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Developing Route Optimization-Based PMIPv6 Testbed for Reliable Packet Transmission

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ABSTRACT Proxy Mobile IPv6 (PMIPv6) allows a mobile node to communicate directly to its peers while changing the currently used IP address. This mode of operation is called route optimization (RO). In the RO process, the peer node learns a binding between the home address and its current temporary care-of-address. Many schemes have been proposed to support RO in PMIPv6. However, these schemes do not consider the out-of-sequence problem, which may happen between the existing path and the newly established RO path. In this paper, we propose a scheme to solve the out-of-sequence problem with low cost. In our scheme, we use the additional packet sequence number and the time information when the problem occurs. We then run experiments on a reliable packet transmission (RPT) laboratory testbed to evaluate the performance of the proposed scheme, and compare it with the well-known RO-supported PMIPv6 and the out-of-sequence time period scheme. The experimental results show that for most of the cases, our proposed scheme guarantees RPT by preventing the out-of-sequence problem.

INDEX TERMS PMIPv6, proxy mobile IPv6, route optimization.

I. INTRODUCTION

Internet usage continues its rapid expansion thanks to the technological advances in wireless access technologies. While overall IP traffic is expected to have 23 percent annual growth between 2012 and 2017, IP traffic from mobile terminals is expected to have 66 percent annual growth during the same period [17]. IP mobility support has been a hot topic over the last years, recently fostered by the role of IP in the evolution of the 4G/LTE mobile communication networks. Standardization bodies are working on different aspects of the mobility aiming at improving the mobility experience perceived by users. Having these requirements of mobility in mind, IETF NETLMM WG has proposed Proxy Mobile (PMIPv6) [1] as a new network-based mobility protocol for IPv6 nodes which does not require host involvements.

The main idea of PMIPv6 is that the Mobile Node (MN) is not involved in any IP layer mobility-related signaling. The MN is a conventional IP device (that is, it runs the standard protocol stack). The purpose of PMIPv6 is to provide mobility to IP devices without their involvement. This provision is achieved by relocating relevant functions for mobility management from the MN to the network. This enables resource optimization in the networks and reduces energy consumption of MN and handover signaling cost. PMIPv6 performs better than MIPv6 in many aspects. A Mobile Access Gateway (MAG) and a Local Mobility Anchor (LMA) are in charge of the mobility of MN in thePMIPv6 domain. However, basic PMIPv6 does not support Route Optimization (RO) and all messages that packets related to MN are managed in LMA and MAG. In other words, all packets are always transmitted via LMA, and this increases the processing overhead of LMA as well as transmission delay. Many schemes are proposed to support the RO to overcome this problem [2]–[4].

When RO is supported in PMIPv6, the MN communicates with the CN via the RO path between two different MAGs. We define the RO path as a new path, and the basic PMIPv6 path as an old path. When the RO path is established, the out-of-sequence problem occurs due to the different transmission time between the old path and the RO path. This problem causes packet loss in UDP and packet retransmission request messages in TCP. These problems increase network overhead and cannot provide reliable data transmission. We propose a new scheme to solve that problem more accurately and effectively. Our scheme uses the identical sequence number of a packet and the original RO control message of PMIPv6. Through the experimental measurement, proposed scheme precisely prevents the out-of-sequence packets compared to the OTP scheme, since it uses the sequence number. In addition, it reduces the buffering cost by reducing the number of entities. This paper introduce the extended features and real test-bed measurement results of our previous work [18].

The remainder of the paper is organized as follows. Section 2 introduces the RO schemes in PMIPv6, the EF-MIPv6 scheme, and the OTP scheme as related works. In Section 3, we explain our proposed scheme. Section 4 presents performance modeling; we define the network and mobility model and the equations for comparing the amount of buffered packets and the packet reception delay. In Section 5, we evaluate the number of out-of-sequence packets and the handover delay via network simulation and testbed measurement. Section 6 concludes the paper and outlines our future work.

II. RELATED WORKS

PMIPv6 is starting to attract much attention among internet communities and telecommunication due to its noble features and it is expected to expedite the real deployment of IP-based mobility management. However, an experimental evaluation of PMIPv6, which analyzes the impact of its practical constraints, is missing. In addition, the route optimization problem is still challenging issue in handover of mobile IP.

P. Loureiro proposed a PMIPv6 scheme [2] to support the RO. When the MN attaches to the MAG domain, MAG and LMA make a bidirectional tunnel by handshaking the Proxy Binding Update (PBU) and Proxy Binding Acknowledgement (PBA) message. After that, when the first packet transmitted from the MN to the CN arrives at the LMA, triggers the RO. The trigger message includes the MN-ID and the MAG address. A new LMA, receiving the RO trigger message, performs the RO control function. Normally, the transmission delay in the RO path is less than the one in the old path. In TCP network, the out-of-sequence problem causes frequent packet retransmissions. In case of UDP, reliable service is not supported yet, although the packet transmission delay is reduced by the RO in PMIPv6.

The Out-of-sequence Time Period (OTP) [5] scheme and Enhanced Fast MIPv6 (EF-MIPv6) [6] are proposed to solve the out-of-sequence problem. The OTP scheme is the solution to restrain the tunnel establishment when the RO path is established. The EF-MIPv6 scheme is one of the solutions using the Enhanced Fast Binding Update (EF-BU) message in MIPv6. However, the EF-MIPv6 scheme is not applicable for PMIPv6, because EF-BU has to change the basic control messages and works only in MIPv6. The OTP scheme cannot provide reliable service to MN, because it is hard to predict the restraint time of the tunnel in the OTP scheme.

Fast Handover Mobile IPv6 (FMIPv6) [7] was proposed to reduce handover delay and packet losses in MIPv6. In their algorithm, MN informs the new Access Router (nAR), as to where MN would be, the previous Access Router (pAR) by predicting its handover. Knowing the nAR's address, the pAR establishes a bidirectional tunnel with the nAR before the MN attaches to the nAR. During MN's handover, the pAR forwards the packets to the nAR via the tunnel. When the nAR receives the packets from the pAR, it stores all the packets in the buffer. After the MN connects to the nAR, the nAR forwards the buffered packets to the MN, and the packets generated between the MN and the CN are forwarded via the nAR without going through the pAR. If the distance between the CN and the nAR is shorter than the tunneled distance from the CN to the nAR via the pAR, the out-of-sequence problem would occur. EF-MIPv6 was proposed to solve this problem.

The scheme in [6] uses the modified snoop protocol to avoid the out-of-sequence problem in FMIPv6. In addition, it solves the problem using Enhanced Fast Binding Update (EF-BU) and the Multilink Procedure (MLP) message and buffering at the nAR and the pAR. The procedure for a handover in the scheme is similar to FMIPv6. However, the MN sends the EF-BU message to the CN after the pAR exchanges the messages for setting up the tunnel with the nAR to manage the out-of-sequence. Receiving the EF-BU message, the CN changes the MLP field of the TCP header in the message to 1 and then the message is forwarded to the nAR. The nAR can determine if the packets come from the pAR or the CN, by checking the number of the MLP field. Then this resolves the out-of-sequence problem.

Even though the out-of-sequence problem in FMIPv6 is solved in [6], it is hard to use this scheme in MIPv6. Because the EF-BU and the MLP message have to be modified. Moreover, the buffering cost and the load of the routers increase while buffering is performed at both the nAR and the pAR. Finally, it is hard to apply the scheme in PMIPv6, because PMIPv6 does not have the revised FMIPv6 protocol stack.

III. PROPOSED SCHEME

Our proposed scheme provides the reliable service for MN more accurately to prevent the out-of-sequence problem while performing the RO. Our scheme manages the problem effectively, using the packet sequence number, and reducing the forwarding delay time using the value of Time-To-Live (TTL).

A. MOTIVATION AND BASIC ASSUMPTIONS

The OTP scheme prevents the out-of-sequence problem through the predetermined time of setting up the tunnel and buffering between MAGs and LMA. In our proposed scheme, only MAG performs buffering for MN so the buffering cost in LMA decreases, whereas both the MAG and the LMA in the OTP scheme. In addition, the OTP scheme does not perfectly prevent the out-of-sequence problem due to the prediction. However, our proposed scheme solves the out-of-sequence problem, using the packet sequence numbers. In this paper, we assume that the MN sends packets to CN after a MN's handover between two domains to explain this more effectively.

We use the IP header information to prevent the out-of-sequence problem more effectively [8]. The identification field, which is the number assigned from a router of the IP header, is a unique number used by devising or recombining a packet following the Maximum Transfer Unit (MTU). Accordingly, it is possible to know the packet sequence using the identification number in the communication between routers. MAGs and LMAs know the packet sequence via the identification number in the IP header. Therefore, our proposed scheme can determine the out-of-sequence packets that arrive at the MAG by the identification number in the IP header.

Our proposed scheme uses the TTL value in the IP header to calculate the transmission time of the old path and the RO path. We can count the number of routers through the old path and the RO path from the TTL value. When a packet passes through the tunnel, the tunnel header is added to the packet. The TTL value in the tunnel header decreases when the packet passes through the tunnel, since the packet is encapsulated, but the TTL value in the IP header does not. The packet is de-capsulated after passing through the tunnel. Then, the TTL value in IP the header decrements by one [9]. It is impossible to count the accurate number of routers in each path due to this situation. Our scheme uses the minimal encapsulation to avoid the problem [10] by reducing the overhead of the tunnel header. The TTL value usually decreases after a packet passes through the tunnel, because the minimum information is kept at the inner IP header, and the remaining information moves to the tunnel header.

Our proposed scheme reduces the load of the router by minimizing the number of routers that take buffering. Entity_{Node} is an entity connecting to a node. All of MAGs and LMA perform buffering in the case of the OTP scheme; however, our proposed scheme performs buffering on the MAG_{CN}. When a packet arrives at MAG_{CN} through an old path, MAG_{CN} forwards the packet to CN. Conversely, if a packet goes via the RO path, MAG_{CN} stores the packet in its buffer. Thus, our proposed scheme reduces the load of the router and packet reception delay of the CN.

B. BASIC OPERATION

The procedure to establish the RO path is similar to scheme [2]. The packets between MN and CN pass through the old path before the RO path is established. If the RO path is completely established, the packets pass through the RO path. MAGCN receiving the packets via the RO path, buffers the packets to cause the non-out-of-sequence problem. From the beginning of buffering in MAGCN, MAGCN compares the sequence number of the first packet in the buffer and the sequence number of the packet that passed via the old path. MAGCN performs buffering until the last packet from the old path arrives at MAGCN. When the last packet from the old path arrives at MAGCN, MAGCN forwards the packet and then forwards the all packets in its buffer.

In the proposed scheme, the out-of-sequence problem is prevented by storing the packets from the RO path in the MAG's buffer, until all the packets pass from the old path. Enabling the sequence number to understand the order of all the packets passing though the old path and the RO path resolves the problem more precisely than other schemes do. In addition, our proposed scheme transfers via the shortest path due to performing buffering in MAG_{CN}. Thus the out-of-sequence problem is not occurred, and the packet reception delay is reduced after the RO path is established. MAG_{CN} forwards the packets in the buffer to CN after the last packet from the old path passes through MAG_{CN}. However, if the last packet from the old path is lost, MAG_{CN} performs buffering infinitely. The maximum forwarding delay time (T_{wait}) is calculated to prevent infinite buffering in our proposed scheme. If the last packet from the old path does not arrive at MAG_{CN} within the T_{wait}, the packets in the buffer are forwarded to CN. The out-of-sequence problem is prevented using the maximum forwarding delay time, even though the packets from the old path are lost.

T_{wait} is used to prevent infinite buffering. T_{wait} is calculated by the time difference between the times that the packets coming from the old path and the RO path, arrive at MAGCN. T_{wait} is calculated by equation (1). T_{OP} defines the time that the packet passes via the old path; and T_{NP} defines the time the packet passes via the RO path. From equation (1), we can calculate the different arrival times between T_{OP} and T_{NP}.

$$T_{wait} = T_{OP} - T_{NP} \tag{1}$$

Equation (2) and (3) are the formulas to calculate T_{OP} and T_{NP}. TTL_{Max} is the maximum value of TTL. TTL_{OP} and TTL_{NP} are the TTL values of the packets from the old path and the RO path, respectively. TTL_{Max} minus TTL_{OP} or TTL_{NP} calculates the number of routers that a packet has passed in each path. We can calculate the packet transmission time of each path by multiplying the counted number of the routers with the packet transmission time per hop, $T_{One-Hop}$.

$$T_{OP} = (TTL_{Max} - TTL_{OP}) \cdot T_{One-Hop} \tag{2}$$
$$T_{NP} = (TTL_{Max} - TTL_{NP}) \cdot T_{One-Hop} \tag{3}$$

$T_{One-Hop}$ is calculated by equation (4). $T_{One-Hop}$ is calculated using the round-trip time and the TTL value of the RO Setup message that sets up the RO path. The Ethernet's MTU is used to calculate the maximum forwarding delay time. TTL_{RS} is the TTL value when the RO Setup message arrives at MAG_{CN}, and L_{MTU} is the MTU size the network has. T_{RS} is the round-trip time of the RO Setup message and $L_{RO\text{-}Setup}$ is the size of the RO Setup message. The transmission time of the old path, the RO path, and the transmission time per hop are calculated using the RO Setup message.

$$T_{One-Hop} = \frac{L_{MTU} \cdot \frac{\left(\frac{T_{RS}}{2}\right)}{L_{RO-Setup}}}{TTL_{Max} - TTL_{RS}} \quad (4)$$

C. SIGNALING OF THE PROPOSED SCHEME

In our proposed scheme, the signaling flow for RO is similar to scheme [2]. The signaling to solve the out-of-sequence problem is performed in MAG_{CN}. Figure 1 shows the signaling flow of our proposed scheme when the last packet of the old path is lost in MN's inter-domain handover. When MAG2 receives the RO Init message from LMA2, MAG2 performs the flow to calculate t T_{wait}. MAG2 saves the TTL value of the RO Setup message and inter-arrival time of the RO Setup message between MAG1 and MAG2. When the RO is completed, MAG2 starts to store the packets from the RO path and checks the packet sequence number from the old path. If the last packet from the old path arrives at MAG2, MAG2 forwards the packet to CN. Next, MAG2 forwards all the buffered packets in MAG2 to CN. However, if the last packet from the old path does not arrive at MAG2 during T_{wait}, MAG2 thinks the last packet from the old path is lost. Therefore, MAG2 forwards all buffered packets in MAG2 to CN.

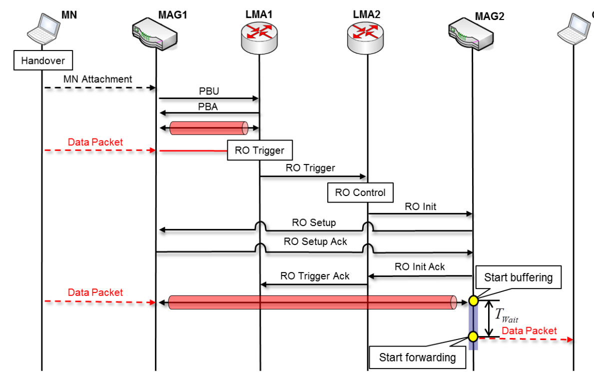

FIGURE 1. Signaling flow of proposed scheme.

Figure 2 is the flow chart of the algorithm in MAG2. The flow chart is performed after the RO path is established between MAG1 and MAG2. Then, MAG2 receives the first packet from the RO path. MAG2 starts to check the elapsed time by the time of starting buffering. When the packet arrives at MAG2, MAG2 checks the path using the packet. If the packet arrives from the RO path, MAG2 stores the packet in its own buffer. If the packet arrives from the old path, MAG2 compares the packet sequence with the packet and the first packet in the buffer. If the last packet from the old path arrives at MAG_{CN}, the packets in the buffer are forwarded to CN after MAG_{CN} forwards the last packet from the old path to CN. However, if the last packet from the old path does not arrive at MAG2 during T_{wait}, MAG2 forwards all buffered packets in MAG2 to CN. Our proposed scheme provides reliable service to avoid the out-of-sequence more

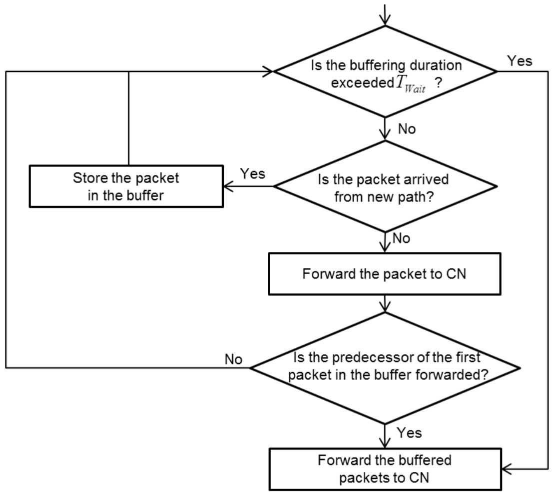

FIGURE 2. Flow chart of the proposed scheme.

precisely than the OTP scheme. The out-of-sequence problem is prevented using T_{wait}, even though the packets from the old path are lost. In addition, the scheme minimizes the end to end packet reception delay, using the old path during the establishment of the RO path. Moreover, our proposed scheme reduces the buffering cost, because buffering is performed only by MAG_{CN}.

IV. PERFORMANCE MODELING

In this section, we use mathematical modeling to compare the performance of our proposed scheme to the OTP scheme. In section 4.1, we define the network model to use in the performance modeling. In section 4.2, we define the equations to compare the amount of buffered packets and the packet reception delay in our proposed scheme and the OTP scheme. Section 4.3 shows the results of the performance evaluation. We developed initial version of Proxy Mobile IPv6 and its analytical model in 2012 [18].

A. NETWORK AND MOBILITY MODEL

Figure 3 is the network topology for our performance modeling. The network model has two LMAs; each LMA connects

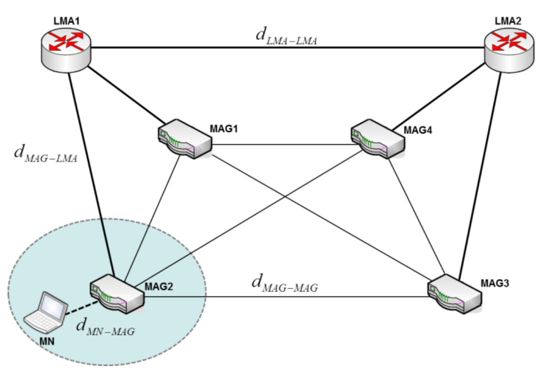

FIGURE 3. Network topology for the performance modeling.

with two MAGs. $d_{X\text{-}Y}$ denotes the number of hops between entity X and entity Y. We use the fluid-flow mobility model, which is popular to use in performance evaluation of mobile network, shows mobility of MN considering the velocity and direction of MN [11], [12]. Our proposed scheme calculates the rate of the MN's handover using the fluid-flow model. The fluid-flow model calculates the average number of MNs that perform the handover by utilizing the number of MAGs composed in the LMA domain and the session arrival rate of MN.

μ_c, the rate of MN's intra-domain handover, is calculated by equation (5). ν is the average velocity of MN, R is the radius of MAG's coverage, and S is the area of MAG's coverage. μ_d, the rate of MN's inter-domain, is calculated by equation (6). N is the number of MAGs in LMA domain. μ_s, the rate of the intra-domain handover, is calculated by equation (7) [11]–[13].

$$\mu_c = \frac{2 \cdot \nu}{\sqrt{\pi \cdot S}} = \frac{2 \cdot \nu}{\pi \cdot R} \tag{5}$$

$$\mu_d = \frac{\mu_c}{\sqrt{N}} \tag{6}$$

$$\mu_s = \mu_c - \mu_d = \mu_c \cdot \frac{\left(\sqrt{N} - 1\right)}{\sqrt{N}} \tag{7}$$

The average number of MNs is determined using λ_s in fluid-flow model mobility; that is, session arrival rate, μ_c, μ_d, and μ_s. $E[N_c]$, the average number of MNs that do the handover is calculated by equation (8). $E[N_d]$, the average number of MNs in the inter-domain handover, is calculated by equation (9), and $E[N_s]$, the average number of MNs in the intra-domain handover, is calculated by equation (10).

$$E\left[N_c\right] = \frac{\mu_c}{\lambda_s} \tag{8}$$

$$E\left[N_d\right] = \frac{\mu_d}{\lambda_s} \tag{9}$$

$$E\left[N_s\right] = \frac{\mu_s}{\lambda_s} = \frac{(\mu_c - \mu_d)}{\lambda_s} \tag{10}$$

B. MATHEMATICAL MODELING

The packet reception delay denotes that a CN receives the first packet from MN after handover. If the packet reception delay is short, CN realizes that the handover delay is short. The OTP scheme restricts the disestablishment of the old path until the RO path is established. Therefore, CN receives the first packet from MN after finishing the binding update for MN and establishing the RO path. In our proposed scheme, CN receives the first packet from MN after finishing the binding update for MN. The packet reception delay of our proposed scheme is shorter than for the OTP scheme due to this feature.

D_{OTP}, the packet reception delay in the OTP scheme, is calculated by equation (11). D_{PBU} and D_{PBA} are the transmission delay of the PBU and PBA messages, respectively. $D_{RO\text{-}Inter}$ and $D_{RO\text{-}Intra}$ are the delay of the RO setup in the inter-domain and intra-domain, respectively. $D_{NP\text{-}Data}$ is the packet transmission delay from MAG_{MN} to CN after the RO [14], [15].

$$D_{OTP} = (D_{PBU} + D_{PBA}) + \left[\frac{\mu_d}{\mu_c} \cdot D_{RO-Inter} + \left(1 - \frac{\mu_d}{\mu_c}\right) \cdot D_{RO-Intra}\right] + D_{NP-Data} \tag{11}$$

D_{PBU} and D_{PBA} are calculated by equations (12) and (13), respectively. α is the transmission cost in a wired network, and L_i is the size of message i. P_t is the packet processing delay in a router. P_{LMA} and P_{MAG} are the packet processing delay in LMA and MAG, respectively. B_w is the bandwidth in a wired network.

$$D_{PBU} = \alpha \cdot \left(\frac{L_{PBU}}{B_w} + P_t\right) \cdot (d_{MAG-LMA} - 1) + P_{LMA} \tag{12}$$

$$D_{PBA} = \alpha \cdot \left(\frac{L_{PBA}}{B_w} + P_t\right) \cdot (d_{MAG-LMA} - 1) + P_{MAG} \tag{13}$$

$D_{RO\text{-}Inter}$ and $D_{RO\text{-}Intra}$ are calculated by equations (14). D_i is the transmission delay of message i. The transmission delay of each message is calculated by equations (15)-(20).

$$D_{RO\text{-}Intra} = D_{RO\text{-}Init} + D'_{RO-InitAck} + D_{RO-Setup} + D_{RO-SetupAck} \tag{14}$$

$$D_{RO-Trigger} = \alpha \cdot \left(\frac{L_{RO-Trigger}}{B_w} + P_t\right) \cdot (d_{LMA-LMA} - 1) + P_{LMA} \tag{15}$$

$$D_{RO-TriggerAck} = \alpha \cdot \left(\frac{L_{RO-TriggerAck}}{B_w} + P_t\right) \cdot (d_{LMA-LMA} - 1) + P_{LMA} \tag{16}$$

$$D_{RO-Init} = \alpha \cdot \left(\frac{L_{RO-Init}}{B_w} + P_t\right) \cdot (d_{MAG-LMA} - 1) + P_{MAG} \tag{17}$$

$$D_{RO-InitAck} = \alpha \cdot \left(\frac{L_{RO-InitAck}}{B_w} + P_t\right) \cdot (d_{MAG-LMA} - 1) + P_{LMA} \tag{18}$$

$$D_{RO-Setup} = \alpha \cdot \left(\frac{L_{RO-Setup}}{B_w} + P_t\right) \cdot (d_{MAG-MAG} - 1) + P_{MAG} \tag{19}$$

$$D_{RO-SetupAck} = \alpha \cdot \left(\frac{L_{RO-SetupAck}}{B_w} + P_t\right) \cdot (d_{MAG-MAG} - 1) + P_{MAG} \tag{20}$$

$D_{NP-Data}$ is the packet reception delay from MN to a CN via the RO path. $D_{NP-Data}$ is calculated by equation (21). S_d and τ are the size of a packet and a tunnel header, respectively. β is the transmission delay in the wireless network, and B_{wl} is the network bandwidth.

$$D_{NP-Data} = \alpha \cdot \left[\left(\frac{s_d + \tau}{B_w} + P_t\right) \cdot d_{MAG-MAG}\right] + \beta \cdot \left[\left(\frac{s_d}{B_{wl}} + P_t\right) \cdot d_{MN-MAG}\right] \tag{21}$$

D_{Pro}, the packet reception delay in our proposed scheme, is calculated by equation (22). D_{Pro} is calculated by adding the delay of the binding update, the data transmission delay from MN to a CN, and the extra delay to lose the last packet from the old path. $D_{OP\_Inter\text{-}Data}$ and $D_{OP\_Intra\text{-}Data}$ are the data transmission delay through the old path in the inter-domain handover and the intra-domain handover, respectively.

$$\begin{aligned} D_{Pro} = {} & (D_{PBU} + D_{PBA}) \\ & + \left[\frac{\mu_d}{\mu_c} \cdot D_{OP\_Inter-Data} + \left(1 - \frac{\mu_d}{\mu_c}\right) \cdot D_{OP\_Intra-Data}\right] \\ & + \lambda_d \cdot \left[\frac{\mu_d}{\mu_c} \cdot T_{Wait-Inter} + \left(1 - \frac{\mu_d}{\mu_c}\right) \cdot T_{Wait-Intra}\right] \end{aligned} \tag{22}$$

$T_{wait-Inter}$ and $T_{wait-Intra}$, the maximum forwarding delay of the RO path of the intra-domain handover and inter-domain handover, respectively, are calculated by the changing value of $TTL_{RO-Setup}$ in formula T_{wait}. We consider the worst delay to lose the last packet from the old path, to measure the accurate packet reception delay in the proposed scheme. $D_{OP_Inter-Data}$ and $D_{OP_Intra-Data}$ are calculated by equations (23) and (24), respectively.

$$\begin{aligned} D_{OP\_Inter-Data} = {} & 2\beta \cdot \left[\left(\frac{s_d}{B_{wl}} + P_t\right) \cdot d_{MN-MAG}\right] \\ & + 2\alpha \cdot \left[\left(\frac{s_d + \tau}{B_w} + P_t\right) \cdot d_{MAG-LMA}\right] \\ & + \alpha \cdot \left[\left(\frac{s_d}{B_w} + P_t\right) \cdot d_{LMA-LMA}\right] \end{aligned} \tag{23}$$

$$\begin{aligned} D_{OP\_Intra-Data} = {} & 2\beta \cdot \left[\left(\frac{s_d}{B_{wl}} + P_t\right) \cdot d_{MN-MAG}\right] \\ & + 2\alpha \cdot \left[\left(\frac{s_d + \tau}{B_w} + P_t\right) \cdot d_{MAG-LMA}\right] \end{aligned} \tag{24}$$

The amount of buffered packets is the total number of stored packets in the buffer at LMA and MAG to prevent packet loss after MN's handover. Our proposed scheme reduces the amount of buffered packets, because the packets are only buffered at MAG, since the OTP scheme stores the packets in both the MAG and *t* LMA.

The amount of buffered packets in the OTP scheme is calculated by equation (25). $S_{OTP\text{-}Buffer}$ is the amount of buffered packets when the RO path is set up in the OTP scheme. λ_p, the generation rate of data traffic, expresses the number of the transmitted packets per unit time [13]. The amount of buffered packets in our proposed scheme is calculated by equation (26). Our proposed scheme sends the packets through the old path during the RO path set up. Therefore, the time to start buffering is the time when the RO path establishment is completed. The maximum time to buffer the packets is $T_{wait\text{-}Inter}$.

$$\begin{aligned} S_{OTP-Buffer} = {} & E(N_d) \cdot \left(D_{RO-Inter} \cdot \lambda_p\right) \\ & + E(N_s) \cdot \left(D_{RO-Intra} \cdot \lambda_p\right) \end{aligned} \tag{25}$$

$$\begin{aligned} S_{Pro-Buffer} = {} & E(N_d) \cdot \left(T_{Wait-Inter} \cdot \lambda_p\right) \\ & + E(N_s) \cdot \left(T_{Wait-Intra} \cdot \lambda_p\right) \end{aligned} \tag{26}$$

C. PERFORMANCE EVALUATION

We define the equations in mathematical modeling to compare the amount of buffered packets and the maximum packet reception delay of our proposed scheme and the OTP scheme. In this section, we compare the performance of our proposed scheme to the OTP scheme using the parameter value in Table 1 [13]–[15]. Figure 4 shows the packet reception delay impacted by the changes of the data size. N is 25, and v is 20 m/s. λ_s and λ_d is 0.1. S_d increases from 100 bytes to 1,500 bytes and MTU is set to 1,500, as the general value of the Ethernet. Mathematical modeling shows the OTP scheme incurs a longer packet reception delay than our proposed scheme does. As the data size increases, the difference between the two schemes lessens, but our proposed scheme has better performance, because it is hard to exceed a 1,500 byte transfer in general Ethernet.

Figure 5 shows the packet reception delay impacted by the changes in the number of MAGs in LMA domain. We set v, λ_s, λ_d, and MTU as the same value, as in the above environment.

S_d is set to 500 and 1,500 bytes, and N increases from 1 to 50. Increasing the number of MAGs in LMA domain decreases the rate of inter-domain handover. Therefore, the packet reception delay decreases, as the number of MAGs increase. The reception delay in our proposed scheme is shorter than that of the OTP scheme.

Figure 6 shows the packet reception delay impacted by losing the last packet from the old path. We set N, v, λ_s, and MTU is the same value as in the environment of the result in figure 6. We set S_d to 500 bytes and λ_d increases from 0 to 1. As the probability that the loss of the last packet from the old path increases, the probability also increases that the extra delay is as much as T_{wait}. Thus, the packet reception delay increases as the probability that the last packet is lost in the old path. However, the packet reception delay in our proposed scheme is shorter, even though the last packet from the old path is always lost.

Figure 7 shows the amount of buffered packets impacted by the sending traffic rate in MN. N is set to 25, v is set to 20 m/s, and λ_s is set to 0.1. λ_p increases from 1 Mbps to 15 Mbps. As the sending traffic rate increases, the OTP scheme stores more packets in the buffer than our proposed scheme does and the difference increases.

Figure 8 shows the amount of buffered packets impacted by the average velocity of MN. N is set to 25, λ_s is set to 0.1, and λ_p is set to 3 Mbps. v increases from 1 m/s to 50 m/s. As MN's average velocity increases, the number of t MNs that perform handover increase. Thus, the amount of buffered packets also

TABLE 1. Parameter values for the performance evaluation.

Notation	Description	Values
v	Average velocity of MNs	1 – 50 m/s
R	Radius of cell	100 m
N	Number of MAGs in a domain	1 – 35 events/ms
λ_s	Session arrival rate	0.05 – 0.2
d_{MN}–MAG	Average number of hops between MN and MAG	1 hop
d_{MAG}–LMA	Average number of hops between MAG and LMA	7 hops
d_{MAG}–MAG	Average number of hops between MAG and MAG	$\sqrt{N}$ hops
D_{LMA}–LMA	Average number of hops between LMA and LMA	15 hops
L_{PBU}	PBU message size	76 Bytes
L_{PBA}	PBA message size	76 Bytes
L_{RO}–$Trigger$	RO Trigger message size	72 Bytes
L_{RO}–$TriggerAck$	RO Trigger Ack message size	72 Bytes
L_{RO}–$Init$	RO Init message size	72 Bytes
L_{RO}–$InitAck$	RO Init Ack message size	72 Bytes
L_{RO}–$Setup$	RO Setup message size	72 Bytes
L_{RO}–$SetupAck$	RO Setup Ack message size	72 Bytes
B_w	Bandwidth of the wired link	100 Mbps
B_{wl}	Bandwidth of the wireless link	11 Mbps
α	Transmission unit cost in wired link	1
β	Transmission unit cost in wireless link	1.5
S_d	Data packet size	200 Bytes – 1460 Bytes
τ	Tunnel header size	40 Bytes
P_t	Routing table lookup and processing delay	0.1 ms
P_{LMA}	Processing cost in the LMA	0.12 ms
P_{MAG}	Processing cost in the MAG	0.24 ms
λ_p	Packet arrival rate	1 – 10 Mbps
λ_d	Drop rate of last packet by current path	0.05 – 1 event/ms

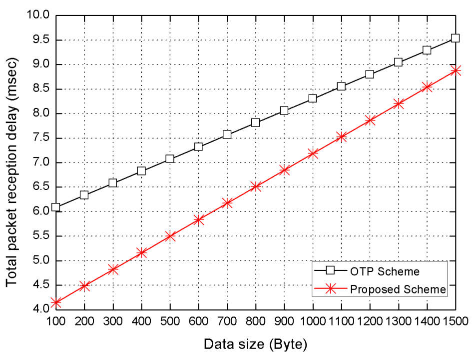

FIGURE 4. Packet reception delay impacted by the changes the data size.

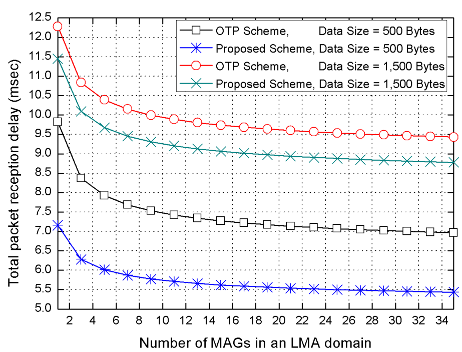

FIGURE 5. Packet reception delay impacted by the changes the number of MAGs in LMA domain.

increases, since the number of the RO path establishments increases. If the average velocity of MN increases, the OTP scheme stores the packet in the buffer more than our proposed scheme does.

Figure 9 shows the amount of buffered packets changes with the number of MAGs in LMA domain. λ_s is set to 0.1, λ_p is set to 3 Mbps, and v is set to 20 m/s. N increases from 1 to 35. As the number of MAGs in LMA domain increases,

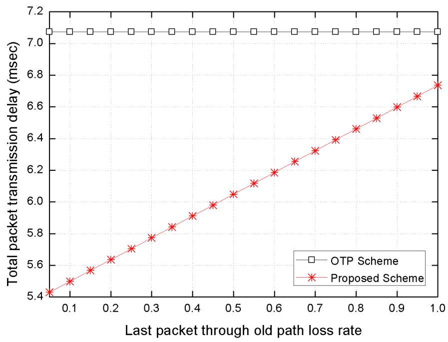

FIGURE 6. Packet reception delay impacted by losing the last packet in the old path.

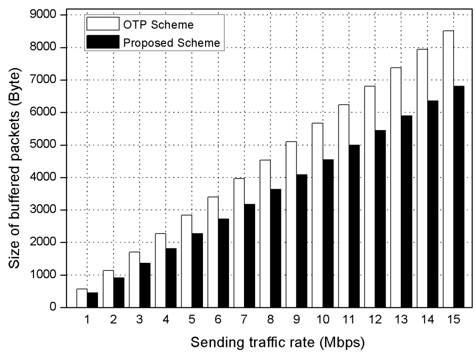

FIGURE 7. Amount of the buffered packets impacted by the sending traffic rate.

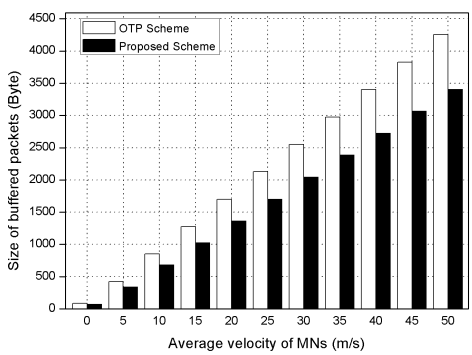

FIGURE 8. Amount of the buffered packets impacted by the average velocity of MN.

the number of the inter-domain handovers increases. Thus, the amount of buffered packets decreases, as the number of MAGs increases. The amount of buffered packets in our proposed scheme is smaller than for the OTP scheme, and buffering is performed effectively, as the number of MAGs decreases.

V. SIMULATION RESULTS

In this section, we verify the number of out-of-sequence packets and the packet reception delay through the computer simulation and testbed experiment. We check the number of out-of-sequence packets in the RO supported PMIPv6, OTP scheme, and our proposed scheme using the comprehensive computer simulation. We also implement a testbed for the RO supported PMIPv6 and verify algorithms in real environment. Our proposed scheme generates fewer out-of-sequences than the OTP scheme and the RO supported PMIPv6 does. In addition, it demonstrates improved performance in terms of packet transmission delay compared to the OTP scheme. We illustrate the simulation results in the former part (5.1 and 5.2) and the testbed measurements are illustrated in later part (5.3 and 5.4).

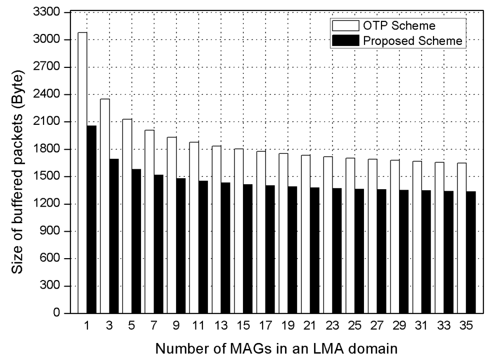

FIGURE 9. Amount of the buffered packets impacted by the number of MAGs in LMA domain.

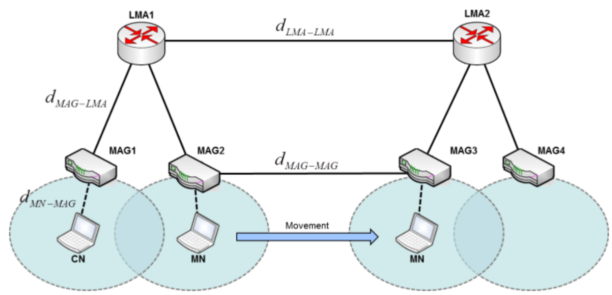

FIGURE 10. Network topology of simulation.

A. SIMULATION ENVIRONMENT

We run the simulator implemented in C++ to measure the number of the out-of-sequence packets. We conduct our simulation in the UDP environment to determine the packet loss and out-of-sequence packets. The simulation uses the CBR traffic generator, and data packets are generated in 0.02 seconds with the size of 500bytes. Using the CBR traffic, we can verify the incidence of packet transmission delay and the number of out-of-sequence packets accurately. Figure 10 is the network topology to conduct the simulation. We configure $d_{LMA-LMA}$ as 15 hops, $d_{MAG-LMA}$ as 7 hops, $d_{MAG-MAG}$ as 7 hops, d_{MN-MAG} as 1hop. In this simulation, the number of the out-of-sequence packets and the packet reception delay are verified during establishment of the RO path in the inter-domain handover.

B. SIMULATION RESULT

Figure 11 shows the simulation results of the RO supported PMIPv6. This scheme cannot prevent occurrence of out-of-sequence packets; 66 out-of-sequence packets occurred.

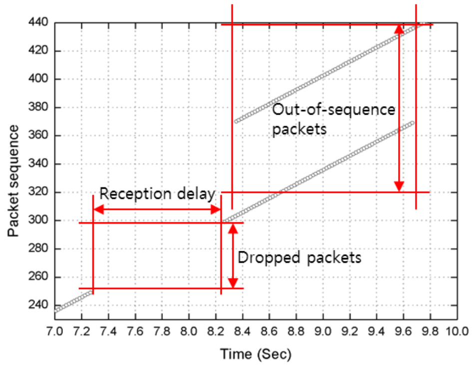

FIGURE 11. RO supported PMIPv6.

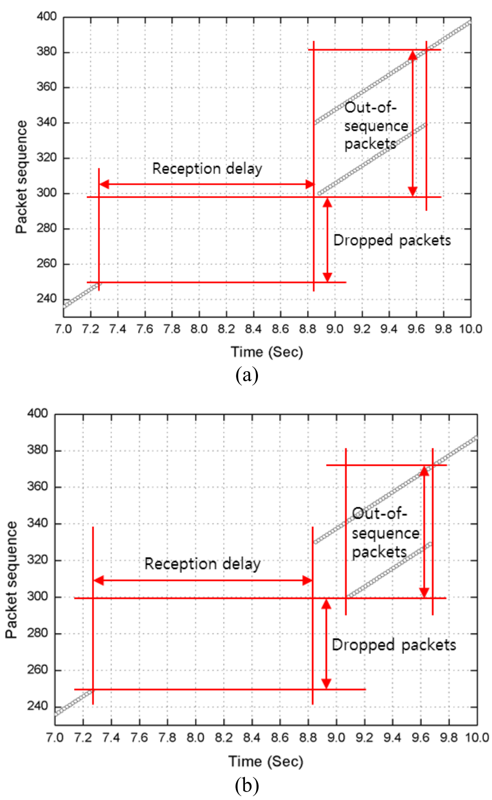

FIGURE 12. Simulation results while changing OTP value. (a) OTP = 0.5. (b) OTP = 0.8.

In addition, 49 packets were lost. It incurred 0.0947 seconds of packet reception delay.

Figure 12 shows the simulation results when OTP is set to 0.5 (a) and 0.8 (b), respectively, in the OTP scheme. 41 out-of-sequence packets occurred when OTP was set to 0.5. 50 packets were lost and it incurred 1.2 seconds of packet reception delay during handover. When OPT was set to 0.8, 30 out-of-sequence packets occurred. 50 packets were lost and it incurred 1.82 seconds of packet reception delay during handover. The out-of-sequence packets decreased when OTP increases, but the packet reception delay increased.

Figure 13 is the simulation results of our proposed scheme. The results show the cases where the last packet from the old path are lost and not lost, respectively. Out-of-sequence

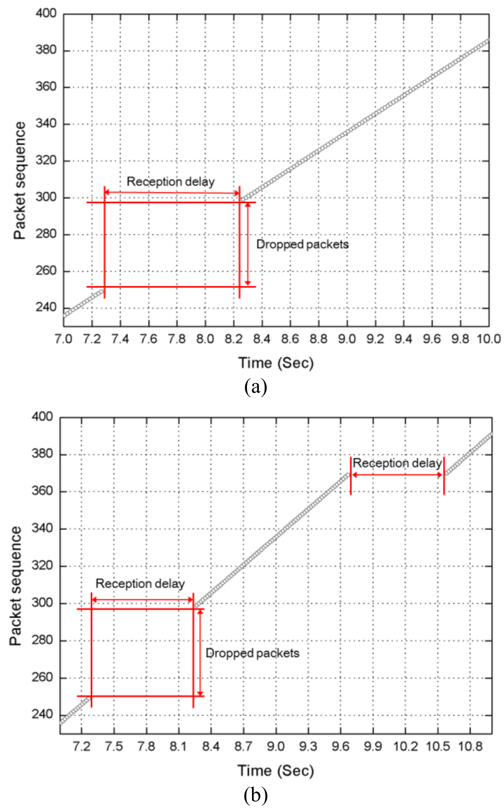

FIGURE 13. Simulation results of proposed scheme. (a) Not loss. (b) Loss.

TABLE 2. Simulation results.

Scheme	Out-of-sequence	Packet drop	Reception delay (sec.)
PIMPv6	66	49	0.947
OTP=0.5	41	50	1.520
OTP=0.8	30	50	1.820
Proposed (not loss)	0	50	0.947
Proposed (loss)	0	50	1.915

will not be incurred, if no packets are lost from the old path. The packets lost and reception delay are the same as in the RO supported PMIPv6. Even if the last packet from the old path are lost, the out-of-sequence packets will not occur, but approximately 1.91 seconds of receiving packet delay is incurred, because it transmits stored packets in the buffer, as much as T_{wait}.

Table 2 shows the simulation results of each scheme. The three compared schemes in the simulation incurred a similar number of lost packets, because they do not have a function to prevent packet loss. The OTP scheme decreases the packet loss compared to the RO supported PMIPv6, but it increases reception delay. However, it prevents all out-of-sequence packets when the RO path is established, because our proposed scheme uses the packet sequence number. If the last packet from the old path is not lost, the delay time is the same as in the RO supported PMIPv6. Our proposed scheme prevents the out-of-sequence problem and supports reliable service more effectively.

C. TESTBED ENVIRONMENT

We establish the PMIPv6 testbed and do experimental work to observe the performance. Our testbed is based on Open Air Interface (OAI) PMIPv6 v0.3 [16]. To establish the testbed for the RO supported PMIPv6 and our proposed scheme, we use Ubuntu 10.04 and C language. Figure 14 represents the topology of our testbed. It includes 2 LMAs, 3MAGs, and MN and CN. MAG1 and MAG2 are connected to LMA1, and MAG3 is connected to LMA2. The MN and CN are connected to MAG1 and MAG3 respectively. The MN sends 200 packets to the CN in a second. Then the MN roams to MAG2 domain, which causes handover latency of 1 second. We use a hub rather than an AP for the wireless link, and connect the MN to MAG with a cable. Although we can obtain the same results in a wireless environment as in a wired environment, the reason to use a cable is to minimize the signal interference and the effect of signaling size in a wireless environment.

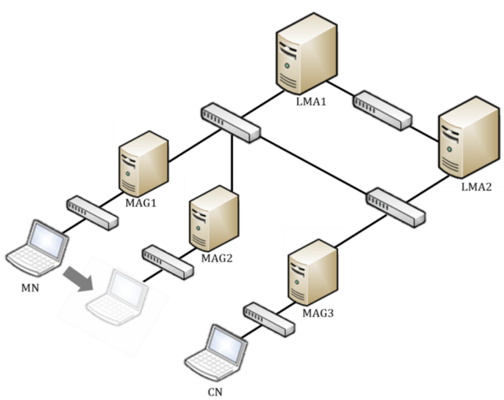

FIGURE 14. Network topology of testbed.

We also regard unified handover time by clarifying the start and end points of the handover in each case within the same environmental conditions. We develop the RO module to establish the RO supported PMIPv6 testbed. In the module, the messages for route optimization such as RO trigger, RO init, and RO Ack, are defined. The LMAs also transfer another message, which is also newly defined for LMAs to share information of MNs in their domain, with each other when MN attaches. We need to use this message because the LMAs in the RO scheme are assumed to share information of MNs in their domain each other. We add the tunneling and packet routing functions for RO path between MAGs to the module.

To establish the testbed for our proposed scheme, MAGs needs packet buffering function. For this, we implement the packet buffering module which uses Netfilter and IP6Tables to hook packets. The Netfilter is a packet filtering framework embedded in Linux kernel 2.4.x and 2.6.x version. It provides hook handlings or hook points for intercepting and manipulating network packets. IP6Tables utility is a tool in user space to provide hook handlers for the hook points of Netfilter. The packet buffering module adds a rule to the IP6Tables to decide which packet should be buffered, and hooks packets through the RO path by using the Netfilter. It also stores the hooked packets by using Libipq library in IP-Tables tool in user space. We finish the implementation of our proposed scheme by adding packet forwarding function, which performs packet forwarding when the MAG receives the last packet through the old path or buffering time, which have been set in advance is over. In our testbed, the MAG3 connected to the CN performs buffering packets from the RO path.

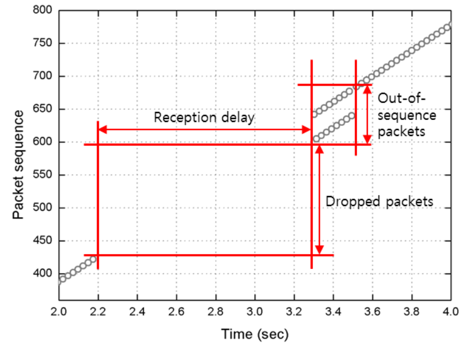

FIGURE 15. RO supported PMIPv6.

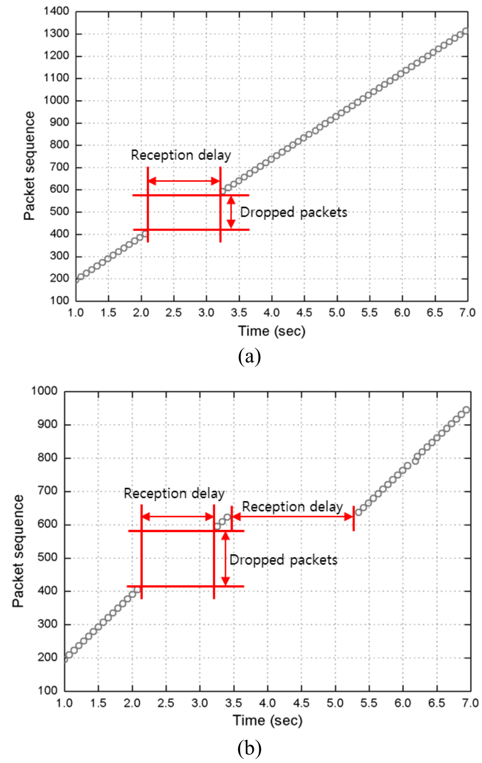

FIGURE 16. Testbed results of proposed scheme. (a) Not loss. (b) Loss.

D. TESTBED RESULT

Figure 15 shows the testbed results of the RO supported PMIPv6. This scheme cannot prevent out-of-sequence packets. We disconnect the MN from the MAG1 and move it to the MAG2. The handover latency is 1 second and 178 packets are lost during the MN's handover. After the MN's handover, the MN begins to receive packets, but 78 out-of-sequence packets are generated right after the RO path is established. As referring to Figure 15, we can see that the RO supported PMIPv6 generates out-of-sequence packets due to the gap of packet transmission latency between the old and RO path in real environment.

Figure 16 is the testbed results of our proposed scheme. The simulation results show the cases where the last packet from the old path is lost and where not lost. Through Figure 16(a), we can see that there are no out-of-sequence packets unless packets are lost in the old path. The implemented packet buffering module performs buffering packets through the RO path, and forwards them when the last packet through the old path arrives. When packets are lost from the old path, the reception delay for 1.88 seconds occurs as Figure 16(b) represents. That is because the MAG should wait for T_{wait} to decide whether packets are lost or not from the old path. However, the out-of-sequence packets are not generated during the measurement time.

VI. CONCLUSION

The difference of the transmission delay between the old path and the RO path generates the out-of-sequence problem in PMIPv6. To solve this problem, several types of literature suggested sophisticate algorithms, but they did not solve the problem entirely. For that reason, we proposed a new algorithm that provides reliable service for MN more accurately. We use the packet sequence number that reduces the forwarding delay time. To evaluate our scheme, we compare with the well-known RO supported PMIPv6 and the OTP scheme via computer simulation and testbed measurement. Our proposed scheme solved the out-of-sequence problem in both case (simulation and system measurement). Furthermore, we saw that our scheme reduced the packet reception delay after the RO path is established. It can be possible to provide a reliable service in PMIPv6 RO by adapting our proposed scheme.

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