Performance Evaluation of Micro-Mobility Protocols in Fail-Tolerant Mesh Networks

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ABSTRACT

This paper describes a Terminal's Independent Mobility Architecture, TIMIP / sMIP, which supports IP mobility of legacy terminals, and presents a complete performance evaluation to compare the proposed architecture with alternative solutions, via simulation studies in complex scenarios featuring wired mesh topologies and wireless disjoint channels.

The NS2 simulation studies compare the selected micro mobility protocols under both stationary and moving conditions, but also when random link failures occur in the wired part of the network, which is a previously unstudied scenario.

The results show that the TIMIP protocol has the best overall efficiency for handover latency and resources optimization, due to its localized handovers and tree-optimal routing features; and that HMIP has the best robustness to wired link failures, a result its data packets encapsulation feature.

I. INTRODUCTION

The number of people that use wireless Local Area Networks (wLANs) is increasing at a very fast rate, being foreseen that wLANs will have a major impact in the Internet and the future 4G mobile data networks [1][2]. Today, Mobile IP (MIP) [3][4] is the standard mobility solution for infra-structured heterogeneous networks, where fixed nodes serve the mobility of mobile terminals. Available for both IP versions, MIP is a good approach for the mobility in wide area networks, where handover performance is not a major issue.

Concerning micro-mobility, quicker and smoother routing changes enable seamless handovers, resulting in the work of Cellular IP (CIP)[5], HAWAII [6] and Hierarchical MIP (HMIP)[7]. Besides their differences, all of them lack support for legacy terminals, which are mobile-unaware IP terminals with legacy fixed IPv4 stacks, like laptops and PDAs. As these are the nodes that would most benefit from mobility, this might represent a constraint preventing the deployment of mobility in the short term, as an entire migration to MIPv4 or IPv6+MIPv6 is not envisaged in the near future [8][9].

To address this problem, a terminal's independent mobility architecture was proposed in [10][11], where a micro-mobility solution, Terminal Independent Mobile IP (TIMIP), is coupled with a MIP adaptation, named Surrogate MIP (sMIP). This unique transparency support can be of major importance to future heterogeneous 4G networks, having TIMIP already been identified as part of the 4G mobile architecture [12].

Initial performance studies of TIMIP/sMIP were presented in [13], where a proposed performance evaluation framework classified the protocols based on their handover efficiency and resource optimization characteristics. The framework was validated with initial simulation studies that compared the protocols in test scenarios using intra-domain traffic and IEEE 802.11 access networks with multiple disjoint channels. However, such studies were limited by addressing only discrete handover situations in tree topologies, and measuring only the lost packets in simple scenarios. On the other hand, performance studies of the mentioned micro-mobility protocols have been done [14][15], but were limited to single metrics in strict tree topologies, focusing on inter-domain traffic only, on a single shared 802.11 channel. Also, to the best of our knowledge, no study was performed considering the effect of link failures on generic mesh networks; although [16] addresses this topic, it is limited to a 3-node topology.

However, the networks and utilisation patterns in which mobility is expected to be deployed will be more complex than the simple scenarios that these previous studies considered.

In fact, the deployed networks commonly use meshed topologies with redundant links to provide robustness against wired link failures. Although having a much higher reliability than wireless links, continuous connectivity requires multiple redundant wired links to prevent from long / permanent link failures in the fixed part of the network. Also, the deployed networks use multiple disjoint channel frequencies to maximize the bandwidth offered to the users. Apart from these options, the users will be most interested in the performance of the mobility service in both stationary and movement periods, using averaged continuous metrics which better characterize the long term characteristics of the mobility service.

Taking into account such requirements, this paper presents a complete performance evaluation of micro-mobility protocols, comparing TIMIP to other well-known protocols, in complex scenarios with meshed topologies networks, in which random link failures occur in the wired part of the network (as failures in the wireless part will have a similar impact on all the protocols). The influence of the protocols is studied thoroughly for both stationary and moving nodes, at several speeds, ranging from low speed pedestrian movement, to high speed car / train movement, in which multiple metrics are evaluated (loss ratio, throughput and delay) in both intra and inter-domain traffic types. Then, the effect of random link failures on the wired part of the domain is studied for stationary and moving nodes.

The remaining part of this paper is organised as follows: section II presents the TIMIP/sMIP architecture; section III presents the simulation studies and the evaluation of the protocols; the paper ends with some conclusions in section IV.

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II. TIMIP/sMIP Global Mobility Solution

The addition of IP mobility support generally requires modification to the standard IP protocol, in both network and end-user terminal equipment. This means that these terminals cannot be legacy terminals, e.g., with regular mobility-unaware IP stacks. To address this problem, TIMIP/sMIP provides a terminal independent mobility solution, in which the network is the sole responsible for the mobile node's (MN) mobility actions, implementing a "surrogate behaviour" for the detection and registration processes in place of the MN [11].

TIMIP uses the *Reactive* Model Detection' Phase [13], in which the network tracks MN movements by a single L2 primitive that signals the attachment of the MN to the Access Point (AP). This primitive uses all available L2 information for unequivocal localisation of the terminal. If the required L2 information is not available, then a Passive Detection model is used, supported on a Generic Detection Algorithm [11].

After detection, the MN's location is dynamically updated inside the domain, using a *Cluster* Model Registration model [13], in which update messages are transparently generated at the MN's AP. During the initial power-up, the signalling messages travel up to the domain's gateway (GW). In case of an handover, these messages are directed to the old AP through the local sub-tree that connects the involved APs. As no information of the old AP is directly available, the network infers its location using the previous outdated routing paths. During the registration between the involved APs, the nodes' routing tables are updated, hop-by-hop, starting from the new AP. TIMIP signalling messages feature reliability mechanisms, using acknowledge packets and timestamps.

In the Execution Phase, TIMIP uses the *Implicit* Model [13]: to keep routing information updated, IP traffic is used to refresh routing entries for the active MN, while explicitly generated signalling information is used only for idle terminals. For minimizing the state maintenance of idle terminals, this signalling is subject to a backoff mechanism, as described in [11]. TIMIP also use *Tree-Optimal* Path Models [13], as packets are always forwarded using the shortest path in the network tree, going up to a crossover node (uplink routing) and then directly down to the correct AP (downlink routing). Lastly, all packets are forwarded inside the TIMIP domain without encapsulation, as the MIP tunnel ends at the GW with its MIP Foreign Agent functionality.

Concerning the macro-mobility support, the sMIP architecture is composed of MIP compliant agents, called surrogate home and foreign agents (sHA, sFA). The sMIP protocol was enhanced with extensions to both agents to detect movements and generate standard MIP signalling automatically on behalf of the MNs for their inter-domain roamings. The sMIP detection is based on the TIMIP mechanisms, where the TIMIP power-up operation triggers the sMIP detection. After that, the sFA uses standard MIP registration procedures, generating MIP messages on behalf of the Legacy Mobile Node (LMN). MIP security procedures may be assured by the sFA or by the legacy MN, with the help of a special authentication application. Thus, no changes are required at the Home Agent side, resulting in the protocol being fully interoperable with MIP.

III. Simulation studies

The objective of this section is to present a complete performance evaluation that compares TIMIP to the other micro-mobility protocols in redundant topologies subject to failures. As the failures on wireless part of the network affect all protocols equally, because the protocols only differ on the paths used to reach the correct AP, this section will focus on the long / permanent failures that can happen on the wired links.

Although these failures can be considered as rare, they can result in a major impact on the mobility service, by affecting all the MN's served by the affected wired link. For this, a robust wired network is used, featuring a redundant mesh topology with extra links, and an ideal dynamic fixed routing that recovers from the wired link failures instantaneously. In these scenarios, continuous situations with averaged metrics (loss ratio, throughput and delay) are presented for intra/inter-domain traffic cases. Using these scenarios, increasing complex simulations are presented: first the averaged behaviour of the protocols is studied in stationary and continuous movement situations; later, these are extended with the effect of random link failures on the wired links.

A. Simulation scenario

The simulations were carried out using Network Simulator v2.26, using implementations of HMIP, CIP and HAWAII upgraded from the CIMS v1.0 mobility suite [17], to which was added the TIMIP protocol. Additionally, the simulator was modified to emulate IEEE 802.11 infra-structured behaviour with multiple disjoint channels. This modification forces L2 hard handover operations, where stations only receive data packets via one AP at a time (previous simulations studies used a soft-L2-handover paradigm where a node could receive data packets from several APs simultaneously). From the set of CIMS options, it was considered the CIP hard-handover option, as L2 hard-handovers being the ones used in real IEEE 802.11 networks and HAWAII Multiple-Stream-Forwarding, due to the interesting packet buffering possibility. The simulations only focused on micro-mobility scenarios, as all protocols use MIP for macro-mobility operations.

Several sets of simulations were performed using the network described in Fig. 1, containing a single domain with 8 APs, each one managing a separate IEEE 802.11 cell. The APs are interconnected to the GW by a node tree with additional mesh links; all internal connections are wired links of 10 Mbit/s and 10ms delay.

The network features 2 MNs connected to it; the first will move sequentially from AP1 to each AP, to perform stationary measurements, or will roam inside the domain, performing circular movements connecting to each AP in sequence, at varying speeds of 1 to 14 handovers/min. The lowest speed intend to emulate foot movement, where a handover is performed each 60 s, in a high density scenario; the higher speeds are intended to emulate faster movements, typical of car or train movement, and to better study the differences introduced by the protocols. In each test, the MN1 will be the receiver of a CBR traffic source, generating 100 pkt/s of 100 bytes per packet. This traffic originates from the second

MN located in AP8, or from a correspondent node (CN) outside the network.

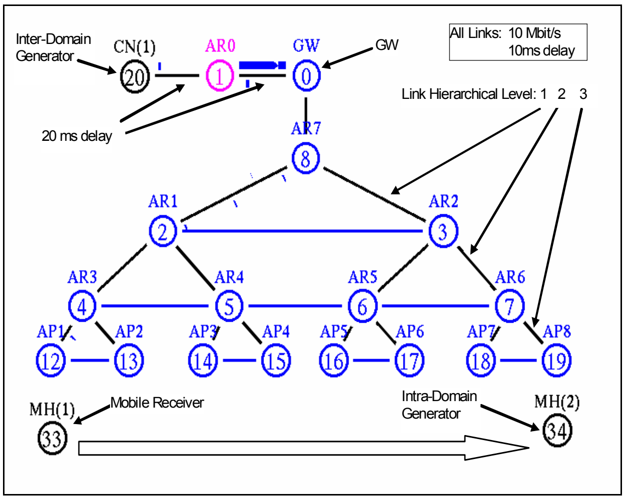

Fig. 1. Simulation Scenario: Logical deployment

B. Test A – Routing paths per MN location in the domain

This section characterizes the routing paths used by the mobility protocols to forward data packets to MNs located a each AP. For this, the one-way delay metric was evaluated at all possible locations in the domain, for both intra/inter-domain sources. This metric is related to the number of hops, being important for the delivery of real-time services like VoIP or video streaming. The results are summarized in **Fig. 2.** , where the X-axis refers to the MN's location in the domain (AP), and the Y-axis refers to the average one-way delay in ms. The loss and throughput values were also measured, being respectively equal to 0% and 100% in all cases (not shown).

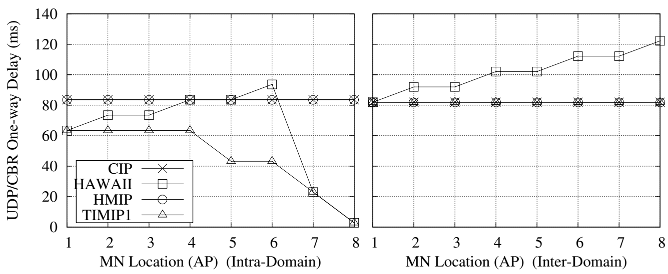

Fig. 2. Stationary CBR/UDP one-way Delay per MN location

Intra-Domain analysis: This experience shows that both TIMIP and HAWAII protocols have varying one-way delay values while the MN approaches the sender (AP8). While TIMIP constantly reduces this value, HAWAII actually increases it until the MN is located in AP7; at AP7 and AP8, the delay values drop to the same values as TIMIP. CIP and HMIP both feature a constant high delay.

TIMIP's handovers reuse the previous paths to achieve fast handovers, but maintain those tree-optimal by always sending the signalling on the tree. As all links have the same delay at each hierarchical level, it results in a constant delay for the left side of the tree (APs 1 to 4); on the right part of the tree, where the MN is closer to the sender, much lower delay values are measured as fewer and fewer hops are used.

Regarding HAWAII, this protocol uses additional links to reduce its handover time, and augments the previous routing paths with additional hops between the involved APs. However, in the presence of meshed networks, these incremental handovers result in sub-optimal paths with higher hop counts [14][15], because the initial hops of the path are not modified by the handover procedure. In the case of this scenario, this means that packets are forced to pass always through node 4. Thus, while HAWAII starts with the same delay value of TIMIP, it increases it each handover. Interestingly, the handover to AP7 cancels this phenomenon, as the crossover node in this case is node 7.

Regarding CIP and HMIP, these protocols impose the constant delay of 83 ms of delay, because all intra-domain packets are forced to pass at the GW always [13].

Inter-Domain analysis: When packets are received from outside the domain, all protocols except HAWAII impose a constant delay of 81 ms, necessary for the 6 hops that the packets pass. Similarly, each HAWAII handover increases the packet delay, up to 122 ms at AP8.

C. Test B – Continuous Handovers with UDP

This section presents simulations using continuous MN movements at varying speeds, from stationary up to 14 handovers per minute. This top speed considers an handover each 4.2 seconds, to better study the losses caused by the protocol's handovers (as the previous test measured 0% loss for stationary situations). The respective results are shown in **Fig. 3**, representing the long-term packet loss ratio per handover rate, for both intra and inter-domain traffic sources. Although not shown, the measured delay values matched the average of test A, and the throughput metric corresponded to the inverse of the loss ratio graph (due to the CBR traffic type).

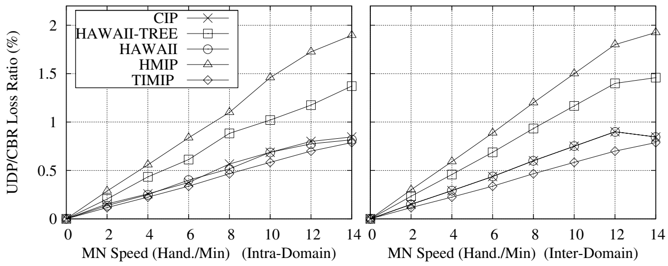

Fig. 3. CBR/UDP Loss Ratio per Handover rate

Intra-Domain analysis: When the MN starts its movement, losses occur due to the protocol's routing reconfiguration. These are perceived by the UDP receiver as missing or out-of-order packets. The graphs present the averaged ratio between such losses and the total received packets, taking into account the in-transit packets. The loss ratio increases linearly with the MN speed, resulting in a linear degradation of the average throughput received. At maximum speed, TIMIP degrades the traffic 0.78%, while CIP, HAWAII and HMIP degrade 0.84, 0.81 and 1.89%.

Considering the graph as a whole, the TIMIP protocol shows the smallest degradation for CBR traffic, being closely followed by CIP, as these handovers are limited to the local sub-tree. HAWAII in Mesh networks also has a similar degradation ratio, but its losses are mainly due to the introduction of out-of-order packets in the UDP stream during an handover. To further explore this HAWAII out-of-order phenomenon [13], additional simulations were performed in a pure tree topology network. The results remained the same for all protocols, except HAWAII which imposed higher losses, up to 1.37%. HMIP shows the worst performance of all protocols, because all handover's signalling must pass through the GW.

These results fully correspond to and extend the previous stationary test results, namely the localized handover support of TIMIP and CIP, the out-of-order phenomenon of HAWAII and the long handover of HMIP [13].

Inter-Domain analysis: For similar reasons as the intra-domain case, in inter-domain TIMIP presents the lowest handover impact, with 0.78% packet loss, and 0.84, 0.84, 1.45 and 1.92% for CIP, HAWAII, HAWAII in Tree, and HMIP.

D. Test C –Network link failures per MN location

This section studies the impact of random network link failures on the mobile routing to stationary MNs. This is done by measuring the loss ratio metric for all possible pairs of permanent link failures and MN locations. The loss ratio results are presented in two different forms: **Fig. 4** presents the effect of a random link failure, per MN location; **Fig. 5** presents the effect of a random MN location, per link failure location (grouped by the hierarchical level location of the link failure).

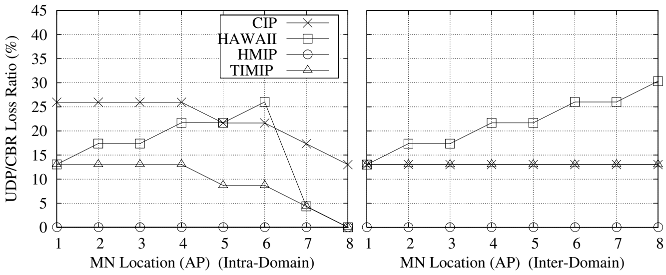

Fig. 4. CBR Loss ratio with random link failure, per Location;

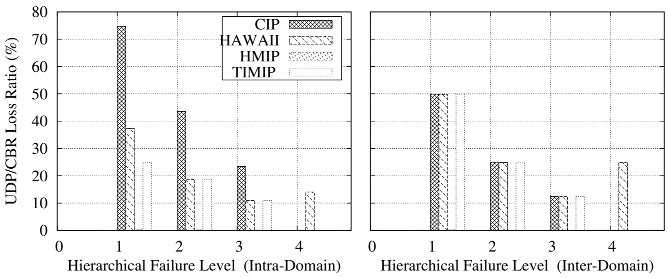

Fig. 5. CBR/UDP Loss ratio per level of hierarchical failure (0 – no failure / 4 – mesh links failure)

Intra-Domain analysis: This experience shows that all efficient protocols are heavily affected by the presence of link failures, resulting in intolerable packet losses. This is due to their direct, static, per-host, un-encapsulated routing entries; although used to provide fast handovers, these fail to address alternative means to route the packets when the path is broken by permanent link failures. Interestingly, the reported behaviour is fairly different for the other protocols, being TIMIP the least affected. In contrast, HMIP has marginal loss ratio in all cases, as packets are encapsulated in IP tunnels from the GW to the correct AP. This enables the use of dynamic fixed routing to recover from the link failures.

When the MN is located at the left part of the domain (**Fig. 4**), CIP has the double of the loss ratio of TIMIP and HAWAII. This happens because CIP requires packets to follow a strict path on the way to the GW; this is not the case with the other protocols, which can use the fixed routing for uplink routing. Thus, CIP is the only affected by failures on the right part of the domain. Although starting equal to TIMIP, HAWAII increases its loss ratio at each location, as its longer paths are more vulnerable to failures. Finally, losses drop to marginal values on AP7 and AP8, because the shorter paths on this location are less vulnerable to failures.

When the failures happen in the upper parts of the tree (**Fig. 5**), CIP is again the most vulnerable, as it forces all traffic to pass through the GW. In particular, a failure in the link that serves the GW results in the loss of all traffic for all locations and terminals. TIMIP and HAWAII have similar loss values, with TIMIP having an advantage because of the longer paths that HAWAII tends to have. As the failures are located on the lower parts of the tree, less traffic is disrupted, as more APs become reachable again. Finally, the graph presents link failure for the mesh links, in group 4. In this case, only the HAWAII protocol is affected by these failures, confirming the earlier conclusions regarding these links usage.

Inter-Domain analysis: Similar conclusions can be reported of the previous test. HMIP only imposes marginal loss ratios in all situations. For TIMIP and CIP, the location of the MN is independent of the loss ratio when in presence of random link failures, resulting in a constant loss ratio (**Fig. 4**). However HAWAII sees its loss increase on the right part of the domain, because of the longer paths it uses. Regarding the level of failure (**Fig. 5**), a failure in each of the levels conducts to cascaded failures of 50%, 25% and 12.5% for each level. Finally, HAWAII is the only protocol affected by mesh-link failures.

E. Test D –Network link failures on moving mobile nodes

While the previous sections studied the effect of handovers and failures for UDP traffic separately, this test will evaluate the effect of both simultaneously. For this, the MN will roam inside the failing network, at the maximum speed of 14 handovers per minute. The results are shown in **Fig. 6**.

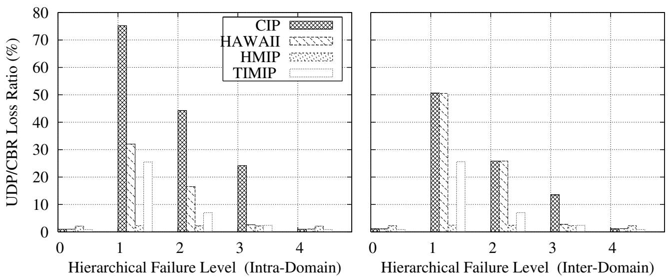

Fig. 6. CBR/UDP Loss ratio for moving nodes, per level of hierarchical failure; Intra and Inter-Domain traffic

Intra-Domain analysis: This experience shows that in the absence of link failures (group 0), all losses are due to the handovers only (studied in test B). This serves as baseline for the later tests with link failures (studied in test C), being the resulting losses largely coincident with the addition the two previous tests. In these, HMIP has the best and most regular behaviour, as all its low losses are due to the handovers only. While the other protocols have lower handover losses, such benefit is overwhelmed by not having failure-recovery mechanisms, resulting in intolerable losses.

Interestingly, for lower-level link failures, both TIMIP and HAWAII can greatly improve their loss ratios comparing to test C, because some handovers redirect the routing paths to working links. That happens because the signalling is directed to a fixed node (the GW or the old AP), which is always reachable. In this light, TIMIP has an advantage over the other protocols: as it performs its handover operations based on the tree, it "fixes" the routing paths, as explained above, better than the other terminals. Although not shown, if the previous AP becomes inaccessible because of link failures (in tree topologies), then HAWAII is unable to complete any subsequent handovers, resulting in 100% packet losses [16].

Inter-Domain analysis: When the packets are received from outside the domain, similar conclusions can be drawn. HMIP imposes a constant low loss in all situations. All protocols are able to decrease their loss in lower level failures, due to the same phenomenon already discussed.

IV. CONCLUSIONS

This paper presented the evaluation of a terminal independent mobility architecture composed of two protocols previously proposed – TIMIP/sMIP – in meshed networks with the presence of link-failures. This global solution supports legacy terminals with high efficiency, regarding both handover latency and network resources utilisation.

Simulations that compared TIMIP with the other micro-mobility protocols were performed, focusing on scenarios that were not addressed in previous research work. In particular, random link-failures impact in fully meshed networks was investigated, for both stationary and continuous movement scenarios. In these simulations, the average results from continuous measurements were presented, featuring varying MN speeds, multiple metrics (loss ratio, throughput and delay), intra and inter-domain UDP traffic sources and IEEE 802.11 multiple disjoint channels networks.

The stationary results showed that TIMIP has the best resource optimisation performance for intra-domain traffic, which is a result of its tree-optimal routing support for all network locations. HAWAII would also be able to share such good performance with intra-domain traffic, but suffers from long routing paths due to its incremental handover operations in mesh topologies. CIP and HMIP have the worst behaviour, as all packets are forced to pass through the GW.

The continuous movement results showed that all protocols except HMIP have good localized handover support, minimizing the handover latency in most handovers. By sending the update message directly to the previous AP, HAWAII would have the lowest handover latency of all protocols; however, such benefit is cancelled by the introduction of out-of-order UDP packets in each handover, a problem particularly evident in tree topologies. HMIP has the worst results, as all handovers require an update to the GW. The results show that for low speed movement utilizations, the micro-mobility protocols only feature small performance differences between themselves; however, in high speed movement scenarios, such differences are greatly amplified and can distinguish the protocols.

The presence of long or permanent wired link-failures results in major packet losses for all protocols, particularly if those occur at the highest levels of the tree. If a wired link-failure occurs in these situations, communication is essentially interrupted for the affected stationary MNs. The exception is the HMIP protocol, which benefits from fixed routing failure recovery by its data encapsulation. Of the efficient protocols, TIMIP has better robustness than the other protocols, a combined result of requiring fewer hops and of being vulnerable in the downlink paths only.

Future work comprises further TIMIP improvements in order to support network independency and smooth deployment, enhanced reliability, seamless handovers and IPv6 support.

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