Migrating Home Agents Towards Internet-Scale Mobility Deployments

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ABSTRACT

While the IETF standardization process of the Mobile IPv6 and Network Mobility (NEMO) protocols is almost complete, their large-scale deployment is not yet possible. With these technologies, in order to hide location changes of the mobile nodes from the rest of the Internet, a specific router called a home agent is used. However, this equipment generates resilience and performance issues such as protocol scalability and longer paths. In order to solve these problems, we describe and analyze a new concept called *Home Agent Migration*. The main feature of this solution is the distribution of home agents inside the current Internet topology to reduce distances to end-nodes. As is usually done for anycast routing, they advertise the same network prefix from different locations; moreover they also exchange information about their associations with mobile nodes. This produces a Global Mobile eXchange (GMX), an overlay network that efficiently handles data traffic from and to mobile nodes, and operates home agents as would an Internet eXchange Point (IXP). When a correspondent node needs to exchange packets with a mobile node, the data traffic will be intercepted by its closest GMX home agent and redirected to the home agent to which the mobile node is bound.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Network communications; C.2.3 [**Network Operations**]: Network management

Keywords

Mobile IPv6, mobility management, route optimization

1. INTRODUCTION

Nowadays in Japan, mobile terminals represent 57%[1] of user access to the Internet. Therefore, mobility is clearly one of the key features for upcoming Internet technologies. We expect that this trend will also evolve in other parts of the world with the deployment of mobility services such as 4G (Fourth Generation) cell phones, vehicle communications (Intelligent Transport System, ITS), and Personal Area Networks (PAN). Since the number of cell phones and vehicles in the world is quite large, we can foresee that the Internet will soon be dominated by mobile computers. Consequently, it is urgent to develop an Internet-Scale Mobility system.

Many mobility technologies have already been introduced and standardized by the Internet Engineering Task Force (IETF). For instance, the Mobile IPv6 [10] and NEMO [5] protocols were selected as the base systems for mobility services embedded in WiMAX and 3GPP2. Moreover, they have already been implemented by the major vendors of networking equipment. In a nutshell, Mobile IPv6 allows a mobile node to communicate using the same address while it moves, thanks to a specific router located in its home network – the home agent. However, it introduces several issues that make the base protocol unsuitable for Internet-Scale Mobility systems. Despite these problems, the main advantage of these protocols against other mobility systems such as HIP [12], or VNAT [18] is that they only require modifications on the mobile node implementations. Therefore, a transitional mobility architecture can be defined while avoiding modification to the deployed Internet architecture.

In this paper, we show that Internet-Scale Mobility deployments are possible using the traditional Mobile IPv6 protocol with an additional mobility management plane called Home Agent Migration. In this new plane, home agents are distributed all over the Internet and are exchanging information about mobile nodes that they can reach. This deployment is performed with the help of anycast routing in which every home agent advertises the same IPv6 prefix. Consequently, a mobile node will transparently exchange its traffic with its topologically closest home agent, reducing communication delays. This paper also introduces the concept of a Global Mobile eXchange (GMX) where a home agent is operated like a router in an Internet eXchange Point (IXP). This research is applied by nature and was successfully deployed in a real BGP Autonomous System.

Unlike other works that focus on end-to-end communications or new routing architecture to provide mobility, our research aims to provide an Internet-Scale Mobility system that does not modify the existing architecture of the Internet. Our proposal is especially interesting compared to

[1] owned by approximately 48 million people, according to The Japanese Ministry of Internal Affairs and Communications

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other solutions as its deployments can be performed with realistic operational and financial costs. In fact, if a mobility system is based on end-to-end communications like HIP, all of the nodes – mobile or not – must be modified to benefit from the system. Thus, during the deployment phase of this mobility system it is unlikely that many nodes will really benefit from it. Likewise, modifications of the routing plane to support mobility introduce important financial issues as core routers must be upgraded or replaced. This will probably slow down the deployment of such technologies. On the other hand, the Home Agent Migration maintains compliance with end-nodes regardless of whether they implement Mobile IPv6, and only requires small changes on regular home agents. Since no modification is made to end-nodes our work can be seamlessly embedded in a network, easing the deployment of an Internet-Scale Mobility system.

This paper addresses the issues of Mobile IPv6 and proposes a new concept called Home Agent Migration. The remainder of this paper is organized as follows: We first give an overview of Mobile IPv6 and its limitations. Then, we introduce the concept of the Home Agent Migration in Section 3. In Section 5, we present operational results from experiments performed in a real network. Finally, prior to the conclusion, we discuss related work in Section 6.

2. MOBILE IPV6

In this section, a brief overview of Mobile IPv6 is given. Then, the issues of this protocol and its route optimization procedure are discussed. The aim of this section is to describe the problems that the Home Agent Migration is trying to address.

2.1 Operation of Mobile IPv6

Mobile IPv6 relies on a specific router called the home agent. Its goals are to delegate an address from its home network to each mobile node, and to forward the mobile node's traffic to it. The mobile node always communicates using its Home Address regardless of what network it is connected to at the time. When the mobile node moves to a new network, it first obtains a new Care-of Address using the auto-configuration mechanism available in IPv6. Then it registers binding information with the home agent, by sending a packet called a Binding Update, containing the Home Address and the new Care-of Address, to its home agent. After the reception of this binding the home agent is able to set up an IPv6-in-IPv6 tunnel with the mobile node. As shown in Figure 1, all of the communications between a mobile node and a correspondent node go through the home agent.

The base specifications of Mobile IPv6 includes a route optimization scheme called the Return Routability Procedure. It allows the mobile node to send a Binding Update packet to its correspondent nodes that also implement Mobile IPv6. After the completion of this procedure, the packets are directly routed between the mobile node and its correspondent nodes. While this optimization reduces the latency of the communications and improves performances, it also introduces several problems that will be discussed in Section 2.3.

2.2 Limitations of Mobile IPv6

The following points represent the fundamental problems of Mobile IPv6. When a home agent manages numerous mobile nodes, they especially weaken the protocol performance

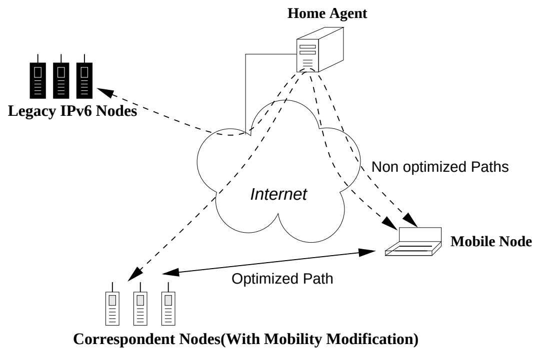


Figure 1: Mobile IPv6

as well as its scalability.

1. **Triangular routing**
   In Mobile IPv6, a mobile node is only associated with a single home agent. As shown in Figure 2-a, a mobile node (MN) communicates with a correspondent node (CN) via its home agent (HA). All packets are routed to the home agent first and forwarded to the destination in an IPv6-in-IPv6 tunnel. Consequently, packets take a non-optimal path because all of the traffic has to transit through the home network. This problem is known as triangular routing and is responsible for increasing communications delays when a mobile node communicates with its correspondent node.

2. **Restricted position**
   The location of a home agent is topologically and physically restricted by its home prefix. It must be in the correct location so that it can receive packets destined to the home prefix; as a result, it must be placed where this prefix is announced on the Internet. This strong location requirement is particularly problematic. Indeed, when the home network becomes unreachable, mobile nodes also become isolated and cannot be reached through their home address.

3. **Constraints for the home link**
   In usual Mobile IPv6 deployments, the home agents intercept packets on behalf of mobile nodes; they thus have to act as neighbor discovery protocol proxies (Proxy NDP) as defined in [15]. This leads to a serious scalability issue, as the number of neighbor discovery packets sent by the home agent is proportional to the number of mobile nodes it serves. Additionally, the total bandwidth of mobile nodes may be bigger than the total home link bandwidth. Therefore, deploying Mobile IPv6 could be an operational challenge to maintain the home link's bandwidth and stability.

2.3 Drawbacks of the Route Optimization Scheme

The route optimization scheme described in the base specifications of Mobile IPv6 has the issues listed below.

1. **Privacy**
   Since the mobile node reveals its Care-of Address to its correspondent node by sending Binding Updates, the real location of the mobile node is revealed to other

nodes on the network. This is a severe problem as it can ease industrial spying. In addition, when route optimization is performed the mobile node's data traffic is not protected by IPsec, which leaves the communications vulnerable to eavesdropping on the visited network.

2. **Modifications of end-nodes**
In order to perform the Route Optimization, every end node must support the Return Routability procedure. However, it is unrealistic to expect that all IPv6 nodes will support route optimization, as it means upgrading existing IPv6 nodes. Therefore, these legacy IPv6 nodes will not be able to benefit from this procedure and all of the data traffic will be destined to the home network in spite of route optimization.

3. **Complexity**
Before sending a Binding Update to a correspondent node, the mobile node must exchange four messages to generate a key that will be used to authenticate the binding. This binding is sent to every correspondent node every time the mobile node moves. In the worst case, this whole message exchange is repeated after each movement. Therefore, the overhead of this procedure is high and implies longer handovers and more communication latency. If the Return Routability Procedure can not be performed after a mobile node's movement, due to strict firewall policies or packet losses, the mobile node can not exchange any data with its correspondent nodes until the binding's lifetime expires.

4. **Server overload**
We must consider that a server communicating with thousands of users may be acting as a correspondent node. In this case, the route optimization procedure dangerously increases the amount of work the correspondent node must perform to serve queries. Unlike non Mobile IPv6 based communications, more packets are exchanged and more powerful hardware is required to handle the same amount of users. Therefore, it is unlikely that Mobile IPv6 will be implemented in servers, as it leads to bigger operational costs. The deployment of Mobile IPv6 using the Return Routability procedure causes its operational cost to also be supported by entities other than the one in charge of the home network. These problems can seriously slow down the adoption of this route optimization scheme as it does not bring direct benefit for the companies managing servers.

3. HOME AGENT MIGRATION

The underlying concept of the Home Agent Migration system is to disengage home agents from the home link so as to distribute them in the Internet topology. The aim of this new kind of home agent deployment is to provide an efficient route optimization scheme that is compatible with Mobile IPv6's mobile nodes, is transparent for correspondent nodes, and reduces communication latency.

The main scenario assumed while developing this solution is a mobile node roaming on a continent- or country-scale, i.e. from Tokyo to Paris. Home agents are globally distributed in every big city around the world in order to be closer to mobile nodes and to provide seamless access to this architecture. While this scenario mainly concerns world-wide operators, our solution also applies to smaller-scale deployments. For example, the Home Agent Migration is also useful to service providers delivering IP connectivity with several network access technologies such as CDMA2000, 1xEvDo and 802.11b. The network operators can each set up a home agent in their networks, causing the mobile nodes to register with a home agent relative to their access technology.

3.1 How it works

In the proposed architecture, multiple home agents advertising the same IPv6 prefix are deployed along the Internet topology as shown in Figure 2-b. This routing operation, known as Anycast Routing [11], helps to solve load balancing and redundancy issues. Nowadays, it is mainly used to operate root DNS servers. Home agents can use any routing protocols interconnected to form an overlay network that allows them to exchange mobile nodes' data traffic as well as signaling packets. These interconnections can be created directly over the Internet or over dedicated high-speed backbones.

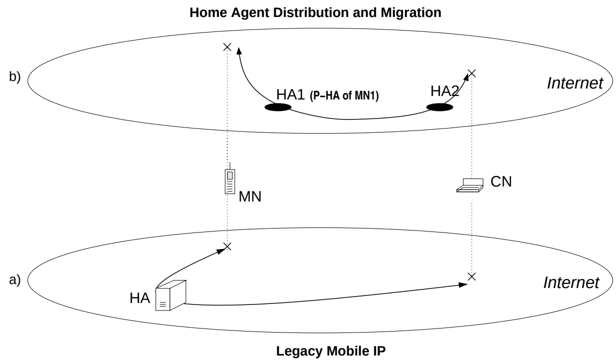


Figure 2: Concept of Home Agent Distribution and Migration

Figure 2 compares the network architectures of legacy Mobile IPv6 and the proposed system. Due to the distribution of home agents in the Internet topology, a mobile node will always use the nearest home agent as if the home agent had migrated close to the mobile node's location. This closest home agent is referred to as the primary home agent (P-HA in Figure 2), since it receives the first Binding Update sent by the mobile node. Similarly, packets sent by a correspondent node are routed to their closest home agent using generic IP routing mechanisms and are then forwarded to the primary home agent over the fast backbone. In Figure 2-b, optimized paths are used when mobile and correspondent nodes communicate with each other.

3.2 GMX: Global Mobile eXchange

The current Internet infrastructure relies on Internet Exchange Points (IXPs). Tier-1 ISPs are interconnected through these IXPs, and use them to exchange most of their data traffic. Using the Home Agent Migration, it is possible to efficiently deploy home agents in IXPs as rendez-vous points for mobility services. The home agents are operated with a concept similar to an IXP; therefore, we call this deployment Global Mobile eXchange (GMX). The primary goals of GMX are to decrease the cost of the transit traffic related to mobile nodes and to allow Internet-Scale Mobility services. Different deployments of GMX are possible depending on the number of providers managing the mobility service. In Figure 3, there are three Mobile Service Providers managing different sets of home agents, MSP1, MSP2 and MSP3. All of them are interconnected by home agents located in GMX1 and GMX2. In a GMX, a home agent exchanges traffic and routing information as a regular router would do in an IXP. In order to enhance performance, GMXs are located where the concentration of users (and thus traffic) is high. For example, in Tokyo and Osaka for a Japanese Mobile Service Provider.

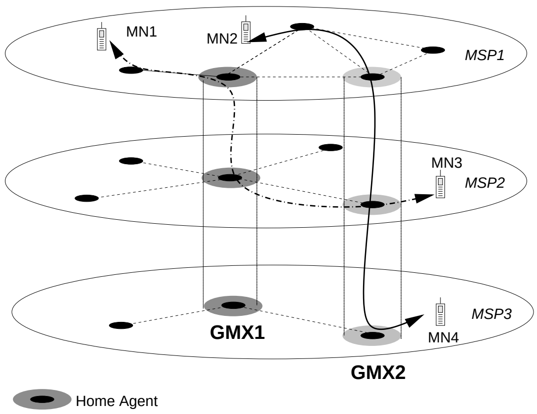


Figure 3: Concept of Global Mobile eXchange

3.3 Advantages

While away from its home network, a mobile node will always be associated with the nearest home agent in terms of network topology. As home agents are distributed throughout the Internet, and signaling and data traffic can be distributed among home agents, the home agent is no longer a performance bottleneck. The distribution of the home agents also reduces delay and optimizes routes. If the home agents exchange routing information, a packet destined or emitted by a mobile node can be directly routed to its primary home agent.

As previously described, home agents are interconnected to exchange mobile nodes' binding information. In addition, they are also able to detect and report each other's failures. Therefore, when a mobile node's primary home agent crashes, another one can send it a failure alert and quickly take the place of the failed one. After receiving the alert, the mobile node can send a binding update to a new home agent and resume communications immediately. Unlike the legacy Mobile IPv6, the Home Agent Migration is not vulnerable to the unreachability of the home link and is able to handle home agents' deficiencies.

Mobile IPv6's route optimization procedure has a serious privacy issue, as a mobile node must disclose its Care-of Address. While this solution allows end nodes to use the optimal path between them, it also exposes the fact that the mobile node is not in its home network, but visiting another network. The proposed solution does not disclose the mobile node's Care-of Address, preserving its location. In addition, unlike with the route optimization procedure, the mobile node's traffic cannot be eavesdropped in the visited network since the tunnel between the home agent and the mobile node can be securely protected with IPsec.

4. SYSTEM OVERVIEW

This section describes in detail the behavior of the Home Agent Migration using the communications between home agents, mobile nodes and correspondent nodes as examples.

4.1 Notion of Binding Cache

For every mobile node, the Binding Cache maintains the relationship between the Care-of Address, the Home Address and the home agent associated with a mobile node. The home agent associated with a mobile node is called the primary home agent. With the Home Agent Migration architecture, the home agents share the same Binding Cache. Therefore, they can always find out the primary home agent of a specific mobile node. This cache is a dedicated routing table that allows the home agents to know if a mobile node is reachable, as well as the primary home agent that will be used to forward packets to the mobile node.

In order to synchronize these relationships, each home agent establishes a secured tunnel with the other home agents and uses it to exchange signaling and traffic of mobile nodes. When a primary home agent receives a binding update, it sends the resulting relationship to the other home agents over the tunnels. When a home agent receives this relationship, it updates its own Binding Cache. This simple mesh-based binding synchronization can obviously be optimized to be more efficient. However, as it does not impact the mobile nodes' performance, this mechanism is sufficient for our experiment.

When a mobile node sends a binding update to a home agent, Mobile IPv6 requires that the home agent verifies the uniqueness of the home address using IPv6's Duplicate Address Detection, DAD, on the home link. However, in our system, as this link is virtual, this detection can not be performed. Instead of the regular DAD, a home agent uses the binding cache in order to perform the uniqueness test.

4.2 Communications example

Thanks to the distribution of the home agents all over the Internet and anycast routing, the home agents are able to intercept the packets sent to the mobile nodes. Consequently, the Home Agent Migration architecture can be seen as a vacuum for the traffic destined to the mobile nodes. The following descriptions of communications assume an architecture with two home agents HA1 and HA2 and two nodes, the mobile node MN, closer to HA1, and the correspondent node CN, closer to HA2. The notion of proximity is given by the regular routing from the nodes to the home agents. The MN is already associated with its primary home agent, HA1, and the Binding Cache of HA1 and HA2 are consistent.

From the MN to the CN: When the MN wants to send a packet to the CN, it sends it to its primary home agent over the tunnel. Subsequently, HA1 directly sends it to the CN as a router usually does.

From the CN to the MN: When the CN sends a packet to the MN, it is intercepted by HA2. HA2 performs a lookup in the Binding Cache to discover the primary home agent of MN. It sends the packet over the secured tunnel that it maintains with HA1. Then, HA1 decapsulates the packet and sends it to MN over the tunnel they share.

The communications between two mobile nodes are similar to the previously described explanations except that data packets are always forwarded using the tunnels.

4.3 Movements of mobile nodes

In Mobile IPv6, the home agent address discovery mechanism is used by a mobile node to discover the home agent that it must use. Similarly in the Home Agent Migration system, it is necessary for a mobile node to find out its closest home agent. As our proposal does not require any modification of the mobile node, this discovery is performed the same way in both systems. As described in [10], a dynamic home agent address discovery (DHAAD) request is sent by the mobile node to a specific address identifying all of the home agents present on the home link. When a home agent receives this message, it sends back a DHAAD reply including the list of reachable home agents. Thus, in our system this reply is used by the mobile node to discover the address of the home agent that it must use to send its Binding Update.

When the mobile node moves and needs to change its primary home agent proactively, it sends a new dynamic home agent address discovery request. Thanks to anycast routing, the message is routed to the closest home agent that will reply to the mobile node. When the change of home agents occurs, the mobile node does not need to de-register from the old home agent before sending a new Binding Update to the new one. This is because the Binding Cache is being shared by all the home agents. However, it is possible that the closest home agent could remain the same after a movement. For example, this will happen if a Japanese mobile node moves from Tokyo to Yokohama and the Home Agent Migration architecture is only deployed in Tokyo and New York.

The change of home agent can also be reactive if a home agent detects that it is closer to a mobile node than its current primary home agent. The trigger occurs when a home agent receives a binding update from a secured tunnel established with another home agent, HA2. The primary home agent will thus ask the mobile node to bind to HA2.

4.4 Example deployment

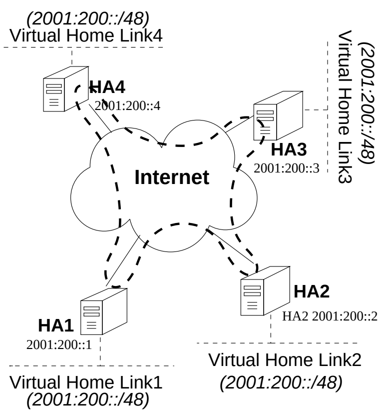


Figure 4: An example of home agent configuration

In Figure 4, there are four home agents HA1 to HA4 serving the same IPv6 home prefix 2001:200::/48 and connected by IPsec tunnels. Each home agent generates a distinct home agent address from the same home network prefix even if the home agents are located in different networks. In the Figure, HA1 configures 2001:200::1 as its address. Each home agent acts as a designated router for the virtually configured home link and intercepts packets meant for mobile nodes.

When multiple home agents are configured in different networks, each home agent should know the other home agents beforehand and establish a security association to ensure secure paths with the other home agents. A home agent inherits a home agent list to manage the other home agents as in Mobile IPv6 [10]. However, the home agent list management requires that all the home agents should be on-link. Thus, a new message called "hello" is used to periodically exchange home agent information and to confirm home agent availability. The home agent information carried by the "hello" message is the same information as router advertisements sent by a home agent in Mobile IPv6.

4.5 The protocol

The Figure 5 shows in detail the packets exchanged in the Home Agent Migration system. The protocol is based on the Inter Home Agents protocol (HAHA) [22, 24, 19]. A mobile node (MN) first registers its binding to its primary home agent (Seq1). The primary home agent creates a binding for the home address of the mobile node, and then sends a copy to other home agents in order to synchronize the Binding Caches. When a home agent receives the copy from the primary home agent, it update its Binding Cache.

When a mobile node communicates with a correspondent node, outgoing packets from the mobile node are tunneled to the primary home agent (here HA1) (Seq4) and incoming packets to the mobile node are intercepted by the home agent HA2, which is close to the correspondent node. Then, the intercepted packets are tunneled to the primary home agent. The primary home agent delivers the packets to the mobile node through the bi-directional tunnel (Seq5).

If the mobile node decides to switch its primary home agent because of its movement, it sends a binding update to the new primary home agent (Seq7). How to discover the closest home agent is described in Section 4.3. The new primary home agent then synchronizes the binding with other home agents (Seq8). After receiving the binding update copy, all the home agents update the binding as well as the new primary home agent address.

The Home Agent Migration can be compliant with Network Mobility (NEMO) protocol. The procedure is same as for Mobile IPv6, except for binding cache information. When NEMO is used, the mobile network prefix information is also managed in a binding cache entry.

5. EVALUATION

In this section, we first describe the benefits of the proposed solution in terms of exchanged signaling messages and handover durations. Then, the results of a real Internet scale experiment are shown and discussed in terms of round trip time between end nodes.

5.1 Performances comparisons

With Mobile IPv6's route optimization, when a mobile

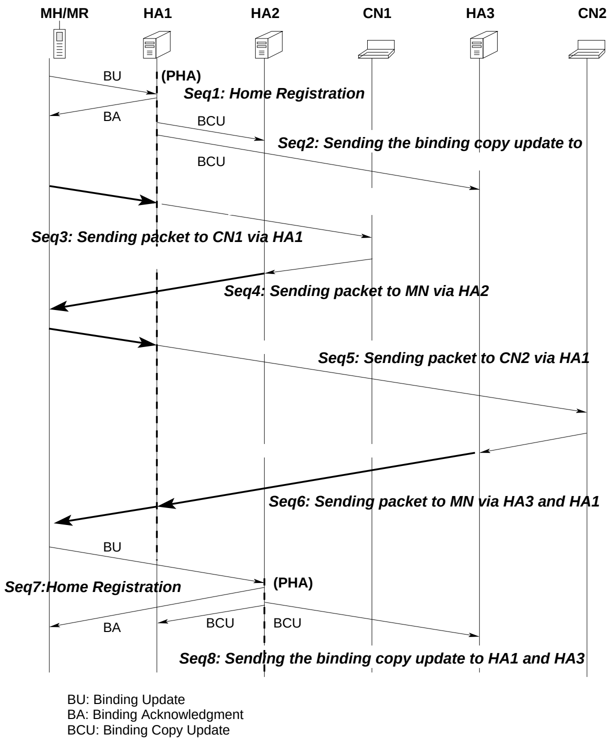


Figure 5: Multiple Home Agents

node performs a handover it must advertise its new Care-of Address by sending a Binding Update to its home agent and possibly to each of its correspondent nodes. Prior to sending a Binding Update to a correspondent node, the mobile node must send four signaling messages. The total number of exchanged messages is thus proportional to the number of correspondent nodes. With Home Agent Migration, a mobile node only register with a single home agent. However, assuming an inefficient distribution system, this binding information must be delivered to every home agent in the GMX. The equations (1) and (2) represent the number of signaling messages necessary to handle a handover for Mobile IPv6 with route optimization (S_{ro}) and the proposed solution (S_p), respectively. N_{cn} and N_{ha} are the numbers of correspondent nodes and home agents. BU and $BACK$ stand for Binding Update and Binding Acknowledgments.

$$S_{ro} = BU + BACK + N_{cn} \times 5 \quad (1)$$

$$S_p = BU + BACK + N_{ha} - 1 \quad (2)$$

When a handover occurs, it takes a certain amount of time to complete the operation. As the processing time of the exchanged packets is not significant regarding their Round Trip Time (RTT), it is safe to describe the handover duration with the RTT. The equations (3) and (4) represent this duration for Mobile IPv6 with route optimization T_{ro} and the proposed solution T_p. R_{mnha} is the RTT between a mobile node and the primary home agent, $R_{hacn(n)}$ is the RTT between the primary home agent and a correspondent node(n), $R_{mncn(n)}$ is the RTT between a mobile node and a correspondent node(n), and $R_{haha(n)}$ is the RTT between the primary home agent and another home agent(n). Depending on the network conditions, $R_{mncn(n)}$ is bound by: $R_{mncn(n)} \leq (R_{mnha} + R_{hacn(n)})$. With Mobile IPv6, depending on the implementation, the handover duration may increase proportionally with the number of correspondent nodes and the R_{mnha} increases as the mobile node moves far away from its home agent. The last correspondent node that receives a Binding Update must wait as long as T_{ro} before it can use the optimized path with the mobile node. In the proposed solution, if home agents are carefully distributed in the Internet, it is possible to bound R_{mha} to a value not related to the mobile nodes' locations. Furthermore, the latest sum of the equation can be optimized according to the solution used to distribute binding information. After the reception of the Binding Acknowledgment, a mobile node can directly tunnel data to its primary home agent and does not need to wait for the completion of binding information distribution. The Home Agent Migration thus provides route optimization with better handover latency, especially if a larger number of correspondent nodes is involved.

$$T_{ro} = R_{mnha} + \sum_{n=1}^{N_{cn}} (R_{mnha} + R_{hacn(n)} + \frac{3}{2} \times R_{mncn(n)}) \quad (3)$$

$$T_p = R_{mnha} + \sum_{n=1}^{N_{ha}-1} R_{haha(n)} \quad (4)$$

5.2 Experimental results

In order to conduct our experiments, a userland daemon was developed using the KAME BSD IPv6 stack and the advanced socket API [17, 3]. It is a lightweight version of a regular home agent that also performs Binding Synchronization. During most of the experiments we used Shisa[2], an implementation of Mobile IPv6 for BSD kernels, for the mobile nodes. However, in some locations as we were unable to set up real mobile nodes we had to emulate them. These emulated mobile nodes were implemented in Python using Scapy6 [20]. However, there was close to no difference in the results between a real and an emulated mobile node.

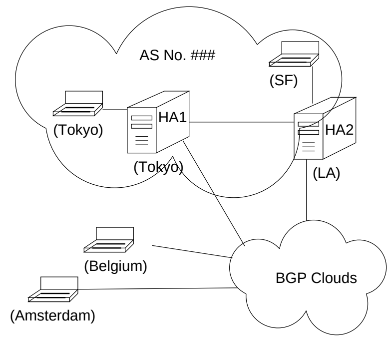


Figure 6: Abstract Network Topology of Experimentation

Two home agents were set up inside a single Autonomous System (AS). One was located in Los Angeles and the other one in Tokyo. In the AS, each home agent advertises the same IPv6 prefix using OSPFv3. The topology used during

[2]http://www.mobileip.jp/

Table 1: Round Trip Time (in ms)

	HA1	HA2	Tokyo
HA1	N/A	110	0.52
HA2	111	N/A	110
	Amsterdam	Belgium	San Francisco
HA1	297	292	141
HA2	188	194	30

the experiment is shown in Figure 6. The operational issue in this network is the Pacific link between its two parts. Therefore, the goal of this experiment is to use the Home Agent Migration to avoid this link if the mobile nodes are not located in Japan. Table 1 details average Round Trip Times between all of the involved nodes. It is given as a reference to check if the Home Agent Migration system can provide a mobility service with a small RTT overhead.

Results of the experiment are presented in Figures 7 to 9. Correspondent nodes differ in each figure. These graphs show Round Trip Time between a mobile node and its correspondent node in three different cases. First, when Mobile IPv6 is not used (i.e. direct path), then when regular Mobile IPv6 is used, and finally when Home Agent Migration is performed. Note that for regular Mobile IPv6, we used HA1 as the home agent.

In Figure 7, the mobile node is located in San Francisco and the correspondent node in Tokyo. In the three cases, the average Round Trip Time is almost the same, around 142 ms. These results were expected as HA1 and HA2 are both located on the path between the correspondent node and the mobile node. The negligible overhead of the Home Agent Migration, around 2 ms, is caused by the tunnel between HA1 and HA2. When home agents are carefully deployed on the Internet, Mobile IPv6 does not provide any overhead. With this pair of nodes, no benefit arose from the Home Agent Migration; however, the performance is the same as with regular Mobile IPv6.

In Figure 8, the mobile node is located in San Francisco and the correspondent node in Amsterdam. In this scenario, HA2 located in Los Angeles is obviously closer to the mobile node and is selected as the primary home agent. As a result, the average Round Trip Time when the mobile node uses HA2 is 220 ms smaller than the Round Trip Time when legacy Mobile IPv6 is used with HA1 (see 8(b)). This difference is caused by the latency of packets traveling over the Pacific Ocean as shown in Table 1. When Home Agent Migration is used, the average Round Trip Time is exactly the same as the direct path. Therefore, Home Agent Migration allows the use of Mobile IPv6 with no significant Round Trip Time overhead.

In Figure 9, the mobile node is in San Francisco and the correspondent node is in Belgium. Whereas results are expected to be the same as in Figure 8, the optimized Round Trip Time, when HA2 is used, is not the same as the direct path. When the Home Agent Migration is used, the path from San Francisco to Belgium is through the nearest home agent (i.e. HA2), while the reverse path is via Tokyo (i.e. HA1) due to BGP peering. Although the Round Trip Time is smaller than the one with regular Mobile IPv6, Home Agent Migration does not provide an improvement as important as in Figure 8.

The critical aspect of Home Agent Migration in a single Autonomous System is the correct placement of the home agents in the network topology. In order to achieve the best performance, the home agents should be located on the direct path between mobile nodes and correspondent nodes. If the path is not symmetric, the optimization provided by our proposal is only partial. This issue can be resolved by the administrators if they carefully configure the costs of paths using routing protocols. For Internet-Scale deployments using GMX, the home agents are located in Internet eXchange Points, and are thus on the direct path between mobile and correspondent nodes. Maximum performance can therefore be achieved as the paths can not be asymmetric anymore.

6. RELATED WORK

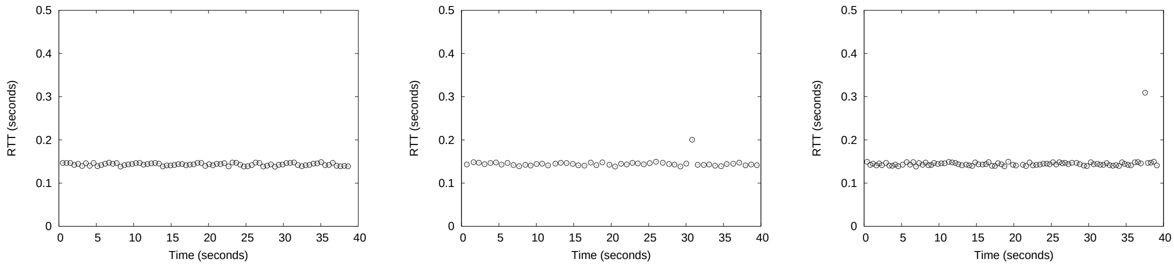
In this section, we introduce and compare several approaches that, like Home Agent Migration, aim to provide better route optimization for Mobile IPv6.

Previous works in route optimization [10, 14, 23] involve caching binding information in the correspondent nodes and in routers on-demand. However, these end-to-end optimizations also introduce the issues described in Section 2.3. Unlike these systems, Home Agent Migration is designed to be transparent to end-nodes and only requires small changes in home agents.

Several regional and hierarchical approaches for reducing the binding overhead have been proposed [2, 1, 7, 16, 8]. The underlying concept of these efforts is to enable a mobile node to associate with a closer agent instead of its home agent. Although the design concept is similar to Home Agent Migration in terms of home agent distribution, these studies significantly modify the implementations of the mobile nodes. For example, HMIP [2] requires the mobile node to manage several addresses.

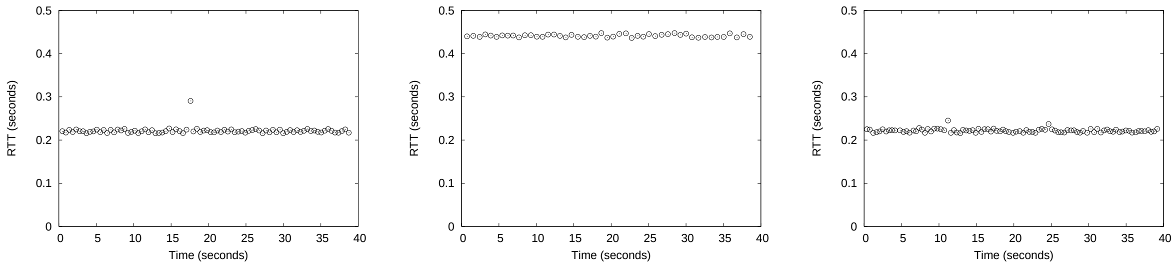
Efficient dynamic assignment of home agents have also been introduced to provide optimal routing between end-nodes. Mobile IPv6 regional mobility management [13] uses a Regional Anchor Point (RAP) located in the network that the mobile nodes visit in order to optimize routes. In [9], NASA and Cisco investigated multiple home agent setups in an Autonomous System. By assigning priority to home agents, mobile nodes can be associated with a closer home agent. This approach is similar to the solution outlined in this paper but the distribution of mobile nodes among home agents is not based on IP routing but rather access lists. In order to set up access lists, the system operator must know beforehand the pattern of mobile node movements. In contrast to this system, Home Agent Migration dynamically selects the best home agent by anycast routing, regardless of mobile node movements.

Finally, the home agent reliability protocol [21] provides redundancy and reliability to Mobile IPv6 by duplicating the home agents on the home link. It exchanges mobile node registration information among home agents. If a home agent fails, another home agent automatically takes its place in order to seamlessly ensure the continuity of a mobile node's sessions. There are several similar works such as the Home Agent Redundancy Protocol (HARP) [4] and Virtual Home Agent Reliability (VHAR) protocol [6]. However, the principal drawback of these systems is that they only activate one home agent at a time. In the Home Agent Migration, every home agent is always active. Furthermore, our proposal is



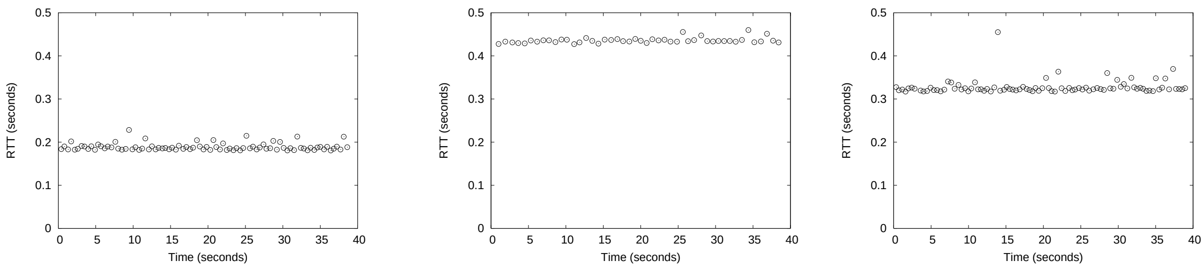
(a) Direct Path (b) Regular Mobile IPv6 (c) Home Agent Migration

Figure 7: RTT between San Francisco and Tokyo.



(a) Direct Path (b) Regular Mobile IPv6 (c) Home Agent Migration

Figure 8: RTT between San Francisco and Amsterdam.



(a) Direct Path (b) Regular Mobile IPv6 (c) Home Agent Migration

Figure 9: RTT between San Francisco and Belgium.

not affected if the home link becomes unreachable.

7. CONCLUSION

In this paper, a new architecture for Internet-Scale Mobility deployment named Home Agent Migration is described. This proposal efficiently solves Mobile IPv6 limitations such as protocol scalability and reliability, and redundant path. In addition, it can also be applied to the Network Mobility (NEMO) basic protocol [5], as it is just an extension of Mobile IPv6. The only difference is that home agents must also exchange mobile network prefixes. Our proposal is especially useful for NEMO as no route optimization procedure is yet standardized.

In our solution, unlike in Mobile IPv6, multiple home agents are distributed over the Internet, and advertise the same IPv6 prefix in an anycast fashion. The mobile nodes only see one home agent and do not need to know about the other ones. From any location, they are always associated with their closest home agent in terms of the network topology. Therefore, if home agents are carefully distributed, it is possible to guarantee the delay between a home agent and a mobile node located anywhere on the Internet.

However, we identified some issues that must be taken into account while deploying the Home Agent Migration system. When routing paths are not symmetric, the performance offered by our solution is not as optimal as direct communication; thus, the benefit is only effective in one way.

In our future work, we will focus mainly on scalability issues. In fact, in the actual proposal, a simplistic approach is used to distribute binding information between home agents, and we are investing the use of Distributed Hash Tables to enhance the performance of the binding synchronization between home agents. Besides, we will also study the effects of our scheme on the scaling of BGP routing.

Compared to other route optimization schemes, Home Agent Migration does not require any modifications on end-nodes and offers performances similar to a communication without Mobile IPv6. Experiments showed that the solution can be deployed on the actual Internet architecture and validated our assumptions about the optimizing effect on the performance of the Mobile IPv6 protocol.

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