A Lightweight NEMO Protocol to Support 6LoWPAN

Jin Ho Kim, Choong Seon Hong, and Taeshik Shon

The Network Mobility (NEMO) and IPv6 over Low power WPAN (6LoWPAN) protocols are the two most important technologies in current networking research and are vital for the future ubiquitous environment. In this paper, we propose a compressed packet header format to support the mobility of 6LoWPAN. Also, a Lightweight NEMO protocol is proposed to minimize the signaling overhead between 6LoWPAN mobile routers and 6LoWPAN gateways by using a compressed mobility header. Performance results show that our Lightweight NEMO protocol can minimize total signaling costs and handoff signaling delay.

Keywords: NEMO, 6LoWPAN, network mobility, sensor network, header compression.

I. Introduction

Currently some sensor network protocols have non-IP network layer protocols, such as ZigBee [1], in which TCP/IP is not used. However, future sensor networks consisting of thousands of nodes may be connected to others via the Internet. Hence, an efficient addressing mechanism will be needed to communicate with the individual sensor nodes in the network. IPv6 [2] can be the best solution for that. Also, a suitable application is needed to make effective use of the IPv6 address. Accordingly, the IETF IPv6 over Low power WPAN (6LoWPAN) Working Group [3] was organized to define the transmission of IPv6 packets over IEEE 802.15.4 [4]. External hosts in the IPv6 Internet will be able to directly communicate with sensor nodes in 6LoWPAN [5] and vice versa because each 6LoWPAN node will be assigned a global IPv6 address.

In this paper, we present a scheme to support mobility for 6LoWPAN sensor nodes. To provide mobility for 6LoWPAN nodes, we adopt the Network Mobility (NEMO) protocol [6]. If NEMO is applied in the 6LoWPAN network, even though each 6LoWPAN node is not equipped with the mobility protocol, it can maintain connectivity with the Internet through the 6LoWPAN mobile router (MR) as a network unit. Thus, the network mobility of the 6LoWPAN sensor nodes can be supported by an interoperable architecture between 6LoWPAN and NEMO. In this paper, we propose a new header compression scheme for mobility headers in 6LoWPAN networks. Moreover, we propose a Lightweight NEMO protocol for efficient support of the 6LoWPAN network mobility.

Our paper is organized as follows. In section II, we briefly introduce the concept of protocols such as NEMO and 6LoWPAN. Section III states the problem of 6LoWPAN mobility. In section IV, we describe the operations of the

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proposed Lightweight NEMO protocol to support 6LoWPAN. Section V presents the performance analysis and results. Finally, we conclude our work in section VI.

II. Background

1. Overview of the NEMO Basic Support Protocol

The NEMO Basic Support protocol maintains the session continuity for all the mobile network nodes (MNNs) [6], even when the MR dynamically changes its point of attachment to the Internet. It also provides connectivity for all MNNs as it moves. The NEMO Basic Support protocol has been standardized in RFC 3963 [6] to support network mobility. NEMO signaling messages such as binding update (BU) and binding acknowledgement (BA) are extended Mobile IPv6 messages. The BU and BA messages have an additional mobile router flag (R) to signal the MR. There are two modes for NEMO: explicit and implicit. In the explicit mode, one or more mobile network prefix (MNP) [6] options should be included in a BU message. In the implicit mode, instead of including MNP options, the home agent (HA) [6] has to make a decision about the MNP owned by the MR and set up a forwarding mechanism for the mobile network, such as a dynamic routing protocol.

When the MR moves to a foreign link away from the home link, the MR sends the BU message to its HA with a new care-of address (CoA), which is the IPv6 address of the MR at its current Internet attachment point. The BU message also includes the MNP option and an R flag. Upon receipt of the BU, the HA updates the MR's information and replies by sending a BA message. If the packets are sent to an MNN from a correspondent node (CN), the HA intercepts the packets and encapsulates them in a bi-directional tunnel to the MR. After that, the MR decapsulates the packets and forwards them to the MNN. Reverse traffic must be tunneled to the HA before it is routed to the CN. The NEMO Basic Support protocol specifies bi-directional tunneling so that only MRs and HAs need to be aware of the network mobility.

2. Overview of the 6LoWPAN Protocol

6LoWPAN is a simple low-cost communication protocol that allows wireless connectivity in applications with limited power. The 6LoWPAN protocol adopts the IPv6 protocol stack for seamless connectivity between IEEE 802.15.4 based networks and the IPv6 based infrastructure. The 6LoWPAN protocol could be more suitable for smaller devices with lower energy consumption. Also, it enhances the scalability and mobility of sensor networks. The challenge of 6LoWPAN is that the IPv6 network and IEEE 802.15.4 network are totally different. The IPv6 network defines the maximum transmission unit (MTU) as 1,280 bytes, whereas the IEEE 802.15.4 packet size is 127 octets. Therefore, the adaptation layer is defined between the IP layer and the MAC layer to transport IPv6 packets over IEEE 802.15.4 links. The adaptation layer is responsible for fragmentation, reassembly, header compression, decompression, mesh routing, and addressing for packet delivery under mesh topology. The 6LoWPAN protocol supports the scheme to compress the IPv6 header from 40 bytes to 2 bytes.

The IPv6 header compression scheme and the format of the 6LoWPAN packet are explained in detail in the following subsections.

A. IPv6 Header Compression Scheme of 6LoWPAN

All fields of the IPv6 header can be compressed except the hop limit (8 bits) field. For example, the version field can be omitted if all packets use IPv6. Both source and destination IPv6 addresses are link local and can be inferred from the EUI-64 address. The packet length field can also be omitted because it can be confirmed by the MAC header, and the traffic class and flow label can be omitted by replacing them with 0. The next header can be simplified by UDP, TCP, and ICMP. However, if the hop limit field is added to last part of the HC1 encoding (8 bits) field, it cannot be omitted. Finally, after the previously mentioned fields are omitted, the IPv6 header of 40 bytes can be compressed to a minimum of 2 bytes. These 2 bytes are divided between the HC1 encoding field and the hop limit field.

The first 2 bits of the HC1 encoding field carry the information about compression of the IPv6 source address. The third and fourth bits carry the information of the IPv6 destination address. The details of each bit and their meanings are shown in [7]. The fifth bit carries the compression status of the traffic class and flow label. If it is 1, this indicates that the information is compressed. If it is 0, the information is not compressed. The 8 bits of the traffic class and the 20 bits of the flow label are located next to the encoding field. The sixth and the seventh bits carry the information of the next header. If they are 00, the next header is not compressed and the 8 bits of the next header are included in the next part of the encoding field. If they are 01, this indicates UDP, while 10 indicates ICMP, and 11 indicates TCP. Finally, the 8th bit indicates the HC2 encoding field. If it is 0, there is no remaining header compression bit, and 1 indicates that the HC2 encoding field corresponds to UDP, ICMP, and TCP next to the HC1 encoding field.

B. 6LoWPAN Packet Format

There are three types of 6LoWPAN header formats: dispatch, mesh, and fragmentation. All types of 6LoWPAN headers are orthogonal. The dispatch header indicates the information of

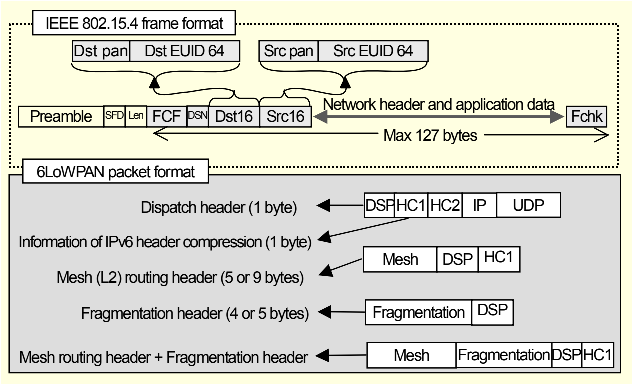

Fig. 1. Structure of a whole IEEE 802.15.4 frame including 6LoWPAN packet.

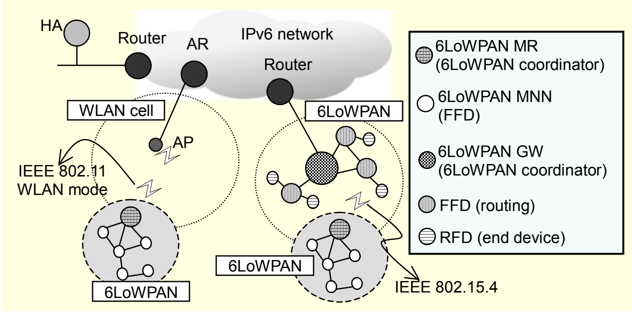

Fig. 2. Possible scenario of 6LoWPAN network mobility.

the next header. For example, a header compression (HC) dispatch indicates the information of the IP or UDP header, and a mesh header is used in mesh routing. A fragmentation header indicates the information for fragmentation and reassembly of the packet. All headers are followed by the dispatch header. The header for a new function can be included by newly defining a dispatch. A dispatch header has the following structure. If the 0 and 1 bits (the first 2 bits of the dispatch header) are 00, the next header is not a LoWPAN header. If they are 01, the next header is a dispatch header for IPv6, while 10 indicates a header for mesh routing, and 11 indicates a header for fragmentation. If the dispatch pattern is 01 000001, the following header is an uncompressed IPv6 header (40 bytes). If the pattern is 01 000010, the following IPv6 header is fully compressed from 40 bytes to 2 bytes. When more than one LoWPAN header is used in the same packet, they should appear in the following order: mesh, fragmentation, and HC header. The dispatch header appears before each header.

Figure 1 shows the whole structure of the IEEE 802.15.4 packet format including a 6LoWPAN packet. The maximum size of the packet is 127 bytes. The IPv6 header is fully compressed by HC1 and the UDP header is also fully compressed by HC2 dispatch header.

III. Problem Statement of 6LoWPAN

Figure 2 shows two NEMO scenarios that are possible in 6LoWPAN. First, the left scenario shown in Fig. 2 is a typical WiFi environment in which the NEMO Basic Support protocol with 6LoWPAN MR is applied. An egress interface of the 6LoWPAN MR to support IEEE 802.11 WLAN can be directly connected to the access router. However, we consider a scenario in which an egress interface of the 6LoWPAN MR can access IEEE 802.15.4 devices such as 6LoWPAN networks, as in the scenario shown to the right in Fig. 2. The 6LoWPAN MR in charge of 6LoWPAN network mobility has two IEEE 802.15.4 interfaces. The 6LoWPAN MR connects to the 6LoWPAN network through an egress interface and supports network mobility for 6LoWPAN mobile network nodes through an ingress interface. The 6LoWPAN gateway (GW) acts as a default Internet GW for 6LoWPAN MRs and 6LoWPAN sensor nodes.

Even though the network mobility concept is suitable for 6LoWPAN mobility, as in the NEMO Basic Support protocol, the current 6LoWPAN packet format cannot support efficient mobility for the 6LoWPAN MR. To support 6LoWPAN mobility, the 6LoWPAN MR needs to send a BU message and receive a BA message from its HA. However, the 6LoWPAN packet format only defines the fragmentation and mesh routing headers. Obviously, these messages are not sufficient to support the mobility of the 6LoWPAN MR because the structure of the 6LoWPAN packet has no solution to compress or support a mobility header for BU and BA messages. Therefore, we have to define a scheme to compress mobility headers in 6LoWPAN networks. To minimize the signaling overhead, a compressed mobility header can be used between the 6LoWPAN MR and the 6LoWPAN GW.

IV. Proposed Lightweight NEMO Protocol

This section discusses the proposed 6LoWPAN packet format to support the mobility header. We also propose a Lightweight NEMO protocol which is applicable to 6LoWPAN networks.

1. Compressed Packet Header Format to Support 6LoWPAN Mobility

The current 6LoWPAN packet format has not been designed to compress or support a mobility header for BU and BA messages. Therefore, we propose a compressed packet format to provide 6LoWPAN mobility in this subsection. To support mobility headers in 6LoWPAN packets, we need to define a new dispatch header pattern. Hence, a new pattern, LOWPAN_MH, is defined to add a compressed IPv6 mobility header to a dispatch. Table 1 shows various kinds of dispatch

Table 1. Dispatch header patterns.

Pattern	Pattern name	Pattern meaning
00xxxxxx	NALP	Not a LoWPAN frame
01000001	IPv6	Uncompressed IPv6 Addresses
01000010	LOWPAN_HC1	LOWPAN_HC1 compressed IPv6
01000011	LOWPAN_MH	LOWPAN_MH compressed IPv6 mobility header
···	Reserved	Reserved for future use
01010000	LOWPAN_BC0	LOWPAN_BC0 broadcast
···	Reserved	Reserved for future use
01111111	ESC	Additional dispatch byte follows

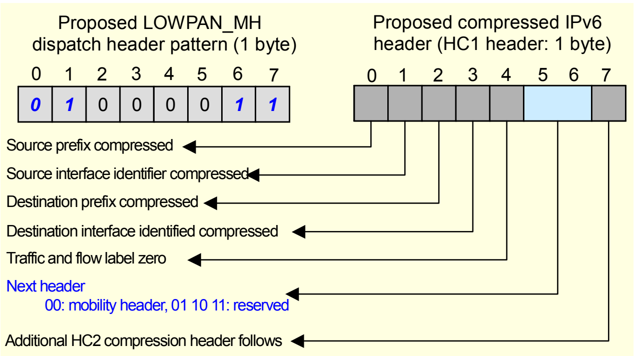

Fig. 3. Proposed LOWPAN_MH dispatch header pattern and compressed IPv6 HC1 header.

headers according to patterns. The pattern of 01000011 means that a mobility header is included. If the dispatch header pattern is 01000011, a BU or BA message is contained in the IEEE 802.15.4 frame.

If the dispatch header is setting up the LOWPAN_MH, the meaning of bits 5 and 6 in the HC1 dispatch should be interpreted differently. In other words, if the mobility header is included, the next header bits of the HC1 header have a different meaning. Figure 3 shows the proposed LOWPAN_MH dispatch header pattern and the compressed IPv6 header (proposed HC1). As shown in Fig. 3, the next header bits of the proposed HC1 have been modified to assign the IPv6 extension header. The reason is that the next header of the current HC1 dispatch header could be only assigned for UDP, TCP, and ICMP. If bits 5 and 6 in HC1 are 00, the next header indicates the proposed mobility header. Other values, such as 01, 10, and 11 are reserved for other extension headers. Therefore, the value 01000011 in LOWPAN_MH dispatch specifies that the following header is the proposed HC1 header and that the value of the next header field is 00.

The LOWPAN_MH header structure has 8 bits. The field definitions are as shown in Fig. 4. The value of bit 0 determines

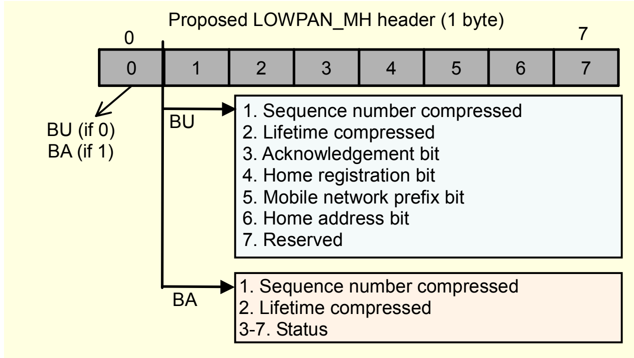

Fig. 4. Field definition of LOWPAN_MH header.

whether the following header is a BU or BA message.

If bit 0 is set to 0, the compressed BU message carries the information of bits 1 to 7. The LOWPAN_MH header format for the BU message can be summarized as follows:

- Sequence number (bit 1): 0 if non-compressed and 1 if compressed to 8 bits
- Lifetime (bit 2): 0 if non-compressed and 1 if compressed to 8 bits.
- Acknowledgement (bit 3): The acknowledge (A) bit is set by the sending the 6LoWPAN MR a request that a BA message be returned upon receipt of the BU message.
- Home registration (bit 4): The home registration (H) bit is set by the sending the 6LoWPAN MR a request that the receiving node should act as this node's HA.
- Mobile network prefix (bit 5): The mobile network prefix (MNP) bit is set to indicate to the HA that the BU message is from a 6LoWPAN MR. In the explicit mode, the MNP bit is set to 1. In explicit mode, the 6LoWPAN MNP should be included in the compressed BU message. In other words, if the mode is implicit, the MNP bit is set to 0, and the MNP field can be omitted.
- Home address (bit 6): The home address bit is set to include a home address of the 6LoWPAN MR in the compressed BU message.
- Reserved (bit 7): These fields are unused.

If bit 0 is set to 1, the compressed BA message carries the information of bits 1 to 7. The LOWPAN_MH header format for the BA message can be summarized as follows:

- Sequence number (bit 1): 0 if non-compressed and 1 if compressed to 8 bits.
- Lifetime (bit 2): 0 if non-compressed and 1 if compressed to 8 bits.
- Status (bits 3 through 7): Values in the status field less than 128 indicate that the BU message was accepted by the receiving node. Values greater than or equal to 128 indicate that the BU message was rejected by the receiving node. For descriptions of all the fields in the message, see [7].

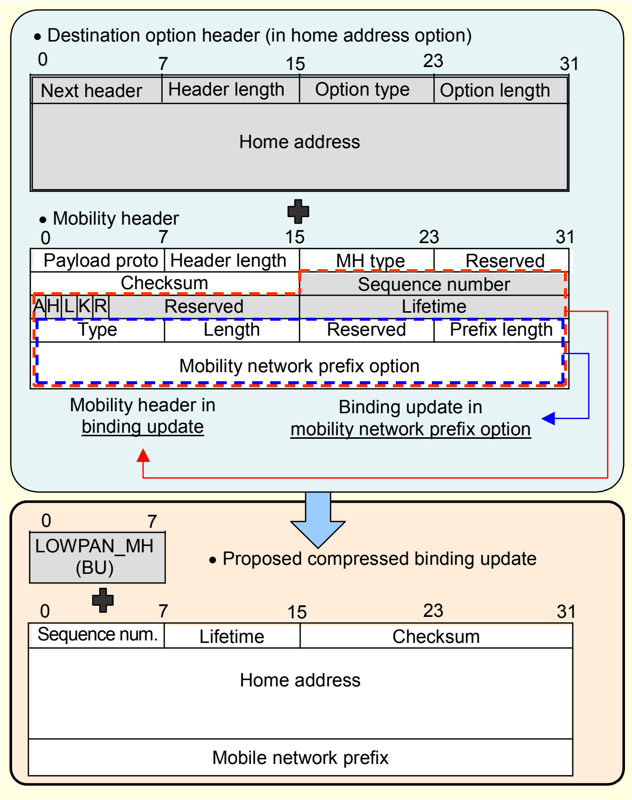

Fig. 5. Header format of proposed compressed BU compared with IPv6 extension headers related to the original BU message.

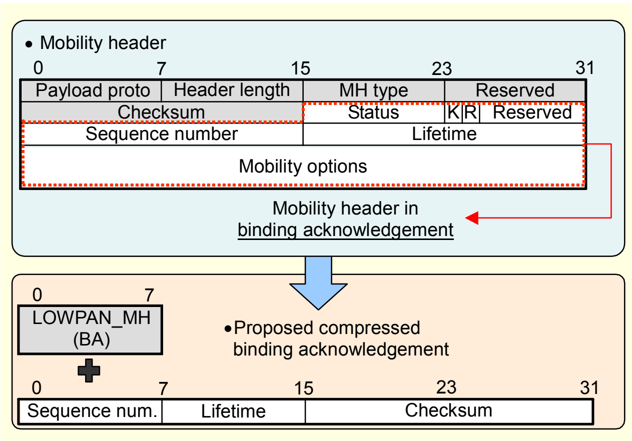

Fig. 6. Header format of proposed compressed BA compared with mobility header related to the original BA message.

In the case of the NEMO Basic Support protocol, when the 6LoWPAN MR sends a BU message to its HA, two extension headers should be included. A home address is included in the destination option header, and a BU message is included in the mobility header. To send the binding information, the overhead packet size is 40 bytes.

Figure 5 shows the header format of the proposed compressed BU compared with the IPv6 extension headers related to the original BU message. We compress the destination option header and the mobility header to generate a compressed BU message. To reduce the binding overhead, we propose a compressed BU message format. According to the above LOWPAN_MH dispatch header, the fully compressed BU message size can be 28 bytes. The checksum (2 bytes), home address (16 bytes), and mobile network (8 bytes) prefix fields cannot be compressed. The BA message is also compressed to reduce the binding overhead. As shown in Fig. 6, the size of the fully compressed BA message is 4 bytes, but an uncompressed BA message is 12 bytes.

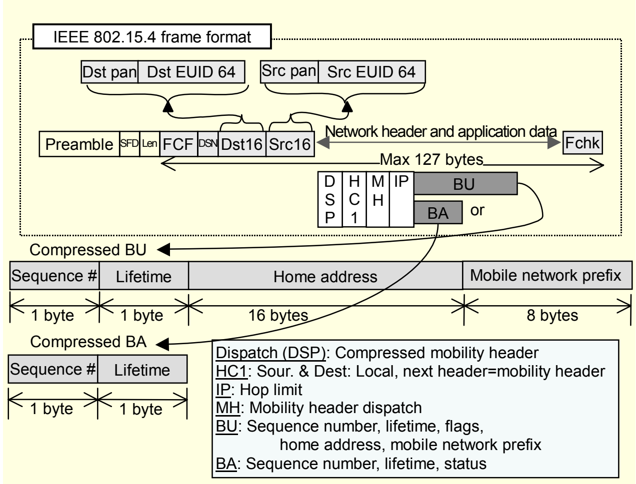

Fig. 7. Proposed whole structure of IEEE 802.15.4 frame format including a mobility header.

Figure 7 shows the proposed packet format of a whole IEEE 802.15.4 frame including a mobility header. The dispatch header indicates whether the following header includes the mobility header. If the next header of HC1 is a LOWPAN_MH, the 6LoWPAN MR can exchange the compressed BU and BA messages with the HA. The compressed mobility header can decrease the size of binding messages, and thus reduce the binding overhead.

2. Overview of Lightweight NEMO Protocol

A. 6LoWPAN GW (Gateway) Discovery

Our proposed Lightweight NEMO protocol can be employed in 6LoWPAN MR which can be attached to a fixed full function device (FFD) [4] in a 6LoWPAN network for connecting to the Internet or communicating with other 6LoWPAN sensor nodes directly. Whenever the 6LoWPAN MR moves to another PAN, a 16-bit address (which is available only within a PAN) will be assigned to the egress interface by the 6LoWPAN coordinator.

We assume that the 6LoWPAN GW is the 6LoWPAN coordinator. Figure 8 shows the scenario for 6LoWPAN GW

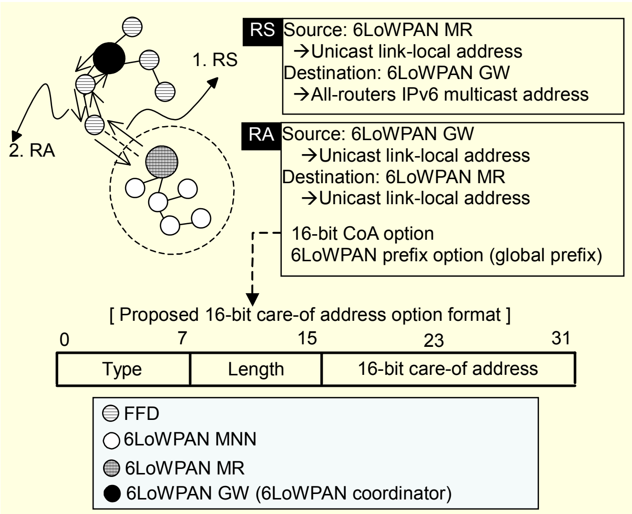

Fig. 8. 6LoWPAN GW discovery operation.

discovery in which the 6LoWPAN MR searches a gateway after moving into the 6LoWPAN network. The neighbor discovery protocol is applied limitedly in the 6LoWPAN network environment [8]. The 6LoWPAN MR obtains the current PAN ID information from the beacon messages. The PAN ID (16 bits) needs to be set to identify the PAN in environments with multiple IEEE 802.15.4 networks. Handoff for the 6LoWPAN MR is carried out in the link layer. If the 6LoWPAN MR detects movement to another PAN, then the 6LoWPAN MR sends a router solicitation (RS) message that the destination address has been set to the all-routers IPv6 multicast address. If the intermediate FFD nodes receive the RS packet, then they just relay the packet to the 6LoWPAN GW. When the 6LoWPAN GW receives the RS packet, it replies with an extended router advertisement (RA) message immediately. Both the source and destination addresses of the RA message are unicast link-local addresses. Therefore, the RA packet will be delivered directly to the 6LoWPAN MR. The RA message includes the global IPv6 prefix of the current 6LoWPAN network and the 16-bit care-of address option. The 6LoWPAN GW assigns a 16-bit address to the 6LoWPAN MR, and it has a list of all the 6LoWPAN nodes with 16-bit addresses. Therefore, the 6LoWPAN GW discovery described in this paper does not require the 16-bit address collision avoidance mechanism. The 6LoWPAN MR's CoA can be obtained by concatenating the prefix of the foreign 6LoWPAN link address, the PAN ID, and the assigned 16-bit address. The PAN ID and the 16-bit address are used as part of an IPv6 address. The 6LoWPAN MR's home address is an egress interface on the home 6LoWPAN link. The 6LoWPAN MR's MNP is also assigned to the ingress interface for the6LoWPAN mobile network. The home address and MNP are the 6LoWPAN MR.

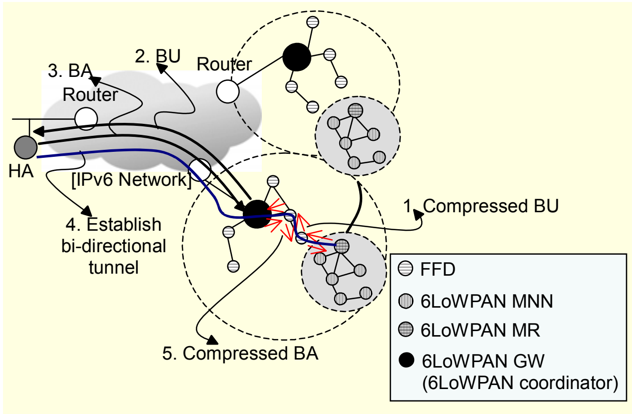

Fig. 9. Scenario of inter-PAN mobility.

Figure 8 shows the 16-bit care-of address option format in an RA message. When the RS and RA message exchange between the MR and GW is completed, the 6LoWPAN GW knows that the new 6LoWPAN MR is connected to the PAN area by extraction of the RS message which is performed by the 6LoWPAN GW. Also, the 6LoWPAN MR can get the 6LoWPAN GW address (the default gateway address in the PAN) from the RA message.

B. 6LoWPAN Mobility

To maintain the session connectivity and support global mobility to the 6LoWPAN mobile network, the 6LoWPAN MR should perform the home registration procedure to inform the HA of movement of the 6LoWPAN mobile network. In other words, whenever the 6LoWPAN MR moves to a new PAN area, binding messages should be exchanged, and a bi-directional tunnel between the 6LoWPAN MR and its HA should be established. From a sensor network mobility point of view, the binding procedure incurs the most energy consumption overhead in 6LoPWAN environments. The Lightweight NEMO protocol can minimize the signaling overhead between the 6LoWPAN MR and the 6LoWPAN GW by using the compressed mobility header.

Figure 9 shows a scenario of inter-PAN mobility. When the 6LoWPAN MR moves to another PAN area, it creates a compressed BU message based on the scheme for compressing the mobility header. Table 2 describes all the necessary headers to send a compressed BU. A mesh header is needed for multi-hop routing between the 6LoWPAN MR and the 6LoWPAN GW. Through the 6LoWPAN GW discovery operation, the 6LoWPAN MR is assigned a 16-bit care-of address from the 6LoWPAN GW. Also, the 6LoWPAN MR can discover the 6LoWPAN GW's 16-bit address by receiving an RA message from the 6LoWPAN GW. So, the original and final addresses in the mesh header are the 6LoWPAN MR's 16-bit address and the 6LoWPAN GW's 16-bit address, respectively. The

Table 2. All the headers necessary to send a compressed BU message.

Header	Main field	Data
Mesh header	Original address	6LoWPAN MR's 16-bit address
	Final address	6LoWPAN GW's 16-bit address
Dispatch (DSP)	-	01000011 (LOWPAN_MH compressed IPv6 mobility header)
IPv6 header compression (HC1)	Source address	0 (non-compressed)
	Destination address	0 (non-compressed)
	Next header	00 (mobility header)
LOWPAN_MH	Sequence number	1 (compressed)
	Lifetime	1 (compressed)
	Acknowledgement	1
	Home registration	1
	Mobile network prefix	1
	Home address	1
IPv6 header (IP)	Source address	6LoWPAN MR's CoA
	Destination address	HA's address
Compressed BU	Sequence number	Compressed sequence number
	Lifetime	Compressed lifetime
	Home address	6LoWPAN MR's home address
	Mobile network prefix	6LoWPAN MR's mobile network prefix

Table 3. All the headers necessary to send a compressed BA message.

Header	Main field	Data
Mesh header	Original address	6LoWPAN GW's 16-bit address
	Final address	6LoWPAN MR's 16-bit address
Dispatch (DSP)	-	01000011 (LOWPAN_MH compressed IPv6 mobility header)
IPv6 header compression (HC1)	Source address	0 (non-compressed)
	Destination address	0 (non-compressed)
	Next header	00 (mobility header)
LOWPAN_MH	Sequence number	1 (compressed)
	Lifetime	1 (compressed)
	Status	00000 (success)
IPv6 header (IP)	Source address	HA's address
	Destination address	6LoWPAN MR's CoA
Compressed BA	Sequence number	Compressed sequence number
	Lifetime	Compressed lifetime

following headers are proposed: LOWPAN_MH dispatch, HC1 and LOWPAN_MH. The details of their data are given in section IV.1. The source and destination addresses of the IPv6 header are the 6LoWPAN MR's CoA and HA, respectively. The compressed BU has the 6LoWPAN MR's home address and MNP information. If the 6LoWPAN MR creates the compressed BU message as shown in Table 2, it sends the message to its HA. The compressed BU message will be routed to the 6LoWPAN GW because the mesh header's final address is the 6LoWPAN GW's 16-bit address. Upon receipt of the compressed BU, the 6LoWPAN GW should decompress the compressed BU message in order to forward an original BU to the HA. If the HA receives the BU message, the home address of 6LoWPAN MR and the mobile network prefix are updated in the binding cache entry. After that, the HA has completed the steps to create or update the binding cache entry for the 6LoWPAN MR, and it sends a BA message to the 6LoWPAN MR. At the same time, a bi-directional tunnel is established between the HA and the 6LoWPAN MR's CoA. After receiving the BA the 6LoWPAN GW should compress the original BA in order to forward a compressed BA message to the 6LoWPAN MR. If the value of the status of the compressed BA message is 0, it means that the home registration procedure has successfully been finished. Table 3 describes in detail all the headers that are necessary to send a compressed BA message. The signaling overhead can be reduced by using the compressed binding messages. Therefore, in the 6LoWPAN sensor network environment, the proposed Lightweight NEMO is more suitable than the NEMO Basic Support protocol.

Intra-PAN mobility means that a 6LoWPAN MR moves within the same 6LoWPAN network. The 6LoWPAN MR is able to detect whether it is still in the same PAN area or has moved to another PAN by comparing the current PAN ID with the previous PAN ID in the beacon message. In the case of intra-PAN mobility, the 6LoWPAN MR only performs the routing protocol to support multi-hop communication to update the routing path. Also, it is not necessary to allocate CoA or 16-bit addresses.

C. Architecture of the 6LoWPAN GW, 6LoWPAN MR, and HA

Figure 10 shows the functional architecture of the 6LoWPAN GW, the 6LoWPAN MR, and the HA, and the operation of exchanging the binding messages between them.

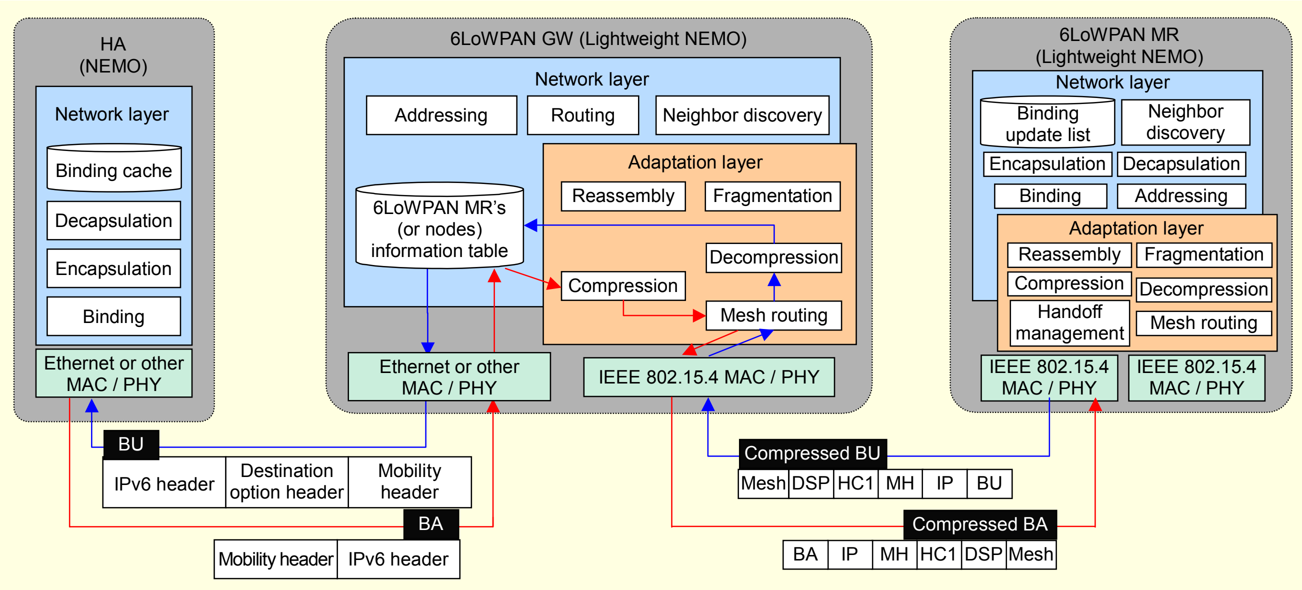

Fig. 10. Functional architecture and operation of exchanging binding messages.

The 6LoWPAN GW needs two network interfaces for interoperability between 6LoWPAN and external IPv6 networks. In the adaptation layer, the main functions are mesh routing, compression/decompression, and fragmentation/reassembly. Multi-hop routing is supported by the mesh routing function. The compression/decompression of the IPv6 header performs the compression or decompression of BU and BA messages. The fragmentation/reassembly to satisfy IPv6 MTU of 1,280 bytes fragmentize the incoming IPv6 packet from the IPv6 networks and reassemble the outgoing IPv6 packet from the 6LoWPAN. In the network layer, the addressing function assigns 16-bit addresses to the 6LoWPAN MR or nodes. Neighbor discovery exchanges RS and RA messages. The 6LoWPAN GW stores the list of all the 6LoWPAN MRs or nodes in a PAN with 16-bit addresses in the information table.

The 6LoWPAN MR has two IEEE 802.15.4 interfaces. The 6LoWPAN MR is connected to the 6LoWPAN network by the egress interface and supports network mobility for 6LoWPAN mobile network nodes by the ingress interface. In the adaptation layer, the main functions are similar to those of the 6LoWPAN GW. The handoff management decides whether the 6LoWPAN MR is in a new PAN area or the same PAN area by overhearing the beacon message. In the network layer, the neighbor discovery and addressing functions are also similar to those of the 6LoWPAN MR. In the binding function, the 6LoWPAN MR sends the BU message to the HA, and the 6LoWPAN MR receives the BA message from the HA. The encapsulation/decapsulation module supports the establishment of a bi-directional tunnel between the 6LoWPAN MR and the HA. The binding update list records entry information which was sent in the binding updates.

The HA uses the conventional NEMO protocol. The HA maintains binding cache entries for each 6LoWPAN MR currently registered with the HA. The encapsulation/decapsulation module supports the establishment of a bi-directional tunnel between the 6LoWPAN MR and the HA. In the binding function, it sends the BA message to the 6LoWPAN MR or receives the BU message from it.

V. Performance Analysis

To evaluate the performance of our proposed scheme we calculate the total signaling cost (in the number of packets) and the handoff delay for both intra-PAN and inter-PAN movement. As there is no known solution of NEMO applied to 6LoWPAN, the Lightweight NEMO protocol has been evaluated alone. We have adopted the random walk mobility model [9] to characterize the movement of the 6LoWPAN MR. Table 4 shows the parameters used in the analysis and their typical values. The parameter values for the analysis are referenced from [10]-[14].

1. Total Signaling Costs

To calculate the total signaling costs, we have used the random walk mobility model for the 6LoWPAN MR. Under this model, the 6LoWPAN MR moves with a particular speed and in a particular direction for a given interval. It stays within the current PAN with probability p and moves to another PAN with probability 1-p. This can be modeled with the following Markov chain as depicted in Fig. 11. Note that even though there are N PANs, from an operational point of view, the

Table 4. Parameters used in the analysis and their typical values.

Symbol	Meaning
τ , κ	Transmission costs in wired and wireless link, respectively
$D_{MR\text{-}GW}$, $D_{GW\text{-}HA}$	Distance between MR and GW, and between GW and HA in hops, respectively
C_{GW}, C_{HA}	Processing costs for binding procedures at the GW and HA, respectively
$BW_{wireless}$, BW_{wired}	Bandwidth of wired (100 Mbps), and wireless links (250 kbps), respectively
$L_{wireless}$, L_{wired}	Latency of wireless links (2 ms), and wired (0.5 ms), respectively: propagation delay + link layer delay
H_{pan} , H_{GW_HA}	Distance between MR and GW, and between GW and HA in hops, respectively
t_s	Time to configure/process a signaling message (1 ms) [13]
t_r	Routing-table look-up and processing time for a packet in every hop (0.001 ms) [14]
P_x	IP packet length of a signaling message x

Markov chain has only two states. Therefore, the transition probability matrix is given as

$$p_{ij} = \begin{bmatrix} p & 1-p \\ 1-p & p \end{bmatrix}. \quad (1)$$

Let π_0 and π_1 be the long term steady state probabilities that represent a 6LoWPAN MR which stays within the same PAN (intra-PAN mobility) and one which moves to a different PAN (inter-PAN mobility), respectively. So, the following equations are valid:

$$\pi_0 + \pi_1 = 1, \quad (2)$$

$$\pi_0 = p\pi_0 + (1-p)\pi_1 , \quad (3)$$

$$\pi_1 = (1-p)\pi_0 + p\pi_1 . \quad (4)$$

Solving these equations we obtain π_0 and π_1 for any values of p.

According to the states, Lightweight NEMO needs to exchange binding and neighbor discovery messages. Therefore, the expected total signaling cost of the proposed protocol can be calculated by

$$C_{\text{total}}^{\text{LW-NEMO}} = \frac{\pi_0 \cdot C_{\text{intra-PAN}} + \pi_1 \cdot C_{\text{inter-PAN}}}{T}, \quad (5)$$

where, $C_{\text{intra-PAN}}$, $C_{\text{inter-PAN}}$, and T are the intra-PAN mobility cost, the inter-PAN mobility cost, and the average resident time of the 6LoWPAN MR, respectively. In case of Lightweight NEMO, when the 6LoWPAN MR moves to another PAN, it requires binding and neighbor discovery messages; therefore, the inter-PAN mobility cost is calculated as

$$C_{\text{inter-PAN}} = C_{\text{nd}}^{\text{LW\_NEMO}} + C_{\text{binding}}^{\text{LW-NEMO}} , \quad (6)$$

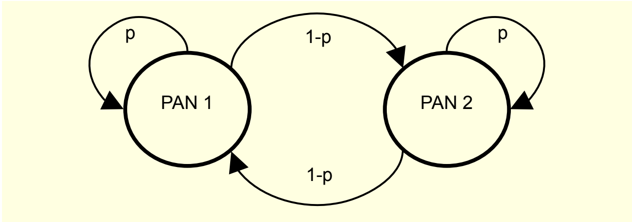

Fig. 11. State diagram for random walk mobility model.

where $C_{\text{nd}}^{\text{LW\_NEMO}}$ and $C_{\text{binding}}^{\text{LW\_NEMO}}$ are the neighbor discovery cost and the binding cost, respectively. If the 6LoWPAN MR stays within the same PAN, it requires only routing messages. We assume that both intra-PAN and inter-PAN mobility have no relation to routing cost; therefore, there is no cost for intra-PAN mobility. The signaling cost of inter-PAN mobility is greater than that of intra-PAN mobility. Therefore, $C_{\text{nd}}^{\text{LW\_NEMO}}$ and $C_{\text{binding}}^{\text{LW\_NEMO}}$ can be calculated as

$$C_{\text{nd}}^{\text{LW-NEMO}} = 2(D_{\text{MR-GW}} - 1) \cdot \kappa + C_{\text{GW}} , \quad (7)$$

$$C_{\text{binding}}^{\text{LW-NEMO}} = 2(D_{\text{MR-GW}} - 1) \cdot \kappa + C_{\text{GW}} + 2(D_{\text{GW-HA}} - 1) \cdot \tau + C_{\text{HA}} , \quad (8)$$

where τ and κ are the unit transmission costs in a wired link and a wireless link, respectively. In general, since the transmission cost in a wireless link is greater than that in a wired link, τ is larger than κ.

For numerical calculations, we use the following parameter values used in [11] and [12]: τ=1, κ =2, $D_{GW\text{-}HA}$=6, C_{GW}=12, and C_{HA}=24.

Figure 12 shows the variation in the total signaling costs when the distance between GW and MR is 3 and 8 hops, with various average PAN resident times using the random walk mobility model. In the case of inter-PAN mobility, the Lightweight NEMO protocol compresses the binding headers and omits the duplicate address detection (DAD) [2] procedure from the signaling messages. Intra-PAN mobility only requires routing messages. Therefore, for larger values of π_1, the total signaling cost, that is, the increase in the probability of inter-PAN movement, also increases the total signaling cost for the proposed protocol. The total signaling cost is reduced as the average resident time of 6LoWPAN MR increases.

2. Handoff Signaling Delay

The total handoff signaling delay the ($D_{handoff}$) is the sum of the delay of movement detection (T_{md}), the delay of CoA configuration and DAD (T_{dad}), and the delay of binding message exchange ($T_{binding}$):

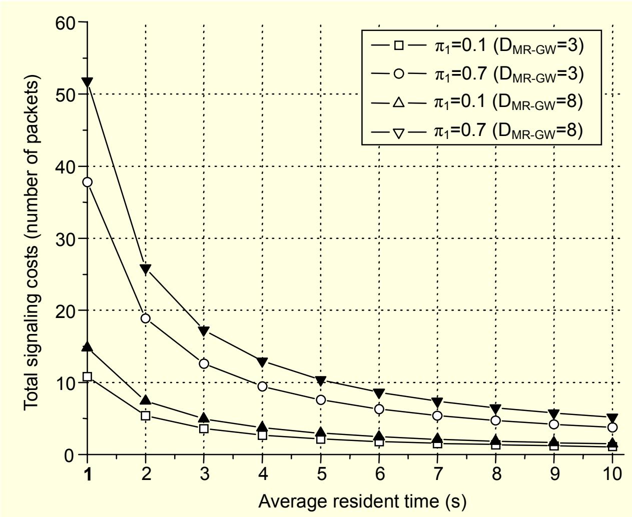

Fig. 12. Total signaling costs as a function of average resident time (random walk mobility model).

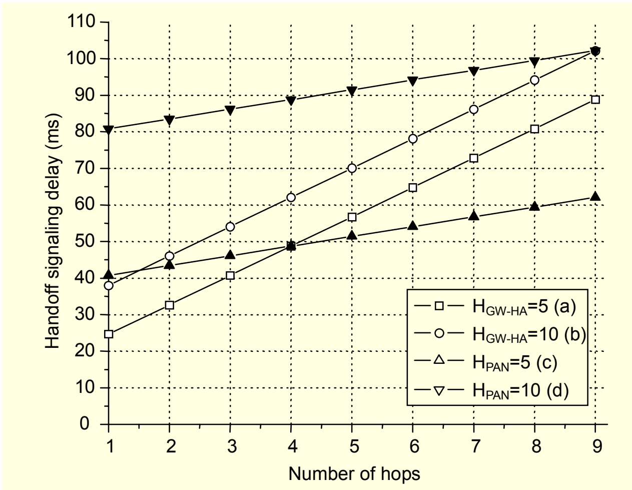

Fig. 14. Handoff signaling delay for Lightweight NEMO vs. number of hops between 6LoWPAN MR and GW in (a) and (b), and between 6LoWPAN GW and HA in (c) and (d).

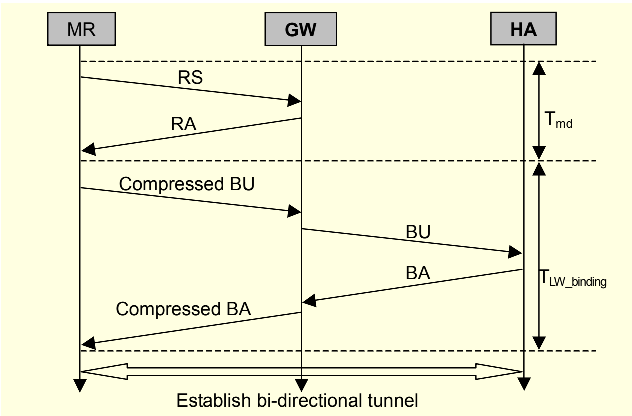

Fig. 13. Proposed lightweight NEMO protocol signaling flow for the handoff procedure.

$$D_{handoff} = T_{md} + T_{dad} + T_{binding}. \qquad (9)$$

Figure 13 shows the proposed Lightweight NEMO protocol signaling flow for the handoff procedure. The handoff signaling delay of the Lightweight NEMO protocol is given as

$$D_{handoff}^{LW-NEMO} = T_{md} + T_{LW\_binding}. \qquad (10)$$

The component delays are then expressed as

$$T_{md} = \left[2t_s + \sum_{H_{pan}} \left(\frac{P_{rs} + P_{ra}}{BW_{wireless}} + 2t_r + 2L_{wireless} \right) \right], \qquad (11)$$

$$T_{LW\_binding} = \left[2t_s + \sum_{H_{pan}} \left(\frac{P_{compressed\_bu} + P_{compressed\_ba}}{BW_{wireless}} + 2t_r + 2L_{wireless} \right) \right] + \left[2t_s + \sum_{H_{GW\_HA}} \left(\frac{P_{nemo\_bu} + P_{nemo\_ba}}{BW_{wired}} + 2t_r + 2L_{wired} \right) \right]. \qquad (12)$$

When the 6LoWPAN MR moves to another PAN area, it performs movement detection by exchanging the RS and RA messages with the 6LoWPAN GW. After that, the 6LoWPAN MR uses the assigned 16-bit address from the RA message. The protocol can skip the DAD procedure (T_{dad}) including the exchange of neighbor solicitation and neighbor advertisement messages. Then, the 6LoWPAN MR sends a compressed BU message to the 6LoWPAN GW for home registration. If the 6LoWPAN GW receives the compressed BU message, it forwards an original BU message to the HA of the 6LoWPAN MR. After that, the HA sends a BA message to the 6LoWPAN GW. When the compressed BA message is received via the 6LoWPAN GW, the 6LoWPAN MR handoff procedure is completed.

To evaluate our scheme in terms of the handoff signaling delay, we used some parameter values given in [10], [13], and [14]. The lengths of the signaling messages are given in [2], [5]-[7].

Figure 14 shows the handoff signaling delay of the proposed protocol. The handoff signaling delay increases linearly with the number of hops. The Lightweight NEMO protocol does not need to perform the DAD procedure. Also, the size of signaling messages such as BU and BA messages can be reduced by using the compressed mobility header scheme within the 6LoWPAN network. As shown in Fig.14, the total handoff latency has a greater impact on the signaling delay within a PAN than in wired networks. Therefore, to improve the overall handoff performance, the signaling overhead should be reduced, especially within a PAN.

VI. Conclusion

In this paper, we proposed a compressed packet header format to support the mobility of 6LoWPAN. Also, we proposed 6LoWPAN GW discovery and the Lightweight NEMO protocol to minimize the signaling overhead between the 6LoWPAN MR and the 6LoWPAN GW by using the compressed mobility header. The compressed mobility header can decrease the size of binding messages, thus reducing the binding overhead. Performance results show that our Lightweight NEMO protocol is capable of minimizing the total signaling costs and the handoff signaling delay. In our future works, we will evaluate the performance of our proposed scheme under various mobility models and implement the architecture proposed in this paper.

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