Distributed Mobility Control in Proxy Mobile IPv6 Networks

Heeyoung Jung‡, Moneeb Gohar††, Ji-In Kim††, Seok Joo Koh††a)

SUMMARY In future mobile networks, the ever-increasing loads imposed by mobile Internet traffic will force the network architecture to be changed from hierarchical to flat structure. Most of the existing mobility protocols are based on a centralized mobility anchor, which will process all control and data traffic. In the flat network architecture, however, the centralized mobility scheme has some limitations, such as unwanted traffic flowing into the core network, service degradation by a single point of failure, and increased operational costs, etc. This paper proposes mobility schemes for distributed mobility control in the flat network architecture. Based on the Proxy Mobile IPv6 (PMIP), which is a well-known mobility protocol, we propose the three mobility schemes: Signal-driven PMIP (S-PMIP), Data-driven Distributed PMIP (DD-PMIP), and Signal-driven Distributed PMIP (SD-PMIP). By numerical analysis, we show that the proposed distributed mobility schemes can give better performance than the existing centralized scheme in terms of the binding update and packet delivery costs, and that SD-PMIP provides the best performance among the proposed distributed schemes.

key words: mobile Internet, distributed mobility control, signal-driven, Proxy Mobile IPv6

1. Introduction

With emergence of various wireless/mobile networks and wide popularity of smart phones, the number of mobile Internet users has been rapidly increasing. It is reported that the number of mobile Internet users will be 1.6 billion in around 2014 and thus exceed the number of desktop users [1]. This mobile-oriented trend inevitably tends to introduce a large amount of traffic into mobile Internet infrastructure.

The cellular system is a typical mobile network, which is being evolved to IP-based infrastructure, as shown in the SAE of 3GPP. It was originally designed as hierarchical architecture to support circuit-based voice traffic. However, the ever-increasing loads imposed by mobile Internet traffic will force the network architecture to be changed from hierarchical to flat structure, so as to provide data services more cost-effectively. Now, the flat architecture can be regarded as an essential requirement for future mobile Internet [2]-[4].

Most of the current mobility protocols are based on a centralized mobility anchor, such as Home Agent (HA) of Mobile IPv6 (MIP) [5] or Local Mobility Anchor (LMA) of Proxy Mobile IPv6 (PMIP) [6], to process all control and data packets. This centralized anchor allows a mobile host to be reachable, when it is away from its home domain, by ensuring the forwarding of data packets destined to or sent from the mobile host. In the flat architecture, however, such a centralized mobility scheme is vulnerable to several problems. First, the centralized mobility anchor tends to induce unwanted control/data traffic into the core network, which may unduly burden the network operator with large operation costs. In addition, a single point of failure of central anchor may degrade overall system performance and increase the cost of network engineering.

To overcome the limitations of this centralized approach, IETF has recently discussed the distributed mobility management, which is divided into the partially distributed approach where only data plane is distributed, and the fully distributed approach where both data and control planes are distributed [7], [8]. In the centralized mobility control, the routing path through a centralized anchor tends to be longer, which results in non-optimal routes and performance degradation. In the distributed mobility control, however, the route optimization will be intrinsically supported, and unnecessary traffic can be reduced if the two hosts communicate directly with each other, not relying on a centralized anchor. This will also be helpful to reduce the handover delay. Moreover, the centralized approach is vulnerable to a single point of failure, whereas the distributed approach will mitigate such problem to a local network.

In this paper, we propose distributed mobility control schemes in PMIP-based mobile networks. This is a part of research on Mobile Oriented Future Internet (MOFI) supported by Korean government [9]. Specifically, based on PMIP, we propose the three schemes for distributed mobility control: Signal-driven PMIP (S-PMIP), Data-driven Distributed PMIP (DD-PMIP), and Signal-driven Distributed PMIP (SD-PMIP). S-PMIP can be regarded as a partially distributed scheme, whereas DD-PMIP and SD-PMIP correspond to the fully distributed schemes.

This paper is organized as follows. In Section 2, we discuss the related works on PMIP and distributed mobility control. In Section 3, we describe the proposed mobility schemes for distribute control in PMIP network. Section 4 analyzes the performance of the existing and proposed schemes in terms of the binding update and packet delivery costs. Section 5 concludes this paper.
2. Related Works

In PMIP, the information of binding between home address (HoA) and care of address (CoA) is maintained at a central mobility anchor such as LMA, and the data packets are routed to mobile nodes via this anchor. That is, the mobility control is centralized via the anchor in both data and control planes. Most of the current mobile networks are based on this centralized mobility control. However, the centralized approach has some limitations, which include degradation of mobility performance, increased cost of network maintenance and operations, and vulnerability to a single point of failure or attack. Moreover, the network operators have a concern due to a large amount of unwanted traffic flowing into the core network \[7\], \[8\].

For route optimization of PMIP, many works have been made \[10\]-\[14\]. In the earlier works \[10\]-\[12\], the movement pattern of mobile node is classified into inter-MAG handover and inter-LMA handover, and several schemes were proposed for route optimization using the information of corresponding node. Recently, IETF is working on the localized routing for PMIP \[13\], \[14\]. In \[13\], the problem statement and requirements for localized routing are described, and \[14\] discusses the four cases for localized routing in the PMIP domain. However, we note that all of these schemes are still regarded as centralized approach, in which the HoA-CoA binding is maintained by a central LMA, and the control operation for localized routing is also done with LMA.

To solve the problems of centralized mobility control, the IETF has recently discussed the distributed mobility control approaches, which are divided into partially distributed approach and fully distributed approach.

In the partially distributed approach, control plane is separated from data plane, and only the data plane will be distributed for route optimization, as shown in Fig. 1.

In step 1, a mobile node (MN) is connected to a mobility agent (MA). Then, MA binds the location of MN with the control function (step 2). If a correspondent node (CN) sends a data packet toward MN (step 3), MA will find the location of MN by contacting with the control function. For this purpose, the location query and query ACK messages can be exchanged (step 4 and 5). Based on the obtained location information, MA of CN can deliver data packets directly to MA of MN (step 6). Now, the data packets are forwarded to MN (step 7).

In the fully distributed architecture, both control and data planes are distributed, and mobility control schemes can be classified into data-driven multicast/broadcast and peer-to-peer search schemes.

In the data-driven multicast/broadcast scheme, as described in Fig. 2, when MN is attached to MA (step 1), no binding operation is performed. For data packets transmitted by CN (step 2), MA of CN will deliver them all MAs in the domain by using multicast/broadcast (step 3). Then, MA of MN will forward them to MN (step 4). This scheme does not use any binding and search (or query) procedures to find the MN. However, unnecessary data packets may be excessively generated, since the data packets shall be delivered to all MAs in the domain.

In the peer-to-peer search scheme, before data transmission, MA of CN will activate a searching process to find the location of MN, which is described in Fig. 3. After network attachment (step 1), CN transmits a data packet to its MA (step 2). MA of CN will find the location of MN (step 3) by using a peer-to-peer searching mechanism such as a distributed hash table \[7\]. Then, MA of MN responds with a response message to MA of CN (step 4). Now, MA of CN can deliver the data packet to MA of MN (step 5). The data packet will be forwarded to MN (step 6).
3. Distributed Mobility Control in PMIP Networks

In this paper, we discuss the distributed mobility control in the PMIP-based mobile networks, since PMIP is the most promising protocol used in the mobile networks, such as 3GPP/SAE and mobile WiMAX.

3.1 Overview

This paper proposes three schemes for distributed mobility control: Signal-driven PMIP (S-PMIP), Data-driven Distributed PMIP (DD-PMIP), and Signal-driven Distributed PMIP (SD-PMIP). Table 1 gives an overview of candidate mobility control schemes, which include the proposed schemes and the existing schemes: PMIP and PMIP with Localized Routing (PMIP-LR) [14].

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Mobility Architecture</th>
<th>Binding Update</th>
<th>Data Delivery</th>
<th>Binding Query</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMIP</td>
<td>Centralized</td>
<td>Used</td>
<td>Data driven</td>
<td>Not used</td>
</tr>
<tr>
<td>PMIP-LR</td>
<td>Centralized with route</td>
<td>Used</td>
<td>Data driven</td>
<td>Not used</td>
</tr>
<tr>
<td></td>
<td>optimization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-PMIP</td>
<td>Partially distributed</td>
<td>Used</td>
<td>Signal driven</td>
<td>Used (unicast)</td>
</tr>
<tr>
<td>DD-PMIP</td>
<td>Fully distributed</td>
<td>Not used</td>
<td>Data driven</td>
<td>Not used</td>
</tr>
<tr>
<td>SD-PMIP</td>
<td>Fully distributed</td>
<td>Not used</td>
<td>Signal driven</td>
<td>Used (multicast)</td>
</tr>
</tbody>
</table>

PMIP is a centralized scheme, in which a Mobile Access Gateway (MAG) performs the Proxy Binding Update (PBU) operation with LMA, and data packets are delivered to LMA and then forwarded to MN.

PMIP-LR is also a centralized scheme, in which the PBU operation is performed, as done in PMIP. However, the route between MN and CN will be optimized after the control operation for localized routing, in which Localized Routing Initiation (LRI) and Localized Routing ACK (LRA) messages are exchanged between MAGs and LMA in the PMIP domain [14].

S-PMIP is a partially distributed scheme in which the control plane is separated from the data plane. The PBU operation is performed, as done in PMIP. For packet delivery, however, MAG of CN will perform the binding query operation with LMA to find the location (i.e., MAG) of MN. For this purpose, the following control messages are newly defined: Proxy Binding Query (PBQ) and Proxy Query ACK (PQA).

DD-PMIP is a fully distributed scheme, which is regarded as a data-driven multicast/broadcast approach described in Section 2. In this scheme, the binding update with LMA is not used. MAG of CN will send a data packet to all MAGs in the domain by multicast, without using any binding query operation.

SD-PMIP is also a fully distributed scheme, which is similar to the peer-to-peer search scheme described in Section 2. No binding update operation is performed. Instead, the binding query operation is used, in which MAG of CN finds MAG of MN by sending a PBQ message to all MAGs in the domain by multicast. Then, MAG of MN will respond with a PQA message to MAG of CN.

For binding query operation in S-PMIP and SD-PMIP, we define the new messages, PBQ and PQA, by adding the ‘Q’ flag bit into the existing PBU and Proxy Binding ACK (PBA) messages of PMIP, respectively, as shown in Fig. 4.
3.2 Signal-driven PMIP (S-PMIP)

Fig. 5 shows the S-PMIP operations. First, MN setups a connection with MAG and obtains its HoA (step 1). MAG of MN sends a PBU message to LMA so as to bind HoA and CoA of MN (step 2). Then, LMA will create the associated database entry and respond with a PBA message to MAG (step 3). Now, CN sends a data packet to MN (step 4). Then, MAG of CN will send a PBQ message to LMA so as to find MAG of MN (step 5). Then, LMA responds with a PQA message to MAG of CN, after lookup of its database (step 6). Now, MAG of CN sends the data packet directly to MAG of MN by using the PMIP tunneling mechanism (step 7). Finally, MAG of MN will forward the data packet to MN (step 8).

Fig. 5  S-PMIP operations

3.3 Data-driven Distributed PMIP (DD-PMIP)

Fig. 6 shows the operations of DD-PMIP. MN setups a connection with MAG (step 1), in which MAG of MN maintains HoA of MN in its cache. When CN sends a data packet to MN (step 2), the data packet contains only the HoA of MN as a destination address in the IP header. To find the location of MN, MAG of CN will send the data packet to all MAGs in the domain by multicast (step 3). In multicast transmission, it is assumed that all MAGs in the domain have already been subscribed to a specific multicast address in the initialization process. We note that this assumption is reasonable because the multicast transmission will be allowed only within the local PMIP domain, and all MAGs in the domain are under the control of the same network administrator. For multicast transmission, MAG of CN will encapsulate the original data packet by adding an outer IP header. In the outer header, the destination address is set to a multicast address and the source address is set to the IP address of MAG of CN.

On receiving the multicast data packet from MAG of CN, only the MAG of MN will respond to MAG of CN with a PQA message (step 4). All the other MAGs in the domain will ignore and drop the data packet. Note that the responding PQA message ensures that the further subsequent data packets of CN can be delivered directly from MAG of CN to MAG of MN by unicast. Now, MAG of MN will deliver the original data packet to MN after de-capsulation of the outer IP header (step 8).

Fig. 6  DD-PMIP operations

3.4 Signal-driven Distributed PMIP (SD-PMIP)

Fig. 7 shows the operations of SD-PMIP. MN setups a connection with MAG (step 1), and CN sends a data packet to MN (step 2). To find the location of MN, MAG of CN sends a PBQ message to all MAGs in the domain by multicast (step 3). The multicast transmission is performed over a pre-specified multicast address, as done in DD-PMIP. Then, only the MAG of MN will respond with a PQA message to MAG of CN (step 4). Note that all the other MAGs in the domain will ignore the PBQ message. Now, the data packet will be delivered to MAG of MN (step 5), and further to MN (step 6).

Fig. 7  SD-PMIP operations
4. Analysis

To evaluate the performance of the proposed mobility control schemes, we analyze the total cost required for binding update with LMA and for data packet delivery from CN to MN. We compare the two existing schemes (PMIP and PMIP-LR) and the three proposed schemes (S-PMIP, DD-PMIP, and SD-PMIP).

4.1 Analysis Model

For analysis, we assume that both CN and MN are located within the same PMIP domain (i.e., both are mobile hosts), as illustrated in Fig. 8.

![Fig. 8 Network model for numerical analysis](image)

In this paper, we will only focus on analysis of performance for intra-domain movement in order to simplify the analysis, since there are various possible scenarios for inter-domain movement.

We define the parameters used for analysis in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{a-b}$</td>
<td>Transmission cost of a packet between nodes $a$ and $b$</td>
</tr>
<tr>
<td>$P_c$</td>
<td>Processing cost of node $c$ for binding update or lookup</td>
</tr>
<tr>
<td>$T_{setup}$</td>
<td>Setup time of PMIP connection between MN and MAG</td>
</tr>
<tr>
<td>$N_{Host/MAG}$</td>
<td>Number of active hosts per MAG</td>
</tr>
<tr>
<td>$N_{MAG}$</td>
<td>Number of MAGs in the PMIP domain</td>
</tr>
<tr>
<td>$H_{a,b}$</td>
<td>Hop count between nodes $a$ and $b$ in the network</td>
</tr>
<tr>
<td>$S_{control}$</td>
<td>Size of a control packet (in byte)</td>
</tr>
<tr>
<td>$S_{data}$</td>
<td>Size of a data packet (in byte)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Unit cost of binding update with LMA</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Unit cost of lookup for MN at LMA or MAG</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Unit transmission cost of a packet per a wired link (hop)</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Unit transmission cost of a packet per a wireless link (hop)</td>
</tr>
</tbody>
</table>

In the analysis, we assume that the transmission delays are symmetric (e.g., $T_{MAG-LMA}$ for MN and CN), since both CN and MN will be attached to a MAG in the same domain with an equal probability.

The binding update cost and the packet delivery cost are denoted by $BUC$ and $PDC$, respectively. Then the total cost ($TC$) is represented as $TC = BUC + PDC$.

4.2 Cost Analysis

A. PMIP

The binding update operations of PMIP are performed as follows. When MN enters a new MAG region, MN sets up a connection and obtains its HoA [6]. We assume that this operation takes roughly $T_{setup}$. After that, MAG performs the PBU operations with LMA by exchanging the PBU and PBA control messages, and LMA will update its database. This operation takes $2T_{MAG-LMA} + P_{LMA}$, where $T_{MAG-LMA} = \tau \times H_{MAG-LMA}$ and $P_{LMA} = \alpha \log (N_{MAG} \times N_{Host/MAG})$. It is assumed that the processing cost for binding update with LMA ($P_{LMA}$) is proportional to the total number of active hosts in the domain ($N_{MAG} \times N_{Host/MAG}$) in the log scale by using a tree-based data structure to implement the database. Accordingly, the binding update cost of PMIP can be represented as follows.

$$BUC_{PMIP} = T_{setup} + S_{control} \times 2T_{MAG-LMA} + P_{LMA}$$

$$= T_{setup} + S_{control} \times 2\tau \times H_{MAG-LMA} + \alpha \log (N_{MAG} \times N_{Host/MAG}) \quad (1)$$

In PMIP, the packet delivery cost of a data packet from CN to MN can be calculated as follows. First, a data packet of CN is delivered to LMA via MAG of CN, which is equal to $T_{CN-MAG} + T_{MAG-LMA}$. LMA will look for the CoA of MN with its database, which takes $P_{LMA} = \beta \log (N_{MAG} \times N_{Host/MAG})$. Then, the data packet is forwarded to MAG of MN, and further to MN, which corresponds to $T_{LMA-MAG} + T_{MAG-MN}$. Accordingly, the packet delivery cost of PMIP can be represented as follows.

$$PDC_{PMIP} = S_{data} \times (T_{CN-MAG} + 2T_{MAG-LMA} + T_{MAG-MN}) + P_{LMA}$$

$$= S_{data} \times (\kappa \times H_{CN-MAG} + 2\tau \times H_{MAG-LMA} + \kappa \times H_{MAG-MN})$$

$$+ \beta \log (N_{MAG} \times N_{Host/MAG}) \quad (2)$$

So, we obtain the total cost of PMIP as

$$TC_{PMIP} = BUC_{PMIP} + PDC_{PMIP}.$$  

B. PMIP-LR

In PMIP-LR, the binding update operation is performed, as done in PMIP. So, we have

$$BUC_{PMIP-LR} = BUC_{PMIP}.$$  

In data packet delivery, for localized routing, the LRI and LRA messages should be exchanged between LMA and MAG of MN, and also between LMA and MAG of CN [14], which takes $S_{control} \times 4T_{MAG-LMA}$. After that, CN will deliver data packets directly to MN, which corresponds to $S_{data} \times (T_{CN-MAG} + T_{MAG-MAG} + T_{MAG-MN})$. Accordingly, the packet delivery cost of PMIP-LR can be represented as follows.

$$PDC_{PMIP-LR} = S_{data} \times (T_{CN-MAG} + T_{MAG-MAG} + T_{MAG-MN}) + P_{LMA}$$

$$= S_{data} \times (\kappa \times H_{CN-MAG} + \kappa \times H_{MAG-MAG} + \kappa \times H_{MAG-MN})$$

$$+ \beta \log (N_{MAG} \times N_{Host/MAG}) \quad (3)$$

So, we obtain the total cost of PMIP-LR as

$$TC_{PMIP-LR} = BUC_{PMIP-LR} + PDC_{PMIP-LR}.$$
PDC\textsubscript{PMIP-LR} = S\textsubscript{data} \left( T\textsubscript{CN-MAG} + T\textsubscript{MAG-MAG} + T\textsubscript{MAG-MN} \right) \\
+ S\textsubscript{control} \times 4T\textsubscript{MAG-LMA} \\
= S\textsubscript{data} \left( \kappa H\textsubscript{CN-MAG} + \tau H\textsubscript{MAG-MAG} + \kappa H\textsubscript{MN-MAG} \right) \\
+ S\textsubscript{control} \times 4\tau H\textsubscript{MAG-LMA} \quad (4)

So, we obtain the total cost of PMIP-LR as

T\textsubscript{C-PMIP-LR} = \text{BUC\textsubscript{PMIP-LR}} + \text{PDC\textsubscript{PMIP-LR}}.

C. S-PMIP

In S-PMIP, the binding update cost is the same with that of PMIP. So, we have

\text{BUC\textsubscript{S-PMIP}} = \text{BUC\textsubscript{PMIP}}. \quad (5)

In the packet delivery, the control operation for binding query is separated from the data packet delivery. Thus, the packet delivery cost from CN to MN can be calculated as follows. First, a data packet of CN is delivered to MAG, which is \( S\textsubscript{data} \times T\textsubscript{CN-MAG} \). Then, MAG of CN obtains CoA of MN by exchanging PBQ and PQA messages with LMA, which takes \( S\textsubscript{control} \times 2T\textsubscript{MAG-LMA} + P\textsubscript{LMA} \). After that, MAG of CN will deliver the data packet to MAG of MN, and further to MN, which corresponds to \( S\textsubscript{data} \times (T\textsubscript{MAG-MAG} + T\textsubscript{MAG-MN}) \). Accordingly, the packet delivery cost of S-PMIP can be represented as follows.

PDC\textsubscript{S-PMIP} = S\textsubscript{data} \left( T\textsubscript{CN-MAG} + T\textsubscript{MAG-MAG} + T\textsubscript{MAG-MN} \right) \\
+ S\textsubscript{control} \times 2T\textsubscript{MAG-LMA} + P\textsubscript{LMA} \\
= S\textsubscript{data} \left( \kappa H\textsubscript{CN-MAG} + \tau H\textsubscript{MAG-MAG} + \kappa H\textsubscript{MN-MAG} \right) \\
+ S\textsubscript{control} \times 2\tau H\textsubscript{MAG-LMA} + \beta \log (N\textsubscript{Host} \times N\textsubscript{MAG}) \quad (6)

So, we obtain the total cost of S-PMIP as

T\textsubscript{C-S-PMIP} = \text{BUC\textsubscript{S-PMIP}} + \text{PDC\textsubscript{S-PMIP}}.

D. DD-PMIP

In DD-PMIP, no binding update is performed between MAG and LMA. Accordingly, the binding update cost of DD-PMIP will simply be

\text{BUC\textsubscript{DD-PMIP}} = T\text{setup} \quad (7)

DD-PMIP is a data-driven scheme and thus the packet delivery cost from CN to MN can be calculated as follows. First, a data packet of CN is delivered to MAG, which is equal to \( S\textsubscript{data} \times T\textsubscript{CN-MAG} \). Then, MAG of CN sends the data packet to all MAGs in the domain by multicast, which corresponds to \( S\textsubscript{data} \times T\textsubscript{MAG-MAG} \times N\textsubscript{MAG} \). Only the MAG of MN will respond to MAG of CN with a PQA message after lookup of its MAG cache, which is equal to \( P\textsubscript{MAG} + S\textsubscript{control} \times T\textsubscript{MAG-MAG} \). After that, MAG of CN can deliver the data packet to MN via MAG, which takes \( S\textsubscript{data} \times (T\textsubscript{MAG-MAG} + T\textsubscript{MAG-MN}) \). Accordingly, the packet delivery cost of DD-PMIP can be represented as follows.

PDC\textsubscript{DD-PMIP} = S\textsubscript{data} \left( T\textsubscript{CN-MAG} + T\textsubscript{MAG-MAG} \times N\textsubscript{MAG} + T\textsubscript{MAG-MN} \right) \\
+ S\textsubscript{control} \times T\textsubscript{MAG-MAG} \times (N\textsubscript{MAG} + 1) + P\textsubscript{MAG} \\
= S\textsubscript{data} \left( \kappa H\textsubscript{CN-MAG} + \tau H\textsubscript{MAG-MAG} \times N\textsubscript{MAG} + \kappa H\textsubscript{MN-MAG} \right) \\
+ S\textsubscript{control} \times \tau H\textsubscript{MAG-MAG} \times (N\textsubscript{MAG} + 1) + \beta \log (N\textsubscript{Host} \times N\textsubscript{MAG}) \quad (8)

So, we obtain the total cost of DD-PMIP as

T\textsubscript{C-DD-PMIP} = \text{BUC\textsubscript{DD-PMIP}} + \text{PDC\textsubscript{DD-PMIP}}.

E. SD-PMIP

In SD-PMIP, the binding update cost is not performed, as done in DD-PMIP. So, we have

\text{BUC\textsubscript{SD-PMIP}} = \text{BUC\textsubscript{DD-PMIP}}. \quad (9)

SD-PMIP is a signal-driven distributed scheme. In data packet delivery, the binding query operation is performed by MAG of CN before transmission of data packet. After that the data packets are delivered directly to MN. Thus, the packet delivery cost of SD-PMIP can be calculated as follows. First, a data packet of CN is delivered to MAG, which is equal to \( S\textsubscript{data} \times T\textsubscript{CN-MAG} \). Then, MAG of CN sends a PBQ message to all MAGs in the domain by multicast, which corresponds to \( S\textsubscript{data} \times T\textsubscript{MAG-MAG} \times N\textsubscript{MAG} \). Only the MAG of MN will respond to MAG of CN with a PQA message after lookup of its MAG cache, which is equal to \( P\textsubscript{MAG} + S\textsubscript{control} \times T\textsubscript{MAG-MAG} \). After that, MAG of CN can deliver the data packet to MN via MAG, which takes \( S\textsubscript{data} \times (T\textsubscript{MAG-MAG} + T\textsubscript{MAG-MN}) \). Accordingly, the packet delivery cost of SD-PMIP can be represented as follows.

PDC\textsubscript{SD-PMIP} = S\textsubscript{data} \left( T\textsubscript{CN-MAG} + T\textsubscript{MAG-MAG} \times N\textsubscript{MAG} + T\textsubscript{MAG-MN} \right) \\
+ S\textsubscript{control} \times T\textsubscript{MAG-MAG} \times (N\textsubscript{MAG} + 1) + P\textsubscript{MAG} \\
= S\textsubscript{data} \left( \kappa H\textsubscript{CN-MAG} + \tau H\textsubscript{MAG-MAG} \times N\textsubscript{MAG} + \kappa H\textsubscript{MN-MAG} \right) \\
+ S\textsubscript{control} \times \tau H\textsubscript{MAG-MAG} \times (N\textsubscript{MAG} + 1) + \beta \log (N\textsubscript{Host} \times N\textsubscript{MAG}) \quad (10)

So, we obtain the total cost of SD-PMIP as

T\textsubscript{C-SD-PMIP} = \text{BUC\textsubscript{SD-PMIP}} + \text{PDC\textsubscript{SD-PMIP}}.

4.3 Numerical Results

For numerical analysis, we set the parameter values, as shown in Table 3, which are partly obtained based on the work made in [12]. In the table, \( \gamma \) represents a hop count ratio of \( H_{\text{MAG-MAG}} \) over \( H_{\text{MAG-LMA}} \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa )</td>
<td>4</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>( \tau )</td>
<td>2</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>3</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>( \beta )</td>
<td>2</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>( N_{\text{Host-MAG}} )</td>
<td>200</td>
<td>100</td>
<td>1,000</td>
</tr>
<tr>
<td>( N_{\text{MAG}} )</td>
<td>20</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>( H_{\text{MAG-LMA}} )</td>
<td>5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>0.3</td>
<td>0</td>
<td>2.0</td>
</tr>
<tr>
<td>( H_{\text{MAG-MAG}}, H_{\text{CN-MAG}} )</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T\text{setup} )</td>
<td>500 (ms)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S\text{data} )</td>
<td>1024 (bytes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S\text{control} )</td>
<td>50 (bytes)</td>
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Fig. 9 compares the total costs of candidate schemes for different transmission cost over wireless or wired link. In Fig. 9(a), it is shown that the total costs linearly increase for all the schemes, as the unit transmission cost of wireless link ($\kappa$) gets larger. It is shown that the three proposed distributed schemes give better performance than the existing PMIP scheme. This is because the distributed schemes can reduce the control operations for PMIP binding update. In Fig. 9(b), we can see that the gaps of performance between distributed schemes and centralized schemes get larger, as the unit transmission cost of wired link ($\tau$) increases. On the other hand, the DD-PMIP scheme gives a nearly same cost with the PMIP-LR. This implies that the performance gain of DD-PMIP is relatively small, compared to PMIP-LR. Among the three distributed schemes, SD-PMIP provides the best performance. This performance benefit comes from the fully distributed architecture and the signal-driven, not data-driven, feature of data packet, in which a small control packet is used to get the location of MN, instead of large data packet.

Fig. 10 illustrates the impact of binding update and database lookup operations on total cost. We can see that the total costs of all the schemes are not nearly affected by the unit binding update cost ($\alpha$), as shown in Fig. 10(a), or by the unit lookup cost ($\beta$), as shown in Fig. 10(b). This is because the binding update and lookup operations do not give any significant impact on total cost, compared to the other parameters. From the figure, it is shown that the signal-driven schemes, S-PMIP and SD-PMIP, give better performance than the data-driven schemes, PMIP, PMIP-LR, and DD-PMIP. This is because the signal-driven approach using a control packet can alleviate the overhead of mobility operation.

Fig. 11 shows the impact of the number of hosts and MAGs in the domain on total cost. In Fig. 11(a), we can see that the total costs of candidate schemes are not affected by the number of hosts per MAG (N_{Host/MAG}). This implies that N_{Host/MAG} does not give significant impact on performance. However, in Fig. 11(b), we can see that DD-PMIP depends severely on the number of MAG in the domain (N_{MAG}). This is because DD-PMIP uses multicast transmission of data packets to all MAGs, which induce severe degradation of cost performance. However, SD-PMIP is not nearly affected by N_{MAG}. Among all the candidate schemes, SD-PMIP provides the best performance.

Fig. 12 shows the impact of the number of hop count on total cost. Fig. 12(a) compares the total costs of candidate schemes for different hop counts between MAG and LMA (H_{MAG-LMA}). In the figure, we can see that H_{MAG-LMA} gives significant impact on total cost for PMIP. This is because PMIP relies on LMA for binding update and data delivery. S-PMIP and PMIP-LR is slightly affected by H_{MAG-LMA}, since they uses LMA only for binding update or query, not data delivery. On the other hand, Fig. 12(b) shows the total costs of candidate schemes in terms of the ratio of hop counts, $\gamma$ (H_{MAG-MAG} over H_{MAG-LMA}), where $\gamma = 0$ (i.e., H_{MAG-MAG} = 0) implies that both MN and CN are located in the same MAG region. Note that the total costs tend to increase, as $\gamma$ gets larger, since the data delivery is performed between two MAGs for all the schemes. In the meantime, it is shown that the signal-driven fully distributed scheme, SD-PMIP, gives the best performance among all the candidate schemes.

From all the numerical results, it seems that the distributed mobility schemes give better performance than the centralized schemes in terms of total cost. DD-PMIP tends to give similar performance with PMIP-LR and worse performance than S-PMIP and SD-PMIP, since DD-PMIP generates a significantly large amount of unnecessary data traffic into the network. In summary, SD-PMIP gives the best performance among all of the distributed mobility control schemes.
(a) Unit cost of binding update at LMA

(b) Unit cost of lookup at LMA or MAG

Fig. 10 Impact of unit binding update and lookup costs on total cost

(a) Number of hosts in MAG

(b) Number of MAGs in the PMIP domain

Fig. 11 Impact of the number of hosts and MAGs on total cost

(a) Hop counts between MAG and LMA

(b) Hop count ratio of $H_{\text{MAG-MAG}}$ over $H_{\text{MAG-LMA}}$

Fig. 12 Impact of hop counts on total cost
5. Conclusions

In this paper, we analyzed the distributed mobility control architecture that has recently been discussed in IETF, and proposed three schemes for distributed mobility control in the PMIP-based mobile networks: S-PMIP, DD-PMIP, and SD-PMIP. S-PMIP is a partially distributed approach, whereas DD-PMIP and SD-PMIP are regarded as fully distributed schemes. In S-PMIP, the control plane for location query is separated from the data plane. In DD-PMIP, no location binding and query operations are used, and a data packet will be delivered to all MAGs in the same domain by multicast. In SD-PMIP, the binding operation is not used. Instead, the location query message is multicast to all MAGs to find the MAG of MN.

By numerical analysis, the three proposed schemes for distributed mobility control are compared with the existing PMIP and PMIP-LR schemes in terms of the binding update cost and the packet delivery cost. From the numerical results, it is shown that the proposed distributed schemes can give better performance than the existing centralized schemes. DD-PMIP shows nearly similar performance with the existing PMIP-LR scheme. The signal-driven S-PMIP and SD-PMIP schemes give better performance than the data-driven PMIP, PMIP-LR, and DD-PMIP schemes. In particular, SD-PMIP provides the best performance among all the candidate schemes. It is noted that the performance of DD-PMIP tends to be degraded, as the number of MAGs in the PMIP domain increases. This is because DD-PMIP will introduce unnecessary data traffic into the network.

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