l}(i+1)N_m^{(i)}\right) + N_m\pi_h\right)f_r. \quad (41)$$

- **Session continuity cost.** Since mobile nodes in OPR do not need MIPv6 route optimization, we assume that no BU is sent to CNs. Therefore, the session continuity cost due to the sending of BUs to CNs is zero. But for every packet sent to the CN from each attached MNN at level $(i+1)$, the MR at level i needs to look up the DPT table for the translated address. Size of the DPT table is proportional to the number of attached LFNs and mobile nodes at level $i+1$. Therefore, the session continuity cost at the root-MR (at level zero) as follows:

$$\Psi_{SC}^{O} = \lambda_{cp}\left(N_f^{(1)} + N_m^{(1)}\right)\left(\psi\log_2(N_f^{(1)} + N_m^{(1)})\right). \quad (42)$$

Considering the lookup cost for all MRs while assuming equal number of MNNs attached under each MR, the session continuity cost for the network becomes

$$\Lambda_{SC}^{O} = \lambda_{cp}\left(\psi\log_2\sum_{i=0}^{l}\frac{1}{N_r^{(i)}}\left(N_f^{(i+1)} + N_m^{(i+1)}\right)^2 + (N_f + N_m)(\pi_h + \pi_{rh})\right), \quad (43)$$

where $N_r^{(i)} \neq 0$.

- **Packet delivery cost.** Similar to MIRON, the first packet go through the HA until the CN receives the translated address from the packet sent to the CN in response to the first packet received at an MNN. Therefore, costs for OPR are as follows:

$$\Psi_{PD}^{O} = \Psi_{PD}^{M}, \quad (44)$$

$$\Phi_{PD}^{O} = \Phi_{PD}^{M}, \quad (45)$$

$$\Lambda_{PD}^{O} = \Lambda_{PD}^{M}. \quad (46)$$

- **Prefix/CoA obtention cost.** Prefix obtention procedure is similar to that of SPD except that only MRs obtain the prefix. Therefore, by excluding the cost for mobile nodes from the expressions derived for SPD, we can find the prefix/CoA obtention cost for the root-MR and the network given by

$$\Psi_{CO}^{O} = \frac{2\sigma\tau_d N_r^{(1)}}{T_r}, \quad (47)$$

$$\Lambda_{CO}^{O} = \frac{2\sigma\tau_d N_r}{T_r}. \quad (48)$$

- **Total cost.** The total costs for OPR are given by

$$\Psi_{T}^{O} = \Psi_{LU}^{O} + \Psi_{SC}^{O} + \Psi_{PD}^{O} + \Psi_{CO}^{O}, \quad (49)$$

$$\Phi_{T}^{O} = \Phi_{LU}^{O} + \Phi_{PD}^{O}, \quad (50)$$

$$\Lambda_{T}^{O} = \Lambda_{LU}^{O} + \Lambda_{SC}^{O} + \Lambda_{PD}^{O} + \Lambda_{CO}^{O}. \quad (51)$$

5.4.5 *Ad-Hoc-Based*

- **Location update cost.** Like OPR, location update after handoff is performed by MRs, and mobile nodes send refreshing BUs. Unlike OPR, BUs sent by attached mobile nodes are tunneled by each MR to its HA. Therefore, the costs incurred at the root-MR and the HA are the costs of refreshing location update of mobile nodes in addition to the similar costs of OPR

$$\Psi_{LU}^{A} = \Psi_{LU}^{O} + 2\left(\left(N_m - N_m^{(1)}\right)\sigma\tau_{ip} + \pi_t N_m^{(1)}\right)f_r \quad (52)$$

$$\Phi_{LU}^{A} = \Phi_{LU}^{O} + N_m(2\pi_t + \tau_{ip} + \pi_{lk})f_r. \quad (53)$$

The location update cost for network is more than that of OPR because BUs sent by the mobile nodes are tunneled through the HA. Thus, in addition to the costs considered in OPR, we need to consider the costs incurred at each hop from HA of the MR to the HA of the mobile node, and the costs of tunneling. Therefore, the cost becomes

$$\Lambda_{LU}^{A} = \Lambda_{LU}^{O} + 2\tau_{ip}\left(\left(N_m h_{ah} + \sigma\sum_{i=0}^{l} iN_m^{(i)}\right) + N_m h_{hh}\tau_l + N_m(\pi_{lk} + 2\pi_t)\right)f_r. \quad (54)$$

- **Session continuity cost.** Mobile nodes send refreshing BUs to CNs, and therefore, session continuity cost for the root-MR in ad-hoc-based scheme is similar to that of SPD except that only refreshing BUs are considered

$$\Psi_{SC}^{A} = 2(\sigma N_m N_c(\tau_s + \tau_{ip}) + \pi_t N_m^{(1)} N_c)f_r. \quad (55)$$

Since BUs are tunneled through the HA, the session continuity cost at the HA is given by

$$\Phi_{SC}^{A} = 2N_m N_c(\tau_s + \tau_{ip} + \pi_t)f_r. \quad (56)$$

Considering the costs at each hop, the session continuity cost for the network is

$$\Lambda_{SC}^{A} = 2N_c f_r\left(N_m((h_{ah} + h_{hc})\tau_s + h_{ah}\tau_{ip} + 2\pi_t + 0.5\pi_h) + \sigma\sum_{i=0}^{l}((i+1)\tau_s + i\tau_{ip})N_m^{(i)}\right) + \lambda_{cp}\pi_{bl}N_m. \quad (57)$$

- **Packet delivery cost.** Like the packets for LFNs in SPD, packets for all MNNs are tunneled through the HA. Therefore, cost for the root-MR can be found from the similar cost for SPD by considering all MNNs instead of considering only LFNs, and is as follows:

$$\Psi_{PD}^{A} = \lambda_{cp}\Big(\big(N_f^{(1)} + N_m^{(1)}\big)\pi_t + \sigma\big(\tau_{ip}\big(N_f + N_m - N_f^{(1)} - N_m^{(1)}\big) + \tau_{dt}(N_f + N_m) + \tau_{rh}N_m\big)\Big) + \sigma\lambda_{cs}\tau_{ip}N_m. \tag{58}$$

Similarly, the cost for the HA can be obtained as follows:

$$\Phi_{PD}^{A} = \lambda_{cp}\Big((N_f + N_m)(\pi_{lk} + \pi_t + \tau_{dt} + \tau_{ip}) + \tau_{rh}N_m\Big) + \lambda_{cs}N_m(\pi_{lk} + \tau_{dt} + 2\tau_{ip}). \tag{59}$$

The cost for the network can also be found from the cost of SPD in a similar way mentioned above except an additional cost which is due to find the route toward the AR using AODV [28]. We assume that the cost of route finding occurs once every handoff because change of AR occurs at handoff. We also assume that the route finding messages only travel one hop because the MRs already know the route to the AR. Thus, each MR broadcasts a route request message, and replies twice once for the MRs above and below. Therefore, packet delivery cost for ad-hoc-based is given by

$$\begin{aligned}\Lambda_{PD}^{A} = \lambda_{cp}\Bigg(&\big(N_f + N_m\big)\big(\pi_{lk} + 2\pi_t + (h_{ah} + h_{hc})\tau_{dt} + h_{ah}\tau_{ip}\big) + (h_{ah} + h_{hc})\tau_{rh}N_m + 2\pi_{rh}N_m \\ &+ \sigma\Bigg((\tau_{dt} + \tau_{ip})\sum_{i=1}^{l} i\big(N_f^{(i)} + N_m^{(i)}\big) + \tau_{dt}(N_f + N_m) + \tau_{rh}\sum_{i=1}^{l}(i+1)N_m^{(i)}\Bigg)\Bigg) \\ &+ \lambda_{cs}\Bigg(N_m(\pi_{lk} + 2\pi_t + h_{hh}(\tau_{dt} + \tau_{ip}) + h_{ah}\tau_{ip} + \sigma\tau_{ip}) + \sigma\tau_{ip}\sum_{i=1}^{l} iN_m^{(i)}\Bigg) \\ &+ 3N_r\sigma\tau_a\frac{1}{T_r}.\end{aligned} \tag{60}$$

- **Prefix/CoA obtention cost.** In ad-hoc-based scheme, MRs obtain CoAs from the router advertisement of the AR, and periodically broadcast the advertisement to the attached MRs. Thus, the cost of CoA obtention becomes the cost of broadcasting the RA. Since the root-MR only broadcast one router advertisement, we ignore the cost for the root-MR. Therefore, the cost for the network becomes

$$\Lambda_{CO}^{A} = \frac{2\sigma\tau_r N_r}{T_r}\left(1 + \left\lfloor\frac{T_r}{T_{ra}}\right\rfloor\right), \tag{61}$$

where τ_r is the transmission cost for the router advertisement.

- **Total cost.** The total costs for ad-hoc-based scheme are given by

$$\Psi_T^A = \Psi_{LU}^A + \Psi_{SC}^A + \Psi_{PD}^A, \tag{62}$$

$$\Phi_T^A = \Phi_{LU}^A + \Phi_{SC}^A + \Phi_{PD}^A, \tag{63}$$

$$\Lambda_T^A = \Lambda_{LU}^A + \Lambda_{SC}^A + \Lambda_{PD}^A + \Lambda_{CO}^A. \tag{64}$$

TABLE 3
Values of Parameters Used in the Numerical Analysis

Parameter	Value	Parameter	Value
N_m	120	N_f	80
N_r	5	N_c	5
T_r	120 sec	T_{lf}	420 sec
h_{ah}	10	h_{ac}	10
h_{hc}	10	h_{hh}	10
l	2	ϕ	0.1
σ	10	ψ	0.3
τ_l	0.68	τ_s	0.68
τ_{ip}	0.4	π_t	0.4
λ_s	0.01	S	10
F	10240 bytes	P	576 bytes
τ_{dt}	5.76	τ_d	1.4
τ_p	0.56	τ_a	1.56
τ_r	0.72	π_h	0.68
τ_{rh}	0.24	π_{rh}	0.4
α	10		

6 RESULTS

In this section, we obtain numerical values for the costs using the expressions derived in the cost analysis section in a simplified format. We present the costs as a function of the number of mobile nodes, the number of MRs, the number of LFNs, the number of CNs, the subnet residence time, and the number of hops between entities. The location update and the session continuity costs vary among the schemes depending on the number and types of MNNs and the number of CNs. The number of data packets sent to the mobile network is proportional to the number of CNs to determine the packet delivery cost. In [20], the subnet residence time has been shown to affect the cost. Moreover, the number of hops between various mobility entities determines the packet delivery cost.

The default values of the parameters used to obtain the numerical results are shown in Table 3. As far as the numbers of MNNs are considered, we consider a large mobile network (e.g., a mobile network onboard a train) with the number of MNNs around 200. We have used $\alpha = 10$. The determination of the actual value of α is not possible since NEMO has not been deployed yet in real operational network. 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 [15]. The number of hops between various mobility entities is 10 which is reasonable for the networks within USA [31].

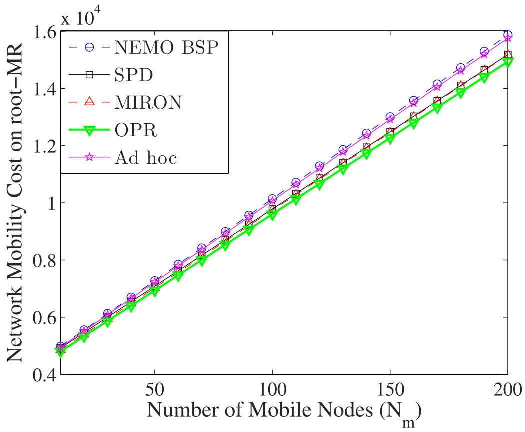

Fig. 3. Network mobility cost on root-MR versus number of MHs for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

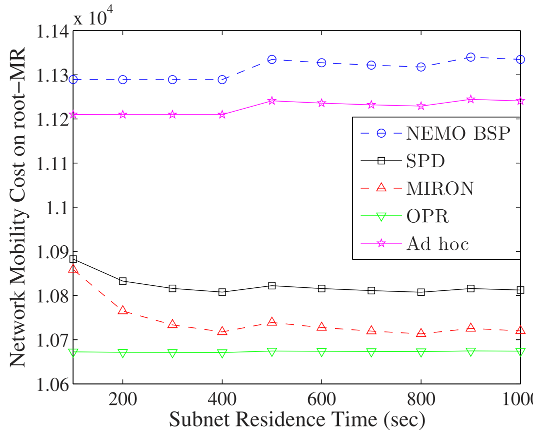

Fig. 4. Network mobility cost on root-MR versus subnet residence time for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

Transmission costs are relative and determined based on the packet size assuming unit cost per 100 bytes. Similarly, processing costs, except the lookup cost, 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 (Table 2), we assume a logarithmic time for the lookup with the proportionality constant as the processing cost per entry.

For the measurement of costs on root-MR, HA, and complete network, we assume a mobile network topology which is simplified from the network shown in Fig. 1. Since there exists no standard architecture for NEMO, we are using a generalized topology upon which different PD-based schemes have been proposed. We are assuming the mobile network to have a two-level hierarchy of Mobile Routers. There is one MR at level 0 or top level (which is the root-MR), hence $N_r^{(0)} = 1$. No LFN, LMN and VMN is connected directly to the root-MR. The root-MR is connected to $N_r^{(1)}$ number of level one routers, so $N_r^{(1)} = N_r - 1$ as there is no other mobile router at level 2. Hence, $N_r^{(2)} = 0$. There is no hosts (mobile or fixed) at level 0, and level 1. So, $N_m^{(0)} = N_f^{(0)} = 0$, and $N_m^{(1)} = N_f^{(1)} = 0$. All LFNs and mobile nodes are at level 2, i.e., $N_m^{(2)} = N_m$, and $N_f^{(2)} = N_f$.

6.1 Root-MR

In this section, we present results to show network mobility costs on the root-MR in NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based schemes. We vary the number of mobile nodes, the number of mobile routers, the number of LFNs, the subnet residence time, and the number of CNs.

The cost incurred at the root-MR is given by Figs. 3, 4, and 5 as functions of the number of mobile nodes, subnet residence time and the number of CNs, respectively. The cost associated with delivery of data packets dominates the other costs to determine the characteristics of the total costs. The cost of NEMO BSP is the highest due to the packet delivery cost that results from the transmission cost of multiple tunneled packets. The cost of ad-hoc-based scheme is higher than the SPD, MIRON, and OPR because of the transmission cost required for one additional tunneling for all packets. SPD's cost is smaller than OPR because the transmission cost of tunneled packets is incurred only for LFNs.

The costs of MIRON and OPR are smaller than other schemes. MIRON's cost is little higher than OPR due to the transmission cost incurred for signaling which is required for only MRs in OPR. Also, MIRONs prefix obtention cost is higher than OPR. The costs as a function of subnet residence time (Fig. 4) show negligible changes because of the dominance of the packet delivery cost that does not depend on these two parameters.

6.2 Home Agent

The effects of the number of mobile nodes, the number of LFNs, and the number of CNs on the cost incurred at the HA are shown in Figs. 6, 7, and 8, respectively. Like the costs incurred at the root-MR, the cost associated with the packet delivery dominates over other costs. Therefore, the characteristics of the costs at the HA are similar to that at the root-MR except some differences that are explained in the following paragraphs.

The costs of NEMO BSP and ad-hoc-based scheme are almost equal because all packets in ad-hoc-based schemes go through one tunnel which is just one less than the number of tunnels required in NEMO BSP. However, had we used a topology with nesting level of more than two, the cost of ad-hoc-based scheme would be much lower than that of NEMO BSP.

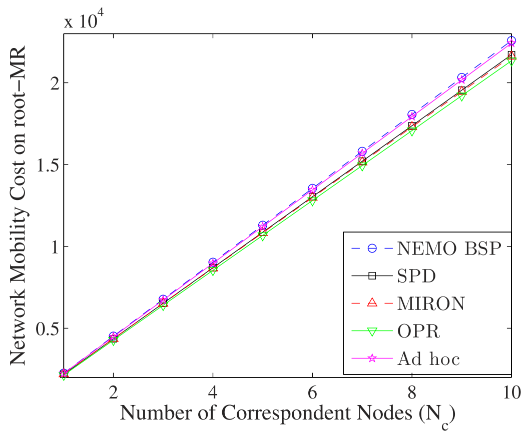

Fig. 5. Network mobility cost on root-MR versus number of CNs for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

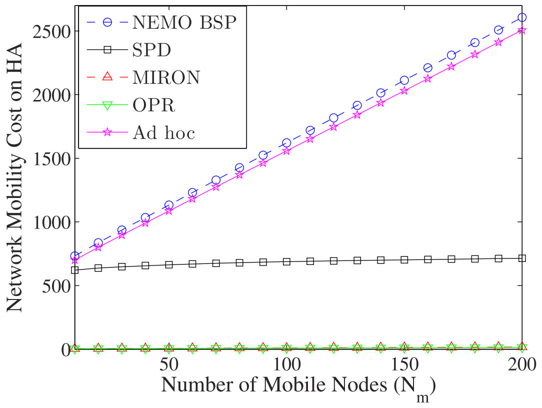

Fig. 6. Network mobility cost of HA versus number of mobile nodes for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

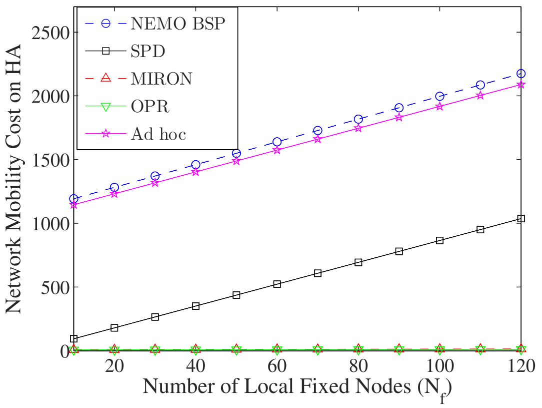

Fig. 7. Network mobility cost on HA versus number of LFNs for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

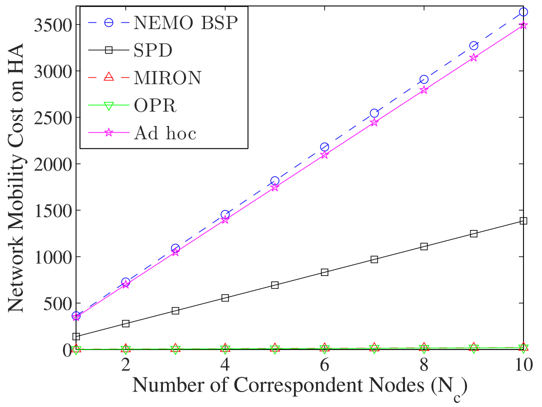

Fig. 8. Network mobility cost on HA versus number of CNs for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

For NEMO BSP and ad-hoc-based schemes, costs increase linearly with the increase of the number of mobile nodes (Fig. 6) due to the lookup cost incurred at the HA for tunneling. Lookup cost is proportional to the number of mobile nodes because lookup is required for each mobile node. For SPD, such look up cost is incurred for LFNs only resulting in a negligible (logarithmic) increase rate due to increase of the size of the binding cache.

For MIRON and OPR, the cost is much lower (when compared to the cost incurred at the root-MR) than the costs of other schemes due to the reason described next. First, the dominant lookup cost is incurred only for the first packet of a session, thus have negligible effect on the overall increase rate of the cost. Second, the location updates sent to the CNs do not incur any cost at the HA.

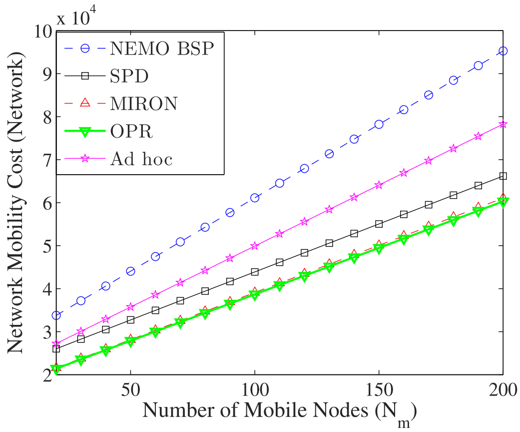

Fig. 9. Network mobility cost on complete network versus number of mobile nodes for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

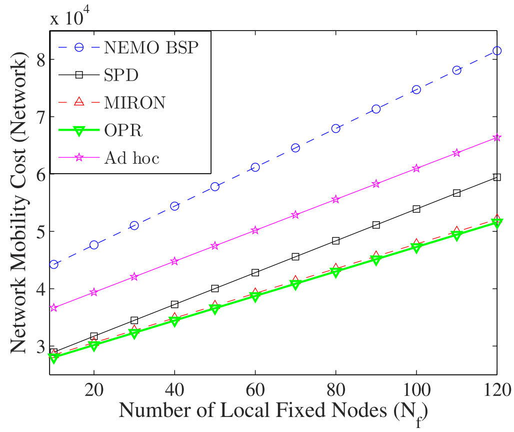

Fig. 10. Network mobility cost on complete network versus number of LFNs for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

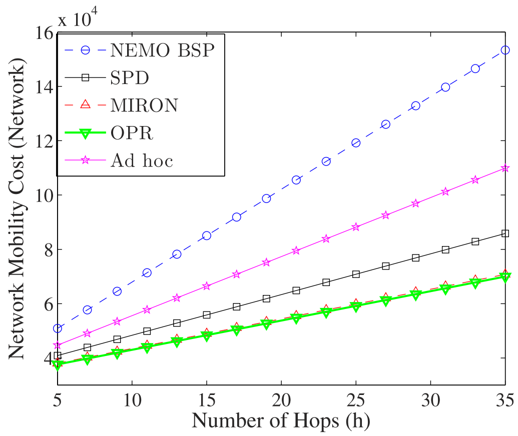

Fig. 11. Network mobility cost on complete network versus number of hops for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

6.3 Complete Network

The cost incurred at the network is given by Figs. 9, 10, 11, and 12 as functions of the number of mobile nodes, the number of LFNs, subnet residence time, the number of hops, and the number of CNs, respectively. The cost of NEMO BSP is higher than the other schemes due to the

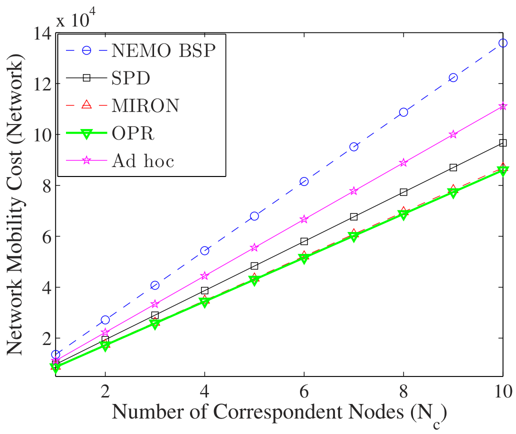

Fig. 12. Network mobility cost on complete network versus number of CNs for NEMO BSP, SPD, MIRON, OPR, and ad-hoc-based scheme.

higher packet delivery cost that results from multiple tunneling of all packets through the unoptimized route. ad-hoc-based scheme incurs higher cost than SPD, MIRON, and OPR due to the single tunneling of all packets. Since only the first packets of sessions (in contrast to all packets) are tunneled through the unoptimized route, MIRON, and OPR incurs the lowest cost.

6.4 Discussions on Results

Analysis of the results shows that there is insignificant difference among the schemes as far as the cost incurred at the root-MR is concerned. However, results and the associated discussions also show the domination of the packet delivery cost incurred at the HA and the network due to the processing and the transmission requirements at the HA and the additional route between the AR and the HA. Thus, results suggest not to compromise the route with the signaling if costs incurred at the HA and the network are to be minimized. However, performance of the schemes needs to be considered along with the costs when choosing a scheme.

Signaling is one factor to be considered because it might affect the performance of the schemes when throughput is considered. OPR might be the best scheme because of its low signaling. However, OPR is incapable of optimizing the route when packets do not flow toward the mobile network. Because of the way ad-hoc-based scheme optimize the routes for all MNNs, it will be suitable for mobile networks where frequent movement of MRs occur within the mobile network. In MIRON, amount of signaling is the largest, and the procedure of obtaining CoAs might be a limiting factor when the nesting level is large. The cost computed in this paper have to be traded off with these pros and cons of the schemes.

7 Conclusion

In this paper, we have developed mathematical models to determine the network mobility costs on various mobility entities of NEMO BSP, and four representative prefix delegation-based NEMO route optimization schemes (SPD, MIRON, OPR, and ad-hoc-based schemes) in terms of network size, mobility rate, distance between mobility agents, and traffic rate. Results show that the effect of packet delivery cost dominates other cost components in the network mobility costs because this cost is incurred per data packet.

Thus, our results lead to an interesting conclusion which is opposite to the general intuition that complete route optimization requires less resources (less cost) than that required for partially optimized route with the reduction in signaling. Our results could be used by the network operators or policy makers to judge the tradeoffs between performance and cost to choose the best scheme.

Acknowledgments

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