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Scalability Analysis of NEMO Prefix Delegation-based Schemes

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Abstract—**A number of prefix delegation-based schemes have been proposed to solve the route optimization problem in NEMO, where a group of hosts move together as a mobile network. The schemes trade off between inefficiency of routes and various overheads. With the rapid growth of mobile computing, this overhead will give rise to the scalability issue of these schemes. However, there has been no quantitative study on the asymptotic scalability analysis of these schemes. In this paper, we have developed analytical models for scalability analysis of these schemes in terms of network size, mobility rate, distance between mobility agents, and traffic rate. Our analysis shows that the prefix delegation-based schemes exhibit asymptotically identical overhead on the network, and they show better asymptotical scalability in terms of number of mobile routers. The analytical framework for scalability analysis presented in this paper will help in visualizing the effects of future network expansion on the performance of these route optimization schemes of NEMO.**

I. INTRODUCTION

Network Mobility (NEMO) [1] was proposed to efficiently manage the mobility of multiple hosts moving together, such as hosts in a vehicle. NEMO Basic Support Protocol (BSP) [1] suffers from the problem of inefficient route. Route optimization schemes, proposed to solve the problem, trade off between inefficiency of route and overheads, such as signaling, processing, and memory consumption. The schemes have been classified and compared [2] based on the approaches used for route optimization, and Prefix Delegation (PD)-based schemes have been found to perform better than other schemes in terms of route efficiency and overheads [2].

In NEMO, *network parameters* (such as, network size, mobility rate, traffic rate, distances from mobility agents) influence signaling and routing overheads incurred by PD-based schemes. These overheads are termed as *network mobility cost* that include tunneling packets through partially optimized routes, updating Home Agents and hosts about location change, and processing and lookup by mobility agents. Expansion of the network size will increase the network mobility cost incurred at the *mobility management entities* (e.g., home agents, mobile routers, etc) resulting in performance degradation of the network. Hence, the scalability of the route optimization schemes has to be analyzed quantitatively to choose a suitable scheme for efficient management of NEMO.

The scalability of a protocol is defined as its ability to support continuous increase of network parameters without degrading performance [3]. Santivanez et al. [3] present a framework to study the scalability of ad hoc routing algorithms. Philip et al. [4] use the same framework [3] for the scalability analysis of location management protocols of MANETs. Gwon et al. [5] present scalability and robustness analysis of MIPv6, FMIPv6, HMIPv6 using large-scale simulations. Some NEMO route optimization schemes [6], [7] are claimed to be scalable with no supportive quantitative evaluation.

Our *objective* is to quantitatively evaluate the scalability of PD-based schemes using mathematical models to find out the impact of network parameters on the network and mobility management entities. The authors are not aware of any such evaluation of route optimization schemes. In this paper, we have selected four representative PD-based schemes for evaluation: Simple Prefix Delegation (SPD) [8], Mobile IPv6-based Route Optimization (MIRON) [9], Optimal Path Registration (OPR) [10] and Ad hoc protocol-based route optimization (Ad hoc-based) [11]. We have used analytical cost models for NEMO PD-based schemes [12] to perform scalability analysis of the four schemes.

Our *contributions* are : (i) developing analytical models for scalability analysis of PD-based schemes for various mobility entities and the network, and (ii) comparative analysis of the schemes based on scalability. Results show that all the schemes (except OPR) scale when compared to NEMO BSP. and they exhibit better asymptotical scalability in terms of number of mobile routers and hosts. This will provide useful framework to analyze other route optimization schemes, and to select suitable schemes in future network.

The rest of the paper is organized as follows. NEMO architecture, NEMO BSP, and PD-based schemes are summarized in Secs. II and III. Scalability analysis of four PD-based schemes are presented in Sec. IV. Sec. V presents comparative analysis of the schemes. Finally, Sec. VI has the concluding remarks.

II. NEMO ARCHITECTURE AND NEMO BSP

Fig. 1 shows the architecture of a Mobile Network (MN) [1] where Mobile Routers (MRs) act as the gateways for each Mobile Network Node (MNN). Different types of MNNs are:

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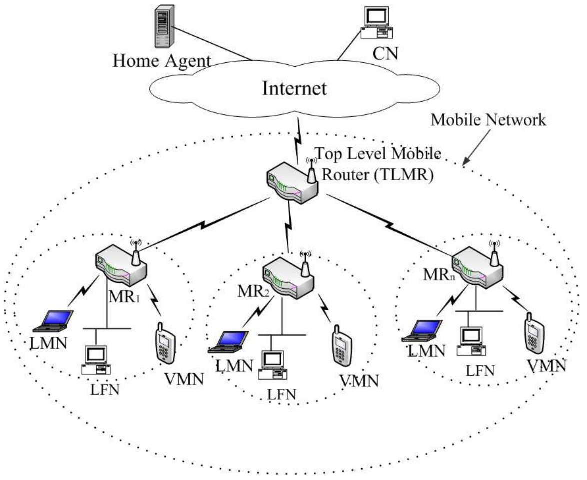

Fig. 1. Architecture of a MN used for Scalability analysis.

Local Fixed Nodes (LFN) that do not move with respect to MN, Local Mobile Nodes (LMN) that usually reside in MN and can move to other networks, and Visiting Mobile Nodes (VMN) that get attached to the MN from another network. The MR, directly attached to the wired network through an Access Router (AR), is called Top Level MR (TLMR) while other MRs are nested under TLMR. An MN is usually connected to a home network to which an MR is registered with a router called the Home Agent (HA). Nodes that communicate with MNNs is called Correspondent Nodes (CNs).

In NEMO BSP [1], an MR gets a prefix in its home network to advertise to MNNs that obtain addresses, called Home Addresses (HoA), from the prefix. When the MN moves to a foreign network, the MR obtains a new address called Care-of-Address (CoA) from foreign network, and sends a Binding Update (BU) to HA informing the CoA. The HA intercepts packets sent to MNNs, and tunnels them to MR. Since an MN, nested under another MN, obtains CoA from the prefix of MN above, packets first go to the HA of nested MN and then to the HA of the MN above, resulting in suboptimal route and header overhead. Therefore, route optimization schemes, based on various approaches, have been proposed.

III. PD-BASED ROUTE OPTIMIZATION SCHEMES

PD-based schemes obtain CoAs for MNNs from the prefix of foreign network, and let CN know the CoA. CN creates a Binding Entry (BE) that maps the HoA of MNN to the CoA. Therefore, CN can send packets directly to foreign network (without going through HAs). Yet, CoA obtaining process and route optimization for LFNs varies across the schemes, and depending on the variations, we have selected four representative schemes.

A. Simple Prefix Delegation (SPD)

In SPD [8], MRs are delegated a prefix, aggregated at foreign network's prefix, to advertise to MNNs for obtaining of CoAs to perform MIPv6 like route optimization. Being MIPv6 incapable, LFNs cannot perform route optimization resulting in packets to be tunneled through their HAs.

B. Mobile IPv6-based Route Optimization (MIRON)

In MIRON [9], an MR, after obtaining a CoA, notifies attached MNNs (except LFNs) to obtain a CoA. An MNN sends a request which is relayed to the foreign network. A reply with a CoA configured from foreign network prefix is sent to the MNN. For LFNs' route optimization, MRs' CoAs are used to communicate with CNs.

C. Optimal Path Registration (OPR)

In OPR [10], CoA obtaining procedure is similar to SPD, except that only MRs obtain CoAs from the delegated prefix. To optimize route for MNNs, MRs translate addresses inside packets into new addresses using the delegated prefix, put the original address in OPR header, and set a bit in OPR header to register the translated address at CN by creating a BE.

D. Ad hoc-based Scheme

Su et al. [11] proposes a scheme where an Ad hoc protocol (e.g. AODV) is used by the MRs to find the AR to use it as the gateway 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.

IV. SCALABILITY ANALYSIS

In this section, we analyze the scalability of NEMO BSP, SPD, MIRON, OPR and Ad hoc-based. We focus on six network parameters: number of mobile nodes (N_m), number of mobile routers (N_r), number of LFNs (N_f), speed of the MNs (V), number of hops (h) and average number of CNs (N_c) with which an MNN is communicating. These parameters mainly influence network mobility costs. To consider the effect of mobility rate on scalability, we use subnet residence time, T_r. The reciprocal of subnet residence time gives the handoff frequency which is typically proportional to the speed (V) of MN; thus $T_r \propto (1/V)$.

A. Definition of Scalability

According to Santivanez et al. [3], scalability is the ability of a network to support the increase of its limiting parameters without degrading performance. Scalability of NEMO schemes is defined as the ability to support continuous increase of network parameters without degrading performance of various network entities that are responsible for mobility management. Let $\Gamma^X(\lambda_1,\ \lambda_2,\ ...)$ be the total overhead induced by PD-based scheme X, dependent on parameters λ_1, λ_2, λ_3, and so on. Therefore, scheme X's network mobility scalability factor with respect to λ_i is defined as

$$\rho^X_{\lambda_i} = \lim_{\lambda_i \to \infty} \frac{\log \Gamma^X(\lambda_1, \lambda_2, ...)}{\log \lambda_i} \tag{1}$$

NEMO BSP is the base protocol on which the PD-based schemes have been built. Let $\rho^N_{\lambda_i}$ be the scalability factor of NEMO BSP with respect to parameter λ_i. Then scheme X is said to be scalable with respect to parameter λ_i, if $\rho^X_{\lambda_i} \leq \rho^N_{\lambda_i}$.

B. Topology of MN

Since no standard architecture for NEMO exists, we use a generalized topology. We assume the MN having a two-level hierarchy of MRs (Fig. 1). TLMR is at level 0, hence $N_r^{(0)} = 1$ ($N_r^{(i)}$ is number of MRs at level i, and similar meaning for N_m and N_f). No LFN, LMN or VMN is connected directly to TLMR. The TLMR is connected to $N_r^{(1)}$ number of level-1 routers, so $N_r^{(1)} = N_r - 1$ as there is no MR at level 2. Hence, $N_r^{(2)} = 0$. There is no host at levels 0 and 1. So $N_m^{(0)} = N_f^{(0)} = N_m^{(1)} = N_f^{(1)} = 0$. All nodes are at level 2, i.e., $N_m^{(2)} = N_m$, and $N_f^{(2)} = N_f$.

C. Notations

Notations [12] used in this paper are listed here.

Λ_Y^X = Cost of type Y incurred at network for scheme X,
Ψ_Y^X = Cost of type Y incurred at TLMR for scheme X,
Φ_Y^X = Cost of type Y incurred at HA for scheme X,
N_r = Number of MRs in MN
N_m = Number of LMNs and VMNs in MN
N_f = Number of LFNs in MN
N_c = Number of CNs communicating with each node,
l = Nesting Level (hops to TLMR),
h_{ah} = Average number of hops from AR to HA
h_{ac} = Average number of hops from AR to CN,
h_{hc} = Average number of hops from HA to CN,
h_{hh} = Average number of hops from HA to HA,
τ_l = Per hop transmission cost for location update
τ_s = Per hop transmission cost for session continuity,
τ_{dt} = Per hop transmission cost for sending data,
τ_d = Transmission cost of DHCPv6 messages,
τ_p = Avg. transmission cost of PANA messages,
τ_a = Avg. transmission cost of route req-reply messages,
τ_r = Transmission cost for the router advertisement,
σ = Proportionality constant of transmission cost over wired and wireless network,
ψ = Linear coefficient for lookup costs,
π_t = Tunnel processing costs at HA and MR,
λ_s = Average session arrival rate for a node,
S = number of sessions,
F = File size,
P = Maximum transmission unit,
T_r = Subnet residence time,
T_{lf} = Lifetime of BE,
T_{ra} = Interval of sending periodic router advertisement.

D. NEMO BSP

Here, we derive the asymptotic expressions of costs [12] for NEMO BSP on the TLMR, HA, and the complete network.

1) TLMR: For the two-level hierarchy, the expression for total costs (Eqn. (10) in [12]) at TLMR can be simplified as the following using the Θ notation[1]:

$$\begin{aligned}
&\Psi_T^N = \Psi_{LU}^N + \Psi_{SC}^N + \Psi_{PD}^N \\
&= 2\sigma\tau_l \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 2\sigma\big((\tau_l + \pi_t)(N_r + N_m - 1) + \\
&\tau_{ip}(N_r + 2N_m - 1) + 2N_cN_m \left[(\sigma\tau_s + \pi_t) + 2\sigma\tau_{ip}\right] \big) \\
&\times \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + N_c\lambda_s \frac{F}{P}(N_f + N_m)(\tau_{dt} + \sigma\tau_{ip} + \pi_t) \\
&+ \sigma N_m N_c \frac{\lambda_s}{S}(\tau_{ip} + \tau_{dt}) = \Theta(V(N_r + N_mN_c) + N_cN_f)
\end{aligned} \tag{2}$$

The values of σ, τ_l, τ_s, π_t, τ_{ip}, T_r/T_{lf}, λ_s, F, P, and ψ are invariant as far as scalability analysis is concerned. Therefore, NEMO BSP's scalability factors for TLMR w.r.t. N_m, N_r, N_f, V, h and N_c are

$$\rho_{N_m}^{N(R)} = \lim_{N_m \to \infty} \frac{\log(V(N_r + N_mN_c) + N_cN_f)}{\log N_m} = 1$$

$$\rho_{N_r}^{N(R)} = \lim_{N_r \to \infty} \frac{\log(V(N_r + N_mN_c) + N_cN_f)}{\log N_r} = 1$$

$$\rho_{N_f}^{N(R)} = \lim_{N_f \to \infty} \frac{\log(V(N_r + N_mN_c) + N_cN_f)}{\log N_f} = 1$$

$$\rho_{V}^{N(R)} = \lim_{V \to \infty} \frac{\log(V(N_r + N_mN_c) + N_cN_f)}{\log V} = 1$$

$$\rho_{h}^{N(R)} = \lim_{h \to \infty} \frac{\log(V(N_r + N_mN_c) + N_cN_f)}{\log h} = 0$$

$$\rho_{N_c}^{N(R)} = \lim_{N_c \to \infty} \frac{\log(V(N_r + N_mN_c) + N_cN_f)}{\log N_c} = 1$$

2) HA: The total costs (Eqn. (11) in [12]) at HA of NEMO BSP can be simplified as:

$$\begin{aligned}
&\Phi_T^N = \Phi_{LU}^N + \Phi_{SC}^N + \Phi_{PD}^N \\
&= \phi N_r(2\tau_l + \pi_h) \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 2\Bigg((N_r + N_m - 1)(\tau_l \\
&+ \pi_t + \frac{1}{2}\pi_h + \psi(N_r + N_m) + \tau_{ip}) + \tau_{ip}N_m + 2N_cN_m \\
&\times \big(\tau_s + 2\tau_{ip} + \pi_t + \psi(N_r + N_m)\big)\Bigg) \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + N_c\lambda_s \frac{F}{P} \\
&\times (N_f + N_m)\Big((\tau_{dt} + 2\tau_{ip}) + (\psi(N_r + N_m) + \pi_t)\Big) \\
&+ N_c \frac{\lambda_s}{S} N_m \Big((\tau_{dt} + 2\tau_{ip}) + (\psi(N_r + N_m) + \pi_t)\Big) \\
&= \Theta((N_r + N_m)(V(N_r + N_cN_m) + N_fN_c))
\end{aligned} \tag{3}$$

So NEMO BSP's scalability factors for HA w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 2, 1, 1, 0, and 1.

3) Complete Network: The location update cost (Eqn. (3) in [12]) of NEMO BSP for the complete network is,

$$\begin{aligned}
&\Lambda_{LU}^N = (2(h + \sigma)\tau_l + \pi_h) \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 2((N_r - 1)((\sigma + h) \\
&\times (5\tau_l + 4\tau_{ip}) + 6\pi_t + 3\psi(N_r + N_m) + \pi_h) + N_m(4\pi_t \\
&+ 3(\tau_l + \tau_{ip})(\sigma + h) + 2\psi(N_r + N_m) + \pi_h/2)) \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} \\
&= \Theta(V(N_r + N_m)(h + N_r + N_m))
\end{aligned} \tag{4}$$

We assume $h = h_{ah} = h_{hc} = h_{ac} = h_{hh}$. Similarly, session continuity cost (Eqn. (6) in [12]) can be written as,

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

$$\begin{aligned}\Lambda_{SC}^{N} &= 2N_cN_m\frac{\lfloor\frac{T_r}{T_{lf}}\rfloor}{T_r}\Bigg(3\sigma\tau_s + 3\sigma\tau_{ip} + 4\pi_t + 3h\tau_s + 3h\tau_{ip}\\ &+ 2\psi(N_r + N_m)\Bigg) = \Theta(VN_cN_m(h + N_r + N_m))\end{aligned} \tag{5}$$

And packet delivery cost (Eqn. (9) in [12]) can be written as,

$$\begin{aligned}\Lambda_{PD}^{N} &= N_c\lambda_s\frac{F}{P}(N_f + N_m)\Big(2\psi(N_r + N_m) + 4\pi_t\\ &+ 3h\tau_{dt} + 3h\tau_{ip} + 3\sigma(\tau_{ip} + \tau_{dt})\Big) + N_c\frac{\lambda_s}{S}N_m\\ &\times\Big(h(2\tau_{dt} + 4\tau_{ip}) + \psi(N_r + N_m) + \pi_t + 2\sigma\tau_{ip}\Big)\\ &= \Theta(N_c(N_f + N_m)(h + N_r + N_m))\end{aligned} \tag{6}$$

Thus total cost of NEMO BSP on complete network is,

$$\begin{aligned}\Lambda_T^N &= \Lambda_{LU}^N + \Lambda_{SC}^N + \Lambda_{PD}^N\\ &= \Theta((V(N_r + N_cN_m) + N_cN_f)(h + N_r + N_m))\end{aligned} \tag{7}$$

Hence, NEMO BSP's scalability factors for complete network w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 2, 1, 1, 1 and 1, respectively.

E. SPD

In this section, we derive the asymptotic expressions of network mobility cost [12] for SPD scheme on the TLMR, the HA, and the complete network.

1) TLMR: The total cost (Eqn. (23) in [12]) at TLMR in SPD scheme can be simplified as:

$$\begin{aligned}\Psi_T^S &= \Psi_{LU}^S + \Psi_{SC}^S + \Psi_{PD}^S + \Psi_{CO}^S\\ &= \Big(2\sigma\tau_l(N_r + N_m) + 2\sigma\tau_sN_mN_c\Big)\frac{1+\lfloor\frac{T_r}{T_{lf}}\rfloor}{T_r} + N_c\lambda_s\frac{F}{P}\\ &\times\Big(\sigma\tau_{ip}N_f + \sigma\tau_{dt}(N_f + N_m)\Big) + \sigma\tau_{ip}N_cN_m\frac{\lambda_s}{S}\\ &+ \frac{2\sigma\tau_d\,(N_r - 1)}{T_r} = \Theta\Big(V(N_r + N_mN_c) + N_cN_f\Big)\end{aligned} \tag{8}$$

So SPD's scalability factors for TLMR w.r.t. N_m, N_r, N_f, V, h and N_c are 1, 1, 1, 1, 0, and 1, respectively.

2) HA: The total cost (Eqn. (24) in [12]) at HA is:

$$\begin{aligned}\Phi_T^S &= \Phi_{LU}^S + \Phi_{PD}^S\\ &= (N_r + N_m)\,(2\tau_l + \pi_h)\,\frac{1+\lfloor\frac{T_r}{T_{lf}}\rfloor}{T_r} + \Big(N_mN_c\frac{\lambda_s}{S} +\\ &+ N_fN_c\lambda_s\frac{F}{P}\Big)\Big(\psi\,(N_r + N_m) + \tau_{dt} + \tau_{ip} + \pi_t\Big)\\ &= \Theta\Big((N_r + N_m)(V + N_fN_c + N_mN_c)\Big)\end{aligned} \tag{9}$$

Therefore, SPD's scalability factors for HA w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 1, 1, 0, and 1.

3) Complete Network: Finally, the total cost (Eqn. (25) in [12]) on complete network is:

$$\begin{aligned}\Lambda_T^S &= \Lambda_{LU}^S + \Lambda_{SC}^S + \Lambda_{PD}^S + \Lambda_{CO}^S\\ &= \Bigg((N_r + N_m)(2\tau_lh + \pi_h) + 2\sigma\tau_l(2N_r + 3N_m - 1)\\ &+ 2\tau_sN_cN_m(h + 3\sigma)\Bigg)\frac{1+\lfloor\frac{T_r}{T_{lf}}\rfloor}{T_r} + N_c\lambda_s\frac{F}{P}\Bigg(hN_m\tau_{dt}\\ &+ N_f\Big(\psi\,(N_r + N_m) + 2\pi_t + 2h\tau_{dt} + (h + 2\sigma)\tau_{ip}\Big)\\ &+ 3\sigma\tau_{dt}(N_f + N_m)\Bigg) + \frac{2\sigma\tau_d(N_r + N_m)}{T_r}\\ &+ N_c\frac{\lambda_s}{S}N_m\Big(\psi(N_r + N_m) + \pi_t + h(\tau_{dt} + \tau_{ip}) + 3\sigma\tau_{ip}\Big)\\ &= \Theta((N_r + N_cN_m)(hV + N_m + N_f))\end{aligned} \tag{10}$$

Hence, SPD's scalability factors for complete network w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 1, 1, 1, and 1.

F. MIRON

In this section, we derive the asymptotic expressions of network mobility cost [12] of MIRON for the TLMR, the HA, and the complete network.

1) TLMR: For the two-level hierarchy, the expression for total network mobility cost (Eqn. (36) in [12]) at TLMR in MIRON can be simplified as follows:

$$\begin{aligned}\Psi_T^M &= \Psi_{LU}^M + \Psi_{SC}^M + \Psi_{PD}^M + \Psi_{CO}^M\\ &= \Big(2\sigma\tau_l\,(N_r + N_{mh}) + 2N_c\,(N_f + N_{mh})\,\sigma\tau_s\Big)\frac{1+\lfloor\frac{T_r}{T_{lf}}\rfloor}{T_r}\\ &+ \sigma\tau_{ip}N_c\frac{\lambda_s}{S}(N_f + N_m) + \sigma N_c\lambda_s\frac{F}{P}\tau_{dt}(N_f + N_m)\\ &+ 2\sigma\frac{(N_r - 1)\tau_p + (N_r + N_m)\,\tau_d}{T_r} = \Theta\Big(V(N_r + N_c(N_m + N_f))\Big)\end{aligned} \tag{11}$$

Hence, MIRON's scalability factors for TLMR w.r.t. N_m, N_r, N_f, V, h and N_c are 1, 1, 1, 1, 0, and 1.

2) HA: For the two-level hierarchy, the expression for total network mobility costs (Eqn. (37) in [12]) at HA in MIRON can be simplified as follows:

$$\begin{aligned}\Phi_T^M &= \Phi_{LU}^M + \Phi_{PD}^M\\ &= (N_r + N_m)\,(2\tau_l + \pi_h)\,\frac{1+\lfloor\frac{T_r}{T_{lf}}\rfloor}{T_r}\\ &+ (N_f + N_m)N_c\frac{\lambda_s}{S}\Big(\psi(N_r + N_m) + \tau_{dt} + \tau_{ip} + \pi_t\Big)\\ &= \Theta\Big(V(N_r + N_m) + N_C(N_f + N_m)(N_r + N_m)\Big)\end{aligned} \tag{12}$$

MIRON's scalability factors for HA w.r.t. N_{mh}, N_r, N_f, V, h and N_c are thus 2, 1, 1, 1, 0, and 1, respectively.

3) Complete Network: Finally, the expression for total network mobility cost (Eqn. (38) in [12]) on the complete network can be obtained as:

$$\begin{aligned}
\Lambda_T^M &= \Lambda_{LU}^M + \Lambda_{SC}^M + \Lambda_{PD}^M + \Lambda_{CO}^M \\
&= \Bigg((N_r + N_m)(2\tau_l h + \pi_h) + 2\sigma\tau_l(2N_r + 3N_m - 1) \\
&+ 2\tau_s N_c (N_f + N_m)(h + 3\sigma) \Bigg) \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + N_c \frac{\lambda_s}{S} \\
&\times \Big((N_f + N_m)(\psi(N_r + N_m) + \pi_t + 2h\tau_{dt} + h\tau_{ip}) \\
&+ \pi_t N_f + \sigma\tau_{ip}(2N_f + 3N_m) \Big) \\
&+ N_c \lambda_s \frac{F}{P}(\tau_{dt} h + 3\sigma\tau_{dt})(N_f + N_m) \\
&+ \Big(8(N_r - 1 + N_m)\tau_p + 2\tau_d(2N_r + 3N_m - 1) \Big) \frac{\sigma}{T_r} \\
&= \Theta(N_c(N_f + N_m + hV)(N_r + N_m))
\end{aligned} \tag{13}$$

Hence, MIRON's scalability factors for the complete network w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 1, 1, 1, and 1, respectively.

G. OPR

In this section, we derive the cost [12] of OPR scheme at TLMR, HA, and complete network.

1) TLMR: For the two-level hierarchy, the total cost (Eqn. (49) in [12]) at TLMR can be simplified as:

$$\begin{aligned}
\Psi_T^O &= \Psi_{LU}^O + \Psi_{SC}^O + \Psi_{PD}^O + \Psi_{CO}^O \\
&= 2\sigma\tau_l N_r \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 2\sigma\tau_l N_m \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 0 + \sigma N_c \lambda_s \\
&\times (N_f + N_m)(\frac{\tau_{ip}}{S} + \frac{F}{P}\tau_{dt}) + \frac{2\sigma\tau_d(N_r - 1)}{T_r} \\
&= \Theta(V(N_r + N_m) + N_c(N_f + N_m))
\end{aligned} \tag{14}$$

OPR's scalability factors for TLMR w.r.t. N_m, N_r, N_f, V, h and N_c are, therefore, 1, 1, 1, 1, 0, and 1, respectively.

2) HA: The total cost (Eqn. (50) in [12]) at HA is:

$$\begin{aligned}
\Phi_T^O &= \Phi_{LU}^O + \Phi_{PD}^O \\
&= (2\tau_l + \pi_h)\Big(N_r \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + N_m \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} \Big) + \\
&(N_f + N_m) N_c \frac{\lambda_s}{S} \left(\psi\left(N_r + N_m\right) + \tau_{dt} + \tau_{ip} + \pi_t \right) \\
&= \Theta\Big((N_r + N_m)(V + N_C(N_f + N_m)) \Big)
\end{aligned} \tag{15}$$

Now, OPR's scalability factors for HA w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 1, 1, 0, and 1, respectively.

3) Complete Network: Finally, the total cost (Eqn. (51) in [12]) of OPR on complete network is:

$$\begin{aligned}
\Lambda_T^O &= \Lambda_{LU}^O + \Lambda_{SC}^O + \Lambda_{PD}^O + \Lambda_{CO}^O \\
&= (2\tau_l(N_r h + \sigma(2N_r - 1)) + N_r \pi_h) \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + \\
&N_m \Big(2\tau_l(h + 3\sigma) + \pi_h \Big) \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + N_c \lambda_s \frac{F}{P} \psi \frac{(N_f + N_m)^2}{N_r - 1} \\
&+ N_c \frac{\lambda_s}{S} \Big((N_f + N_m)(\psi(N_r + N_m) + \pi_t + 2h\tau_{dt} + h\tau_{ip}) \\
&+ \pi_t N_f + \sigma\tau_{ip}(2N_f + 3N_m) \Big) \\
&+ N_c \lambda_s \frac{F}{P}(\tau_{dt} h + 3\sigma\tau_{dt})(N_f + N_m) + \frac{2\sigma\tau_d N_r}{T_r} \\
&= \Theta((N_r + N_m)(hV + N_c N_f(N_f + N_m)))
\end{aligned} \tag{16}$$

Hence, OPR's scalability factors for complete network w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 2, 1, 1, and 1, respectively.

H. Ad hoc-based

In this section, we derive the total costs [12] of Ad hoc-based scheme for the TLMR, HA, and complete network.

1) TLMR: For the two-level hierarchy, the expression for total cost (Eqn. (62) in [12]) at TLMR of Ad hoc-based scheme can be simplified as:

$$\begin{aligned}
\Psi_T^A &= \Psi_{LU}^A + \Psi_{SC}^A + \Psi_{PD}^A \\
&= 2N_r\sigma\tau_l \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 2\sigma N_m \left((\tau_l + \tau_{ip}) + N_c(\tau_s + \tau_{ip}) \right) \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} \\
&+ N_c \lambda_s \frac{F}{P}(\sigma\tau_{ip} + \sigma\tau_{dt})(N_f + N_m) + \sigma N_m N_c \frac{\lambda_s}{S}\tau_{ip} \\
&= \Theta(V(N_r + N_m N_c) + N_c N_f)
\end{aligned} \tag{17}$$

So Ad hoc-based scheme's scalability factors for TLMR w.r.t. N_m, N_r, N_f, V, h and N_c are 1, 1, 1, 1 , 0, and 1, respectively.

2) HA: The total cost (Eqn. (63) in [12]) at HA can be simplified as:

$$\begin{aligned}
\Phi_T^A &= \Phi_{LU}^A + \Phi_{SC}^A + \Phi_{PD}^A \\
&= N_r \left(2\tau_l + \pi_h\right) \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + N_m \Big(2\tau_l + \pi_h + 2\pi_t + \\
&\tau_{ip} + \psi(N_r + N_m) + 2N_c \left(\tau_s + \tau_{ip} + \pi_t\right) \Big) \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + \\
&\left(N_f + N_m\right) N_c \lambda_s \frac{F}{P} \left(\psi\left(N_r + N_m\right) + \pi_t + \tau_{dt} + \tau_{ip} \right) \\
&+ N_m N_c \frac{\lambda_s}{S}(\psi(N_r + N_m) + \tau_{dt} + 2\tau_{ip}) \\
&= \Theta(N_c(N_r + N_m)(V N_m + N_f))
\end{aligned} \tag{18}$$

Therefore, Ad hoc-based scheme's scalability factors for HA w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 1, 1, 0, and 1, respectively.

3) Complete Network: Finally, the total cost (Eqn. (64) in [12]) for Ad hoc-based scheme on complete network is:

$$\begin{aligned}
\Lambda_T^A &= \Lambda_{LU}^A + \Lambda_{SC}^A + \Lambda_{PD}^A + \Lambda_{CO}^A \\
&= 2\Big(\left(N_r h + \sigma(2N_r - 1)\right) \tau_l + N_r \pi_h \Big) \frac{1 + \lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} + 2N_m \\
&\times \Bigg((2h + 3\sigma)\tau_l + \pi_h + (h + 2\sigma)\tau_{ip} + \psi(N_r + N_m) + 2\pi_t \\
&+ N_c \Big(2h\tau_s + h\tau_{ip} + 2\pi_t + \sigma(3\tau_s + 2\tau_{ip}) \Big) \Bigg) \frac{\lfloor \frac{T_r}{T_{lf}} \rfloor}{T_r} \\
&+ N_c \lambda_s \frac{F}{P} \left(N_f + N_m\right) \Big(\psi\left(N_r + N_m\right) + 2\pi_t + 2h\tau_{dt} \\
&+ h\tau_{ip} + 2\sigma\tau_{ip} + +3\sigma\tau_{dt} \Big) + N_c \frac{\lambda_s}{S} N_m \Big(\psi\left(N_r + N_{mh}\right) + \pi_t \\
&+ h\tau_{dt} + (2h + 3\sigma)\tau_{ip} \Big) + 3\sigma N_r \tau_a \frac{1}{T_r} + 2\sigma\tau_r N_r \frac{1 + \lfloor \frac{T_r}{T_{ra}} \rfloor}{T_r} \\
&= \Theta((N_r + N_m N_c)(hV + N_f + N_m))
\end{aligned} \tag{19}$$

Hence, Ad hoc-based schemes's scalability factors for the complete network w.r.t. N_m, N_r, N_f, V, h and N_c are 2, 1, 1, 1, 1, and 1, respectively.

V. COMPARATIVE ANALYSIS

Table I summarizes the asymptotic cost expressions of NEMO BSP, SPD, MIRON, OPR and Ad hoc-based schemes for the TLMR, the HA, and the complete network. In Table II, all the scalability factors are listed with respect to N_m, N_r, N_f, V, h and N_c. Although the asymptotical scalability factors of the four schemes are almost identical, there exist some differences that are discussed below.

TABLE I
ASYMPTOTIC COST EXPRESSIONS

Scheme	Network Mobility Cost	Entity
NEMO BSP	$\Theta(V(N_r + N_m N_c) + N_c N_f)$	TLMR
	$\Theta((N_r + N_m)(V(N_r + N_c N_m) + N_f N_c))$	HA
	$\Theta((V(N_r + N_c N_m) + N_c N_f)(h + N_r + N_m))$	Com. Net.
SPD	$\Theta\Big(V(N_r + N_m N_c) + N_c N_f\Big)$	TLMR
	$\Theta\Big((N_r + N_m)(V + N_f N_c + N_m N_c)\Big)$	HA
	$\Theta((N_r + N_c N_m)(hV + N_m + N_f))$	Com. Net.
MIRON	$\Theta\Big(V(N_r + N_c(N_m + N_f))\Big)$	TLMR
	$\Theta\Big(V(N_r + N_m) + N_C(N_f + N_m)(N_r + N_m)\Big)$	HA
	$\Theta(N_c(N_f + N_m + hV)(N_r + N_m))$	Com. Net.
OPR	$\Theta(V(N_r + N_m) + N_c(N_f + N_m))$	TLMR
	$\Theta\Big((N_r + N_m)(V + N_C(N_f + N_m))\Big)$	HA
	$\Theta((N_r + N_m)(hV + N_c N_f(N_f + N_m)))$	Com. Net.
Ad hoc Based	$\Theta(V(N_r + N_m N_c) + N_c N_f)$	TLMR
	$\Theta(N_c(N_r + N_m)(V N_m + N_f))$	HA
	$\Theta((N_r + N_m N_c)(hV + N_f + N_m))$	Com. Net.

TABLE II
SCALABILITY FACTORS OF NEMO AND FOUR PD-BASED SCHEMES

Schemes	$\rho^X_{N_m}$	$\rho^X_{N_r}$	$\rho^X_{N_f}$	ρ^X_V	ρ^X_h	$\rho^X_{N_c}$	Entity
NEMO BSP	1	1	1	1	0	1	TLMR
	2	2	1	1	0	1	HA
	2	2	1	1	1	1	Com. Network
SPD	1	1	1	1	0	1	TLMR
	2	**1**	1	1	0	1	HA
	2	**1**	1	1	1	1	Com. Network
MIRON	1	1	1	1	0	1	TLMR
	2	**1**	1	1	0	1	HA
	2	**1**	1	1	1	1	Com. Network
OPR	1	1	1	1	0	1	TLMR
	2	**1**	1	1	0	1	HA
	2	**1**	**2**	1	1	1	Com. Network
Ad hoc-based	1	1	1	1	0	1	TLMR
	2	**1**	1	1	0	1	HA
	2	**1**	1	1	1	1	Com. Network

It is found that all the schemes scale when compared to NEMO BSP, except OPR in case of N_f. In OPR, MRs have to lookup a database of size proportional to N_f. But for NEMO BSP, lookup has to be performed for each LFN in a table whose size is independent of N_f. OPR's scalability could be improved using techniques used in MIRON.

All the PD-based schemes scale better than NEMO BSP with respect to N_r for HA and complete network since the location update in NEMO BSP is tunneled through HAs, resulting in lookup cost for each MR in a database (binding cache) of size proportional to N_r. Therefore, lookup cost becomes a quadratic function of N_r at HA of NEMO BSP.

VI. CONCLUSION

In this paper, we have developed mathematical models to compute scalability factors for various mobility entities of NEMO BSP and four representative PD-based route optimization schemes (SPD, MIRON, OPR, and Ad hoc-based) of NEMO in terms of network size, mobility rate, distance between mobility agents, and traffic rate. Our results show that all the schemes (except OPR) scale when compared to NEMO BSP, and they exhibit better asymptotical scalability feature in terms of N_r than NEMO BSP. Analytical models developed in this paper will provide useful framework to analyze other route optimization schemes, and to choose suitable scheme as network expands.

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