Modelling and Simulating IPv6 Mobility

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Abstract

Mobile Internet Protocol version 6 (IPv6) is a protocol enhancement that is designed to allow transparent routing of IPv6 packets to mobile nodes. Without specific support for mobility in IPv6, packets destined to a mobile node would not be able to reach it while the mobile node is away from its home link. Mobility support in IPv6 is particularly important, as mobile computers are likely to account for a majority or at least a substantial fraction of the population of the Internet during the lifetime of IPv6. This paper describes a modelling of the IPv6 mobility using Estelle, an internationally standardised Formal Description Technique (FDT), and its simulation using the Estelle Development Toolset.

1 Introduction

The extremely popular uses of the Internet have stimulated the further development of the Internet Protocol. Current IP addressing only utilises 32 bits and leads to a near saturated IP address space. Internet Protocol Version 6 (IPv6) [1] is the next generation IP that is going to replace the current version (IPv4) [2]. On the other hand, mobile telecommunication technology is developing rapidly. Without specific support for mobility in IPv6, packets destined to a mobile node (host or router) would not be able to reach it while the mobile node is away from its home link (the link on which its home IPv6 subnet prefix is in use), since routing is based on the subnet prefix in a packet’s destination IP address. In order to continue communication in spite of its movement, a mobile node could change its IP address each time it moves to a new link, but the mobile node would then not be able to maintain transport and higher-layer connections when it changes location. Mobility support in IPv6 is particularly important, as mobile computers are likely to account for a majority or at least a substantial fraction of the population of the Internet during the lifetime of IPv6. A protocol enhancement, known as Mobile IPv6, is therefore designed to allow transparent routing of IPv6 packets to mobile nodes.

The Internet Engineering Task Force (IETF) publishes drafts, Request for Comments (RFCs) and standards to describe every part of the Internet communication. All these documents form the foundation of the Internet. However, they are described in natural languages. As networks get larger and faster, more people of more diverse backgrounds will read specifications of protocols. Using an informal method of protocol specification such as English could lead to mis-interpretation. This led to the need of developing new techniques and languages. As a result of the work, two new Formal Description Techniques (FDTs) - Estelle [5] that is based on an Extended Finite State Machine (EFSM) model, and LOTOS [7] that is based on Milner’s Calculus of Communication Systems - were formalized and standardised by ISO in 1989.

This paper describes a modelling of the IPv6 mobility using Estelle [5], an internationally standardised Formal Description Technique (FDT), and its simulation using the Estelle Development Toolset. Modelling of the mobility and lifetime management are critical points in the specification. By wrapping all subnets, mobile node and correspondent node modules into one module, Estelle is able to specify mobility with its dynamic disconnect/connect ability. This work is based on a working draft of Mobile IPv6 [3]. The main contributions of this paper are the successful modelling of the mobility of a popular protocol using the standardised FDT Estelle and that it provides pointers for further analysis of Mobile IPv6 which is expected to make a significant impact on the Internet world in the future.

2 Mobile Internet Protocol Version 6

Mobile IPv6 [3] allows a mobile node to move from one link to another without changing the mobile node’s IP address. A mobile node is always addressable by its “home address”, an IP address assigned to the mobile node within its home subnet prefix on its home link. Packets may be routed to the mobile node using this address regardless of
the mobile node’s current point of attachment to the Internet, and the mobile node may continue to communicate with other nodes (stationary or mobile) after moving to a new link. The movement of a mobile node away from its home link is thus transparent to transport and higher-layer protocols and applications. The main objective of Mobile IPv6 is to solve the problem of transparently routing packets to and from mobile nodes while away from home. Mobile IPv6 is intended to enable IPv6 nodes to move from one IP subnet to another. It is just as suitable for mobility between subnets across homogeneous media as it is across heterogeneous media.

All packets used to inform another node about the location of a mobile node must be authenticated. The number of administrative packets sent over the link by which a mobile node is directly attached to the Internet should be minimized, and the size of these packets should be kept as small as is reasonably possible. Because wireless link and battery-powered mobile nodes are most likely the case. The protocol is also designed to accommodate mobile nodes that will generally not change their point of attachment to the Internet more frequently than once per second.

3 Estelle

Estelle [5] is a FDT based on Extended Finite State Machines (EFSM) and Pascal [6] with specific extensions and omissions to facilitate protocol specifications. An Estelle specification consists of modules, transitions, channels and structuring. A system specified in Estelle is viewed as a collection of communicating components called modules that contain relevant variables, transitions, and interaction points and may be structured into sub-modules. Modules communicate with each other through channels. Modules and channels are the fundamental building blocks of Estelle.

4 Formal Specification of Mobile IPv6

This section provides a specification framework for Mobile IPv6. It focuses on the main features of the Mobile IPv6 and builds a specification that can be extended. The modelling makes the following assumptions. There are always sufficient resources for any hosts and routers, e.g. they do not drop information because of insufficient memory or disk space. Authentication and security features are not within the scope of this work. Every subnet permits connection requests from the mobile node and always provides a connection point. Reliable media provides a reliable packet routing infrastructure.

Section 4.1 of the specification [3] mentioned two ways of sending binding packets, piggyback within any IPv6 packet or a separate packet. From the viewpoint of modelling, there is no semantic difference between them. For the first way, the recipient node can read the binding destination option, process it, then read payload, process payload. For the second way, there is empty payload. Therefore, modelling can assume separate binding packets only. It is not necessary to model alignment requirements of options and sub-options. This is an implementation issue.

4.1 Difficulties and Solutions

Estelle was designed to meet the OSI requirements. However, there is a new requirement in the Mobile IPv6. The mobile node needs to disconnect and connect to any subnet frequently. In Estelle terms, this means the mobile node module disconnects from a subnet module and connects to another subnet module. It was questioned in the early stage whether Estelle is able to specify mobility. If Estelle could not specify mobility, an extension would need to be built or a different specification language should be chosen. We tried an approach to change the mobile node’s subnet prefix dynamically. However, it did not work very well. Finally, this was resolved by Estelle’s dynamic disconnect/connect ability. Because the Specification Module does not permit transitions, all subnets, the mobile node and the correspondent node are wrapped in one module. Inside this module, mobile node’s random movement transitions can be easily specified. More details are explained in the next section.

4.2 Specification Structure

The overall Estelle specification structure is presented in Figure 1. In it module and instances names are bolded and instance names are in brackets. IP addresses of relevant modules are included as well.

4.2.1 LNL Module

Mobile IPv6 is operating in the higher layer of the Network Layer. The layers below are modelled as one module called LNL (Lower Network Layer). Although the name of LNL only indicates the Network Layer, it actually includes the underlying Data Link Layer, Physical Layer and transmission media. This module just routes packets to the correct subnet according to the subnet prefix in the packet’s destination IPv6 address. Therefore, the Internet routing mechanism is modelled in this module. An array of four external interaction points is provided to connect to every subnet.

4.2.2 Subnets Module

The mobile node (MN) module, the mobile node user (MNUSER) module, the correspondent node (CN) module, the correspondent node User (CNUSER) module and the
subnet (SN) modules are wrapped into one module called Subnets (SNS). The name Subnets does not mean that only subnet module is included. Estelle does not permit transitions in the Specification. The mobile node module needs to connect and disconnect to a different SN module dynamically. This behaviour has to be specified in transitions. By wrapping all relevant modules into one module, the Specification Module does not need to contain transition and the mobile node movement transitions are embedded into the Subnets (SNS) child module. This solves the problem and does not change any semantics.

The Internet contains many subnets. However, these subnets can be categorised into four types from the mobile node’s perspective.

- the mobile node’s home subnet SMN;
- the correspondent node’s home subnet SCN;
- possible previous foreign subnet that the mobile node visited last time, SF1, and
- possible current foreign subnet that the mobile node is visiting, SF2.

The above four subnet’s network prefix could be different, or the same. For example, current visiting foreign subnet could be the same one to the correspondent node’s home subnet. However, the mobile node only needs to remember the above four types of subnets. The mobile node does not need to keep the whole history of visited subnets. Therefore, only four subnet modules are instantiated in the Subnets (SNS) module. They represent the above four types of subnet. In Figure 1, the mobile node connects to its home subnet and the correspondent node connects its own subnet too. This is the initialised situation. The mobile node starts moving from its home subnet. The Subnets module also has an array of four external interaction points that are connected to the relevant LNL module interaction points. In Figure 1, it can be seen that these interaction points are attached to subnets child modules’ external interaction points. Therefore, the actual communication channel is from the Home Agent module to the LNL module. The Subnets and Subnet modules just transfer the packets and do not receive these packets.

4.2.3 Subnet Module

To support Mobile IPv6, the mobile node’s home subnet and the foreign subnet just visited must contain at least one IPv6 router that is able to function as the Home Agent (HA). All other subnets need to have at least one IPv6 router. Because the Home Agent is an IPv6 router that has more mobility supporting functions, this work assumes that every subnet has one Home Agent to support Mobile IPv6. A subnet can have multiple Home Agents. The draft also contains sections to describe communication among Home Agents, especially router advertisement. However, this work only models that every subnet contains only one Home Agent. This simplification does not affect the simulation of Mobile IPv6 theory. In the practical world, a subnet may need multiple Home Agents to provide reliability. Router advertisement is used to build a router list for every router. Therefore, any router can send the mobile node a router list on the subnet. In the modelling, it is assumed that the Home Agent is reliable.

Every subnet also provides two external interaction points. The interaction point SA is designated for the correspondent node; and SB is for the mobile node. This enables every subnet to have resources to fulfil the mobile node’s connection request. The mobile node is able to connect to any subnet’s SB interaction point. The subnet will not deny the connection request. For any subnet that the mobile node is not connected to, all packets sent to SB would be lost. The correspondent node is a stationary node. Therefore, only its home subnet’s SA interaction point is always connected, and other subnets’ SA interaction points are always not connected to any module. Any packet sent to other subnet’s SA interaction points would be lost. The nature of packet loss is typical of a network. Every subnet also has an internal interaction point SI. This is designed for subnet internal communication. Any packets received from SI would be forwarded to external interaction points SA and
SB. Any packets received from SA/SB would be forwarded to SI. Therefore, the Home Agent can communicate to the connected correspondent node and mobile node.

4.2.4 Home Agent Module

The Home Agent module does not contain any child modules. It has two external interaction points, HE and HI. The interaction point HE is designed for subnet external communication, for example packets sent to and received from the LNL module. The interaction point HI is designed for internal communication, for example packets sent to and received from the connected correspondent node and mobile node. Once the Home Agent receives a packet from the LNL module, the LNL module guarantees that the packet is for its subnet, e.g. the subnet prefix in the packet’s destination address is the same as the subnet’s prefix. If the packet is for the Home Agent, the relevant transition will be fired. If the packet is not for the Home Agent, the packet will be forwarded to the interaction point HI. By following transitions, the packet will be forwarded to the Subnet’s interaction points SA and SB. In this case, the Home Agent functions as a normal router.

4.2.5 Mobile Node, Correspondent Node and Users Module

The Transport Layer and the layers above are modelled as mobile node user and correspondent node user. It is assumed that the correspondent node user keeps sending data packets with a sequence number to the mobile node user. The mobile node user responds with a data packet having the same sequence number when receiving a data packet from the correspondent node user. This data packet is actually an acknowledgement. If the correspondent node user did not receive correct acknowledgement in a certain time, it will re-transmit the data packet with the same sequence number until correct acknowledgement is received. If the mobility is not supported very well when the mobile node keeps moving, the correspondent node user will be in a situation to re-transmit the data packet with the same sequence number. Both the mobile node and the correspondent node have two external interaction points. One (the interaction point M for the mobile node, and the interaction point C for the correspondent node) is designed for the communication to and from the Subnet module; and another one is for the communication to and from the user module.

4.3 Modelling Mobile Node Movement

4.3.1 Mobile Node Random Movement

Figure 1 has provided a framework for modelling the mobile node’s random movement on the Internet. The mobile node module is able to disconnect from current linked subnet and connect to another subnet. This actions of disconnection and connection describe physical connection characteristics in the mobile node’s movement. The mobile node itself does not know that it has been connected to a different subnet. The mobile node needs to use movement detection procedures described in Section 10.4 of the draft to detect movement. In the Subnets module, at least two methods can be utilised to model random movement. The Estelle codes shown below, illustrate the use of non-deterministic execution behaviour for choosing fireable transitions. A pre-defined array is used for controlling a random movement path. This helps in simulation and debugging. A specified path can be designed to test certain conditions. From the specification structure and the codes mentioned, it can be seen that the mobile node can only connect to at most one subnet at a time. Multiple care-of addresses can help smooth hand-off between subnets. However, the mobile node only can have one primary care-of address at a time.

Const
SN_NO = 4;
Var
v_CurrentSubnet: integer;
v_NextSubnet: integer;
i: integer;
Any i: 1..SN_NO do
Delay (MAX_UPDATE_RATE, MIN_UPDATE_RATE)
begin
v_NextSubnet := i;
if v_NextSubnet <> v_CurrentSubnet then
begin
disconnect MN_1.M;
connect MN_1.M to SNA[v_NextSubnet].SB;
v_CurrentSubnet := v_NextSubnet;
end;
end;

4.3.2 Movement Detection and Forming New Care-of Address

Section 10.4 (Movement Detection) and 10.5 (Forming New Care-of Addresses) in the draft provides the details on these two issues. IPv6 Neighbour Discovery is used in the specification to detect movement. In the above section, the SNS_MN_RandomWalk transition in the Subnets module randomly connects the mobile node to a different subnet. The mobile node module does not know to which subnet it connects to. To assist movement detection, every home agent needs to send unsolicited multicast router advertisements at a certain rate. The draft also recommends decreasing the advertisement interval to accommodate faster
movement. Once the mobile node receives a router advertisement that contains different subnet prefix to its current subnet prefix, it knows that the current subnet has become unreachable and it should start configuring a new care-of address and start sending binding updates.

From the above mechanism designed in the draft, we can see there should be a movement limit that can be supported by the network. This limit is that the mobile node will generally not change the point of attachment to the Internet more frequently than once per second. After detecting that it has changed the point of attachment, the mobile node should form a new primary care-of address using one of the on-link subnet prefixes advertised by the new router. The mobile node can use either stateless or stateful Address Auto-configuration. In addition, the mobile node may already know a constant IPv6 address that has been assigned to it for use when visiting foreign subnets. This approach is used in the Estelle specification. Because there is only one mobile node in the specification, this approach simplifies some engineering details. To implement this, Home Agents, the correspondent node and the mobile node are assigned a different interface ID. Therefore, the mobile node can always use its own interface ID (constant) to form a new primary care-of address. In this case, the mobile node does not need to perform Duplicate Address Detection after forming a new care-of address.

### 4.4 Sending Binding Updates

After forming a new primary care-of address, the mobile node needs to start sending binding updates. Section 10 (Mobile Node Operation) of the draft describes many cases about sending the binding update. They can be summarised as follows:

- **Case 1:** Movement detected, send it to the Home Agent in the home subnet,
- **Case 2:** Movement detected, send it to the correspondent node,
- **Case 3:** Movement detected, send it to the Home Agent in the previous visited foreign subnet,
- **Case 4:** Returning home subnet, send it to the Home Agent in the home subnet,
- **Case 5:** Returning home subnet, send it to the correspondent node, and
- **Case 6:** Received the Binding Request, send it to the requested node.

Case 6 only happens in an as-needed basis and generally does not need the Binding Acknowledgement. Therefore, this case can be modelled in one transition. Only the other five cases should be optimised. Every case, except Case 6, has different retransmit strategies. If no acknowledgement is received from the Home Agent, the mobile node should retransmit the Binding Update, until a Binding Acknowledgement is received. The retransmissions by the mobile node must use an exponential backoff process, in which the timeout period is doubled upon each retransmission until either the node receives a Binding Acknowledgement or the timeout period reaches the value $\text{MAX\_BINDACK\_TIMEOUT}$. However, in notifying the correspondent node and the acknowledgement is required, the mobile node should not continue to retransmit the Binding Update once the retransmission timeout period has reached $\text{MAX\_BINDACK\_TIMEOUT}$.

The first five cases can be "folded" into one state - SENDING_UPD. However, control parameters are needed. A Binding Update has the following parameters: destination address; home address field in the home address option; home registration flag; retransmission strategy; acknowledgement flag; router flag; and duplicate address detection flag.

There is no specific description about the sending sequence of the Binding Updates. However, the following sequence requirements are derived from the draft and it should be reasonable. After forming a new primary care-of address or returning home, the mobile node should notify its Home Agent in the home subnet first. After receiving matching positive acknowledgment from the Home Agent, the mobile node needs to notify the correspondent node and the Home Agent in the previous visited foreign subnet, if any. There is no sequence preference between the correspondent node and the previous foreign subnet’s Home Agent. Therefore, a folding technique is utilised to minimise the number of transitions.

### 4.5 Lifetime Management

The lifetime attribute is associated with almost every data structure. For instance, every primary care-of address registration must contain a lifetime field. After the lifetime reaches zero, the entry must be deleted. According to the draft specification, the remaining lifetime should keep pace with the clock. In many cases, it is very important. For instance, if the mobile node receives a Binding Request, it should return its current primary care-of address and the remaining lifetime of the primary care-of address registration. After a time unit lapses, the transition will decrease its value in the lifetime filed of all relevant data structures. For the Home Agent module, Binding Cache and Home Agents List contain a lifetime field. If the lifetime reaches zero, relevant IP addresses will be removed as well (set IP address to nil). Other modules use a similar mechanism to maintain their own lifetime fields.
5 Simulation

The simulation tool used was the Estelle Development Toolset (EDT) [4]. It is a set of tools mainly developed by Bull S.A and further extended by the Institut National des Tlcommunications, France (INT). The tools allow the development of reliable implementations of systems specified in Estelle.

The EDT is an open toolset. This means that other tools, designed by the user, may be added. The opening is provided by offering the user a programming interface to the intermediate form (IF). It allows simulations to be run which would test such things as failure modes, interoperability between different versions, heavy load conditions, mis-configurations, and so on. It can also be checked for unreachable states, unassigned variables, deadlocks, livelocks, and other global properties.

5.1 Results

The Estelle specification codes were compiled successfully using EDT. This enabled the simulation of the Mobile IPv6 to be done. It was noticed that the mobile node could just move away before a data packet reaches its previous connected subnet. The correspondent node user needs to employ a retransmission strategy. The correspondent node user retransmits the same data packet if the correct reply packet is not received in a certain time. This is reasonable because of the nature of wireless/mobile links.

It was found that the binding management does work well to maintain connectivity. Even the mobile node moves too fast (the mobile node moves away again from the new subnet just after sending the Binding Updates), the mobile node user was still able to receive retransmitted packets from the correspondent node user.

However, the packet forwarding from a previous care-of address was not observed in the simulation. Because there is only one correspondent node user and the mobile node would send the Binding Update to it first, before sending to the home agent in the previous connected link, there is almost no chance for that home agent in the previous connected link to tunnel the data packet received from the correspondent node user.

The connectivity to and from the mobile node after and when the mobile node moves, is maintained, even though the correspondent node user needs to employ a retransmission strategy. No protocol errors were found in this Mobile IPv6 simulation work.

6 Conclusions

In this paper, mobility or physical movement of the mobile nodes, has been modelled in Estelle. Estelle specification structure has been presented and modelling of each module has been detailed. Modelling of three important fields - mobile node movement, folding technique of sending binding updates, and lifetime management - have been described in the paper. By wrapping all subnets, the mobile node and the correspondent node modules into one module, the mobile node’s random movement transition can be specified with Estelle’s dynamic disconnect/connect ability. Logical disconnect/connect between the mobile node and the subnets have been modelled. Lifetime management were also effectively modelled by Estelle spontaneous transitions with time unit delay.

The simulation work showed that the binding management does work well to maintain connectivity. Even the mobile node moves too fast, the mobile node user was still able to receive retransmitted packets from the correspondent node user. However, the packet forwarding from a previous care-of address is not able to be observed because there is only one correspondent node user and the mobile node would send the Binding Update to it first before sending to the home agent in the previous connected link. The connectivity to and from the mobile node after and when the mobile node moves, is maintained, even though the correspondent node user needs to employ a retransmission strategy.

References