PAPER

Performance of Handovers between NEMO and Mobile Ad Hoc Networks Using Buffering

Jirawat THAENTHONG[†a)], ***Student Member and*** **Steven GORDON**[†b)], ***Member***

SUMMARY A MANEMO node is an IP-based mobile node that has interface attachments to both a mobile network, using Network Mobility (NEMO), and a Mobile Ad Hoc Network (MANET). While communicating with a correspondent node in the Internet, the MANEMO node should use the best possible path. Therefore, as conditions change, a handover between NEMO and MANET is desirable. This paper describes the operation of a MANEMO handover when IEEE 802.11 is used. An analytical model illustrates that packet loss during a MANEMO handover may severely affect data and real-time applications. We therefore propose using buffering during the handover, by making use of the Power Save Mode in IEEE 802.11. In the proposed algorithm, a MANEMO node may rapidly switch between the two interfaces, eventually receiving packets delivered via the old network interface while initiating the Mobile IP/NEMO handover on the new interface. Performance results show that packet loss can be significantly reduced, with small and acceptable increases in signalling overhead and end-to-end delay.

key words: *network mobility (NEMO), mobile ad hoc network (MANET), handover performance, IEEE 802.11 wireless LAN, power save mode, buffering, Mobile IP*

1. Introduction

MANEMO[1], [2] refers to a network that integrates a *mobile network* with a *mobile ad hoc network* (MANET). The mobile network consists of a set of mobile hosts and (at least) one mobile router (MR), where the MR manages the mobility of all nodes using IETF's Network Mobility protocol [3]. Thus the NEMO mobile network is infrastructure-based. A MANET however is normally infrastructure-less and unstructured. Mobile nodes form a network amongst themselves, often using multi-hopping to allow communication between pairs of hosts. Hence MANET hosts also act as routers, although they may use a routing protocol and forwarding mechanisms distinct from typical IP routers. A MANET may have one or more gateways to the Internet: nodes that participate in MANET routing, as well as IP routing.

A MANEMO network is formed when a node in the NEMO/MANET also participates in the MANET/NEMO mobile network. This MANEMO node (MN) can gain Internet access via the infrastructure-based NEMO point of attachment and/or via the unstructured MANET point of attachment. Allowing multiple, independent paths for Internet access can be beneficial for vehicular networking, personal/body area networks, emergency services and military networks. As network conditions change, the MN may handover between the NEMO path and MANET path in order to obtain best possible service.

Several research challenges arise in MANEMO. For example, the MANEMO node must be able to discover the MANET and NEMO gateways. Once discovered, criteria and algorithms for selecting the MANET or NEMO interface are needed. A significant problem of using NEMO, especially with nested MRs, is sub-optimal routes. Research on route-optimization for MANEMO is ongoing [6], [7], as well as using MANETs as a backup in event of NEMO infrastructure failure [8]. Finally, methods for minimising network service disruption (handover delay, packet loss) are needed. This is the problem addressed in our research.

In many cases a MANEMO node will have only one wireless egress interface (to minimise cost and power consumption). If the MANET and NEMO interface uses different technologies or frequencies, then the MANEMO node can only communicate on one interface at a time. Hence during handover significant packet loss and handover delay can occur, to a level that is unacceptable for real-time communications such as voice calls [9].

The contribution of this paper is a scheme to reduce packet loss in MANEMO handovers by buffering IEEE 802.11 wireless LAN frames arriving from uplink nodes. Although buffering is a well-known approach for Mobile IP handovers, we propose the use of existing IEEE 802.11 mechanisms to allow buffering to occur on both the MANET and NEMO interface. Our algorithm uses IEEE 802.11 Power Saving Mode frames, which has been used by [10] for buffering between two APs. We extend this to work between an access point (NEMO) and ad hoc mode (MANET). We analyse the scheme to show the conditions when our optimised handover scheme provides acceptable packet loss and delay for voice communications.

The remainder of the paper is organised as follows. Section 2 explains the concept of handover in MANEMO. Section 3 summarises the related work. Section 4 describes the design of our optimised MANEMO handover using power saving mode. In Sect. 5 the signalling overhead, buffer size, buffer delay, and packet loss are derived. Section 6 gives numerical results to illustrate the advantages of the optimised handover algorithm, and Sect. 7 concludes the paper.

Manuscript received April 7, 2010.
Manuscript revised January 16, 2011.
[†]The authors are with Sirindhorn International Institute of Technology, Thammasat University, Pathumthani 12000, Thailand.
a) E-mail: jirawat@ict.siit.tu.ac.th
b) E-mail: steve@siit.tu.ac.th
DOI: 10.1587/transcom.E94.B.2763

2. MANEMO Handover

This section explains the assumptions and technologies used in performing MANEMO handovers. Figure 1 is an example network representative of the general scenario under consideration.

2.1 NEMO

A Mobile Router (MR) performs mobility management (similar to Mobile IP) on behalf of its attached nodes. The attached nodes may be: Local Fixed Node (LFN), a fixed host and permanently attached to the MR; Local Mobile Node (LMN), a mobile node currently in its home network; and a Visiting Mobile Node (VMN), a mobile node currently visiting a foreign network. The LMN and VMN run Mobile IP to allow them to move between networks; both nodes have a Home Agent (HA), as does a MR. In NEMO, as in Mobile IP, a HA records the current location of the mobile node/network and forwards packets to/from it to a Correspondent Node (CN). In NEMO it is the MR that informs the HA of the mobile networks location using a Binding Update. As in the example in Fig. 1, a mobile network may be nested within another, referred to as *nested NEMO*. The *nested depth* in the example is two: there is one mobile network nested in another. The top-most NEMO network accesses the Internet via a NEMO gateway (an access router).

2.2 Internet-Connected MANET

The MANET comprises a set of mobile nodes running a MANET routing protocol (e.g. AODV, OLSR). At least one of these nodes, the MANET Gateway, also has a connection to the Internet that is offered for other nodes to use. For addressing, MANET nodes can be assigned IP addresses with a common prefix. Mechanisms such as IPv6 stateless autoconfiguration can achieve this. However we assume that some of the MANET nodes may be roaming from other networks, i.e. they have a home IP address that they should be reachable via. In this case the address assigned in the MANET is a Care-of-Address (CoA), and Mobile IPv6 is used for the node to update the binding of CoA to home IP at its Home Agent. By using Mobile IPv6, packets sent by a corresondent node (CN) on the Internet to the home IP of a MANET node will be forwarded by the HA to the MANET Gateway, and then delivered across the MANET to the destination MANET node. Several researchers have proposed this approach for providing Internet connectivity to MANET nodes [11]–[13].

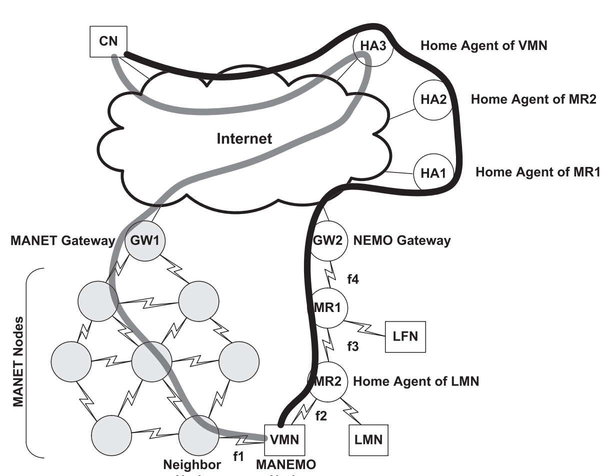

Fig. 1 A scenario of MANEMO handover.

2.3 MANEMO and Handovers

Now consider a mobile node that is a VMN in a mobile network, while also having a point of attachment to a MANET. This MANEMO node has two paths to the Internet: one via the NEMO point of attachment and another via the MANET point of attachment. Assume the MANEMO node has two IP interfaces (Sect. 2.4 discusses how this is achieved), referred to as the NEMO interface and the MANET interface. On the NEMO interface the MANEMO node has an IP address within the mobile network, while on the MANET interface it has a different IP address obtained from the MANET address configuration mechanism.

A MANEMO handover involves the MANEMO node changing its IP network attachment between the MANET and NEMO interfaces. Assuming the MANEMO node is currently using the NEMO interface, the black line illustrates the path of packets to/from the CN. NEMO requires all packets to be routed via the MR's HA, and in this example with nested NEMO the packets pass via HA1 and HA2 (and also route via MANEMO HA). If the MANET interface was used, the MANEMO node only routes packets via its Mobile IP HA, as shown via the gray line.

Lets assume a MANEMO node decides to handover (the decision to handover is not considered here but may be based on measurements of each networks capabilities). A MANEMO handover involves the MANEMO node obtaining a new CoA (on either NEMO or MANET interface) and informing its HA to change the destination address for routing packets from/to CN. This process can be divided into four steps [9]:

1. Establish layer 2 connectivity. Assuming IEEE 802.11 is used for both interfaces, in a handover to NEMO, the MANEMO node must associate with 802.11 Access Point (AP) in the MR. In a handover to MANET, a 802.11 ad-hoc connection must be made with a neighbour node.
2. MANEMO node obtains a global IP address (care-of-address) from the MR or MANET Gateway.
3. MANEMO node establishes an IPsec security association with its HA (IPsec Association Request, IPsec Association Reply and IPsec Authentication Request, IPsec Authentication Reply).

4. MANEMO node informs its HA of its new CoA using a Mobile IP Binding Update procedure (Binding Update and Binding Acknowledgment).

If a MANEMO node is to have regular handovers between NEMO interface and MANET interface, then significant time and signalling would be used to complete the above steps each handover. At minimum, if CoA's have already been obtained, the MANEMO node must perform security association and Binding Update with the HA each handover. To avoid packet losses when this procedure takes place, we propose using buffering. Alternative approaches are discussed in Sect. 3.

2.4 Packet Loss and Buffering in MANEMO Handover

If a MANEMO node has a single IEEE 802.11 physical wireless interface, then a MANEMO handover involves disconnecting from the old network interface (and subsequently losing packets) while performing the four handover steps on the new network interface. In [9] it is shown that significant packet loss may occur during a MANEMO handover, disrupting real-time applications as well as file transfers. Having a second physical wireless interface would improve the handover performance, however in some cases this is not possible due to cost and power savings necessary in a MANEMO node. Note that in a MANET, even though nodes act as routers, they typically use a single wireless interface; using two separate interfaces introduces significant complexity, such as frequency management. As we consider the MANEMO node to be a host, as opposed to a MR, in this paper we assume only a single physical wireless interface is available. Therefore, to minimise the packet loss during a MANEMO handover, the MANEMO node should inform its neighbour node or AP on the old network interface to buffer incoming frames while the MANEMO node initiates the handover in the new network interface. Later the MANEMO node can retrieve the buffered frames. Using buffering, packet loss can be reduced (possibly eliminated), at the expense of increase delay and signalling overhead.

2.5 Power Saving Mode Operation

IEEE 802.11 wireless nodes support Power Saving Mode (PSM), where a node can tell its neighbour (or AP) about its intention to sleep for a period of sleep time, during which the neighbour buffers frames until the sleeping node awakens. Figure 2 shows the procedures for using PSM when MN is in (a) ad-hoc mode and (b) infrastructure (AP) mode.

When using ad-hoc mode (Fig. 2(a)), when MN has no packet to send, it can send a beacon frame (with PM bit set to 1, and ATIM window is not zero) to tell its neighbor node it wants to sleep and allow the neighbor node to buffer incoming frames. The ATIM window interval defines the time that MN will wait for an Announcement Traffic Indication Message (ATIM) frame from its neighbor node if it has buffered frames. After ATIM window interval MN enters sleep mode. At the next interval MN must wake up to

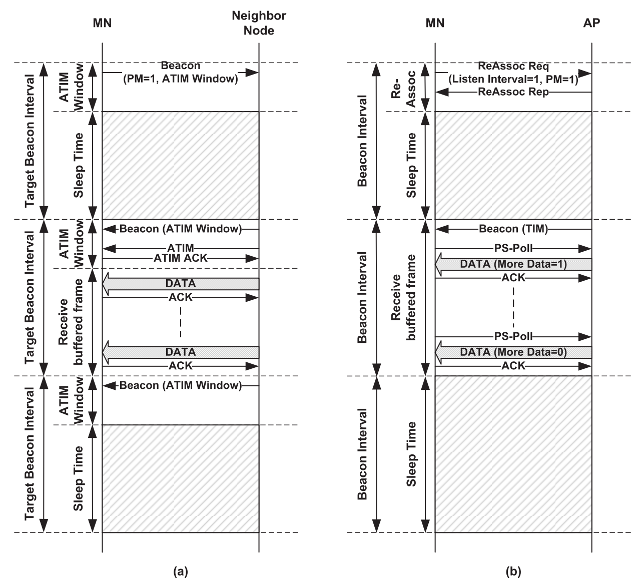

Fig. 2 Power saving mode operation in IEEE 802.11 WLAN (a) ad-hoc mode (b) infrastructure mode.

listen for Beacon frame (with ATIM window) and an Announcement Traffic Indication Message (ATIM) frame from the neighbor. If it receives an ATIM frame, it will reply with an Acknowledgment (ACK) frame, then buffered Data frames can be received. The MN can sleep again after the next ATIM window.

When using infrastructure mode (Fig. 2(b)), the MN can enter to sleep mode by re-associating with its AP (where $PM = 1$ and *ListenInterval* is set to the number beacon intervals to sleep in the Re-Association Request frame). In Fig. 2, *ListenInterval* is set to 1. The MN can sleep at most *ListenInterval* beacon intervals. At the next interval MN must wake up to listen for beacon with TIM. If MN receives a beacon with TIM and MN's ID in TIM identifies the MN has buffered frames, it has to send a PS-Poll frame to request each buffered frame. The AP sends a Data frame back to MN, then MN reply ACK back to AP. This continues until the AP sends a data frame with *MoreData* bit field set to 0 that means no more buffer frames at AP. When MN finish receiving Data frames, it can enter sleep mode again at next interval.

Although PSM is available in IEEE 802.11 wireless LANs, there are several issues in its usage, including: PSM is designed only for one link (works for only one AP/neighbour node); synchronisation of clocks between participating nodes is necessary; and there is an overhead of switching between modes. After reviewing related work, in Sect. 4 we propose taking advantage of PSM to assist a MANEMO handover.

3. Related Work

Handover procedures can be classified as either layer 2 (e.g. between IEEE 802.11 APs) or layer 3 (e.g. using Mobile IP). In this paper we focus on layer 3 handover with using

Mobile IP, in particular when a mobile node or router can attach to two different IP networks.

3.1 Handovers with Mobile IPv6

Mobile IPv6 allows for session continuity for mobile nodes handing over between networks. However the delay for a handover (including Binding Update) can be significant and has led to efforts to reduce handover delay and packet loss. Mobile IPv6 Fast Handovers (FMIPv6) [14] is designed to reduce handover latency by using layer 2 triggers. For example, when a mobile node is still present at the current link, it may discover available access points using link-layer-specific mechanisms. This indicates that the mobile node will be likely to perform a layer 2 handover soon, allowing the mobile node to complete some IP handover procedures prior to layer 2 handover. The drawback of FMIPv6 in MANEMO is relying on layer 2 triggers and requiring communication between the NEMO MR and MANET gateway, which would be difficult to acheive in many networks.

Hierarchical Mobile IPv6 (HMIPv6) [15] introduces a Mobility Anchor Point so that when a mobile node handovers within a domain, the Binding Update is performed with the MAP, instead of HA. HMIPv6 can reduce packet loss, but relies on additional network infrastructure. In addition for MANEMO, having a MAP common for both the NEMO and MANET is unlikely.

Multiple Care-of-Address (MCoA) extensions to Mobile IPv6 [16] allow a mobile node to register more than one CoA at its HA. This is beneficial for fault tolerance, policy-based routing and sending traffic over two (or more) paths simultaneously. In resource constrained MANETs and wireless networks, the latter will result in significant network overhead and is not considered in our research. Using MCoA to allow fast switching between the paths used (MANET or NEMO) is desirable, but in many cases will not offer a benefit in our MANEMO scenario. We assume the MANEMO node knows the best path (MANET or NEMO), and therefore must inform the HA which one to use in a handover. Hence even with MCoA a Binding Update is needed. In this paper we therefore assume MCoA is not used.

3.2 Handover in MANET

A handover in a MANET involves a MANET node changing its IP subnet, normally by changing the gateway it uses to connect to the Internet. [5] presents the challenges and surveys possible solutions for MANET handovers (or MANET/Internet integration). Gateway discovery, necessary before a handover, can be performed using proactive, reactive or hybrid algorithms. [5] (and the references within) compare the tradeoffs between these approaches: proactive offers easy detection of roaming, reactive has low routing overhead and prompt handoffs, while hybrid approaches reduce the overheads by scoping the flooding of advertisements. Other issues covered in [5], but outside of the scope of our work, are interoperability of MANET and Internet routing protocols, as well as security of integration.

[17] proposed a gateway selection scheme for MANET and infrastructure network integration (e.g. cellular network, Internet) by using multiple metrics. Several architectures for supporting mobility between a MANET and Internet have been proposed, e.g. [11]–[13]. These focus on new features for the gateways to support the handover, as well as gateway selection and IP address allocation mechanisms. Handovers are between gateways supporting only MANET/Internet integration. In our work we focus on handovers between a MANET gateway and NEMO mobile router.

3.3 Handover in NEMO

Handover in NEMO occurs when a mobile network (i.e. a Mobile Router) changes from an old to new access router. The NEMO Basic Support Protocol [3] is used to send Binding Updates to the HA, informing it of the new access router. With potentially multiple HAs to forward the Binding Updates via, delays and packet loss can be significant in NEMO handovers.

NEMO route optimization (RO) aims to reduce delay and packet loss by ensuring the HA is on or close to the normal routing path between CN and MR. Several techniques for NEMO RO are available [18], such as delegation, hierarchical and source routing. [19] proposed simple prefix delegation. A prefix can be aggregated at the prefix of a foreign network and is hierarchically delegated to the MRs. MRs advertise the delegated prefix inside its own network. All mobile nodes that used same aggregated prefix can forward packets within network based on prefix of packets' destination address, avoiding routing via HAs. [20] proposed the method for using ad-hoc routing protocols for route optimization in nested NEMO. This allows all nodes within the nested NEMO to route packets directly, rather than via mutiple HAs. Although there are several proposed solutions for NEMO RO, there are no agreed upon standard. In this paper we design a scheme assuming route optimisation is not used (although we also illustrate that the proposed scheme may be suitable in the presence of RO as well).

[21] proposed extending Route Advertisements to convey address information from the Top Level of Mobile Router (TLMR) to each mobile router in nested NEMO. This allows each MR to use a common prefix, thereby allowing packets from mobile to bypass the MR's HAs. The drawback of this method is that it requires extra communication between CN, HA, TLMR and MR.

[22] proposes a multihoming-based seamless handover scheme using a MR with dual egress interfaces for wireless train networks. This scheme allows the train's MR to use one egress interface for handover while an old attached egress interface continuously receive incoming packets. It provides no service disruption and packet loss. However, the proposed solution is only designed for cases where two MR egress interfaces are available.

[23] proposed a Multiple Mobile Router Management (MMRM) system using multiple MR in a mobile network to

support Internet connection for their members. Each mobile router has only one egress interface. Overall bandwidth for the nodes in the mobile network are increased. However, the benefit comes with increased cost of handover (e.g. signaling overhead) and required modifications on MRs and HA.

[24] developed a Cooperative Mobile Router-based Handover (CoMoRoHo) scheme for vehicular networks. As MR performs a handover, another nearby AR in the old access network receives its packets and forwards to the MR performing the handover, thereby reducing packet loss. Although our proposal is similar in concept to CoMoRoHo (having a neighbour node buffer packets), this scheme is specific to NEMO handovers, and does not consider how the buffering can be performed in a MANEMO using IEEE 802.11.

3.4 Handover in MANEMO

The concept of MANEMO is described in [1]. Several examples of applying MANEMO in vehicular networks [6], [25], [26] and emergency services communications [27] have been presented. A particular benefit of MANEMO arises when the MANET path can be used instead of the highly sub-optimal NEMO path, i.e. route optimization [6]. Handovers in MANEMO exhibit similar challenges to handovers in MANETs and NEMO, e.g. high delay of Binding Updates, knowing when to handover. There have been few researchers that have address handover specifically in MANEMO. Our previous work [9] quantifies the handover time and packet loss for a MANEMO handover assuming a single physical egress interface and multiple virtual interfaces. It shows that the number of NEMO MRs is a significant factor in handover delay. No solutions for minimising the handover delay are presented.

A key difference between MANEMO handovers and pure NEMO (or MANET) handovers is the two different access techniques used. Specifically, assuming wireless LAN, the MANEMO node switches between infrastructure mode (NEMO) and ad-hoc mode (MANET). In a pure NEMO handover, the MR switches between two APs both using infrastructure-mode. Efficiently utilising both ad-hoc- and infrastructure-modes is key to minimising handover delay in MANEMO.

Although not specifically addressing MANEMO handovers, a number of researchers have described how a single IEEE 802.11 wireless LAN card can switch between ad-hoc and infrastructure mode. [28] presents an architecture that allows switching between modes by introducing new frames for a node to inform the AP/neighbour that a switch is about to occur. The AP/neighbour keeps state information about the node. An alternative technique is to use Power Save Mode (PSM), which is part of the IEEE 802.11 standard. The idea is that the node uses PSM to inform one interface (ad-hoc or infrastructure) that will sleep for a period. However instead of entering a power save state, the wireless card switches to the other interface to transmit/receive data. The card alternates between the two interfaces. [10] proposes MutiNet, driver software for controlling the wireless card using PSM. Similarly, [29] also uses PSM and introduces techniques for QoS negotiation between nodes, so the wireless card can better select which interface to use.

4. Proposed Handover Scheme

We propose an algorithm for using IEEE 802.11 PSM to implement buffering in MANEMO handovers. Using PSM, the MANEMO node informs its neighbour node on the old network to buffer incoming frames. Then, assuming the MANEMO node has a single physical wireless interface that can be virtualized, instead of sleeping the MANEMO uses the alternate virtual wireless interface to initiate a handover on the new network. It is important to note that the MANEMO node, although using PSM, does not enter a sleep state. That is, PSM is not used to save power but to allow two virtual wireless interface. This approach has been used in different operating systems [10], [30]. With the proposed algorithm, a MANEMO node can perform a handover with minimal packet loss.

4.1 Assumptions and Scope

In the design and analysis of the MANEMO handover algorithm, a number of assumptions are made. The MANEMO node, MANET nodes and the ingress interface of the MR use IEEE 802.11 wireless LAN (no specific physical layer is assumed). The MANET nodes (including MANEMO when using MANET interface) use IEEE 802.11 ad-hoc mode. The MR and MANEMO node when using NEMO interface use IEEE 802.11 infrastructure mode, i.e. the MR is an access point. The MANEMO node can quickly switch between the ad-hoc and infrastructure interface (switching times less then a 1 ms, down to a few microseconds have been report [10], [31], [32]). PSM is supported on all nodes. The assumption of IEEE 802.11 is reasonable, as it is not only available in end-user devices, but also likely to be supported in vehicles.

It is assumed some coordination between the MANET and NEMO networks is available. Firstly, both networks use two different, non-overlapping frequency channels. Without non-overlapping channels, transmissions on the new network may interfere with those in the old network. The handover may still work in this case, but our analysis in Sect. 5 does not consider the effects of interference. Secondly, clocks across all wireless nodes involved in the handover are synchronized. This is necessary to allow the sleep intervals in the PSM frames to be aligned on MANET and NEMO. Synchronization is possible if all nodes have external timing sources, e.g. GPS. Alternatively, nodes can use their own coordination protocol. [33] developed a synchronization protocol giving a mobile node higher priority in sending timing information, allowing for neighbour nodes to collect timing information and synchronize to the fastest clock by self-correcting its timer periodically. A final assumption is the beacon interval used in NEMO is the same as the Target Beacon Interval used in the MANET. Coordination of these timing intervals could be performed during network operation.

The solution presented in this paper assumes IEEE 802.11 frames and protocol mechanisms cannot be modified. It is possible the handover algorithm could be optimized by, for example changing frame formats, but at the expense of compatibility.

Our analysis of MANEMO handover focusses only on the procedure once a MANEMO node decides to handover. The methods for making the decision are outside of the scope of this paper. It is also assumed that at the time the handover begins, the MANEMO node has already associated with the MR. That is, wireless link connectivity does not need to be established.

4.2 MANEMO Handover Algorithm Using PSM

Our handover algorithm has been designed for handovers in both direction: from NEMO to MANET and from MANET to NEMO. Due to lack of space, we describe only NEMO to MANET in depth, and then briefly state the key differences when handing over in the opposite direction.

MANEMO node first informs the MANET neighbour node it wants to sleep by sending a Beacon frame with PM bit set to 1 and ATIM Window field indicating how long it is prepared to wait for a ATIM frame (in this case it can be short, as there should be ATIM frame to be received). Instead of sleeping, the MANEMO node switches to the NEMO interface and immediately initiates a handover (i.e. sending IPsec packet).

Depending on the delay to the HA, the IPsec/NEMO handover may not complete in a single beacon interval. Figure 3 shows an example where the IPsec exchange completes in the first beacon interval, but the Binding Update is still remaining. As the MANEMO node must switch back to the MANET interface at the end of the interval, it informs the NEMO MR it will sleep by sending a Re-association Request (with PM bit set to 1, Listen Interval of 1 beacon

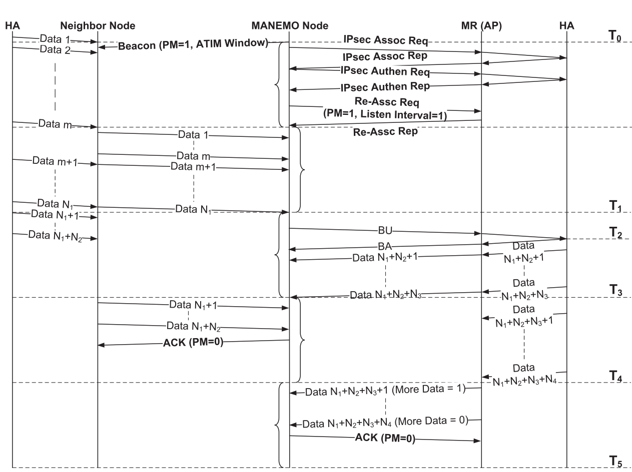

Fig. 3 MANEMO Handover with PSM algorithm (Handover to NEMO).

period). Note that in IEEE 802.11 the duration a node can sleep in infrastructure mode is defined by the Listen Interval (as a multiple of beacon periods). A Listen Interval of 2 means the MANEMO node would sleep for 2 beacon periods, wake-up, and then sleep for 2 beacon periods and so on. However in ad-hoc mode the MANEMO node can only sleep for a single beacon period at a time. Therefore to coordinate between MANET and NEMO, the Listen Interval is always 1 in infrastructure mode.

The MANEMO node switches back to the old MANET interface to receive any buffered frames from its neighbour. A Beacon frame is received by the neighbour, with the ATIM Window indicating the time the MANEMO node has to request buffered frames. It does so by sending an ATIM frame. Then the buffered Data frames are received. If the MANEMO node has finished the handover the neighbour can be informed to stop using PSM by setting PM bit to 0 in the last ACK.

In general, the IPsec exchange may take several beacon intervals to complete, in which the above steps are repeated. Assuming the IPsec exchange is completed by time T_1, the MANEMO node switches to NEMO and then performs the Binding Update. After the HA receives the Binding Update packet (at time T_2), it will forward data packets to the NEMO network. At the end of the beacon interval (time T_3), the MANEMO node switches to receive the last batch of buffered frames on the MANET. Finally at time T_4 MANEMO node switches back to NEMO, receives remaining buffered frames (by sending PS-Poll frames), and informs the MR to stop using PSM by setting the PM bit to 0 in the final ACK frame. At time T_5 the handover is complete.

For the handover from NEMO to MANET the procedure is similar, however to start the handover the MANEMO node sends a Re-association Request (with PM bit = 1, Listen Interval = 1) to inform the MR it is entering sleep mode.

5. Performance Modelling

5.1 Performance Metrics and Notation

We consider a MANEMO handover where the MANEMO node is a VMN with a real-time, constant bit rate (e.g. voice) session with the CN. To evaluate the effectiveness of using PSM to perform buffering in a MANEMO handover the performance metrics are: packet loss (L packets) during the handover; buffering delay (B seconds) experienced at neighbour node (in MANET or NEMO); maximum size of the buffer (S bytes) needed at neighbour; and end-to-end data packet delay. Only data packets sent from CN to MANEMO are considered. In addition, the cost of signalling overhead (C bytes) is measured. It is generally understood that sending packets in a wireless network (i.e. MANET, NEMO) costs more than across a core network (in our work, the Internet). Hence, to determine the cost associated with signalling overhead weight ω_h is assigned to a transmission across a single wireless (NEMO/MANET) hop and weight

ω_{int} for a transmission across the Internet.

Other notation used in the modelling include: D_A^B represents the one-way delay between A and B, where ha is a HA, gw is either MANET or NEMO gateway, mn is the MANEMO node and ne is the MANET neighbour node; D_h is the one-way delay across a single (MANET or NEMO) wireless hop; h_M and h_N are the number of hops from MANEMO node to MANET and NEMO gateways, respectively (where h_N is the nested depth of NEMO, η_d, plus one, since the MANEMO node is 1 hop away from the lower most MR); and P represents the size, in bytes, of a data packet. The subscripts N and M refer to variables relevant for the NEMO and MANET networks, respectively.

Although we assume no NEMO route optimization in this paper, in Sect. 5.4 we present extensions of our model that allow us to illustrate that our proposed scheme can be of benefit if route optimization was used.

5.2 Analysis of MANEMO Handover without PSM

Sections 5.2.1 and 5.2.2 calculate the metrics of packet loss and signalling overhead, respectively, in the case that PSM is not used. As there is no buffering, the buffer size and buffer delay are both 0.

5.2.1 Packet Loss

All packets transmitted by the correspondent node from the time when the MANEMO node initiates the handover (i.e. disconnects from the old network) until when the HA receives a Binding Update will be lost during a handover. In addition, packets already in the path from HA to the old network when the handover starts will be lost. With a constant packet transmission rate of λ, the packet loss can be determined from the handover delay (up until the Binding Update is received, that is, T_2 in Fig. 3) and from the delay between HA and MANEMO node, i.e. D_{ha}^{mn}.

For handover to NEMO, T_2 depends on the nested depth of NEMO (and hence HA's) the 5 signalling messages must pass via. D_{ha}^{mn} depends on the hops to MANET gateway. The packet loss, L_N, can then be calculated as:

$$T_2 = 5(h_N D_h + \eta_d D_{ha}^{ha} + D_{gw}^{ha}) \tag{1}$$

$$D_{ha}^{mn} = D_{gw}^{ha} + D_h h_M \tag{2}$$

$$L_N = \lambda(T_2 + D_{ha}^{mn}) \tag{3}$$

The equation for loss during a handover to MANET is identical to (3) except T_2 and D_{ha}^{mn} are calculated as:

$$T_2 = 5(h_M D_h + D_{gw}^{ha}) \tag{4}$$

$$D_{ha}^{mn} = h_N D_h + D_{gw}^{ha} + D_{ha}^{ha}\eta_d \tag{5}$$

5.2.2 Signalling Overhead

For brevity, P_{IPsec} is defined as the sum of the size of the four IPsec related packets sent during a handover, i.e. the IKE Security Association initialisation/authentication request/reply packets. Similarly, P_{MIP} is the sum of the size of the Mobile IP Binding Update and Binding Acknowledge packet.

In a handover without PSM buffering, all IPsec and Mobile IP packets are sent once over both the wireless access network and Internet. Hence the cost of signalling is:

$$C_N = (\omega_h h_N + \omega_{int})(P_{IPsec} + P_{MIP}) \tag{6}$$

$$C_M = (\omega_h h_M + \omega_{int})(P_{IPsec} + P_{MIP}) \tag{7}$$

5.3 Analysis of MANEMO Handover with PSM

The performance of using PSM for buffering depends on the time it takes to complete the handover (i.e. send the IPsec and binding messages to HA). For a fixed beacon interval, I, a longer handover duration will result in switching between the old and new network multiple times. The handover duration depends on the round trip time of a handover message from MANEMO node to HA, i.e. $2D_{mn}^{ha}$. To consider the effect of the handover duration we define η_I as the number of intervals from when the handover is initiated until the first batch of buffered frames on the new network are received by the MANEMO node as shown in Fig. 4. By analysing different cases of the round trip time relative to the beacon interval I, η_I can be calculated as:

$$\eta_I = \begin{cases} f(\lceil 10D_{mn}^{ha} \rceil) & \text{if } 2D_{mn}^{ha} < I \\ f(\lceil 8D_{mn}^{ha} \rceil + \lceil 2D_{mn}^{ha} \rceil) & \text{if } 2D_{mn}^{ha} = I \\ 2\lceil 4D_{mn}^{ha} \rceil + f(\lceil 2D_{mn}^{ha} \rceil) & \text{if } \lceil 4D_{mn}^{ha} \rceil \text{ is even} \\ f(\lceil 8D_{mn}^{ha} \rceil + \lceil D_{mn}^{ha} \rceil) & \text{otherwise} \end{cases} \tag{8}$$

where $f(x) = x + 2^{mod(x,2)}$.

Similarly, if a *round* involves a beacon interval on the new network followed by the old network, the number of

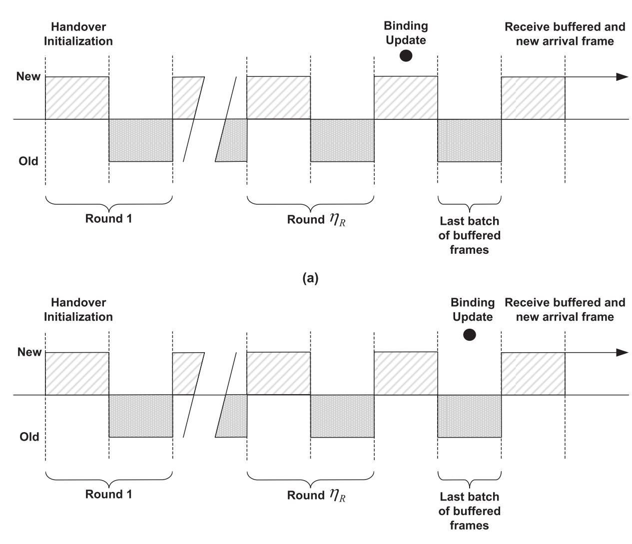

Fig. 4 MANEMO handover with PSM and $\eta_R > 1$. (a) Finish Binding Update in the interval of new network, (b) Finish Binding Update in the interval of old network.

rounds before the Binding Update is received (at time T_1 in Fig. 3) is:

$$\eta_R = (\eta_I - 3)/2 \tag{9}$$

To simplify the analysis in the following sections the packets arriving during handover procedure can be grouped based on four phases. Firstly, between the start and T_1, packets arrive at the old network; while the MANEMO node is active on the new network, packets arriving will be buffered. The number of buffered packets in the first phase, N_1 depends on the number of rounds:

$$N_1 = \eta_R \lfloor 2I\lambda \rfloor \tag{10}$$

In the second phase between T_1 and T_2 the Binding Update arrives at the HA. In this beacon interval, assuming the Binding Update arrives at the middle of the interval, N_2 packets are buffered at the old network during this phase:

$$N_2 = \lfloor I\lambda/2 \rfloor + 1 \tag{11}$$

and N_3 packets are received on the new network:

$$N_3 = \begin{cases} 0 & \text{if } I/2 < D_{ha}^{mr} \\ \left\lfloor \lambda(I/2 - D_{ha}^{mr}) \right\rfloor + 1 & \text{otherwise} \end{cases} \tag{12}$$

Finally, in the fourth phase between T_3 and T_4, N_4 packets are buffered on the new network during the last interval that the MANEMO node collects buffered frames from the old network:

$$N_4 = \begin{cases} \lfloor I\lambda \rfloor & \text{if } I/2 > D_{ha}^{mr} \\ \left\lfloor \lambda(3I/2 - D_{ha}^{mr}) \right\rfloor & \text{if } 3I/2 > D_{ha}^{mr} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

5.3.1 Signalling Overhead

When using PSM for buffering, a MANEMO handover requires the same IPsec and Mobile IP signalling as when buffering is not used (i.e. C_N). There is also additional IEEE 802.11 frames sent. At the start of the handover the MANEMO node must inform the neighbour node that buffering is required by sending a special Beacon frame (Beacon-TIM in infrastructure mode, Beacon-ATIM in adhoc mode). On the infrastructure (NEMO) network, the MANEMO must also re-associate with the AP. As the handover may take multiple beacon intervals, the process of informing the neighbour node about buffering must be repeated. Finally on the NEMO network, a PS-Poll frame must be sent for each buffered frame to be received (although there is other power saving information sent in frames, it is transferred in headers of DATA and ACK frames, therefore contributing no additional overhead). Hence the cost of signalling is:

$$\begin{aligned} C'_N = {} & C_N + \omega_h(P_{BATIM} \\ & + P_{ReassocReq} + P_{ReassocRep} \\ & + (\eta_R + 1)(P_{BATIM} + P_{ATIM} + P_{ATIMAck})) \end{aligned} \tag{14}$$

$$\begin{aligned} C'_M = {} & C_N + \omega_h(P_{BATIM} \\ & + P_{ReassocReq} + P_{ReassocRep} \\ & + (\eta_R + 1)P_{BTIM} \\ & + (\eta_R + 1)(\lfloor I\lambda \rfloor + 1)P_{PSPoll}) \end{aligned} \tag{15}$$

5.3.2 Buffer Size

The maximum buffer size, S', that is necessary depends on the number of packets that can be sent during a beacon interval. In most cases a full interval (I) worth of packets must be buffered. (in cases if a short handover it is slightly less. For data packets containing P_{data} bytes, the maximum buffer sizes at the NEMO MR is:

$$S'_N = \begin{cases} P_{data}(\lfloor I\lambda \rfloor) & \text{if } \eta_R = 0 \text{ and } I > T_2 \\ P_{data}(\lfloor I\lambda \rfloor + 1) & \text{otherwise} \end{cases} \tag{16}$$

Equation (16) also applies for the MANET neighbour, i.e. $S'_M = S'_N$, and $D_{ha}^{mr} = D_{ha}^{ne}$. Notice that S'_N occurs when MANEMO node has handover to MANET, and S'_M occurs when MANEMO node has handover to NEMO.

5.3.3 Buffering Delay

Considering the four different phases in the case of handover to NEMO, the buffering delay of each individual packet, B_{pkt_i}, can be calculated. In the first phase, in each round, the first $m = \lfloor I\lambda \rfloor + 1$ packets that arrive in a beacon interval are buffered, while the remaining packets are not. While MANEMO node is on the new network, the first packet that arrives on the old network is buffered for the entire interval (I), the second packet that arrives $\frac{1}{\lambda}$ seconds later must be buffered for $I - \frac{1}{\lambda}$, and so on. When the MANEMO node switches to the old network, there is additional delay before the buffered packets can be received: the time to send 3 frames (Beacon, ATIM, ATIM-Ack) and the time for preceding buffered packets to be received and ACK. Hence:

$$B_{pkt_i} = \begin{cases} I - \frac{i-1}{\lambda} + D_h(3 + 2(i-1)) & i = 1 \to m \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

There are η_R rounds in the first phase, therefore the total buffering delay experienced by the N_1 packets is:

$$\begin{aligned} B_1 &= \sum_{i=1}^{N_1} B_{pkt_i} \\ &= m\eta_R \left[\frac{2I + 6D_h + (m-1)(2D_h - \frac{1}{\lambda})}{2} \right] \end{aligned} \tag{18}$$

Equation (17) also applies in phase two where N_2 packets are buffered resulting in a total buffer delay of:

$$B_2 = N_2 \left[\frac{2I + 6D_h + (N_2 - 1)(2D_h - \frac{1}{\lambda})}{2} \right] \tag{19}$$

In phase three no packets are buffered because of new packets arrive while MN stays on new network and therefore $B_3 = 0$. In phase four the individual and total buffering delay for the N_4 packets is:

$$B_{pkt_i} = \begin{cases} I - \frac{i-1}{\lambda} + D_h(2 + 3(i-1)) & \text{if } \frac{I}{2} > D_{ha}^{mr} \\ \frac{3I}{2} - \frac{i-1}{\lambda} - D_{ha}^{mr} + \\ \quad D_h(2 + 3(i-1)) & \text{if } \frac{3I}{2} > D_{ha}^{mr} \\ 0 & \text{otherwise} \end{cases} \quad (20)$$

$$B_4 = \begin{cases} N_4\left[\frac{2I + D_h(1-3N_4) + \frac{1}{\lambda}(1-N_4)}{2}\right] & \text{if} \frac{I}{2} > D_{ha}^{mr} \\ N_4\left[\frac{3I + D_h(1+3N_4) + \frac{1}{\lambda}(1-N_4) - 2D_{ha}^{mr}}{2}\right] & \text{if} \frac{3I}{2} > D_{ha}^{mr} \\ 0 & \text{otherwise} \end{cases} \quad (21)$$

From the above modeling of the number of packets buffered, and the delay experienced by those packets, the average buffer delay can be determined. Similar analysis is applied for the case of handover to MANET.

5.3.4 Packet Loss

When buffering is used (with an infinite sized buffer) packets will be considered lost if their end-to-end delay is greater than an acceptable delay, γ. The end-to-end delay, D_{cn}^{mn}, consists of the path delay plus buffering delay. Hence packet i is lost if:

$$D_{cn}^{ha} + D_{ha}^{mn} + B_{pkt_i} > \gamma \quad (22)$$

From Eq. (17) (and Eq. (20) for phase four), B_{pkt_i} is decreasing as the packet number decreases. Therefore the first i_γ packets with delay greater than γ will be considered lost and the remaining will be successfully received. i_γ can be found be by substituting Eq. (17) in Eq. (22) and re-arranging:

$$i_\gamma = \left\lfloor \frac{tr - D_{cn}^{mn} - I - 3D_h}{2D_h - (1/\lambda)} + 1 \right\rfloor \quad (23)$$

In phase one there may be multiple rounds. In each round packets may be buffered (and lost) on the new (NEMO) network (l_{new}) or the old (MANET) network (l_{old}), resulting in the total packet loss of L_1:

$$l_{new} = \begin{cases} \lfloor min(i_\gamma, m) \rfloor & \text{if } i_\gamma > 0 \\ 0 & \text{otherwise} \end{cases} \quad (24)$$

$$l_{old} = \begin{cases} \lfloor 2I\lambda \rfloor - \lfloor I\lambda \rfloor + 1 & \text{if } D_{cn}^{mn} > \gamma \\ 0 & \text{otherwise} \end{cases} \quad (25)$$

$$L_1 = \eta_R * (l_{new} + l_{old}) \quad (26)$$

Similar analysis is used for phase two and three:

$$L_2 = \begin{cases} \lfloor min(i_\gamma, N_2) \rfloor & \text{if } i_\gamma > 0 \\ 0 & \text{otherwise} \end{cases} \quad (27)$$

$$L_3 = \begin{cases} N_3 & \text{if } D_{cn}^{mn} > \gamma \\ 0 & \text{otherwise} \end{cases} \quad (28)$$

In phase four Eq. (20) is used for B_{pkt_i}, and therefore i_γ and L_4 are calculated as:

$$i_\gamma = \left\lfloor \frac{\gamma - D_{cn}^{mn} - I - 2D_h + D_{ha}^{mr} - D_{ha}^{ne}}{3D_h - (1/\lambda)} + 1 \right\rfloor \quad (29)$$

$$L_4 = \begin{cases} \lfloor min(i_\gamma, N_4) \rfloor & \text{if } i_\gamma > 0 \\ 0 & \text{otherwise} \end{cases} \quad (30)$$

Therefore the total number of packets lost during a handover to NEMO is:

$$L'_N = L_1 + L_2 + L_3 + L_4 \quad (31)$$

A similar approach is used for a handover to MANET, except the equations for B_{pkt_i} and D_{cn}^{mn} differ.

5.4 Impact of NEMO Route Optimization

Our scheme is designed for the case when NEMO route optimization is not available or used. However if it was used, then in the best case packets between MANEMO and its HA can be routed on their optimal path, rather than via HA's of MRs in the nested NEMO network. In our performance model, this means both the time to send a Binding Update on the NEMO path and the time to send packets from HA to MANEMO are reduced. That is, Eqs. (1) and (5) are replaced with Eqs. (32) and (33), respectively.

$$T_2 = 5(h_N D_h + D_{gw}^{ha}) \quad (32)$$

$$D_{ha}^{mn} = h_N D_h + D_{gw}^{ha} \quad (33)$$

6. Performance Results

This section presents a selection of results, obtained from the mathematical analysis in the previous section, illustrating the key performance trends when performing MANEMO handovers. Unless otherwise stated the results are from a scenario containing a NEMO network with 1 MR ($h_N = 2$), a 2-hop MANET and the CN sending based on G.711 voice codec ($\lambda = 50$ pkt/s) with an acceptable delay (γ) of 250 ms [34]. We assume the delay across a single wireless hop (D_h) is 1 ms. Most IEEE 802.11 control packets will take less than 1 ms when using CSMA/CA in a lightly-loaded network. We assume the cost of transmission in the wireless network is twice that of in the wired Internet ($\omega_h = 2$, $\omega_{int} = 1$). The default IEEE 802.11 beacon interval (I) is set to 100 ms. The delays D_{gw}^{ha} and D_{ha}^{ha} are set to the same value as each other, ranging from 10 ms to 100 ms (based on measured data from [35] for North America backbone networks in June 2009). The results refer to this value as Internet delay. Other values of the parameters have been investigated (e.g. h_N, h_M, D_h, I), but the results show that they have negligible impact on performance or are have similar trends (e.g. handover to NEMO versus handover to MANET), and hence are not shown.

Figure 5 shows the cost of signalling overhead incurred for a handover to NEMO for varying values of Internet delay. Without PSM, the cost is constant as the Internet delay increases. A larger cost is incurred as the nested depth

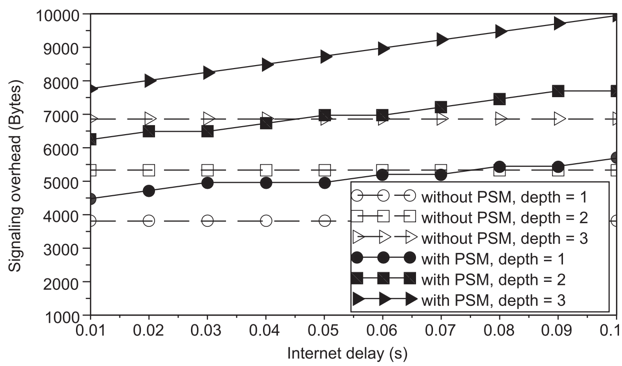

Fig. 5 Cost of signalling for handover to NEMO.

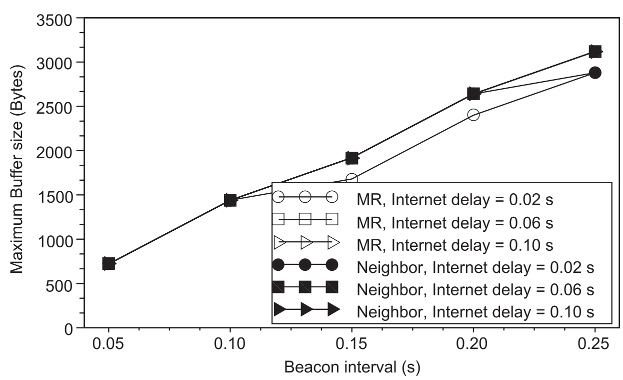

Fig. 6 Maximum buffer size needed at MR/Neighbour.

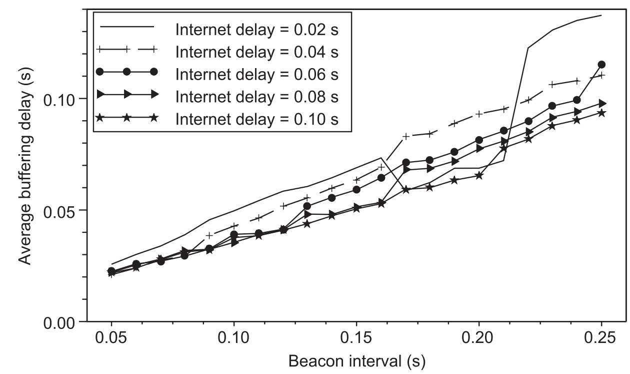

Fig. 7 Average buffer delay for handover to NEMO.

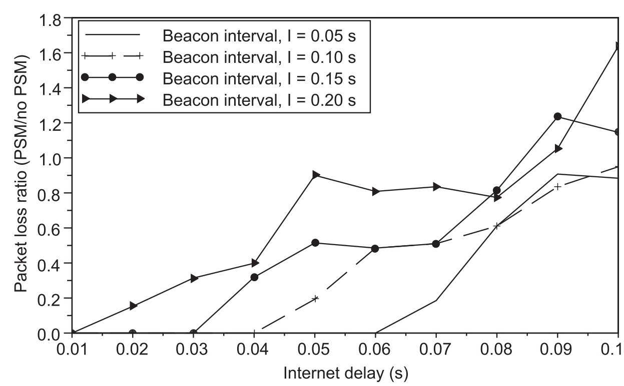

Fig. 8 Packet loss (ratio with PSM to without) for handover to MANET.

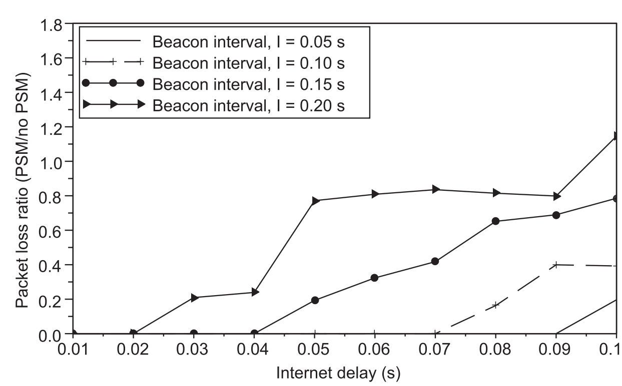

Fig. 9 Packet loss (ratio with PSM to without) for handover to MANET, with NEMO route optimization.

of NEMO increase as packets have to be sent across an increased number of wireless hops. Introducing PSM increases the cost of signalling. Also, the cost increases as the Internet delay increases as the number of rounds necessary to complete the handover increases (for each round, wireless LAN beacon and poll messages must be sent). The increased cost of signalling is acceptable in most cases, so long as the number of nested MRs is limited. Also if there are multiple MANEMO nodes performing a handover at the same time, then the signalling overhead due to PSM may reduce the capacity available for data transfer.

Using PSM introduces an additional requirement on the MR/neighbour node in terms of buffer space. Figure 6 shows the maximum buffer space needed by both the MR and neighbour node when different beacon intervals are used. Firstly note that in most values of Internet delay the maximum buffer size is constant. In addition, as the beacon interval increases the amount of buffer space needed increases because packets must be buffered for an entire interval. Although not shown, varying hop delay (D_h), nested depth of NEMO (η_d) and number of MANET hops (h_M) has negligible impact on the size of the buffer needed. For all analysed cases, the maximum buffer size is less than 4000 Bytes. It is reasonable to expect another IEEE 802.11 node has this amount of memory available to support buffering. Even for a MR that needs to serve multiple MANEMO nodes, several KBytes of memory is normally available.

Figure 7 shows the average buffer delay for data packets when PSM is used. When the MANEMO node is performing the handover on the new network, packets arriving on the old network are buffered. Similar to the buffer size, the average buffer delay increases as the beacon interval increases.

Without PSM, 100% of packets sent during the handover period are lost. Using PSM reduces the packets lost, at the expense of introducing a buffer delay. This additional buffer delay adds to the end-to-end delay, and in some cases results in packet loss (if the packets are received with delay greater than that acceptable). Figures 8, 9 and 10 show the packet loss for a handover to MANET, while Fig. 11 shows

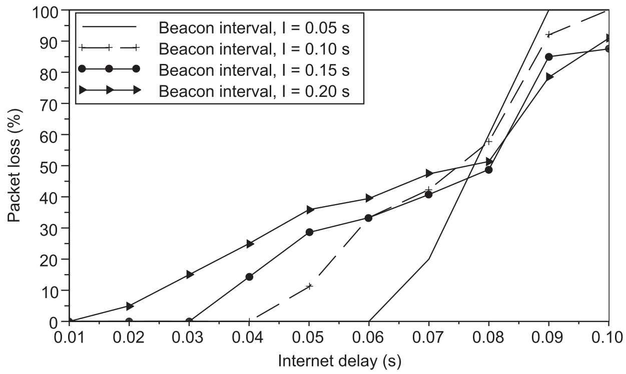

Fig. 10 Packet loss (% of all packets sent during handover) for handover to MANET.

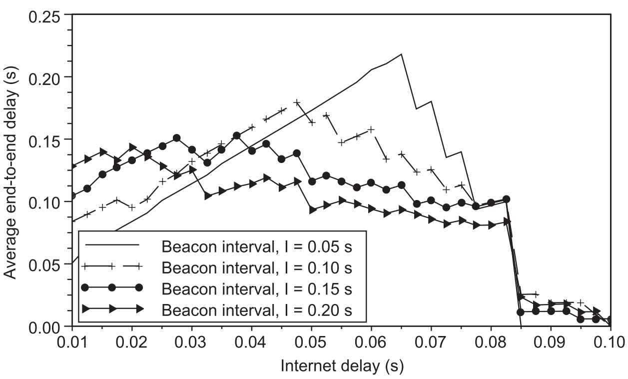

Fig. 11 Average end-to-end delay for handover to MANET.

the average end-to-end delay. The packet loss is shown in two forms. The ratio in Fig. 8 compares the packets lost when using PSM (L'_N) versus not using PSM (L_N). Figure 9 is similar, except considers the case when NEMO route optimization is available. A lower value indicates better performance for PSM; a value of 1 means there is no advantage of using PSM compared to without. Figure 10 shows the percentage of packets lost out of all packets sent during a handover when using PSM (without PSM is not shown — it will always be 100%). The results are shown for the handover to MANET as they are slightly worse (for PSM) compared to a handover to NEMO.

Firstly, Fig. 8 illustrates that with the default beacon interval of 100 ms PSM is beneficial (i.e. reduced packet loss compared to without PSM) with Internet delay up to 100 ms. With larger beacon intervals, the benefits of PSM are reduced, as even a small Internet delay (50 ms) results in almost the same number of packets lost as when PSM is not used.

Although in most cases we have assumed NEMO route optimization is not used, comparing Fig. 8 (no RO) with Fig. 9 (with RO) illustrates that if route optimization is used, our proposed scheme still offers benefits. That is, the packet loss is reduced by a combination of RO and buffering. Further research is needed to consider the detailed interactions between specific RO mechanisms and buffering in MANEMO.

Now consider Figs. 10 and 11. For small Internet delay (relative to beacon interval), no packets are lost, as those received during the handover are buffered and later transferred to the MANEMO node. However as the Internet delay increases, the RTT increases (with only small changes in the buffer delay), increasing average end-to-end delay. Eventually, some packets start to be dropped when received by the MANEMO node as the end-to-end delay is outside the acceptable limit (250 ms in all results). Hence the packet loss starts to increase as Internet delay increases. The reason for the average end-to-end delay going down at this point is because packets with delays greater than 250 ms are not counted. Hence it is important to view the packet loss and delay results in tandem.

Note that the sawtooth nature of the results in Fig. 11 (and seen to a lesser extent in other results) is due to the different behaviour depending on when the Binding Update is received. As the Internet delay increases, the number of rounds increase, as does the end-to-end delay. However if the Binding Update is received in round r, then there is also a difference in performance depending on whether the Binding Update is received at the HA when the MANEMO is currently on the old network, or if it is on the new network. This is also the reason why there is a drop in the average buffer delay when the Internet delay is 0.02 in Fig. 7.

In summary, the performance model developed in Sect. 5 allows us to evaluate the trade-offs in using PSM to support MANEMO handover. The results in this section show, for example, that using a default IEEE 802.11 beacon interval of 100 ms, the benefits of PSM (reduced packet loss) are significant with Internet delay less than 70 ms, leading to minor increases in signalling overhead and acceptable end-to-end delay.

7. Conclusions

In heterogeneous wireless networks, mobile nodes should take advantage of the best path to the destination. In MANEMO, a mobile node has at least two potential paths: one via an infrastructure-based NEMO network and the other via a MANET. A handover between the two networks requires Mobile IP/NEMO signalling, introducing delays that can severely degrade application performance. Assuming the mobile MANEMO node can switch its layer 2 (IEEE 802.11) interface between the two networks, we have developed an analytical model that can evaluate the performance of a MANEMO handover under different conditions. We have also shown that buffering, a common technique for handover optimisation in wireless networks, can be applied using the IEEE 802.11 Power Saving Mode. By using PSM, the packet loss can be reduced in MANEMO handovers, with acceptable increases in signalling overhead and end-to-end delay.

Our work has focussed on Mobile IP/NEMO for layer 3 mobility signalling. The same approach of using PSM for buffering could also provide benefits if other signalling protocols were used (e.g. HMIP, FMIP). Although our proposed solution is for MANEMO, it potentially could be used for handovers between a MANET node and single-hop wireless network. However in this scenario, there may be less opportunities for handover (the single-hop link will normally provide better performance than a MANET), meaning the benefits of our scheme may be outweighed by the additional complexity. We have focussed only on IEEE 802.11 wireless LAN, providing a solution that is compatible with the current standard. Further optimisations, such as dynamically selecting the time to sleep, rather than using a fixed Listen Interval of 1, may be possible if not restricted by compatibility. If other layer 2 technologies are used, then an additional protocol for informing neighbours that buffering is occurring would be needed (e.g. [28]).

Similar to [24], our analytical model makes the simplifying assumptions that the hop delay and Internet delay are fixed. Hence the results are applicable for light to moderate loaded wireless networks, and stable Internet paths. Future work will consider the dynamics of the link-layer and network path performance. The results for the selected scenarios show that the packet loss for PSM approaches that without PSM as the delay to the HA increases. However, techniques that control the delay to HA [36], mean this is not a significant limitation. Finally, mechanisms for learning and selecting the best path, as well as binding specific application flows to different MANEMO paths will be considered in the future.

Acknowledgment

This research was supported by the Telecommunications Research and Industrial Development Institute (TRIDI), National Telecommunications Commission (NTC), Thailand.

References

[1] R. Wakikawa, T. Clausen, B. McCarthy, and A. Petrescu, "MANEMO topology and addressing architecture," IETF Internet Draft (draft-wakikawa-manemoarch-00.txt), July 2007.
[2] B. McCarthy, C. Edwards, and M. Dunmore, "Advances in MANEMO: Definition of the problem domain and the design of a NEMO-centric approach," Proc. 2007 International Symposium on Applications and the Internet Workshops, pp.47–47, Hiroshima, Japan, Jan. 2007.
[3] V. Devarapalli, R. Wakikawa, A. Petrescu, and P. Thubert, "Network mobility (NEMO) basic support protocol," IETF RFC 3963, Jan. 2005.
[4] D. Johnson and C. Perkins, "IP mobility support for IPv6," IETF RFC 3775, July 2007.
[5] S. Ding, "A survey on integrating MANETs with the Internet: Challenges and designs," Comput. Commun., vol.31, no.14, pp.3537–3551, Sept. 2008.
[6] M. Tsukada, O. Mehani, and T. Ernst, "Simultaneous usage of NEMO and MANET for vehicular communication," Proc. 4th International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities, pp.1–8, Innsbruck, Austria, March 2008.
[7] R. Wakikawa, R. Koodli, and A. Nilsson, "Design of vehicle network: Mobile gateway for MANET and NEMO converged communication," Proc. 2nd ACM international workshop on Vehicular ad hoc networks, pp.81–82, Cologne, Germany, Sept. 2005.
[8] B. McCarthy, A. Petrescu, and T.H. Clausen, "MANEMO Configuration Problems (MCP)," IETF Internet Draft (draft-mccarthy-manemo-configuration-problems-00), March 2007.
[9] J. Thaenthong and S. Gordon, "Delay and packet loss analysis for handovers between MANETs and NEMO networks," Proc. 5th International Conference on Computer Networks and Mobile Computing, pp.486–491, Singapore, Aug. 2009.
[10] R. Chandra, P. Bahl, and P. Bahl, "MultiNet: Connecting to multiple ieee 802.11 networks using a single wireless card," Proc. 23rd Annual Joint Conference of the IEEE Computer and Communications Societies, pp.882–893, Hong Kong, China, March 2004.
[11] S. Ding, A. Dadej, and S. Gordon, "Internet integrated MANET using Mobile IP," Proc. 3rd Workshop on the Internet, Telecommunications and Signal Processing, pp.125–130, Glenelg, Australia, Dec. 2004.
[12] M. Denko and C. Wei, "An architecture for integrating mobile ad hoc networks with the Internet using multiple mobile gateways," Proc. 18th Annual Canadian Conference on Electrical and Computer Engineering, pp.1097–1102, Saskatchewan, Canada, May 2005.
[13] S. Bin, S. Denglian, and Y. Bai, "Interconnect between MANET and Internet," Proc. 5th International Conference on Wireless Communications, Networking and Mobile Computing, pp.1–4, Beijing, Chaina, Sept. 2009.
[14] R. Koodli, "Mobile IPv6 fast handovers," IETF RFC 5568, July 2009.
[15] H. Soliman, C. Castelluccia, K. ElMalki, and L. Bellier, "Hierarchical mobile ipv6 (HMIPv6) mobility management," IETF RFC 5380, Oct. 2008.
[16] R. Wakikawa, V. Devarapalli, G. Tsirtsis, T. Ernst, and K. Nagami, "Multiple care-of addresses registration," IETF RFC 5648, Oct. 2009.
[17] F. Setiawan, S. Bouk, and I. Sasase, "Multiple metrics gateway selection scheme in mobile ad hoc network (MANET) and infrastructure network integration," IEICE Trans. Commun., vol.E92-B, no.8, pp.2619–2627, Aug. 2009.
[18] A. Shahriar, M. Atiquzzaman, and W. Ivancic, "Route optimization in network mobility: Solutions, classification, comparison, and future research directions," IEEE Communications Surveys and Tutorials, vol.12, no.1, pp.24–38, 1st Quarter 2010.
[19] K. Lee, J. Park, and H. Kim, "Route optimization for mobile nodes in mobile network based on prefix delegation," Proc. 58th IEEE Vehicular Technology Conference, pp.2035–2038, Florida, USA, Oct. 2003.
[20] T. Clausen, E. Baccelli, and R. Wakikawa, "Route optimization in nested mobile networks (NEMO) using OLSR," Proc. IASTED International Conference on Networks and Communication Systems (NCS 2005), Krabi, Thailand, April 2005.
[21] M. Watari, T. Ernst, R. Wakikawa, and J. Murai, "Routing optimization for nested mobile networks," IEICE Trans. Commun., vol.E89-B, no.10, pp.2786–2793, Oct. 2006.
[22] H. Park, D. Kum, Y. Kwon, K. Lee, and Y. Cho, "IP mobility support with a multihomed mobile router," Proc. 5th International IFIP-TC6 Networking Conference, pp.1144–1149, Coimbra, Portugal, May 2006.
[23] M. Tsukada, T. Ernst, R. Wakikawa, and K. Mitsuya, "Dynamic management of multiple mobile routers," Proc. 13th IEEE International Conference on Networks, Kuala Lumpur, Malaysia, Nov. 2005.
[24] V. Kafle, E. Kamioka, and S. Yamada, "CoMoRoHo: Cooperative mobile router-based handover scheme for long-vehicular multihomed networks," IEICE Trans. Commun., vol.E89-B, no.10, pp.2774–2785, Oct. 2006.
[25] M. Tsukada and T. Ernst, "Vehicle communication experiment environment with MANET and NEMO," Proc. 2007 International Symposium on Applications and the Internet Workshops, p.45, Hiroshima, Japan, Jan. 2007.

[26] A. de La Fortelle and T. Ernst, "Geonet project," http://www.geonet-project.eu/

[27] B. McCarthy, C. Edwards, and M. Dunmore, "The integration of ad-hoc (MANET) and mobile networking (NEMO): Principles to support rescue team communication," Proc. 3rd International Conference on Mobile Computing and Ubiquitous Networking, London, UK, Oct. 2006.

[28] J. Chen, S. Chan, J. He, and S. Liew, "Mixed-mode WLAN: The integration of ad hoc mode with wireless LAN infrastructure," Proc. 18th IEEE Global Telecommunications Conference, pp.231–235, San Francisco, USA, Dec. 2003.

[29] C. Parata, V. Scarpa, and G. Convertino, "Flex-WiFi: A mixed infrastructure and ad-hoc IEEE 802.11 network for data traffic in a home environment," Proc. 8th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, pp.1–6, Espoo, Finland, June 2007.

[30] Atheros, "ath9k Linux wireless driver," http://wireless.kernel.org/en/users/Drivers/ath9k

[31] P. Bahl, P. Bahl, and R. Chandra, "MultiNet: Connecting to multiple IEEE 802.11 networks using a single wireless card," Technical Report, Microsoft Corporation, Redmond, WA, Aug. 2003.

[32] P. Kyasanur and N. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," Proc. 18th IEEE Wireless Communications and Networking Conferences, pp.2051–2056, New Orleans, LA, March 2005.

[33] J. Sheu, C. Chao, W. Hu, and C. Sun, "A clock synchronization algorithm for multihop wireless ad hoc networks," Wirel. Pers. Commun., vol.43, no.2, pp.185–200, Oct. 2007.

[34] TIA, "Voice quality recommendations for IP telephony," TIA/TSB-116-A, March 2006.

[35] ITR-AnalogX, "Internet traffic report," http://www.internettrafficreport.com

[36] G. Valadon, C. Magnien, and R. Wakikawa, "Mobile IPv6 deployments: Graph-based analysis and practical guidelines," Comput. Commun., vol.32, no.17, pp.1871–1880, Nov. 2009.

Jirawat Thaenthong received a B.S. in computer science from Prince of Songkhla University, 1996, and M.S. in Information Technology from King Mongkut's Institute of Technology Ladkrabang, 1998, Thailand. He is currently a Ph.D. student in the Sirindhorn International Institute of Technology, Thammasat University, Thailand. His research interests include mobile network and mobile ad-hoc network in heterogeneous wireless network. He is a student member of IEEE.

Steven Gordon obtained a Ph.D. in Telecommunications from the University of South Australia in 2001. He worked as a senior researcher at the Institute for Telecommunications Research, UniSA, up until 2006. He has since been with Thammasat University, Thailand, as an Assistant Professor within Sirindhorn International Institute of Technology. His research interests includes: formal analysis of protocols; integration of IP-based mobile networks with ad hoc networks; design of wireless networks for QoS guarantees; Internet and mobile peer-to-peer protocols; and Internet security protocols. He is a member of IEEE and ACM.