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Vassiliou, Vasos

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An Analysis of the Handover Latency Components in Mobile IPv6

Vasos Vassiliou and Zinon Zinonos

Abstract - This article analyses the latency components in Mobile IPv6 handovers. It provides real-implementation results for significant parts of the handover process through measurements in a real MIPv6 implementation on a wireless testbed based on IEEE 802.11b. Our work aims to extract information on the actions taken by network entities during the movement of a mobile node and to correctly measure and characterize all handover delay components, something not readily achieved by simulation studies. Particular attention is given to the period leading to the L3 registration part of the handover, since this has been identified by many as the “choking point” of the whole process. The experimental results help in understanding the effect of Duplicate Address Detection, Movement Direction, Router Advertisement Intervals, Router Solicitations, and Wireless Beacon Intervals on the overall handover delay. This work can be of benefit to those trying to build, modify, or optimize mobility management protocols, since it can help them utilize real-life values in their simulations, emulations, or equations. The outcome of this work can also be utilized in recognizing items for future research.

Index Terms—Handovers, Latency, Mobile IPv6.

I. INTRODUCTION

Next generation networks (NGNs) are experiencing a great development in terms of the number of users and the number of applications supported. Those systems will offer to the users the possibility to roam between different access networks, and a multitude of services. Roaming between various network technologies, continuously growing in heterogeneity, necessitates their seamless integration. Such integration involves all networks that simply co-exist nowadays, namely 3G cellular systems, Wireless Local Area Networks (WLANs), Mobile Ad-hoc Networks, Personal Area Networks etc.

IPv6 is the networking technology of choice to enable the internetworking and unification of these diverse technologies in the effort to move to an all-IP 4G environment. Mobility is seen as an integral part of future networks, where the initiatives for next generation networks (NGN) will meet more traditional and established networks to form heterogeneous architectures.

To achieve ubiquitous and pervasive computing a common mobility solution, Mobile IPv6 (MIPv6) is adopted. MIPv6

provides independence of access network technologies and common solutions for fixed and wireless networks. It also provides application transparency which has become a requirement for all reasonable solutions.

Mobility in IPv6 is, therefore, an enabler for future services. Even if the ingenious Mobile IPv6 protocol performs sufficient, in macro environments with non real-time traffic, seamless mobility requires some more enhanced protocol procedures in between the mobile node and the involved network entities. Limiting the effect of handovers has the potential to considerably improve application performance in terms of latency and packet loss.

A handover (HO) is the process during which a mobile node (MN) creates a new connection and disassociates from its old one. The decision for a new association may be initiated due to movement, if we are moving away from the old connection point and we are approaching a new one; low signal quality, because of interference or other impairments in the wireless path; quality of service decision, trying to effect a balanced load among neighboring or overlapping cells; better service, if we recognize a network with services that we require; or policy and cost decision, where the network or the user decide that it is more appropriate, or advantageous to relate to a different location.

Handovers can be characterized as Horizontal if they are performed between connection points using the same access technology, or Vertical if they are performed between access points of different technologies, a case which will be more common in future heterogeneous networks. In addition Handovers are considered Link Layer (L2) if they are performed between connection points belonging to the same subnet, or Network Layer (L3) if they are performed between different subnets and require the configuration of a different IPv6 address.

IP mobility protocols have a long history of rigorous research. The purpose of this article is not to provide another set of performance evaluation results for IP mobility protocols, but to examine the horizontal handover process of Mobile IPv6 (L3) in a real wireless testbed, based on IEEE 802.11b. The aim is to extract information on the actions taken by network entities during the movement of a mobile node and to decompose and analyze all the initiated events and exchanged signals both in the Link and the Network layer.

This work provides real-implementation results for significant parts of the handover process which cannot be obtained through simulation. We consider that simulators, though useful to some extent from an analytical point of view, either introduce unnecessary uncertainty into the network, or strictly specify significant parameters. Therefore, there is always a margin of error in simulation results. In addition, items not easily measured, are deduced analytically.

The rest of the paper is structured as follows: In Section II

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V. Vassiliou is with the Department of Computer Science, University of Cyprus, P.O.Box 20537, Nicosia 1678, Cyprus, phone: +357-22892750, fax: +357-22892701; e-mail: vasosv@cs.ucy.ac.cy (corresponding author).

Z. Zinonos is with the Department of Computer Science, University of Cyprus, P.O.Box 20537, Nicosia 1678, Cyprus, e-mail: zinonos@cs.ucy.ac.cy.

the mobility management, address resolution and other protocols related to MIPv6 handovers are presented. The handover process is analyzed in Section III and related work is outlined. The experimental evaluation of MIPv6 handovers in IEE802.11b is described in Section IV. Concluding remarks and items for future work are given in Section V.

II. PROTOCOL OVERVIEW

This section provides background information on the MIPv6 mobility protocol, the address resolution protocols and the L2 handover process which will be referenced in later sections.

A. Mobile IPv6

Mobile IP version 6 is the mobile extension to IP version 6 [19]. The MIP fundamental principle is that a mobile node should use two IP addresses, a permanent address (the home address, assigned to the host and acting as its global identifier) and a temporary address (the care-of address -CoA, providing the host's actual location). MIPv6 retains the general ideas of home network, encapsulation, home agent, and care-of address from MIPv4 [20]. However, it has a slightly different philosophy and a much-improved design than its predecessor.

While a mobile node is attached to its home network, it is able to receive packets destined to its home address, and being forwarded by means of conventional IP routing mechanisms. When the mobile node moves into a new network (visited/foreign network), its movement is detected and a new association is made with mobility agents (foreign agents) in the new domain. In MIPv6 a mobile node is more "independent" and does not have to rely on an access router to obtain a CoA and register with the home agent. To obtain its CoA, a mobile node uses the IPv6 protocols for Address Autoconfiguration [24] and Neighbor Discovery [17].

Fig. 1 illustrates the process and the messages exchanged during a handover.

Once configured with a CoA, the MN needs to send a Binding Update (BU) message to its Home Agent (HA) to register its current primary CoA. The first time a correspondent node (CN) needs to communicate with the MN, it sends the packets to the mobile node's home address. The HA is then encapsulating the packets and forwards them to the MN's CoA, where they are de-capsulated by the corresponding mobility agent and forwarded to the mobile node.

Upon a new association, the MN transmits BUs to its HA and the communicating CNs for them to associate the MN's home address with the new CoA. When the MN received a Binding Acknowledgement from the HA, it is once again routable at the new location.

After establishing a binding update with the HA the MN initiates a return routability procedure with the CN. The procedure involves four messages. The Home and Care-of Test Init messages (HoTi and CoTi) are sent from the MN to the CN at the same time, the first one using the HA as intermediate router. The procedure requires very little processing at the correspondent node, and the Home and Care-of Test messages (HoT and CoT) can be returned quickly, perhaps nearly simultaneously. The purpose of this procedure is to enable the CN to make sure that the mobile node is in fact addressable at its claimed care-of address as

well as at its home address. Only with this assurance is the correspondent node able to accept Binding Updates from the mobile node which would then instruct the correspondent node to direct that mobile node's data traffic to its claimed care-of address [19].

From then on, CNs will use IPv6 Routing headers for forwarding the packets to the MN. These packets have as destination address the MN's CoA. The 'home address' information is also included in the routing header to preserve transparency to upper layers and ensure session continuity. In the reverse direction, datagrams sent by the mobile node can be delivered to their destination using standard IP routing, without having to go through the home agent. Packets have as a source address the host's CoA while the home address is also included for the same reasons as above. By following this process, MIPv6 has inherent route optimization and does not suffer from Triangular routing problems as its predecessor.

When the home agent discovers that the mobile node has moved, it uses techniques from Neighbor Discovery to indicate the new MAC address for the mobile node to all the correspondent nodes on the mobile node's home network.

Two well-known approaches in reducing the MIP handoff latency have been proposed in the literature. One aims to reduce the (home) network registration time through a hierarchical management structure, while the other tries to minimize the lengthy address resolution delay by address pre-configuration through what is known as the fast-handoff mechanism.

Hierarchical mobility management protocols, like Hierarchical MIPv6 (HMIPv6) [23] decide when to perform an action (registration in this case), whereas fast handover protocols, like Fast MIPv6 (FMIPv6) [11], address the problem of how to perform L3 actions in a faster way.

B. Stateless Address Autoconfiguration and Duplicate Address Detection

The stateless address autoconfiguration mechanism [24] allows a host to generate its own addresses in the following way. Access routers advertise prefixes that identify the subnet(s) associated with a link, while hosts generate an 'interface identifier' that uniquely identifies an interface on each subnet. A global address is formed by combining the two. The formation of an address must be followed by the Duplicate Address Detection (DAD) procedure in order to avoid address duplication on links where stateless address autoconfiguration is used. The address autoconfiguration is composed of the following steps:

The host generates a link-local address for its interface on a link. When in handoff, the host can use the same interface identifier as the one used in the previous link. It then performs DAD to verify the uniqueness of this address, i.e. the interface identifier on the new link. It uses the prefix(es) advertised by routers for forming a global address so as to be able to communicate with hosts other than the neighboring ones. During DAD, the host transmits a Neighbor Solicitation for the tentative link-local address and waits for some specified delay (RetransTimer) [17] till it considers the address unique. DAD only fails if in the mean time, the host receives a Neighbor Advertisement for the same address, meaning that another host is using the being questioned address or if another host is in the progress of performing DAD for the same address and has also transmitted a Neighbor

Solicitation.

C. Layer 2 Handovers

The IEEE 802.11 handover procedure is composed of three distinct phases: scanning, authentication, and reassociation phase. During the IEEE 802.11 handoff procedure the MN performs a channel scanning to find the potential APs to associate with. In the passive scan mode, each MN listens for beacon messages which are periodically sent by APs. In addition to the passive scan, each MN may broadcast a probe frame on the channel and receive probe responses from APs in the active scan mode. Regardless of scanning modes, all possible channels defined by the IEEE 802.11 standard (11 or 13 channels) are examined during a scan.

The scanning results in a list of APs that have been detected and it includes the related information for each detected AP, such as ESSID, the AP's MAC address, and the measured signal strength of each AP. Based on the scan result, the MN chooses an AP to associate with (usually the one with the highest signal strength). After that, the MN initiates the authentication procedure by transmitting the frames related to it. If the authentication phase is successful, the MN tries to re-associate with the AP by sending a reassociation request message to the AP. Then, the AP responds with a re-association reply message which contains the results of the reassociation. If everything is successful, this phase becomes the last step of the handover. The length of the scanning procedure may vary from one implementation to the other but is generally considered to be the heaviest part of a Wireless LAN handover [8][9][26].

III. HANDOVER LATENCY ANALYSIS

A mobile node is unable to receive IP packets on its new association point until the handover process finishes. The period between the transmission (or reception) of its last IP packet through the old connection and the first packet through the new connection is the handover latency. The handover latency is affected by several components:

- **Link Layer Establishment Delay (D_{L2}):** The time required by the physical interface to establish a new association. This is the L2 handover between access routers.
- **Movement Detection (D_{RD}):** The time required for the mobile node to receive beacons from the new access router, after disconnecting from the old AR.
- **Duplicate Address Detection (D_{DAD}):** The time required to recognize the uniqueness of an IPv6 address.
- **BU/Registration Delay (D_{REG}):** The time elapsed between the sending of the BU from the MN to the HA and the arrival/transmission of the first packet through the new access router.

The overall handover process, as well as the component delays identified above, are presented in Fig. 1. The handover delay for MIPv6 can analytically be computed as:

$$DMIPv6 = D_{L2} + D_{RD} + D_{DAD} + D_{REG} \quad (1)$$

The delays can be further broken down to:

$$D_{MIPv6} = (T_{PRB} + T_{AUTH} + T_{RASS}) + (T_{RSOL} + T_{RADV}) + D_{DAD} + (T_{HBU} + T_{HBA} + 2T_{HOTI} + 2T_{HOT} + T_{CBU} + T_{CBA}) \quad (2)$$

Where: D_{L2} , D_{RD} , D_{DAD} , D_{REG} as described above, T_{PRB} , T_{AUTH} , T_{RASS} : probe, authentication and reassociation delays at L2, T_{RSOL} , T_{RADV} : Router solicitation and Router Advertisement, T_{HBU} , T_{HBA} : BU and BAcK with HA, $2T_{HOTI}$, $2T_{HOT}$: HoTi and HoT process and T_{CBU} , T_{CBA} : BU and BAcK with CN.

Due to the differences in access networks, hardware, implementation versions and traffic, there can be no single value for the overall MIPv6 delay. Related values found in the literature vary from 1.3 sec in [13][6] to 1.9 sec in [16][2], and 2.6 sec in [14][26]. It should be noted that only the last four refer to real implementations.

As it can be seen from Fig. 1 and equation (2), the overall MIPv6 handover latency can be reduced by direct manipulation of a number of parameters. Solutions like HMIPv6 and FMIPv6 manage to reduce the BU/Registration Delay. In our work we focus on the other three delay components: the D_{L2} , D_{RD} , and D_{DAD} .

A. L2 Delays

The values measured or considered in the literature for the D_{L2} delay are between 50ms [12] and a few hundred milliseconds [11]. In [21] and [18] the value is at 100ms. In [1] the range is from 100-300ms. In [14] the range is from 50-400ms. L2 delays are, however, very dependent on the physical medium and always exhibit great variations. Since the scanning, or probing, delay is the most prevalent one during an L2 handover, we believe that it merits special attention. In this work we shorten the wireless beacon interval to values below 100ms in an effort to reduce D_{L2} . We also combine our measurements with analytical methods to extract additional information on L2 delays.

B. Router Advertisements

Router Solicitations (RSol) and Router Advertisements (RA) help the MN identify that it has changed subnets and provide it with the necessary information for the creation of the new CoA. While in traditional IPv6, the values for RAs were in the order of 3 to 5 seconds, for Mobile IPv6 these values need to be significantly lower. In this work, we change (reduce) the RSol and RA intervals in an effort to deduce their effect on D_{RD} .

C. Duplicate Address Detection

Once the MN discovers a new router and creates a new CoA it tries to find out if the particular address is unique. This process is called Duplicate Address Detection and it is a significant part of the whole IPv6 process, with very little room for improvement. In this work we evaluate MIPv6 HOs with this feature either enabled or disabled. We also examine how this process is performed in different handover directions (from and to the home network).

D. Related Work

Reducing the L2 probe delay is not a protocol issue, but an implementation issue. In [16] the authors examine different IEEE802.11-based network cards and propose the reduction of the *MaxChannelTime* to 100ms in order to reduce the effect

of the probing procedure. In addition they suggest that another possible way to reduce L2 handovers is to extend the protocol with new IEEE 802.11 specific options that allow access routers to send to mobile nodes, all details that they might need for rapidly associating with a new Access Point, such as frequency, ESSID, and authentication info.

In [13] they recognize that the DAD time is significant during a handoff and they propose a scheme for HMIP in order to reduce the DAD time on handoff delay. The scheme is called Stealth-time HMIP (SHMIP) and assigns a unique on-link care-of address (LCoA) to each mobile node and switches between one-layer IPv6 and two-layer IPv6 addressing. In this mechanism when a mobile node sends a local BU, it also sends Bus to its home agent and correspondent nodes at the same time, using LCoA instead of RCoA. To further reduce packet losses, they also adopt pre-handoff notification to request previous mobility anchor points (MAP) to buffer packets for the mobile node.

In [25] they work specifically on the registration delay component. They make the assumption that the link layer delay can be considered equal to zero for link layer technologies supporting soft handover. They also consider the movement detection delay depends upon the frequency of router advertisement and could be large in a bandwidth constraint environment.

In [12] the total handover latency MIPv6 is found to be 5 seconds. Based on the author's assumptions, if the L2 handover takes about 1 second, then the remaining 4 seconds are used for the L3 handover. This happened because the minimum period of RA (Router Advertisement) was 3 seconds and the maximum period was 5 seconds which corresponds to the default setting in wired IPv6. In MIPv6 these values are expected by the RFC to be smaller. In a subsequent paper [10] the same authors consider that the router advertisement (RA) message is sent to wireless link in every 1-3 seconds which is a better interval, but as we will show in Section IV it can also be considered large.

In [5] the authors use analytical models to evaluate MIPv4, MIPv6, FMIPv6, and HMIPv6 and compare their performances in terms of handover delay for VoIP services. They propose an adaptive timer for the retransmission of router solicitations, binding updates and other control signals, to replace the backoff timer usually found in MIP implementations. The results obtained using the adaptive timer technique show a 50% improvement compared to the fixed-timers option. However, these results are purely analytical and make specific static assumptions on the values of the different L2 and L3 component delays.

In [6] they do similar comparisons, utilizing a simulator instead of mathematical analysis. They compare Standard MIP, HMIP, FMIP, FHMIP and FFHMIP focusing on L3 HO values, and ignoring L2 and DAD delays.

The authors in [22] claim that none of the Fast or "assisted" methods of handover can be applied in IEEE 802.11 systems since such systems are based on the fact that the APs involved in a MN's reassociation can "anticipate" the handover before it is actually performed. However, the 802.11 APs become aware of a MN's movement only after real occurrence of a reassociation event at the new AP. Other methods of shortening the movement detection delay are: (a) the MN pre-caches the IP information needed to perform the IP

movement detection, without depending on the MIP advertisements for this purpose and (b) the APs are either pre-configured with information useful to perform movement detection for a newly connected MN, or obtain this information via periodic announcements or other similar methods (centralized caching of the necessary information in each subnet).

In [26] a method is proposed, which does not change the MIPv6 protocol, but achieves faster handoffs (by a factor of 10) by introducing a dedicated MAC bridge to connect the different foreign agents. This option seems not to scale well and inserts another complex node in the network which is also a single point of failure.

Our work aims to correctly measure and characterize all handover delay components and indicate the significance of certain parameters in reducing them. This work can be of benefit to those trying to build, modify or optimize mobility management protocols, since it can help them utilize real-life values in their simulations, emulations, or equations.

IV. EXPERIMENTAL EVALUATION

The work items identified in Section III are evaluated experimentally in this Section. The testbed setup is explained in Section IV.A and the results of each evaluation are analyzed separately afterwards.

A. Testbed Setup

The experimental testbed consists of three wireless LANs connected through an IPv6 cloud as shown in Fig. 2. The Home Agent, the Foreign Agent and the Correspondent Node are all in different subnets. The three subnets are connected through the IPv6 network. This setup topology provides the simplest configuration for a realistic study of L2 and L3 handover components.

The devices used in the testbed have the specifications shown in Table I. It is worth noting that the Home and Foreign Agents have the same type of wireless cards. This removes any asymmetry in our readings. Table II contains some of the configuration parameters in the testbed: Autoconfiguration is enabled, Forwarding is enabled only on the IPv6 routers and not on the MN, the MTU is 1500 bytes and the backoff timers for router solicitations, BU and Home / Co Test Initialization are set to the default values.

TABLE I LIST OF EQUIPMENT AND SOFTWARE

Mobile Node	Home Agent	Foreign Agent	Correspondent Node
IBM ThinkPad T42p	Acer Veriton 9100	Dell Optiplex GX1	Dell Optiplex GX1
Intel Pentium M 1.86GHz 2048 cache	Intel Pentium 4 1500MHZ 256 cache	Intel Pentium III 500MHz 512 cache	Intel Pentium III 500MHz 512 cache
Atheros AR5212 802.11abg NIC	D-Link, PCI IEEE802.11b card, GWL-520, Atheros chipset		
Auto channel	Channel 1	Channel 6	
LINUX, Fedora Core 5, kernel 2.6.16			
MIPL v2.02			

TABLE II MIPv6 TESTBED PARAMETERS

Parameter	Value
mtu	1500 bytes
autoconf	1
forwarding	1 (MN=0)
Home / Co Test Init	1
BU	1.5
RetransTimer	1s
Router Solicitations	3
Beacon Interval	50-100 ms (100)
MinRouterAdvInterval	0.03 - 0.5s (0.5)
MaxRouterAdvInterval	0.07 - 1.5s (1.5)
DAD	On / Off (On)
Router Solicitation Delay	0 / 1s (1)
Router Solicitation Interval	1 / 4s (4)
MinDelayBetweenRAs	0.03 / 3s (3)

The parameters on the lower part of the table are those changed in our experimental evaluation. The values in brackets are the default values. The Beacon Interval is the time between successive beacons sent by the APs. *MinRouterAdvInterval* and *MaxRouterAdvInterval* refer to the minimum and maximum values of the range specified for randomly sending unsolicited router advertisements. Router Solicitation Delay is the number of seconds to wait after an interface is brought up before sending Router Solicitations. Router Solicitation Interval is the number of seconds to wait between Router Solicitations. Router Solicitations is the number of Router Solicitations to send until assuming no routers are present. *MinDelayBetweenRAs* is the minimum time allowed between sending multicast router advertisements from the interface in reply to solicitations.

B. Results

The results presented in this section are averaged over 30 different handover events. The handovers represent the movement from the home network to a foreign network. The change of network is initiated by the `iwconfig [interface] [channel] command`, where `interface` is the name of the wireless interface, and `channel` the wireless network channel that we want the card to associate with. This method was preferred since it provides us with the ability to explicitly control the handover start time and have a concrete reference with respect to time about that. Alternatively, we could have an environment where a declining signal strength from one of the two access points would trigger the L2 process, but this is not an easily repeatable process in an experimental setting.

The testbed was isolated from other networks through a firewall and no additional traffic was entering or leaving the network during the experiments. This has helped us guarantee that no external factors have influenced the measurements. To ensure that all measured events could be correlated and confirmed at different points in the network, the testbed was configured to the (same) NTP [7] server of the Computer Science Department, which provides millisecond accuracy. The measurements were done using Ethereal [4] and produced traces similar to the one in Fig. 3. A similar methodology has been suggested in [3].

The Ethereal traces were parsed and the delay components were extracted as follows:

$$D_{L2+RD} = T_{RECEPTIONOFRA} - T_{IWCONFIG}$$

$$D_{DAD} = T_{BUHA} - T_{RECEPTIONOFRA}$$

$$D_{HAREG} = T_{BACKHA} - T_{BUHA}$$

$$D_{CNREG} = T_{BACKCN} - T_{BUCN}$$

$$D_{REG} = D_{HAREG} + D_{CNREG}$$

Based on the default values of Table II, the total MIPv6 handover latency recorded in our setup was $D_{MIPv6} = 3.68$ sec. The values of the individual components of the handover delay are broken down in Table III.

The major share in the handover latency goes to D_{REG} as expected. The BU and registration functions account for 45% of the total delay. The DAD function takes another 38% and the movement detection (including the L2 delay) accounts for the rest 17%.

TABLE III MIPv6 HANDOVER DELAY BREAKDOWN

Delay Component	Mean(s)	Std. Deviation
D_{L2+RD} (L2 probe + RA reception) ¹	0,648477	0,234283018
D_{DAD} (IPv6 DAD)	1,413679	0,216024101
D_{REGHA} (registration with HA)	1,003168	0,001591049
D_{REGCN} (registration with CN)	0,612352	0,116414246
Total	3,677676	0,284333078

It must be noted that the total handover duration considered here includes the L2 handover time and the registration with the CN, two items sometimes not counted in the MIPv6 handover delay [28][29]. Overall, the delay is larger than that suggested by similar works. We believe that this is caused by slightly higher delays in all components, but especially in D_{REG} which contains the most transitions through the IPv6 cloud. It is important to mention that, to the best of our knowledge, no other work has taken this feature, i.e. a real IPv6 network, into account. Similar evaluations are made with the visited network directly connected to the home network [26][29] and sometimes the visited/foreign router directly connected to a different interface of the HA. [15]

1) Movement Direction

A similar analysis of the handover, when the MN returns to the home network has resulted in an average total handover delay of 0.561227 seconds. There are two reasons for this significant decrease. First, the MN was returning back to its home network while its home address was still valid; therefore, no DAD was performed, i.e. $D_{DAD}=0$ sec. Second, the association with the HA and CN was faster ($D_{REGHA} = 0.0153524$ and $D_{REGCN} = 0.1119782$) since the return routability procedure is shorter because of the exchange of only one key with the CN instead of two [29]. The movement detection delay was similar to the previous values $D_{L2}+D_{RD}=0.4338964$ sec.

2) Duplicate Address Detection

As mentioned in Section IV.B, a significant part of DMIPv6 is D_{DAD} . In Fig. 4 we observe that when the DAD function is switched off the respective delay is reduced by almost 1sec, which is the default timer value for this

¹ Due to the experimental setup, it was not possible to obtain separate values for D_{RD} and D_{L2} .

operation. In reality D_{DAD} is reduced on average by 0.835 and 0.979 sec for L2 wireless beacon intervals of 100ms and 60ms respectively.

Based on these results we can safely conclude that if we operate in a controlled environment where the probability of duplicate addresses is negligible, then we can discard the DAD function and achieve a decrease in the total MIPv6 delay of at most one second. Such environments may be small networks where only one router advertises the prefix and the IPv6 addresses are based on the MAC address (EUI-64).

3) Router Advertisement Interval

The discovery of a new router is affected by two factors: the probe/scanning delay on L2 and the router discovery on L3. In this section we will examine the effect of the latter on the overall and component latencies in MIPv6.

Typical values for the min and max router advertisements are of the order of a few seconds in wired IPv6 networks. In MIPv6 these values are lower and are usually centered around 1sec. We have started with our default values of 0.5 – 1.5 sec and lowered the intervals down to 0.03-0.07 sec which are the minimum values identified in the MIPv6 RFC.

In Fig. 5 we recognize that the change in the RA interval only affects the combined $D_{L2} + D_{RD}$. We observe a 200-400% reduction in the corresponding delay between the default and lower values. This dramatic reduction is significant in terms of the handover delay, but may have other repercussions in the network which are not visible in these results. In this work we cannot comment yet on the effect of a lower interval on the overall network traffic and on the processing load of the routers.

Even though the change in RA intervals has reduced by a significant percentage the router discovery time, the effect on the overall handover delay is not as dramatic as it can be seen from Fig. 6. This is expected since the contribution of the D_{RD} delay to the total is only 17%.

Based on the standards, $MaxRouterAdv$ needs to be at least three times larger than the $MinRouterAdv$ interval. Therefore, pending an evaluation of the effect of shorter intervals on the CPU load, we propose using the 0.5-1.5 range.

4) Beacon Interval

As described in Section IV.B, the Wireless Beacon Interval is another potential factor for a change in the delay of the lower layer. Based on Fig. 7 we see that a reduction of the Beacon Interval from 100ms to 60ms corresponds to an almost equal reduction in the L2 delay.

The direct relationship of the beacon interval to the handoff delay is unfortunately not an item which can be exploited. Both from Fig. 7 and Fig. 8 we can recognize that we cannot consider it a significant factor. In addition, a small interval may adversely affect the MAC layer functions (introduce contention) [27] and/or increase the energy consumption of the mobile terminals. For these reasons we propose to keep the interval to the default recommended value of 100ms.

5) Router Solicitation

The analysis of the D_{MIPv6} delay in Section III (equations 1 and 2) suggests that D_{RD} is composed of $T_{RSOL} + T_{RADV}$. The effect of T_{RADV} has been examined previously, where a threshold of 150ms was reached for $D_{L2}+D_{RD}$ at the lower

acceptable RA interval values. In order to reduce D_{RD} further we have changed the router solicitation intervals and forced the MN to send a router solicitation message immediately after recognizing that it has moved to a new AP.

Table IV compares the $D_{L2}+D_{RD}$ delay when the Router Solicitation Delay is reduced from 1 second (Case 1) to zero seconds (Cases 2 & 3). In case 3 the $MinDelayBetweenRAs$ is also changed from 3sec to 0.03 seconds.

TABLE IV HANDOVER DELAYS WITH ROUTER SOLICITATION

	Case 1 (default)		Case 2		Case 3	
	Mean	Std.Dv	Mean	Std.Dv	Mean	Std.Dv
DL2+DRD	0,6484	0,2342	0,5668	0,3365	0,0771	0,0207
Total	3,6776	0,2843	3,5740	0,4909	3,0985	0,3933

Case 1 (default):

Router Solicitation Delay = 1 sec
Router Solicitation Interval = 4 sec
MinDelayBetweenRAs = 3 sec

Case 2:

Router Solicitation Delay = 0 sec
Router Solicitation Interval = 1 sec
MinDelayBetweenRAs = 3 sec

Case 3:

Router Solicitation Delay = 0 sec
Router Solicitation Interval = 1 sec
MinDelayBetweenRAs = 0.03 sec

The corresponding average delay with immediate solicitation in Case 2 is 90ms less than the default. In Case 3, where the minimum time allowed between sending multicast router advertisements from the interface in reply to solicitations is also reduced to the very small value of 30ms, the decrease is in the order of 580ms, a whole half a second lower than before.

6) Extraction of L2 delay

Due to implementation issues all wireless cards (MN and APs) in the experiment were set to ad-hoc mode, which means that the MN was not going through the usual three parts of L2 handover: Probing, Authentication, Re-association, but only through the first one. Since the probing delay accounts for about 90% of the L2 delay [14][26] we get a good understanding of the magnitude of the total L2 delay. Based on the results of case 3 in Table 4, we can safely state that the L2 delay (probing) in our experiments was not more than 100ms. The value of L2 can also be theoretically extracted if we follow the MIPv6 delay analysis in [15] where

$$D_{RD} = \frac{1}{4} (MinRtrInterval - MaxRtrInterval) \quad (3)$$

Applying equation 3 on the values of $D_{L2}+D_{RD}$ from Table III and Section IV.B.3), we obtain the following:

TABLE V ESTIMATION OF D_{L2} FROM RA INTERVALS

MinRtrInterval	0.03	0.04	0.1	0.2	0.3	0.4	0.5
MaxRtrInterval	0.07	0.08	0.3	0.6	0.9	1.2	1.5
$D_{L2}+D_{RD}$	0.15	0.16	0.19	0.27	0.36	0.51	0.64
Calculated D_{RD}	0.01	0.01	0.05	0.1	0.15	0.2	0.25
Estimated D_{L2}	0.14	0.15	0.15	0.17	0.21	0.31	0.39

V. CONCLUSION

The existing L2 handoff schemes in technologies such as IEEE 802.11, 3GPP, and 3GPP2 do not consider the L3 handoff. In addition the L3 handoff like Mobile IPv6 does not consider the L2 handoff. Although the HMIPv6 and FMIPv6 protocols and their extensions can reduce the L3 handoff latency, they cannot reduce the L2 handoff latency. In these networks, the L2 handoff scheme in newly defined wireless access network technologies should be designed carefully and should consider the L3 handoff scheme to reduce the handoff latency.

In this paper we have examined the handover process of Mobile IPv6 in a real wireless testbed, based on IEEE 802.11b. This work has performed a detailed decomposition and analysis of the handover delay, with a focus on the pre-registration phase.

This work provides real implementation results for significant parts of the handover process which cannot be obtained through simulation. The testbed setup is considered to reference a very realistic topology and all the results were obtained with no optimizations on the L3 part of the implementations used. Our results illustrate how the link layer detection, the movement detection, and the address autoconfiguration parts of the handover can be reduced. Link layer delays have been shown to be reduced by increasing the Beacon frequency. The same happens when RA Intervals are shortened. However, for both these changes there is an indication that the processing load on the nodes and the increased traffic in the wireless medium and the network will increase, respectively. DAD functions can be foregone, if the network meets certain requirements. Furthermore, an optimal range of Router Solicitation Delays may also benefit the network and the MNs.

In this paper we have also identified the amount of change which can be expected if all the parameters examined above are fully utilized. The result is that the overall mobile IPv6 handover delay can be reduced by more than 2.3 seconds (from 3.6776 secs to 1.3694 secs). This is a significant reduction which may be extended when L3 registration delay reduction methods are also employed.

Related work has been undertaken to address these and similar issues, both by individual researchers and the IETF. Significant steps have been taken in the IETF community with the introduction of protocols for the reduction of L3 registration delays. From the presented results is clear that the current movement detection process is unnecessarily slow, so that it now hampers the use of current MIPv6 for real-time traffic.

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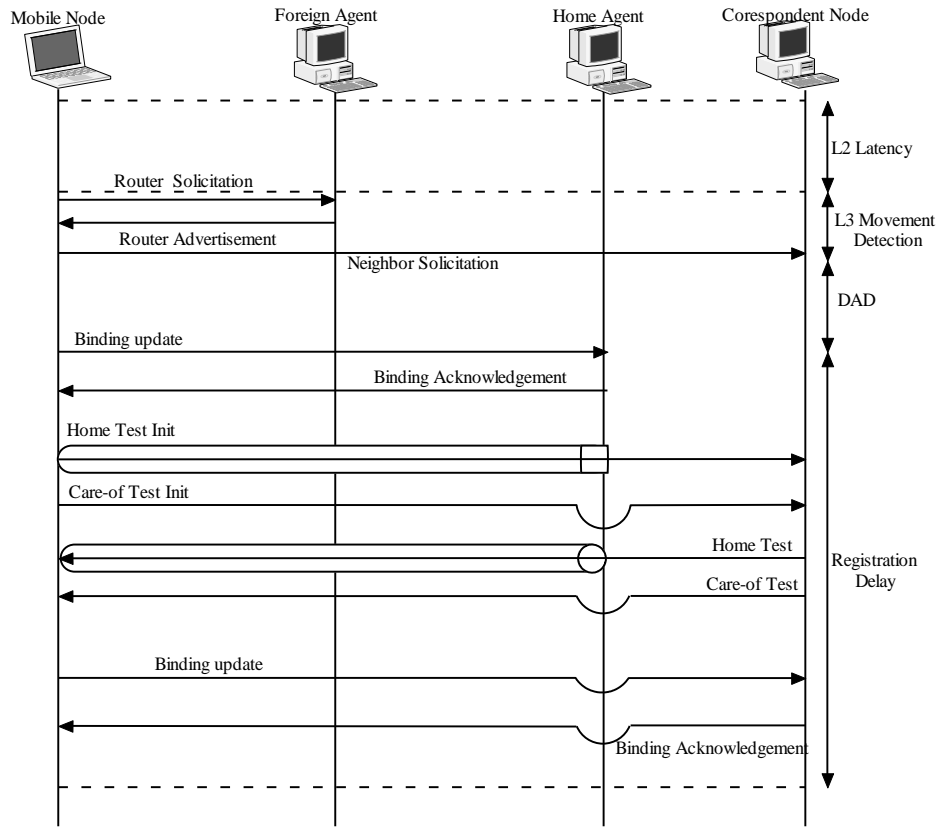


Fig. 1 MIPv6 Handoff Signaling

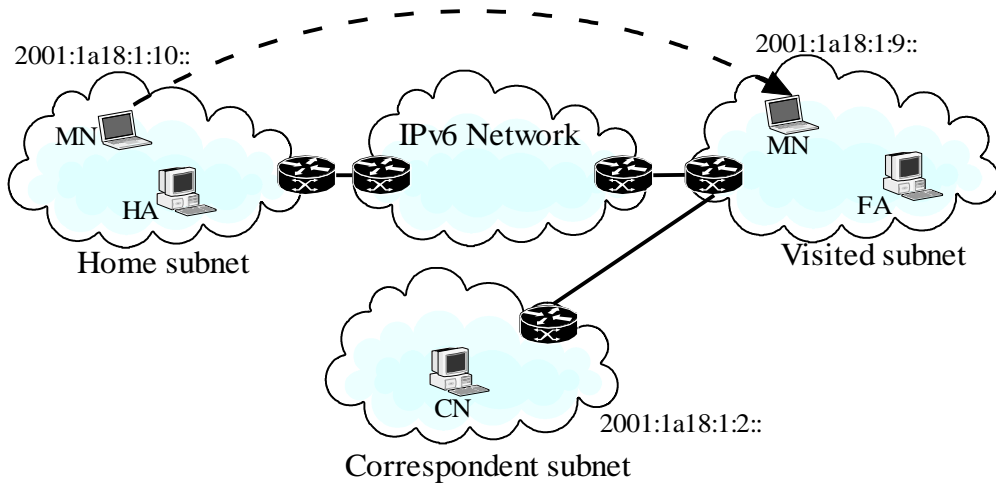


Fig. 2 Testbed Topology

Time (s)	Source	Destination	Type	Content
11:37:00.076576	fe80::20d:88ff:fea9:3ee	ff02::1	ICMPv6	Router advertisement
11:37:00.114307	2001:1a18:1:1:2e0:7dff:fee9:8915	2001:1a18:1:10:205:4eff:fe49:bc50	UDP	
11:37:00.129567	fe80::20d:88ff:fea9:3ee	ff02::1	ICMPv6	Router advertisement
11:37:00.818557	::	ff02::2	ICMPv6	Router solicitation
11:37:00.822233	fe80::20d:88ff:fea9:1d34	ff02::1	ICMPv6	Router advertisement
11:37:00.830379	::	ff02::16	ICMPv6	Multicast Listener Report
11:37:01.041912	fe80::20d:88ff:fea9:1d34	2001:1a18:1:9:205:4eff:fe49:bc50	ICMPv6	Neighbor solicitation
11:37:01.626462	::	ff02::1:ff49:bc50	ICMPv6	Neighbor solicitation
11:37:01.634451	::	ff02::1:ff49:bc50	ICMPv6	Neighbor solicitation
11:37:01.964565	fe80::20d:88ff:fea9:1d34	ff02::1	ICMPv6	Router advertisement
11:37:02.635628	2001:1a18:1:9:205:4eff:fe49:bc50	2001:1a18:1:10:20d:88ff:fea9:3ee	MIPv6	Binding Update
11:37:02.792780	fe80::20d:88ff:fea9:1d34	ff02::1	ICMPv6	Router advertisement
11:37:03.308170	fe80::20d:88ff:fea9:1d34	ff02::1	ICMPv6	Router advertisement
11:37:03.642960	fe80::20d:88ff:fea9:1d34	ff02::1:ff49:bc50	ICMPv6	Neighbor solicitation
11:37:03.643041	2001:1a18:1:9:205:4eff:fe49:bc50	fe80::20d:88ff:fea9:1d34	ICMPv6	Neighbor advertisement
11:37:03.644019	2001:1a18:1:10:20d:88ff:fea9:3ee	2001:1a18:1:9:205:4eff:fe49:bc50	MIPv6	Binding Acknowledgement
11:37:04.106998	2001:1a18:1:1:2e0:7dff:fee9:8915	2001:1a18:1:10:205:4eff:fe49:bc50	UDP	
11:37:04.115020	2001:1a18:1:10:205:4eff:fe49:bc50	2001:1a18:1:1:2e0:7dff:fee9:8915	MIPv6	Home test Init
11:37:04.115352	2001:1a18:1:9:205:4eff:fe49:bc50	2001:1a18:1:1:2e0:7dff:fee9:8915	MIPv6	Care-of Test Init
11:37:04.182018	2001:1a18:1:1:2e0:7dff:fee9:8915	2001:1a18:1:9:205:4eff:fe49:bc50	MIPv6	Care-of Test
11:37:04.182786	2001:1a18:1:1:2e0:7dff:fee9:8915	2001:1a18:1:10:205:4eff:fe49:bc50	MIPv6	Home test Init
11:37:04.183411	2001:1a18:1:9:205:4eff:fe49:bc50	2001:1a18:1:1:2e0:7dff:fee9:8915	MIPv6	Binding update
11:37:04.185656	2001:1a18:1:1:2e0:7dff:fee9:8915	2001:1a18:1:9:205:4eff:fe49:bc50	MIPv6	Binding Acknowledgement
11:37:04.660398	fe80::20d:88ff:fea9:1d34	ff02::1	ICMPv6	Router advertisement

Fig. 3 Ethereal Trace during a MIPv6 HO with forced Router Solicitation (measured events are in bold)

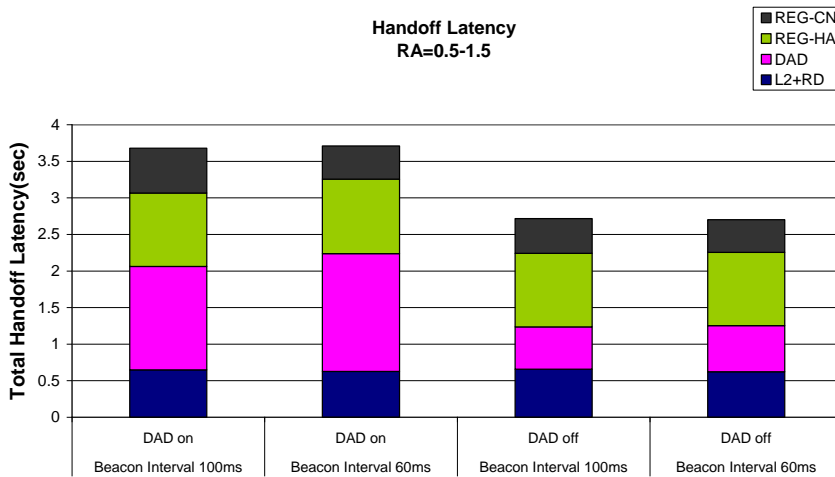


Fig. 4 DAD component contribution to the MIPv6 Handover Latency

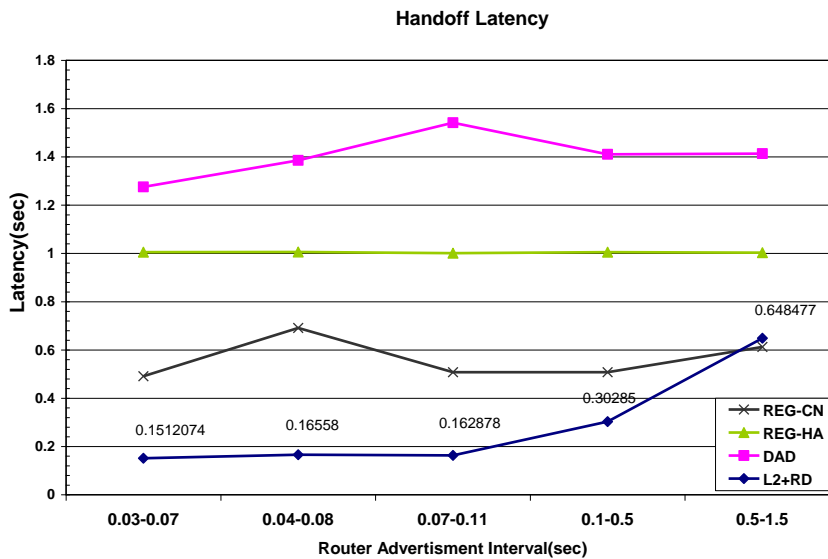


Fig. 5 Router Advertisement Interval effect on handover component latencies

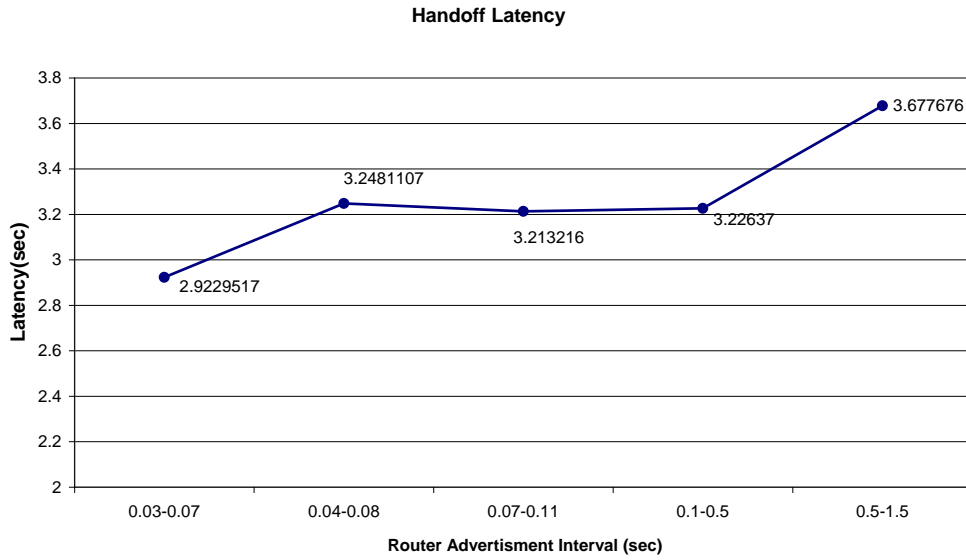


Fig. 6. Router Advertisement Interval effect on overall handover latency

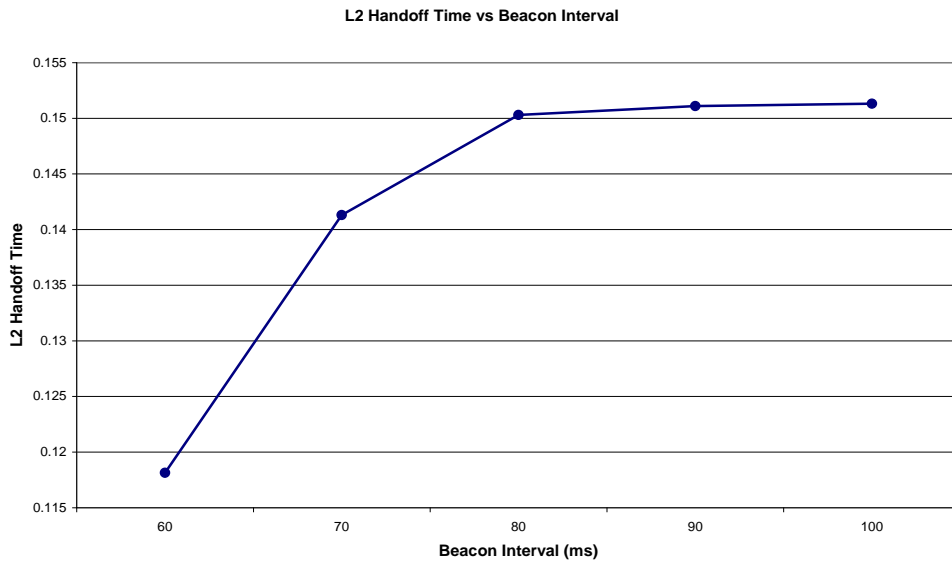


Fig. 7. L2+RD delay vs Beacon Interval

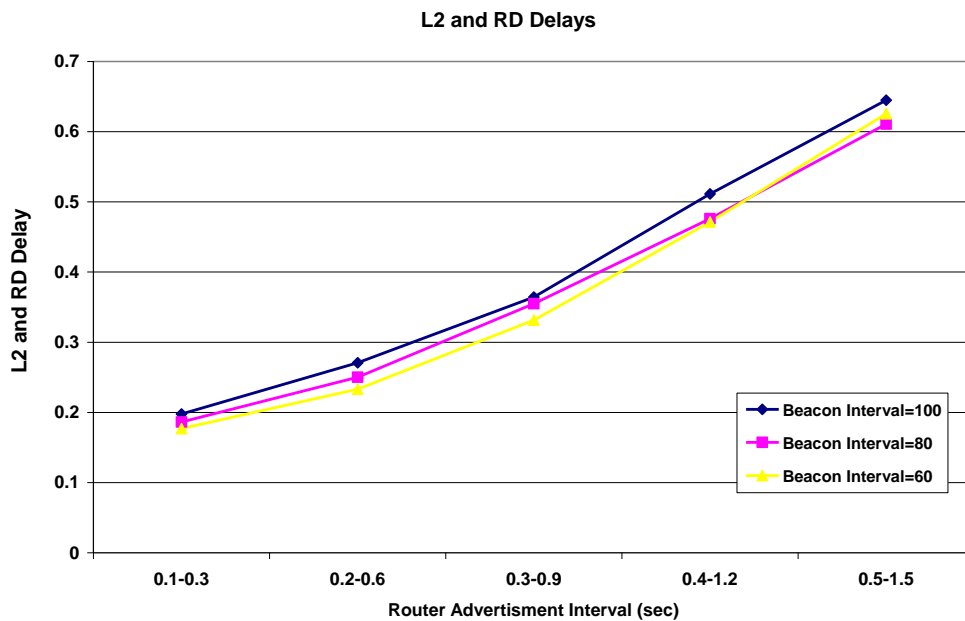


Fig. 8. Router Advertisement and Beacon Interval



Dr. Vasos Vassiliou is a Lecturer at the Computer Science Department of the University of Cyprus since 2005. He is also the Associate Director of the Networks Research Laboratory (NetRL) at UCY. He held positions as a Visiting Lecturer at the same department (2004-2005) and as an Assistant Professor at the Computer Science Department of the University of Nicosia (2002-2004). He has published several articles in International Conferences and Journals and participates actively in COST actions, local, and European Projects. His research interests include High Speed Network Architectures (MPLS), Mobile Networks (Mobile IP, MMPLS, Ad Hoc and Sensor Networks), Wireless Communications (Protocol enhancements for 3G/4G cellular wireless networks) and Quality of Service (QoS) and Traffic Engineering for computer and telecommunication networks. He holds an M.Sc. (1999) and a Ph.D. (2002) from the Georgia Institute of Technology both in Electrical and Computer Engineering. He is a member of IET (former IEE), IEEE, ACM, and participates in the Technical Program Committees of several international conferences, such as Globecom, VTC, PIMRC, WNET, EW. He is also an Associate Editor of the Journal of Telecommunication Systems.



Zinon Zinonos completed his undergraduate studies at CEID (Computer Engineering and Informatics Department, U. of Patras) in 2005 and his MSc studies at the Department of Computer Science at the University of Cyprus in 2007. He is currently a PhD student at the Department of Computer Science at the University of Cyprus. In his PhD he is studying mobility issues in sensors networks, sensor applications performance and sensor architectures. His advisor is Dr. Vasos Vassiliou.

He was involved in the IST-funded MOTIVE and the RPF-funded NET6 project and at the moment in the ICT-funded GINSENG. He is a member of IEEE and the Cyprus Scientific and Technical Chamber. His research interests include Mobile Networks (MIPv4, MIPv6, Ad Hoc, Sensors), Wireless Communications (3G/4G cellular wireless networks) and Quality of Service (QoS in IPv6 networks).