A Performance Study of Fast Handovers for Mobile IPv6

Marc Torrent-Moreno
Network Laboratories
NEC Europe Ltd., Germany
torrent@ccrle.nec.de

Xavier Pérez-Costa
Network Laboratories
NEC Europe Ltd., Germany
perez@ccrle.nec.de

Sebastià Sallent-Ribes
Universitat Politècnica
de Catalunya (UPC), Barcelona
sallent@mat.upc.es

Abstract

We conducted a simulative evaluation of the overall performance of Fast Handovers for Mobile IPv6 in comparison with the baseline Mobile IPv6 using the network simulator ns-2 for a 'hot spot' deployment scenario. The simulation scenario comprises four access routers and up to 50 mobile nodes that move randomly and communicate in accordance with the IEEE 802.11 wireless LAN standard. The study provides quantitative results of the QoS improvements obtained by FMIPv6 with respect to handoff latency, packet loss rate and bandwidth per station. The simulation environment allowed us also to investigate the behavior of the protocol in extreme cases, e.g. under channel saturation conditions and considering different traffic sources: CBR, VoIP, Video and TCP transfers. As a complementary part of the study, the signaling load costs associated to the performance improvements provided by the enhancement proposal was analysed. While some simulation results corroborate the intention of the protocol specification, other results give insights not easily gained without performing simulations.

1 Introduction

The fast introduction of cellullar systems on our normal life in addition to the wide usage of Internet has resulted in a convergence trend towards the support of Internet mobile users. 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, latency and packet losses issues due to Mobile IP handoff have been discussed in the IETF resulting in several proposals [3, 4]. *Fast Handovers for Mobile IPv6* [4] is the current Mobile IPv6 extension proposal to smooth the quality of service degradation that a mobile user would experience due to a change in its point-of-attachment. 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 the 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 overall 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 Fast Handovers for Mobile IPv6 (FMIPv6) in comparison with the baseline Mobile IPv6 (MIPv6) protocol. We are primarily interested in evaluating two parameters: the degradation of quality of service a mobile user perceives during a handoff when receiving a data stream (e.g., video or voice over IP) and the signaling load costs associated with Mobile IPv6 and its enhancement. Thus, we are interested in performance metrics like handoff latency, packet loss rate, obtained bandwidth per station and signaling load. Moreover, the impact of different traffic sources is studied: CBR, video, VoIP and TCP transfers.

The scenario chosen for this study resembles a 'building block' of a potential wireless LAN 'hot spot' deployment. It comprises four access routers and up to 50 mobile nodes that move randomly and communicate in accordance with the IEEE 802.11 wireless LAN standard. The mobility model used for the random movement is the Random Waypoint Mobility Model [6]. We consider the impact of different parameters like number of mobile nodes, handoff rate, number of correspondent nodes, wired link delay, random movement and protocol options over the various performance metrics. Due to the complexity and broadness of the required study, simulation was chosen as the most suitable analysis method. As simulation tool we used the network simulator *ns-2*.

Regarding related work about Fast Handovers for Mobile IPv6, a protocol overview of FMIPv6 is provided in [10] but the obtained results are restricted to the case of the handoff latency for MIPv6, excluding FMIPv6 and considering only the interference of up to 4 *static* users. In [11] Mobile IPv6 and FMIPv6 are studied but the results are limited to TCP handoff latency and obtained bandwidth of a single user following a deterministic path without the interference of other users. Moreover, a key aspect of IPv6, the Neighbor Discovery protocol, was not implemented, which could have a relevant impact on the results, as explained in Section 2.1 and shown in 4.1.

In contrast to the related literature, in our previous work [12, 13] we performed a detailed study of Mobile IPv6 and Hierarchical Mobile IPv6 focusing not only on handoff latency but studying also the packet loss rate, the experienced bandwidth, the associated signaling load costs and considering the impact of different system parameters, e.g, handoff rate, traffic source type, protocol options, etc. Moreover, previous analyses usually studied a single mobile node without the interference of others. In our work [12, 13], as well as in this paper a more realistic scenario with up to 50 mobile nodes and random movement patterns is considered. The results provide a complete picture of the overall system performance studying not only the metrics that FMIPv6 is supposed to improve but also its effect over other network metrics relevant to the system performance and show how is it influenced by the different studied parameters.

The rest of the paper is structured as follows. Section 2 recalls the basics of Neighbor Discovery and FMIPv6. In Section 3 we describe the simulation model. Simulation results are provided in Section 4. Finally, Section 5 summarizes the conclusions.

2 Mobile IPv6

2.1 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 Access Router's (AR) 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, delaying thus 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. Note that in both cases, addresses will be resolved in parallel while sending packets, then no delay is added. Besides, some channel utilization can be saved if confirmation of reachability is received from upper layers.

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 [15].

2.2 Fast Handovers for Mobile IPv6

To prevent the quality of service degradation that a mobile node could suffer due to a change in its point of attachment *Fast Handovers for Mobile IPv6* has been proposed [4]. In the draft two different mechanisms are described: anticipated and tunnel-based handover. Tunnel-based handover relies on L2 triggers to potentially obtain better results than Anticipated Handover, introducing though a L2 dependence that could make the solution unfeasible for some L2 technologies. In principle, a L2 independent solution would be a more desirable solution. Therefore, we have focused on the performance study of the *Anticipated Handover* proposal, which is solely based on L3 information.

Anticipated Handover proposes a 'make-before-break' approach. When a MN has predictive information about the next point of attachment to which the MN will move, e.g. reception of a Router Advertisement from a new AR (nAR), it sends a Router Solicitation for Proxy (RtSolPr) to the old AR (oAR) with an identifier of the attachment point to which it wants to move. Once the oAR receives information that a MN wants to move to a nAR, it constructs a nCoA based on the MN's interface ID and the nAR's subnet prefix. It then sends a Proxy Router Advertisement (PrRtAdv) to the MN containing the proposed nCoA and the nAR's IP address and Link Layer Address. At the same time, the oAR sends a Handover Initiate (HI) message to the nAR, indicating the MN's oCoA and the proposed nCoA. Upon receipt of the HI message, the nAR first establishes whether the nCoA is a valid address on its subnet, performing checks to ensure that it is not a duplicate. If the nCoA is accepted by the nAR, the nAR adds the nCoA to the Neighbor Cache for a short time period so it can defend it. The nAR then responds with a Handover Acknowledge (HACK), indicating that the proposed nCoA is valid. In case the nCoA is not valid (duplicated address) the nAR adds a host route for the oCoA pointing to its mobility interface, for a short time period and responds to the oAR with a HACK indicating that the proposed nCoA is not valid. Upon receipt of the HACK, if the HACK indicates that the nCoA is valid, the oAR prepares to forward packets for the MN to the nCoA. If the HACK indicates that the nCoA is not valid, the oAR prepares to tunnel packets for the MN to the oCoA at nAR. As soon as the MN received confirmation of a pending Layer 3 handover through the PrRtAdv and has a nCoA, it sends a Fast Binding Update (F-BU) to oAR, as the last message before the Layer 2 handover is executed.

On receipt and validation of the F-BU, the oAR responds with a Fast Binding Acknowledgement (F-BAck), destined to the nCoA. The oAR waits for a F-BU from the MN before actually forwarding packets. On receipt of the F-BU, the oAR forms a temporary tunnel for the lifetime specified in the F-BAck, and the F-BAck is sent through the tunnel to the MN on the new link. When the MN arrives on the nAR and its Layer 2 connection is ready for Layer 3 traffic, it sends a Fast Neighbor Advertisement (F-NA) to initiate the flow of packets that may be waiting for it. The nAR will deliver packets to the MN as soon as it receives an indication that the MN is already attached to it, usually receiving a F-NA from the mobile node. The oAR is responsible for forwarding any packets that arrive for the MN under its oCoA after the MN has moved. For more details about Fast Handovers for Mobile IPv6 see [4].

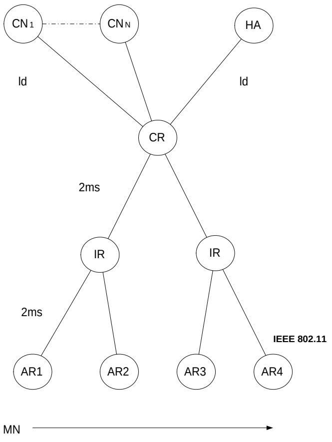

Figure 1. Simulation scenario

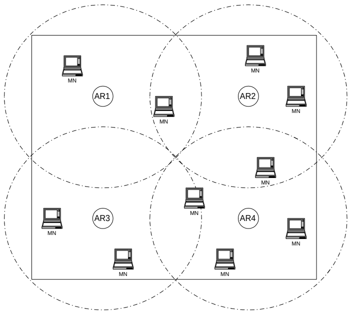

Figure 2. Access routers distribution

3 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. 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 4. As wireless medium the 2Mbps Wireless LAN 802.11 DCF [16] provided by *ns-2* [17] 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[1].

Within the local 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.

While moving within the overlapping area, the mobile nodes are able to send/receive data only via the access router that corresponds to their current care-of address. Technologies like 802.11 allow the mobile nodes gathering information about the neighboring access routers, but do not allow to receive IP flows with different destination addresses or at different frequency bands simultaneously from two access routers, except for particular cases like having an additional wireless interface.

In order to simulate a realistic case where a MN will receive packets from the shared AR queue and where a MN

---

[1] A recent study has concluded that the 802.11 beacon scanning function may take several hundred milliseconds to complete, during this period sending and receiving IP packets is not possible [18]

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.

In our simulations two different scenarios will be considered. First, the performance of a single mobile node following a deterministic path while all other mobile nodes move randomly is studied. This scenario allows for a comprehensive study of the impact of different parameters over the quality of service experienced by the studied mobile node considering the interference of other mobile nodes moving randomly but avoiding to take into account in the measurements the effect of the studied mobile node random movement. In the second scenario the studied mobile node moves randomly, too. By doing this, we can analyse the impact of considering random movement for the studied mobile node over the performance metrics separately, which facilitates the study and comprehension of the impact of the different parameters over the various protocols.

The first type of sources used in our simulations will be UDP CBR sources. UDP Constant Bit Rate (CBR) sources provide constant traffic where no acknowledgments are required. This kind of traffic is usually generated by real-time applications and due to its deterministic characteristics, without recovery mechanisms, eases the protocols study and comparison. This will be the traffic source generally used in our performance evaluation.

As a streaming application, for real-time video traffic we have used a real H.263 [19] video encoding provided by [20]. 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 [21]. 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 [22], an average talk spurt of 38.57% and an average silence period of 61.47% is considered. A rate of 88 kbps[2] 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 enhanced solution.

The simulation code used for the experiments was designed on top of INRIA/Motorola MIPv6 [23] code for *ns-2* [17] implementation. We have extended the code with two main modules: Neighbor Discovery and Fast Handovers for 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.

4 Performance evaluation & discussion

We analyze the degradation of the performance metrics from the point of view of a single mobile node that follows a deterministic path while all other mobile nodes in the system follow the random waypoint mobility (RWP) model. In Section 4.5 the random movement of the studied mobile node is considered.

The RWP model is well-suited to represent movements of mobile users in campus or hot spot scenario at moderate complexity. The mobile nodes move according to a modified *ns-2* random waypoint model. With the random waypoint mobility model provided by *ns-2*, a node selects a target location and a speed (sampled uniformly from an interval $[0, v_{max}]$) and moves linearly towards the target location with the selected speed until a specific timer fires. When the timeout occurs, the mobile nodes restart the procedure. When no other value is indicated, all the simulations have been performed with a maximum speed of 5m/s.

We have chosen a UDP probing traffic from the CN to our specific mobile node of 250 bytes transmitted at intervals of 10 ms. The other mobile nodes create background traffic sending or receiving data at a rate of 32 kbps.

All simulations have a duration of 125 seconds with a 5 seconds warm-up phase. Each point in the following graphs represent the average of at least 100 simulations. The sample size necessary to achieve a confidence interval of 99% with respect to the average value has been selected as indicated in [24]. This required in some cases to perform up to 1000 simulations, e.g., in the 50 mobile nodes or random movement case.

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

---

[2] 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

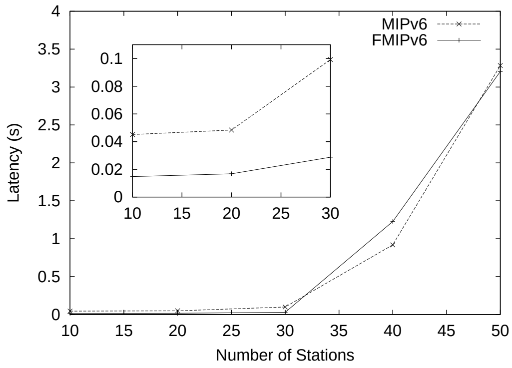

Figure 3. Impact of number of stations on handoff latency

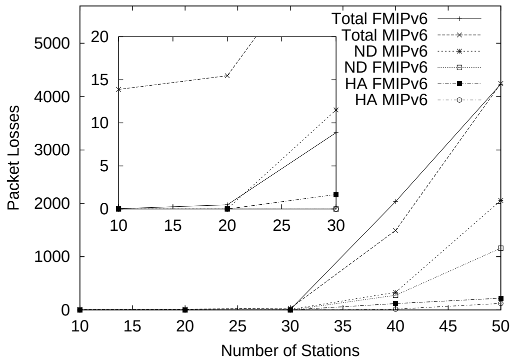

Figure 4. Impact of number of stations on packet losses

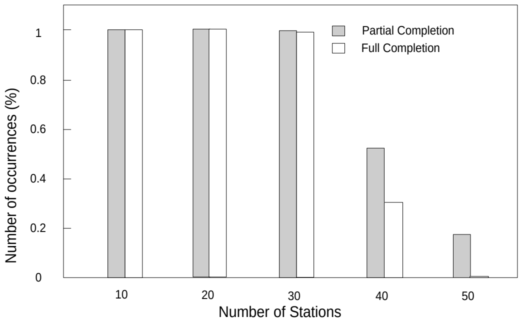

Figure 5. Fast handover performance histogram

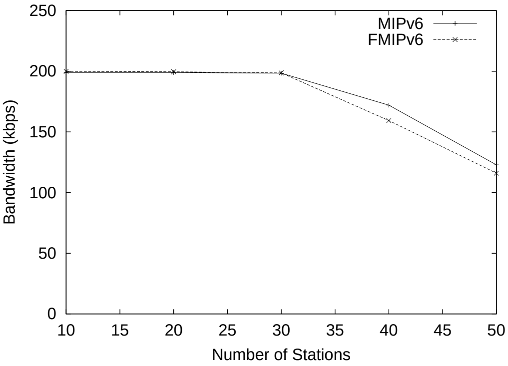

Figure 6. Impact of number of stations on bandwidth

consuming resulting in a noticeable disruption of the service.

4.1 *Impact of number of stations*

We present here the results of the impact of the number of competing stations on the following parameters: handoff latency, packet loss, obtained bandwith and the fast handoff process probability of success.

The studied MN performs 4 handoffs during a simulation run moving at 10 m/s from center to center of the AR's coverage areas until it reaches again the starting point. The values represented in the graphs are the ones corresponding to the analyzed MN.

We can observe that the usage of FMIPv6 results in a better performance for all the parameters up to 30 MNs, as expected. Until this point, FMIPv6 meets its goal of reducing handoff packet loss and latency. Figure 3 shows the increase in handoff latency due to an increase in the number of MNs sharing the wireless channel. FMIPv6 performs better than standard MIPv6, since the MN, after a handoff, does not have to wait for the HA or CN to be updated to start receiving packets again. With FMIPv6 packets are redirected by the oAR to the nAR through the wired link and thus only this delay is noticed. Based on this, Figure 4 shows how FMIPv6 packet losses are insignificant in front of MIPv6 ones.

On the other hand, although the Fast Handover protocol is designed to minimize packet losses and latency during a handoff, we can observe a worse performance with respect to MIPv6 in high load conditions. To understand this behavior a few factors must be considered. In the scenarios with 30 or more MNs the load in the wireless channel is high, resulting in a channel with a long access time and high collision rate. If we take a look at the packets lost due to the neighbor discovery (ND) process, Fig.4, we can see that they are higher when FMIPv6 is not used (the double with 50 MN). Those packets, that are dropped in the ND entry queue, are not sent through the wireless channel, what results in a lower channel load for the MIPv6 case and, what is more important, a shorter access delay. In the FMIPv6 scenario though, the nAR learns the LL address of the MN before having to send a packet to it (via the reception of the HI by the nAR) even if the FMIPv6 process has not been succesfully performed. Therefore, the AR will send packets to the channel without waiting the address to be confirmed resulting in a lower packet loss rate in the AR's ND queue but introducing a higher load on the channel. Another factor that yields the FMIPv6 worse performance in high load conditions is its additional signaling load in the local domain, as will be shown in section 4.2, which results in FMIPv6 reaching earlier the saturation level on the wireless channel. A good measure of whether the route updating mechanisms are working properly are the packet losses at the HA. Packet are lost in the HA only when the BU lifetime of both, CN and HA, has expired. As it can be seen in Figure 4 the higher load for the FMIPv6 case produces a higher rate of packet losses at the HA for 30 or more MNs, which corroborates the arguments commented above.

Once the saturation level has been reached by both protocols, if we increase the number of MNs the performance metrics tend to converge since for both cases the wireless channel presents a high collision rate and long channel acces time reducing thus, the impact of the differences between both approaches. Figure 5 shows that up to 30 MNs the wireless channel conditions allows for a proper completion of the fast handoff process. However, for a higher number of MNs the probability of the process success decreases dramatically. This result justifies the bad performance shown by FMIPv6 above the 30 MNs case. We have differentiated between two cases: full completion of the fast handoff process and partial completion, meaning that the redirection of the traffic from the oAR to the nAR has been established. We believe that the latter case is a significant value since it means that the FBACK packet has been lost but not the previous FMIPv6 corresponding messages, resulting in a smoother handoff compared to MIPv6.

Figure 6 corresponds to the bandwidth obtained by our specific mobile node. As we can see, the bandwidth matches almost perfectly the results shown for packet losses. The slight difference appreciated between both graphics (in the 40 and 50 MN case), is a consequence of the higher wireless load for FMIPv6. A higher signaling load and data packets sent through the wireless channel yields a longer channel access delay and higher collision rate, resulting in a higher number of packets waiting to be sent in the current MN's AR interface queue when the simulation ends.

For the following studies we have focused on the case of 20 MNs since this represents the case where the cannel can be accessed without experiencing a high degradation in the quality of service due to competing nodes.

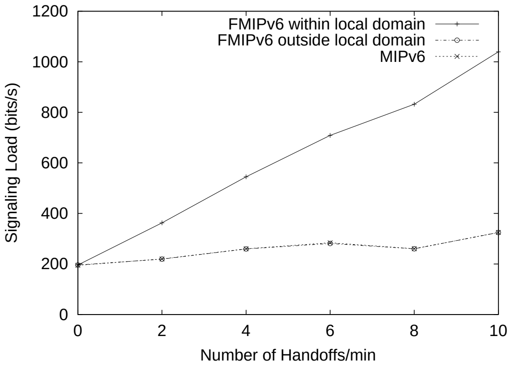

Figure 7. Impact of handoff rate on signaling load

4.2 *Impact of handoff rate*

In Section 4.1 we have shown that the aim of FMIPv6, reduction of handoff latency and packet loss is achieved if the wireless channel is not saturated. However, several additional signaling messages have been introduced to achieve those results. A trade-off between additional signaling load and handoff latency and packet loss improvements has to be considered. In Figure 7 we studied the differences in signaling load between MIPv6 and the proposed enhancement, FMIPv6, for a handoff rate range varying from 0 to 10 handovers per minute. As expected, the signaling load outside of the local domain is the same for both approaches and thus, the difference inside the local domain is due to the additional FMIPv6 messages. As we can observe, already in the case of performing 4 handoffs per minute, the signaling load within the local domain is more than the double for the FMIPv6 case. This is a coherent result with the results presented in Section 4.1 showing that saturation is reached earlier by FMIPv6.

The signaling load corresponding to standard MIPv6 presents, a priori, a strange behavior having a local minimum for the case of 8 handoffs/min. However, if we recall that for each handoff the MN re-schedules the periodic BUs to be sent we realize that if the timer of the periodic BUs is below the time between two consecutive handoffs we will observe the periodic BUs and afterwards the ones due to a handoff. On the other hand, if the time between two consecutive handoffs is below the timer of the periodic BUs the periodic BUs will be always re-scheduled without being sent during the whole simulation. Thus, in the case of 8 handoffs/min, considering a timer of 10 seconds for the periodic BUs, they are always re-scheduled due to a handoff and never sent, resulting in a reduction of signaling load compared to the previous case.

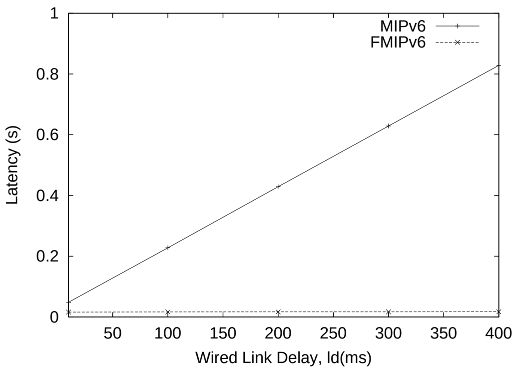

Figure 8. Impact of wired link delay on handoff latency

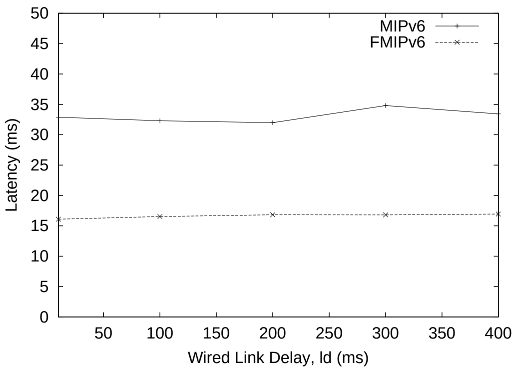

Figure 9. Impact of previous access router forwarding on handoff latency

4.3 *Impact of wired link delay*

We have computed the diferences in handoff latency and packet losses between FMIPv6 and MIPv6 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.

FMIPv6 reduces the time that elapses between a MN change of point of attachment and the traffic redirection to its nCoA. The MN informs its oAR to start forwarding its traffic before changing its link layer connection. Thus, the delay experienced by the redirected traffic is proportional to the wired path between its oAR and the new one, both in the local domain. On the other hand, with MIPv6, the BUs sent after performing the handover, have to reach the HA and CNs (outside of the local domain) in order to send the traffic to the proper CoA resulting on a direct dependence with the *ld* value.

As we can see in Figure 8 the results are as expected: while an increase in the wired link delay implies an icrease in the handoff latency for MIPv6, it does not affect FMIPv6 handoff latency. The graph with respect to packet losses directly corresponds to the one of handoff latency so we do not include the results here.

4.4 *Impact of Previous Access Router Forwarding*

Section 4.3 has shown handoff latency and packet losses reduction due to FMIPv6 usage when the 'distance' to the HA and CNs increases. In this section we study the MIPv6 option of establishing forwarding from a previous care-of-address. When this option is enabled, a MN after performing a handoff sends a BU not only to HA and CNs but also to the previous access router (PAR), i.e. previous point-of-attachment. We have repeated the experiment of the previous section but now using the previous access router forwarding option.

As we can observe from Figure 9 the results for MIPv6 are quite different compared to the ones obtained before. MIPv6 and FMIPv6 perform in a similar way in latency terms, only about 15 ms difference, since now the dependence with the *ld* value has been removed. Note that in this case, to contact the previous access router, is not necessary to go outside of the local domain, reducing thus the wired 'distance' to the forwarding entity. The difference between both approaches is due to the FMIPv6 make-before-break enhancement which starts the forwarding process from the oAR to the new one before actually performing the link change instead of afterwards. Moreover, the MIPv6 BU to the PAR is sent after the HA and CN ones introducing an additional latency. The MIPv6 draft does not provide any indication about the order to be followed when sending BUs so part of the observed difference could be easily reduced changing the sending order. As in the previous section the packet losses graph directly corresponds to the handoff latency one, so the results are not included. Note, however, that in this case the difference between FMIPv6 and MIPv6 is about 5 packet losses, averaging 0.5 versus 5.5 respectively.

Finally, we would like to remark that the advantages of FMIPv6, shorter latency and lower packet losses, produce a significant higher signaling load within the local domain compared to MIPv6 which introduces only one additional message with the Previous Access Router Forwarding option usage. This results in an average difference of 120 bits/s (235 versus 360) for this case.

4.5 *Impact of random movement*

Mobile users are unaware of overlapping areas where handoff decisions are taken. This section studies whether

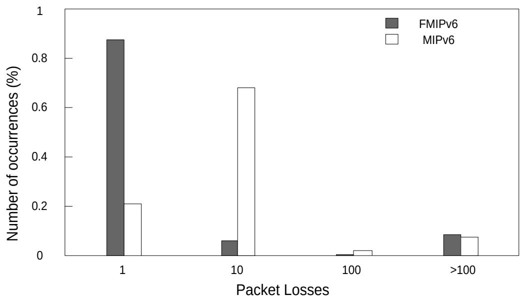

Figure 10. Packet losses histogram considering random movement

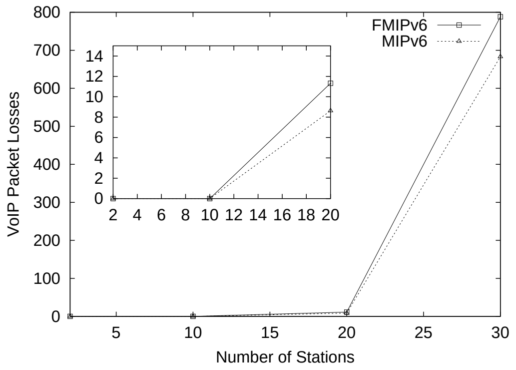

Figure 11. Impact of traffic sources on VoIP packet losses

the performance metrics differences observed between both protocols in previous sections still hold considering a mobile node moving randomly. Note that unexpected movements can have a quite negative effect on the received bandwidth due to back and forth movements around the overlapping areas. This effect could potentially prevail over the protocol enhancements.

Figure 10 shows the histogram of total packet losses experienced by our mobile node moving randomly in the case of 20 mobile nodes and for MIPv6 and FMIPv6. The packet losses occurrences have been grouped in lower or equal than 1, 10, 100 and over 100. As we can observe in the figure, the results are consistent with the ones presented in Section 4.1. FMIPv6 outperforms MIPv6 keeping most of the packet losses on lower values than MIPv6.

4.6 *Impact of traffic sources*

Until this section we have studied the impact of different parameters over a target station receiving a high constant traffic load (*probe*) in order to obtain results with a significant precision and without the interference of source burstiness (VoIP, Video) or recovery mechanisms (TCP). In this section we repeat the experiment of Section 4.1 but considering more realistic traffic sources and a simulation scenario where all the MNs send or receive the same type of traffic at the same rate. By doing this, we analyse whether the different performance improvements observed in previous sections are affected by the traffic source type, i.e., whether a user would notice a quality of service improvement or the improvements are 'masked' by the traffic sources characteristics. Specifically, three different types of traffic are studied: VoIP, Video and TCP transfers.

As explained in Section 3, our VoIP source produces bursty traffic following an on-off Markov process that results in a high variance between packet arrivals. Figure 11 shows the impact of the number of stations over the packet loss rate of VoIP traffic until the congestion level is reached. Since VoIP sources produce relatively a low traffic load ($\simeq$ 24kbps per source) no packet loss is observed for any of the protocols until the 20 MNs case. In this case, surprisingly, MIPv6 performs better than FMIPv6. The additional load introduced by FMIPv6 in the wireless channel, as shown in Section 4.1, is the reason for this behavior. We can conclude that, for a scenario with low rate traffic sources sending small packets the overhead introduced by FMIPv6 would result in a worse performance in handoff latency and packet losses terms compared to the baseline Mobile IPv6.

The H.263 video source produces packets of different length at a semi-constant rate for a target rate of 64 kbps. We show the impact of the number of stations over the handoff latency. As we can observe in Figure 12, the results are similar to the ones already described in Section 4.1, i.e., FMIPv6 performs better in handoff latency terms than MIPv6. In this case, in contrast to the VoIP one, the implementation of the Mobile IPv6 enhancement results, as expected, in a better user experienced quality of service since the additional signaling load is less relevant compared to the data traffic load.

Finally, we study whether a regular user downloading a file using TCP would notice any difference in the received service by using FMIPv6. For a user performing a download, handoff latency or packet loss rate are not relevant performance metrics but the experienced bandwidth during the TCP transfer is of major interest.

Figure 13 shows the differences on the available bandwidth for TCP users depending on the considered protocol. In the figure we can observe the TCP sources adjustment of the sending rate to the available channel capacity when the number of mobile users increases. For a number of mobile nodes below 10, a lower packet loss rate obtained by FMIPv6 results in users achievement of larger bandwidth. When the number of mobile nodes increases, the probability

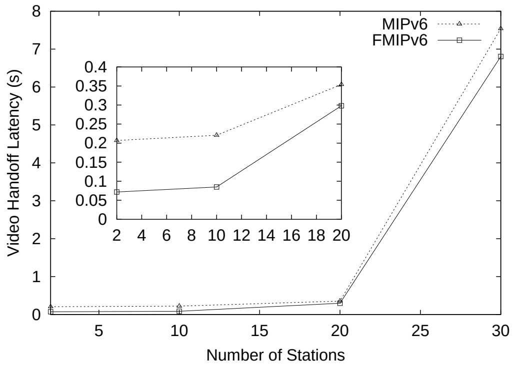

Figure 12. Impact of traffic sources on Video handoff latency

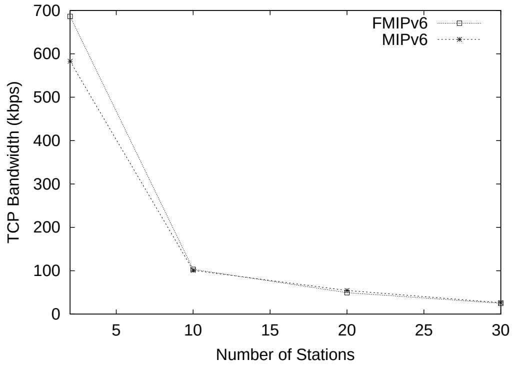

Figure 13. Impact of traffic sources on TCP bandwidth

of experiencing a collision while trying to access the channel increases, too. This, in turn, triggers the TCP congestion avoidance mechanism more often reducing the packet losses experienced by the MNs and thus, decreasing the bandwidth differences between the proposals. These differences would otherwise be much bigger, as it has been shown is Section 4.1, when the users try to get a larger bandwidth than the one actually available in the channel.

As a conclusion, TCP users would also benefit from the implementation of the FMIPv6 protocol when the wireless channel is not congested.

5 Conclusions

In this paper we have provided quantitative results on the level of improvement that can be expected by using Fast Handovers for Mobile IPv6 instead of pure Mobile IPv6 in a 'hot spot'-like IEEE 802.11-based scenario with four access routers and up to 50 mobile nodes. The results were achieved through a thorough study via simulation that required to implement Fast Handovers for Mobile IPv6 and Neighbor Discovery for the network simulator *ns-2*.

We performed a 'stress test' of the protocol where we studied how handoff latency, packet loss rate, obtained bandwidth and fast handoff process success probability are affected by the number of mobile nodes, i.e., by competition for the wireless medium or by protocol interactions, e.g., with the Neighbor Discovery process of IPv6. The behavior of the protocols for a general case considering random movements and more realistic traffic sources, i.e., Video, VoIP and TCP, was also studied. Finally, the signaling load costs associated to the Mobile IPv6 proposed enhancement compared to the performance improvements obtained were analysed considering a broad range of handoff rates. These factors were shown to have a significant influence over the performance metrics and we indicated the points to be taken into account in a real implementation.

Specifically, we have shown that while some simulation results corroborate the intention of the protocols specifications, other results give insights not easily gained without performing simulations. Some of the most remarkable results are that *i)* Mobile IPv6 can eventually outperform FMIPv6 in packet losses terms in saturation conditions due to the higher number of packets discarded directly in the Neighbor Discovery entry queue that lower the load in the wireless channel, *ii)* random movements affect the experienced performance improvements but the difference in the perceived quality of service when using FMIPv6 is still clearly noticeable, *iii)* in scenarios where the users produce a low rate with small packets, e.g., VoIP sources, the additional load in the wireless channel introduced by FMIPv6 can result in a worse performance than the baseline Mobile IPv6 one, and *iv)* by using pure Mobile IPv6 and enabling the option of establishing forwarding from the previous care-of-address, handoff latency and packet losses can be also improved without requiring and additional implementation effort and at a lower signaling load cost, however, without reaching the same level of improvement achieved by FMIPv6.

Through this analysis a deep insight on the different overall system performance of both protocols and their causes was acquired. Therefore, the results of this study are twofold. First, we provided quantitave results for Mobile IPv6 and Fast Handovers for Mobile IPv6 of the overall system performance and checked whether they perform as expected in a realistic 'hot spot' scenario. Second, we provided the reasoning behind the impact of the different parameters over the performance of both protocols in saturation and no saturation conditions paying special attention to the cases where the behavior was different to the expected one. The application of this reasoning is not restricted to our specific scenario but also holds for any other scenario considering different wireless technologies.

6 Acknowledgments

This work has been partially supported by the IST project *Moby Dick* [25]. The authors would like to thank Hannes Hartenstein for his valuable discussions.

References

[1] C.Perkins (Ed.), "IP Mobility Support," RFC 2002, October 1996.

[2] D.B. Johnson, C.Perkins, and Jari Arkko (Eds.), "Mobility Support in IPv6," Internet Draft, work in progress, January 2003.

[3] K.El-Malki et al., "Low Latency Handoff in Mobile IPv4," Internet Draft, work in progress, September 2002.

[4] G.Tsirtsis, A.Yegin, C.Perkins, G.Dommety, K.El-Malki, and M.Khalil, "Fast Handovers for Mobile IPv6," Internet Draft, work in progress, September 2002.

[5] "3GPP, technical specification group radio access network, utra high speed downlink packet access," 3G TR 25.950 V4.0.0, 2001.

[6] Chr.Bettstetter, H.Hartenstein, and X.Pérez-Costa, "Stochastic Properties of the Random Waypoint Mobility Model," to appear in ACM Kluwer Wireless Networks Special Issue on Modeling & Analysis of Mobile Networks (WINET), 2003.

[7] C.E.Perkins and K-Y.Wang, "Optimized Smooth Handoffs in Mobile IP," IEEE Symposium on Computers and Communications (ISCC), 1999.

[8] H.Yokota et al., "Link Layer Assisted Mobile IP Fast Handoff Method over Wireless LAN Networks," ACM International Conference on Mobile Computing and Networking, September 2002.

[9] Andrew T. Campbell et al., "Comparison of IP Micromobility Protocols," IEEE Wireless Communications Magazine, Vol. 9, February 2002.

[10] Nicola Montavont and Thomas Noel, "Handover Management for Mobile Nodes in IPv6 Networks," IEEE Wireless Communications Magazine, August 2002.

[11] R.Hsieh et al., "Performance analysis on Hierarchical Mobile IPv6 with Fast-handoff over End-to-End TCP," IEEE Global Telecommunications Conference (GLOBECOM), 2002.

[12] Xavier Pérez-Costa and Hannes Hartenstein, "A Simulation Study on the Performance of Mobile IPv6 in a WLAN-Based Cellular Network," Computer Networks, special issue on "Towards a New Internet Architecture", September 2002.

[13] Xavier Pérez-Costa and Marc Torrent-Moreno, "A Performance Study of Hierarchical Mobile IPv6 from a System Perspective," to appear in Proceedings of IEEE International Conference on Communications (ICC), May 2003.

[14] C.Perkins, "IP encapsulation within IP," RFC 2003, October 1996.

[15] T.Narten et al., "Neighbor Discovery for IP Version 6," RFC 2461, December 1998.

[16] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE Standard 802.11, June 1999.

[17] "Network Simulator (ns), version 2," http://www.isi.edu/nsnam/ns.

[18] A. et al. Mitra, "An Empirical Analysis of the IEEE 802.11 MAC Layer Handoff Process," CS-TR-4395, University of Maryland Department of Computer Science, September 2002.

[19] "H.263, video coding for low bitrate communication," ITU-T/SG15 Recommendation, 1996.

[20] Frank H.P. Fitzek and Martin Reisslein, "MPEG-4 and H.263 Video Traces for Network Performance Evaluation," IEEE Network,Vol. 15,No. 6,pages 40-54, November/December 2001.

[21] C-N.Chuah et al., "QoS Provisioning Using a Clearing House Architecture," International Workshop on Quality of Service (IWQoS), June 2000.

[22] "Artificial conversational speech," ITU-T p.59, Recommendation, 1993.

[23] "Mobiwan: ns-2 extensions to study mobility in Wide-Area IPv6 Networks," http://www.inrialpes.fr/planete/mobiwan.

[24] William Mendenhall et al., "Mathematical Statistics with Applications, p.368," 4th Ed.PWS-KENT, 1990.

[25] "Mobility and Differentiated Services in a Future IP Network," IST-2000-25394,http://www-int.berkom.de/ mobydick/, 2000.