Mobility in 6LoWPAN

Qizhe Cai
qizhec@cs.princeton.edu

Abstract

The IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs) standard [3] enables heavily restricted IoT devices (such as wireless sensors) to connect to IPv6 networks. It is interesting to investigate how IPv6-based mobility management protocols, such as Mobile IPv6 and Proxy Mobile IPv6 are implemented on wireless sensors using the 6LoWPAN standard. In this paper, we will describe the network architecture of these IP based mobility protocols over the 6LoWPAN layer, explain how different routing schemes affect the deployments of these mobility protocols on mobile sensors and routers and what aspects can be improved in the future.

1 Introduction

Wireless Sensor Networks(WSNs) have been widely used in a large range of applications like home automation, nuclear reactor control, traffic monitoring and health care. Sensors are low-cost and operate at low power. In order to support communication within WSNs, IEEE 802.15.4 standard defines a wireless link for low-power wireless personal area networks(LoWPAN). A key characteristics of IEEE 802.15.4 is the small size of MTU(127 bytes). The overhead of the physical layer is 25 bytes and the overhead imposed by the link-layer security is 21 bytes. There are only 81 octets available for upper layers. It is difficult to transmit IPv6 packets through IEEE802.15.4 since the overhead of IPv6 is 40 bytes and leaves only 41 bytes available, while the MTU of IPv6 is 1280 bytes. In order to support IPv6 over IEEE 802.15.4 networks, the IETF proposes the 6LoWPAN adaption layer which lays above the MAC layer and under the network layer (Fig. 1). The 6LoWPAN adaption layer enables IPv6 packets to be effectively transferred in the small link layer frame, such as frames defined by Bluetooth and IEEE 802.15.4 [5]. The details of 6LoWPAN adaption layer are explained in Section 2. The 6LoWPAN adaption layer also allows IP-based mobility protocols such as MIPv6 and PMIPv6 to be applied on wireless sensors as well. Sensors are no longer confined in the same network and can move across different networks.

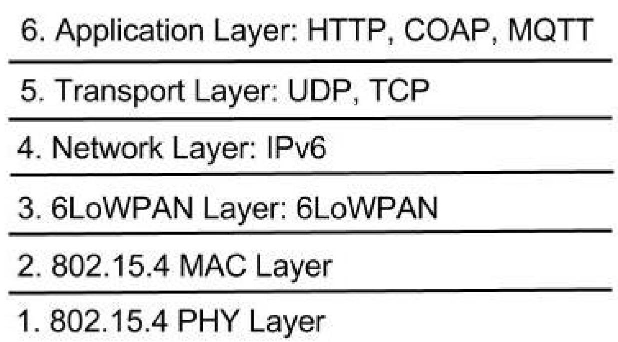

Figure 1: 6LoWPAN Network Stack

2 The 6LoWPAN Adaption Layer

The 6LoWPAN adaption layer is the level of optimization of transporting IPv6 packets through lossy and low-power networks, such as IEEE 802.15.4 networks and Bluetooth networks. The 6LoWPAN standard defines a mesh addressing header (used for mesh_under routing), a fragmentation header and compressed IPv6 and UDP headers (Fig. 2). All these sub-headers are optional and can be removed if not needed.

2.1 Mesh Addressing

The 6LoWPAN layer allows mesh-under routing within a PAN, by providing a mesh addressing header. The header contains the originator and final destination addresses which are link-layer addresses

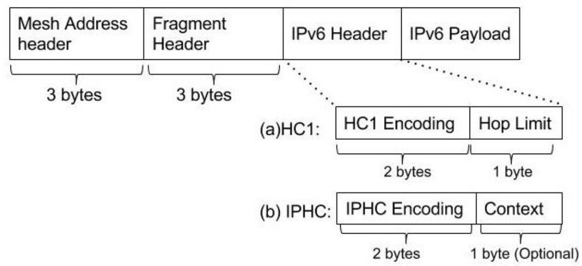

Figure 2: 6LoWPAN Header Format

(EUI-64 addresses or 16-bit short addresses). These two addresses keep unchanged during transmission, while the source and destination fields in link-layer headers are modified at each router. The details of mesh-under routing is explained in the section 3.

2.2 Fragmentation

The MTU of IEEE 802.15.4 frame is 127 bytes, but the MTU of IPv6 packets is 1280 bytes [5]. In order to achieve IPv6 packet transimission over IEEE 802.15.4, entire IPv6 datagrams including IPv6 headers are segmented into smaller fragments. This fragmentation happens after IP layer fragmentation.

2.3 Header Compression

Using fragmentation may increase the loss rate and latency; retransmisson due to the loss of fragments also increases energy consumption of nodes. Certainly, reducing the usage of fragmentation is crucial for saving the power of sensors. Using a proper header compression scheme is one way to reduce the usage of fragmentation. The key idea of the header compression is to elide header fields that can be inferred from the link layer or are some common values. Any header fields that cannot be compressed are carried in-line after the compressed header. For example, the Hop Limit field in the IPv6 header can be compressed to two bits if the Hop Limit value is 1, 64 or 255 [5]. Any other value of Hop Limit should be carried in-line. Header compression is used for the IPv6 header and the UDP header. Here, we focus on discussing IPv6 header compression.

The most important compression is the IPv6 address compression. There are two modes of header compression: stateless header compression (LOWPAN_HC1 and LOWPAN_HC2) and context-based compression (LOWPAN_IPHC) [3, 5].

Stateless header compression elides the prefix of IPv6 address assuming the prefix is link-local and the Interface Identifier(IID) which is inferred from the link layer address (eg. IEEE 802.15.4 address). At the best case, the stateless compression compresses IPv6 packets from 40 bytes to 3 bytes. Stateless header compression is the most effective on link-local communication since it can only omit the link-local IPv6 prefix. If stateless header compression is used for the global communication, the global IPv6 prefixes of destination and source IP address must be in the header as well [3].

Context-based header compression, for efficient compression of unique local, global, and multicast IPv6 Addresses, is based on shared states within contexts [3]. In a "context", an address or prefix is identified by a Context Identifier (CID), which is then used as a shortcut for a source or destination address in header compression [8]. The context can map to a 64-bit, 112-bit IP prefix or a 128-bit full IP address. There are at most 16 prefixes within a 6LoWPAN network. The mapping between prefixes and context IDs is shared within all routers and hosts in a 6LoWPAN network. Instead of the full IP prefix, only 4-bit context ID is needed to be carried in-line.

2.4 Neighbor Discovery in 6LoWPAN

RFC 6775 [8] defines a special Neighbor Discovery Optimization mechanism for 6LoWPANs to reduce energy consumption of the nodes and routers. The key idea is to reduce the use of multicast and make periodic Router Advertisements optional. Instead, hosts send unicast Router Solicitations (except the first Router Solicitation) to get and maintain their IP prefixes. In the context of Neighbor Discovery for 6LoWPAN, 6LBRs (6LoWPAN Border Routers) are responsible for propagating and maintaining the mapping between IPv6 prefixes and contexts within the network. All nodes within a 6LoWPAN network should have a complete and valid mapping between IP prefixes and context IDs.

When first attaching to a 6LoWPAN network, a host first send a multicast Router Solicitation message for requesting a global IP prefix. Once receiving the RS, routers always send back unicast Router Advertisements to hosts. Router Advertisements retain the existing Prefix Information Options and one or more 6LoWPAN Context Options that carry the mapping between context IDs and prefixes [8].

After receiving a Router Advertisement, a host creates a global IPv6 address using the prefix included in the RA message and sends a Neighbor Solicitation to register the created IPv6 address. Upon reception, the access router use special duplicate address detection mechanism to check whether the created address is available. If the address is available, the router registers the tuple (link layer address / IPv6 address of the node) in its neighbor cache and sends back a Neighbor Advertisement with the address registration option including the registration status. If the registration is successful, the host starts to use the configured IPv6 address. The host continues to periodically send Neighbor Solicitations to keep the router inform of their presence. It also periodically sends Router Solicitation messages to update the prefix information and the context information.

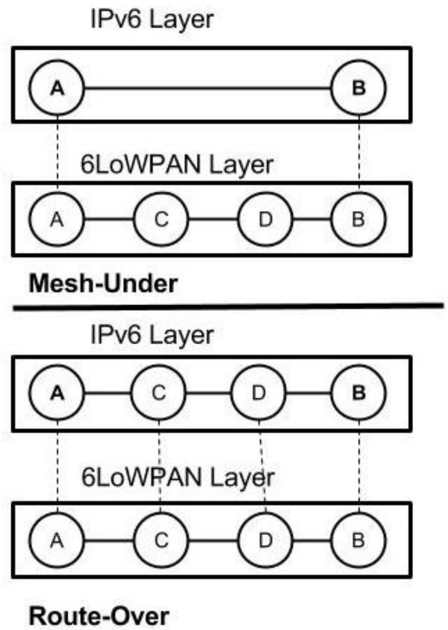

Figure 3: Mesh Under Vs Route Over

3 Routing

There are two categories of routing schemes within the PAN: mesh-under or route-over. The mesh-under routing uses link-layer addresses for routing on the 6LoWPAN layer, while the route-over routing uses IPv6 addresses for routing on the network (IP) layer.

3.1 Mesh-Under Routing

In a mesh-under routing system, to send packets to a particular destination, a node specifies the final destination in the mesh addressing header. When receiving a packet, a router forwards packets by changing the destination field in the link-layer header to the next router or final destination based on the forwarding table. The forwarding mechanism is similar as the IP forwarding. The distance between any two nodes within the network is considered one IP hop away, while multiple link layer hops are used to complete this hop (Fig. 3). Under mesh-under routing, fragmentation of packets if needed is done by senders. Then, different fragments of a single packet can go through different paths and they are reassembled at the final destination. Fragmentation or Reassembly only happens at the source or the destination.

3.2 Route-Over Routing

In a route-over scheme, routing is based on the IP address on the network layer. Each hop on the link-layer is an IP hop [1]. Since routing is happened on the network layer, fragmentation and reassembly of IP packets on the 6LoWPAN layer if needed should happen on each IP hop. On each hop except the source and the destination, the adaption layer reassembles all fragments of a IP packet and send the packet to the network layer; The network layer forwards the packet based on the routing information table and before forwarding, fragmentation of the packet happens again in order to satisfy the MTU requirement of IEEE 802.15.4.

4 Mobility Protocol Over 6LoWPAN

There are two categories of the mobility management protocols: host-based mobility protocols and network-based mobility protocols. In host-based mobility protocols such as MIPv6, data messages as well as mobility-related signaling messages are handled by mobile nodes directly. In network-based mobility protocols such as PMIPv6, localized mobility management is supported by some third parties (eg. access routers) rather than mobile nodes. In this paper, we focus on MIPv6 over 6LowPAN, PMIPv6 over 6LowPAN, the difference between these twos and what problems they have.

4.1 MIPv6 over 6LoWPAN

The mobile IPv6 protocol allows nodes to remain reachable while moving around in the IPv6 internet. Home agents redirect IPv6 packets sent to or originated from mobile nodes. A mobile node(MN) maintains two IPv6 addresses: the home address and the care-of address [6]. While the mobile node in the home network, it communicates with a correspondent node(CN) by standard IPv6 protocol and only uses its home address [6]. While out of the home network, the MN acquires a care-of address from the current local network it resides as its locator and uses its home address as its identifier [6]. The details of communication between a MN and a CN are explained below:

4.1.1 Home Agent Registration

Using Neighbor Discovery mechanism in 6LoWPAN networks explained in 2.4, a MN configures its care-of address in the foreign network. Then, the MN sends a Binding Update (BU) message to its home agent [6]. Its home agent registers MN 's primary care-of address contained in the BU message and sends a Binding Acknowledgement (BA) to the MN [6] (Fig. 6). BUs and BAs contain additional IPv6 extension headers such as the Destination Option header, Routing Option header and Mobility header. Also, BU and BA messages are encrypted through the mechanism called the Encapsulating Security Payload(ESP). Using extension headers and ESP headers increase the overhead of packets.

4.1.2 Data Flow

No Router Optimization: packets from a CN, that does not have a Binding Cache entry for a MN, are sent to MN's home address first and tunneled to the MN. Similarly, packets sent by the MN will be tunneled to the home agent first and then sent to the CN (Fig. 4). The extra overhead of packets is due to IPv6 tunneling.

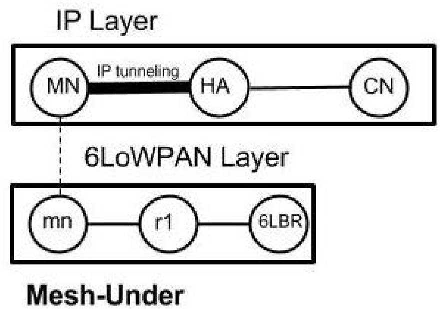

Figure 4: Data Traffic without Route Optimization

Under Router Optimization: a MN and a CN can create the binding using the similar way as home agent registration procedure so that the traffic between the MN and the CN does not go through MN's home agent. Once the binding has been established, instead of using IPv6 encapsulation, the MN or the CN uses IPv6's destination option or routing option to specify MN's home address. The extra overhead comes from the routing option header or the destination option header.

4.2 PMIPv6 over 6LoWPAN

PMIPv6 protocol [2] defines four members: Local Mobility Anchor(LMA) which serves as the home agent of mobile nodes, Mobile Access Gateway(MAG) which serves as a proxy for MNs sending or receiving packets, Mobile Node(MN) and Correspondent Node(CN). Unlike Mobile IPv6, Proxy Mobile IPv6 is designed to provide network-based IP mobility management support for MNs [2]. Mobility related events are not handled by MNs. Instead, Mobility entities (i.e. LMA and MAG) track the movement of MNs and send signaling messages to others. From the point of view of a mobile node, the Proxy Mobile IPv6 domain is displayed as a single link [2]. The IPv6 header format for packets sending from MNs to CNs is the standard IPv6 format, without IP tunneling. Packets are encapsulated or decapsulated for IP tunneling on either its LMA or its MAG.

4.2.1 Home Registration

When a MN enters a foreign network and connects to a link, the mobile access gateway (the MN's access router), first identifies and verifies the MN and acquires MN's identity(MN-ID) and profile, containing its LMA(Home) address (Fig. 7). Unlike Mobile IP which requires the MN to establish a binding to its home agent, PMIPv6 specifies its MAG to maintain the binding and the tunnel to its LMA on behalf of the MN. As part of the process of standard IPv6 neighbor discovery, the MN sends a Router Solicitation in the access link [8]. After receiving a Router Solicitation from the MN, the MAG sends Proxy Binding Update message to the LMA [2]. If its LMA accepts the binding update, it will send back Proxy Binding Acknowledgement containing a set of home-network prefixes for the MN to configure its IP address.

4.2.2 Data Flow

A MN first sends packets destined to a CN to its MAG; the packet format is the same as the normal IPv6 header. Then its MAG tunnels packets to its LMA. The LMA decapsulates packets and directs packets to the CN. The CN sends back packets by the reverse path. There is no route optimization defined in PMIPv6 protocol so traffic cannot directly go from the MN to the CN or from the CN to the MN. However, there is one exception. If there is a local connected path between the mobile node and the corresponding node, the MAG may route the packet locally to optimize the delivery effort and not transmit it back to the anchor.

4.2.3 Home Network Emulation

The MAG is responsible for emulating the MN's home network on the accessed link. It must ensure that the MN even after changing the connection point will not detect any change in connectivity of the network layer [2]. PMIPv6 requires all MAGs in the Proxy Mobile IPv6 domain to use the same link-local and link-layer address on any access link that is attached to a particular MN [2]. One method is that MAGs in the entire Proxy Mobile IPv6 domain can configure a fixed IP and link-layer address in the links that access all mobile nodes [2]. In addition, the LMA may generate a link-local address of the MAGs with a particular MN and provide this address as a part of the signaling messages to MAGs.

4.2.4 Neighbor Discovery in PMIPv6 over 6LoWPAN

As mentioned in Section2.4, in order to save the energy of devices, IETF proposes Neighbor Discovery Optimization for 6LoWPAN networks. It turns out that some parts of Neighbor Discovery are unnecessary for devices in the PMIPv6 domain. In the PMIPv6 domain, MNs need the mapping between contexts and IPv6 prefixes only if correspondent nodes are within the 6LoWPAN network, since the home network prefixes of MNs unlikely have corresponding context IDs as there are only sixteen contexts available in total. So it is unnecessary for Router Advertisement messages to carry information related to the mapping between contexts and IP addresses. In a 6LowPAN network, the host triggers sending NS messages containing an Address Registration Option when a new address is configured, when it discovers a new default router, or well before the Registration Lifetime expires [8]. However, MNs using PMIPv6 protocol doesn't register their IP addresses within the 6LoWPAN networks, since these addresses are belonged to MNs' home networks and should be only visible to MNs and their MAGs within the 6LoWPAN networks. Also, a MN never discovers a new default router within the PMIPv6 domain after it has already attached to the network, due to the home network emulation explained in 4.2.3. A MN may still need to send NS messages well before the Registration expires for notifying its reachability to its MAG, since its MAG needs to detect the detachment of the MN and deregisters the binding.

4.2.5 MAG Roles on the 6LoWPAN Layer

Under mesh-under routing, routers except 6LBRs inside a 6LoWPAN network are on the 6LoWPAN layer, do not have their IP addresses and do not inspect headers above the 6LoWPAN layer. However, signaling messages like Routing Solicitation messages or Routing Advertisement messages or IPv6 tunneling data packets should be handled on the network layer and MAGs need global IPv6 addresses in order to receive these messages from LMAs. One possible solution is to choose 6LBRs as MAGs under mesh-under scheme (Fig. 5). Also within the PAN, only one 6LBR can be the MAG. In order to emulate the home network as explained in 4.2.3,

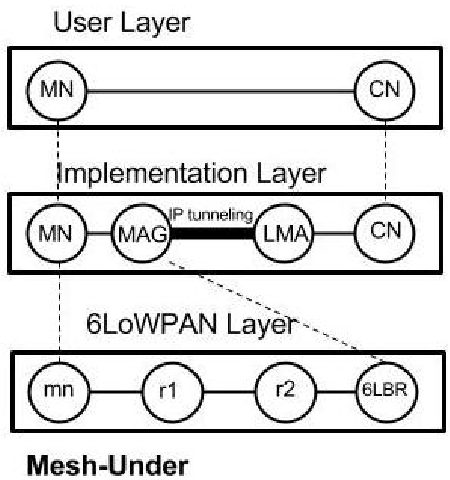

Figure 5: PMIPv6 Data Flow Under Mesh-Under Routing: Both User and Implementation Layer are IP layers.

PMIPv6 requires all mobile access gateways to use the same link-layer address on any of the access links [2]. If multiple 6LBRs becomes MAGs, the duplicate address problem will occur. However, becoming a MAG may impact the performance of the 6LBR which is already responsible of IPv6 routing, IPv6 prefix management and header compression. Under route-over schemes, a MAG is the first-hop router (the access router) as defined in [2].

4.3 Packet Overhead

After applying the header compression scheme of 6LoWPAN to Mobile IPv6 or PMIPv6, the size of packets may be still larger than the MTU of IEEE 802.15.4. In the MIPv6 protocol, after applying the header compression, the overhead of a Binding Update message or a Binding Acknowledgment message above the link layer is at least 108 bytes due to the use of the IPsec header and the Route or Destination Option header. Without Route Optimization, the overhead of data packets is at least 59 bytes, caused by the usage of IP tunneling. Under Route Optimization, the overhead reduces to 43 bytes. In the PMIPv6 protocol, the size of a Binding Update or a Binding Acknowledgement is at least 283 bytes which is larger than the size of MIP's mobility signaling. Since PMIPv6 uses IP tunneling for transmission data packets between LMA and MAG, the overhead of packets is at least 59 bytes.

The header compression mechanism is not effective on reducing the overheads of these two protocols. Due to the increase size of overheads, packets may be frequently fragmented on the 6LoWPAN layer. Under mesh-routing, 6LoWPAN provides the mesh header for routing, where destination and source addresses are link-layer addresses. When a node (eg. mobile node or MAG) within a 6LowPAN communicates with another node (eg. a correspondent node or a Home Agent) outside 6LowPAN, all fragments of a packet should be sent and resembled at any of 6LBRs, since compressed header is only meaningful within the 6LoWPAN. This can be done by setting the destination address in mesh addressing header to the link layer address of one 6LBR. After reassembling packets, the 6LBR should decompress headers and send packets to the destination outside the network. A similar mechanism can be used when the traffic is from nodes outside the network to nodes within the 6LoWPAN network. Under router-over, fragmentation and reassembly should happen on each router; 6LBRs should decompress the compressed IPv6 header. The role of 6LBRs is to compress or decompress the IPv6 header for traffic in or out of 6LoWPAN networks.

4.4 Movement Detection

Reducing the time of movement detection is crucial for mobility management. In MIPv6, MNs rely on receiving Router Advertisements from routers for movement detection. However, defined in Neighbor Discovery Optimization on 6LoWPAN networks, routers should not send periodic RA messages for saving the energy and will only sends RAs if hosts send Router Solicitations. MNs send Router Solicitations only if the default router list is empty, one of its default routers becomes unreachable, or the lifetime of the prefixes and contexts in the previous RA is about to expire [8]. Setting a small default router lifetime to trigger RS is not a good solution, since sending RS messages too frequently wastes the energy of mobile sensors. When a MN moves to different 6LoWPAN networks, it is very likely that the MN sends RS messages for movement detection because the Neighbor Unreachability Detection (NUD) of its default routers fails [6]. However, if there is no well-designed mechanism for triggering NUD promptly from upper layers, then the time of movement detection may be too long [7]. Therefore, the mobile node should supplement this method with other information (eg. link-layer events). In PMIPv6, MAGs are responsible for detecting the movement of nodes. PMIPv6 doesn't define how MAGs should do movement detection. It only suggests MAGs can find new MNs or detect MNs unreachable though link-layer events specific to the access technology or IPv6 Neighbor Unreachability Detection(NUD) event from IPv6 layer. Using only IPv6 NUD event has a similar issue comparing to MIPv6 [2]. MAG needs to rely on link-layer events for movement detection as well.

5 Related Work

R.Silva et al. [9] propose an adaption model for MIPv6 support in lowPANs. The adaptation uses the same compression mechanism as the 6LoWPAN adaptation layer to compress the mobility header and its options. However, this adaption model is expired and there is no updated solution coming up. Some researchers have already done some experiments of MIPv6 over 6LoWPAN networks. In [7], researchers have evaluated the performance of MIPv6 over 6LoWPAN networks under mesh-under routing. The result shows MIPv6 could be a practical solution for layer 3 mobility support in low power and lossy networks. However, the movement detection takes too much time to complete. J.Kim et al. [4] implement WSNs based on PMIPv6 over 6LoWPAN networks. Mobile sensors perform an active scan for the movement detection by periodically sending beacon requests on the link layer. It is not technically a network-based mobility management protocol because movement detection should be handled by mobility entities (such as MAGs) rather than mobile nodes. But it gives us an insight that in MIPv6, mobile nodes can use this movement detection mechanism to reduce the handoff latency.

6 Conclusions

The 6LoWPAN adaption layer enables IPv6 packets to be sent effectively in link layer frames whose size are relatively small, such as IEEE 802.15.4. The 6LoWPAN adaption layer provides header compression, packet fragmentation and mesh-under routing. However, header compression of 6LoWPAN is not effective on reducing the overheads of IP-based mobility protocols such as PMIPv6 and MIPv6. So packets are needed to be fragmented within a 6LoWPAN network. Under mesh-under routing, fragmentation happens on source nodes and reassembly happens on either destination nodes or any of 6LBRs depending on whether final destinations are within the 6LoWPAN network. Under route-over routing, fragmentation and reassembly should happen on each router. In MIPv6, mobile sensors use 6LoWPAN Neighbor Discovery to get their care-of addresses. In PMIPv6, mobile sensors do not need some parts of 6LoWPAN Neighbor Discovery due to the nature of PMIPv6. MIPv6 uses a generic method that uses the facilities of IPv6 Neighbor Discovery, including Router Discovery and Neighbor Unreachability Detection. However, this method is not sufficient to support fast movement detection. Mobile nodes should supplement this method with other information such as using link-layer indication for NUD.

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Appendix

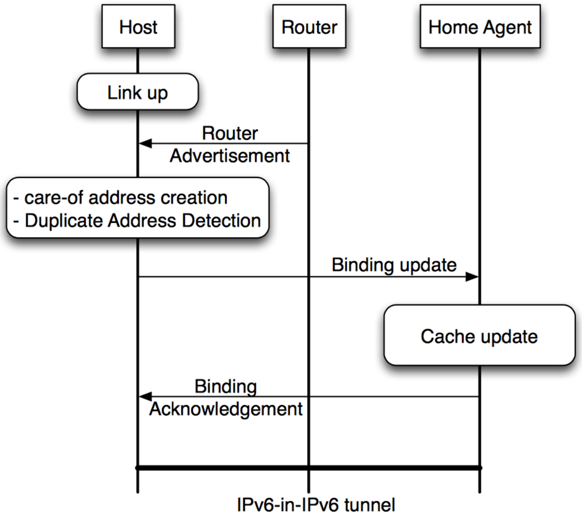

Figure 6: Protocol operations of Mobile IPv6 [7]

```
+-----+                 +-----+                 +-----+
| MN  |                 | MAG |                 | LMA |
+-----+                 +-----+                 +-----+
   |                       |                       |
MN Attached                |                       |
   |                       |                       |
   |        MN Attached Event from MN/Network      |
   |         (Acquire MN-Id and Profile)           |
   |                       |                       |
   |--- Rtr Sol ---------->|                       |
   |                       |                       |
   |                       |--- PBU -------------->|
   |                       |                       |
   |                       |                   Accept PBU
   |                       | (Allocate MN-HNP(s), Setup BCE and Tunnel)
   |                       |                       |
   |                       |<------------- PBA ---|
   |                       |                       |
   |                   Accept PBA                  |
   |            (Set Up Tunnel and Routing)        |
   |                       |                       |
   |                       |==== Bi-Dir Tunnel ===|
   |                       |                       |
   |<--------- Rtr Adv ---|                       |
   |                       |                       |
 IP Address                |                       |
Configuration              |                       |
   |                       |                       |
```

Figure 7: Protocol operations of Proxy Mobile IPv6 [2]