Research Article

Implementing PMIPv6 Protocol Based on Extended Service Set for IEEE 802.11 Infrastructure WLAN

Deqing Zhu,1,2 Lin Xu,3 Yi-hua Zhu,1 and Xianzhong Tian1

1 School of Computer Science and Technology, Zhejiang University of Technology, Hangzhou, Zhejiang 310023, China
2 Education Technology Center of Hangzhou Normal University, Hangzhou, Zhejiang 310018, China
3 Institute of Information Intelligence and Decision Optimization, Zhejiang University of Technology, Hangzhou, Zhejiang 310023, China

Correspondence should be addressed to Yi-hua Zhu; yhzhu@ece.ubc.ca

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With the popularity of IEEE 802.11 based wireless fidelity (Wi-Fi) portable devices, it becomes increasingly significant to support the mobile users carrying Wi-Fi devices to access the Internet of Things (IoT) so that the communications between the mobile users and the smart objects deployed in the IoT stay uninterrupted when the mobile users are in movement. A scheme using Extended Service Set (ESS)-based architecture is presented to implement the proxy mobile IPv6 protocol, that is, PMIPv6, for IEEE 802.11 infrastructure Wireless Local Area Networks (WLANs). The key signaling packets together with their time sequences for the mobility management in the proposed scheme are proposed. Moreover, the handoff delay in the proposed scheme is derived, through which the performance of the proposed scheme is analyzed. Numerical analysis indicates that the proposed scheme considerably outperforms the existing scheme that uses the Basic Service Set (BSS) based architecture in terms of handoff delay in the case when the delay between Mobile Access Gateway (MAG) and local mobile anchor (LMA) is relatively large.

1. Introduction

Wireless Local Area Network (WLAN) interfaces or Wi-Fi are increasingly incorporated in multimedia portable electronic devices such as portable computers and smart phones. These interfaces enable these devices to access the Internet wherever WLAN Access Points (APs) are located. Most IEEE 802.11 WLANs operate in the infrastructure mode, in which each node is associated with an AP to access the Internet [1].

In Internet of Things (IoT), it is required to attach IP addresses to everyday objects allowing people to remotely communicate with and control networked devices. Having the advantages of easy integration with existing infrastructure, built-in IP-network compatibility, and familiar protocols and management tools [2], Wi-Fi enabled sensors have been used in IoT [3–5]. The Wi-Fi enabled sensors have the feature of at least two wireless interfaces: one is the Wi-Fi interface used to access IEEE 802.11-based WLAN and the other is the low-power interface to support IEEE 802.15.4 standard. Thus, data packets can be transmitted with high data-rate via the Wi-Fi interface while the communications between low-power devices go through the low-power interface [1].

Nowadays, Wi-Fi enabled portable smart phones equipped with some sensors have become increasingly popular. For example, the Samsung Galaxy smart phone includes more than 10 kinds of sensors, such as temperature and humidity sensors, accelerometer, and gyroscope, and so forth. Many applications have been developed to use the sensors embedded in the smart phones, in which the data collected by the embedded sensors from the environment are transmitted via the Wi-Fi interface connecting to the AP in the WLAN.

Internet Protocol Version 6 (IPv6) [6], which has been widely used in the Internet, was applied in wireless sensor networks (WSNs). For instance, IPv6 was used in the WSN for ambient monitoring [7]; the double adaptively clustering hierarchy (DACH) algorithm used IPv6 in WSN [8]; and IPv6-based all-IP WSNs were investigated in [9]. To support delivering IPv6 packets over low-power and low-rate WSNs,
6LoWPAN protocol [10] was developed by the Internet Engineering Task Force to enable nodes in the IP network to communicate with the low-powered WSN nodes operating at low data rates [11]. The adaptation layer introduced in 6LoWPAN is located between the medium access (MAC) layer and the network layer in the protocol stack [10].

With the rapid growth in the number of portable electronic devices, it becomes urgent to support the users carrying these devices to access the IoT when the users are moving, which inspires researchers to investigate the problem of implementing mobile IPv6 (MIPv6) in the infrastructure WLANs. MIPv6 is a technology which allows users to stay connected to the Internet when they are moving. MIPv6 protocols can be classified into two categories: the host-based protocol, such as MIPv6 [12] and HMIPv6 [13]; and the network-based protocol, such as PMIPv6 [14].

IEEE 802.11 standard supports link-layer mobility; that is, it supports mobile node (MN) to move across the boundary of radio coverage of an AP within the same WLAN. But, it does not support network-layer mobility [15], which supports the MN to move across an IP subnet. As a result, we need the network layer mobility protocol that supports the MN to seamlessly move in different WLANs such that the MN keeps its ongoing communications uninterrupted when moving across the boundary of IEEE 802.11 WLANs. Considering that the PMIPv6 has many advantages (e.g., MNs are free from handling mobility management), Gundavelli [16] presented in 2010 the idea of implementing PMIPv6 protocol in WLANs. Unfortunately, this idea has not been finalized as a standard up to date although it has undergone six times of improvements [17].

There are two core functional entities in PMIPv6 protocol. That is, the local mobility anchor (LMA) and the Mobile Access Gateway (MAG). According to Gundavelli’s suggestion, relationship between MAG and AP can be as follows: (1) a MAG manages only one AP referred to as single AP architecture below; and (2) a MAG manages more than one AP referred to as multi-AP architecture below. In 2012, Chai et al. [18] proposed a scheme to implement PMIPv6 for single AP architecture. To the best of our knowledge, there is still a lack of the implementation scheme for multi-AP architecture, which motivates us to address the problem. We extend our previous research [19] in this paper, which has the main contributions as follows.

1. A novel scheme to implement PMIPv6 using Extended Service Set (ESS) based architecture, that is, ESS-based architecture, is presented.
2. The signaling commands used in mobility management and their timing diagrams for the proposed scheme are designed.
3. Delay and signaling traffic in the proposed scheme are derived, based on which performance analysis is conducted.

The remainder of this paper is organized as follows. Our scheme is presented in Section 2 and performance analysis is given in Section 3. We conclude the paper in Section 4.

2. Implementing PMIPv6 Using ESS-Based Architecture

In PMIPv6 protocol, LMA and MAG manage mobility on behalf of an MN, releasing the MN from the burden of handling mobility-related signaling. LMA maintains the MN’s home network prefix (HNP) and records entries relevant to the associations between MAG and MN, and it acts as the home agent (HA) of the MN, while MAG is used to detect the MN’s movement and reports its current position to LMA when necessary. A packet destined to the MN from corresponding node (CN) is first delivered to its LMA using IP protocol and then, via the tunnel between the LMA and the MAG, the packet is tunneled to the MN’s MAG through which it is delivered to the MN using the point-to-point link between the MN and the MAG. Compared to MIPv6, HMIPv6, and the other host-based mobility management protocols, PMIPv6 has the following advantage in addition to saving bandwidth [20]: mobility management is transparent to the MN (i.e., the MN is not involved in mobility management). This strength frees the MN from installing or updating the software to support mobility. Thus, PMIPv6 is highly likely to be widely used.

2.1. The ESS-Based Architecture

In an infrastructure IEEE 802.11 WLAN [15], nodes access the Internet via an AP and the radio coverage of the AP is known as basic service area (BSA). Each node must be associated with one AP before joining the WLAN. The AP and all its associated MNs form a Basic Service Set (BSS) and multiple BSSs form an Extended Service Set (ESS).

The key to implement PMIPv6 in WLAN lies in handling the relationship between MAG and AP. That is, how many APs should be managed by a single MAG. The structure in which one MAG manages only one AP (i.e., the MAG manages one BSS) is illustrated in Figure 1, where each AP is collocated with a MAG. This structure will be referred to as BSS-based architecture below. In this paper, we present the ESS-based architecture shown in Figure 2, where a MAG manages an ESS containing multiple APs. For the sake of easy
description, an AP that is collocated with a MAG is called a “MAG-AP” hereinafter. Thus, in Figure 1, each AP is a MAG-AP; whereas, in Figure 2, only one of the APs in the same ESS is chosen as MAG-AP (e.g., AP₁ and AP₂ are MAG-APs). In both architectures, all APs are wiredly connected.

In the BSS-based architecture, whenever an MN crosses the boundary of a BSA, a handoff operation is triggered, which sends a proxy binding update (PBU) message to the LMA from the MAG in order to update the MN’s new location [14]. For example, in Figure 1, when the MN moves from the BSA of AP₁ to that of AP₂, the MAG related to AP₂ sends a PBU message to the LMA. In the proposed ESS-based architecture, a PBU message is sent only when the MN goes across the boundary of the radio coverage of the ESS. Moreover, when the MN moves within the radio coverage of the same ESS, no PBU message is needed no matter how many BSAs are crossed. For instance, when the MN moves from the BSA of AP₃ to that of AP₄, no PBU is needed. But, when the MN moves from the BSA of AP₄ to that of AP₅, the MAG collocated with AP₅ (i.e., MAG₂) sends a PBU to the LMA.

In the proposed scheme, in every MAG-AP, a cache called “AssocTable” is set to record the information of current APs of MNs. AssocTable contains two fields: “MN_ID” and “Current_AP,” which are used to save the MN’s unique identifier and the currently associated APs, respectively.

2.2. Mobility Management Strategy for the ESS-Based Structure. In infrastructure WLAN, the MN uses active scanning or passive scanning to find existing networks in the area. With active scanning, the MN sends probe frames to solicit responses instead of awaiting the announcement of the network. With passive scanning, the MN searches in each of the preset channels for at least a beacon interval (BI) to receive a possible beacon frame from an AP. The default value of BI is 0.1 s. Therefore, the time consumed in passive scanning can be up to a couple of seconds, which is far greater than that in active scanning. Hence, in this paper, we assume that the MN uses active scanning to detect APs. After scanning, the MN has obtained all necessary information including MAC addresses and signal strengths of the scanned APs, which enable the MN to choose a desired AP to associate with.

The MN judges whether it has entered the area of a new ESS by comparing its buffered service set identifier (SSID) with the SSID carried in the received beacon frame. Before association with a new AP, authentication is needed to verify the identity of the MN. In the case when open system authentication is in use, only one set of authentication request (AuReq) and response (AuRes) exchange suffices for the authentication process [21]. After that, the MN is associated with the new AP by exchanging reassociation request (RAReq) and response (RARes). Considering the above handoff process is only involved in MAC layer, we call it “L2 handoff.”

The events occurring after L2 handoff are as follows.

(1) Association with an AP in Different ESS. In this case, the MN sends a router solicitation message (RtrSol) to the MAG. After receiving RtrSol, the MAG sends a PBU to the LMA. Once the LMA accepts the PBU, it sends back to the MAG a proxy binding acknowledgment (PBA) message, which contains the MN’s home network prefix option, and then it sets up a route over the tunnel to the MAG. After successfully receiving the PBA, the MAG sends router advertisement message (RtrAdv), from which the MN constructs its IP address using the carried HNP. The above process happens in network layer, which will be referred to as “L3 handoff” in the sequel. The events involved in the L2 and L3 handoffs are illustrated in Figure 3. Furthermore, the signaling exchanges among the MN, the new AP, the MAG-AP, and the LMA are shown in Figure 4(a). There exists an exception that happens when the new AP is also a MAG-AP such that the signaling exchanges of RtrSol and RtrAdv can be omitted, which is shown Figure 4(b).

(2) Association with AP in the Same ESS. In this case, the MN neither sends a RtrSol message nor updates its IP address. The only thing it needs to do is to let the new AP inform the MAG-AP of updating its AssocTable. The events in this case are shown in Figure 5. Additionally, the signaling exchanges among the MN, the new AP, and the MAG-AP are illustrated in Figure 6(a), in which the UAT-Req and UAT-ACK represent the message of updating AssocTable and the acknowledgement, respectively.

2.3. Other Specifications. The MAG acts as the default router of the MN and emulates the MN’s home link [14]. As a mobility entity, the MAG can access the policy profile of the MN, which includes a set of configuration parameters for the MN. When PMIPv6 is implemented in an infrastructure WLAN, the configuration parameters such as the MN’s identifier and the LMA address can be piggybacked in association request message, thus saving the time required to access the policy profile. Apart from the MN’s static HNP in the policy profile, the MAG can get a dynamically allocated HNP from PBA.
message. With the HNP and its identifier in hands, the MN can use stateless address configuration method to build its IP address.

In the infrastructure IEEE 802.11 WLAN, upon receiving a frame destined to the MN, the AP uses the distribution service provided by the distribution system to deliver the frame to MN. But, IEEE 802.11 standard does not specify how to implement the distribution system. In this paper, the APs in an ESS are wiredly connected to form the distribution system. When a frame from the wired network is forwarded to the 802.11 WLAN, its format has to be converted before it is delivered to the MN [15]. In addition, some mobility signaling messages sent by the MN should be treated as a new kind of control messages defined according to IEEE 802.11 standard. For example, following IEEE 802.11 standard, we assign new control frame subtype values of "0001" and "0010" in the header of IEEE 802.11 MAC frame for the RtrSol and RtrAdv messages, respectively.

In PMIPv6, the Access Technology Type option is mandatory. We set it to 4, which means that the access technology is 802.11 [14].

3. Performance Analysis

3.1. Handoff Delay. In this section, we use handoff delay as a metric to compare our scheme that uses the ESS-based architecture shown in Figure 2 with the BSS-based architecture shown in Figure 1. Similar to [22], we use a square to represent a BSS. As shown in Figure 7, each small square represents a BSS and several small squares constitute a big square with bold box to represent an ESS. The MN in a BSS is allowed to move into any of the 8 adjacent BSSs. The lower left corner in Figure 7 shows the 8 possible moving directions if the MN is located in square X.

Noting that an ESS is formed by \(n \times n\) adjacent squares with each standing for a BSS, the ESS contains \(n^2\) BSSs. In Figure 7, letter “C” represents the MN in the corner of an ESS, letter “B” indicates the MN in the edges rather than the corner of an ESS, and letter “I” represents the MN in the inner of an ESS. Then, the probabilities of the MN in the BSSs labeled with letters “C,” “B,” and “I” are, respectively, as follows:

\[
a_C = \frac{4}{n^2}, \quad a_B = \frac{4(n-2)}{n^2}, \quad a_I = \frac{n^2 - 4(n-1)}{n^2}. \quad (1)
\]
When the MN is at the corner of an ESS (refer to the BSS labeled with letter "C" in Figure 7), the probability that the MN also crosses the boundary of the ESS when it crosses a BSS is $\frac{5}{8}$; when the MN is in the BSS with "B", the probability of ESS boundary-crossing is 0 as it does not cross the boundary of an ESS when the MN crosses a BSS. Thus, the probability that the MN crosses the boundary of an ESS after the MN crosses a BSS is

$$p = \frac{5}{8} a_c + \frac{3}{8} a_B = \frac{3n-1}{2n^2}. \quad (2)$$

Let $q_0$ be the probability that the MN moves from a BSS to the coverage of a MAG-AP. Now, we calculate $q_0$. Assume that the MN is currently in ESS$_0$ (see Figure 8). After one BSS boundary crossing, the MN enters a new BSS (i.e., a new AP), which leads to the following three cases according to whether the MN has crossed the boundary of ESS$_0$ or not.

**Case 1.** The MN is currently located at the corner of ESS$_0$ as shown in Figure 8(a). There are two subcases for Case 1: (1) when the MN crossed the boundary of ESS$_0$ (with probability 5/8), the probability that the new AP (i.e., the AP the MN is newly associated with when the MN enters a new BSS) is a MAG-AP is $1/2$ and (2) when the MN does not cross the border of ESS$_0$ (with probability 3/8), the probability that the new AP is a MAG-AP, which occurs only when the MN is not located in MAG-AP (with probability $(n^2-1)/n^2$), is $\frac{(n^2-1)}{n^2} \times 1/(n^2-1) = 1/n^2$. Thus, when the MN is located at the corner, the probability that the MN moves into an area of a MAG-AP is equal to $a_c \times (\frac{5}{8})(1/n^2) + (\frac{3}{8})(1/n^2) = a_c \times 1/n^2$.

**Case 2.** The MN is currently located at edge "B" as shown in Figure 8(b). Similarly, we can obtain the probability that the MN moves into an area of a MAG-AP is $a_B \times 1/n^2$.

**Case 3.** The MN is currently located at inner "I" as the square with "X" shown in Figure 7. In this case, only when the MN is not in a MAG-AP (that is, the MAG-AP is collocated with one of the other $n^2-1$ APs, can the MN enter the area of a MAG-AP. Thus, the probability that the MN moves into an area of a MAG-AP is $a_I \times ((n^2-1)/n^2) \times 1/(n^2-1) = a_I \times 1/n^2$.

In summary, no matter where the MN is located in ESS$_0$, the probability that the MN moves into an area of a MAG-AP is the sum of the probabilities derived in the above three cases, which equals (3) using (1). Consider

$$q_0 = a_c \frac{1}{n^2} + a_B \frac{1}{n^2} + a_I \frac{1}{n^2} = \frac{1}{n^2} (a_c + a_B + a_I) = \frac{1}{n^2}. \quad (3)$$

Let $D_{ESS}$ be the expected handoff delay in the proposed scheme, that is, the ESS-based architecture shown in Figure 2. From the mobility management strategy presented in Section 2.2, $L_2$ handoff definitively occurs regardless of whether the MN crosses a BSS or not. Further, if the MN crosses the boundary of a MAG-AP, the events of PBU, PBA, and IP address configuration follow (see Figure 4(b)); if the new AP with which the MN is associated is not a MAG-AP, $L_3$ handoff takes place (see Figures 3 and 4(a)). If the MN does not cross the boundary of an ESS, that is, the MN moves within the ESS, when the new AP is a MAG-AP, only $L_2$ handoff happens (see Figure 6(b)); otherwise, UAT-Req and UAT-ACK messages are exchanged
(see Figures 5 and 6(a)). As a result, the expectation of handoff delay can be calculated as

\[ D_{\text{ESS}} = p \left[ q_0 (t_{L2} + \tau_{\text{PBU}} + \delta + t_{\text{PBA}} + \delta) \right. \]
\[ + \left. (1 - q_0) (t_{L2} + \tau_{\text{BU}}) \right] + (1 - p) \left[ q_0 t_{L2} + (1 - q_0) (t_{L2} + \tau_{\text{UAT}}) \right] \]
\[ = p q_0 (t_{\text{PBU}} + t_{\text{PBA}} + 2\delta) + p (1 - q_0) \tau_{\text{BU}} + t_{L2} + (1 - p) (1 - q_0) \tau_{\text{UAT}}, \tag{4} \]

where \( \delta \) is the propagation delay between the MAG and the LMA and the time of configuring IP address is ignored.

Obviously, the BSS-based architecture shown in Figure 1 is a special case of the ESS-based architecture shown in Figure 2 when \( n = 1 \). As a result, letting \( n = 1 \) in (2) and (3), we obtain \( p = 1 \) and \( q_0 = 1 \). Thus, from (4), we obtain that the expected handoff delay in the BSS-based architecture is

\[ D_{\text{BSS}} = t_{\text{PBU}} + t_{\text{PBA}} + t_{L2} + 2\delta. \tag{5} \]

It can be seen from (4) and (5) that the key to finding \( D_{\text{ESS}} \) and \( D_{\text{BSS}} \) lies in determining \( t_{\text{PBU}}, t_{\text{PBA}}, \tau_{\text{BU}}, \tau_{\text{UAT}}, \) and \( t_{L2} \). Since UAT-Req and UAT-ACK are sent in wired link, their propagation speeds are as high as \( 2 \times 10^8 \) m/s such that the propagation only takes \( 5 \mu s \) if the distance between the AP and the MAG-AP is 1 km. Besides, the payload of UAT-Req or UAT-ACK is only 1 B, which totals 33 B when the 802.11 MAC header is taken into account. Hence, the delay in transmitting UAT-Req or UAT-ACK is less than \( 3 \mu s \) in 100 Mbps Ethernet, which reduces to \( 0.3 \mu s \) in a Gigabit Ethernet. Therefore, the propagation and transmission delay of UAT-Req and UAT-ACK can be omitted. Thus, using (2) and (3), (4) can be simplified as

\[ D_{\text{ESS}} = \frac{3n - 1}{2n^4} \left( t_{\text{PBU}} + t_{\text{PBA}} + 2\delta \right) + \frac{(3n - 1) \left( n^2 - 1 \right)}{2n^4} \tau_{\text{BU}} + t_{L2}. \tag{6} \]
Table 1: Delay of signaling frames.

| Frame type | Length (B) | Transmission delay (μs) | Frame type | Length (B) | Transmission delay (μs) |
|------------|------------|-------------------------|------------|------------|-------------------------|
| PBU        | 96         | 𝑡_{PBU} = 76.8          | PBA        | 96         | 𝑡_{PBA} = 76.8          |
| RtSol      | 72         | 𝑡_{RS} = 57.6           | RtAdv      | 84         | 𝑡_{RA} = 67.2           |
| RAReq      | 56         | 𝑡_{RAReq} = 44.8        | RARes      | 40         | 𝑡_{RARes} = 32          |
| AuReq      | 34         | 𝑡_{AuReq} = 27.2        | AuRes      | 34         | 𝑡_{AuResp} = 27.2       |
| UAT-Req    | 35         | 𝑡_{UAT-Req} = 28        | UAT-ACK    | 35         | 𝑡_{UAT-ACK} = 28        |

Considering that 𝑡_{Scan} is in the range of 105–210 ms [24], we set 𝑡_{Scan} = 150 ms = 150 000 μs. Thus, (8) turns into

\[ 𝑡_{c} = 1270\theta^4 - 3170\theta^2 + 2210. \]  

(9)

Before transmitting, the node must sense the medium idle for period of 𝑡_{DIFS} and then backoffs. Thus, we get

\[ t_{Authen} = (t_{DIFS} + t_C + t_{AuRes}) + (t_{DIFS} + t_C + t_{AuReq}) \]
\[ + 2(t_{DIFS} + t_C) + t_{AuRes} + t_{AuReq}. \]  

(10)

From Figures 3 and 5, (10), and Table 1, we have

\[ t_{L2} = t_{Scan} + t_{Authen} + t_{RAAssoc} \]
\[ = 4t_C + t_{AuRes} + t_{AuReq} + t_{RAReq} + t_{RRes}. \]  

(11)

Using Table 1 and (9), we obtain

\[ t_{L2} = 4t_C + 150331.2 = 5080\theta^4 - 12680\theta^2 + 159171.2. \]  

(12)

From Figure 3, we have

\[ t_{BU} = (t_{DIFS} + t_C + t_{RA}) + (t_{PBU} + \delta) \]
\[ + (t_{DIFS} + t_C + t_{RA}) \]
\[ = 2t_C + 2t_{DIFS} + t_{RS} + t_{PBU} + t_{PBA} + t_{RA} + 2\delta. \]  

(13)

From Table 1 and (9), we have

\[ t_{BU} = 2t_C + 378.4 + 2\delta \]
\[ = 2540\theta^4 - 6340\theta^2 + 4798.4 + 2\delta. \]  

(14)

Thus, using (12) and (14), (6), and (5) can be rewritten as follows:

\[ D_{ESS} = (153.6 + 2\delta) \frac{3n - 1}{2n^2} \]
\[ + \frac{(3n - 1)(n^2 - 1)}{2n^3} \]
\[ \cdot (2540\theta^4 - 6340\theta^2 + 4798.4 + 2\delta) \]
\[ + (5080\theta^4 - 12680\theta^2 + 159171.2) \]  

(15)

\[ D_{BSS} = 5080\theta^4 - 12680\theta^2 + 159324.8 + 2\delta. \]  

(16)
Further, the difference of (5) and (6) is

\[
\Delta(n) = D_{\text{BSS}} - D_{\text{ESS}} = 153.6 + 2\delta - (153.6 + 2\delta) \frac{3n - 1}{2n^4} - \frac{(3n - 1)(n^2 - 1)}{2n^4} \cdot (2540\theta^4 - 6340\theta^2 + 4798.4 + 2\delta),
\]

where “≡” is used to define the notation on its left side, that is, \( \Delta(n) \), which is expressed as its right side. It can be seen from (17) that, the condition that our scheme using the ESS-based architecture is better than the BSS-based architecture is \( \Delta(n) > 0 \).

Next, we investigate influence of \( n, \theta, \) and \( \delta \) on \( \Delta(n) \). The influence for the case when \( \delta = 1 \) ms is shown in Figure 9, which indicates that: (1) a larger \( n \) or \( \theta \) cause \( \Delta(n) > 0 \), that is, our scheme outperforms the BSS-based scheme in terms of delay in the case when more APs are included in an ESS or when the PSPTs over wireless links are larger; and (2) the increase either in \( n \) or \( \theta \) causes \( \Delta(n) \) to increase, that is, as the PSPTs over wireless links increase or more APs are added to an ESS, the delay difference between the BSS-based architecture and our scheme becomes increasingly apparent, that is, our scheme is better than the BSS-based scheme considerably.

To clearly observe the tendency of \( \Delta(n) \) when \( n \) and \( \theta \) vary, we plot the cross sectional views of Figure 9 in Figures 10 and 11. Figure 10 shows the case when \( \theta \) are fixed to 0.2, 0.5, and 0.8, and Figure 11 shows the case when \( n \) are fixed to 2, 6, 11, 16, and 20. Both figures clearly illustrate that our scheme prefers a larger \( n \) such that \( \Delta(n) > 0 \). Moreover, in the case where PSPSs of wireless links are small, we can choose a larger \( n \) such that \( \Delta(n) > 0 \) (see Figure 11).

Influence of \( \delta \) on \( \Delta(n) \) is shown in Figure 12, from which we observe that (1) \( \Delta(n) \) increases proportionally with the propagation delay between the LMA and the MAG (i.e., the parameter \( \delta \)) and (2) a larger \( \delta \) contributes a larger \( \Delta(n) \). In other words, our scheme considerably outperforms the BSS-based one in the case when \( \delta \) is relatively large.
In fact, by solving the following optimization problem, the optimal $n$ can be found for our scheme using the ESS-based architecture such that the handoff delay is minimized. Consider

$$\text{Min} \quad D_{\text{ESS}}$$

w.r.t. $n$

s.t. $\Delta (n) > 0$

$$2 \leq n \leq n_0,$$ (18)

where $n_0$ is a predefined threshold for the number of APs to be included in the ESS. Considering that the optimization problem shown in (18) can be solved easily even through the method of exhaustion, we omit the solution of (18).

### 3.2. Signalling Traffic from Handoff

Now, we turn to analyze the signaling traffic (in bits) incurred in a handover. From Figures 4 and 6, the expectation of handoff traffic in the ESS-based scheme can be calculated as

$$C_{\text{ESS}} = p \left[ q_0 (c_{L2} + c_{\text{PBUs}} + c_{\text{PBA}}) + (1 - q_0) (c_{L2} + c_{\text{BU}}) \right]$$

$$+ (1 - p) (q_0 c_{L2} + (1 - q_0) (c_{L2} + c_{\text{UAT}}))$$

$$= p q_0 (c_{\text{PBUs}} + c_{\text{PBA}}) + p (1 - q_0) c_{\text{BU}}$$

$$+ c_{L2} + (1 - p) (1 - q_0) c_{\text{UAT}},$$ (19)

in which $c_{L2}$ denotes the traffic generated by $L2$ handover event; $c_{\text{PBUs}}$ and $c_{\text{PBA}}$ denote the traffics generated from a PBU and a PBA messages, respectively; in a binding update operation; $c_{\text{BU}}$ denotes the total traffic of an RS, an RA, and a binding update message; and $c_{\text{UAT}}$ is the traffic caused by sending a UAT message. In the case when $n = 1$, we have $p = 1$ and $q_0 = 1$ from (2) and (3). Thus, from (19), we get the expected handoff traffic for the BSS-based architecture as follows:

$$C_{\text{BSS}} = c_{\text{PBUs}} + c_{\text{PBA}} + c_{L2}.$$ (20)

First, we calculate the traffic for transmitting a packet over wireless link. As positive acknowledgement (ACK) scheme is adopted in the IEEE 802.11 standard-based WLAN, only when a packet together with its ACK is successfully received, the packet is considered being successfully delivered. As in the previous subsection, we ignore the probabilities of three or more consecutive failure transmissions for the same packet. Thus, for a given packet, say packet $a$, all of its possible transmission/retransmissions and its ACK can be listed in Table 2, where $a$, $\text{ACK}$, and $\overline{\text{ACK}}$ means “packet $a$ is successfully received,” “packet $a$ is NOT successfully received,” “ACK is successfully received,” and “ACK is NOT successfully received,” respectively. Additionally, $L_a$ and $L_{\text{ACK}}$ represent the lengths of packet $a$ and the ACK packet, respectively.

Now, we explain the contents in Table 2. We use pair $(x, y)$ to represent the position of the item at the $x$th row and $y$th column in the table. The “$a$, $\text{ACK}$” at position (2, 2) in the table indicates that both packet $a$ and ACK are successfully received; that is, packet $a$ is successfully delivered to the receiver at its first transmission, which has the probability of $\theta^2$ and generates the traffic of $L_a + L_{\text{ACK}}$. The event in which packet $a$ is successfully delivered at the 2nd transmission trial is equivalent to the event in which the packet fails at the 1st trial but succeeds at the 2nd one, which consists of two subevents: (1) “$a$, ACK,” which is listed at the positions (3, 2) and (3, 3); and (2) “$a$, ACK, $a$, ACK,” which is listed at the positions (4, 2) and (4, 3) in Table 2. Here, the event “$a$, $\text{ACK}$” means that packet $a$ is lost (represented by the notation “$\overline{\text{a}}$”) at the 1st trial and then both packet $a$ and ACK are successfully received at the 2nd trial; and the event “$a$, $\overline{\text{ACK}}$, $a$, $\overline{\text{ACK}}$” means that at the 1st trial packet $a$ succeeds but ACK fails, which causes retransmission of packet $a$, whereas the packet is successfully delivered at the 2nd trial. In fact, the first event happens with the probability of $(1 - \theta) \theta^2$ and produces the traffic of $2L_a + L_{\text{ACK}}$ due to packet $a$ and ACK being transmitted twice and once, respectively; and the second event happens with probability of $\theta^2 (1 - \theta)^2$ and generates traffic of $2L_a + 2L_{\text{ACK}}$. Moreover, the 3rd and 4th rows in Table 2 reflect the event in which the packet is successfully delivered at the 2nd transmission trial. Similarly, rows 5–8 in Table 2 reflect the event in which the packet is successfully delivered at the 3rd transmission trial, which consists of the subevents of “$\overline{\text{a}}$, $\overline{\text{a}}$, $\text{ACK}$,” “$\overline{\text{a}}$, $\text{ACK}$, $\overline{\text{a}}$, $\text{ACK}$,” “$a$, $\overline{\text{ACK}}$, $a$, $\overline{\text{ACK}}$,” and “$a$, $\overline{\text{ACK}}$, $\overline{\text{a}}$, $\text{ACK}$.”

It should be pointed out that at the 3rd trail the packet is delivered with probability of $1$ in Table 2 because we ignore the failure probabilities of three or more consecutive failure transmissions for the same failed packet.
Table 2: Events, Probabilities, and Traffic at the first three transmission trials.

| EVENT                        | The 1st trial | The 2nd trial | The 3rd trial | Traffic (bits) | Probability |
|------------------------------|---------------|---------------|---------------|---------------|-------------|
| Success at the 1st trial     | \(a, \text{ACK}\) | \(\\) | \(\\) | \(L_a + L_{\text{ACK}}\) | \(\theta^2\) |
| Success at the 2nd trial     | \(\bar{a}\) | \(a, \text{ACK}\) | \(\\) | \(2L_a + L_{\text{ACK}}\) | \((1 - \theta)\theta^2\) |
| Success at the 3rd trial     | \(\bar{a}\) | \(\bar{a}\) | \(a, \text{ACK}\) | \(3L_a + L_{\text{ACK}}\) | \((1 - \theta)(1 - \theta)\) |

From Table 2 we obtain the average traffic to transmit the packet (i.e., packet \(a\)) over a wireless link as follows:

\[
c_a = \theta^2 \left( L_a + L_{\text{ACK}} \right) + (1 - \theta) \theta^2 \left( 2L_a + L_{\text{ACK}} \right)
+ \theta (1 - \theta)^2 \left( 2L_a + 2L_{\text{ACK}} \right)
= 7192 \left( \theta^2 + 2 \left( 1 - \theta^2 \right) \theta^2 + 3 \left( 1 - \theta^2 \right)^2 \right)
+ 1456 \left( \theta^4 - \theta^3 - 2\theta^2 + 2\theta + 1 \right) L_{\text{ACK}}.
\] (21)

As mentioned earlier, the handoff process on L2 (i.e., the link layer) contains three phases: scanning, authentication, and reassociation. We assume that the MN adopts active scanning to identify the best AP. To do so under IEEE 802.11 standard, the MN multicasts a probe request frame at Channels 1, 6, and 11 to its neighboring APs for the designed frame. Thus, 3 probe requests are multicast and 9 probe responses from the neighboring APs in both the proposed scheme shown in Figure 2 and the BSS-based architecture shown in Figure 1 because we adopt scenario in Figure 7 in which an AP has 8 neighboring APs. Considering the length of the probe request message \(L_{\text{ProReq}} = 50\) B and that of the probe response message \(L_{\text{ProRes}} = 65\) B [15], using (21) and Table 1, we achieve

\[
c_{L2} = 7192 \left( \theta^2 + 2 \left( 1 - \theta^2 \right) \theta^2 + 3 \left( 1 - \theta^2 \right)^2 \right)
+ 1456 \left( \theta^4 - \theta^3 - 2\theta^2 + 2\theta + 1 \right) L_{\text{ACK}}.
\] (22)

Recall that a bidirectional tunnel is established between the LMA and the MAG. Let \(L_{\text{thd}}\) be the length of tunneling packet header, which is set to 40 [6], and \(H_1\) be the number of hops between the MAG and the LMA. Then, when PBU and PBA messages are exchanged through the tunnel between the MAG and the LMA, the total traffic generated by the \(H_1\) hops in the tunnel can be calculated by

\[
c_{\text{thd}} = c_{\text{PBU}} + c_{\text{PBA}} = \left( L_{\text{PBU}} + L_{\text{thd}} \right) H_1
= 2176H_1.
\] (23)

Note that the RS, RA and UAT messages are delivered over both wireless and wired links. We assume the number of hops between the AP and the MAG is \(H_2\). In an ESS containing \(n \times n\) BSSs, the worst scenario is that these BSSs are connected in a line, which leads to \(H_2 < n^2\). Considering that the time to live (TTL) field in the header of an IP packet is usually initialized to 32 or 64 [6], we set the upper limit of the number of hops between the MAG and the LMA to 64. Thus, \(H_1\) ranges from 1 to 64. Usually the number of hops between the MAG and the LMA is greater than that between an AP and the MAG. Hence, we assume \(H_1 = cH_2\), where \(c\) is a constant valued 2, 4, 6, or 8.

Using (21) and (23), we get

\[
c_{\text{BU}} = c_{\text{PBU}} + \left( L_{\text{RS}} + L_{\text{RA}} \right)
= 7192 \left( \theta^2 + 2 \left( 1 - \theta^2 \right) \theta^2 + 3 \left( 1 - \theta^2 \right)^2 \right)
+ 1456 \left( \theta^4 - \theta^3 - 2\theta^2 + 2\theta + 1 \right) L_{\text{ACK}}.
\] (22)

From Figure 6, we have

\[
c_{\text{UAT}} = \left( L_{\text{UAT-Req}} + L_{\text{UAT-Res}} \right) H_2 = 560H_2.
\] (25)
To simplify the above expression, we introduce the following notations:

\[
\begin{align*}
    u &= \theta^3 + 2\left(1 - \theta^2\right) \theta^2 + 3 \left(1 - \theta^2\right)^2; \\
    v &= \theta^4 - \theta^3 - 2\theta^2 + 2\theta + 1. 
\end{align*}
\]

(26)

Then, using (22)–(26), we can rewrite (19) and (20) as follows:

\[
\begin{align*}
    C_{\text{ESS}} &= 2176pq_nH_1 + p \left(1 - q_0\right) \\
        &\quad \cdot \left(2176H_1 + 1248u + 224v + 1248H_2\right) \\
        &\quad + 7192u + 1456v + \left(1 - p\right) \left(1 - q_0\right) \cdot 560H_2 \\
        &= \frac{2176 \left(3n - 1\right)}{2n^3}H_1 + 7192u + 1456v \\
        &\quad + \frac{\left(3n - 1\right) \left(n^2 - 1\right)}{2n^4} \cdot \left(2176H_1 + 1248u + 224v + 1248H_2\right) \\
        &\quad + \frac{560H_2 \left(2n^2 - 3n + 1\right) \left(n^2 - 1\right)}{2n^4} \\
        &= C_{\text{ESS}} = 2176H_1 + 7192u + 1456v. 
\end{align*}
\]

(27)
To compare the proposed scheme with the BSS-based architecture in signaling traffic, we introduce the traffic ratio as follows:

\[ \eta = \frac{C_{\text{BSS}}}{C_{\text{ESS}}} \]  

(28)

The traffic ratio reflects the proposed scheme is better than the BSS-based architecture when \( \eta > 1 \).

Finally, we investigate influence of \( n, \theta, \) and \( H_2 \) on the traffic ratio. It can be seen from Figure 13 that (1) when \( n \) grows, \( \eta \) increases and is bigger than 1, which indicates that the proposed scheme has less signaling traffic than the BSS-based architecture (see Figure 13(a)); (2) in the case when \( c > 2 \) in the expression of \( H_1 = cH_2 \), which indicates that the number of hops between the MAG and the LMA is more than 2 times of that between the MAG and the AP, the proposed scheme is better than the BSS-based architecture, that is, \( \eta > 1 \) (see Figure 13(b)); and (3) in the case when the number of hops between the MAG and AP, that is, \( H_2 \), is bigger than 1, the proposed scheme is better than the BSS-based architecture (see Figure 13(c)). In a word, from point of view of signaling traffic, the proposed scheme is better than the BSS-based architecture in the case when \( n, c, \) or/and \( H_2 \) has a bigger value.

4. Conclusion

In this paper, we present the scheme that uses the ESS-based architecture shown in Figure 2 to implement PMIPv6 for IEEE 802.11 infrastructure WLAN. The numerical analysis results show that, in the case when the propagation delay between LMA and MAG is relatively large (e.g., LMA are far away from MAG), the proposed scheme outperforms the existing scheme using the BSS-based architecture shown in Figure 1 in terms of handoff delay. Moreover, the proposed scheme prefers more APs being included in one ESS so that handoff delay is reduced. Though we arrive at the conclusion by using a square to represent a BSS as shown in Figure 7, the same conclusion holds when regular hexagon [25] is used to represent a BSS.

Conflict of Interests

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

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References

[1] Y.-H. Zhu, S. Luan, V. C. M. Leung, and K. Chi, "Enhancing timer-based power management to support delay-intolerant uplink traffic in infrastructure IEEE 802.11 WLANs," IEEE Transactions on Vehicular Technology, vol. 64, no. 1, pp. 386–399, 2015.

[2] S. Tozlu, "Feasibility of Wi-Fi enabled sensors for Internet of Things," in Proceedings of the 7th International Wireless Communications and Mobile Computing Conference (IWCMC '11), pp. 291–296, IEEE Press, July 2011.

[3] S. Tozlu and M. Senel, "Battery lifetime performance of Wi-Fi enabled sensors," in Proceedings of the IEEE Consumer Communications and Networking Conference (CCNC ’12), pp. 429–433, IEEE Press, January 2012.

[4] A. Berger, A. Pötsch, and A. Springer, "Synchronized industrial wireless sensor network with IEEE 802.11 ad hoc data transmission," in Proceedings of the 2nd IEEE International Workshop on Measurements and Networking (M & N'13), pp. 7–12, IEEE Press, October 2013.

[5] T. Zheng, R. Sridhar, and S. Venkatesh, "A switch agent for wireless sensor nodes with dual interfaces: implementation and evaluation," Tsinghua Science and Technology, vol. 17, no. 5, Article ID 6314534, pp. 586–598, 2012.

[6] S. Deering and R. Hinden, "Internet protocol specification, version 6 (IPv6)," RFC 2460, 1998.

[7] D. F. Larios, J. M. Mora-Merchan, E. Personal, J. Barbancho, and C. León, "Implementing a distributed WSN based on ipv6 for ambient monitoring," International Journal of Distributed Sensor Networks, vol. 2013, Article ID 328747, 14 pages, 2013.

[8] D. Yang and Q. Guo, "DACH: an efficient and reliable way to integrate WSN with IPv6," International Journal of Distributed Sensor Networks, vol. 2012, Article ID 714786, 12 pages, 2012.

[9] X. Wang and S. Zhong, "A routing scheme for IPv6-Based All-IP wireless sensor networks," International Journal of Distributed Sensor Networks, vol. 2012, Article ID 750681, 9 pages, 2012.

[10] N. Kushalnagar, G. Montenegro, and C. Schumacher, "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals," RFC 4919, 2007.

[11] J. W. Hui and D. E. Culler, "Extending IP to low-power, wireless personal area networks," IEEE Internet Computing, vol. 12, no. 4, pp. 37–45, 2008.

[12] C. Perkins, D. Johnson, and J. Arkko, "Mobility support in IPv6," IETF, RFC 6275, July 2011.

[13] H. Soliman, C. Castelluccia, K. El-Makri, and L. Bellie, Hierarchical mobile IPv6 (HMIPv6) Mobility Management, RFC 5380, IETF, 2008.

[14] S. Gundavelli, K. Leung, V. Devarapalli, K. Chowdhury, and B. Patil, "Proxy mobile IPv6," IETF, RFC 5213, August 2008.

[15] IEEE Computer Society, "Part II: wireless LAN medium access control (MAC) and physical layer (PHY) specifications," IEEE Std 802.11, 2007.

[16] S. Gundavelli, "Applicability of proxy mobile IPv6 protocol for WLAN access networks," draft-gundavelli-netext-pmipv6-wlan-applicability-00.txt, IETF, October 2010.

[17] S. Gundavelli, "Applicability of proxy mobile IPv6 protocol for WLAN access networks," IETF, 2013, https://tools.ietf.org/html/draft-gundavelli-netext-pmipv6-wlan-applicability-06.

[18] R. Chai, J. Zhou, and Q. Chen, "PMIPv6-based mobility management in WLAN," in Proceedings of the 7th International
[19] D. Zhu, L. Xu, Y.-h. Zhu, and X. Tian, "Implementing PMIPv6 protocol based on extended service set for IEEE 802.11 infrastructure WLAN," in Proceedings of the International Conference on Identification, Information and Knowledge in the Internet of Things (IKI '14), pp. 266–273, Beijing, China, July 2014.

[20] K.-S. Kong, W. Lee, Y.-H. Han, M.-K. Shin, and H. You, "Mobility management for all-IP mobile networks: mobile IPv6 vs. proxy mobile IPv6," IEEE Wireless Communications, vol. 15, no. 2, pp. 36–45, 2008.

[21] M. S. Gast, 802.11 Wireless Networks: The Definition Guide, O'Reilly Media, Sebastopol, Calif, USA, 2005.

[22] K.-H. Chiang and N. Shenoy, "A 2-D random-walk mobility model for location-management studies in wireless networks," IEEE Transactions on Vehicular Technology, vol. 53, no. 2, pp. 413–424, 2004.

[23] J.-H. Lee, J.-M. Bonnin, I. You, and T.-M. Chung, "Comparative handover performance analysis of IPv6 mobility management protocols," IEEE Transactions on Industrial Electronics, vol. 60, no. 3, pp. 1077–1088, 2013.

[24] I. Purushothaman and S. Roy, "FastScan: a handoff scheme for voice over IEEE 802.11 WLANs," Wireless Networks, vol. 16, no. 7, pp. 2049–2063, 2010.

[25] Y.-H. Zhu, J. Gao, G.-G. Zhou, and J. Peng, "Mobility management strategy with ring search in cellular networks," Chinese Journal of Electronics, vol. 31, no. 1, pp. 1655–1658, 2003.
