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Research Article

Distributed Mobility Management in 6LoWPAN-Based Wireless Sensor Networks

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In 6LoWPAN networks, several mobility management schemes have been proposed based on Mobile IPv6 (MIPv6) and Proxy Mobile IPv6 (PMIPv6). However, the existing schemes are centralized, and thus they have many serious drawbacks such as nonoptimal data route, injection of unwanted data traffics into core networks, increased cost of network engineering, and large registration and handover delays. To overcome these limitations, we propose new distributed mobility management schemes for 6LoWPAN networks. In the proposed schemes, Home Agent (HA), Local Mobility Anchor (LMA), and Mobile Access Gateway (MAG) functions are implemented in 6LoWPAN gateways, and the handover operations are performed directly between two neighboring 6LoWPAN gateways. By numerical analysis, we show that the proposed distributed schemes can significantly reduce the registration and handover delays, compared to the existing centralized mobility schemes.

1. Introduction

Currently, some sensor network protocols do not use TCP/IP [1], such as ZigBee [2]. However, future sensor networks may be connected to others network via the Internet. Hence, an Internet Protocol (IPv6) [3] is the best solution for the future sensor network because of efficient addressing mechanism.

Recently, the IPv6 over Low power Wireless Personal Area Network (6LoWPAN) has been discussed by IETF [4, 5], which uses the IEEE 802.15.4 interfaces [6]. The protocol enables the wireless sensors on a physical object to be connected to IPv6 networks efficiently. However, to deliver data packets over mobile wireless networks, the sensors need a support from the mobility management scheme.

Many IPv6-based mobility management protocols have attracted much interest in 6LoWPAN networks. We can classify the protocols into the host-based schemes and the network-based schemes. For example, Mobile IPv6 (MIPv6) is a host-based protocol [7] and Proxy Mobile IPv6 (PMIPv6) is a network-based protocol [8]. In host-based mobility schemes, when a Mobile Sensor Node (MSN) moves from one mobility domain to another, the protocols require the exchange of Binding Update (BU) and Binding Acknowledgement (BA) messages with its Home Agent (HA) in order to continue the session. On the other hand, in network-based mobility schemes, when an MSN changes the domain, the protocols do not require any mobility-related signaling. Instead, a Mobile Access Gateway (MAG) is responsible for detecting movement and exchanging signaling messages on behalf of the MSN.

The protocols explained are Centralized Mobility Management (CMM) approaches, in which HA and/or Local Management Anchor (LMA) plays the role of a centralized mobility agents that process all the control and data packets. The centralized agents allow an MSN to be reachable from other nodes even when it is away from the home domain, by forwarding the data packets to and from the MSN. However, CMM schemes are vulnerable to many problems. First, the centralized mobility agents induce undesired control and data traffic into the core network, which can be a big burden

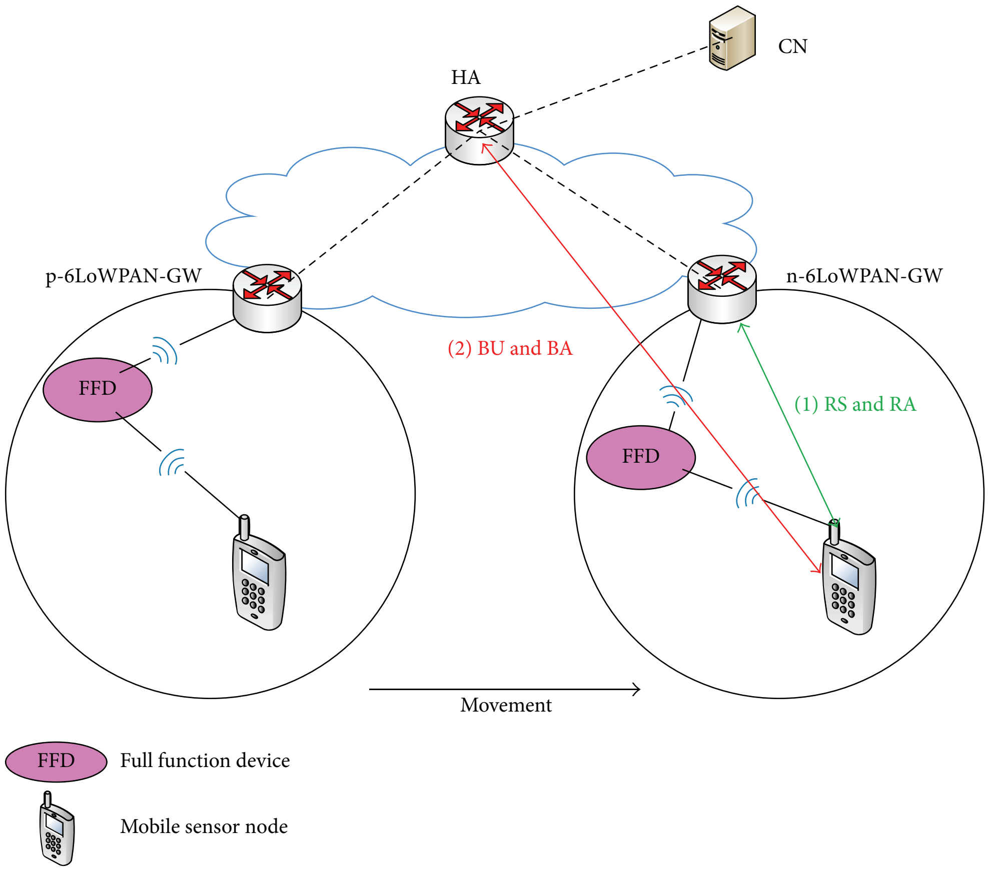

Figure 1: Overview of host-based CMM in 6LoWPAN networks.

to network service providers increasing the operational cost. In addition, a single point of failure problem can incur a serious performance degradation of the overall system and raise the network engineering cost. Further, the centralized schemes suffer from large registration and handover delays. To resolve the limitations of CMM schemes, IETF has begun to discuss the Distributed Mobility Management (DMM) recently [9–11].

In this paper, we propose the IPv6-based DMM schemes for the 6LoWPAN wireless sensor networks. In our proposed schemes, HA, LMA, and MAG functions are combined into the 6LoWPAN gateway, denoted as 6LoWPAN-GW, and the handover operation is directly performed between the two neighboring 6LoWPAN-GWs. Our schemes provide the optimal data routes and reduce the registration and handover delays.

The rest of this paper is organized as follows. In Section 2, we review the existing CMM schemes for 6LoWPAN networks and in Section 3, we describe the proposed DMM schemes in detail. The performances of the considered schemes are analyzed in Section 4 in terms of the registration delay and the handover delay. We provide the numerical results and discuss them in Section 5. Finally, we conclude this research in Section 6.

2. Related Work

In this section, we illustrate the previous CMM schemes for 6LoWPAN wireless sensor networks, which are classified as the host-based CMM (HCMM) and the network-based CMM (NCMM), respectively.

2.1. Host-Based CMM in 6LoWPAN Networks (HCMM-6LoWPAN) [12]. We denote the host-based CMM in 6LoWPAN networks as HCMM-6LoWPAN. In this scheme, when an MSN moves from one mobility domain to another, it sends a *Router Solicitation* (RS) message to the new gateway, n-6LoWPAN-GW, as in Figure 1. Upon the reception of the RS message, the n-6LoWPAN-GW responds with *Router Advertisement* (RA) message to the MSN (Step 1). As the next step, the MSN exchanges the *Binding Update* (BU) message and the corresponding *Binding Acknowledgement* (BA) message with HA (Step 2). The messages between MSN and 6LoWPAN-GW (or HA) are exchanged via the Full Function Device (FFD) rather than directly. Now the MSN can communicate with the Corresponding Node (CN) over the Internet.

In the similar context, Hierarchical Mobile IPv6 (HMIPv6) has been proposed to reduce the mobility-related

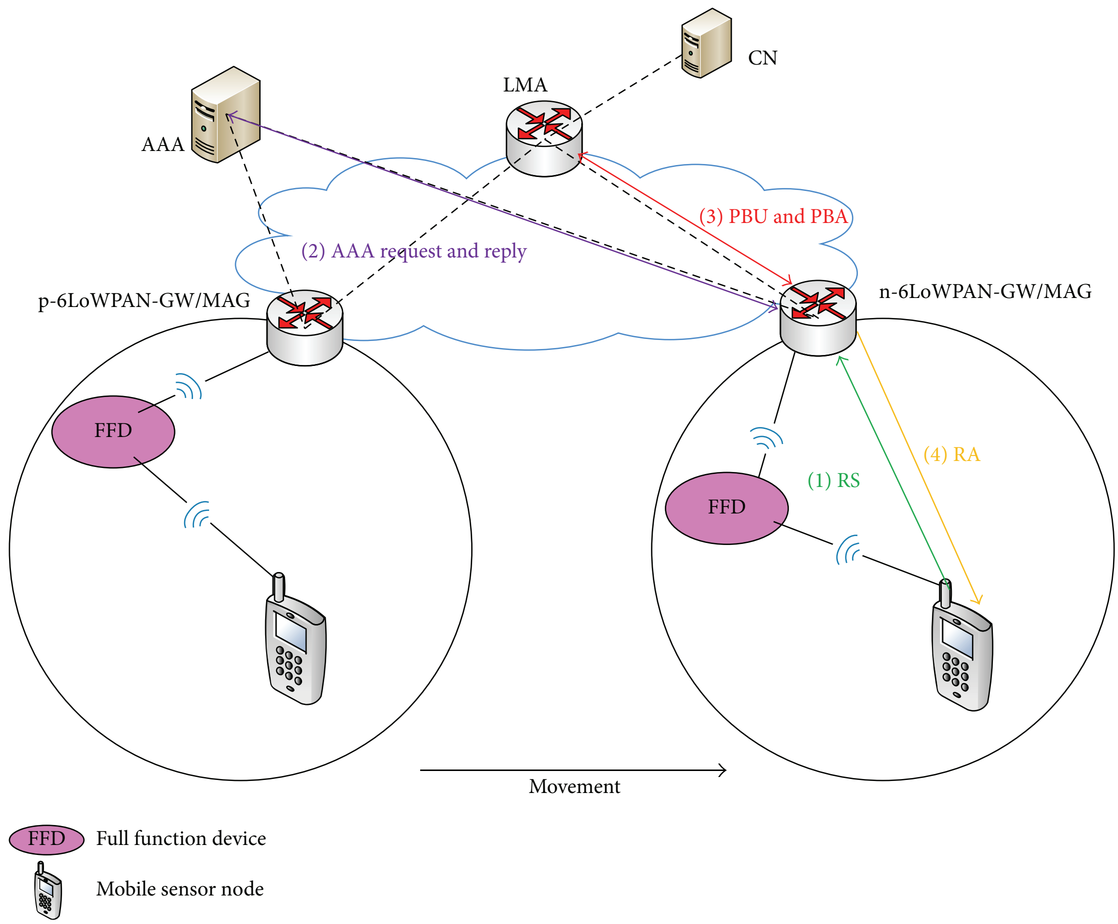

Figure 2: Overview of network-based CMM in 6LoWPAN networks.

signaling messages [13, 14]. It introduces a new mobility entity called Mobile Anchor Point (MAP), which acts as a local HA and improves the network performance, especially the intradomain handover and signaling delays. However, as a cost, it increases the signaling overhead substantially because each MSN should perform both local binding with MAP and the global binding with HA. So in the interdomain mobility scenario, we consider the MIPv6-based scheme as the basic one instead of the HMIPv6-based scheme.

2.2. Network-Based CMM in 6LoWPAN Networks (NCMM-6LoWPAN). As an alternative to HCMM, we can consider the network-based CMM scheme, which will be denoted as NCMM-6LoWPAN. The NCMM scheme is more suitable for wireless networks because it does not consume the scarce wireless bandwidth by mobility-related signaling messages and does not require the duplicate address detection procedure to configure the care-of-address, the temporary identifier for the current mobility domain.

The conventional PMIPv6 [8] did not support the multihop based 6LoWPAN. If MSN enters the multihop based Personal Area Network (PAN) area, then there is no way for MSN to inform the MAG for PAN attachment. In order to solve the multihop communication problem, [15] proposed the intra-PAN mobility schemes for 6LoWPAN network by using the static nodes within an intra-PAN area. However, this solution only supports intra-PAN mobility. The works in [16] proposed both intra-PAN and inter-PAN mobility scenarios by using the 6LoWPAN gateways (6LoGWs). Each 6LoGW acts as MAG and has a unique PAN identifier (PAN ID). The 6LoGWs manage the mobility-related signaling on behalf of MSN.

In the NCMM scheme [16], if an MSN moves from one mobility domain to another as in Figure 2, the MSN sends an RS message to the new 6-LoWPAN-GW/MAG, denoted as n-6LoWPAN-GW/MAG (Step 1). When the n-6LoWPAN-GW/MAG receives the RS message from the MSN, it sends an *AAA request* message to the AAA server to authenticate the MSN. If the authentication is successful, the server responds to the n-6LoWPAN-GW/MAG by an *AAA reply* message, which contains the address of LMA (Step 2). Then, the n-6LoWPAN-GW/MAG sends a *Proxy Binding Update* (PBU) message to the LMA for the MSN, and the LMA returns *Proxy Binding Acknowledgement* (PBA) message (Step 3). Finally, n-6LoWPAN-GW/MAG responds to the MSN with an RA message (Step 4).

Table 1: Comparison of mobility management architectures.

Architectures	HCMM-6LoWPAN	NCMM-6LoWPAN	HDMM-6LoWPAN	NDMM-6LoWPAN
Relevant protocols	MIP [12]	PMIP [16]	Proposed scheme	Proposed scheme
Mobility agent	HA	LMA	6LoWPAN-GW/HA	6LoWPAN-GW/MAG/LMA
Mobility control model	Centralized	Centralized	Distributed	Distributed

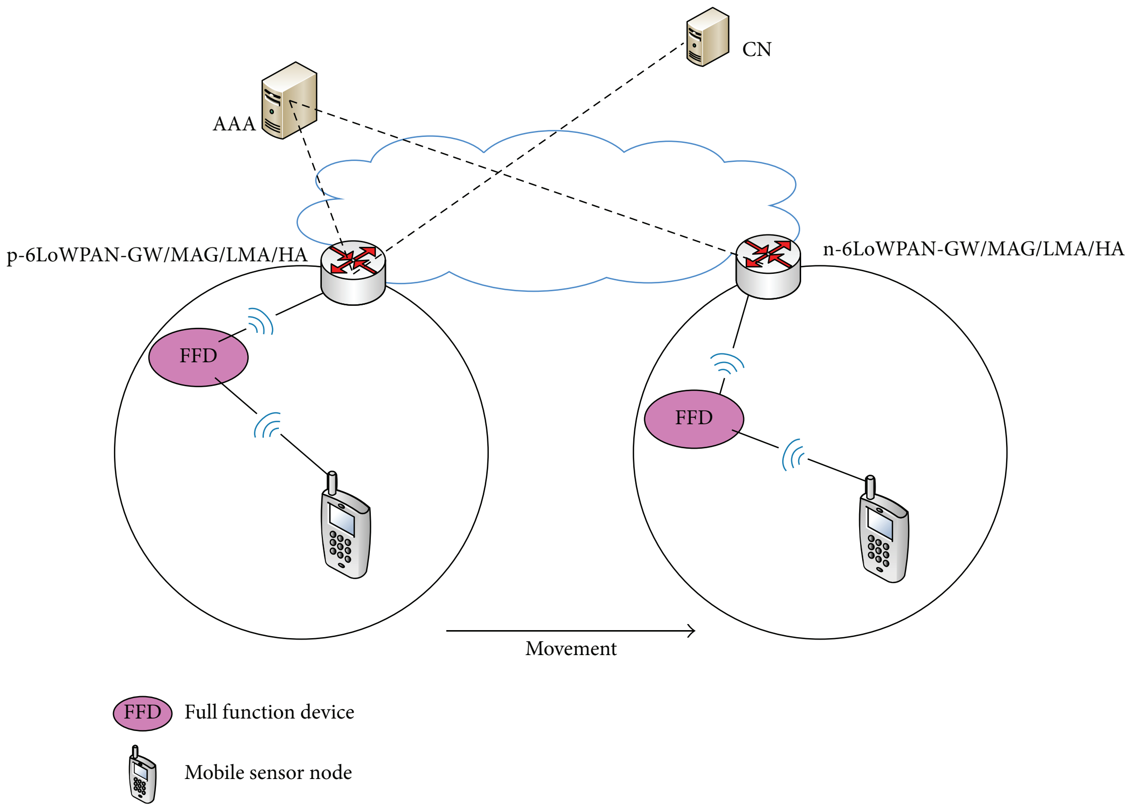

Figure 3: Network model for the proposed schemes.

3. Proposed Schemes

In this section, we describe the proposed distributed mobility management schemes. To this end, first we need to specify the network model.

3.1. Network Model. Figure 3 shows the network model for the proposed schemes. We assume that an MSN is attached to the FFD. Each 6LoWPAN-GW incorporates the functions of HA for the host-based scheme and the functions of MAG/LMA for the network-based scheme, respectively. In this sense, we denote the new entity as 6LoWPAN-GW/MAG/LMA/HA temporarily. In the considered scenario, MSN initially communicates with CN via the previous 6LoWPAN-GW/MAG/LMA/HA, denoted by p-6LoWPAN-GW/MAG/LMA/HA, and then it hands over to the new n-6LoWPAN-GW/MAG/LMA/HA.

3.2. Comparison of CMM and DMM. Before describing the proposed schemes in detail, we compare the considered mobility management schemes in the architectural perspective in Table 1.

In the viewpoint of the mobility management, MIP and PMIP are the CMM architectures, in which all the control and data traffic are processed by a centralized agent such as HA and LMA. Data packets are delivered to the centralized agents first and forwarded to the corresponding host. The centralized agents, HA and LMA, manage the mobility of MSNs. On the other hand, in the proposed schemes, such centralized agents are not used any more. Instead, each 6LoWPAN-GW acts as HA and MAG/LMA as described in the subsequent sections.

3.3. Host-Based DMM in 6LoWPAN Networks (HDMM-6LoWPAN)

3.3.1. Initial Registration. The initial registration procedure of the host-based DMM scheme is shown in Figure 4.

In this scheme, HA function is implemented in the 6LoWPAN-GW together, so we denote the entity as 6LoWPAN-GW/HA. When an MSN is attached to a 6LoWPAN-GW/HA, the MSN sends a *Router Solicitation* (RS) message to the 6LoWPAN-GW/HA (Step 1). As soon as

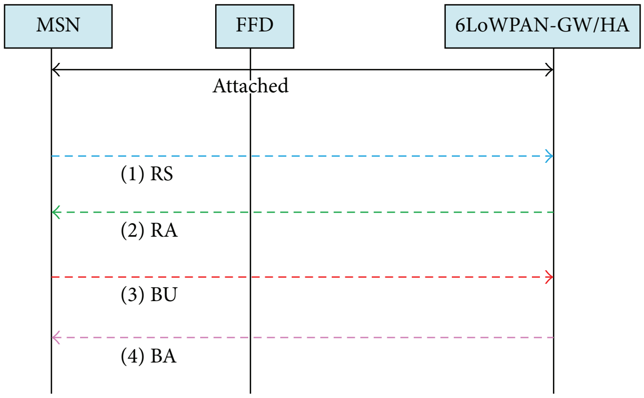

Figure 4: Initial registration procedure of HDMM-6LoWPAN.

the 6LoWPAN-GW/HA receives the RS message, it returns a *Router Advertisement* (RA) message to the corresponding MSN (Step 2). Subsequently the MSN sends a *Binding Update* (BU) message to the 6LoWPAN-GW/HA (Step 3), and the 6LoWPAN-GW/HA responds with a *Binding Acknowledgement* (BA) message to the MSN (Step 4).

3.3.2. Handover Operation. When an MSN is detached from the previous 6LoWPAN/HA (p-6LoWPAN/HA) and attached to the new 6LoWPAN/HA (n-6LoWPAN/HA) as Figure 5, the MSN sends an RS message to the n-6LoWPAN/HA (Step 1). As a response, the n-6LoWPAN/HA returns an RA message to the MSN (Step 2). Then, the MSN sends a BU message to the n-6LoWPAN-GW/HA (Step 3). Note that the BU message carries the address of MSN configured at the previous gateway and the address obtained at the new gateway. The n-6LoWPAN-GW/HA exchanges the BU and BA messages with the p-6LoWPAN-GW/HA while setting up the handover tunnel (Steps 4 and 5). Finally, the n-6LoWPAN-GW/HA responds to the MSN with the BA message (Step 6).

Figure 6 shows a HDMM-6LoWPAN procedure of 6LoWPAN-GW/HA. When a 6LoWPAN-GW/HA receives a BU signaling message from MSN, the 6LoWPAN-GW/HA determines whether the MSN is in the binding update list or not. If the MSN is a new one, the 6LoWPAN-GW/HA creates a new entry for the MSN in the binding update list. After that, the location of the MSN should be determined and updated. If the MSN is not a new one, then 6LoWPAN-GW/HA will only update location of MSN in the binding update list.

3.4. Network-Based DMM in 6LoWPAN Networks (NDMM-6LoWPAN)

3.4.1. Initial Registration. Figure 7 illustrates the initial registration procedure of the network-based DMM scheme. When an MSN is attached to a 6LoWPAN-GW/MAG/LMA, the MSN sends an RS message to the 6LoWPAN-GW/MAG/LMA (Step 1). Receiving the RS message, the 6LoWPAN-GW/MAG/LMA sends an *AAA request* message to the AAA server to authenticate the MSN. After completing the authentication, the server returns an *AAA reply* message to the 6LoWPAN-GW/MAG/LMA (Steps 2 and 3). Then, 6LoWPAN-GW/MAG/LMA provides an RA message to the MSN for the initial RS message (Step 4).

3.4.2. Handover Operation. When an MSN is detached from a previous p-6LoWPAN-GW/MAG/LMA and attached to a new n-6LoWPAN-GW/MAG/LMA as Figure 8, the MSN sends an RS message to the n-6LoWPAN-GW/MAG/LMA (Step 1). Triggered by the RS message, the n-6LoWPAN-GW/MAG/LMA exchanges the *AAA request* and *reply* messages with the AAA server (Steps 2 and 3). After authentication, the n-6LoWPAN-GW/MAG/LMA exchanges the *Proxy Binding Update* (PBU) and *Proxy Binding Acknowledgement* (PBA) messages with the p-6LoWPAN-GW/MAG/LMA for handover control (Steps 4 and 5). The n-6LoWPAN-GW/MAG/LMA reads the address of the p-6LoWPAN-GW/MAG/LMA from the initial RS message and, using the information, it establishes the handover tunnel with p-6LoWPAN-GW/MAG/LMA. As a final step, n-6LoWPAN-GW/MAG/LMA sends an RA message to the MSN (Step 6).

Figure 9 shows a NDMM-6LoWPAN procedure of 6LoWPAN-GW/MAG/LMA. When a 6LoWPAN-GW/MAG/LMA detects MSN movement, the 6LoWPAN-GW/MAG/LMA determines whether the MSN is in the binding update list or not. If the MSN is a new one, the 6LoWPAN-GW/MAG/LMA creates a new entry for the MSN in the binding update list. After that, the location of the MSN should be determined and updated. If the MSN is not a new one, then 6LoWPAN-GW/MAG/LMA will only update location of MSN in the binding update list.

4. Performance Analysis

We compare the registration delay and the handover delay of the four considered mobility management schemes, that is, HCMM-6LoWPAN, NCMM-6LoWPAN, HDMM-6LoWPAN, and NDMM-6LoWPAN, because the delays are the key performance metrics.

4.1. Analysis Model. We define several notations for the analysis and summarize them in Notations section. We illustrate the considered network model in Figure 10.

In Figure 10, we denote by $T_{x-y}(S)$ the transmission delay of a message with size S from node x to node y via a *wireless* link, where each message can experience the failure at the probability of q by using "*iid*" error model. It can be expressed as $T_{x-y}(S) = 1/(1-q) \cdot (S/B_{\text{wl}} + L_{\text{wl}})$. In the meantime, we denote by $T_{x-y}(S, H_{x-y})$ the transmission delay of a message with size S from node x to node y via a *wired* link, where H_{x-y} represents the number of wired hops between node x to node y. Note that it is expressed as $T_{x-y}(S, H_{x-y}) = H_{x-y} \cdot (S/B_w + L_w + T_q)$.

4.2. Analysis of Registration Delay

4.2.1. HCMM-6LoWPAN. As shown in Figure 1, when an MSN is attached to a 6LoWPAN-GW, it sends an RS message

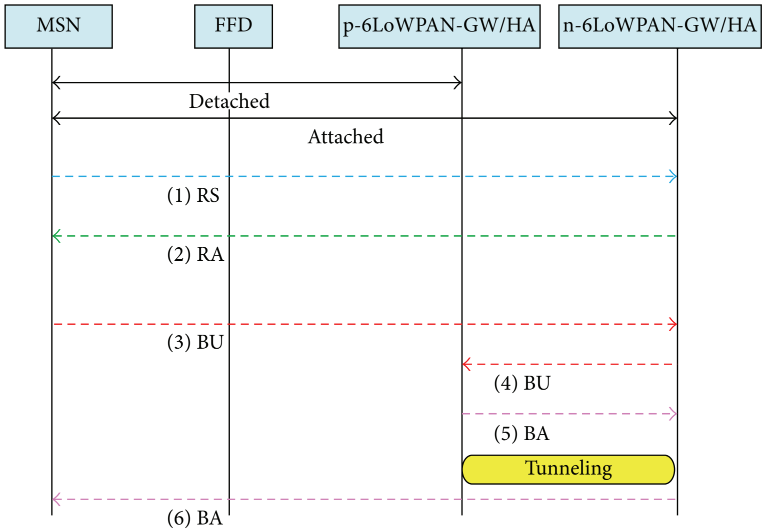

Figure 5: Handover operation of HDMM-6LoWPAN.

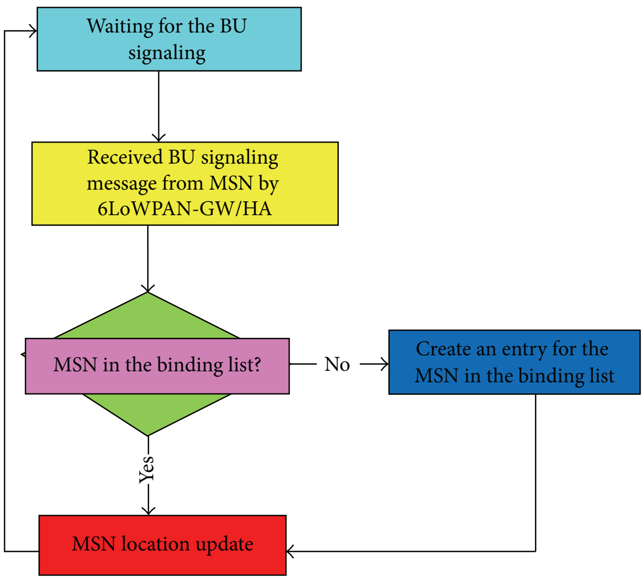

Figure 6: HDMM-6LoWPAN procedure of 6LoWPAN-GW/HA.

to the 6LoWPAN-GW via FFD, and the 6LoWPAN-GW responds with an RA message to the MSN. Then, the MSN exchanges the BU and BA messages with HA. Accordingly, the registration delay of HCMM-6LoWPAN is given by

$$\begin{aligned} \mathrm{RD}_{\text{HCMM-6LoWPAN}} &= 4T_{\text{MSN-FFD}}\left(S_c\right) + 4T_{\text{FFD-GW}}\left(S_c\right) \\ &\quad + 2T_{\text{GW-HA}}\left(S_c, H_{\text{GW-HA}}\right). \end{aligned} \tag{1}$$

4.2.2. NCMM-6LoWPAN. When an MSN is attached to a 6LoWPAN-GW/MAG, it sends an RS message to the 6LoWPAN-GW/MAG via FFD (See Figure 2). Then, the 6LoWPAN-GW/MAG performs the *AAA request* and *reply* operations with the AAA server. As a next step, the 6LoWPAN-GW/MAG exchanges the PBU and PBA messages with LMA. Right after receiving the PBA message, the 6LoWPAN-GW/MAG returns an RA message to the MSN. Thus, the registration delay of NCMM-6LoWPAN is given by

$$\begin{aligned} \mathrm{RD}_{\text{NCMM-6LoWPAN}} &= 2T_{\text{MSN-FFD}}\left(S_c\right) + 2T_{\text{FFD-GW}}\left(S_c\right) \\ &\quad + 2T_{\text{GW-LMA}}\left(S_c, H_{\text{GW-LMA}}\right) \\ &\quad + 2T_{\text{GW-AAA}}\left(S_c, H_{\text{GW-AAA}}\right). \end{aligned} \tag{2}$$

4.2.3. HDMM-6LoWPAN. As Figure 4, if an MSN is attached to a 6LoWPAN-GW/HA, the MSN sends an RS message to the 6LoWPAN-GW/HA via FFD, and the 6LoWPAN-GW/HA replies to the MSN by an RA message. Then the MSN performs the BU and BA operation with 6LoWPAN-GW/HA, and the registration completes. So we get the registration delay of HDMM-6LoWPAN as

$$\mathrm{RD}_{\text{HDMM-6LoWPAN}} = 4T_{\text{MSN-FFD}}\left(S_c\right) + 4T_{\text{FFD-GW}}\left(S_c\right). \tag{3}$$

4.2.4. NDMM-6LoWPAN. As shown in Figure 7, when an MSN is attached to a 6LoWPAN-GW/MAG/LMA, it sends an RS message to the 6LoWPAN-GW/MAG/LMA via FFD. Then, the 6LoWPAN-GW/MAG/LMA performs the AAA request and reply operation with the AAA server. After authentication, the 6LoWPAN-GW/MAG/LMA responds to the MSN as an RA message. Thus, the registration delay of NDMM-6LoWPAN is written as

$$\begin{aligned} \mathrm{RD}_{\text{NDMM-6LoWPAN}} &= 2T_{\text{MSN-FFD}}\left(S_c\right) + 2T_{\text{FFD-GW}}\left(S_c\right) \\ &\quad + 2T_{\text{GW-AAA}}\left(S_c, H_{\text{GW-AAA}}\right). \end{aligned} \tag{4}$$

4.3. Analysis of Handover Delay. The handover delay is defined as the interval between the time when an MSN cannot receive the packets from p-6LoWPAN-GW/MAG/LMA/HA and the time when the MSN receives the first packet from n-6LoWPAN-GW/MAG/LMA/HA.

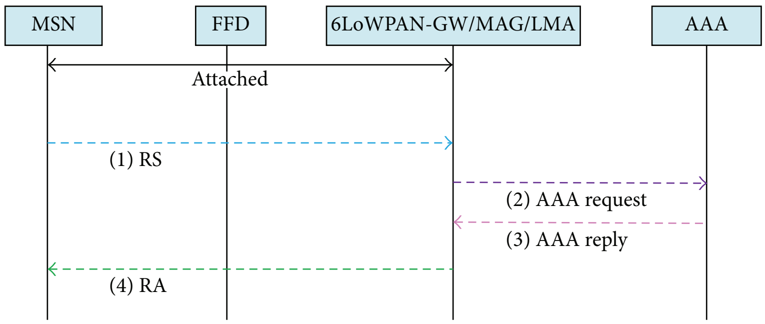

FIGURE 7: Initial registration procedure of NDMM-6LoWPAN.

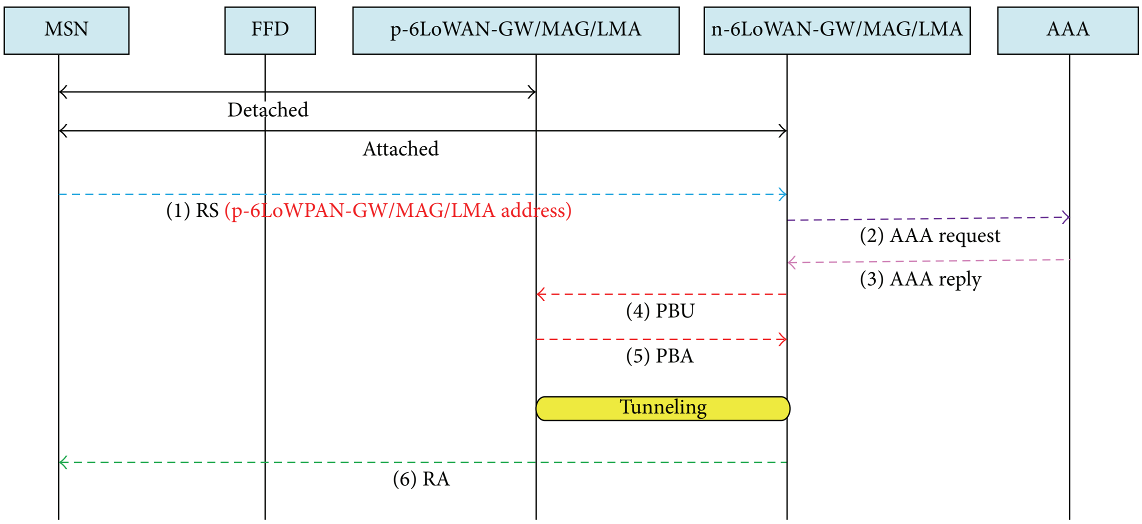

FIGURE 8: Handover operation of NDMM-6LoWPAN.

4.3.1. HCMM-6LoWPAN. An MSN is attached to an n-6LoWPAN-GW and sends an RS message to the n-6LoWPAN-GW via FFD. The n-6LoWPAN-GW responds with an RA message to the MSN. To ensure the uniqueness of the configured care-of-address, the MSN needs to perform the duplicate address detection procedure with the n-6LoWPAN-GW [17], which spends the time of T_{DAD}. Next, the MSN exchanges the BU and BA messages with HA. Data packets are now delivered to the MSN by way of the n-6LoWPAN-GW. So, we analyze the handover delay of HCMM-6LoWPAN as

$$\begin{aligned} \mathrm{HD}_{\text{HCMM-6LoWPAN}} = {} & T_{\mathrm{DAD}} + 4T_{\text{MSN-FFD}}(S_c) \\ & + 4T_{\text{FFD-GW}}(S_c) \\ & + 2T_{\text{GW-HA}}(S_c, H_{\text{GW-HA}}) \\ & + T_{\text{GW-HA}}(S_d, H_{\text{GW-HA}}). \end{aligned} \tag{5}$$

4.3.2. NCMM-6LoWPAN. When an MSN is attached to an n-6LoWPAN-GW/MAG, it sends an RS message to the n-6LoWPAN-GW/MAG via FFD. The n-6LoWPAN-GW/MAG exchanges the *AAA request* and *reply* messages with the AAA server, and it performs the PBU and PBA operation with LMA. Based on the received PBA message, the n-6LoWPAN-GW/MAG builds and returns an RA message to the MSN. Data packets are now delivered to MSN via n-6LoWPAN-GW/MAG. The handover delay of NCMM-6LoWPAN is written as

$$\begin{aligned} \mathrm{HD}_{\text{NCMM-6LoWPAN}} = {} & 2T_{\text{MSN-FFD}}(S_c) + 2T_{\text{FFD-GW}}(S_c) \\ & + 2T_{\text{GW-LMA}}(S_c, H_{\text{GW-LMA}}) \\ & + 2T_{\text{GW-AAA}}(S_c, H_{\text{GW-AAA}}) \\ & + T_{\text{GW-LMA}}(S_d, H_{\text{GW-LMA}}). \end{aligned} \tag{6}$$

4.3.3. HDMM-6LoWPAN. Suppose that an MSN is attached to an n-6LoWPAN-GW/HA. The MSN sends an RS message to the n-6LoWPAN-GW/HA via FFD, and the n-6LoWPAN-GW/HA responds with an RA message to the MSN. To ensure that a configured care-of-address is unique on the new link, the MSN performs the duplicate address detection procedure, spending the time of T_{DAD}. Subsequently the MSN sends a BU message to the n-6LoWPAN-GW/HA, which contains the address of p-6LoWPAN-GW/HA, and the n-6LoWPAN-GW/HA exchanges the BU and BA messages with the p-6LoWPAN-GW/HA. The handover tunnel is established and

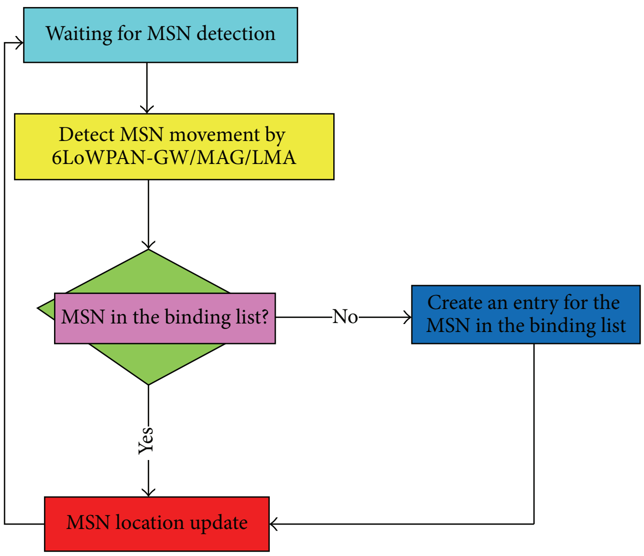

Figure 9: NDMM-6LoWPAN procedure of 6LoWPAN-GW/MAG/LMA.

the n-6LoWPAN-GW/HA returns a BA message to the MSN. Now the data packets can be delivered to the MSN via the n-6LoWPAN-GW. Accordingly, we obtain the handover delay of HDMM-6LoWPAN as follows:

$$\begin{aligned} \mathrm{HD}_{\text{HDMM-6LoWPAN}} &= T_{\text{DAD}} + 4T_{\text{MSN-FFD}}\left(S_c\right) \\ &\quad + 4T_{\text{FFD-GW}}\left(S_c\right) \\ &\quad + 2T_{\text{GW-GW}}\left(S_c, H_{\text{GW-GW}}\right) \\ &\quad + T_{\text{GW-GW}}\left(S_d, H_{\text{GW-GW}}\right). \end{aligned} \quad (7)$$

4.3.4. NDMM-6LoWPAN. In the NDMM-6LoWPAN scheme, the MSN attached to an n-6LoWPAN-GW/MAG/LMA sends an RS message to the n-6LoWPAN-GW/MAG/LMA via FFD. In the following, the n-6LoWPAN-GW/MAG/LMA exchanges the *AAA request* and *reply* messages with the AAA server. Moreover, the n-6LoWPAN-GW/MAG/LMA performs the PBU and PBA operation with the p-6LoWPAN-GW/MAG/LMA to establish the handover tunnel. So, the handover delay of NDMM-6LoWPAN is written as

$$\begin{aligned} \mathrm{HD}_{\text{NDMM-6LoWPAN}} &= 2T_{\text{MSN-FFD}}\left(S_c\right) + 2T_{\text{FFD-GW}}\left(S_c\right) \\ &\quad + 2T_{\text{GW-AAA}}\left(S_c, H_{\text{GW-AAA}}\right) \\ &\quad + 2T_{\text{GW-GW}}\left(S_c, H_{\text{GW-GW}}\right) \\ &\quad + T_{\text{GW-GW}}\left(S_d, H_{\text{GW-GW}}\right). \end{aligned} \quad (8)$$

5. Numerical Results and Discussion

Based on the analytical equations given in Section 4, we compare the performances of the considered mobility management schemes. In the numerical results, the default value of each parameter has been configured as follows: referring to [18]; that is, $H_{\text{GW-LMA/HA}} = 10$, $H_{\text{GW-GW}} = \sqrt{N_{\text{GW}}}$, $H_{\text{GW-AAA}} = 5$, and $L_{\text{wl}} = 10$ (ms), $L_w = 2$ (ms), $q = 0.5$, $N_{\text{GW}} = 30$, $T_q = 5$ (ms), $S_c = 96$ (bytes), $S_d = 200$ (bytes), $B_{\text{wl}} = 11$ (Mbps), and $B_w = 100$ (Mbps), where N_{GW} denotes the number of gateways in the network. Among the various parameters, we note that L_{wl}, T_q, L_w, N_{GW}, and $H_{\text{GW-LMA/HA}}$ can depend on the network conditions. Thus, we evaluate the performances of the considered schemes by varying the values of these parameters.

5.1. Registration Delay. We show the impact of the delay of wireless links (L_{wl}) on the registration delay in Figure 11. We can see that the registration delay increases linearly as L_{wl} becomes larger in every considered scheme. Particularly, the host-based mobility schemes are more sensitive to the delay of wireless links than the network-based mobility schemes since they exchange the signaling messages for the registration over wireless links. We observe that the NDMM-6LoWPAN performs best in the candidate schemes.

Figures 12 and 13 compare the registration delay of each scheme varying the average queuing delay (T_q) at each node and the delay of wired links (L_w). For the three schemes, HCMM-6LoWPAN, NCMM-6LoWPAN, and NDMM-6LoWPAN, the registration delay increases linearly as T_q and L_w increase because the three schemes exchange the signaling messages with AAA, LMA, and HA over the wired network. In contrast, HDMM-6LoWPAN is not affected by the average queuing delay and L_w at all since it exchanges the signaling messages for the registration over wireless links only. We can see that the network-based schemes perform poorly compared to the host-based schemes since they exchange more signaling messages over the wired network.

We next illustrate the registration delay for different hop counts between GW and LMA/HA ($H_{\text{GW-LMA/HA}}$) in Figure 14. We observe that the centralized schemes give worse performances than the distributed schemes. This is because the centralized schemes depend on the far-away mobility agents for the registration and the data delivery. In contrast, the proposed distributed schemes do not use such agents as LMA and HA incorporating their functions in the 6LoWPAN gateway. Further, among the distributed schemes, we can see that the host-based scheme performs slightly better than the network-based scheme since it does not exchange the signaling messages with the AAA server in the wired network.

5.2. Handover Delay. The delay of wireless links (L_{wl}) gives a significant impact on the handover delay for all the considered schemes, as shown in Figure 15. We can see that the handover delay linearly increases as L_{wl} becomes larger in every scheme. The host-based mobility schemes are affected more severely by the delay of wireless links than the network-based schemes. It can be explained as follows: The host-based schemes exchange the signaling messages over the wireless links and, further, spend much time in configuring a new care-of-address through the duplicate address detection procedure whenever the MSN moves to another domain by handover. Particularly, among the network-based schemes,

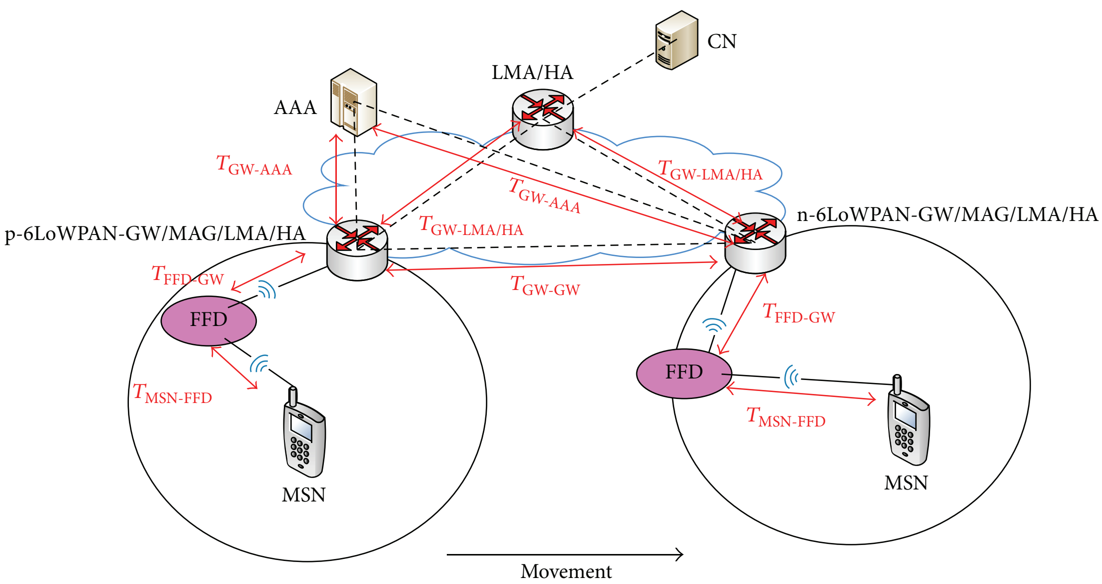

Figure 10: Network model for performance analysis.

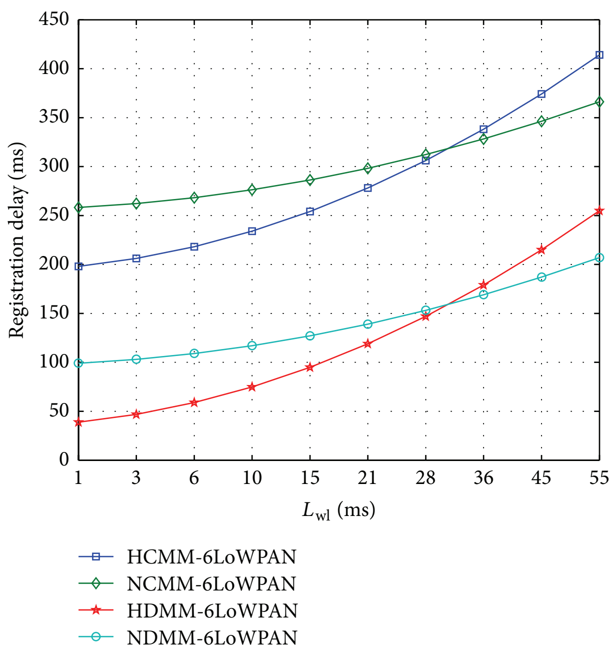

Figure 11: Impact of L_{wl} on the registration delay.

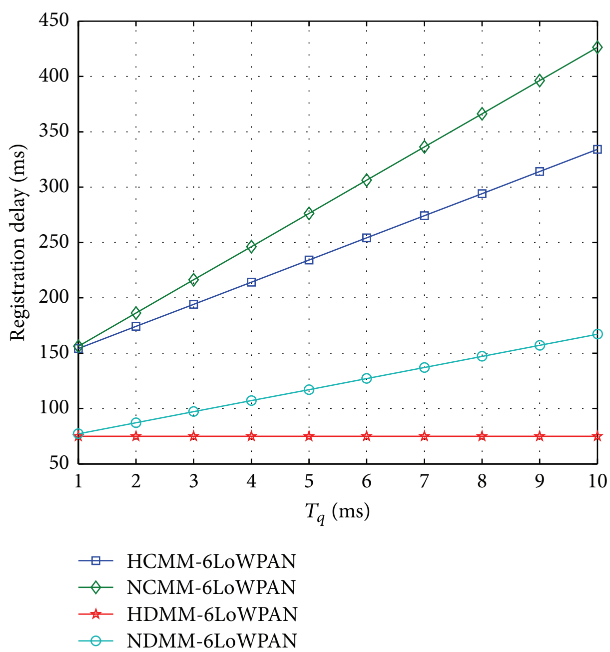

Figure 12: Impact of T_q on the registration delay.

our proposed NDMM scheme shows the better performance since it does not depend on LMA and establishes the handover tunnel for data forwarding, which incurs only the PBU and PBA operation on the wired network.

Figure 16 shows the impact of the average queuing delay (T_q) on the handover delay. The delay rises up linearly as T_q increases in all the schemes. We observe that the HCMM scheme performs worst while consuming much time in the duplicate address detection procedure.

We illustrate the handover delay for different hop counts between GW and LMA/HA ($H_{\text{GW-LMA/HA}}$) in Figure 17. We can see that $H_{\text{GW-LMA/HA}}$ affects the performances of the centralized mobility schemes significantly since they rely on LMA/HA in the distance for the registration and the data delivery.

Figure 18 shows the impact of the number of gateways (N_{GW}) on the handover delay, which is a measure of the network size. Note that N_{GW} gives a significant impact on the handover delay for the proposed DMM schemes.

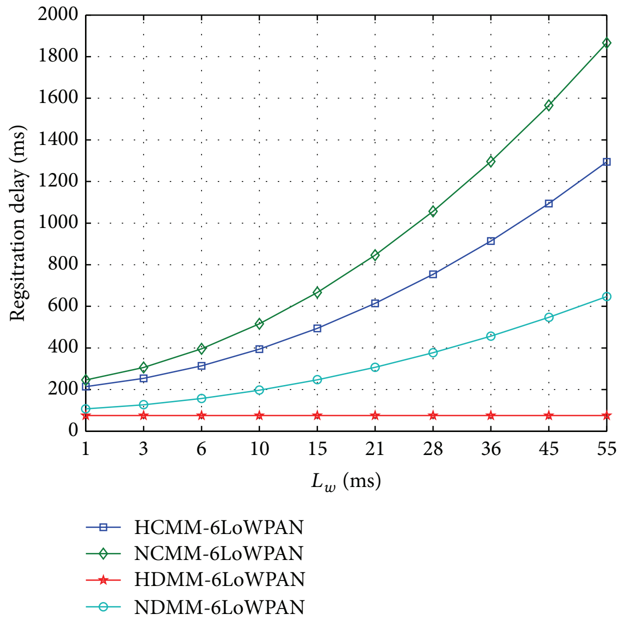

FIGURE 13: Impact of L_w on the registration delay.

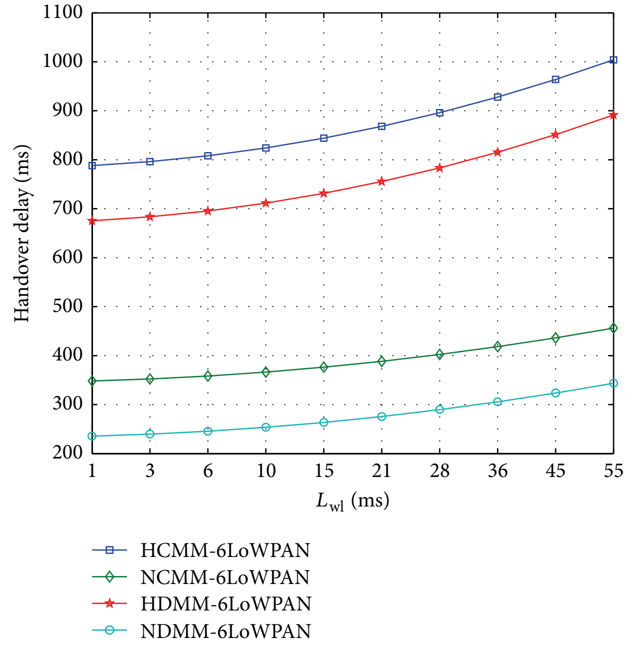

FIGURE 15: Impact of L_{wl} on the handover delay.

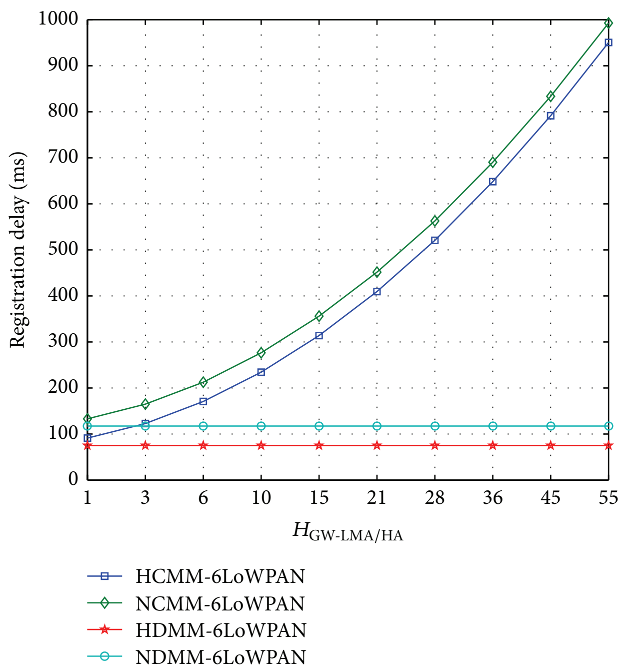

FIGURE 14: Impact of $H_{GW\text{-}LMA/HA}$ on the registration delay.

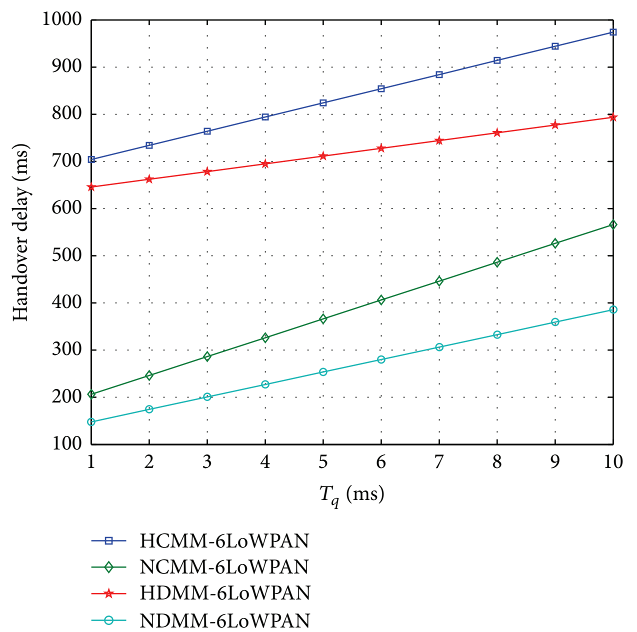

FIGURE 16: Impact of T_q on the handover delay.

This is because each 6LoWPAN-GW/MAG has the functionality of LMA, and PBU/PBA operation should be performed between n-6LoWPAN-GW/MAG/LMA and p-6LoWPAN-GW/MAG/LMA for handover tunnel establishment.

6. Conclusions

In this paper, we proposed two distributed mobility management schemes for 6LoWPAN networks: (1) Host-based Distributed Mobility Management in 6LoWPAN (HDMM-6LOWPAN) and (2) Network-based Distributed Mobility Management in 6LoWPAN (NDMM-6LOWPAN). In the proposed schemes, Home Agent, Local Mobility Anchor, and Mobile Access Gateway functions are incorporated in the 6LoWPAN gateway, and the handover operation is directly performed by two neighboring 6LoWPAN gateways.

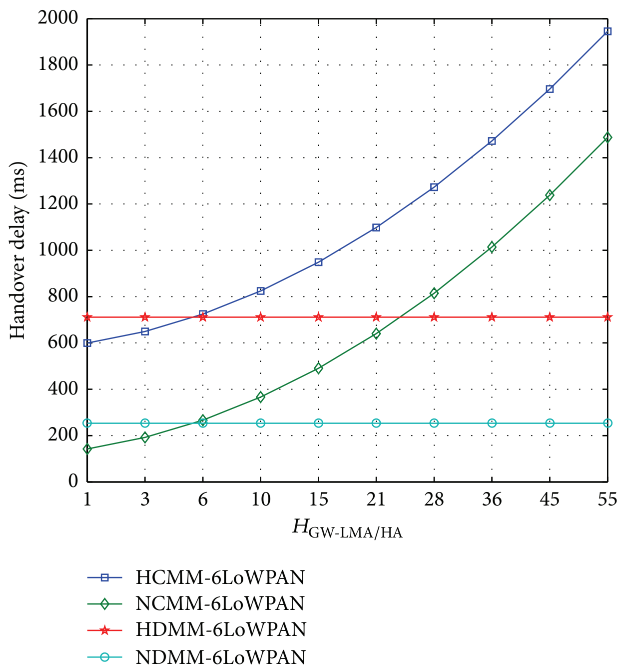

Figure 17: Impact of $H_{\text{GW-LMA/HA}}$ on the handover delay.

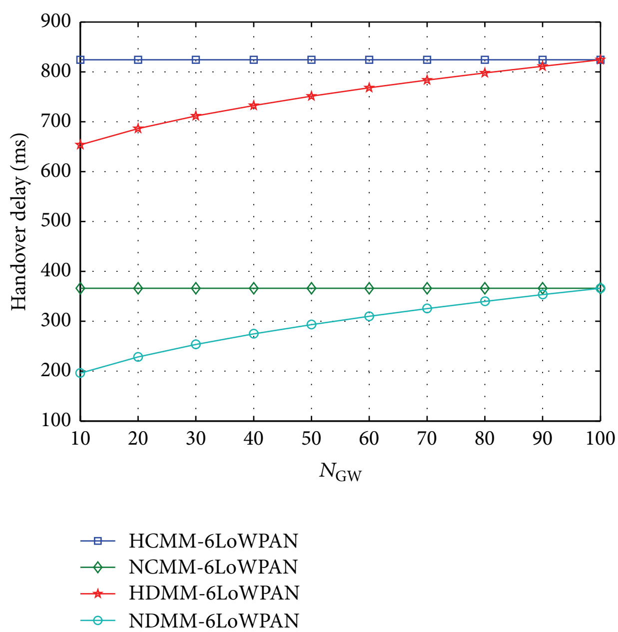

Figure 18: Impact of N_{GW} on the handover delay.

The numerical analysis shows that the proposed schemes reduce the registration delay and the handover delay significantly, compared to the existing mobility schemes. The HDMM-6LoWPAN performs poor over wireless links on the registration delay while it performs well over wired links. The NDMM-6LoWPAN gives the best performance among the considered mobility schemes on the handover delay. The proposed scheme may be incorporated for ameliorating the performance of routing algorithms in mobile wireless sensor. Some recent novel related ideas are given in [19, 20].

Notations for Numerical Analysis

S_c: Size of control packets (bytes)
S_d: Size of data packets (bytes)
B_{wl}: Wireless bandwidth (Mbps)
L_{wl}: Wireless link delay (ms)
B_w: Wired link bandwidth (Mbps)
L_w: Wired link delay (ms)
H_{x-y}: Hop count between node x and y
T_q: Average queuing delay at each node (ms)
q: Wireless link failure probability
N_{GW}: Number of gateways in the network.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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