Performance of Prefix Delegation-based Route Optimization Schemes for NEMO

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***Abstract*—A number of prefix delegation-based schemes have been proposed in the literature to solve the route optimization problem in NEMO, where a group of hosts move together as a mobile network. The route optimization solutions generate different amounts of overheads that depend on the characteristics of the mobile network and mobility parameters. The overheads limit performance, giving rise to the need to carry out a comparative performance evaluation of the schemes to aid in the selection of a scheme; currently there is no tool which can aid in the selection. The objective of this paper is to develop analytical models to allow comparison among the schemes, and selection of an appropriate scheme for a given mobility scenario and mobile network characteristics. Results show that a single scheme does not suit all mobility scenarios and network characteristics. Selection of a scheme should, therefore, consider adaptation to the scenario and characteristics. The schemes could also be extended to dynamically adapt to changing scenario and characteristics.**

I. 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]. In NEMO, hosts belong to a moving subnetwork, called mobile network, containing one or more mobile routers that manage mobility on behalf of the hosts that can be either MIPv6 [2] capable or incapable. The basic protocol called NEMO Basic Support Protocol (NEMO BSP) enables communication with mobile network through a bidirectional tunnel between mobile routers and a router called home agent in the home network [1]. Tunneling results in the problem of inefficient route between end hosts [3]. The problem worsen when the mobile network is nested i.e. a mobile network attaches to another one. Therefore, route optimization has been an active area of research.

An overview of several route optimization schemes, proposed in the literature, can be found in [4], [5]. Route optimization schemes are based on avoiding packets going through home agents; but requires additional resources such as memory, signaling bandwidth, and processing time at mobility entities (home agents and mobile routers) when compared to NEMO BSP. Based on the approaches used, Lim et al. [5] classified the schemes into Recursive approach, Hierarchical approach and Prefix Delegation (PD)-based approach. Lim et al. [5] show that PD-based schemes perform better than other schemes in terms of resource consumption.

The work has been supported by NASA Grant NNX06AE44G.

PD-based schemes optimize routes by providing new addresses to hosts in the mobile network. But they differ in the procedure to obtain the address, and the degree of optimizing route depending on the types of hosts. This results in differences in the performance metrics such as handoff delay, end-to-end delay, signaling volume, and memory consumption. The significance of these differences depends on the number and types of mobile network hosts, the number of communicating hosts, nesting level and the distance of the mobile network from its home agent. Therefore, it is not obvious which scheme will have the optimal performance, given a mobility scenario and mobile network characteristics such as number and types of hosts in the mobile network, nesting level and distance from home agent. This necessitates a comparative evaluation of the PD-based schemes. Currently, there is no tool to evaluate the schemes. Our *objective* is to develop analytical tools to enable performance evaluation of the individual schemes, and thus permit one to pick the best scheme.

To evaluate, we have selected four schemes - Simple Prefix Delegation (SPD) [6], MIPv6-based Route Optimization (MIRON) [7], Optimal Path Registration (OPR) [8] and Ad hoc protocol-based route optimization (Ad hoc) [9]. As far as the differences mentioned in the previous paragraph are concerned, these four schemes are representatives for all PD-based schemes. The schemes have been evaluated in the literature using either simulation [9], modeling [8] or experimental testbed [7], making it harder to compare the schemes due to differences in evaluation methodology. *To facilitate fair comparison, based on a common framework, we develop analytical models for the schemes*, and validate the models using simulation. Unlike [5], this paper develops separate models for the PD-based schemes to enable a quantitative comparison among the schemes.

Our *contributions* are: (i) Development of analytical models for PD-based schemes, (ii) validation of the models using simulation, and (iii) performance comparison of the schemes. Results reveal that performance of a scheme depends on the characteristics of the mobile network, number of communicating hosts, and the distance of the mobile network from its home agent. Comparative analysis shows that to obtain high performance, either a suitable scheme has to be selected based on mobility and network characteristics, or the schemes have to be extended to adapt to changing network scenarios.

The rest of the paper is organized as follows. In Sec. II, we present the NEMO architecture and BSP, followed by the suboptimal routing problem and route optimization schemes in Sec. III. A brief overview of the PD-based schemes is presented in Sec. IV. Sec. V presents the analytical models, followed by numerical results in Sec. VI. A comparative analysis of the schemes is presented in Sec. VII. Finally, Sec. VIII concludes the paper.

II. NEMO: Architecture and basic protocol

NEMO architecture and BSP are described in this section for convenience of the reader to understand the PD-based schemes (see Sec. IV).

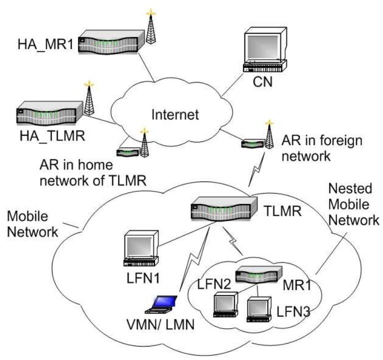

Fig. 1. Architecture of NEMO.

A. Architecture

Fig. 1 shows the architecture of a mobile network [1]. Mobile Routers (MRs) 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 forward. 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 Top Level MR (TLMR) while MR1 is nested under TLMR.

A mobile network is usually connected to a network called the home network where an MR is registered with a router called Home Agent (HA). HA is notified the location of the MR, and re-directs packets, sent by the Correspondent Node (CN) to MNNs. In Fig. 1, HA_TLMR and HA_MR1 are the HAs for TLMR and MR1, respectively.

B. NEMO Basic Support Protocol (BSP)

The home network delegates prefixes to MRs, such as TLMR (see Fig. 1), to advertise to MNNs. TLMR has a Home Address (HoA) through which it is reachable in its home network. When TLMR moves to another network (called foreign network), it obtains a new address (called Care-of-Address (CoA)) from the foreign network, and sends a Binding Update (BU) to HA_TLMR, informing its CoA and, optionally, the prefixes delegated by the home network. HA_TLMR creates a binding cache entry that maps the HoA and prefixes to the CoA of TLMR. This establishes a tunnel [10] between HA_TLMR and TLMR. When the mobile network under MR1 moves into TLMR's network, thereby creating a nested mobile network, MR1 obtains a CoA from TLMR's prefix. This is followed by MR1 sending a BU to HA_MR1 to setup a tunnel like the one discussed above.

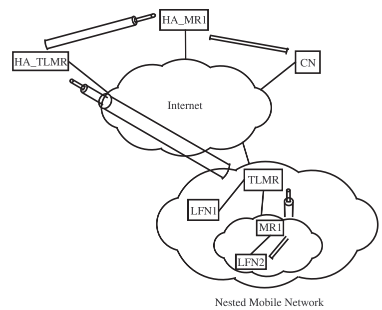

Fig. 2. Multiple tunneling in nested mobile network.

Fig. 2 shows packets going from CN to LFN2 through multiple tunnels in a nested mobile network. Since LFN2 obtains its address from MR1's prefix (which is obtained from MR1's home network), the packets are intercepted by HA_MR1 which encapsulates and tunnels the packets to MR1. Since MR1's CoA is obtained from TLMR's prefix, the packets are intercepted by HA_TLMR which again encapsulates and tunnels them to TLMR, resulting in multiple encapsulations.

Encapsulated packets on reaching TLMR are decapsulated and forwarded to MR1, which again decapsulates the packets and forwards them to LFN2. Thus, two encapsulations are required for a single level of nesting. The number of encapsulations increases with the nesting level.

NEMO BSP has the advantages of reduced signaling and power consumption, and increased manageability. Yet, sending packets through tunnels gives rise to the problems described in Sec. III.

III. Sub-Optimal Routing and Route Optimization schemes

In this section, we present the problems of sub-optimal routing of NEMO BSP, followed by a brief overview of the proposed solutions.

A. Problem of sub-optimal route in NEMO BSP

In NEMO BSP, CNs and MNNs exchange packets through tunnels between MRs and HAs (see Sec. II-B). This may result in sub-optimal routing if a shorter path exists between the CN and the MNN. Sub-optimal routing due to the MR-HA tunnel results in the following inefficiencies that increases with the increase of level of nesting:

1) End-to-end delay increases due to traversal of sub-optimal route. Moreover, sub-optimal route results in waste of resources on those routes that could be avoided if an optimal route were used.
2) Encapsulation of packets requires additional header resulting in reduced bandwidth efficiency.

B. Solutions to sub-optimal routing problem

A number of RO schemes for NEMO have been proposed in the literature. Some schemes provide RO by extending NEMO BSP, while others introduce new entities in the infrastructure for location management, or introduce additional signaling. However, in all schemes a hierarchical (with parent-child relationship among MRs) topology is assumed for the mobile network. Lim et al. [5] classified RO solutions according to the approach they use: Recursive approach, Hierarchical approach, and Prefix delegation.

1) Recursive approach: In recursive approach, partial nesting information are sent to the CN or the HA of the MNN's MR. Partial nesting information consists of the CoAs of MRs (intermediate MRs) on the route from TLMR to the MNN. Therefore, CN or HA can send packets directly to TLMR with the information about how to route packets inside the mobile network. Either the extensions of IPv6 extension headers are used to carry CoAs or the intermediate MRs send BUs to the CN. Schemes proposed in [11]–[14] uses this approach with the differences in the procedure of sending CoAs to CNs.

2) Hierarchical approach: In hierarchical approach, only TLMR's CoA is sent to HA of an MR attached to an MNN so that HA is able to send MNN's packets directly to TLMR. This requires sending CoA of TLMR to other MRs. Moreover, TLMR or nested MR's need to have the CoAs of the MRs underneath to be able to route packets inside the mobile network. CNs send packets to the MNN's HoA. Therefore, HA of MR attached to MNN intercepts packets that are tunneled to TLMR by the HA. Packets are then routed inside the mobile network by TLMR adding intermediate MR's CoA in packet's header or by having intermediate MR knowing HoA-next hop (CoA) mapping. Schemes [3], [15]–[18] differ in how to send CoA of TLMR to intermediate MRs and/or how intermediate MRs have HoA-next hop (CoA) mapping.

3) Prefix Delegation (PD) approach: In PD-based RO schemes, prefixes of the foreign access network are delegated inside the mobile network. Lee et al. proposed a scheme where the MRs get a prefix from the foreign network [6]. The prefix is advertised by the MR inside its own network so that MIPv6 capable nodes inside the network can obtain CoA from that prefix. Similar approach is used in [19], [20] and [7]. Su et al. [9] proposed a PD-based RO scheme that uses an Ad hoc routing protocol for routing inside the mobile network. All these schemes generate large amount of BUs. Park et al. [8] proposes a scheme that aims to reduce the number of BUs while providing RO.

Performance evaluation shows that PD-based approach perform better than other schemes [5]. Therefore, we focus on analyzing PD-based schemes in Sec. IV.

IV. PD-BASED RO SCHEMES FOR NEMO

PD-based schemes differ in optimizing routes for LFNs, obtaining CoAs for MNNs, and sending CoAs to CNs. These differences affect the performance metrics such as handoff and end-to-end delay, signaling and memory usage. We selected four PD-based schemes for comparison by developing analytical models that quantify the metrics. *Models developed for the selected schemes can capture the characteristics of all PD-based schemes as far as the metrics mentioned above are considered.* In this section, we provide a brief overview of the selected schemes.

A. Simple prefix delegation (SPD)

In this scheme [6], the TLMR obtains a CoA from the foreign network, and obtains a prefix to advertise and delegate inside the network. Therefore, the prefix inside the mobile network are hierarchically delegated. Like in MIPv6 [2], MNNs (except LFNs) obtain CoA from the advertised prefix, and registers the CoA with their HAs and CNs. This scheme defines a new neighbor discovery option, called Delegated Prefix Option, which is used by MR to advertise prefix for delegation requiring a specialized prefix delegator (in every mobile network) that has the overhead of performing extra functionality (e.g. authentication, accounting etc.) related to prefix delegation. Moreover, route optimization is not performed for the LFN resulting in LFN's packets being tunneled through the HA of the LFN's MR.

B. MIPv6 based Route Optimization (MIRON)

In MIRON [7], an MIPv6 capable MNN obtain a CoA from the foreign network using PANA [21] and DHCPv6. When the mobile network moves to a new network, the TLMR obtains a CoA using DHCPv6, and starts PANA re-authentication phase to inform the attached MNNs that a new CoA has to be obtained. Attached MNNs 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.

C. Optimal Path Registration (OPR)

Unlike the other prefix delegation-based schemes, OPR [8] does not use MIPv6 route optimization. Prefixes of the foreign network are delegated hierarchically to MRs only through multi-cast 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 original address is put in a header called OPR header which also carries information for the CN to register the translated address in the BC. 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.

D. Ad hoc protocol based (Ad hoc)

Su et al. [9] proposes a scheme where an Ad hoc protocol (e.g. AODV [22]) is used by the MRs to find the AR to use as gateways 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 broadcast by the MRs to the attached MRs. After every 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.

Table I summarizes the differences that affect the performance of the schemes. SPD and Ad hoc do not optimize route for LFNs resulting in higher end-to-end delay due to packets traveling through HA. End-to-end delay can be significant when mobile network is away from the HA and the nesting level is high. The procedure to obtain CoA in MIRON may lead to higher handoff delay when the nesting level is high. In MIRON, route optimization for LFNs requires additional signaling whose amount is dependent on number of LFN-CN communicating pairs. Amount of memory required for OPR and DPT procedures depends on number of MNN-CN communicating pairs. To quantify the differences for a comparative evaluation of the schemes described in this section, we develop analytical frameworks in Sec. V.

TABLE I
DIFFERENCES AMONG THE PD-BASED SCHEMES.

Schemes	**CoA obtained from**	**LFNs' route optimization**	**Additional BU**	**Memory requirement**
SPD	MR	No	No	Depends on number of MRs
MIRON	AR	Yes	Yes, depends on number of CN	Depends on number of MNNs and CNs
OPR	MR	Yes	No	Depends on number of MNNs and CNs
Ad hoc	MR	No	No	Depends on number of MNNs

V. ANALYTICAL MODELS

This section presents the models [23] for the selected PD-based schemes. For convenience, models were developed based on assumptions that do not affect the results as far as comparison of the schemes is concerned. Assumptions, notations, and the models are presented in this section.

A. Notations and assumptions

The models for the schemes, described in Sec. IV, are developed in Sec. V-B. In this section, we introduce the notations that are common among all the schemes, and the assumptions under which the models are developed.

1) Assumptions: We make the following assumptions to simplify development of the models for the RO schemes described in Sec. IV.

- BUs that are sent for refreshment are not considered. This quantity is deterministic and same for all the schemes.
- Number of CNs to which each MNN is communicating is uniform throughout the mobile network.
- Processing capacity of all the nodes are equal. This has little effect on the models because of negligible values of processing delays compared to link delays.
- Time required for packets' processing such as encapsulation/ de-capsulation, address swapping, table searching etc. are similar. This assumption does not affect the models because of negligible values of the processing delay when compared to link delays.
- We only consider the movement of the entire mobile network as a whole (assuming no relative movements among the MNNs) for number of BUs and handoff delay calculations. This type of movement of the mobile network is more likely in the real world.
- We assume a hierarchical (with parent-child relationship) and static topology for the nested mobile network, and this assumption was implicitly made in all previous works on NEMO. Link state and prefix can be disseminated efficiently by broadcasting router advertisements down the hierarchy. When multiple connections are available to MRs, formation and maintenance of the topology in an efficient way can be done using schemes such as proposed in [24]. Such schemes can also be used to setup a path from MNNs to the TLMR for RO in NEMO.
- Handoff delay of an MNN can be expressed as the sum of the delay to obtain a CoA after TLMR's hands off to an AR and the location update delay. Since location update delays are equal for the schemes, differences among handoff delays are determined by the differences in the delay to obtain the CoA.

2) Notations common to all schemes: In this section, we describe the notations that have been used to describe the models in Sec. V-B. Since congestion and contention is different during handoff because of increase in the number of signaling packets, we differentiated them from the congestion and contention delays during times other than handoff. It is also to be noted that the delays due to congestion and contention can be different for the schemes due to differences in signaling. Therefore, we have used different variables to denote the delays due to congestion and contention.

T_f^c = End-to-end delay from LFN to CN
T_a = Delay to obtain CoA
l = Nesting Level of an MNN
s_p = Size of data packet
s_a = Size of router advertisement packet

τ_r	= Average Router Processing Time to process a packet
τ_e	= Average Router Processing Time to encapsulate or decapsulate a packet
b_w	= Average bandwidth available at a wireless node
$c_d^s(l), c_d^m(l), c_d^o(l), c_d^a(l)$	= Hop delay for data packets in wireless links as a function of l for SPD, MIRON, OPR and Ad hoc, respectively
$c_h^s(l), c_h^m(l), c_h^o(l), c_h^a(l)$	= Hop delay during handoff in wireless links as a function of l for SPD MIRON, OPR and Ad hoc, respectively
b_d	= Average bandwidth available at a wired node
m_r	= Memory required by MR
n_b, n_c	= Number of BUs and CNs, respectively
n_r, n_f, n_m, n_v	= Number of MRs, LFNs, LMNs and VMNs, respectively in the entire mobile network
$h_a^h, h_a^c, h_h^c, h_h^h$	= Avg. number of hops from AR to HA, AR to CN, HA to CN, and HA to HA, respectively
n'_r, n'_f, n'_m, n'_v	= number of MRs, LFNs, LMNs and VMNs, respectively attached to an MR

B. Models for RO schemes

In this section, we develop analytical models for the four PD-based schemes to measure the following metrics:

- *Number of BUs:* Number of BUs is measured by the number of BUs generated from a mobile network during handoff. BU consumes bandwidth in both mobile network and wired network, and its number varies among the schemes depending on the number and type of MNNs.
- *End-to-End delay:* End-to-end delay measures the time taken by a packet sent from an MNN to reach a CN. It is a very crucial performance metric for real time applications, and affects the throughput of acknowledgment-based transport protocols. End-to-end delay is significantly different for the schemes when the mobile network is away from the HA, and when nesting level is high.
- *Memory overhead:* Memory overhead reflects the additional memory required at MRs for RO, and it is measured by the number of IPv6 addresses stored in the MR. Memory overhead can be an limiting factor in resource constrained environment, and depends on the number of MNNs.
- *Delay to obtain CoA:* This measures the delay to obtain the CoA during handoff. This delay adds to the handoff delay, varies among the schemes, and is a function of nesting level.

The models are presented in the following subsections:

1) SPD:

- **Number of BUs:** SPD provides RO for all MNNs (except LFNs) that send BUs to CNs and HAs. Thus the number of BUs from each MNN is $(n_c + 1)$, and the number of BUs sent by all MNNs is given by -

$$n_b = (n_c + 1)(n_r + n_m + n_v) \tag{1}$$

- **End to End Delay:** Since no RO is provided for LFNs, packets sent by an LFN are tunneled through its MR's HA. Since other MRs above optimize their route, there is one tunnel only. Therefore, we use number of hops from CN to HA, HA to LFN multiplied by sum of propagation delay, transmission delay, per hop delay and processing delay at each router to calculate end-to-end delay which is given by

$$T_f^c = (l+1)\left(\frac{s}{b_w} + p_w + c_d^s(l) + \tau_r\right) + \left(h_a^h + h_h^c\right)\left(\frac{s}{b_d} + p_d \quad + \tau_r\right) + 2\,\tau_e \tag{2}$$

- **Memory Overhead for TLMR:** In SPD, a prefix is assigned to each attached MR resulting in an entry in the routing table that maps a prefix to the next hop MR. Therefore, memory required is,

$$m_r = 2n'_r \tag{3}$$

- **Delay to obtain CoA:** TLMR obtains a CoA and prefix from the prefix advertised by an AR. Obtained prefix is then advertised inside the mobile network. All MNNs except LFNs, on reception of this advertisement, obtain CoAs from the prefix whereas MRs, like TLMR, obtain a prefix to advertise to its MNNs. The delay to propagate the prefix to an MR at a level is the sum of hop delays due to congestion and contention during handoff, propagation delay, and transmission delay multiplied by the level.

$$T_a = l\left(\frac{s_a}{b_w} + p_w + c_h^s(l) + \tau_r\right) \tag{4}$$

2) MIRON:

- **Number of BUs:** MNNs except LFNs send BUs to respective HAs and CNs. In addition, MRs send BUs to the CNs that are communicating with LFNs. Therefore, the number of BUs for MIRON is given by Eqn. (5).

$$n_b = (n_c + 1)(n_v + n_m + n_r) + n_c n_f \tag{5}$$

- **End to End Delay:** End-to-end delay includes propagation delay, transmission delay, per hop delay and processing delay at each router on the optimized route. Additional delay is incurred for LFNs due to MR replacing the source address by its CoA, and placing the LFN's source address in the extension header. End-to-end delay from LFN to CN is given below.

$$T_f^c = \tau_r\left(l + h_a^c + 1\right) + \left(\frac{s_p}{b_w} + p_w + c_d^m(l)\right)(l+1) + \left(\frac{s_p}{b_d} + p_d\right)h_a^c + \tau_{ad} \tag{6}$$

where τ_{ad} is the average per packet processing time at an MR.

- **Memory overhead for TLMR:** An MR creates a host route entry for each MNN (except LFNs) under it to route packets inside the mobile network. An MR also keeps track of the CN-LFN (attached to MR) pairs. Thus, the memory overhead for MR in MIRON is computed as follows:

$$m_r = 2 \times \left(n_v + n_m + n_r + n_c n'_f\right) \quad (7)$$

- **Delay to obtain CoA:** After obtaining the CoA, an MR starts PANA re-authentication phase (requires four messages) [21] to tell the attached MNNs to obtain a CoA. An MNN sends a DHCPv6 request to obtain a CoA from the foreign access network. The request is relayed by the MRs, on the path to the TLMR, towards the foreign network. The DHCPv6 reply, containing the CoA, reach the MNN along the same path. Therefore, time to obtain CoA for an MNN at any level is the sum of time required to obtain CoA by all the MRs on the path to the TLMR, and the time for DHCPv6 request/reply messages exchange. Let, s_n = Size of PANA message
s_h^q = Size of DHCPv6 request message
s_h^r = Size of DHCPv6 reply message
Then address configuration time is given by

$$T_a = 4\left(\frac{s_n}{b_w} + p_w + c_h^m(l) + \tau_r\right) l + \Big(\frac{s_h^q + s_h^r}{b_w} + 2p_w + 2c_h^m(l) + 2\tau_r\Big) \sum_{i=1}^{i=l} (i+1) \quad (8)$$

Eqn. (8) shows that delay to obtain CoA is quadratic in terms of level.

3) OPR:

- **Number of BUs:** In OPR, only MRs obtain CoA, and send BUs to their HA. No BU is sent to the CN for RO. Thus the number of BUs becomes equal to the number of MRs in the mobile network.

$$n_b = n_r \quad (9)$$

- **End-to-End delay:** OPR procedure to register the new translated address with the CN requires table searching at MR, and binding cache searching at CN for every packet. Also, the address of the packet is changed by MR before forwarding it. We combine these three processing costs as OPR processing cost in our model. Therefore, end-to-end delay in OPR is the sum of OPR processing time and the end-to-end delay of MIRON (Eqn. (6)) as given below.

$$T_f^c = \tau_r\left(l + h_a^c + 1\right) + \left(\frac{s_p}{b_w} + p_w + c_d^o(l)\right)(l+1) + \left(\frac{s_p}{b_d} + p_d\right) h_a^c + \tau_{ad} + \tau_{OPR} \quad (10)$$

where, τ_{OPR} is the OPR processing time at MR.

- **Memory overhead for TLMR:** In addition to routing entries like SPD, OPR scheme stores a table at each MR for the OPR procedure. For each CN-MNN pair attached to the MR, the table requires an entry containing original address, translated address and the flags. Hence, memory overhead for MR in OPR scheme is given by Eqn. (11).

$$m_r = 2n'_r + 3n_c\left(n'_v + n'_m + n'_f + n'_r\right) \quad (11)$$

- **Delay to obtain CoA:** This delay is the same as that of SPD, and is given by Eqn. (4).

4) Ad hoc:

- **Number of BUs:** Like SPD, Ad hoc scheme optimizes route for all MNNs except LFNs. Therefore, number of BUs can be found from Eqn. (1).
- **End to End Delay:** End-to-end delay for this scheme is equal to the end-to-end delay for SPD ignoring the the additional delay incurred at the start of packet delivery to find a route to the AR using AODV [22], and is given by Eqn. (2).
- **Memory Overhead for TLMR:** When an MNN communicates with one or more CNs, TLMR has to maintain one routing entry to forward packets for that MNN. Therefore, the memory overhead of this scheme is given by Eqn. (12).

$$m_r = n_v + n_m + n_r \quad (12)$$

- **Delay to obtain CoA:** An MR obtains a CoA from the advertised prefix followed by path discovery to AR using AODV, and advertise the prefix inside its network. Therefore, the delay will be the sum of propagation delay of prefix, and the path discovery delay. To calculate path discovery delay, we use the number of hops between the AR and an MR which is essentially the level of that MR.

$$T_a = l\left(\frac{s_a}{b_w} + \frac{s_r^q}{b_w} + \frac{s_r^r}{b_w} + 3\left(p_w + c_h^a(l) + \tau_r\right)\right) \quad (13)$$

Where,
s_r^q = Size of AODV request message
s_r^r = Size of AODV reply message

The models developed in this section are used to compare the schemes using numerical results that are validated by simulation, and analyzed in Sec. VI.

VI. Simulation and results

In this section, we present numerical results obtained from the models developed in Sec. V, and validate the results using ns-2 [25] simulation. Since ns-2 can not be used to validate memory overhead, and the number of BUs is deterministic, we only validate delay to obtain CoA and end-to-end delay. Delay to obtain CoA is the time difference between the time instant TLMR obtains a CoA and the time instant the lowest level MR obtains a CoA. On the other hand, end-to-end delay was measured by the difference between the time instant of CN receiving a packet and the time instant of LFN sending the packet.

A. Simulation environment

Fig. 3 shows the simulation topology for two nesting levels. LFN1 was set as the constant bit rate data source over UDP and CN was the destination. The mobile network moves between ARs resulting in mobile network handoff. Since the results differ among the schemes only for LFNs, we used LFNs in our simulation. IEEE 802.11 was used for all wireless communications. The number of hops between HA_MR3 and the mobile network was varied by varying the number of routers between HA_MR3 and R. Values of parameters used in the simulation and models are summarized in Sec. VI-B.

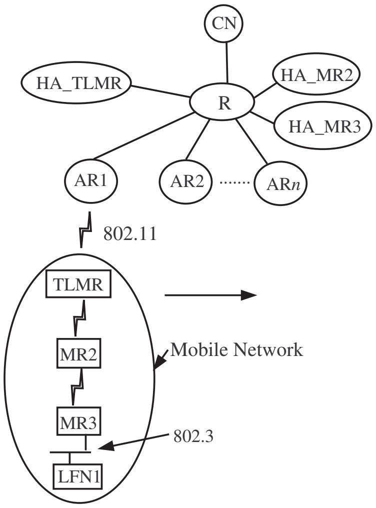

Fig. 3. Topology used for simulation with two levels of nesting.

B. Simulation and model parameters

Table II shows the values of parameters used in the models and simulation. Values for processing time, bandwidth and propagation delays are those used in [8]. Since the DPT processing time includes table searching, address changing and copying new address, we set DPT processing time as three times of the processing time. Packet sizes for the schemes are taken from the corresponding schemes. Average hop delays (propagation, contention and congestion) in wireless links are obtained from simulation.

TABLE II
VALUES OF THE PARAMETERS USED IN THE MODELS

$s_p = 1000$ bytes	$s_a = 88$ bytes
$\tau_r = 10\mu$s	$s_n = 76$ bytes
$\tau_e = 10\mu$s	$s_h^q = 96$ bytes
$b_w = 10^7$ Mbps	$s_h^r = 184$ bytes
$s_r^q = 88$ bytes	$s_r^r = 84$ bytes
$\tau_{dpt} = 30\mu$s	$\tau_{ad} = 10\mu$s
$p_w = 30/(3 \times 10^8)$ s	$p_d = 1.8$ ms
$c_d^s(l), c_d^m(l), c_d^o(l), c_d^a(l)$ = Presented in Fig. 8	$c_h^s(l), c_h^m(l), c_h^o(l), c_h^a(l)$ = Presented in Fig. 11

C. Results

1) Number of BUs: Fig. 4 shows that the number of BUs for SPD, Ad hoc and MIRON increases linearly with the number of CNs. This is because RO requires BUs to be sent to each CN. Number of BUs for MIRON is higher than Ad hoc and SPD because MIRON optimizes routes for LFNs that requires additional BUs to CN.

Fig. 5 shows that the number of BUs in MIRON increases linearly with the number of LFNs as BUs are sent for each LFN. The number of BUs for SPD and Ad hoc are constant with respect to number of LFNs which require no BUs as their routes are unoptimized.

As revealed by Figs. 4 and 5, the number of BUs for OPR is the lowest and constant because no BUs are sent to CNs.

2) Memory overhead for TLMR: Fig. 6 shows the impact of the number of CNs on the memory overhead of TLMR. The rate of increase for OPR is the highest as the TLMR tracks all CN-MNN (attached) communications. In MIRON, only CN-LFN (attached) communications are tracked. Memory overhead in SPD and Ad hoc is constant with respect to the number of CNs because tracking of ongoing communications are required. Memory overhead for Ad hoc is higher than that of SPD due to memory used to maintain routing entries for all MNNs (except LFNs) in contrast to SPD's maintaining routing entry for attached MRs only (because of hierarchical prefix delegation).

3) End-to-end delay: Fig. 7 shows the end-to-end delay as a function of level, where the end-to-end delay increases almost linearly except for the Ad hoc scheme where it tends to be non-linear at higher levels. The end-to-end delay depends on sum of hop delays. Since hop delay for Ad hoc scheme increases linearly with level (see Fig. 8), increase of end-to-end delay is quadratic (see Eqn. (2)) as a function of level (see Fig. 7). End-to-end delay for the other schemes is linear as a function of level because increase of hop delay with level is insignificant.

Hop delay for the schemes is presented in Fig. 8. The reason for higher rate of increase for Ad hoc scheme is the increased contention and congestion due to periodic signaling for updating routes.

End-to-end delay as a function of number of hops between the mobile network and its HA is shown in Fig. 9. End-to-end delay for SPD and Ad hoc schemes increases with increasing number of hops due to increase in route length as packets traverse through HA. End-to-end delay for MIRON and OPR is independent of the number of hops because packets do not go through the HA.

4) Delay to obtain CoA: Fig. 10 presents the delay for the lowest level MR to obtain a CoA. For MIRON, rate of increase is higher than others due to quadratic nature of the delay as a function of level (see Eqn. 8) compared to the linear nature (see Eqn. (4)) for other schemes. Delay to obtain CoA in Ad hoc is higher than that of SPD and OPR due to additional time required to find route to an AR using AODV request/reply messages after the CoA is obtained. Delay to obtain CoA for SPD and OPR is similar because of the similar procedure to obtain CoA. At lower levels, delay in Ad hoc scheme is higher than the delay in MIRON due to two reasons. First, the lack of domination of the quadratic delay of MIRON at lower values of level. Second, hop delay of Ad hoc scheme is higher than that of MIRON.

Fig. 11 shows the hop delays for the schemes during handoff. Hop delays for SPD and OPR are the highest due to the following reason. Hop delay for the first packet (RA, PANA message, etc.), sent from the TLMR to the attached MNNs after the discovery of an AR, is much larger compared to hop delays for the rest of the signaling packets. Since we compute hop delays by taking mean of the hop delays for all signaling packets generated during handoff, it is small when number of signaling packets generated is large, and vice versa. Hop delays are higher in SPD and OPR than that of MIRON and Ad hoc because of smaller number of signaling packets.

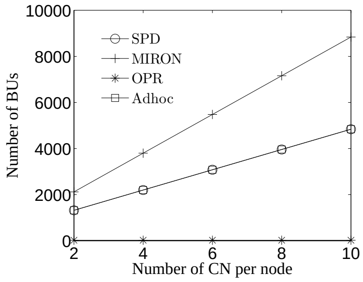

Fig. 4. Number of BUs with $n_r = 20$, $n_m = 20$, $n_v = 400$ and $n_f = 400$. Values for SPD and Ad hoc are equal and superimposed. Values for OPR is small and superimposed on the axis.

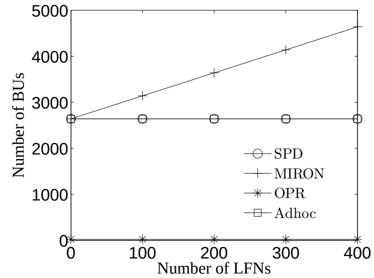

Fig. 5. Number of BUs with $n_r = 20$, $n_m = 20$, $n_v = 400$ and $n_c = 5$. Values for SPD and Ad hoc are equal and hence, superimposed. Values for OPR is small, and superimposed with the axis.

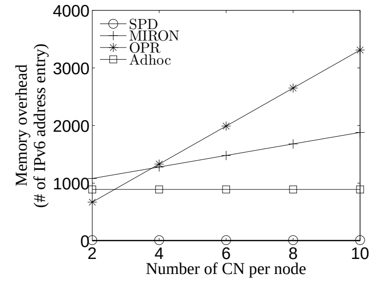

Fig. 6. Memory overhead with increasing number of CNs.

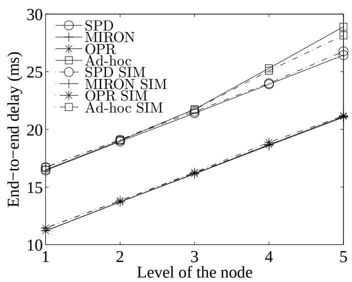

Fig. 7. End-to-End delay between CN and LFN. Data for MIRON and OPR are very close and almost superimposed.

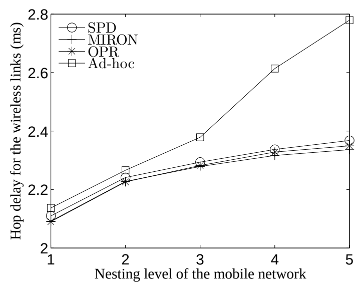

Fig. 8. Hop delay in the wireless links for different schemes.

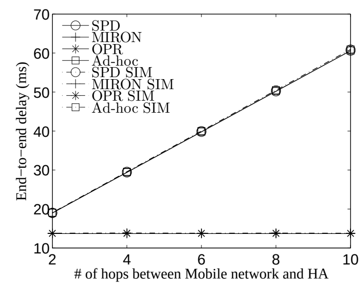

Fig. 9. End-to-End delay between CN and the LFN. Data for SPD and Ad hoc, and values for MIRON and OPR are very close and superimposed.

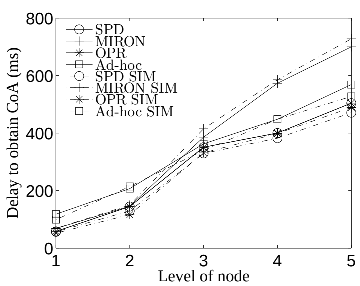

Fig. 10. Delay to obtain CoA by the lowest level MR for the schemes.

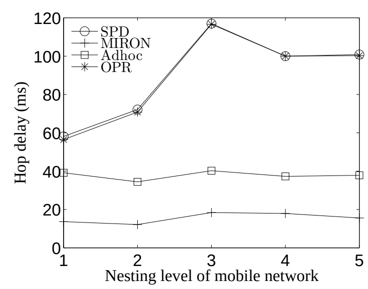

Fig. 11. Hop delay for different schemes during handoff.

Hop delay in Ad hoc is higher than MIRON due to more congestion and contention during handoff because of broadcast of signaling packets.

VII. Comparative analysis of the schemes

Sec. VI-C presented the metrics (discussed in Sec. V-B) as a function of level, number of hops between mobile network and HA, and number of CNs and LFNs. The metrics can affect the performance, and limit the application of the schemes depending on handoff frequency (due to generation of signaling and handoff delay during handoff), number and types of MNNs, distance of the mobile network from the HA, and level. Among the parameters, handoff frequency is determined by the mobility scenario whereas others are the characteristics of the mobile network. Therefore, in this section, we perform a qualitative comparison of the schemes to discuss the suitability of the schemes under various scenario that affects the parameters and hence, the metrics. We also present a comparative summary of the schemes that shows the major advantages achieved by the schemes, and the cost for achieving the advantages.

A. Comparison based on mobility characteristics

Results for delay to obtain CoA and signaling of the schemes presented in Sec. VI-C can be analyzed for comparison of the schemes under the following mobility scenario.

- Scenario 1 (high mobility): A mobile network, traveling at high velocity, has low residence time and high handoff frequency. Since OPR generates the minimum number of BUs with low handoff delay, it is the most preferable scheme for this scenario. SPD can be the next choice in high mobility scenario due to handoff delay similar to OPR along with signaling lower than MIRON.
- Scenario 2 (low mobility): This can be a mobile network in a vehicle moving at a low velocity and thus, having low

handoff frequency. MIRON and OPR will provide better throughput than other schemes, as these schemes optimize route for all MNNs. Effect of large delay to obtain CoA on throughput will be low in MIRON because of fewer number of handoffs.

B. Comparison based on number of LFNs

Packets to or from LFNs are tunneled in SPD and Ad hoc in lie of the advantage of having low signalling. Additional bandwidth required due to tunneling headers might be compensated by low bandwidth consumption of small number of signaling. But tunneling also results in high end-to-end delay that affects performance of real-time traffic and acknowledgement-based transfer protocols. Since the end-to-end delay due to tunneling is small in SPD and Ad hoc when the mobile network is close to home agent, and bandwidth consumption due to BUs will be high in MIRON when number of LFNs is high, SPD and Ad hoc will be preferable to MIRON.

C. Comparison based on memory requirement

In memory constrained environments (such as mobile phones or sensors acting as routers which are also characterized by low processing capability), Ad hoc is the best choice due to low memory overhead. Although SPD has even lower memory overhead than Ad hoc, the requirement for each MR in SPD to be a prefix delegator seems to be infeasible due to additional processing overhead required by MRs to act as prefix delegators.

D. Comparison: Principal advantages and associated cost

Table III summarizes principal advantages of the schemes and cost to achieve those advantages. Because of tractability reasons, not all the costs mentioned here were modeled in this paper.

Comparison shows that there is no single scheme which is best for all mobility scenarios and mobile network characteristics. Therefore, either a choice has to be made to adapt to the current scenario (static case), or schemes have to be extended to adapt to changing scenarios. If the scenario is known in advance, a suitable scheme, as suggested in this section, can be selected to get better performance. For example, if it is known that the mobile network will have low mobility and a small number of LFNs, then MIRON can be the best option. Alternatively, a scheme can be extended to adapt to dynamically changing scenarios. For example, depending on the mobility scenario, number of LFNs and distance from home, SPD can be extended to operate in RO or non-RO mode for LFNs.

VIII. Conclusion

In this paper, we have presented analytical model-based analysis and evaluation tool for PD-based route optimization schemes. Evaluation metrics include number of BU messages, end-to-end delay, memory overhead, and time required to obtain CoA. Results obtained from the models can be used to select an appropriate PD-based scheme for a mobile network as a function of mobility scenario, number and types of MNNs, number of CNs, distance of mobile router from its HA, and nesting level.

Results showed that the performance of a scheme depends on the characteristics of the mobile network, and there is no single scheme which suits all mobility scenarios. OPR performs better than other schemes, but can optimize the route only when packets flow from the mobile network to the CN. MIRON performs better at low speeds of the mobile network with small number of LFNs, and low nesting level. SPD and Ad hoc perform better when a mobile network with a large number of LFNs is close to its home. These findings might lead to the use of different mobility protocols for different mobile network characteristics and resources at MRs. Therefore, for optimal performance, choice of a scheme should be based on adaptation to the mobility scenario and characteristics of the mobile network. Schemes may also be extended to adapt to the dynamic mobility scenario and mobile network characteristics.

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TABLE III
SUMMARY OF MAJOR PERFORMANCE GAINS AND COSTS FOR PERFORMANCE GAIN

Schemes	**Advantages**	**Cost of achieving the advantages**
SPD	Lowest memory overhead.	Prefix delegation involves security, authentication and accounting overheads, and is not possible through extended RA only. It might not be feasible to use all MRs as prefix delegators.
MIRON	1) Optimize route for LFNs 2) Use of standard protocols for CoA configuration.	Increased signaling, memory overhead and delay to obtain CoA.
OPR	Lowest signaling.	1) Memory overhead to track communication of all attached MNNs can increase significantly with the number of actively communicating CNs. 2) Additional processing per packet at MRs and CNs. 3) Inability to optimize route when packets are not sent from the mobile network to CN
Ad hoc	1) Lower expected memory overhead because routes are dynamically discovered at the start of communication (thus no permanent route entry is required.). 2) Resistant to creation of self loop when the MRs move relative to each other like MRs in a MANET	1) Large delay to obtain CoA due to route discovery after handoff. 2) Mobile networks have hierarchical architecture with stable connectivity but ad hoc protocols are designed for networks without hierarchy where connections are intermittent. Therefore, Ad hoc RO causes unnecessary signaling for mobile networks.

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