Design and Evaluation of eTIMIP – an Overlay Micro-Mobility Architecture based on TIMIP

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Abstract

All the proposed IP mobility protocols assume that the mobile nodes always have a mobility-aware IP stack. On the other hand, efficient micro-mobility solutions entail specific topologies and mobile-aware routers, requiring major changes in the existing infra-structures. Major advantages are foreseen if mobility can be supported using the existing legacy infra-structure, on both client and network sides, allowing a smooth upgrade process.

This paper describes such kind of solution, by proposing an efficient terminal independent mobility architecture (eTIMIP – enhanced TIMIP) which is compliant with the macro-mobility standard and which uses an overlay network to provide transparent micro-mobility support in all existing networks, using an enhanced version of the previously proposed TIMIP protocol.

Simulation results have revealed the efficiency, the transparency and the reliability of the proposed architecture through comparison to other proposals.

1. Introduction

Currently, there is great effort towards the unification of all networks under the IP protocol, turning the Next Generation Internet (NGI) increasingly more important and complex, as users may use it to connect all types of equipment and access a broad range of services [1][2].

Wireless technology plays a major role in this NGI and brings new challenges, business and social opportunities, as it extends the network usability beyond the traditional situations. In this new scenario, users can communicate while they freely move, even if they change the kind of access technology they are using.

This new communication paradigm represents a major shift in the existing IP based networks, where routing decisions are based on the destination IP address of the terminal, which is associated with its current location. Several mobility extensions have been proposed to solve this lack of mobility support, ranging from application to link layer. Both application and data-link layer solutions have a restricted scope, as the former require the modification of existing applications, and the latter are not independent of the access technologies. IP layer provides a heterogeneous solution, which can offer mobility support to all applications and wireless access technologies.

In the past few years, several IP layer mobility solutions have been proposed, ranging from the standard Mobile IP (MIP) [3][4], a fairly good approach for the mobility in wide area networks, to a set of non-standard proposals, like Cellular IP (CIP) [5] and Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) [6], aiming to provide seamless handovers for micro-mobility scenarios. As the end-systems need to be modified to support any of these solutions, then the legacy terminals and embedded systems with reduced processing capacity could be precluded from this new paradigm. Surrogate MIP (sMIP) coupled with Terminal Independent Mobile IP (TIMIP) [7][8] presented a global mobility architecture to solve this issue in a very efficient way. 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 [9].

However, all these solutions require the use of a specialized and hierarchical network, which must be enhanced to offer mobility to its users. Major economical advantages are foreseen if mobility is supported using the existing legacy structure, as users can immediately start using new services, increasing providers' revenues at a marginal cost and allowing a smooth upgrade of their networks.

This paper aims at defining a new mobility solution, which provides both network and terminal independent mobile architectures, based on the use of an overlay network, where mobility is given by an enhanced version of TIMIP, from now on called enhanced TIMIP (eTIMIP).

The remaining part of the paper is organized as follows: section II describes the related work; section III presents the mobile overlay network architecture; the simulation studies are presented in section IV and the conclusions and future work are described in section V.

2. Related Work

Layer 3 (L3) mobility solutions can be divided into two main categories:

- **IP Macro-mobility**, which concerns mobility across different administrative domains, typical of nomadic computing, where scalability is the major point.

- **IP Micro-mobility**, which solves the mobility issues that arise when a Mobile Node (MN) roams inside a domain, providing efficient solutions with reduced handover latency.

MIPv4 and MIPv6 are the standard macro-mobility solutions for both IPv4 and IPv6 networks. Both of them present a scalable network-independent mobility solution, which relies on the use of specialised mobility agents, at both the home and the foreign domains. When MIP is used, the handover latency is too high to achieve a seamless handover precluding its utilization in micro-mobility scenarios. Hierarchical MIP (HMIP) [10] tries to increase handover efficiency by augmenting the number of hierarchical levels inside each domain, leading to a micro-mobility MIP-based solution. However, the number of hierarchical levels is limited in HMIP, as the MN must maintain a separate care-of address per hierarchical level.

MIP and its variants can be easily deployed inside any network, as it only requires the use of specialized agents in selected network locations; nevertheless, it requires the existence of a MIP client inside each MN, reducing the possibility of achieving a transparent mobility service. The transparent MIP (tMIP) protocol [11] was a first approach to achieve such kind of service, although without special efficiency or standard-compliance considerations. MN movement detection is only performed when the terminal sends data - a quite limited and inefficient solution.

The CIP protocol was a first approach to provide a mobility support that is more efficient than the one provided by MIP, complementing it in an independent way. This protocol is based on fairly different principles than MIP's, being limited to single IP domains, and having the network elements organized in a strict tree structure topology. With the necessary Layer 2 (L2) cooperation and control, CIP also supports an alternative "soft" handover that aims at reducing packet loss during the handover.

The HAWAII protocol is an alternative proposal that transparently extends MIP with micro-mobility support. A difference from CIP is that the MNs are only required to implement a slightly modified MIP client, as the protocol provides micro-mobility transparently. For this, a similar division of domains and hierarchy of nodes is established. Considering both protocols, they are able to improve efficiency compared to a pure MIP scenario, at the cost of restricting transparency and robustness.

TIMIP presents similar network organization and performance as CIP or HAWAI, although sometimes slightly better, as shown in [12]. However, its major advantage is the terminal independence it supports, as it permits efficient mobility support for all existing terminals without any modifications.

3. Mobility Architecture

3.1. Mobility Overlay Network Architecture

eTIMIP proposes an architecture based on the concept of the Overlay Network, outlined in Figure 1, which is aimed at supporting the mobility service with transparency and efficiency. Each eTIMIP domain is logically organized in two networks planes: physical and overlay.

Regarding the ***physical network***, each eTIMIP domain can have any possible topology, comprising different kinds of network elements and links, as it can heterogeneously support any kind of network elements and access technologies. Topology-aware intra-domain routing may be assured at the domain's legacy IP routers by an appropriate intra-domain routing protocol, like Open Shortest Path First (OSPF) or Routing Information Protocol (RIP). Some boundary routers may also participate in inter-domain routing, by running an inter-domain routing protocol, like the Border Gateway Protocol (BGP). From now on, these protocols will be designated as ***fixed routing***, in opposition to eTIMIP routing, which will be called ***mobile routing***.

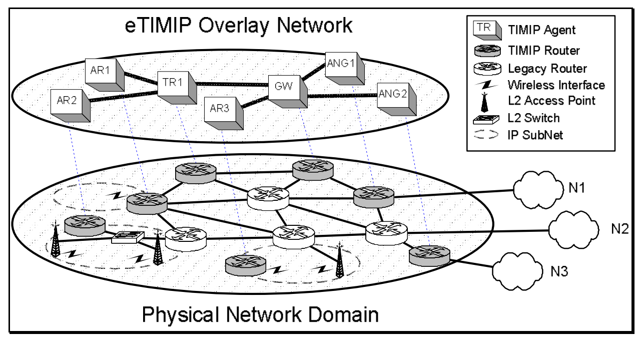

Figure 1: eTIMIP Mobility overlay network architecture

Wireless access may be performed via L2 equipments, such as Access Points (APs), or L3 APs, which are IP routers enhanced with AP functionalities. Some of these access devices may be able to detect new MNs through specific L2 mechanisms, or standard management procedures, while others may be totally unable to detect them.

On top of the physical network, an ***overlay network*** is built to provide efficient mobility support, using software agents that maintain distributed mobile routing information. These agents are deployed on the network incrementally, either by upgrading existing upgradeable routers, or by introducing additional routers on the network.

The eTIMIP agents constitute the overlay network by establishing and maintaining a logical tree among them. The basic building block of this network is a generic agent designated as eTIMIP Router (TR). Inside the overlay, control and data packets are swapped between the TRs to provide MN´s mobility support. Control packets are used to distribute the MN's routing information inside the network, which is subsequently used to forward the MN's data packets.

Depending on the location in the tree, their adjacency to the Legacy MNs (LMN) and the type of connections to the outside, the TRs can also be endowed with additional roles. At the top of the tree, a special TR called Gateway (GW) is used to centralize the management functions, being unique to any given eTIMIP domain. To connect with the networks outside the domain, multiple enhanced TRs, named Access Network Gateways (ANG), can be used. The ANG's dual is the Access Router (AR), which is a TR that offers connectivity to MNs by means of the mobile routing. The most important features of the ARs are the detection of LMN's movements and their surrogate signalling generation and maintenance. The final components of this overlay network are the LMNs themselves, which only have to connect to the network via a suitable wireless interface. Using terminal independence, it is the network that automatically detects every incoming LMN and reconfigures itself to provide the necessary IP connectivity to these terminals.

The provisioning of a network independent solution is essentially related to the problem of how to force the packets to reach the eTIMIP agents, as IP routing uses IP destination addresses to forward packets based on a hop-by-hop paradigm. The problem is solved by having eTIMIP agents located at the boundary of the network, enabling the interception of all incoming traffic.

Deploying ARs at the network boundary does not represent a difficulty, as the eTIMIP agents can either be added with L2 techniques to the same subnets of the LMNs [3] or incorporated in upgradeable access routers.

However, the same does not apply to ANGs, as typically these cannot be introduced in the domain's boundaries without modifying the pre-existing topology. eTIMIP solves this problem by defining a ***mobile subnet***, which is a regular Classless Inter Domain Routing (CIDR) subnet, created and managed by the fixed routing that is associated with the GW, the ARs and all the LMNs of the domain. Every incoming packet, arriving through a legacy border router, is directly sent to the GW via the fixed routing and, from this point on, it can benefit from mobility support and start using the mobile routing; packets arriving through AR or ANG nodes have the mobility support already guaranteed at the IP network boundary, as such nodes are eTIMIP agents.

Inside the overlay network, both control and data packets are swapped between the TRs using the logical connections of the agent tree. Each logical connection on the overlay network is dynamically mapped by the fixed routing to a physical path, comprising the most adequate physical links and routers. Concerning eTIMIP control packets, they travel agent-by-agent, following the strict path inside the logical tree; data packets also travel following the strict path inside the overlay agent tree, using the eTIMIP mobile routing.

Encapsulation or source routing techniques are employed for data packets destined to LMNs if legacy routers are present in the path chosen by the fixed routing. Should direct links exist between TRs, no encapsulation or source routing techniques need to be employed.

Original support has been introduced to improve the scalability and efficiency of the protocol. Based on the current network usage, LMNs can be considered ***active*** or ***idle***. Active LMNs are those that are actually sending and/or receiving data and the network will make all efforts to accurately track them, ensuring a quick and prompt service. However, LMNs which aren't currently using the network (idle) can be subject to a minimal mobility service. In this case, the network will perform a lesser exact location service, with an idle LMN being paged on demand by the network if and when there is new data for delivery. As it has been widely studied, such support greatly helps to increase protocol scalability and reduce the state maintenance overhead [5].

Another advantage of eTIMIP is the generic definition of the architecture, being deployable in both IPv4 and IPv6 networks with minor adaptations. The IPv6 control packets carry their mobility fields efficiently encapsulated in the IPv6 mobility header or in regular UDP for IPv4. Similarly, the data packets that need special treatment for forwarding in the physical network are to be efficiently encapsulated using the IPv6's native source routing field, or with regular IPIP tunnels using an outer IPv4 header.

3.2. Detection and Registration operations

The support of the mobility service is provided by the eTIMIP mobile routing, which keeps accurate LMN´s routing information.

The first phase of the mobility service is executed when a LMN arrives at an eTIMIP domain and performs a ***Power-Up*** operation. eTIMIP detects this arrival and adds a new routing entry in all the agents that need to know about the existence of this new LMN. The second phase of the mobility service is executed when the LMN roams between two APs of the domain, performing a **Handover** operation. eTIMIP detects the LMN's arrival and updates the correspondent routing entry in order to keep it consistent with the current LMN location.

In both cases, the detection of a LMN is continuously executed by the ARs connected to the network, which sense the LMNs' movements. Whenever the LMN attaches to a new AR, a single primitive is used to detect this event, which collects all the available L2 information. In this new version of TIMIP, a technology-dependent mechanism is provided through the introduction of different ways of collecting such information: when the LMN attaches to a L3AP this information is locally retrieved, but if it connects to a L2 AP, it is collected through remote management procedures. Finally, if this information is unavailable, a generic detection algorithm can be used that is independent of the network element and access technologies [8].

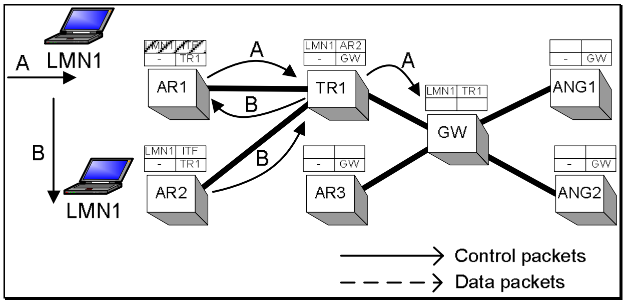

Figure 2: eTIMIP registration: A) power-up; B) handover:

During the registration phase, the LMN's location is dynamically updated by the network itself to be kept consistent with the terminal's movements inside the domain. For this, the AR that detected the LMN is responsible for starting the registration operation, informing the *interested* TIMIP agents of the new LMN's location. During a power-up operation, these agents are the ones that lie between the AR and the GW, while, during a handover, are restricted to the local sub-tree that connects both the old and the new ARs. As depicted in Figure 2, each one of these agents updates its own routing table and transmits TIMIP update messages up the tree, up to the GW (case A), in case of a power-up, or to the cross-over node, in a handover occurs (case B). Should the number of eTIMIP agents be restricted and higher handover latency is expected, as the cross-over node becomes closer to the GW.

Two reliability mechanisms – acknowledgement packets and clock synchronization procedures – are embedded into TIMIP signalling messages to resolve conflicts, race conditions and packet losses that may happen in any unreliable message transmission [8].

3.3. Security

After the detection phase is completed, eTIMIP security procedures are triggered to ensure that only authenticated users can use the mobility services. For this, each eTIMIP network possesses a secret network key, which is only known by the eTIMIP agents.

At the Power-Up registration, either the GW or the AR will authenticate and authorize the LMN and construct a shared secret for it (named PID), by hashing the network secret key with the IP addresses of the LMN. This hash is sent to the terminal encrypted with its public key, which is securely obtained from a trusted third party.

At each handover, the AR can independently verify the LMN identity, through a challenge/response pair of messages, which must be signed by the LMN using the PID. The main advantage of this method is that the PID remains the same during each handover and can be independently computed by each AR without any communication with the previous ARs or GW, resulting in a very efficient authentication.

3.4. Transmission of Data packets and State Maintenance

When an eTIMIP agent receives a data packet, its destination is checked against the eTIMIP agent's routing table. If a match is found, the packet is forwarded to the next eTIMIP agent defined in that entry, using a ***downlink routing*** procedure; in the opposite case, the packet is forwarded to the default upstream agent, towards the GW, resulting in an ***uplink routing***.

Intra-domain traffic is transferred over the local logical sub-tree that connects the communicating LMN and the CN, while inter-domain traffic must pass through the domain's GW. Both traffic cases are depicted in Figure 3.

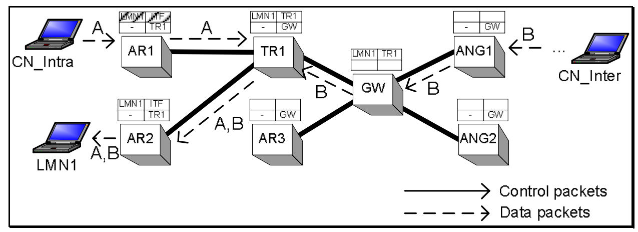

Figure 3: eTIMIP transmission of data packets: A) intra-domain data; B) inter-domain data

To optimize performance, data packets are used to keep the routing entries up-to-date. Therefore, eTIMIP control messages used to refresh routing entries are transmitted to the GW only for inactive terminals, being subject to a back-off procedure [8]. Using a series of cascaded time-outs, the state maintained by the network can optionally be reduced by deferring the LMN's entries to the higher tree levels only. When required, the LMN is paged by the network, as the first data packet is broadcasted on the sub-tree containing the terminal; when it responds, the first data packet recreates the routing entries, ending the paging operation.

4. Simulation studies

Multiple sets of simulation studies have been carried out to evaluate the eTIMIP architecture and to compare it with other mobility proposals, namely the original TIMIP protocol, and the CIP, HAWAII and HMIP proposals.

The architecture evaluation studied the transparency vs. efficiency trade-off, concerning the number and location of mobility-aware nodes and the achieved handover efficiency in each case. To evaluate the reliability, redundant topologies have been used and the impact of network failures in the performance of protocols has been studied. As the failures on the wireless part of the network equally affect all protocols, this section will focus on the failures that happen on the wired links. Although these failures can be considered as rare, they can result in a major impact on the mobility service.

4.1. Simulation scenarios

The simulations were carried out using Network Simulator v2.26, using the CIMS v1.0 mobility suite, to which the TIMIP and eTIMIP protocols were added. As already described in [12], from the set of CIMS options, the CIP hard-handover option was chosen, as L2 hard-handovers are the ones used in real IEEE 802.11 networks and HAWAII Multiple-Stream-Forwarding, due to the interesting packet buffering possibility and the HMIP protocol. The simulations only focused on micro-mobility scenarios, as all protocols use MIP for macro-mobility.

Several sets of simulations were performed using the network described in Figure 4. According to that figure, the physical network contains 10 eTIMIP routers (8 APs, the GW and a single ANG), 7 legacy IP routers and 3 end-systems (1 LMN and 2 CN, one located inside the domain and the other outside). Redundant physical links exist between each pair of connected network elements, which have 10 Mb/s of capacity and a delay of 10ms; the only exception is the connection to the outside of the domain, where the capacity is 2Mb/s and the delay 20 ms.

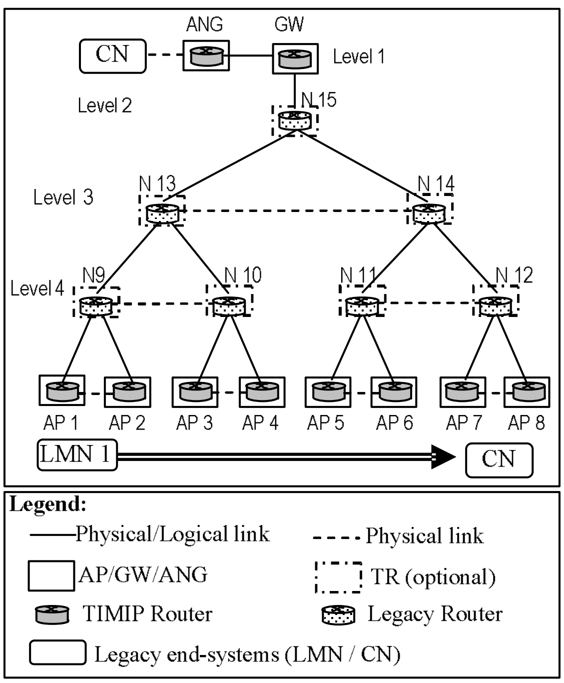

Figure 4: Simulation scenario

Concerning the overlay network, it comprises all the eTIMIP routers (ANG, GW and 8 APs), the end-systems and an additional number of TRs, which provide mobility support for a selected set of legacy IP routers. The eTIMIP agents are organised as a strict tree and use the physical connections that lead to the shortest path. The TR number and location vary from each simulation.

At each simulation run, one of the CNs transmits a CBR traffic flow to the LMN, at a rate of 100 packets/s, 100 bytes of size. Inter-domain simulations use CN1 while intra-domain ones use CN2. In all of them, the LMN roams between the APs, starting at AP1.

4.2. Simulation results

Transparency versus Efficiency evaluation

The first set of simulation studies evaluated the trade-off between transparency and efficiency, by measuring the impact of the number and the location of additional TRs on the handover efficiency. The transparency metric considers the number of IP routers with mobility capabilities, besides the minimum set required by all micro-mobility protocols; the handover efficiency metric is measured by the ratio of lost packets, as perceived by the UDP receiver, due to missing and out-of-order phenomena incurred by the handovers.

To perform the test, TRs were successively introduced at each hierarchical level, enhancing all the corresponding legacy IP routers. Thus, in the base test L1 no agents are added; test L2 comprises one more TR, located at level 2 (N15); test L3 enhances both levels 2 and 3; test L4 comprises 7 more TRs than the base case, by enhancing all the legacy IP routers with mobility capabilities.

Another set of tests comprises an alternative option, where the transparency metric measures the location of IP routers with mobility capabilities, being the additional TRs introduced at a single hierarchical level. Thus, in the base test L1 no additional agents are added; test L2 comprises one more TR, located at level 2 (N15); test L3 adds 2 TRs located at level 3 (N13, N14); and test L4 adds 4 TRs located at level 4 (N9-N12).

The respective results, shown in Figure 5, show the average ratio between the losses and the number of sent packets: the left part represents the first set of tests and the right one, the second set.

Considering the number of additional TRs (left part of Figure 5), only eTIMIP offers the flexibility of supporting any combination of legacy and mobility-aware routers in the network, for maximum transparency or efficiency. The results show that, as more and more agents are mobile-aware, the eTIMIP protocol efficiency increases, up to the same levels as the traditional efficient proposals.

As HMIP only has one hierarchical level, it has the worst efficiency, as all handover updates must reach the GW. On the other hand, the efficient micro-mobility protocols, which require a strict hierarchical tree of mobile-aware routers, show the best performance, as the handovers are highly localized in lower parts of the tree.

The scenario featuring a single hierarchical level of agents (right part of Figure 5), is only supported by eTIMIP. However, no discernable differences occur when such line is located in the middle or in the lowest part of the domain; this is due to the unbiased simulation scenario, that considers a circular movement type and a perfectly balanced topology with uniform link delays, resulting in a equal mixture of “short” and “long” handovers.

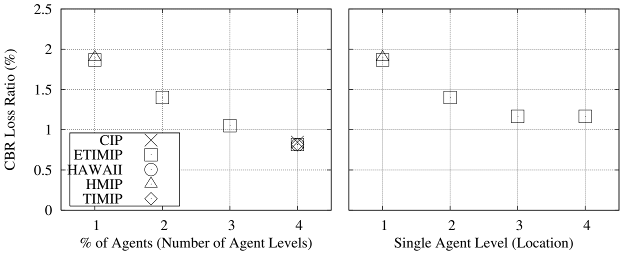

Figure 5: Number and location of the additional TRs

To further explore the previous result, additional scenarios were used where the LMN performs a series of short, medium or long range handovers, by moving between AP1 and 2, 2 and 3 or 4 and 5. These movement types are then tested with the previous scenario featuring a single hierarchical level of agents, ranging from no extra agents (L1) to agents that are very close to the APs (L4). The results are shown in Table 1.

Table 1: movement type per TR location (loss ratio (%))

	L1	L2	L3	L4
Type 1 – (AP1↔AP2)	1.86	1.40	0.93	0.46
Type 2 – (AP2↔AP3)	1.86	1.40	0.93	1.86
Type 3 – (AP4↔AP5)	1.86	1.40	1.86	1.86

The results show that the location of the additional TR influences the achieved performance, being highly dependant on the mobility pattern and concentration of the LMNs. Thus, a mix of agent locations are required for improving performance, depending on the expected usage patterns; the available TRs should be placed as close as possible to the high-density, limited-movement locations (e.g. rooms), and in the middle of the domain for low density, wide-movement utilizations (e.g. open spaces), while keeping the tree as balanced as possible.

Network reliability evaluation

The second set of simulation studies evaluated the mobility service reliability, through the study of the impact of the link failures in the communication process. In this simulation set, a TR is co-located with every legacy IP router in order to achieve the best performance.

Random link failures were introduced and the packet loss ratio was evaluated for a stationery LMN, which changes its location from simulation run to simulation run. The loss ratio results are presented in two forms, for both intra and inter domain traffic sources: Figure 6 shows the effect of a random link failure when the LMN is stable at each possible location; Figure 7 shows the effect of a specific hierarchical level failure when the LMN is stable at random locations.

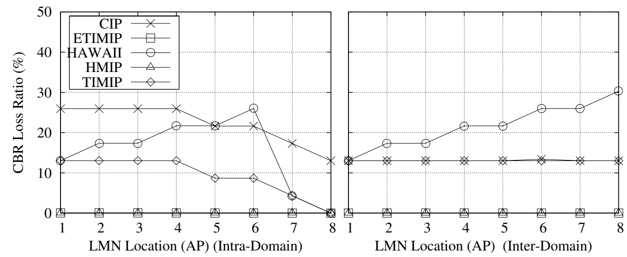

Figure 6: Packet loss ratio with random link failures

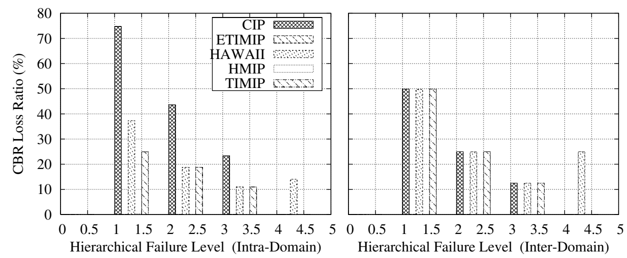

Figure 7: Packet loss ratio with hierarchical link failures (0 – no failure / 4 – mesh links failure)

Concerning intra-domain communication, the results show that the absence of link failures results in 0% losses. The presence of link failures result in intolerable packet losses in CIP, HAWAI and TIMIP, due to their direct, static, un-encapsulated per-host routing entries that fail to address alternative means to route the packets when the path is broken. In contrast, eTIMIP and HMIP have marginal loss ratios in all cases, as the fixed routing is able to recover from the network impairments and can find alternative routes to send the data.

When the MN is located at the left part of the domain (AP 8, Figure 6), CIP doubles the loss ratio of TIMIP or HAWAII, because CIP requires packets to follow a strict uplink path on the way to the GW. Thus, CIP is the only protocol affected by failures on the right part of the domain. Although starting like 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 the right part of the domain because of these protocols’ short tree-optimal paths.

When the failures happen in the upper parts of the tree (Figure 7), 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. TIMIP and HAWAII have similar loss values, with TIMIP having an advantage because of the longer paths that HAWAII tends to have [13].

Concerning the inter-domain communication, similar conclusions can be reported.

Another set of tests describes the effect of link failures on moving LMNs, which roam between adjacent APs, in a circular way, at a rate of 14 handovers/min. The results are shown in Figure 8 and in Table 2.

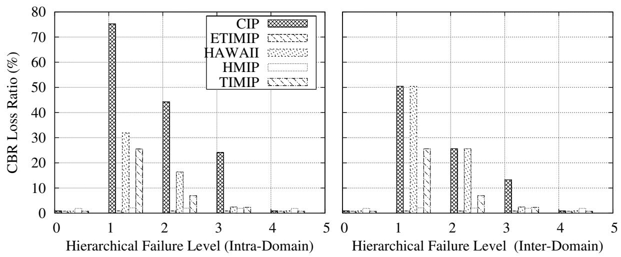

Figure 8: Packet loss ratio with hierarchical link failures and a moving LMN

Table 2: Average packet loss ratio per protocol (intra-domain traffic)

%	CIP	eTIMIP	HAWAII	hMIP	TIMIP
link failures	36.0	0.86	12.9	1.99	8.9
no link failures	0.81	0.81	0.81	1.89	0.81

Concerning an intra-domain traffic situation, the results show that in the absence of link failures, all losses are due to the handovers only. In the presence of link failures, eTIMIP and HMIP have the most regular behaviour, as all losses are mostly due from their handovers only, having eTIMIP the best result due to its optimised handover.

This is not the case of the other protocols, as the small handover losses are eclipsed by major losses due to link failures. In higher-level link failures, the uplink impact phenomenon in CIP is also present, reaching more than twice the number of TIMIP or HAWAII losses. For lower-level link failures, both TIMIP and HAWAII can greatly improve their loss ratios, because some handovers can result in a different routing path unaffected by the failure. Such is possible as the signalling is directed to a fixed node always reachable (GW or old AP).

5. Conclusions

This paper proposes an overlay micro-mobility architecture (eTIMIP – enhanced TIMIP) which is compliant with MIP and uses an overlay network to provide transparent micro-mobility support in all existing networks, using an enhanced version of the previously proposed TIMIP protocol. Besides the terminal independence paradigm present in TIMIP, the new architecture proposed is also network independent. This way, the proposed solution provides both transparency and efficiency aspects simultaneously, enabling an incremental upgrade path while providing efficient mobility support.

In eTIMIP, the mobility service is provided by an overlay network, which operates in any kind of physical network, without any intervention of the terminals. This overlay is built over the physical network, using eTIMIP agents, which are responsible for the mobile routing and can be based either in IPv4 or IPv6 protocols, with efficient security and paging procedures being proposed.

Simulation results have shown that there is a trade-off between transparency and efficiency, which must be taken into account when the service deployments are planned and the agents' location have to be defined. Simulation results had also shown that a very good performance may be achieved by eTIMIP under the occurrence of physical network impairments, which does not happen in the other efficient micro-mobility protocols.

Future work comprises the definition of the reliability procedures to be used to recover from agent failures.

6. References

[1] Suk Yu Hui, et al, "Challenges in the migration to 4G mobile systems", IEEE Communications Magazine IEEE , Volume 41, Issue: 12, Pages:54 – 59, December 2003.

[2] G. Carneiro, J. Ruela, M. Ricardo, "Cross-layer design in 4G Wireless Terminals," IEEE Wireless Communications, pp. 7-13, April 2004.

[3] C. Perkins, Ed., "IP Mobility Support for IPv4", RFC-3320, IETF, January 2002.

[4] D. Johnson, C. Perkins, "Mobility Support in IPv6", RFC-3775, June 2004.

[5] A. Campbell, et al, "Design, Implementation and Evaluation of Cellular IP", IEEE Personal Communications, Vol. 7 Nº4, August 2000.

[6] R. Ramjee, et al, "HAWAII: a domain-based approach for supporting mobility in wide-area wireless networks", IEEE/ACM Transactions on Networking, Vol. 10, Issue 3, June 2002.

[7] A. Grilo, P. Estrela, M. Nunes, Terminal Independent Mobility for IP (TIMIP)", IEEE Communications, Vol. 39 Nº12, Dec 2001.

[8] P. Estrela, A. Grilo, T. Vazão and M. Nunes, "Terminal Independent Mobile IP (TIMIP)", draft-estrela-timip-01.txt, Jan 2003.

[9] D. Saha, et al, "Mobility Support in IP: A Survey of Related Protocols", IEEE Network, vol. 18, no. 6, Nov/Dec 2004.

[10] E. Gustafsson, et al, "Mobile IP Regional Registration", draft-ietf-mobileip-reg-tunnel-09, June 2004.

[11] A. Giovanardi, G. Mazzini, "Transparent mobile IP: an approach and implementation" Global Telecommunications Conference (GLOBECOM '97), IEEE Volume 3, Page(s):1861 – 1865, November 1997.

[12] P. Estrela, T. Vazão and M. Nunes, "Micro Mobility Performance Evaluation of a Terminal Independent Mobile Architecture", 2º International Working Conference on Performance Evaluation of Heterogeneous Networks, July 2004.

[13] A. Campbell, et al, "Comparison of IP MicroMobility Protocols", IEEE Wireless Communications, February 2002.