Evaluating the Benefits of Introducing PMIPv6 for Localized Mobility Management

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***Abstract*—Since recent years, it has been recognized that using global mobility protocol for managing localized mobility causes a number of problems, such as a long registration delay. To overcome these problems, Proxy Mobile IPv6 is proposed, which can avoid tunneling overhead over the air and support for hosts without an involvement in the mobility management.**

In this paper, we first discuss the recent localized mobility proposals and explore three major benefits that PMIPv6 can bring. In particular, we evaluate two aspects of the handover performance through a simple mathematical model for Fast Handovers for MIPv6, Hierarchical MIPv6, Fast handovers for HMIPv6 and PMIPv6. These analytical studies show that PMIPv6 may cause high handover latency if the local mobility anchor is located far from the current mobility access gateway. Therefore, some enhancements for PMIPv6 are suggested to further reduce the handover latency. The analysis ascertains that F-PMIPv6 is a promising mobility scheme to efficiently manage the localized mobility.

I. INTRODUCTION

Mobile IPv6 (MIPv6) [1] is a host based global mobility management scheme for IPv6 networks. However, there are three well-known problems involved in using global mobility protocol for every movement between access routers: 1) remote update latency; 2) signaling overhead; 3) location privacy [2]. These problems call for a protocol that is able to efficiently manage regional movements. Furthermore, recent IETF works on the global mobility management, such as Host Identity Protocol (HIP) [3] and IKEv2 Mobility and Multihoming (MOBIKE) [4], suggest that the future wireless IP nodes may be able to support diverse types of global mobility protocols. In addition, the success of Wireless LAN (WLAN) switch approach [5] that performs localized management without any host stack involvement, provides a possible paradigm to reduce host stack software complexity on the mobile node.

Motivated by above observations, localized mobility management has been intensively discussed in the IETF. Some previous efforts on the localized mobility management, such as Fast-Handovers for Mobile IPv6 (FMIPv6) and Hierarchical Mobile IPv6 (HMIPv6) rely on host-based solutions that require host involvement at the IP layer, which, however, may not be compatible with some global mobility protocols other than MIPv6. Therefore, a network-based localized mobility protocol without requiring additional software support at the host is preferable for localized mobility management.

Proxy Mobile IPv6 (PMIPv6) [6] provides a solution for network-based mobility management that can avoid both tunneling overhead over the air and stack updates in the host. Furthermore, the IETF expects that scaling benefits can be realized by introducing PMIPv6 for localized mobility management. Among these benefits, we emphasize the following three aspects since they are also the major important goals for the Network-based Localized Mobility Management (NETLMM) [7].

- *Handover performance optimization.* PMIPv6 can reduce the latency in IP handovers by limiting the mobility management within the PMIPv6 domain. Therefore, it can largely avoid remote service which not only cause long service delays but consume more network resource.
- *Reduction in handover-related signaling overhead.* The handover-related signaling overhead can be alleviated in PMIPv6 since it avoids tunneling overhead over the air and as well as the remote Binding Updates either to the Home Agent (HA) or to the Correspondent Node (CN).
- *Location privacy.* Keeping the mobile node's Home Address (MN-HoA) [6] unchanged over the PMIPv6 domain dramatically reduces the chance that the attacker can deduce the precise location of the mobile node.

In this paper, we explore the above benefits of PMIPv6 for the localized mobility. Following the introduction, we give a brief overview of PMIPv6. Section 3 presents related works including FMIPv6 and HMIPv6. Based on theoretical analysis, we identify the benefits of introducing PMIPv6 for the localized mobility. However, PMIPv6 may cause high handover latency if the local mobility anchor is located far from the current mobility access gateway. In order to further enhance the handover performance for PMIPv6, in Section 5 we propose two approaches. Finally, we conclude this paper and outline future work in Section 6.

II. PMIPV6 OVERVIEW

In each PMIPv6 domain, two mobility entities involve in the mobility management [6]. One is Mobile Access Gateway (MAG), which performs the following three functions: (1) detecting the MN's movement and initiating the signaling with the MN's Local Mobility Anchor (LMA) for updating the route to the MN's home address; (2) setting up the data path for enabling the MN to use its home address for communication from the access link; (3) emulation of the MN's home link on the access link.

The other entity is LMA that has the functional capabilities of a home agent as defined in MIPv6 base specification [1] and with the additional required capabilities for supporting PMIPv6 as defined in the specification [6].

As the handover procedure is our main focus for analysis, it is presented in details.

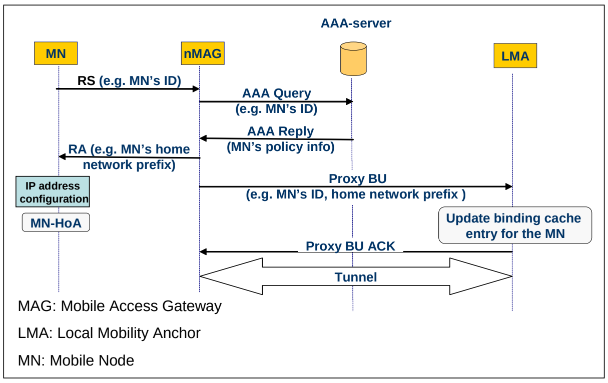

Fig. 1. PMIPv6 handover operations.

In Figure 1, a IPv6-enabled mobile node (mobility-unaware) attaches to a new MAG (nMAG). After a successful access authentication, it typically sends a Router Solicitation (RS) message to the nMAG. Based on the MN's identity, the nMAG can obtain the mobile node's configuration profile from the policy store, such as an AAA-server. Then, the nMAG responds to the RS message with a Router Advertisement (RA) which contains the mobile node's home network prefix, the nMAG's address and other configuration parameters.

Since the mobile node always detects the same home network prefix on the access link, it can continue to use its Home Address (MN-HoA) in the PMIPv6 domain. Such an operation exactly meets the requirement of location privacy because it is now quite difficult for attackers to interpret the current location of the mobile node. Differently, MIP6-enabled MN periodically updates its Care-of-Address (CoA) either to HA or to CN, which exposes MN's current location. Thus, the third benefit of location privacy has been identified through the above description of PMIPv6 operations.

Upon receiving the RA, the MN may detect that the current link local address is different from the one received in the previous RA, which makes the MN believe that there is a new default router on the home link. To update MN's current location, the MAG sends a Proxy Binding Update (PBU) message to the LMA. If the nMAG receives a Proxy Binding Acknowledgment from the LMA, it sets up a tunnel to the LMA and adds a default route over the tunnel. Then, the LMA can forward subsequent packets from any corresponding node to the mobile node through the nMAG.

III. RELATED WORK

In this section, we shortly overview FMIPv6 and HMIPv6 in order to facilitate an better understanding of the analytical evaluations in Section 4.

A. *Fast Handover for MIPv6*

FMIPv6 [8] has proposed two mechanisms to reduce the service degradation during the movement: predictive and reactive fast handover. The reactive mode relies on link layer triggers to perform fast handovers, which makes the solution unfeasible for some link layer technologies. Differently, the predictive mode is a L2 technology independent approach and in principal would be a feasible solution. For brevity, the predictive mode is selected for the analysis in Section 4.

Suppose a mobile node discovers the new point of attachment (e.g. New Access Router (NAR)), it sends a Router Solicitation for Proxy (RtSolPr) to the Previous AR (PAR) with the identifier of the NAR. Upon receiving the PrRtAdv with some information about the network, the MN formulates an new CoA (NCoA) based on the mobile node's interface ID and the New Access Router's associated subnet prefix.

To reduce the BU latency and to alleviate the packet loss, FMIPv6 specifies a tunnel between the PAR and the NAR. The mobile node can send a Fast Binding Update (FBU) to its PAR to establish such a tunnel. Simultaneously, the PAR sends a Handover Initiate (HI) message to the NAR, indicating the mobile node's Previous CoA (PCoA) and the proposed NCoA. On the receipt of HI message, the NAR first determines whether the proposed NCoA is a valid address. If the NCoA is acceptable, the NAR responds with a Handover Acknowledgment (HAck).

Once the PAR is ready to forward packets to the NAR, it sends a Fast Binding Acknowledgment (FAck), respectively, to the MN and the NAR. When the MN physically attaches to the NAR, it notifies the NAR about its reachability using Fast Neighbor Advertisement (FNA). Afterwards, all packets will be forwarded from the NAR to the mobile node.

B. *Hierarchical Mobile IPv6*

The idea of mobility management in HMIPv6 mainly relies on a Mobility Anchor Point (MAP) to manage the movement. The MAP performs the identical operations as the Home Agent in MIPv6. The functionality of LCoA is similar to that of the CoA in the MIPv6 while Regional CoA (RCoA) represents the virtual home of address in the HMIPv6-aware domain. As long as the MN moves within the same administrative domain, the RCoA is kept constant. In order to achieve this objective, the MAP using Proxy Neighbor Advertisement to synchronize the mapping between RCoA and LCoA.

To discover and configure different MAPs, HMIPv6 relies on a MAP option in the Router Advertisement. This option includes the distance vector from the mobile node, the preference for this particular MAP, AND the MAP's global address and subnet prefix. When the MN receives more than one MAP option, it needs to select an appropriate MAP. For instance, a mobile node can register with the MAP with relatively higher *Preference* value and highest value in the *Distance* field.

When a mobile node performs a handover between two access routers within the same HMIPv6 domain, only the MAP has to be informed. However, it does not apply any change to the periodic BUs, and thus the mobile node has to update its location to the Home Agent, Correspondence Node and, now additionally, to the MAP.

IV. ANALYTICAL STUDIES OF HANDOVER PERFORMANCE

In this section, we analyze the handover performance against different local mobility solutions through a simple mathematical model. The analytical studies will be carried out in two aspects, namely, handover latency and handover signaling overhead. Note the analytical model may not be very comprehensive, however, we emphasize that the target is to highlight the benefits of PMIPv6 even through a basic model.

A. Considered Scenario

We firstly introduce a hierarchical topology used for the following analytical study. Figure 2 depicts the considered scenario, where we assume that a mobile node is initially located at the AR and then moves to a new AR (nAR).

The analysis will study the cases of FMIPv6, HMIPv6, F-HMIP6 and PMIPv6. The reason why we choose above four approaches is that all of them are complimentary to MIPv6 in terms of enhancing handover performance within a locality. It might be unfair to compare them with a global mobility solution like MIPv6 or HIP directly.

When HMIPv6 is considered, the function of MAP will be performed at one of the routers within the HMIPv6 network. Similarly, when considering PMIPv6 the function of the MAG will be performed at access routers. Besides, the function of the LMA will be at the same place as MAP for fairness and simplicity.

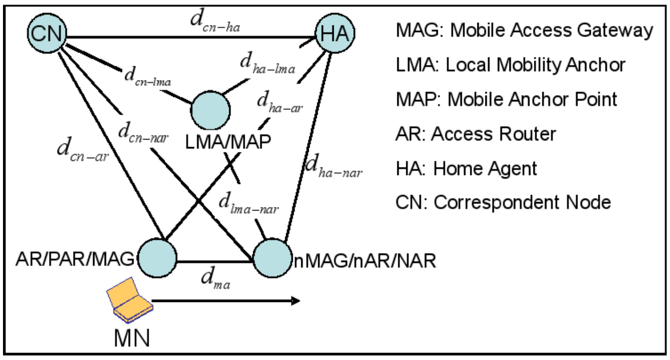

Fig. 2. Considered Scenario.

B. Assumptions and Parameters

In the following analysis, we consider the latency introduced by both the wireless and the wired part. The handover latency will be analyzed considering the mobile node initiated handover case. We assume that the processing delays are negligible compared to that for accessing the channel and transmission. For the wireless part, we configure the same value for both uplink and downlink cases. Moreover, we configure the following parameters:

- d_i denotes the transmission delay between any two entities. For example, d_{cn-ar} is referred to as the time required by forwarding packets from the CN to the AR.
- It is assumed that the AR and nAR locate at the same access network since we only focus on the localized handovers. If d_{ma} is the latency of forwarding packets between two neighboring access routers, d_{ma} can be regarded as a quite small value when being compared with d_{ha-nar} or d_{cn-ar}.
- The following inequality is satisfied: $d_{ma} < d_{lma-nar} < d_{ha-nar}$, since the term LMA and HA are interchangeable [6].
- The processing latency of a local trigger in the MN's protocol stack is ignored. That is, the period used to receive a movement hint with any link-layer support is zero.

C. Handover Latency Study

1) FMIPv6: Considering FMIPv6 in the proposed scenario, we assume sending the FBack from the PAR as the start point for the analysis. The latency is: 1) the time required to send the FBack to the mobile node through the wireless medium and to the NAR; plus 2) the time required to send FNA; plus 3) the time required by the forwarded packet from the PNAR to the NAR; plus 4) the time required by the FNA to reach the NAR; and plus 5) the delay caused by the wireless part to send the packet to the mobile node.

Thus, the latency when performing a handover from the PAR to the NAR in FMIPv6 can be computed through the following formula:

$$max(d_w, d_{ma}) + d_{ma} + 2d_w. \tag{1}$$

where d_w denotes the delay introduced by the wireless part. Since the PAR responds with a Fast Binding Acknowledgement (FAck) to the mobile node and to NAR at the same time, we choose the maximum value of their delay, namely, $max(d_w, d_{ma})$.

2) HMIPv6: Considering HMIPv6, the latency is: 1) the time required to send the LBU to and receive the LBAck from the MAP; plus 2) the time required by the forwarded packet from the MAP to arrive at the current nAR; and plus 3) the delay caused by the wireless part to send the packet to the mobile node.

Thus, the handover latency in HMIPv6 can be computed through the following formula:

$$3d_w + 3d_{lma-nar}. \tag{2}$$

3) F-HMIPv6: If we further consider the Fast handovers for HMIPv6 (F-HMIPv6) [9] which is actually a combination of HMIPv6 and FMIPv6. The latency is: 1) the time required by the FBack from the MAP to reach the NAR who will forward the packet to the MN, and to reach the PAR; plus 2) the time required by the forwarded packet from the MAP to the NAR; plus 3) the time required by the FNA to reach the NAR; and plus 4) the delay caused by the wireless part to send the packet to the mobile node.

Thus, the handover latency in F-HMIPv6 can be represented by the following formula:

$$max(d_{lma-ar}, d_{lma-nar}) + d_{lma-nar} + 2d_w. \tag{3}$$

4) PMIPv6: Considering the case of PMIPv6, the latency is: 1) the time required to send the PBU from nMAG to LMA and receive PBA from LMA; plus 2) the time required by the forwarded packet from LMA to nMAG; plus 3) the delay caused by the wireless part to send the packet to the mobile node.

Thus, the handover latency from the MAG to the nMAG in PMIPv6 can be computed through the following formula:

$$3d_{lma-nar} + d_w. \tag{4}$$

5) Comparison: For simplicity, we can further assume that $max(d_{lma-ar}, d_{lma-nar}) = d_{lma-nar}$ since AR and nAR are usually deployed nearby.

First, we compare the handover latency introduced by HMIPv6 with that of the PMIPv6. Since $d_w > 0$, it is very easy to get the following result: $l_{hmip6} > l_{pmip6}$. Though PMIP6 deploys a local mobility agent in the similar way of HMIP6 for handling handovers, they were thought getting same performance. Very interestingly, through the above analysis we clearly deny this conjecture. In fact, i1t is reasonable because PMIPv6 can avoid the tunneling overhead over the air as well as hosts' involvement in mobility management.

When we compare the equation l_{fmip6} with l_{pmip6}, the difference between them is $d_w + d_{ma} + max(d_w, d_{ma}) - 3d_{lma-nar}$. Note that the LMA/MAP is usually an aggregated router located far from the current AR (i.e. the nAR) but the AR is very near from nAR. Without loss of generality, we can assume $d_{ma} < d_{lma-nar}$ and $d_{ma} < d_w$. Therefore, the difference between the handover latency caused by FMIPv6 and that of PMIPv6 is $2d_w + d_{ma} - 3d_{lma-nar}$.

If we compare the latency caused by F-HMIPv6 during the handover with that of PMIPv6, the difference between them is as follows: $d_w - d_{LMA-AR}$.

6) Impacts of parameters: As the latency caused by wireless part and wired part are uncertain, we need to further consider them in details. Nevertheless, we can assume that the wireless latency is similar to wired part, regardless of unwanted noise and signals in wireless systems.

Due to the above assumption, the difference between l_{fmip6} and l_{pmip6} becomes $2d_w + d_{ma} - 3d_{lma-nar} < 0$, thus indicating the latency caused by FMIPv6 is less than that of PMIPv6.

Likewise, the latency caused by F-HMIPv6 is very similar to that of PMIPv6. We can conclude that PMIPv6 performs better than HMIPv6 but FMIPv6 causes the least latency among all of them. Besides, F-HMIPv6 seems to achieve quite better performance than HMIPv6 because it takes advantage of the "make-before-break" trait in FMIPv6. However, the latency caused by it is still higher than that of FMIPv6.

D. Handover Signaling Overhead

Following the above proposed scenario and assumptions, we further compare the handover overhead caused by FMIPv6, HMIPv6, F-HMIPv6, and PMIPv6 respectively. For simplicity, the minimal required overhead for each of the proposals is considered.

1) Handover Overhead Analysis: In FMIPv6, the signaling overhead is calculated as: 1) FBU message to the PAR; plus 2) FBack message sent to the mobile node and the NAR; plus 3) HI and HAck messages between PAR and NAR; and plus 4) message FNA sent to NAR.

For HMIPv6, the signaling overhead includes: 1) the MAP option carried in the Router Advertisement message in order to indicate the MN that it roams within the same MAP domain; plus 2) LBU message sent to the MAP; and plus 3) LBack message received by the MAP. Note that the MAP option is extra overhead required by HMIPv6.

For F-HMIPv6, the signaling overhead is: 1) the Router Advertisement message with MAP option in order to indicate the mobile node that it roams within the same MAP domain; plus 2) LBU message sent to the MAP; and plus 3) LBack message received by the MAP.

In contrast, the signaling overhead of PMIPv6 contains: 1) PBU message sent to the LMA; and plus 2) PBack message received by the LMA.

2) Comparison: The signaling overhead caused by above protocols is summarized in Table I. To be realistic, we differentiate the signaling over the air from the signaling in the network since the former may be more problematic than the latter. Moreover, we summarize the number of signaling messages required for handovers.

TABLE I
HANDOVER SIGNALING OVERHEAD

Protocol	Overhead (air)	Overhead (network)	Nr.
FMIPv6	72 bytes	86 bytes	5
HMIPv6	56 bytes	72 bytes	3
F-HMIPv6	42 bytes	74 bytes	5
PMIPv6	0 bytes	72 bytes	2

In conclusion, PMIPv6 causes much less overhead than FMIPv6 and F-HMIPv6. Meanwhile, F-HMIPv6 introduces less overhead than FMIPv6 both over the air and in the network. Moreover, HMIPv6 brings the same handover overhead in the network as PMIPv6 because they both deploy a local home agent to provide mobility for the mobile nodes. However, HMIPv6 still introduces 56 bytes additional overhead over the air (e.g. wireless part) because it is a host-based mobility solution and the mobile node inevitably involves in managing the mobility.

V. HANDOVER ENHANCEMENT FOR PMIPV6

The above analysis implies that combining with FMIPv6 may bring additional benefits, especially for reducing the handover latency. In the this section, we propose two enhancement schemes: 1) fast handovers for PMIPv6 (F-PMIPv6); 2) an

802.21 assisted PMIPv6, to improve the handover performance of the basic PMIPv6.

In the basic PMIPv6, during the handover the nMAG sends a PBU message to the LMA. Until receiving the PBack with indicating the acceptance of the Binding Update, the nMAG can setup a tunnel to the LMA and waits for the data forwarded from the LMA. We argue that the LMA may locate far from the current nMAG and such a mechanism wastes too much time.

A. F-PMIPv6 Handover Procedure

Motivated by FMIPv6, we propose the F-PMIPv6 protocol to reduce the handover latency and the packet loss ratio in Figure 3.

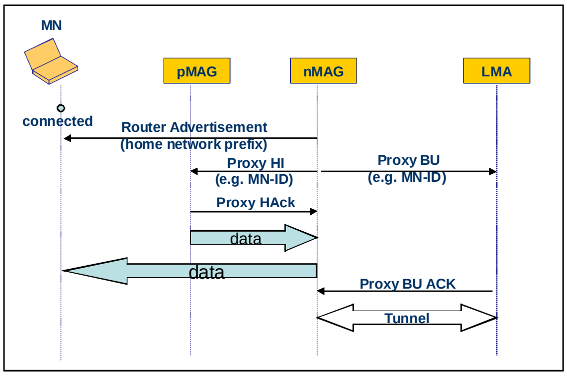

Fig. 3. Handover message flows of F-PMIPv6.

- After the nMAG sends AR message advertising the MN's home network prefix and other parameters, it sends a *Proxy-HI (P-HI)* message to the previous MAG (pMAG). Besides, the nMAG sends *PBU* to the LMA in order to update the MN's new location.
- Upon receiving the *P-HI* message, the pMAG responses with the *Proxy HAck (P-HAck)* message.
- Data can be forwarded directly through the tunnel between the pMAG and nMAG. Then, the nMAG immediately forwards the received data to the MN.
- After the LMA updates the MN's location at its binding cache entry, it sends a *PBU Ack* back to the nMAG. The subsequent data packets will be forwarded directly through the tunnel from the LMA to the nMAG.
- The nMAG tears down the tunnel towards pMAG.

Meanwhile, the *P-HI* can be an *ICMPv6* message sent by the AR (e.g. nMAG) to another AR (e.g. pMAG) to indicate the mobile node's movement. Different from the HI message in FMIPv6, *P-HI* may only require the mobile node's home network prefix and MN-ID in the options field. Likewise, the *P-HAck* may include the MN's home network prefix in the option field.

By doing this, data packets can be immediately forwarded from the nMAG to the MN instead of long-time waiting for the *PBAck* from the LMA. Besides, it can also reduce the packet loss ratio in case the LMA still sends the packets to the pMAG.

B. 802.21 Assisted PMIP6 Handover Procedure

Due to the development of 802.21 [10] for discovering the local network information, we attempt to apply the Media Independent Handover (MIH) functions into the current PMIPv6 (MIH-PMIPv6). There are two possibilities to trigger the handover: 1) network initiated; 2) MN initiated. Since PMIPv6 is designed to avoid mobility management involvement in the MN, we choose the network initiated approach to enhance the handover performance of PMIPv6. Here, we only focus on the predictive mode that Layer-2 handover signaling finishes on the pMAG's link.

The whole handover procedure is shown in Figure 4.

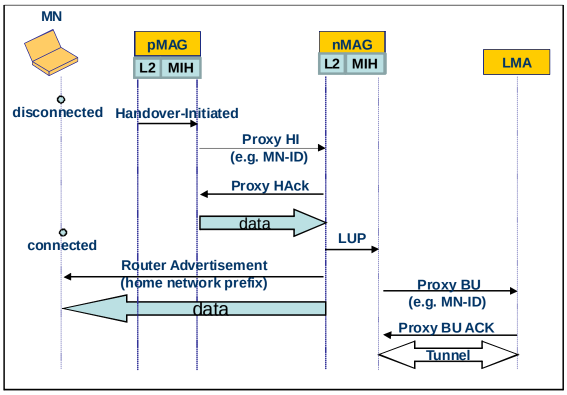

Fig. 4. Handover message flows of MIH-PMIPv6.

- Before MN moves from the pMAG to the nMAG, the disconnection is triggered on the link of the pMAG. The details about handover-initiated trigger is out of our scope.
- Upon receiving the *Handover-initiated* message, the pMAG collects MN-related information (e.g. MN's home network prefix, ID), and sends a *P-HI* message to the nMAG.
- The nMAG creates a Binding Update List [6] for the MN based on the information within the *P-HI*. The nMAG sends back *P-HAck* to the pMAG.
- After receiving the data through the tunnel between the pMAG and nMAG, the nMAG needs to buffer the data until the link between the MN and nMAG is ready.
- When the MN attaches to the link of nMAG, a *Link UP (LUP)* message is sent to the upper layer.
- The nMAG sends a *RA* message with nMAG's information to the MN, and sends a *PBU* to the LMA in order to update MN's new location.
- Once the LMA updates the MN's location at its local binding cache entry, it sends a *PBU Ack* back to the nMAG. The data packets will be forwarded directly through the tunnel from the LMA to the nMAG.
- The nMAG tears down the tunnel to pMAG.

Meanwhile, *LUP* is used as a trigger from the link layer to the MIHF layer to report the connectivity is ready. After detecting the movement of MN, the pMAG will send *P-HI* to other MAGs within the same domain. For example, the pMAG can retrieve the nMAG's address by requesting the MIH server or its LMA. For efficiency, the pMAG could select some neighboring MAGs, however, the details about determining the nMAG is out of the scope of this paper.

C. Handover Latency Analysis

1) F-PMIPv6: According the same scenario in Figure 2, the latency caused by F-PMIPv6 is: 1) the time required to send the P-HI from the nMAG to the pMAG and receive P-HAck from the pMAG; plus 2) the time required by the forwarded packet from pMAG to nMAG; plus 3) the delay caused by the wireless part to send the packet to the MN.

The handover latency is calculated from the time of sending P-HI to the pMAG to the time that the mobile node receives the data:

$$l_{f-pmip6} = 3d_m + d_w. \tag{5}$$

2) MIH-PMIPv6: The latency caused by MIH-PMIPv6 can be calculated as follows: 1) the time required to send P-HI from pMAG to the nMAG and receive P-HAck from the nMAG, plus 2) the time required to forward packet from pMAG to nMAG, plus 3) the time used to send the RA from the nMAG to the MN, plus 4) the time caused by the wireless part to send the packet to the MN.

Therefore, the handover latency in MIH-PMIPv6 can be depicted as:

$$l_{mih-pmip6} = 3d_m + 2d_w. \tag{6}$$

TABLE II
HANDOVER LATENCY

Protocol	Handover Latency
FMIPv6	$2d_w + d_{ma} + max(d_w, d_{ma})$
HMIPv6	$3d_w + 3d_{LMA-nAR}$
F-HMIPv6	$2d_w + 2d_{LMA-nAR}$
PMIPv6	$d_w + 3d_{LMA-nAR}$
F-PMIPv6	$d_w + 3d_{ma}$
MIH-PMIPv6	$2d_w + 3d_{ma}$

3) Comparison: Table II summarizes the handover latency. Based on the above assumption that $d_{ma} < d_{lma-nar}$, it is easy to get the following inequality: $l_{f-pmip6} < l_{pmip6}$. Further, we can infer that $l_{f-pmip6} < l_{mih-pmip6} < l_{hmip6}$ since $d_{ma} < d_{lma-nar}$ is satisfied.

Besides, the difference between $l_{mih-pmip6}$ and l_{fmip6} is $2d_{ma} - max(d_w, d_{ma}) > 0$. Therefore, 802.21 assisted PMIPv6 causes higher handover latency than FMIPv6.

Furthermore, we can deduce that the following inequality is satisfied: $l_{f-pmip6} < l_{pmip6}$ since $d_{ma} < d_w$. So far, we can ascertain that F-PMIPv6 performs quite better than the PMIPv6, or even better than the FMIPv6.

If we compare $l_{mih-pmip6}$ with l_{pmip6}, the difference is $d_w + 3(d_{ma} - d_{lma-nar})$. Assume that d_{ma} is much less than $d_{lma-nar}$ and d_w is comparable to $d_{lma-nar}$. We can conjecture that MIH-PMIPv6 may alleviate more handover latency than PMIPv6.

To conclude, F-PMIPv6 and MIH-PMIPv6 can alleviate the more handover latency than PMIPv6. F-MIPv6 performs even better than MIH-PMIPv6. Although F-PMIPv6 may require some extra signaling exchanges between the MAG and nMAG, they are regional signaling so that they will neither cause any message overhead over the air, nor cause inter-domain overhead.

D. Handover Overhead

1) F-PMIPv6: For F-PMIPv6, the signaling overhead is: 1) P-HI message sent from the nMAG to the pMAG; plus 2) P-HAck message received by the nMAG; plus 3) PBU message sent from the nMAG to the LMA; and plus 4) PBU Ack message sent from the LMA to the nMAG.

2) MIH-PMIPv6: Concerning MIH-PMIPv6, the signaling overhead is: 1) P-HI message sent from the pMAG to the nMAG; plus 2) P-HAck message received by the pMAG; plus 3) PBU sent to the LMA and PBU Ack message sent from the LMA to the nMAG.

TABLE III
HANDOVER SIGNALING OVERHEAD

Protocol	Overhead (air)	Overhead (network)	Nr.
FMIPv6	72 bytes	86 bytes	5
HMIPv6	56 bytes	72 bytes	3
F-HMIPv6	42 bytes	74 bytes	5
PMIPv6	0 bytes	72 bytes	2
F-PMIPv6	0 bytes	116 bytes	4
MIH-PMIPv6	0 bytes	116 bytes	4

From Table III, F-PMIPv6 causes the same overhead as MIH-PMIPv6 during the handover. Unfortunately, both of them cause much higher overhead (44 bytes) in the network compared with PMIPv6. Nonetheless, F-PMIPv6 and MIH-PMIPv6 perform better than F-HMIPv6 and FMIPv6 in terms of signaling overhead.

To conclude, the proposed F-PMIPv6 can be a desirable solution for network-based localized mobility management. It can avoid tunneling overhead over the air and provide mobility to hosts that are not required to involve in any mobility management. Moreover, it can alleviate the handover latency and reduce the packet loss ratio by simply notifying the previous MAG about the mobile node's movements. Therefore, F-PMIPv6 is able to support real-time applications which are sensitive to handover latency and packet loss.

E. Numerical Results

The theoretical model developed in the previous section has been a simplification, as it did not account for variations in link delays and anticipation timing. To analyze handover performance in a more realistic way, a numerical analysis is provided as follows.

According to discussions in [11], [12], we can assume:

- *Wireless Link Delay*: 18 ms, deviation: 8 ms
- *Router Distance Delay*: 10 ms, deviation: 5 ms
- *Delay between LMA and nAR*: 15 ms, deviation: 5 ms

Here, ms represents million seconds. Therefore, we will further discuss the delay performance in terms of wireless

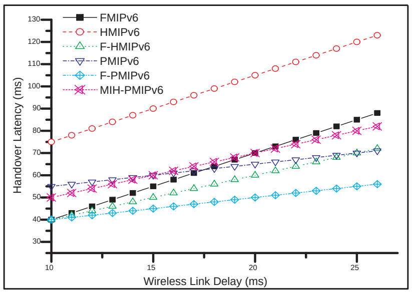

Fig. 5. Varying wireless delay.

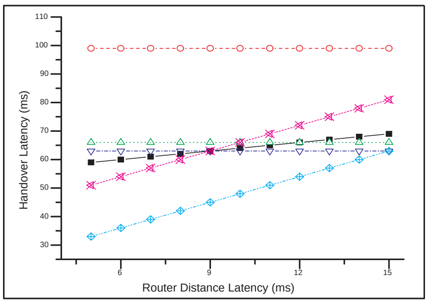

Fig. 6. Varying router distance delay.

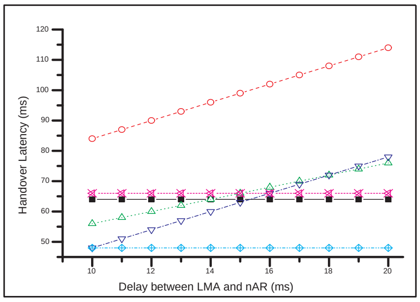

Fig. 7. Varying delay between LMA and nAR

delay, router distance delay (d_{ma}) and the delay between LMA and nAR.

1) Wireless Link Delay: From Figure 5, the handover latency of HMIPv6 is quite large if the wireless link delay is long. F-PMIPv6 performs the best of all six protocols and F-HMIPv6 also achieves a good handover latency performance. The result suggests that FMIPv6 can efficiently alleviate the handover latency. If the wireless link delay is less than $15ms$, 802.21 assisted PMIPv6 performs better than PMIPv6. However, when the d_w increases than $16ms$, PMIPv6 can alleviate more handover latency than MIH-PMIPv6.

2) Router Distance Delay: Figure 6 illustrates the handover latency if the router distance delay, namely, d_{ma} varies. The handover latency of HMIPv6 is still very high. Similar to the above result, F-PMIPv6 achieves the best performance. However, when the router distance delay increases the handover latency of F-PMIPv6 linearly increases. Differently, the latency of PMIPv6, HMIPv6 and F-HMIPv6 remain stable when the router distance delay varies since the pAR does not involve in directing data traffic during their handovers.

3) Delay between LMA and nAR: Moreover, we analyze the handover latency in case the delay between LMA and nAR changes. From Figure 7, F-PMIPv6 achieves the best performance and HMIPv6 performs the worst among six protocols. MIH-PMIPv6 and FMIPv6 perform similarly and keep stable regardless of the delay variance. When the delay between LMA and nAR rises, the handover latency of PMIPv6 and F-HMIPv6 increases.

Overall, F-PMIPv6 causes less handover delay than any other protocols, which conforms the results in Section V-C.

VI. Conclusions and Future Work

In this paper, we focused on evaluating two most important benefits of introducing PMIPv6 for the localized mobility management through an appropriate mathematical model. After analytical studies and comparisons on the handover latency and overhead, we can conclude that PMIPv6 can achieve fairly good performance but may cause high handover latency. To alleviate the latency, we propose two enhancements to PMIPv6, namely, F-PMIPv6 and MIH-PMIPv6. Based on both theoretical and numerical analysis, it is identified that F-PMIPv6 can dramatically reduce the handover latency but may cause higher handover signaling overhead in the network.

Thus, there are still some avenue left for future work. For example, how to improve the handover performance for both latency and signaling overhead will be the next step. Furthermore, the link layer intelligent detection techniques and hierarchical architecture have been developed in the community and being considered useful, how to incorporate these techniques into PMIPv6 for further performance improvement is a meaningful work in the future. In addition, PMIPv6 has no specific concerns on global mobility management, but only relies on MIPv6, which lacks sufficient scalability and efficiency of delivery. Hence, inter-domain handover mechanisms will be further investigated for PMIPv6.

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