Micro-Mobility Performance Evaluation of a Terminal Independent Mobile Architecture

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Abstract. *All IP mobility protocols currently proposed by the IETF assume that the mobile nodes always have a mobility-aware IP stack, which is still a scenario that can seldom be found nowadays. Most terminals, including the laptops and PDAs which would most benefit of the mobility support, still use legacy IP stacks, limiting their use to layer 2 mobility within a single IP subnet.*

The deployment of a terminal independent mobility solution, which efficiently supports handover, while providing resource optimisation, will increase mobile services offer, as it may be easily deployed by changing the network infrastructure, while using the existing terminals.

This paper proposes a classification's framework for existing mobility protocols; describes a terminal's independent mobility architecture – TIMIP/sMIP – and compares the performance of these solutions via simulation studies.

1. Introduction

The number of people that use wireless LANs (wLANs) is increasing at a very fast rate, so it is foreseen that wLANs will have a major impact in the Internet.

Today, Mobile IP (MIP) [1] is the standard mobility solution, representing a fairly good approach for the mobility in wide scale, where handover performance is not a major issue. Although developed within the scope of IPv4, it is accepted now as the macro mobility solution for IPv6 networks in its correspondent version (MIPv6).

As far as micro-mobility is concerned, quick and smooth routing changes are required in order to achieve seamless handover, resulting on the work of Cellular IP (CIP) [2], HAWAII [3] and Hierarchical MIP (hMIP) [4]. In spite of their differences, all of them lack support for legacy terminals. Today, most of the terminals that would benefit from mobility, like laptops and PDAs, still use legacy IPv4 stacks (defined in [5]). This might represent a constraint that prevents the deployment of mobility in the short term, as an entire migration to MIPv4, or even IPv6 + MIP6 is not envisaged for the near future [6].

A terminal's independent mobility architecture was already proposed in [10], [11], and implemented in a real testbed prototype. This architecture comprises a micro-mobility solution, named Terminal Independent Mobile IP (TIMIP), coupled with a MIP compatible adaptation for macro-mobility scenarios, Surrogate MIP (sMIP). In spite of the good experimental results achieved by TIMIP/sMIP architecture, a more complete evaluation study of the performance of the available mobility solutions must be done, concerning the different phases of a roaming operation.

This paper presents a performance evaluation study of several mobility solutions. This evaluation study is based on an original framework used to classify these proposals, according to their handover and resource utilisation efficiency.

The remaining part of this paper is organised as follows: section 2, presents the framework and classifies the protocols according to it; section 3 presents the TIMIP/sMIP architecture; section 4 presents the performance studies; and, finally, section 5 presents some conclusions and future work.

2. Classification Framework

This section presents an original framework used to classify the mobile protocols, according both to the efficiency of their handover and the optimisation of network resources. Such approach differs from other models that are focused on the routing operations used to support mobility, like [7], or other generic features of the mobility protocols [8].

2.1 Framework Model Presentation

When a Mobile Node (MN) roams between two Access Points (APs) and looses Layer 3 (L3) connectivity, the **Handover** procedure is triggered.

At first, the MN is connected to the network via an old AP, having the entire set of IP mobility mechanisms properly created and stable for its current location. When it moves away, it is assumed that physical connectivity is broken and Layer 2 (L2) handover starts.

The MN will be physically unreachable until L2 connectivity is restored at the new AP. If the new AP lies in a different sub-network, IP routing information becomes inconsistent, which is a situation that must be addressed by the appropriate IP mobility protocol to restore IP connectivity. The time gap between reestablishment of L3 and L2 connectivity represents the L3 Handover.

This framework considers that L3 operations are divided into three main phases, concerning the MN roaming between APs:

- **Detection Phase:** This phase happens after L2 handover is completed, until the IP layer becomes aware that the network has outdated routing information about the MN's location;

- **Registration Phase:** During this phase the routing information is updated at the relevant nodes, by registering the new MN location;

- **Execution Phase:** This phase occurs between handovers, when the routing information is kept updated and data traffic can reach the MN in a stable way;

Figure 1 represents the framework and classifies the several mobility solutions according to it. MIP has been studied considering either the standard version or several extensions, like MIP Post Registration Trigger [9], MIP Pre Registration Trigger and Hierarchical MIP (hMIP). Other micro-mobility solutions have also been evaluated, namely HAWAII and CIP, considering both hard and soft-handover variants.
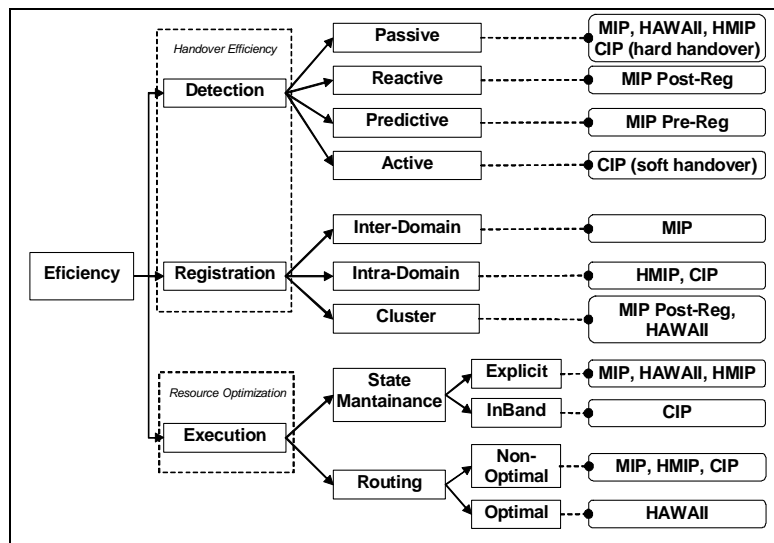

Figure 1: Classification Framework

Regarding the *Detection* Phase, the traditional IP layer is not aware of the MN`s movements, as it is independent of the lower layers. However, on most radio technologies, the L2 is fully aware of these movements, and thus able to help L3 on their detection. The level of integration between L2 and L3 provides different Detection Phase Models.

If a **Passive** Model is used, no integration is required, being this either the sole or a fallback solution of the existing mobility protocols. In the **Reactive** Model, there is a minimal cooperation between the two layers, where the L2 operations are simply exposed, without further interactions. In a **Predictive** Model, L2 becomes responsible to predict handovers and inform L3 before they actually take place. Finally, the **Active** Model requires a total cooperation and integration of L2, as L3 fully takes control on the L2 handover operations. Regarding this phase, Handover Latency is expected to decrease as cooperation between the two layers increases.

During the *Registration* Phase, the latency is mainly dominated by the time needed to restore the MN`s connectivity, in all the nodes forming the critical registration path. Thus, both the number and the relative locations of these nodes influence the registration latency, resulting in the different proposed models for this phase.

The **Inter-Domain** Model, usually used in macro-mobility solutions like MIP, requires that nodes outside MNs current domain must be informed about the new MN location. The **Intra-Domain** Model, requires only the notification of nodes belonging to the current MN domain. Finally, in the **Cluster** Model only the nodes belonging to the shortest possible path, between the old and new APs, must be notified. In this phase, Handover Latency is expected to decrease as long as the network nodes to be informed are kept closer to the MN.

Concerning the *Execution* Phase, the critical issues to consider are those that lead to an optimisation of network resources, during stationary periods, which occurs when the MN stays in the same AP. Efficiency of the mobility protocols is related to both the state maintenance overhead and the actual routing paths used to carry data traffic.

The **Explicit State Maintenance** Model implies the existence of signalling messages, used to detect refresh MN information, at the necessary nodes. Its dual is the **Implicit State Maintenance** Model, which uses IP traffic to refresh MN information, at the relevant nodes. Concerning data paths, **Non-Optimal Route** Model uses paths that may be longer than needed. The **Optimal Route** Model sends data through the shortest path, for the generality of situations. Regarding this phase, efficiency increases when fewer resources are needed both to maintain the MN active and to forward its data packets.

3. TIMIP/sMIP Global Mobility Solution

The mobile architecture evaluated in this paper is based on a dual mobility protocol, which uses TIMIP to support micro-mobility, and an extended version of the standard MIP, called surrogate MIP (sMIP), to support macro-mobility. Although it has been already described in [10] and [11], no evaluation has been done, comparing its performance with other solutions.

The addition of IP mobility support requires changes and additions to the standard IP protocol, in both the network-side and the end-user terminal equipment, meaning that the terminals cease to be legacy terminals (defined in [5]).

To address this problem, TIMIP/sMIP provides a terminal independent mobility solution, in which the network is the sole responsible for the mobility actions that are typically executed by the terminals while roaming, implementing thus a "surrogate behaviour", which was defined originally in [12]. For Detection Phase, the identification of legacy MN's movement is done at network-side only. Concerning the Registration Phase, the network generates signalling information that triggers routing update process. There are no requirements for the Execution Phase concerning this support.

TIMIP uses the *Reactive* Model Detection' Phase, as the network tracks MN movements by a single L2 primitive that signals the attachment of MN to the AP. This primitive uses all available L2 information for unequivocal localisation of terminal. If the required L2 information is not available, or is not enough to perform unequivocal localisation of terminal's point of attachment, then a Passive Detection model is used, supported on a Generic Detection Algorithm, as described in [11].

After detection, the MN location is dynamically updated inside the domain, using a *Cluster* Model Registration, with the update messages generated transparently by the current AP of the MN. When a MN arrives at a TIMIP domain (power-up), the TIMIP's signalling messages travel up to the domain's gateway. For subsequent roaming operations they are directed to the old AP, being confined to the local sub tree that connects the old and new APs. As no information of the old AP is available at the network-side, the network has to infer about its location, using the previous outdated routing paths to pass the messages in a guaranteed way. This registration process is initiated by the new AP, when it detects a new MN and generates signalling information; it ends when that signalling reaches the old AP. During this process, routing tables are updated, hop-by-hop, starting from the new AP. Reliability mechanisms were embedded into TIMIP signalling messages, by using acknowledge packets and clock synchronisation procedures.

In the Execution Phase, TIMIP uses *Implicit* Model: to keep routing information updated, IP traffic is used to refresh routing entries for active MN, while explicitly generated signalling information is used only for idle terminals, being subject to a back off mechanism. TIMIP also use *Optimal* Path Models, as packets are always forwarded using the shortest path in the network tree, which means that they go up to only the crossover node (uplink routing) and then go directly down to the current AP of the destination (downlink routing).

Concerning macro-mobility support, the sMIP architecture is composed by MIP compliant agents, called surrogate home and foreign agents (sHA, sFA). In a similar way to TIMIP, the sMIP protocol was enhanced with extensions to both to detect movements and generate standard MIP signalling automatically, on behalf of the MN that can now roam transparently between TIMIP domains.

The sMIP detection is based on the TIMIP mechanisms. For this, at the Access Network Gateway (ANG), the TIMIP power-up operation triggers the sMIP detection. After that, the sFA uses standard MIP registration procedures, but generates and receives standard MIP messages on behalf of the legacy MN. MIP security procedures may be assured by the sFA or by the legacy MN, with help of a special authentication application. Thus, no changes are required at the Home Agent side, as the protocol is fully interoperable.

4. Simulation studies

The efficiency of existing micro-mobility solutions were evaluated by simulation and compared to TIMIP, by measuring the latency of the handover and the optimisation of network resources. As TIMIP's macro-mobility solution is MIP-compliant, its performance is similar to the one presented by MIP and so, will not be addressed in this paper.

The simulations were carried on Network Simulator (NS), version 2.26, enhanced with CIMS v1.0 mobility additions that provide support to hMIP (1-level), CIP and HAWAII. Additionally, NS was modified both to support the TIMIP protocol, and to simulate 802.11 infra-structured behaviour with multiple channels. This forces L2 hard handoffs operations, where a station can only receive packets via its current associated AP, being this behaviour much closer to real 802.11 networks [13] than soft-handoffs.

From the set of CIMS options, a sample subset was selected: CIP hard-handover option, due to L2 hard-handoffs being the ones used in real 802.11 networks; HAWAII Multiple-Stream-Forwarding (MSF), due to the interesting packet buffering possibility.

Two different set of simulations were performed, as described in the following sections, using the network of Figure 2. This network contains a single domain with 4 APs, organised on a straight line. The APs are interconnected to the single GW by a series of internal nodes, disposed on a tree structure; all internal connections are point-to-point wired links of 10Mbit/s throughput and increasing delays, for each hierarquical level closer to the GW (respectively 10, 20 and 40ms). Finally, a single MN roams inside the domain, connecting to it by each AP in turn.
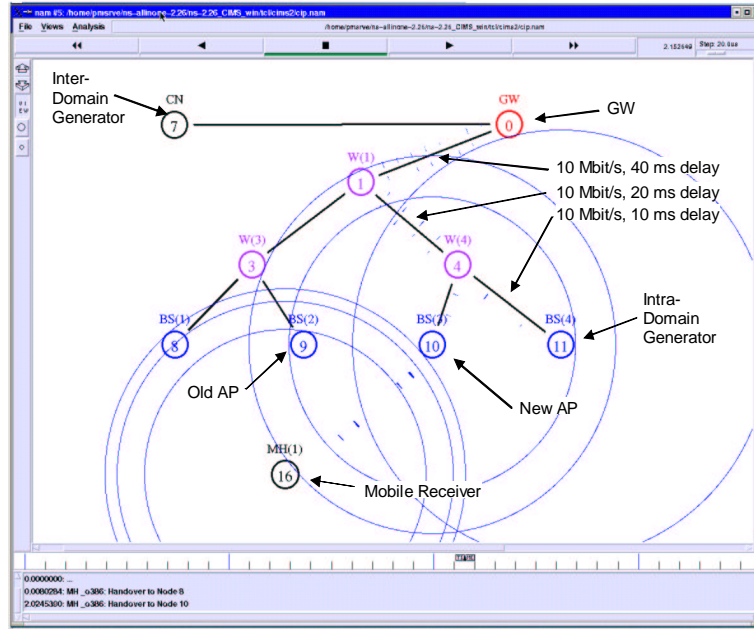

Figure 2: Simulation Scenario

4.1 Simulation Experiment A

The first experiment evaluated both handover latency and resource optimisation. For this, a Constant Bit Rate (CBR) traffic source, generating 200 pkt/s of 30 bytes, is allocated either outside the domain (Node 7), or inside it (Node 11), respectively for intra-domain and inter-domain traffic types. The traffic receiver is Mobile Node 16, which roams between Node 9 and Node 10.

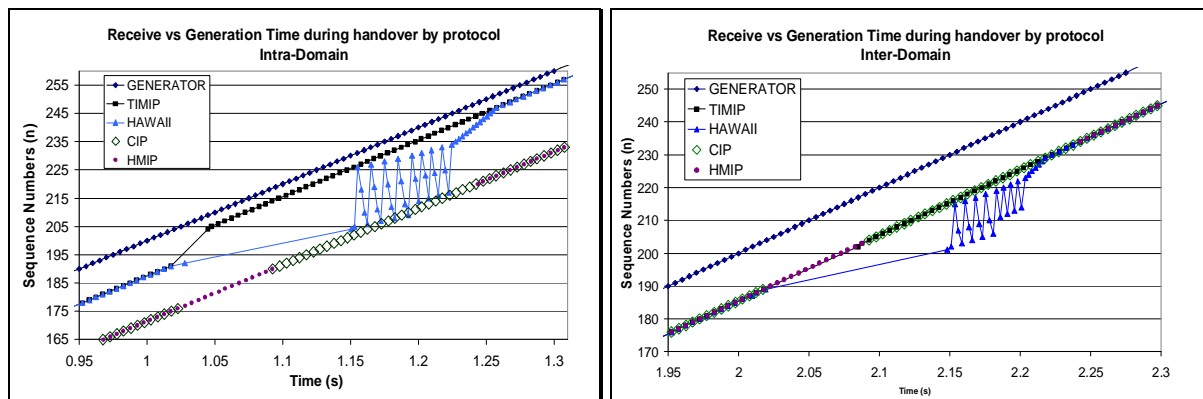The respective results are shown on Figure 3, which represents the packet sequence number evolution with time.

Figure 3: Handover Latency: Intra and Inter-Domain Situations

4.1.1 Evaluation of the Handover Efficiency

The handover latency represents the time gap between the first packet received by the new AP (AP10) and the last packet received by the old AP (AP 9). This gap may be estimated by the number of missing packets during a roaming situation. Table 1 contains the handover latency, obtained from the data series used to generate Figure 3.

Latency [ms]	Intra-Domain	Inter-Domain
TIMIP	27.3	67.3
HAWAII	196.8	184.5
CIP	69.7	75.4
HMIP	151.4	155.2

Table 1: Handover Latency values (ms) for different protocols

Intra-domain analysis

Considering intra-domain traffic situations, all protocols feature packet drops at the old AP, as the terminal must switch frequencies to the new AP; in HAWAII there are also out-of-order packets, immediately after the handover, for a short period of time. While the terminal is stationary at an AP, TIMIP and HAWAII protocols have similar results for routing delay, both lower than those of hMIP and CIP.

A more detailed analysis, shows also that TIMIP takes 27.3 ms to perform handover, as the last packet received by AP9 is received at time 1.0177s (packet 191) and the reception of the first one by AP10 occurs at time 1.0449s (packet 204). Similarly, HAWAII, CIP, hMIP, have handover times of 196.8, 69.7 and 151.4ms, respectively (summarized in Table 1). TIMIP has the lowest latency, as it only has to inform Node 4 to re-establish routing (crosshover node); CIP must also inform Node 1, because as all packets must pass through the gateway, they will only be diverted on the first node common to both (old & new) paths; hMIP must inform the gateway, in order to reconfigure the local tunnel; finally, although HAWAII must inform the same nodes of TIMIP, its routing updating starts at the old AP. Due to this, out-of-order packets are received, which for a real-time CBR flow counts as packets lost.

This experiment shows that, concerning the efficiency of registration phase defined previously in section 2, both TIMIP and HAWAII limit their updates to the minimum set of nodes that must be informed, and thus, can have the most efficient registration type - Cluster. However, by introducing methods that cause out-of-order packets, HAWAII can cancel this benefit, as showed above. Regarding the hMIP protocol, and also CIP (in a lesser degree), there are nodes inside the domain, further away from the MN's location, that need also to be informed about its new location the domain's gateway resulting in higher handover times (caused by intra-domain registration type).

Inter-Domain Analysis

Concerning inter-domain traffic situations, packets are also dropped by the old AP while the terminal switches to the new AP channel; in HAWAII there are also out-of-order packets, immediately after the handover, during a short period of time. While the terminal is stable at an AP, all protocols have similar results for routing delay.

A more detailed inspection shows also that TIMIP takes 67.3 ms to perform handover, as the last packet received by AP9 is received at time 2.0178s (packet 189) and the reception of the first one by AP10 occurs at time 2.0851s (packet 202). Similarly, HAWAII, CIP, hMIP, have handover times of 184.5, 75.4 and 155.2ms, respectively. TIMIP has the lowest latency, as it only has to inform Node 4 and Node 1 to re-establish routing (crosshover node); in the same group, CIP has a similar handover time, as the first node common to both paths is also Node 1. Like the previous case, hMIP must always inform the gateway, in order to reconfigure the tunnel, thus resulting in an higher time; also as before,

HAWAII must inform the same nodes of TIMIP, but as routing updating starts at the old AP, again out-of-order packets are received, resulting in the highest handover time results.

This experiment shows that, concerning the efficiency of registration phase previously defined in section 2, again both TIMIP and HAWAII limit their updates to the minimum set of nodes that must be informed, and thus, have the cluster registration type, although HAWAII cancels it's benefit by causing packets to arrive out-of-order. As CIP and hMIP force all packets to pass through the domain's gateway, the registration classification defined previously for these protocols remain unchanged with inter-domain traffic.

4.1.2 Evaluation of the Resource Optimisation

Experiment A can also be used to evaluate the resource optimisation of the different protocols, for both traffic types, by checking the end-to-end latency that the packets suffer when passing through the network. This metric, of key importance to real-time services deployment, can be checked during stable conditions, before and after the handovers, by measuring the time interval between generation and reception of data packets. Table 2 contains these delay values, obtained from the data series used to compose Figure 3.

Delay [ms]	Intra-Domain		Inter-Domain	
	Node 9	Node 10	Node 9	Node 10
TIMIP	62.5	22.3	72.5	72.5
HAWAII	62.4	23.5	74.5	74.5
CIP	142.7	142.8	72.5	72.5
HMIP	142.6	142.6	72.5	72.5

Table 2: Average Packet Delay (ms), per Location

Intra-Domain Analysis

During stable conditions, the gap between sending and receiving packets is smaller in TIMIP and HAWAII than in the other solutions. This gap represents the end-to-end delay. After roaming, TIMIP reaches the stable condition before HAWAII does, due to the transmissions of the buffered packets at the old AP. In TIMIP the average delay is 62.5 ms on AP9, being this value reduced to 22.3 ms on AP10. Regarding the other protocols, HAWAII, CIP, hMIP have, respectively, 62.4, 142.7 and 142.6ms delay on AP9, with these values being reduced to 23.5, 142.8, 142.6ms, respectively, on AP10. From these values, it's quite clear that both CIP and hMIP impose much higher delays for intra-domain type of traffic.

These results show that, for intra-domain traffic, both TIMIP and HAWAII can route packets efficiently inside the network, while both CIP and hMIP force all packets to pass through the domain's gateway. Thus, considering the efficiency of routing at the execution phase defined previously in section 2, both TIMIP and HAWAII feature optimal intra-domain routing, by using the shortest paths inside the network, which optimizes both the resource utilisation, and the end-to-end delay. On the other hand, by forcing all traffic to pass at the domain's gateway, both hMIP and CIP have a non-optimal routing execution, resulting in longer delays and higher link usage inside the network.

Inter-Domain Analysis

During stable conditions, all end-to-end delays incurred by the protocols have similar values, in all MN locations. For TIMIP, the average routing delay is 72.5 ms, for both AP9 and AP10, and the other protocols, HAWAII, CIP, hMIP, have, respectively, 74.5, 72.5, and 72.5 ms.

These results show that, for inter-domain traffic, all protocols route packets in the same way inside the network, without penalties associated with the requirement for traffic to pass through the domain's

gateway (case of CIP and hMIP). This causes all protocols to have optimal routing for inter-domain routing.

4.2 Simulation Experiment B

The second experiment evaluated resource optimisation, using a different metric – the sum of all packets forwarded inside the network, in all network nodes, per time interval. Several sequential handovers are simulated, where the Mobile Node arrives at the first AP (Node 8), and moves up to the last (Node 11). A CBR traffic source generating 100 pkt/s of 30 bytes, is allocated either outside the domain (Node 7), or inside it (Node 11). This CBR source starts its transmission at time 1 second.

Again, two different situations have been studied: in the former, intra-domain traffic is generated, by placing the source closer to the initial location of the mobile terminal (at Node 11, the last AP of the domain), and, in the later, inter-domain traffic is generated, as the source is located outside the domain (at Node 7).

The average number of packets forwarded in the wired networks is measured by the number of packets forwarded at each hop, being this summed for all network nodes, for each time interval of 50ms. The respective results are shown on Figure 4, with the handover time instants that were taken directly from the simulation dumps present in Table 3.
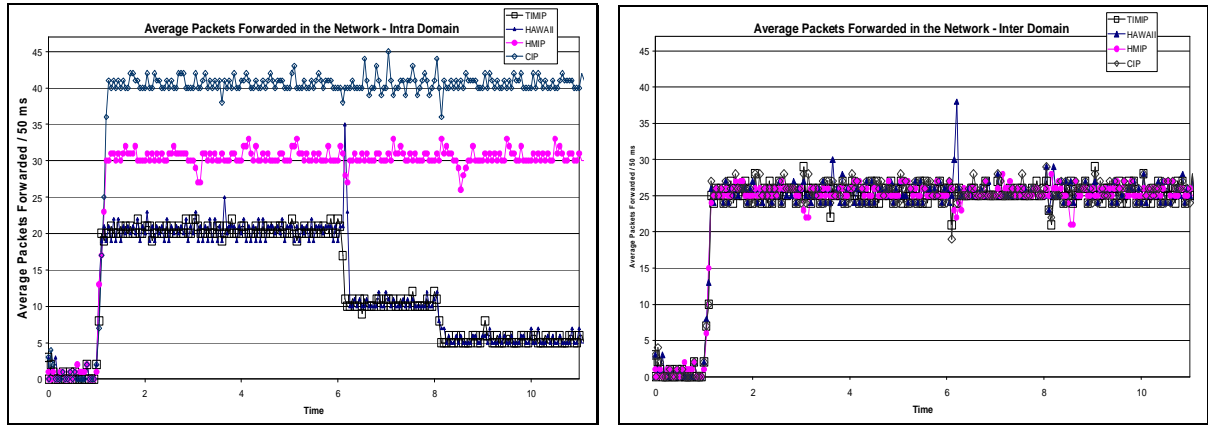

Figure 4: Average packet forwarded: Intra and Inter-Domain Situations

Handover time [s]	Node 9	Node 10	Node 11
TIMIP	3.56	6.03	8.09
HAWAII	3.57	6.03	8.10
CIP	3.56	6.02	8.09
HMIP	3.52	6.09	8.45

Table 3: Time of handovers at each AP, per protocol

4.2.1 Evaluation of the Resource Optimisation

Intra-domain analysis

Concerning intra-domain roaming situations, all protocols exhibit fairly constant resource utilisation of the network in the periods that the terminal is stable at each AP. The figure also shows that both TIMIP and HAWAII protocols have similar results for their network resource utilisation, which varies according to the present MN's location. However, this resource utilisation is always lower than those of hMIP and CIP, as these have fairly constant results for all positions of the MN inside the network. Finally, it is possible to confirm the approximate instants of the handovers (that are present in Table 3), by observing the sharply changes incurred at these time instants in the graphs.

A more detailed inspection shows also that TIMIP and HAWAII forward an average of 20 packets per time interval, relative to 4 hops, when the MN is at the leftmost part of the domain (Node 8); concerning hMIP, this rotocol forwards 30 packets per time interval, relative to the 6 hops the packets must transverse to reach the gateway. CIP has the largest resource utilisation, by forwarding 40 packets per time interval, as its routing additionally forces packets to completely exit the domain in order to be being treated as coming from outside the domain. This results that packets must reach Node 7, summing thus a total of 8 hops per packet.

At time 3 s, the MN performs a handover to the next AP (Node 9), but the resource utilisation of the protocols remains equal for all protocols. This happens because in this topology, the new MN location is reachable by the same number of hops.

The situation changes at time 6 s, where a handover occurs to Node 10. Here, both TIMIP and HAWAII reduce their network utilisation to 10 packets per time interval, as packets only need 2 hops to reach the new location of the MN. At this instant of time, there is a spike in HAWAII, which is a result of the out-of-order packets, due to the routing reconfigurations performed. As before, both hMIP and CIP maintain their high resource utilisation, as packets are forced to pass the gateway, maintaining the 6 hops minimum that was described previously.

The next change happens around time 8s, where the last handover changes the MN point of attachment to the rightmost part of the domain – Node 11. In this situation, both TIMIP and HAWAII reduce their utilisation to only 5 packets per time interval, relative to the single hop needed to reach the MN; again, CIP and hMIP must still force packets to reach the gateway, maintaining the 6 hops minimum.

The results show, considering the efficiency of routing at the execution phase, that both TIMIP and HAWAII feature optimal routing, by using the shortest paths inside the network, which optimizes both the resource optimisation and the end-to-end delay. On the other hand, by forcing all traffic to pass at the domain's gateway (or even beyond), both hMIP and CIP have a non-optimal routing execution, resulting in longer delays and higher link usage inside the network.

Inter-Domain Analysis

Concerning inter-domain roaming situations, all protocols exhibit stationary resource utilisation of the network in the periods that the terminal is stable at each AP, being this utilisation always the same for all locations of the MN inside the domain. Again, it can be verified in the protocol behaviour the handovers instants (present in Table 3), by observing the sharp changes incurred in the number of packets forwarded per time interval.

A more detailed inspection shows also that all protocols forward an average of 25 packets per time interval, relative to 5 hops needed to reach all existing APs, including the source node (Node 7). These results show that, for inter-domain traffic, all protocols route packets in the same way inside the network.

5. Conclusions

This paper evaluated a global mobility solution, TIMIP/sMIP, which supports legacy terminals, efficiently, regarding handover latency and optimisation of network resources.

To define its requirements, an original classification framework has been proposed, describing different models of detection, registration and execution. Existing mobility protocols have been classified according to it, while the models that best fit the proposed requirements were selected as the basis of our solution. Thus, TIMIP/sMIP uses reactive detection phase, cluster registration type, and in-band state maintenance coupled with optimal routing, both for execution phase.

Simulation studies were performed, comparing TIMIP/sMIP with other mobility protocols, namely hard handover CIP, 1-level hMIP and HAWAII. Handover latency and resource utilisation have been measured, either for intra-domain or inter-domain traffic situations.

The results achieved for intra-domain situations have shown that TIMIP and HAWAII have the best performance. However, TIMIP has slightly better latency performance, due to the existence of out-of-order packets in HAWAII during roaming situations. CIP and hMIP present the worst results, as all the traffic must be forwarded through the domain's gateway. Concerning inter-domain situations, apart from HAWAII's out-of-order packets behaviour, no significant differences occur.

Future work comprises optimisation and support of multicast routing, non-hierarchical networks, IPv6 mobility mechanisms, quality of service and always-best-connected service support.

Acknowledgements

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