SLNEMO: An Efficient Protocol to Provide Internet Connectivity in NEMO

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Abstract-**Accessing Internet by the mobile nodes in a vehicle on the move, give rise network mobility (NEMO) for which IETF has standardized NEMO Basic Support Protocol (NBSP). However, NBSP suffers from sub-optimal route problem for both data and signaling packets, and as the nesting level increases, the problem worsens, resulting high handoff delay. High handoff delay also reduces bandwidth utilization per unit time. NBSP also suffers from late movement detection which disrupts the continuous service to the applications. To solve these issues, this paper proposes SLNEMO protocol that also reduces the cost of location update and remains mobility transparent to the nodes in the mobile network. Making the protocol mobility transparent also solves the problem of binding update storm. We utilize the hierarchical topology of a mobile network to reduce the cost of location update, and use buffering scheme to provide seamless handoff. Numerical results show that SLNEMO performs better than ROTIO in terms of average handoff delay and packet loss duration.**

Keywords— ***Nested NEMO, NBSP, MAP, handoff delay, intra-MAP, inter-MAP, packet delivery time.***

I. INTRODUCTION

Due to the advancement of network technology and availability of low cost mobile devices, people want to access the Internet even during their travel in public transport vehicles. In such cases, a group of mobile devices (or mobile nodes, *MN*) moves as a single unit, which gives rise to network mobility (*NEMO*) [1]. The network containing the MNs is called a mobile network, and the MNs in the mobile network are called mobile networking nodes (*MNNs*). To provide Internet access to a mobile network, IETF has standardized NEMO Basic Support Protocol (*NBSP*) [1], in which a specialized router called mobile router (*MR*), is responsible for maintaining connectivity to the Internet on behalf of the MNNs. According to NBSP, MR detects its point of attachment to the Internet using internetwork layer [2] router advertisement (*RA*), i.e., handoff, and then performs binding update with its home agent (*HA*). The binding update process results a bi-directional tunnel between the MR and its HA (*HA_MR*). The data and signaling packets are exchanged using this tunnel.

An MR can also visit another MR, so that the former comes under the domain of the later, which results a nested NEMO scenario, where the MR connected directly to the Internet through an access router (*AR*) is called the Top Level Mobile Router (*TLMR*). When NBSP is applied to nested mobile network, packet delivery takes place through nested tunnels containing MRs and their corresponding HA_MRs. Consequently, increase in nesting level of a mobile network results nesting in the nested tunnels, resulting high delay in both packet delivery and completion of handoff process. The situation of high handoff delay is worsened by the use of internetwork layer RA for move detection, which introduces additional delay of 30ms [3]. Thus, NBSP cannot provide seamless connectivity. In this paper, we propose *Seamless NEMO Protocol* (*SLEMO*) to provide seamless Internet connectivity at the internetwork layer, thereby, providing uninterrupted service to the higher layer applications using the Internet. Additionally, SLNEMO reduces binding update cost and remains mobility transparent, i.e., the MNNs remains unaware of the binding update process, thus solving the binding update storm problem [4]. We have compared SLNEMO with ROTIO [5], and found that SLNEMO outperforms them in terms of average handoff delay and packet loss duration.

Rest of the paper is organized as follows. Section II briefly discusses the related works. Section III describes the SLNEMO protocol. Section IV analyzes SLNEMO and compares its performance with ROTIO. Section IV concludes the paper, followed by references.

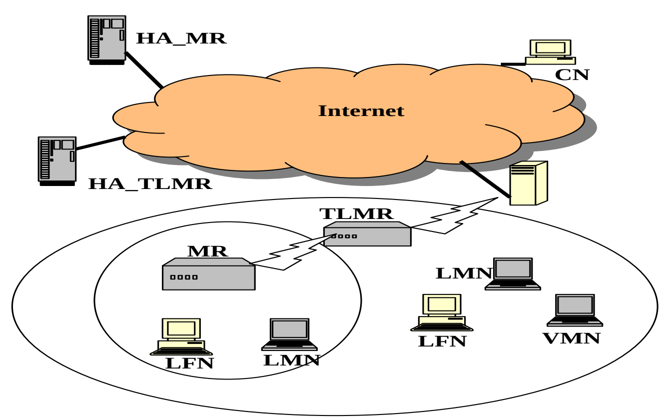

Fig. 1 Nested NEMO

II. RELATED WORKS

Many protocols have been proposed for providing seamless mobility in NEMO [6]-[11]. These protocols can be categorized into seamless NEMO protocols [6]-[8] and non-seamless NEMO protocols [4], [9]-[11]. NBSP is a non-seamless NEMO protocol. A seamless NEMO protocol acquires new CoA (*NCoA*) using L2 information [12], and after completion of the L2 handoff, performs L3 handoff. On the other hand, a non-seamless NEMO protocols acquires new CoA using RA, and then performs the handoff. In this section, we briefly discuss some novel seamless and non-seamless NEMO protocols and state their merits and demerits.

A. Seamless NEMO Protocols

In MM-NEMO [6], authors proposed to use mobility anchoring point (MAP) [13] to support handoff. An MR sends a RtSolPr [12] packet to the current MAP (cMAP) after receiving L2-trigger. The FBU [12] packet is sent along with the RtSolPr packet. On receiving the RtSolPr packet, cMAP formulates on-link CoA (LCoA) and regional CoA (RCoA) [13] for the MR. Then the cMAP sends PrRtAdv to the MR to notify about the LCoA and RCoA. cMAP also sends HI [12] packet to new MAP (nMAP). Rest of the handoff process is same as in FMIPv6 [12]. After the MR completes the handoff process, it sends a local binding update (*BU*) packet (*LBU*) to the nMAP, to which the nMAP replies with a local binding acknowledgement (*BAck*) packet (*LBAck)* to the MR. The protocol enables an MR to acquire NCoA in lesser number of signaling packets as FBU is sent along with the RtSolPr packet. However, the binding update process is time consuming as FMIPv6. Moreover, the protocol does not consider the lost packets if the MR does not move under the predicted nMAP.

In [7], the authors extended the HMIPv6, where the the L3 handoff is done in parallel. The MR exchanges RtSolPr and PrRtAdv and formulates LCoA and RCoA. The MR sends a fast LBU (FLBU) to previous MAP (pMAP). The pMAP first registers the LCoA with the higher level MR under which the MR can move into, and then registers the RCoA with new MAP (nMAP). The nMAP then exchanges BU and BAck packets with HA_MR. Though the protocol achieves parallel handoff mechanism in L3, the local handoff process is elaborate since signaling packets are exchanges separately for registering LCoA and RCoA.

To reduce the packet loss during handoff, [8] proposes to deploy two new entities: Multi-mobile Router (MMR) having heterogeneous physical interfaces (say, WLAN and Wi-MAX) and; Temporary Control Server (TCS) at home network of MMR. An MMR, through AR of the foreign network, stores information of the neighboring ARs in its vicinage table. The updated version of the vicinage table is sent to TCS periodically by MMR. During fast handoff, MMR uses its vicinage table to formulate new CoA and complete its handoff procedure. During inactivity of MMR, the MMR sends a solicitation packet to its TCS and requests it to act as an agent on its behalf, and goes to sleep mode, thus consuming less power. Whenever a packet for the MMR arrives at TCS, it sends a wakeup packet to the MMR. The packets are buffered at TCS, until the MMR responds to the wakeup packet. This procedure ensures zero packet loss. However, the delay caused to transfer the packets from TCS to MMR is high since the path involves the Internet.

In SNEP [22], it is assumed that the topology of a hierarchical mobile network with TLMR does not change during two consecutive stoppages of mobile network traveling in a predefined route. This fact is used create RA with validity duration as the time duration between two successive stoppages. RA from TLMR is sent after finite duration of time and is used to maintain “Next Node to Forward” table for routing of packets. The handoff process can either be intra-MAP handoff or inter-MAP handoff, which is distinguished by receipt of RA from AR and comparing binding caches of AR and TLMR, both starting after L2 trigger and following the process similar to FMIPv6. Though SNEP takes advantage of static nature of a mobile network for reducing local binding updates, RAs from TLMR are sent at regular intervals which could be only be transmitted on change of topology; this approach unnecessarily increases control packet traffic. The traffic for control packet is also increased by exchange of binding cache for distinguishing between intra-MAP and inter-MAP handoff which can be solved by using longest prefix match algorithm. The approach for not using the longest prefix match algorithm also forces SNEP to use “Next Node to Forward” table. The prediction mechanism is also redundant since the mobile network follows a predefined route.

Based on the discussions of the seamless NEMO protocols, we observe that though the protocols may achieve zero packet loss, the delay caused to recover the buffered packet is huge making seamlessness futile.

B. Non-seamless NEMO Protocols

In [9], the authors proposed to limit the nesting level to one, by using AODV routing protocol to find the AR of the foreign network, and formulate the CoA. Rest of the process follows NBSP. Though the protocol limits the nesting level, the delay caused in formulating the CoA is large causing high amount of packet loss.

ROTIO also limits the nesting level to two by registering home address of TLMR (HoA_TLMR) to HA_MR, which creates a bi-directional tunnel from CoA of MR to HoA_MR. The protocol, by virtue of registering HoA_TLMR, is less sensitive to mobility of intermediate MRs.

In [10], the problem of exposing the mobility to lower level MRs when a nested mobile network moves and the resulting binding update storm, is addressed. When a nested mobile network moves into a foreign network, the TLMR of the nested mobile network first performs binding update and then using repeated exchange of RtSolPr and PrRtAdv, NCoAs are assigned to lower level MRs. Though the problem of binding update storm is mitigated, it may not be solved for the VNNs.

Based on the discussion on seamless and non-seamless NEMO protocols, we observe that seamless and non-seamless cannot provide total seamlessness: seamless protocols no longer remain seamless when MR does not move into the predicted MR/AR; the non-seamless protocols suffer from late detection and packet loss during handoff. This calls for a seamless NEMO protocol that does not suffer from late movement detection and remains seamless when prediction goes wrong. In the next section, we propose SLNEMO that solves these problems.

III. PROPOSED PROTOCOL: SLNEMO

A. Assumption

1. The nested mobile network under observation has hierarchical topology as in Fig. 1, with TLMR as the root of the hierarchy.
2. TLMR is connected to an AR, which is connected to a MAP [12]. Each MAP can contain more than one AR under its domain.
3. Network topology of the nested mobile network remains approximately same during the time duration between the stoppages of vehicle [14] [22].
4. A VMN does not leave a mobile network it has got into until its destination has been reached. The destination of MR is far away, but at a finite distance from the position it has joined the mobile network.
5. Each AR and MAP maintains a list of IP address allocated to the MRs. This eliminates the need for DAD [15] by ARs and MAPs (but not by an MR when it requires to configure its CoA).

B. Protocol Description

A nested mobile network, along with the TLMR, can either move within a MAP, or from one MAP to another MAP. When the mobile network moves within the domain of a MAP and performs handoff, the handoff is called *intra-MAP handoff*. When the mobile network moves from the domain of one MAP to another and performs handoff, then the handoff is called *inter-MAP handoff*. TLMR, along with infrastructure support may use prediction mechanisms in intra-MAP handoff or inter-MAP handoff, to detect next AR under which it can move into. In case the prediction succeeds in intra-MAP handoff or in inter-MAP handoff, then the handoffs will be called *predictive mode intra-MAP handoff* and *predictive mode inter-MAP handoff* respectively. If the prediction fails, then the corresponding handoff mechanisms used in intra-MAP handoff and inter-MAP handoff will be called *reactive mode intra-MAP handoff* and *reactive mode inter-MAP handoff* respectively. Predictive mode intra-MAP handoff and predictive mode inter-MAP handoff are jointly called *predictive modes of SLNEMO*, whereas, reactive mode intra-MAP handoff and reactive mode inter-MAP handoff are jointly called *reactive modes of SLNEMO*. We describe intra-MAP and inter-MAP handoffs with respect to TLMR (assumption 3 of section III.A).

B.1.Predictive Modes of SLNEMO: Inter-MAP and Intra-MAP Handoffs

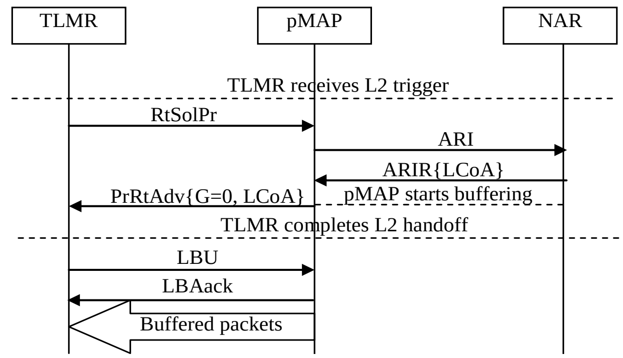

Fig.2. Predictive Mode Intra-MAP Handoff for SLNEMO

The workings of predictive modes of inter-MAP and intra-MAP handoffs are shown in Fig 2 and Fig. 3 respectively. The handoffs process starts from receipt of L2 trigger. In case of predictive mode inter-MAP handoff, RtSolPr, address request (AdR), address request init (ARI), address request init response (ARIR), address request response (AdRR), and PrRtAdv, are exchanged between MR and pMAP, pMAP and new MAP (nMAP), pMAP and nMAP, nMAP and pMAP , respectively and in sequence. With these exchanges the locally and globally unique IP addresses (LCoA and RCoA respectively) to be used under NAR (which is under nMAP), are obtained. The intra-MAP handoff, that is, presence of LCoA and RCoA in PrRtAdv, is indicated by setting a bit G in PrRtAdv to 1. Then local and global binding updates are performed to register LCoA (using LBU and LBAck packets) and RCoA (using BU and BAck packets) respectively. In the duration of registering the RCoA, once the BU packet is forwarded by the pMAP, it also requests the pMAP to send the buffered packets for TLMR to it by exchanging *buffered_packets_send_request (BPSR)* and *buffered_packets-send_request_response (BPSRR)* with the pMAP.

In predictive mode intra-MAP handoff, ARI, ARIR and PrRtAdv packets are exchanged in sequence between pMAP and NAR, NAR and pMAP, pMAP and TLMR, respectively, to obtain LCoA to be used under NAR. Then local binding update is performed with nMAP by exchanging LBU and LBAck. As soon as pMAP sends the LBAck, it sends buffered packets to TLMR.

B.2. Reactive modes of SLNEMO: Reactive mode of Intra-MAP handoff and Reactive mode of Inter-MAP handoff

SLNEMO operates in reactive mode, if, after receiving PrRtAdv the TLMR moves under an NAR which is not predicted by the pMAP.

In case of *reactive mode intra-MAP handoff*, the TLMR detects its movement using RA, i.e., detects the NAR under which it has moved into. Using the RA packet, the TLMR formulates LCoA and sends LBU to the pMAP, to which the pMAP replies with LBAck. The LBU has same format as described in predictive modes of SLNEMO. The working of reactive mode intra-MAP handoff is shown in Fig. 4.

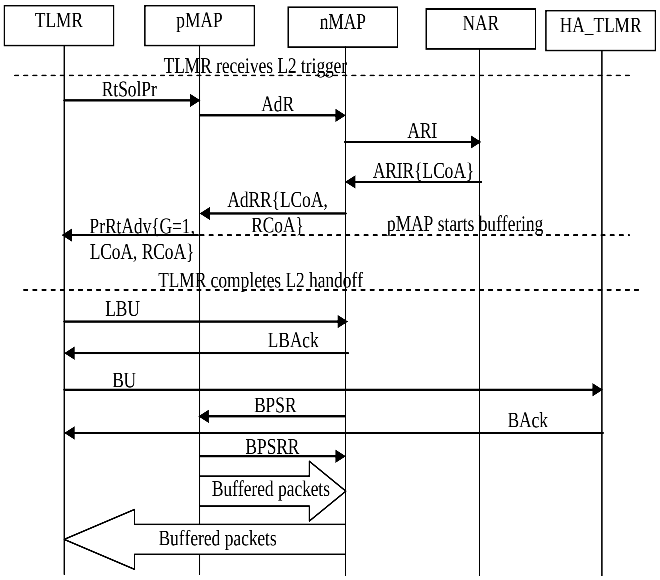

Fig. 3.Predictive Mode Inter-MAP Handoff for SLNEMO

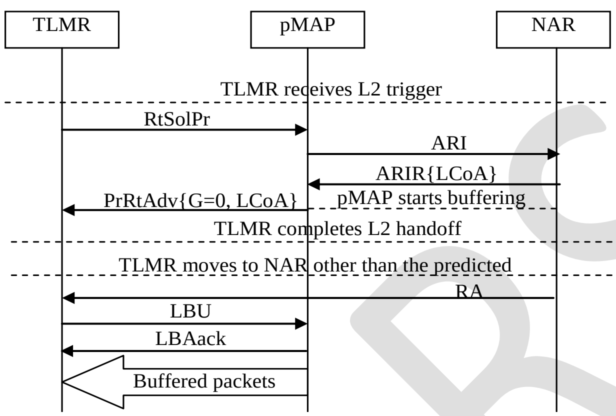

Fig. 4. Reactive Mode Intra-MAP handoff for SLNEMO

In case of *reactive mode inter-MAP handoff*, TLMR detects its movement using RA, and using the RA packet the TLMR formulates LCoA and RCoA. Then, the TLMR sends LBU to nMAP for registering its LCoA and RCoA, to which the nMAP replies with LBAck. The LBU has same format as described in the predictive modes of SLNEMO. As soon as the nMAP sends LBAck, it sends BPSR packet to the pMAP. The pMAP replies with BPSRR packet and forwards the buffered packets (for TLMR) through nMAP. After receiving the LBAck from the nMAP, TLMR exchanges BU and BAck with its HA, registering its RCoA. The working of reactive mode inter-MAP handoff is shown in Fig. 5.

It is to be noted that in inter-MAP handoffs (Fig. 3 and Fig. 5), although it appears that the BPSR packet is sent by the nMAP after the TLMR has sent its LBU, this is not the case: the BPSR packet is sent after the nMAP replies with LBAck, and the event of sending the BPSR by nMAP is independent of the event of sending the BU by TLMR, and either of them may happen before the other, but *not* before sending the LBAck by the nMAP.

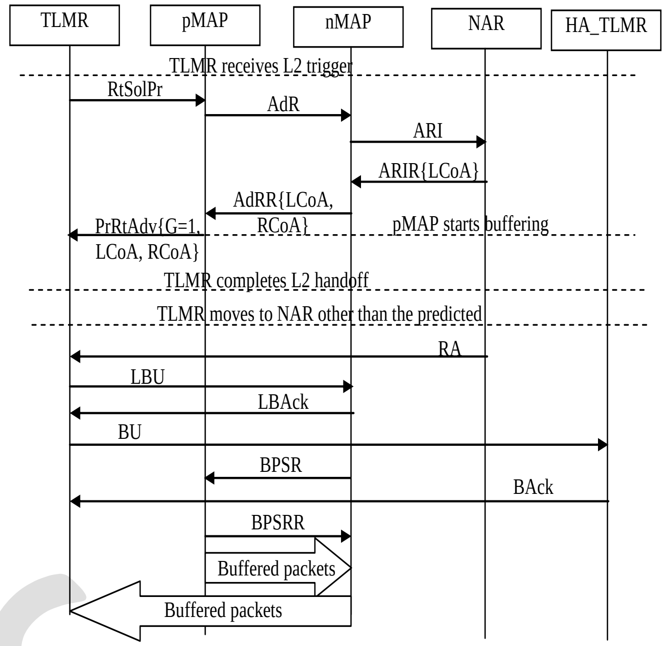

Fig. 5. Reactive Mode Inter-MAP Handoff for SLNEMO

IV. PERFORMANCE ANALYSIS OF SLNEMO

In this section we compare SLNEMO with ROTIO with respect to intra-MAP handoff delay, inter-MAP handoff delay, and, packet loss duration in intra-MAP and inter-MAP handoffs processes. The notations used for analysis are given in Table 1. First, we define the parameters used for analysis, then we state the assumptions used for the analysis, followed by the comparative analysis of SLNEMO with ROTIO. We perform the analysis with respect to TLMR (assumption 3 of section III.A).

A. *Definitions*

1. *Handoff Delay*: It is the time taken to exchange signaling packets to complete the handoff process and includes the time taken in L2 handoff.
2. *Packet Loss Duration*: It is the duration in which neither the TLMR receives any packet, nor the packets get buffered anywhere in the infrastructure nodes to which TLMR is directly attached.

B. *Assumptions*

Apart from the assumptions made in section III.A, following are the additional assumptions.

1. Wired and wireless links are symmetric with respect to time delay. For example, if two network entities, A and B, are connected by a wired or wireless link, then the delay in sending a packet from A to B is same as the delay in sending the packet from B to A.

2. The AR and MAP are the only infrastructure network entities that can connect directly to a TLMR.

3. Processing delay in a node is negligible as compared to the delay in transmitting a packet in a wired or wireless link.

TABLE 1: List of Notations

Notation	Meaning
$S_{RtSolPr}$	Size of RtSolPr packet
$S_{PrRtAdv}$	Size of PrRtAdv packet
S_{ARI}	Size of ARI packet
S_{ARIR}	Size of ARIR packet
S_{AdR}	Size of AdR packet
S_{AdRR}	Size of AdRR packet
S_{LBU}	Size of LBU packet
S_{LBAck}	Size of LBAck packet
S_{BU}	Size of BU packet
S_{BAck}	Size of BAck packet
S_{RA}	Size of RA packet
b_w	Bandwidth of wired link
b_{wl}	Bandwidth of wireless link
h_{avg}	Average number of hops between routers in the Internet
$T_{RtSolPr}$	Delay in sending RtSolPr packet
$T_{PrRtAdv}$	Delay in sending PrRtAdv packet
T_{ARI}	Delay in sending ARI packet
T_{ARIR}	Delay in sending ARIR packet
T_{AdR}	Delay in sending AdR packet
T_{AdRR}	Delay in sending AdRR packet
T_{LBU}	Delay in sending LBU packet to MAP from TLMR
T_{LBAck}	Delay in sending LBAck packet from MAP from TLMR
T_{BU}	Delay in sending BU packet from TLMR to HA_TLMR
T_{RA}	Delay in receiving RA packet by TLMR from the time instant the AR has sent RA that is not received by TLMR
T_{RA_int}	Interval between two consecutive RAs
T_{L2}	Delay in L2 handoff
T_{DAD}	Delay in performing DAD
p	Probability that a MAP predicts NAR successfully.
$T^{(proto)}_{intra-MAP-P}$	Intra-MAP handoff delay for NEMO protocol 'proto' in predictive mode
$T^{(proto)}_{intra-MAP-R}$	Intra-MAP handoff delay for NEMO protocol 'proto' in reactive mode
$T^{(proto)}_{inter-MAP-P}$	Inter-MAP handoff delay for NEMO protocol 'proto' in predictive mode
Notation	**Meaning**
$T^{(proto)}_{inter-MAP-R}$	Inter-MAP handoff delay for NEMO protocol 'proto' in reactive mode
$T^{(proto)}_{intra-MAP-Avg}$	Average intra-MAP handoff delay
$T^{(proto)}_{inter-MAP-Avg}$	Average inter-MAP handoff delay
$L^{(proto)}_{intra-MAP-P}$	Duration of packet loss in intra-MAP handoff for NEMO protocol 'proto' in predictive mode
$L^{(proto)}_{intra-MAP-R}$	Duration of packet loss in intra-MAP handoff for NEMO protocol 'proto' in reactive mode
$L^{(proto)}_{inter-MAP-P}$	Duration of packet loss in inter-MAP handoff for NEMO protocol 'proto' in predictive mode
$L^{(proto)}_{inter-MAP-R}$	Duration of packet loss in inter-MAP handoff for NEMO protocol 'proto' in reactive mode

C. Analysis of Handoff Delay

C.1.Analysis for Predictive Mode Intra-MAP Handoff

For ROTIO, which also does not use any prediction mechanism, the intra-MAP handoff involves exchange of LBU and LBAck with pMAP, after move-detection. So, $T^{(ROTIO)}_{intra-MAP-P}$ will include T_{L2}, T_{RA}, T_{DAD}, T_{LBU}, and T_{LBAck}. So,

$$T^{(ROTIO)}_{intra-MAP-P} = T_{L2} + T_{RA} + T_{DAD} + T_{LBU} + T_{LBAck} \quad (7)$$

The link used for sending LBU and receiving LBAck by TLMR contains one wireless link and one wired link. So, expression for T_{LBU} and T_{LBAck} will be:

$$T_{LBU} = \frac{S_{LBU}}{b_{wl}} + \frac{S_{LBU}}{b_w} = S_{LBU}\left(\frac{1}{b_{wl}} + \frac{1}{b_w}\right) \quad (8)$$

Similarly, $$T_{LBAck} = S_{LBAck}\left(\frac{1}{b_{wl}} + \frac{1}{b_w}\right) \quad (9)$$

Putting equations (3), (8) and (9) in (7), and re-arranging, we get the final expression for $T^{(ROTIO)}_{intra-MAP-P}$ as:

$$T^{(ROTIO)}_{intra-MAP-P} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}\left(\frac{S_{RA}}{2} + S_{LBU} + S_{LBAck}\right) + \frac{1}{b_w}\left(S_{LBU} + S_{LBAck}\right) \quad (10)$$

For predictive mode SLNEMO (Fig. 2), $T^{(SLNEMO)}_{intra-MAP-P}$ consist of $T_{RtSolPr}$, T_{ARI}, T_{ARIR}, $T_{PrRtAdv}$, T_{L2}, T_{LBU}, and T_{LBAck}. So,

$$T_{intra-MAP-P}^{(SLNEMO)} = T_{RtSolPr} + T_{ARI} + T_{ARIR} + T_{PrRtAdv} + T_{L2} + T_{LBU} + T_{LBAck} \quad (11)$$

The link used for sending RtSolPr and PrRtAdv packets contains one wireless link (TLMR to AR) and one wired link (AR to pMAP), whereas, the link for sending ARI and ARIR packets contains one wired link (pMAP to AR) only. So, the expressions for $T_{RtSolPr}$, $T_{PrRtAdv}$, T_{ARI}, and T_{ARIR} will be respectively:

$$T_{RtSolPr} = S_{RtSolPr}\left(\frac{1}{b_{wl}} + \frac{1}{b_w}\right) \quad (12)$$

$$T_{PrRtAdv} = S_{PrRtAdv}\left(\frac{1}{b_{wl}} + \frac{1}{b_w}\right) \quad (13)$$

$$T_{ARI} = \frac{S_{ARI}}{b_w} \quad (14)$$

$$T_{ARIR} = \frac{S_{ARIR}}{b_w} \quad (15)$$

Putting equations (12), (14), (15), (13), (8) and (9) in (11), and re-arranging we get the final expression for $T_{intra-MAP-P}^{(SLNEMO)}$ as:

$$T_{intra-MAP-P}^{(SLNEMO)} = T_{L2} + \frac{1}{b_{wl}}(S_{RtSolPr} + S_{PrRtAdv} + S_{LBU} + S_{LBAck}) + \frac{1}{b_w}(S_{RtSolPr} + S_{ARI} + S_{ARIR} + S_{PrRtAdv} + S_{LBU} + S_{LBAck}) \quad (16)$$

Using equations (6), (10), (16), and the values of the parameters in Table 2, we compare the predictive mode intra-MAP handoff delays, plot of which is shown in Fig. 6. The values are taken from [18]-[21].

TABLE 2: Parameter Values

Parameter	Value
$S_{RtSolPr}$	2088 bytes
$S_{PrRtAdv}$	2088 bytes
S_{ARI}	2081 bytes
S_{ARIR}	2081 bytes
S_{AdR}	2081 bytes
S_{AdRR}	2081 bytes
S_{LBU}	2081 bytes
S_{LBAck}	2081 bytes
S_{BU}	2081 bytes
S_{BAck}	2081 bytes
S_{RA}	2096 bytes
b_{wl}	11 Mb/s
b_w	100 Mb/s
h_{avg}	100
$T_{RA_}$int	30ms
T_{L2}	50ms
T_{DAD}	500ms
p	50%

From Fig. 6, we see that intra-MAP predictive mode handoff delay for SLNEMO is least among NBSP, ROTIO and SLNEMO. The minimum handoff delay is attributed to elimination of DAD and using prediction mechanism that reduces dependency on RA.

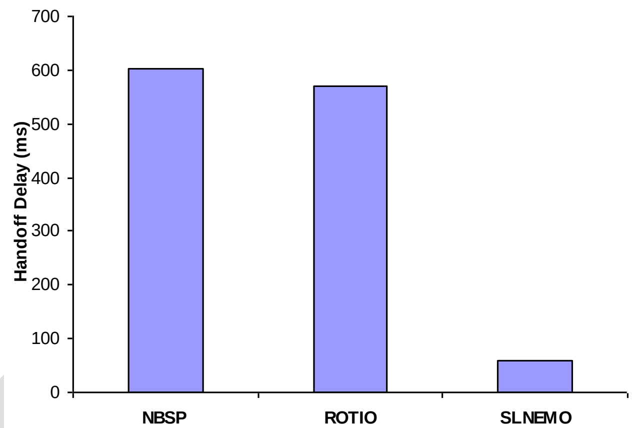

Fig. 6. Predictive mode Intra-MAP Handoff Delays for NEMO Protocols

C.2. Analysis of Reactive Mode Intra-MAP Handoffs

NBSP and ROTIO protocols do not use prediction mechanisms to anticipate handoff, so the handoff delays in reactive modes will be same as that of their handoff delays in predictive modes. Thus, we have:

$$T_{intra-MAP-R}^{(NBSP)} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}\left(\frac{S_{RA}}{2} + S_{BU} + S_{BAck}\right) + \frac{1}{b_w}\{h_{avg}(S_{BU} + S_{BAck})\} \quad (17)$$

$$T_{intra-MAP-R}^{(ROTIO)} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}\left(\frac{S_{RA}}{2} + S_{LBU} + S_{LBAck}\right) + \frac{1}{b_w}(S_{LBU} + S_{LBAck}) \quad (18)$$

For SLNEMO, $T_{inter-MAP-R}^{(SLNEMO)}$ includes (Fig. 4) of $T_{RtSolPr}$, T_{ARI}, T_{ARIR}, $T_{PrRtAdv}$, T_{L2}, T_{RA}, T_{DAD}, T_{LBU}, and T_{LBAck}. So, we have:

$$T_{intra-MAP-R}^{(SLNEMO)} = T_{RtSolPr} + T_{ARI} + T_{ARIR} + T_{PrRtAdv} + T_{L2} + T_{RA} + T_{DAD} + T_{LBU} + T_{LBAck} \quad (19)$$

Putting (12)-(15), (8), (9), (4), (3), and (5) in (19), and re-arranging we get the final expression for $T_{inter-MAP-R}^{(SLNEMO)}$ as in equation (20). Using equations (17), (18), (20) and Table 2, we draw the comparison plot for reactive mode intra-MAP handoff delays (Fig. 7).

$$T^{(SLNEMO)}_{intra-MAP-R} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}(S_{RtSolPr} + S_{PrRtAdv} + \frac{S_{RA}}{2} + S_{LBU} + S_{LBAck}) + \frac{1}{b_w}(S_{RtSolPr} + S_{ARI} + S_{ARIR} + S_{PrRtAdv} + S_{LBU} + S_{LBAck}) \quad (20)$$

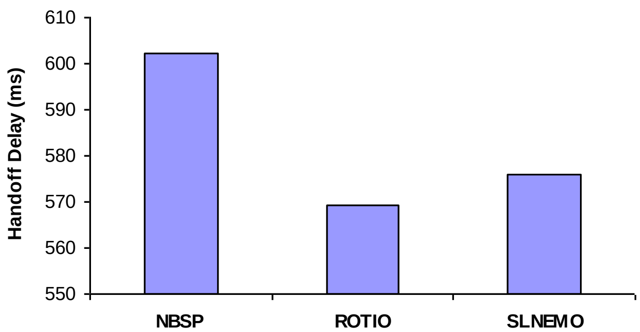

Fig. 7. Reactive Mode Intra-MAP Handoff Delays

From the Fig.7, we observe that $T^{(SLNEMO)}_{inter-MAP-R}$ is much less than $T^{(NBSP)}_{inter-MAP-R}$ but marginally more (~6ms) than $T^{(ROTIO)}_{inter-MAP-R}$. This difference is due to the delays incurred in exchanging RtSolPr, ARI, ARIR and PrRtAdv packets.

C.3. Analysis of Predictive Mode Inter-MAP Handoffs

For NBSP, every handoff is a inter-MAP handoff, therefore the expression for $T^{(NBSP)}_{inter-MAP-P}$ will be same as that of $T^{(NBSP)}_{intra-MAP-P}$. So, we can write:

$$T^{(NBSP)}_{inter-MAP-P} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}(\frac{S_{RA}}{2} + S_{BU} + S_{BAck}) + \frac{1}{b_w}\{h_{avg}(S_{BU} + S_{BAck})\} \quad (21)$$

For ROTIO, the $T^{(ROTIO)}_{inter-MAP-P}$ will contain, in addition to $T^{(ROTIO)}_{intra-MAP-P}$, T_{BU} and T_{BAck}. Then, using equations (10), (4) and (5), and re-arranging we get:

$$T^{(ROTIO)}_{inter-MAP-P} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}(\frac{S_{RA}}{2} + S_{LBU} + S_{LBAck} + S_{BU} + S_{BAck}) + \frac{1}{b_w}\{S_{LBU} + S_{LBAck} + h_{avg}(S_{BU} + S_{BAck})\} \quad (22)$$

For predictive mode inter-MAP handoff for SLNEMO, $T^{(SLNEMO)}_{inter-MAP-P}$ contains $T_{RtSolPr}$, T_{AdR}, T_{ARI}, T_{ARIR}, T_{AdRR}, $T_{PrRtAdv}$, T_{L2}, T_{LBU}, T_{LBAck}, T_{BU}, and T_{BAck}. Then, using (11), we can write the expression for $T^{(SLNEMO)}_{inter-MAP-P}$ as:

$$T^{(SLNEMO)}_{inter-MAP-P} = T^{(SLNEMO)}_{intra-MAP-P} + T_{AdR} + T_{AdRR} + T_{BU} + T_{BAck} \quad (23)$$

Where:

$$T_{AdR} = \frac{S_{AdR}}{b_w} \quad (24)$$

And,

$$T_{AdRR} = \frac{S_{AdRR}}{b_w} \quad (25)$$

Then putting equations (16), (24), (25), (4) and (3) in (23), and re-arranging we get the final expression for $T^{(SLNEMO)}_{inter-MAP-P}$ as:

$$T^{(SLNEMO)}_{inter-MAP-P} = T_{L2} + \frac{1}{b_{wl}}(S_{RtSolPr} + S_{PrRtAdv} + S_{LBU} + S_{LBAck} + S_{BU} + S_{BAck}) + \frac{1}{b_w}\{S_{RtSolPr} + S_{AdR} + S_{ARI} + S_{ARIR} + S_{AdRR} + S_{PrRtAdv} + S_{LBU} + S_{LBAck} + h_{avg}(S_{BU} + S_{BAck})\} \quad (26)$$

We compare the predictive mode inter-MAP handoff delays using equations (21), (22), (26) and Table 2. The plot is shown in Fig. 8.

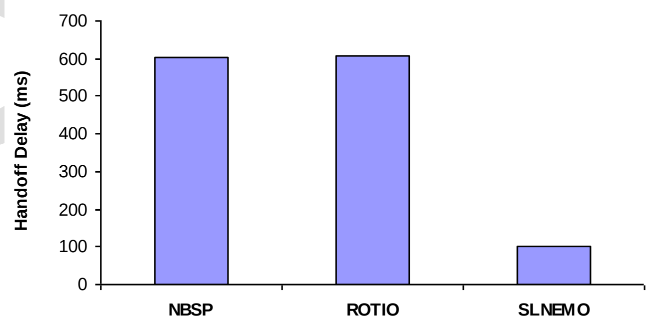

Fig. 8. Predictive Mode Inter-MAP Handoff Delays

From Fig. 8, we clearly see the benefit of using prediction mechanism and maintaining list of allocated IP address at ARs and MAPs, which, respectively, eliminated delay due to DAD and reduced dependency on RA and hence resulting significantly less value of handoff delay for SLNEMO.

C.4. Analysis of Reactive Mode Inter-MAP Handoffs

Both NBSP and ROTIO do not use any prediction mechanism for anticipating handoff. So, their reactive mode inter-MAP handoff delays will be same as their corresponding predictive mode inter-MAP handoff delays. Hence, we get the equations as in (27) and (28).

$$T_{inter-MAP-R}^{(NBSP)} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}(\frac{S_{RA}}{2} + S_{BU} + S_{BAck}) + \frac{1}{b_w}\{h_{avg}(S_{BU} + S_{BAck})\} \quad (27)$$

$$T_{inter-MAP-R}^{(ROTIO)} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}(\frac{S_{RA}}{2} + S_{LBU} + S_{LBAck} + S_{BU} + S_{BAck}) + \frac{1}{b_w}\{S_{LBU} + S_{LBAck} + h_{avg}(S_{BU} + S_{BAck})\} \quad (28)$$

For SLNEMO, the reactive mode inter-MAP handoff can occur only after receipt of PrRtAdv and when the TLMR does not move into the NAR that is not predicted by the pMAP. Then, by Fig. 5, $T_{inter-MAP-R}^{(SLNEMO)}$ contains $T_{RtSolPr}$, T_{AdR}, T_{ARI}, T_{ARIR}, T_{AdRR}, $T_{PrRtAdv}$, T_{L2}, T_{RA}, T_{DAD}, T_{LBU}, T_{LBAck}, T_{BU}, and T_{BAck}. Using (23), we can write the expression for $T_{inter-MAP-R}^{(SLNEMO)}$ as:

$$T_{inter-MAP-R}^{(SLNEMO)} = T_{inter-MAP-P}^{(SLNEMO)} + T_{RA} + T_{DAD} \quad (29)$$

Using equations (26) and (3) in (29), we get the final expression for $T_{inter-MAP-R}^{(SLNEMO)}$ as:

$$T_{inter-MAP-R}^{(SLNEMO)} = T_{L2} + \frac{1}{2}T_{RA\_int} + T_{DAD} + \frac{1}{b_{wl}}(\frac{S_{RA}}{2} + S_{RtSolPr} + S_{PrRtAdv} + S_{LBU} + S_{LBAck} + S_{BU} + S_{BAck}) + \frac{1}{b_w}\{S_{RtSolPr} + S_{AdR} + S_{ARI} + S_{ARIR} + S_{AdRR} + S_{PrRtAdv} + S_{LBU} + S_{LBAck} + h_{avg}(S_{BU} + S_{BAck})\} \quad (30)$$

The comparison plot using equations (27), (28) and (30) is shown in Fig. 9.

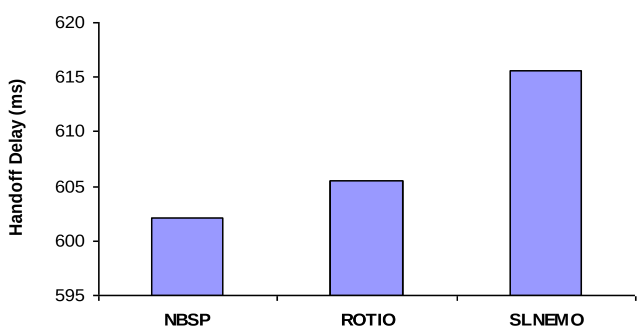

Fig. 9. Reactive Mode Inter-MAP Handoff Delays

From the Fig. 9, we see that the handoff delay for SLNEMO is slightly more (~10ms) than the NBSP and ROTIO. This difference is due use of RtSolPr, AdR, ARI, ARIR, AdRR and PrRtAdv packets used the handoff process.

It may appear that the handoff delays for SLNEMO are not less than that of NBSP and ROTIO in general, but as we see in the next section SLNEMO outperforms them even if the predictions have success rate as low as 50%.

D. Analysis of Average Handoff Delay

The average handoff delay for intra-MAP and inter-MAP handoff delay is defined as:

$$T_{intra-MAP-Avg}^{(proto)} = pT_{intra-MAP-P}^{(proto)} + (1-p)T_{intra-MAP-R}^{(proto)} \quad (31)$$

$$T_{inter-MAP-Avg}^{(proto)} = pT_{inter-MAP-P}^{(proto)} + (1-p)T_{inter-MAP-R}^{(proto)} \quad (32)$$

Then using equations (6) and (17) (for NBSP), (10) and (18) (for ROTIO), and, (16) and (20) (for SLNEMO) in equation (31) and using the values in table 2, we get the comparison plot for average intra-MAP handoff delay as in Fig. 10.

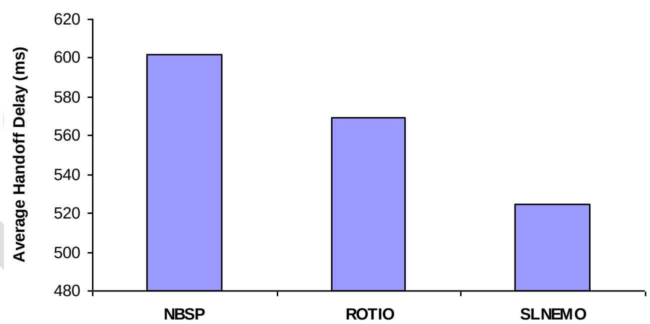

Fig. 10. Average Intra-MAP Handoff Delay

Using equations (21) and (27) (for NBSP), (22) and (28) (for ROTIO), and, (26) and (30) (for SLNEMO) in equation (32) and using the values in table 2, we get the comparison plot for average inter-MAP handoff delay as in Fig. 11.

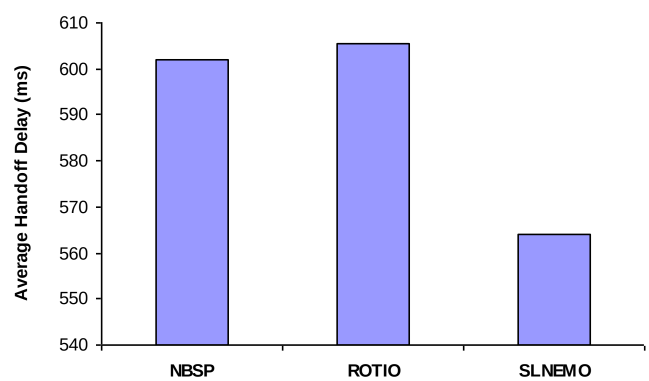

Fig. 11. Average Inter-MAP Handoff Delay

As we see from Fig. 10 and Fig. 11, SLNEMO clearly outperforms NBSP and ROTIO even if the prediction mechanism has very low success rate. This reduction in the average handoff delay is about 41%.

E. Analysis of Packet Loss Duration

NBSP and ROTIO use RA for movement detection. Moreover, these protocols do not employ any buffer mechanism to hold the arrived packets during their handoff processes. The packets are not redirected to NCoA of TLMR (new LCoA in case of intra-MAP handoff, and new RCoA in case of inter-MAP handoff) until the TLMR sends a successful BU packet to HA_TLMR (in case of NBSP handoffs, and in case of inter-MAP handoff for ROTIO) or successful LBU packet to nMAP (in case of intra-MAP handoff for ROTIO). So, all packets, from the start of L2 handoff to the receipt of BU (or LBU) packet by HA_TLMR (or nMAP), are lost. So, expressions for $L^{(NBSP)}_{intra-MAP-P}$, $L^{(NBSP)}_{intra-MAP-R}$, $L^{(NBSP)}_{inter-MAP-P}$, $L^{(NBSP)}_{inter-MAP-R}$, $L^{(ROTIO)}_{intra-MAP-P}$, $L^{(ROTIO)}_{intra-MAP-R}$, $L^{(ROTIO)}_{inter-MAP-P}$, and $L^{(ROTIO)}_{inter-MAP-R}$ are given respectively by:

$$L^{(NBSP)}_{intra-MAP-P} = T^{(NBSP)}_{intra-MAP-P} - T_{BAck} \tag{31}$$

$$L^{(NBSP)}_{intra-MAP-R} = T^{(NBSP)}_{intra-MAP-R} - T_{BAck} \tag{32}$$

$$L^{(NBSP)}_{intter-MAP-P} = T^{(NBSP)}_{inter-MAP-P} - T_{BAck} \tag{33}$$

$$L^{(NBSP)}_{intter-MAP-R} = T^{(NBSP)}_{inter-MAP-R} - T_{BAck} \tag{34}$$

$$L^{(ROTIO)}_{intra-MAP-P} = T^{(ROTIO)}_{intra-MAP-P} - T_{LBAck} \tag{35}$$

$$L^{(ROTIO)}_{intra-MAP-R} = T^{(ROTIO)}_{intra-MAP-R} - T_{LBAck} \tag{36}$$

$$L^{(ROTIO)}_{intter-MAP-P} = T^{(ROTIO)}_{inter-MAP-P} - T_{BAck} \tag{37}$$

$$L^{(ROTIO)}_{intter-MAP-R} = T^{(ROTIO)}_{inter-MAP-R} - T_{BAck} \tag{38}$$

Using equations (6), (17), (21), (27) and (5) in (31)-(34), we get the following equation:

$$\begin{aligned} L^{(NBSP)}_{intra-MAP-P} &= L^{(NBSP)}_{intra-MAP-R} = L^{(NBSP)}_{inter-MAP-P} \\ &= L^{(NBSP)}_{inter-MAP-R} = T_{L2} + \frac{1}{2} T_{RA\_int} + T_{DAD} \\ &\quad + \frac{1}{b_{wl}} \left(\frac{S_{RA}}{2} + + S_{BU}\right) + \frac{1}{b_w}(h_{avg} S_{BU}) \end{aligned} \tag{39}$$

Using equations (10), (18), (22), (28), (5) and (9) in (35)-(38), we get:

$$\begin{aligned} L^{(ROTIO)}_{intra-MAP-P} &= L^{(ROTIO)}_{intra-MAP-R} = T_{L2} + \frac{1}{2} T_{RA\_int} + T_{DAD} \\ &\quad + \frac{1}{b_{wl}} \left(\frac{S_{RA}}{2} + S_{LBU}\right) + \frac{1}{b_w}(S_{LBU}) \end{aligned} \tag{40}$$

And,

$$\begin{aligned} L^{(ROTIO)}_{inter-MAP-P} &= L^{(ROTIO)}_{inter-MAP-R} = T_{L2} + \frac{1}{2} T_{RA\_int} + T_{DAD} + \\ &\quad \frac{1}{b_{wl}} \left(\frac{S_{RA}}{2} + S_{LBU} + S_{LBAck} + S_{BU}\right) + \\ &\quad \frac{1}{b_w}(S_{LBU} + S_{LBAck} + h_{avg} S_{BU}) \end{aligned} \tag{41}$$

For SLNEMO, if the pMAP receives ARIR packet (in case of intra-MAP handoffs) or AdRR (in case of inter-MAP handoffs), the pMAP starts buffering. Thus, whether SLNEMO operates its predictive mode handoffs or reactive mode handoffs, the packets are not lost. Hence:

$$\begin{aligned} L^{(SLNEMO)}_{intra-MAP-P} &= L^{(SLNEMO)}_{intra-MAP-R} = L^{(SLNEMO)}_{inter-MAP-P} = L^{(SLNEMO)}_{inter-MAP-R} \\ &= 0 \end{aligned} \tag{42}$$

The comparison plot for packet loss duration for predictive mode intra-MAP handoffs and reactive mode intra-MAP handoffs are shown in Fig. 12 and Fig. 13 respectively, we have used equations (39), (40) and (42).

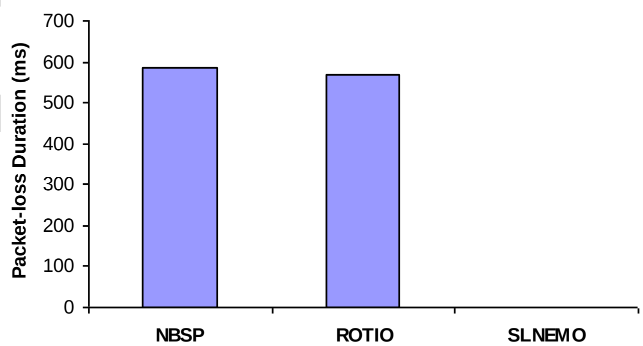

Fig. 12. Packet Loss Duration for Predictive Mode Intra-MAP Handoffs

From Fig. 12 and 13, it is clear that SLNEMO ensures zero packet loss during handoff. This happens because pMAP buffers the packets for TLMR until the TLMR has moved under NAR. The zero packet loss in case of reactive handoff is attributed to the use of buffering mechanism in pMAP which ensures independence of the outcome of the prediction mechanism and actual movement of the TLMR.

The comparison plot for packet loss duration for predictive mode inter-MAP handoffs and reactive mode inter-MAP handoffs are shown in Fig. 14 and 15 respectively. Here also we have used equations (39), (40) and (42).

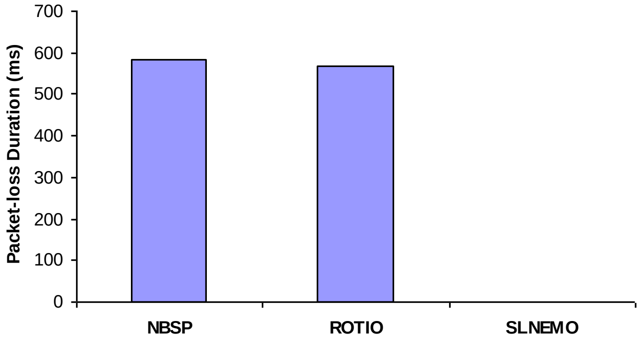

Fig. 13. Packet Loss Duration for Reactive Mode Intra-MAP Handoffs

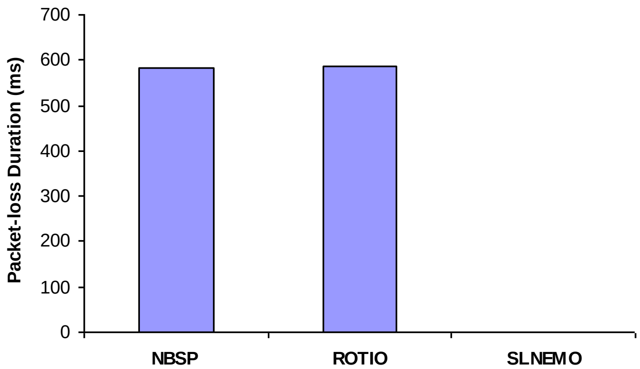

Fig. 14. Packet Loss Duration for Predictive Mode Inter-MAP Handoffs

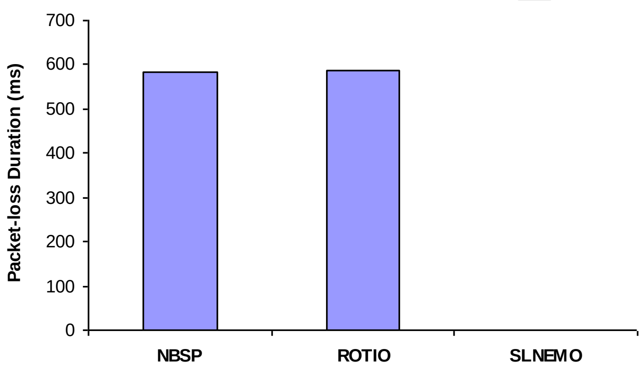

Fig. 15. Packet Loss Duration for Reactive Mode Inter-MAP Handoffs

From Fig. 14 and 15, we see that SLNEMO outperforms both NBSP and ROTIO in terms of packet loss duration in reactive and predictive mode inter-MAP handoffs. The zero packet loss is also attributed to the use of buffering mechanism in pMAP itslef, which makes the success of the buffering mechanism independent of matching or mismatching between the predicted NAR and the NAR under which the TLMR actually moves into.

V. CONCLUSION

We have proposed SLNEMO protocol for NEMO where the protocol uses three mechanisms, namely, allocated IP address list to eliminate delay due to DAD, NAR prediction for fast handoff, and a entirely new type of buffering mechanism in which the buffering is done at pMAP itself. The buffering at pMAP served two purposes: first, independence of outcome of prediction mechanism and actual movement of TLMR; and the second is the fast transfer of buffered data when the handoff by TLMR is completed.

We have compared SLNEMO with NBSP and ROTIO in terms of handoff delay, average handoff delay and packet loss duration and found that SLNEMO outperforms them and ensured 41% reduction in average handoff delay and zero packet loss even if the employed prediction mechanism has only 50% success rate.

Significant reduction in average handoff delay and zero packet loss makes the protocol an attractive solution for the time critical applications and the applications that require high reliability.

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