A Performance Study of Hierarchical Mobile IPv6 from a System Perspective

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Abstract— **We performed a simulative evaluation of standard Mobile IPv6 in comparison with Hierarchical MIPv6 via *ns-2* for a 'hot spot deployment' scenario. The simulation scenario comprises four access routers and up to 30 mobile nodes that move randomly and communicate in accordance with the IEEE 802.11 wireless LAN standard. The study collected the performance metrics of all mobile nodes from the system. As data traffic video, VoIP and TCP sources were considered. The goal of the study was to obtain quantitative results of the improvements provided by HMIPv6 with respect to handoff latency, packet loss, signaling load and bandwidth per station as well as an indication of the number of users that could be accommodated depending on the traffic source. Moreover, we performed a 'stress-test' of the protocol to investigate the behavior of the protocol in extreme cases, e.g. under channel saturation conditions. In addition to the quantitative results provided, the simulations taught us insights on the protocol performance not easily gained without performing simulations. E.g., we learned that *i)* in our scenario a low HMIPv6 signaling load reduction outside of the micro-mobility domain implies a significant increase within it, *ii)* under high saturation conditions we can expect a better performance of HMIPv6 in latency terms but not in packet losses or bandwidth and *iii)* the consideration of network coverage user unawareness impacts the performance results.**

Keywords— **Mobile IP, IPv6, handoff, simulation, performance evaluation, ns-2**

I. INTRODUCTION

During the last several years a trend towards convergence between Internet and cellular systems using IP as the common network protocol is becoming stronger. As a result, there have been several proposals for IP-based mobility management protocols. The IETF working group on Mobile IP is proposing Mobile IPv4 [1] and Mobile IPv6 [2] as the main protocols for supporting IP mobility. Additionally, some solutions have been proposed in order to extend Mobile IP for environments where the mobile nodes change their point of attachment so frequently that the Mobile IP protocol would result in a high signaling load as well as high handoff latency and severe packet losses. These proposals are referred as *micro-mobility* protocols, see [3] and [4]. On the cellular systems side there is currently an increased interest for providing improved bit rates in hot spot environments, e.g., as can be seen by development of the so-called High Speed Downlink Packet Access (HSDPA) [5]. Mobile IP in combination with the high speed access provided by wireless LANs is a competitor technology candidate to provide high speed access in such scenarios. Therefore, a thorough study of the performance of a wireless LAN Mobile IP based Hot Spot scenario is necessary to assess the suitability of the technology.

In this paper we study the protocol performance of Hierarchical Mobile IPv6 (HMIPv6) in comparison with the baseline Mobile IPv6 (MIPv6) protocol. Apart from measuring signaling load we are primarily interested in evaluating the degradation of service a mobile user observes of a real-time application (e.g., video or voice over IP) or TCP traffic during a handoff. Thus, we are interested in performance metrics like handoff latency, packet loss, and obtained bandwidth per station. The scenario for this study was chosen to resemble a 'building block' of a potential wireless LAN hot spot deployment. It comprises four access router and up to 30 mobile nodes that move randomly and communicate in accordance with the IEEE 802.11 wireless LAN standard. We consider the impact of different parameters like degree of mobility, number of mobile nodes, wired link delay and protocol options over the various performance metrics. Due to the complexity of the required study, simulation was chosen as the most suitable analysis method. We use network simulator *ns-2*. Mobile nodes move according to the Random Waypoint Mobility Model [6].

Previous work on simulative evaluations of Mobile IP almost exclusively dealt with IPv4 networks. Perkins and Wang [7] have used *ns-1* to analyze the effects of route optimization and buffering ('smooth handoff'). Caneel and Lamprecht [8] have designed *ns-2* modules for Cellular IP, HAWAII, and THEMA. The Columbia IP Micro-Mobility Suite [9] comprises *ns-2* modules for Cellular IP, HAWAII, and Hierarchical Mobile IP. An evaluation of Cellular IP is provided by Campbell et al. in [10]. Campbell et al. provide a comparison of IPv4 micro-mobility protocols in [3]. For HMIPv6 there exists an analitycal study that focused on the update signaling messages frequency and is based on an early version of the HMIPv6 internet-draft, see [11].

Because of the significant differences between Mobile IPv6 and Mobile IPv4 as outlined in the following section, results obtained for MIPv4 do not take over for MIPv6. Therefore, in our previous work [12], we performed a detailed study of Mobile IPv6 and a fast handoff procedure. Moreover, previous analysis usually studied a single mobile node without the interference of others. In [12] as well as in this paper a more realistic scenario with more than one mobile node and random movement patterns is considered. Our results show that consideration of an arbitrary number of mobile nodes and random movements significantly impacts the obtained performance results. This paper represents the continuation of a previous study, currently still under reviewing process, where we studied the performance of HMIPv6 from the perspective of a single mobile node following a deterministic path and considering only UDP CBR traffic. On this paper, we have focused on collecting the statistics of all mobile nodes, moving randomly and considering video, VoIP and TCP traffic.

The paper is structured as follows. Section II recalls the basics of MIPv6 and HMIPv6. In Section III we describe the simulation model. Performance aspects subject of interest are given in Section IV. Simulation results are provided in Section V. Finally, Section VI presents some open issues and conclusions.

II. MOBILE IPV6

Mobile IP supports mobility of IP hosts by allowing them to make use of (at least) two IP addresses: a home address that represents the fixed address of the node and a care-of address (CoA) that changes with the IP subnet the mobile node is currently attached to. Clearly, an entity is needed that maps a home address to the corresponding currently valid CoA.

In Mobile IPv4, [1] these mappings are exclusively handled by 'home agents' (HA). A corresponding node (CN) that wants to send packets to a mobile node (MN) will send the packets to the MN's home address. In the MN's home network these packets will be 'intercepted' by the home agent and tunneled, e.g., by IP-in-IP encapsulation [13], either directly to the MN or to a foreign agent to which the MN has a direct link.

In MIPv6, home agents no longer exclusively deal with the address mapping, but each CN can have its own 'binding cache' where home address plus care-of address pairs are stored. This enables 'route optimization' compared to the triangle routing via the HA in MIPv4: a CN is able to send packets directly to a MN when the CN has a recent entry for the MN in its corresponding binding cache. When a CN sends a packet directly to a MN, it does not encapsulate the packet as the HA does when receiving a packet from the CN to be forwarded, but makes use of the IPv6 Routing Header Option. When the CN does not have a binding cache entry for the MN, it sends the packet to the MN's home address. The MN's home agent will then forward the packet. The MN when receiving an encapsulated packet will inform the corresponding CN about the current CoA.

In order to keep the home address to CoA mappings up-to-date, a mobile node has to signal corresponding changes to its home agent and/or corresponding nodes when performing a handoff to another IP subnet. Since in MIPv6 both, HA and CN, maintain binding caches, a common message format called 'binding updates' is used to inform HA and CNs about changes in the point of attachment. Binding updates (BU) can be acknowledged by BU ACKs. Additionally, Mobile IPv6 allows a MN to send a binding update to a MIPv6 agent in the previously visited IP subnet, i.e., establishing forwarding from a previous CoA . Then, packets sent by CNs that have not yet learned the MN's new CoA will be tunneled from the previously visited subnet to the current point of attachment. To acquire a CoA in Mobile IPv6, a mobile node can build on IPv6 stateless and stateful auto-configuration methods. The stateless auto-configuration mechanism is not available in IPv4. In our work, we assume stateless auto-configuration for all tests since with this the mechanism is not necessary to contact any entity to obtain a new CoA, reducing the handoff process duration. For more details on Mobile IPv6 see [2]. In the following, we briefly look at the Neighbor Discovery [14] mechanism, one of the main differences when comparing IPv4 and IPv6.

A. *Neighbor Discovery*

One of the major novelties between IPv4 and IPv6 is the Neighbor Discovery protocol for IPv6. This protocol is used by nodes to resolve the link-layer addresses and keep track of the reachability of their neighbors. Hosts use it as well to locate routers in their link.

A MN, when performing a handover, has to learn the AR's MAC address before being able to inform about the new point of attachment via the BUs. In IPv4 a MN runs the ARP process and has to wait until its completion thus delaying the BUs transmission. On the other hand, the IPv6 Neighbor Discovery protocol optimizes this process obtaining the AR's MAC address from the Router Advertisement. This results in the MN being able to send the BU without any delay after a handover and running the neighbor unreachability detection process in parallel. However, in IPv4, after the ARP process is completed MAC addresses on both sides are obtained. This is not the case for IPv6 where the AR has to run the address resolution process to obtain the MN's MAC address when having to send a packet to it. In fact, in the IPv6 case, when a MN learns a node's MAC address in a different way than the usual Request-Reply exchange or when it wants to send a packet after some time without using the entry, the neighbor unreachability detection has to be launched to resolve the MAC address, but this is a one way process, only one address is resolved.

As mentioned above, the differences between MIPv4 and MIPv6 with respect to signaling and data flow requires separate studies to evaluate overall protocol performance. In this paper, we focus on Mobile IPv6 specific features. We have implemented in *ns-2* the Neighbor Discovery protocol comprising the new functionality explained above plus the Neighbor Cache and the five different states: Incomplete, Reachable, Stale, Delay and Probe. The full Neighbor Discovery specification can be found in [14].

B. *Hierarchical Mobile IPv6*

It is a well-known observation that MNs moving quickly as well as far away from their respective home domain or corresponding nodes produce significant BU signaling traffic and will suffer from handoff latency and packet losses when no extension to the baseline Mobile IP protocol is used. Hierarchical Mobile IPv6 (HMIPv6) is a localized mobility management proposal that aims to reduce signaling load outside a predefined domain. The mobility management inside the domain is handled by a Mobility Anchor Point (MAP). Mobility between separate MAP domains is handled by MIPv6.

The MAP basically acts as a local Home Agent. When a mobile node enters into a new MAP domain it registers with it obtaining a regional care-of-address (RCoA). The RCoA is the address that the mobile node will use to inform its Home Agent and corresponding nodes about its current location. Then, the packets will be sent to and intercepted by the MAP, acting as a proxy, and routed inside the domain to the on-link care-of-address (LCoA) by the MAP. When a mobile node then performs a handoff between two access points within the same MAP domain only the MAP has to be informed. Note, however that this does not imply any change to the periodic BUs a MN has to sent to HA, CNs and now additionally to the MAP.

HMIPv6 presents the following advantages: it reduces the signaling load outside the MAP domain in case of handoffs within the same domain and may improve handoff performance

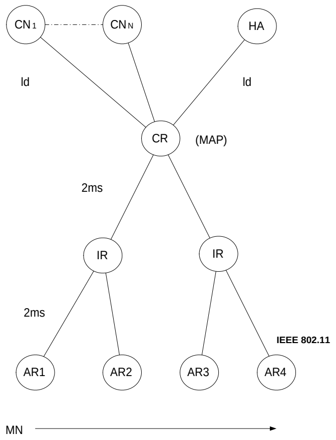

Fig. 1. Simulation scenario

reducing handoff latency and thus packet losses since intra-domain handoffs are performed locally. However, since the periodic BUs are not reduced but the ones due to handoffs the improvement importance depends on the mobility of the mobile nodes. For more details on HMIPv6 the reader is referred to [4].

III. SIMULATION SETUP

The studied scenario was designed in order to be large enough to provide realistic results but to be small enough to be handled efficiently within *ns-2*. The chosen scenario, depicted in Figure 1, is composed by the Home Agent and the Correspondent Nodes that are connected via the 'Internet' (modeled by adjusting the link delay *ld*) to a central router (CR). Four access routers (AR) –each one representing a different IP subnet– are connected via two intermediate routers (IR) to the central router. When Hierarchical MIPv6 is considered the functionality of the Mobility Anchor Point is placed on the central router and the CR, IRs,and ARS form the micro-mobility domain. At simulation start the mobile nodes are uniformly distributed over the coverage area.

The access routers have been positioned in a way to provide total coverage to an area of approximately 700×700 square meters considering a transmission range of 250 meters, see Figure 2. The mobile nodes move randomly within the coverage area following the random waypoint mobility model [6]. This model has been previously used mainly for ad-hoc simulations but it is well suited as well also for our purposes as we will explain in Section V. As wireless medium the 2Mbps Wireless LAN 802.11 DCF [15] provided by *ns-2* [16] is used. The access routers use the same frequency band since no roaming process is standardized for 802.11 and thus, roaming protocols are proprietary.

Within the micro-mobility domain each wired connection is modeled as a 5Mbps duplex link with 2ms delay. The 'Internet' connecting the central router and the HA or CNs is modeled also as a 5Mbps duplex link with a default link delay (ld) of 10ms. In the simulations, the *ld* value has been varied to model various 'distances' between the MNs and the HA and CNs.

In order to simulate a realistic case where a MN will receive packets from the shared AR queue and where a MN will also compete with other MNs and with an AR to access the channel, half of the MNs receive data from the CNs and the other half send data to the CNs. The CNs sending to the MNs introduce delay in the AR queue and the MNs sending to the CNs introduce delay in the wireless link. The study though focuses on the MNs receiving data from the CNs since the purpose is to analyze the degradation of the experienced quality of service due to mobility.

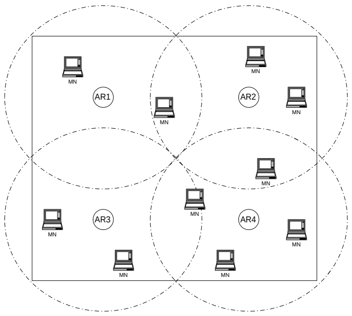

Fig. 2. Access routers distribution

In our simulations different types of traffic will be simulated. As a streaming application for real-time video traffic we have used a real H.263 [17] video encoding provided by [18]. The encoded video corresponds to the film "Star Trek: First Contact" for a target bit rate of either 256 or 64 kbps. The obtained frame sizes (in bytes) of the individual encoded video frames are used as input for the *ns-2* video traffic application. Since these traces include only the raw packetized video, additional streaming protocol overhead has been added. We considered a 12 byte RTP header plus 8 byte UDP header and plus 40 byte IPv6 header as the streaming protocol overhead.

One of the applications expected to be used with MIPv6 is VoIP. We have implemented a VoIP model based on [19]. The model assumes silence suppression and models each voice source as an on-off Markov process. The alternating active *on* and silence *off* periods are exponentially distributed with average durations of 1.004 and 1.587 s. As recommended by the ITU-T specification for conversational speech [20], an average talk spurt of 38.57% and an average silence period of 61.47% is considered. A rate of 88 kbps[1] in *on* periods and 0 kbps in *off* periods is assumed for a voice source that generates CBR traffic.

TCP is the most widely used transport protocol. We simulate endless FTP sources to understand the impact of IP mobility on the congestion control mechanism of TCP using the different protocols.

The simulation code used for the experiments was designed on top of INRIA/Motorola MIPv6 MIPv6 [21] code for *ns-2* [16] implementation. We have extended the code with two main modules: Neighbor Discovery and Hierarchical Mobile IPv6. Some modifications have been done to the original release in order to extend the code to work with more than one mobile node.

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[1] Assume 8KHz 8 bits/sample PCM codec was used with 20 s frame per packet. With 12 byte RTP header, 8 byte UDP header and 40 byte IPv6 header, the size of each voice packet is 220 bytes. The bandwidth required will be (220 x 8)/20=88kbps

IV. PERFORMANCE METRICS

The purpose of the performance evaluation is to check the improvements that users would experience in a system using HMIPv6 in comparison to standard MIPv6. HMIPv6 aims to make local handoffs transparent to Mobile IPv6 entities, e.g. HA and CNs, outside of the micro-mobility domain and thus reduce the signaling load. Additionally, because generally the Mobility Anchor Point is closer to the MN than the HA or CNs, the entity responsible to forward the traffic reacts faster which in turn can reduce handoff latency and packet losses. The obtained bandwidth experienced by the stations which is influenced by handoff latency and packet losses is also studied. The parameters to be studied are as follows:

Handoff Latency: Handoff latency is defined for a receiving MN as the time that elapses between the last packet received via the old route and the arrival of the first packet along the new route after a handoff. Latency is an important parameter for delay sensitive applications like video or VoIP that could suffer from a period with a higher rate of packet drops due to a long latency time. This packet drop period would result in a flickering image for a video application or in a noticeable disruption in the voice transmission for VoIP. We study handoff latency for various values of link delays ld, for different video rates and for an increasing number of mobile nodes.

Packet Loss: Packet loss is defined for a receiving MN as the number of packets lost during the handoff. While usually one assumes that packet losses are directly proportional to latency it will be shown that this is not true in some cases. We have studied separately the packet losses due to the process of address resolution and packet losses in the previous access router. We study packet losses for various values of link delays ld, for different video rates and for an increasing number of mobile nodes.

Signaling Load: We study the signaling load due to sending of BUs and BACKs. The number of BUs and BACKs sent differs for MIPv6 and HMIPv6. We study the signaling load for various handoff rates (number of handoffs per minute) and differentiate between signaling load within or outside the micro-mobility domain.

Bandwidth per Station: We study the probability to obtain the required bandwidth and the corresponding expected variance for an increasing number of competing stations and for different kinds of traffic: video, VoIP and TCP.

Note that the whole set of performance metrics have been obtained for each scenario but only the most relevant results have been included.

V. PERFORMANCE EVALUATION & DISCUSSION

With our *ns-2* simulations we study the parameters explained in Section IV for the scenario described in Section III. We analyze the degradation of the performance metrics from a system point of view, i.e. collecting the statistics of the whole set of mobile nodes moving randomly instead of focusing in a single mobile node following a deterministic path. A main difference of this scenario is the impact of unexpected movements over the studied parameters. Note that unexpected movements can have a quite negative effect on the experienced quality of service due to back and forth movements around the overlapping areas, more details will be given in Section V-D. All mobile nodes follow the random waypoint mobility (RWP) model which is well-suited to represent movements of mobile users in campus or hot-spot scenario at moderate complexity.

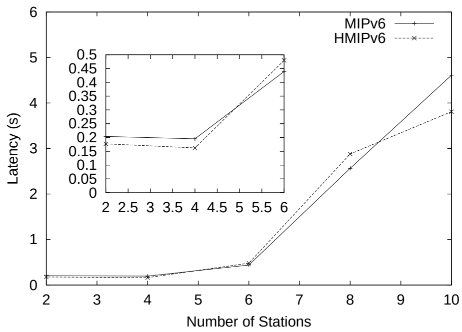

Fig. 3. Impact of number of stations on handoff latency, 256 kbps

We have chosen the video source as the most suited to make a ’stress-test’ of the protocols since it’s the one that requires a higher bit rate from the wireless channel. Therefore, it will be used as the default source when no otherwise indicated. The differences between MIPv6 or HMIPv6 usage for video, VoIP and TCP sources are studied in Section V-E.

All simulations have a duration of 125 seconds with a 5 seconds warm-up phase All the points in the following graphs represent the average of 100 simulations.

We assume a system where mobile nodes use the IPv6 stateless address auto-configuration feature performing Duplicate Address Detection (DAD) in parallel to avoid the introduction of an additional delay to the handoff process. Note that the delay introduced by DAD would be too time consuming resulting in a noticeable disruption of the service.

A. Impact of number of stations

We have studied the impact of the number of competing stations in the shared medium on handoff latency and packet loss for two target rates of the video sources: 256 and 64 kbps. The 256 kbps video source is an ’intensive’ source that allows the study of the protocols at higher detail since the transmission rate is higher. On the other hand, the 64 kbps source provides still a high detail but it allows the study of a higher number of mobile nodes in the system.

Figure 3 shows the increase in handoff latency due to an increase in the number of MNs sharing the wireless channel for the 256 kbps case. We can observe that HMIPv6 performs almost always better or equal than standard MIPv6, as expected, since the wired ‘distance’ in order to update the respective agent that forwards packets to the mobile node is always shorter. For a small number of MNs, e.g., 5 or below, the dominating factor for handoff latency is the wired delay not the wireless one. Therefore, the latency obtained with HMIPv6 is smaller compared to the MIPv6 one. However, for a higher number of MNs the wireless delay becomes more and more important decreasing the handoff latency advantage of using HMIPv6. However, when the wireless delay becomes very high due to saturation in the channel, e.g., 10 stations case, we see again a better performance of HMIPv6 due to two reasons. First, only one BU is sent

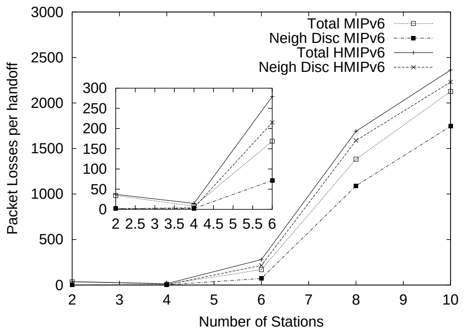

Fig. 4. Impact of number of stations on packet losses per simulation, 256 kbps

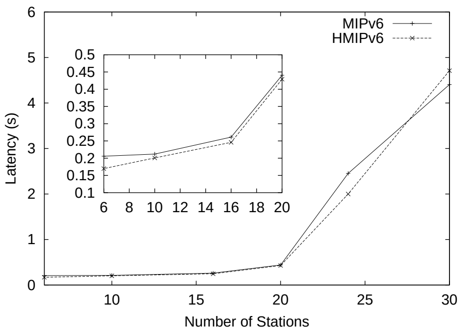

Fig. 5. Impact of number of stations on handoff latency, 64 kbps

to the MAP in the HMIPv6 case while MIPv6 sends a BU to the HA and afterwards one to the CN, i.e., introducing an additional wireless delay. This difference could be removed sending the BU first to the CN and then to the HA. Second, while the BAcks to HA and MAP BUs are mandatory, the BAck to the CN BU is optional. In our implementation BAcks to CN BUs are not sent to avoid additional overhead. Under high saturation channel conditions the probability of a BU to be lost is increased, therefore, when using standard MIPv6 if a BU to the CN is lost[2], it is not retransmitted, increasing significantly the latency value. On the other hand, when the BU to the MAP is lost it will be retransmitted after a one-second timeout without receiving the corresponding acknowledge. An exceptional case can be observed for 6-8 MNs where MIPv6 shows a slightly better performance than HMIPv6. Due to the encapsulation that HMIPv6 always does from the MAP to the current point of attachment, we have a higher load to the channel, i.e. 40 additional bytes per packet, and thus the saturation throughput is reached earlier by HMIPv6.

In principle, one would expect a direct relationship between handoff latency and packet losses. In Figure 4 we can see that this is not the case. From the graph we can observe that for up to 4 stations the usage of HMIPv6 results in similar packet losses compared to MIPv6. However, when the number of MNs increases the total number of packet losses is higher for HMIPv6 than for MIPv6. In order to understand this effect we have differentiated between packets lost at the previous AR –the MN is no longer there to pick them up – and packets lost at the new AR due to Neighbor Discovery, i.e., address resolution[3]. The usage of HMIPv6 shows similar packet losses at the previous access router even though the updating ‘distance’ is shorter than for MIPv6 due to the unexpected movements which reduce the importance of the optimization. On the other hand, the number of packets lost with HMIPv6 due to Neighbor Discovery are larger than for standard MIPv6 as can be seen as follows. When performing a handoff with standard MIPv6 the MN first sends a BU to the HA and immediately after (one wireless delay) to the CN. The first packet that arrives to the new AR triggering the address resolution process of neighbor discovery (see Section II-A) is the BAck from the HA and the first data packets arrive to the new AR after a wireless delay. However, if HMIPv6 is used, after performing a handoff the mobile node will send a single BU to the MAP which will send the corresponding BAck followed *without* delay by the next data packets. Since in this case there is no delay between the packet that triggers the address resolution process and the next ones all the packets that will arrive during this process once the buffer for this address is full will be dropped. Therefore, when the number of MNs increases the address resolution process takes longer and more packets are lost due to Neighbor Discovery. A strange behavior can be observed in the range from 2 to 4 mobile nodes where the packet losses instead of experiencing an increase, decrease. In fact, if a mobile node enters in an overlapping area, performs a handoff informing about its new location and immediately after moves back to its previous location, until the handoff algorithm realizes that a new handoff is necessary all packets will be routed to the wrong care-of-address. Therefore, when the number of mobile nodes is low, the impact of the back and forth movements due to random movements is higher since the updates about the new point-of-attachment are faster.

Figure 5 corresponds to the handoff latency for the 64 kbps case. It shows the same behavior described previously for the 256 kbps case but arriving to the saturation conditions with a higher number of stations, as expected. The packet losses graph has not been included here for space reasons since it presents the same characteristics as Figure 4.

For the following studies we have focused on the case of 64 kbps and 16 MNs since this represents the case where the channel can be accessed without experiencing a high degradation in the quality of service due to competing nodes with a quite large number of mobile users.

B. Impact of handoff rate

The main purpose of HMIPv6 is to keep constant the signaling load outside of the micro-mobility domain when the number of handoffs increases. We have performed a simulation increasing the handoff rate by increasing the maximum speed of the mobile nodes. Figure 6 shows the relationship between maximum speed and number of handoffs. We cover maximum speeds from 5 m/s, e.g. pedestrian, until 25 m/s (90 km/h), e.g. vehicles.

Figure 7 shows that the goal of HMIPv6 is achieved. On the other hand, HMIPv6 increases the signaling load within the micro-mobility area. This is a coherent result as we can see

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[2] IEEE802.11 realizes when a packet was not correctly transmitted over the wireless medium due to the lack of a MAC layer acknowledgment and re-tries the transmission eight times before discarding it.

[3] During the address resolution process only a small amount of packets are buffered for the same destination address, e.g. three in our implementation [14].

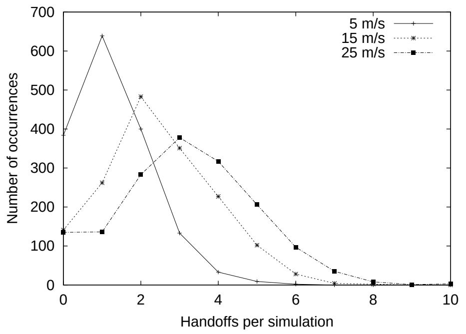

Fig. 6. Histogram of number of handoffs per simulation

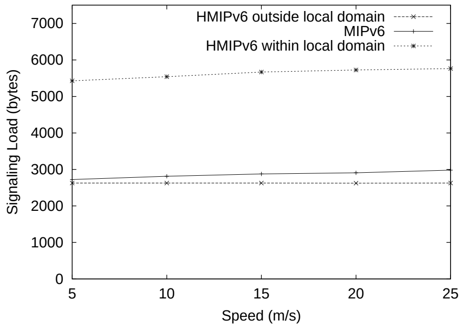

Fig. 7. Impact of handoff rate on signaling load

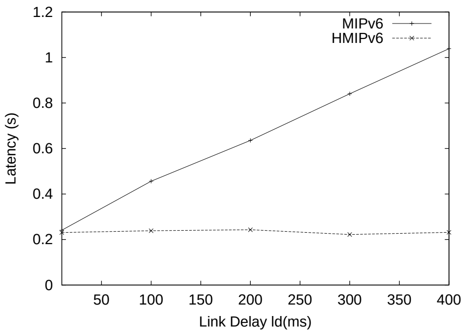

Fig. 8. Impact of wired link delay on latency

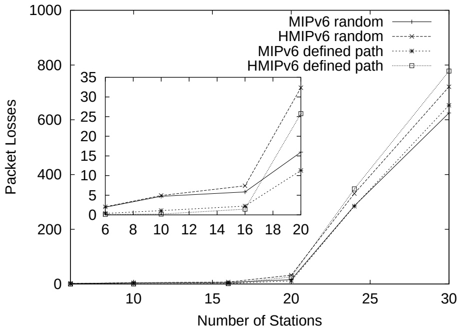

Fig. 9. Impact of random movements on packet losses

as follows. When roaming within the local domain, HA and CNs do not realize any change in the point of attachment and receive the BUs periodically, therefore the signaling load is constant outside the local domain. However, with standard MIPv6 whenever a MN performs a handoff the periodic BUs are rescheduled and thus, an increase in the number of handoffs can imply a reduction in the number of periodic BUs. Since with HMIPv6 the handoffs within a micro-mobility area are transparent to the HA and CNs, the periodic BUs are not re-scheduled, and therefore an increase in the number of handoffs does not imply a reduction in the number of periodic BUs. Additionally, the implementation of HMIPv6 results in an increase in the number of periodic BUs sent in the micro-mobility domain, i.e., additional one sent to the MAP plus BAck, and the BAcks originated by the HA have to be encapsulated which increases the signaling load. Another aspect to be considered is that if a MN has more than one CN, when a handover is performed the number of sent BUs increases linearly with the number of CNs for standard MIPv6 while it remains constant for HMIPv6. As a conclusion, the HMIPv6 saved signaling load within the local domain heavily depends on the number of CNs per MN and the number of handoffs peformed until the periodic BU timer fires, when these values are low HMIPv6 could perform worse than standard MIPv6 in signaling load terms while when they increase more signaling load is saved with HMIPv6. Note that, in our scenario, the signaling load due to the handoffs only contributes a marginal part to the overall load.

C. Impact of wired link delay

Hierarchical Mobile IPv6 eliminates the necessity of informing outside of the micro-mobility domain about the new point of attachment when performing a local handoff. Therefore, we have computed the differences between MIPv6 and HMIPv6 in handoff latency and packet losses when the wired link delay *ld* from the CR to the HA and CN is increased. The different *ld* values model different 'distances' to the HA and CNs. As we can see in Figure 8 even considering random movements HMIPv6 accomplishes one of its expected goals, while an increase in the wired link delay implies an increase in the handoff latency for Mobile IPv6 it does not affect Hierarchical MIPv6 handoff latency. The packet losses graph directly corresponds to the handoff latency one so we do not include the results here.

D. Impact of random movements

Mobile users are unaware of overlapping areas where handoff decisions are taken. This section studies the difference on the performance metrics between a user following a defined path and users moving randomly. Figure 9 shows packet losses due to handoffs for mobile nodes moving random compared to one mobile node following a defined path. We can observe that in no saturation conditions the mobile node following a pre-defined path experiences lower packet losses compared to the random ones since the back and forth movements result in a higher packet loss rate. However, when the wireless channel suffers saturation the packet losses for the random movement users are lower. The reason is that the impact of BUs lost due to saturation on users following a defined path is higher compared to users moving randomly since due to their back and forth movements more BUs, i.e. in principle unnecessary, are sent decreasing the impact of lost BUs.

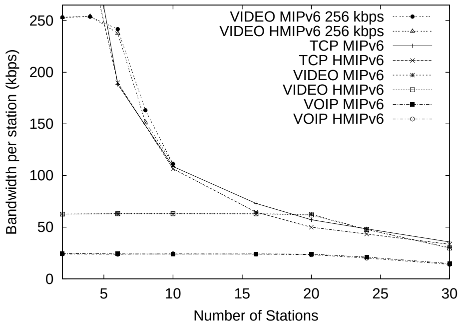

Fig. 10. Impact of traffic sources on received bandwidth per station

E. *Impact of traffic sources*

Section V-A has shown the handoff latency and packet losses behavior with MIPv6 and HMIPv6 when the number of mobile nodes increases. In this section we study the impact of the number of stations over the *receiving* stations for three different types of traffic: H.263 video, VoIP and TCP. As we can observe from Figure 10 the 256 kbps video sources experience a degradation of the received bandwidth from 4 stations on, as expected, since in the next point the saturation throughput is reached. For the 64kbps case no more than 16 mobile nodes could receive the desired bandwidth. TCP sources show the adaptation of the sending rate to the available channel capacity when the number of mobile users increases. For the case of VoIP, even though we would expect that a higher number of mobile users could be accommodated due to the lower sending rate we obtain a number of users similar to the 64 kbps video case, 20 mobile nodes. The reason is the burstiness of the VoIP sources. We can observe that the differences in received bandwidth between MIPv6 and HMIPv6 correspond to the packet losses results in Section V-A, i.e. HMIPv6 reaches earlier the saturation throughput and presents a smaller received bandwidth due to the MAP encapsulation.

VI. CONCLUSIONS AND FUTURE WORK

During the design process of an IPv6-based wireless access network the question of whether or not to implement Hierarchical Mobile IPv6 it's likely to arise. In this paper we have provided quantitative results on the improvement degree one can expect by using Hierarchical Mobile IPv6 instead of pure Mobile IPv6 in a 'hot spot'-like IEEE 802.11-based scenario with four access routers and up to 30 mobile nodes. We performed a 'stress test' of the protocol where we studied how handoff latency, packet loss, and obtained bandwidth are affected by the number of mobile nodes, i.e. by competition for the wireless medium, or by different traffic sources, e.g. video, VoIP and TCP, or by protocol interactions, e.g. with the Neighbor Discovery process of IPv6.

These factors were shown to influence the packet loss rate of HMIPv6, and we indicated the points that can be improved in an implementation. Handoff latency values of HMIPv6 outperformed the ones from MIPv6 in almost every case. We also quantitatively studied the trade-off between HMIPv6 signaling load reduction outside of the HMIP domain and the increase within. Furthermore, we provided and indication on the number of users that could be accommodated in our system depending on the considered traffic and showed the impact over the performance metrics of defined path mobility in comparison with random movements. The study via simulation required to implement HMIPv6 and Neighbor Discovery for *ns-2*.

Clearly, our results take over also for IEEE802.11 variants with higher bit rates when the values are adjusted accordingly with respect to the point where saturation throughput is achieved.

In our future work we include header compression in order to judge the protocol overhead on the wireless link in a fair manner and in order to understand the corresponding protocol interactions with respect to the performance metrics analyzed in this study.

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