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Design, Implementation and Performance of Multicast-Based Paging for IP Mobility

(Extended Version)

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Abstract

Originally, paging has been used in cellular networks to alert a mobile station of an incoming call within a paging area comprised of several cells. Today's most popular usage of paging is the exchange of short messages. With growing importance of all-IP mobile networks it is expected that an IP paging service will prevail. This report studies the usage of paging in IP-based networks to search mobile hosts in order to find their current point-of attachment. It allows the mobile host to update the network less frequently and to provide the network with only approximate location information. The approach is contrary to the case where a mobile host registers each time a handover occurs and the network tracks the exact location of the mobile host. Clearly, there is a tradeoff between tracking and searching.

In this report the utilization of IP multicast for paging in mobile access networks supporting micro-mobility is investigated. The paging service is intended to facilitate efficient mobility support, supplementing multicast-based micro-mobility which supports host mobility by means of location-independent addressing and routing. The scheme is augmented by multicast-based paging to improve its efficiency and scalability. Hence, we propose a multicast-based paging architecture and protocol, highlight selected implementation issues and estimate the gain/costs of paging for mobility support in a performance evaluation.

Chapter 1

Introduction

In mobile networks, a mobile host usually registers on each handover with its actual access point and the network tracks the current location of a mobile host. Instead of tracking a mobile host, a paging service can be utilized to find the mobile host's current location in a cellular network when this is needed by the network. This allows the mobile host to update the network less frequently and provides the network only with approximate location information. Clearly, the mobile host consumes less power. A tradeoff between tracking and paging exists: A more precise tracking would lessen the search effort. If the location information has low precision the area which has to be covered by a page is increased and bandwidth is wasted. The basic goal of an efficient paging is to minimize the combined cost of tracking and paging operations and therefore to reduce the signaling load on the wireless link as well as in the core network.

In this report the utilization of IP multicast for a paging service is proposed. The main benefit of multicast for paging is the flexibility to create paging areas. By using multicast a paging area is identified by an IP multicast address. A paging area is set up by subscription of access points to pre-defined multicast channels for paging. This allows to set up overlapping paging areas easily where an access point belongs to multiple multicast channels. A paging area can be defined independently of the access network topology. Neighboring wireless cells can belong to the same paging area without being on the same outgoing router interface. The size and shape of a paging area can be optimally adjusted to the expected velocity of mobiles and paging update interval. Moreover, a multicast tree interconnecting the cells of a paging area adapts automatically to a reconfigured access network topology. Finally, IP multicast eases the usage of different paging algorithms. For example, with hierarchical paging, a mobile host is first paged in a small paging area. If the mobile host is not found, the size of the paging area is increased. This can be easily accomplished when access points belong to multiple paging areas realized with multiple multicast channels.

We address access networks and assume a separation between global and local mobility support. Local mobility is handled by a *micro*-mobility protocol, whereas global mobility between different access networks is provided by a *location service* (e.g. IETF Mobile IP [1, 2]), Mobile People Architecture [3], ICEBERG [4]). The paging service is intended to facilitate efficient mobility support, supplementing *multicast-based micro-mobility* which supports mobility by means of location-independent addressing and routing. We present here a new approach called MOMBASA (*MObility support - a Multicast-BASed Approach*) [5, 6]. Since the today's IP multicast suffers from a number of problems (group management, including authorization, address allocation, security, network management) [7] which are subject of current research efforts, MOMBASA investigates alternate multicast approaches for their application to host mobility. In this report we focus on *Single-Source Multicast* [8] which is essentially based on the EXPRESS channel model [9] where a multicast group is identified by a IP source address and IP multicast address. The advantage of SSM in this context is that SSM avoids traffic from unwanted sources and solves some of the serious problems that have prevented standard IP multicast from commercial deployment. Moreover, since SSM does not require an IP multicast address management there is no need for a global address allocation. Although this is not relevant in this context (multicast is applied only in the access network) we expect that SSM can be more easily deployed and requires a simpler management than today's IP multicast.

To illustrate the advantages of paging for multicast-based mobility support, suppose an access network with multiple access points and multicast routers. In order to shorten the service interruption to an absolute minimum, the mobile host may use a predictive handover technique: Neighboring access points are grouped to a multicast group. The current access point is called *active*, the others *passive*. The active access point forwards packets to the mobile, whereas the passive access points buffer them. The buffered packets are forwarded as soon as the mobile host registers with one of the passive access point. Each time the mobile host moves to a new cell the group of access points is updated and access points subscribe or un-subscribe the multicast channel. Clearly, the multicast-based approach causes a considerable overhead in terms of buffering, signaling for multicast group maintenance and maintenance of multicast states in routers. By utilizing IP paging, we distinguish between active and inactive mobile hosts. Multicast channels are established for active mobile hosts only. Handover of inactive mobile hosts does not result in multicast operations, allocation of buffer in access points, etc. With the assumption that the major part of the mobile hosts in the network is inactive, IP paging has the potential to reduce the overhead significantly. But, in addition to the tradeoff problem mentioned before, for multicast-based mobility support enhanced by paging, the overhead of re-establishing the multicast tree for the mobile host contributes to the signaling overhead and must be taken into account.

The outline of this report is as follows: First, a paging architecture and protocol providing a paging service based on IP multicast is proposed (section 2). Then different paging algorithms are examined (section 3). A prototype implementation of a paging protocol based on IP multicast (PIM-SSM [10]) is described in section 4. In a performance evaluation in section 5 the gain/costs of paging for mobility support to find the optimal tradeoff between paging and tracking are given.

Chapter 2

MOMBASA Architecture and Protocols

We assume a network architecture (figure 2.1) which separates the global Internet and the *access network*. [1] Basic elements of the access network are mobility-enabling proxies (MEPs), routers and gateways. MEPs serve as access points providing wireless service to mobile hosts and perform mobility-related functions. Routers interconnect network elements and transport packets. A gateway interconnects the access network and the global Internet. When a mobile host enters the access network it gets assigned a temporary unicast address and registers with the gateway via its current MEP. The assigned IP address remains as long as the mobile does not change the access network. The unicast address is mapped to a multicast address transparently to the mobile host. Packets are routed by multicast routes. [2] To transport packets between gateway and MEP, the addresses of the packets are translated from unicast to multicast addresses in the gateway and reverse translated in the MEP. Address translation mechanisms can be either IP-IP encapsulation and tunneling, or by network address translation. When a handover occurs, the mobile host updates the routing states in the mobile access network. Thus, the local mobility within the access network is handled transparently to the gateway. The routing state is stored in a distributed manner in the access network and there is no centralized network node. Multicast routing states are soft and need to be refreshed at regular time intervals.

Paging can be utilized to locate a mobile host within the access network. To avoid broadcasting of paging requests to all MEPs in the access network, the access network is segmented into paging areas. Each paging area consists of several (at least one) cells. Size and shape of a paging area depend on a number parameters, such as the mobile's velocity, the interval of paging updates and on the environment (walls, floors, buildings, streets, etc.). In figure 2.2, paging areas with non-overlapping and overlapping paging areas are shown. In this report, we propose a *centralized* paging architecture, where the paging state is stored in the gateway.

To integrate paging into this micro-mobility network architecture, the following general functionality must be realized:

- Inactive state of a mobile host and state transitions from the active to the inactive state and vice versa,

[1] An access network is defined as a subnetwork under control of a single authority

[2] This is contrary to other micro-mobility protocols: Hierarchical Mobile IP, e.g.[11] applies IP-IP encapsulation and tunneling; Cellular IP [12] uses host specific-routes, etc.

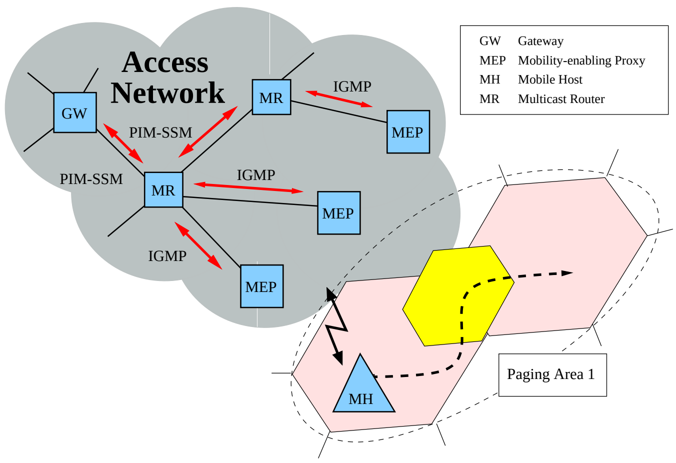
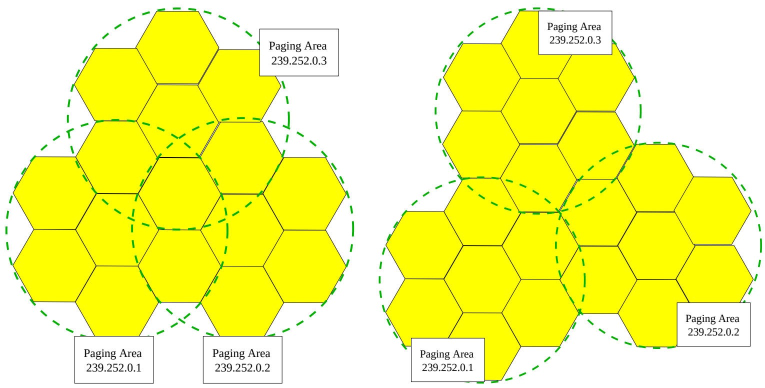


Figure 2.1: Paging architecture and protocols



(a) Overlapping paging areas (b) Non-overlapping paging areas

Figure 2.2: Paging area of size $s = 2$

- Storing of paging states in a database,
- Management of paging areas,
- Triggering of paging updates,
- Triggering of paging requests,
- Buffering of packets while paging is ongoing,
- Transport of paging updates and paging requests.

An important prerequisite for IP paging is the differentiation between active and inactive state of mobile hosts (figure 2.3), which is not common in today's IP protocols. [3] A mobile host is in active

[3]Also IETF Mobile IP has no notion of inactive mobile hosts.

Name	Meaning	Representative value
re-registration timer	Expected inter-arrival time of registrations in active/inactive mode. Triggers a re-registration with the MEP.	10 sec./30 sec.
registration timeout	Validity of a registration table entry.	30 sec.
paging timeout	Validity of a paging entry.	90 sec.
activity timeout	Time the host remains in active state w/o incoming data.	10 sec.
advertisement timer	Expected inter-arrival time of advertisements.	100 msec.

Table 2.1: MOMBASA timers related to paging

state as long as it transceives user data. It switches into the inactive state, when it does not transceives user data packets for a certain duration of time. This duration is determined by the system-specific parameter *ACTIVITY_TIMEOUT*. When a mobile host is in active state, it updates the network whenever it moves out of its current cell. When the mobile host is in inactive state, it updates the network less often, at least when it leaves the current paging area: The mobile host sends a *PAGING_UPDATE* to the MEP. The MEP inserts the paging area identification and forwards the *PAGING_UPDATE* towards the gateway. The multicast routers forward the message to their upstream router. Finally, the gateway receives the *PAGING_UPDATE* and updates its paging table.

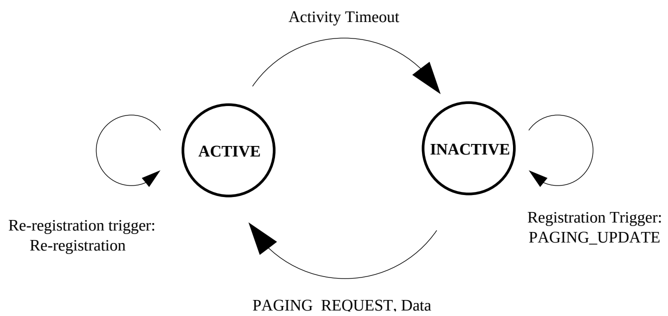


Figure 2.3: Mobile host state machine

When the gateway receives a packet for a mobile host which is in inactive state, the packet is buffered and a *PAGING_REQUEST* is sent out on the correspondent multicast channel. On receiving a *PAGING_REQUEST* the mobile host becomes active and registers with its current MEP. The MEP subscribes for the multicast channel and sends a *PAGING_UPDATE* with a lifetime of 0 to the gateway.

The case where the mobile host is in inactive state and wishes to send data packets is simple: the mobile host registers and forwards packets.

The behavior of the paging protocol is strongly dependent on system-specific timers and intervals listed in table 2.1. Details of the protocol are described in [13].

Chapter 3

Paging Algorithms

A paging algorithm determines how a mobile host is searched in the access network, in particular the method to trigger paging updates and paging requests. To illustrate the impact of paging algorithms on performance, consider the two most simple tracking and paging algorithms: *always-register* and *never-register*. Clearly, with the first scheme the overhead due to registration messages is high, especially in networks with small cells and a high number of active mobile hosts. But the overhead for finding a mobile host is zero since the current location of each mobile host is always known. With the second scheme there is no overhead for registration, but whenever there is a need to find a particular mobile host, the whole access network must be paged, and this results in a high overhead.

For multicast-based paging we make use of algorithms to trigger paging updates which have been examined in several studies (e.g. [14]): *time-based* update, *movement-based* update and *distance-based* update.

In the *time-based* update scheme the mobile host sends periodically a paging update. The interval between two consecutive paging updates is controlled by a parameter. The parameter is set according to the paging area size and the mobile host's maximum velocity. Another scheme is the *movement-based* update in which the mobile host counts the number of boundary crossings between cells incurred by its movements and when this parameter exceeds a specific value it transmits a paging update message. In the *distance-based* scheme the mobile host tracks the distance it has moved (in terms of cells) since last transmitted paging message, and whenever the distance exceeds a specific parameter it transmits a paging update message. The distance-based strategy requires knowledge about the network topology.

The two latter schemes are independent of the mobile host's velocity. But if the mobile host remains in its cell (or in its paging area in the distance-based scheme), the mobile host's paging table entry is not refreshed and its lifetime will expire. To keep the soft-state paradigm we complement the movement-based and distance-based schemes with an additional refresh timer.

Chapter 4

Implementation Issues and Testbed Setup

The proposed paging scheme has been implemented and examined in a testbed (figure 4.1). All hosts are standard PCs running under Linux 2.2/2.4. The operating system on the gateway and on the access point are patched to support paging and NAT [1] between unicast and multicast realm. The hosts are connected by 100Mbps Ethernet (hubs between CH/GW and MH/AP1/AP2, all other connections point-to-point). At this stage the gateway and multicast router run a multicast router implementation PIM-SM Version 2 as the multicast routing protocol [2] and IGMPv2 between access points and their multicast routers. Although the analysis in this document assumes PIM, the MOMBASA implementation provides a generic interface to other multicast protocols and is able to support other multicast routing protocols as well. In particular it can be easily adapted to single-source multicast (PIM-SSM and IGMPv3). Our implementation of MOMBASA including paging support is publicly available as a generic platform for experimentation with multicast-based mobility support in IP networks at [13, 15, 16]

The implementation deals with the following issues: *idle detection in the mobile agent, interaction between paging daemon and multicast routing daemon in the gateway* and *forwarding of multicast packets from the gateway*. These issues are discussed in the following sections. The implementation of general protocol mechanisms (timer management, exchange of protocol messages) is beyond the

[1] Network Address Translation

[2] pimd-2.1.0-alpha28, implementation of University of Southern California for Linux 2.2.

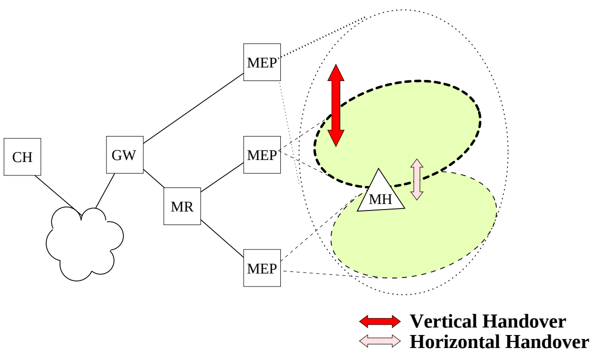


Figure 4.1: Testbed setup

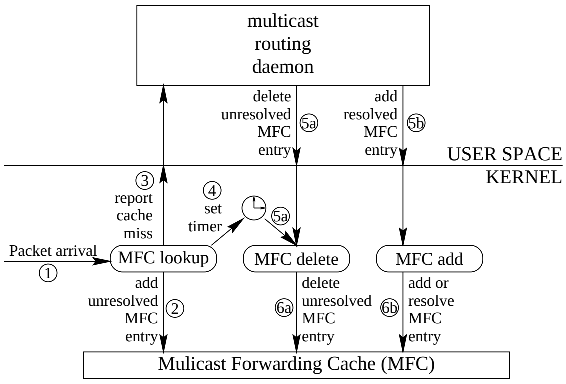


Figure 4.2: Interaction between kernel, multicast routing and paging daemon

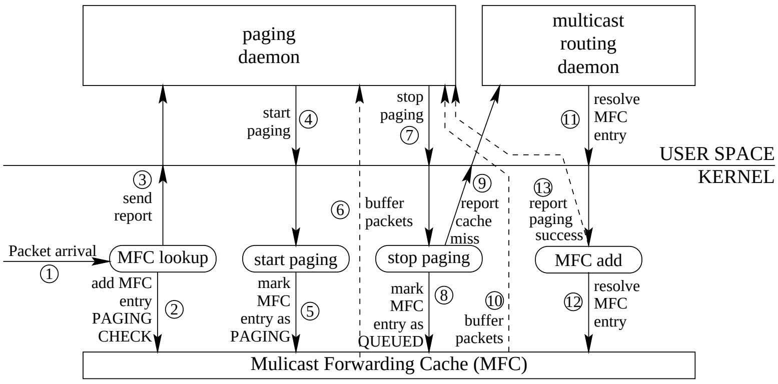


Figure 4.3: Interaction between kernel, multicast routing and paging daemon

scope of this document.

The idle detection, discussed in section 2, works as follows: A packet socket, which receives all incoming and outgoing packets of the host, is opened. A socket filter [3], which only accepts IP data packets but rejects non-IP, signaling and broadcast packets, is attached to the socket. In active mode the so-called idle thread does nothing than observing the packet socket and recording the timestamp of the last data packet. The main thread sets a timer to the duration of the activity timeout. When the timer expires, the timestamp of the last data packet is checked. If it lies within the last timer period the timer is prolongated, otherwise the mobile host switches to inactive mode. The change from inactive to active mode is triggered by the reception of an incoming or outgoing packet by the idle thread or by a *PAGING_REQUEST*. In the case of outgoing data the packets are buffered in the mobile until a valid registration at an access point can be obtained.

Paging is triggered by the reception of a data packet for an inactive mobile host by the gateway. Since the packets are translated to multicast, this is equivalent to the reception of a multicast packet for a mobile-associated group for which a paging cache entry exists in the paging daemon. To signal this condition to the paging daemon the Linux kernel had to be modified.

In an unmodified multicast router (see Fig. 4.2) when a multicast packet first arrives (1) an un-

[3] The Linux socket filter model is essentially an in-kernel implementation of the Berkeley Packet Filter model.

resolved entry is inserted into the MFC [4] (2) and the cache miss is reported to the multicast routing daemon via the *mroute_socket* (3). A timer is set for the MFC entry (4). For a non-existent multicast group the timer will expire or the MFC entry will be deleted explicitely by the multicast daemon (5a, 6a). Otherwise the MFC entry will be resolved (5b, 6b).

In the modified Linux kernel (see Fig. 4.3) the arrival of a multicast packet to a pageable group (1) is first reported to the paging daemon via a *paging_socket* (3). If an entry exists in the daemon's paging table it will start paging and signal this condition to the kernel (4). The MFC entry is marked as paging (5), data packets to the multicast group are sent up to the paging daemon (6). When the paging cache entry in the daemon was deleted, denoting that paging was successful this is again signaled to the kernel (7). The MFC entry is marked as unresolved (8) and a cache miss report is sent to the multicast routing daemon (9). Data packets are still buffered in the paging daemon (10). The resolution of the MFC entry by the multicast routing (11/12) is signaled to the paging daemon (13). Buffering is stopped and the buffers are flushed.

The real behavior is however even a bit more complicated since the previous description omitted some exceptional cases (e.g. timeouts and retries). For all details please consult the source code at [15].

PAGING_REQUESTs and buffered packets are multicast packets originating at the gateway, which is also a multicast router. Under Linux, sending of multicast packets from a multicast router is treated as if the router acted as a normal end system. On sending you have to specify a single interface on which a multicast packet should leave the host. In our case it is however desired that multicast packets are fed into the multicast routing mechanism the same way as forwarded packets are. This is achieved by a trick:

The *Ethertap* device, a software network device simulating an Ethernet adapter, is used. Everything that is written into a special socket from user space appears in the kernel as if it was received from the *Ethertap* network device. Everything that is sent to the *Ethertap* device appears on the socket. Only small modifications were necessary to allow an MTU [5] of up to 65535 bytes (to avoid useless fragmentation) and to enforce acceptance of packets from *Ethertap*, which were expected from another interface.

[4] Multicast Forwarding Cache
[5] Maximum Transfer Unit

Chapter 5

Performance Evaluation

5.1 Assumptions

For performance evaluation we make certain assumptions about the access network topology, mobility of hosts, traffic load and handover.

Regarding the access network topology we assume that a wireless cell has a hexagonal shape. All cells are uniform and each cell has six neighbors. For predictive handover a MEP forms a MEP group with its 6 neighbors. Also we assume a paging area as a cell cluster of same hexagonal shape. The number of cells in a paging area of size s is given by $3s(s-1)+1$. For example, a paging area of size $s=1$ has a single cell, and a paging area of size $s=2$ has 7 cells.

The area of a wireless cell of hexagonal shape with radius R is

$$\frac{3}{2}R^2\sqrt{3} \tag{5.1}$$

Accordingly, the area of a paging area amounts to

$$\frac{9\sqrt{3}}{2}s(s-1)R^2 + \frac{3}{2}R^2\sqrt{3} \tag{5.2}$$

For analysis, we assume multicast routers with 8 interfaces – 1 upstream and 7 downstream interfaces. Routers create a regular tree-like topology of multiple levels where each subtree has 7 downstream edges (figure 5.1). The router at the highest level acts as gateway. The routers at level 1 are interconnected to access points acting as MEPs. Given the hierarchical level l, the numbers of routers in the access network is

$$7^l + 7^{l-1} + \ldots + 7^1 + 7^0 \quad l \geq 0 \tag{5.3}$$

In the access topology model no direct interconnection between MEPs is assumed and messages between MEPs (e.g. inter-MEP advertisements) are exchanged indirectly through a router.

Example topologies are listed in table 5.1. For demonstration purposes we consider only a topology with a hierarchical level of 3. Results for other topologies (also irregular topologies) can be obtained with the same method. can be derived easily.

To describe the mobility of a mobile host, the *cell dwell time* is used indicating the amount of time that a mobile host remains in a cell. The cell dwell time depends on a number of parameters: the

Hierarchical level	Number of cells	Numbers of routers in access network
1	$7^1 = 7$	1
2	$7^2 = 49$	8
3	$7^3 = 343$	57
4	$7^4 = 2401$	400

Table 5.1: Number of cells and multicast routers in the access network model

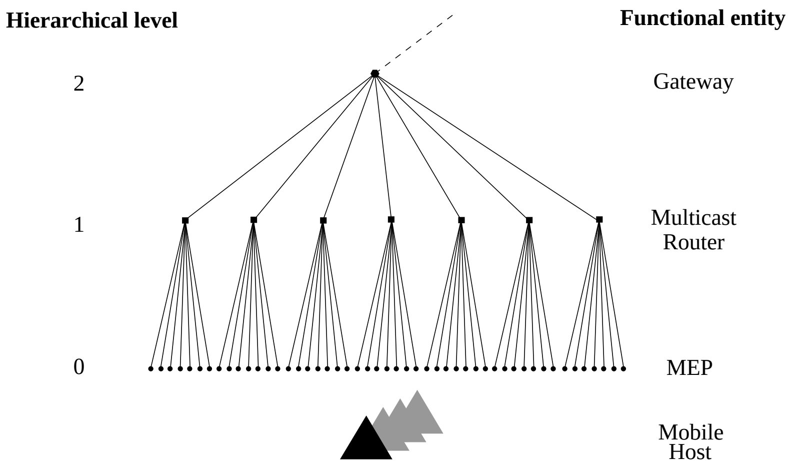


Figure 5.1: Tree topology model

velocity of the mobile host, the cell size, cell shape and the traversed path. To simplify the complex model, we assume that the cell-dwell time is a random variable with a mean T. T is assumed to be proportional to the cell radius R and inverse proportional to the average velocity v of the mobile host:

$$r_{cc} = \frac{1}{T} = \eta \frac{v}{R} \tag{5.4}$$

Each mobile moves in a purely random fashion and the probability of moving to each of the 6 neighbors is equal ($\frac{1}{6}$). Correlation between successive movements is ignored.

Regarding the traffic model we assume that a mobile host has communication periods in which packets are sent and received, as it is typical in IP-based applications. When the communication pause is larger than the inactivity interval, a mobile host becomes inactive. The proportion of active mobile hosts to the overall number of mobile hosts is indicated by α.

5.2 Signaling Cost Analysis

In this section the gain of paging for mobility support is estimated. We define *signaling costs* as the product of weighted hops signaling messages and the signaling rate. The signaling costs reflect the consumption of communication bandwidth and their processing in the network, as well as the consumption of battery power in the mobile hosts. In the following we quantify the signaling costs for multicast-based mobility support (without paging) and then for the paging-enhanced approach by analysis. The signaling cost analysis include MEP advertisements, inter-MEP advertisements, refreshes of registrations and multicast states, paging updates and handover signaling. Based on that analysis we study the impact of paging area size, mobile host's velocity and density of mobile hosts on the signaling costs to find the optimum between tracking and paging.

5.2.1 Signaling costs without paging support

Signaling for mobility consists of

1. advertisements sent by MEPs on the wireless link to advertise their availability,
2. inter-MEP advertisements exchanged between MEPs belonging to the same MEP group to pre-register mobiles for support of predictive handover,
3. registration refreshes,
4. multicast membership queries/responses between MEPs and their designated multicast router, to refresh the multicast state of MEPs (IGMP),
5. PIM-SSM state refresh messages (subscribe - and un-subscribe - messages to update multicast channels, hello messages between multicast routers),
6. handover signaling between mobile host – MEP, MEP – designated multicast router (IGMP), and between multicast routers (PIM-SSM).

To calculate the total costs of signaling, we consider only mobility within the access network and exclude signaling outside of the access network from the analysis. Thus, we include local mobility only.

Based on the assumptions in section 5.1, we can make the following statements regarding the numbers of multicast channels and signaling operations per handover:

- *Number of multicast channels*: A MEP is subscribed for a multicast channel for each directly-registered mobile host. For predictive handover a MEP is subscribed to a multicast channel for a mobile host which is indirectly registered by the neighboring MEP. Additionally, a MEP belongs to certain *static* multicast channels: pre-defined multicast channels for the MEP channels to exchange inter-MEP advertisements (1 multicast channel per MEP group the MEP belongs to) and the default *all hosts* multicast group (224.0.0.1). This results in 7 *static multicast channels*. The default multicast channels for routers are neglected.
- *Number of signaling operations per handover*: We differentiate between predictive and soft handover. For predictive handover the MEP group is updated: Some MEPs are added to the MEP group, some are dropped. In summary, this results in 3 subscribe- and 3 un-subscribe-operations of MEPs. Soft handover results in 2 operations: the new MEP subscribes to the multicast channel and the old MEP un-subscribes.

The total cost of signaling is a function of

$$C_{\text{w/o paging}} = f(\omega_c, \omega_w, r_{Adv}, r_{IMEPAdv}, r_{MQR}, r_{PIMR}, r_{Rereg}, S_{MEPGr}, \delta, R, v, L) \qquad (5.5)$$

where

$C_{\text{w/o paging}}$	Total cost of signaling without paging; $\left[\frac{\text{weighted hops * bytes}}{s}\right]$
ω_c	Weight of a hop in the fixed segment of the handover domain; [ ]
ω_w	Weight of a wireless hop; [ ]
r_{Adv}	Rate of MEP advertisements per MEP; $[\frac{1}{s}]$
$r_{IMEPAdv}$	Rate of inter-MEP advertisements per MEP; $[\frac{1}{s}]$
r_{MQR}	Rate of multicast state refreshes (IGMP membership queries) per link; $[\frac{1}{s}]$
r_{PIMR}	Rate of multicast state refreshes (PIM state refreshes) per link; $[\frac{1}{s}]$
r_{PIMH}	Rate of multicast hello messages per link; $[\frac{1}{s}]$
r_{Rereg}	Re-registration rate of mobiles per mobile; $[\frac{1}{s}]$
r_{cc}	Cell crossing rate per mobile [1/s] with $r_{cc} = \eta \frac{v}{R}$; [cells]
S_{MEPGr}	Size of MEP group for predictive handover; [cells]
δ	Density of mobiles in the handover domain; $[\frac{1}{m^2}]$
R	Cell radius; $[m]$
v	Velocity of mobile host; $[\frac{m}{s}]$
m	Number of mobiles in cell with $m = \delta\, \frac{3}{2} R^2 \sqrt{3}$; [ ]
η	Constant proportional factor for relation between velocity v and cell radius R; [ ]
L_{Adv}	Length of MEP advertisement messages; [bytes]
$L_{IMEPAdv}$	Length of inter-MEP advertisement messages; [bytes]
L_{Rereg}	Length of re-registration messages; [bytes]
L_{HOR}	Length of handover request/response messages; [bytes]
L_{MQ}	Length of IGMP membership query messages; [bytes]
L_{MR}	Length of IGMP membership report messages; [bytes]
L_{MS}	Length of IGMP membership solicitation messages; [bytes]
L_{PIMH}	Length of PIM hello message messages; [bytes]
L_{PIMR}	Length of PIM subscribe-/un-subscribe messages; [bytes]

In addition to the above assumptions we make the simplifications that all members of a MEP group belong to the same multicast router. Then the branching point of the multicast tree is the router at the first hierarchical level. In reality, the MEPs can be interconnected to arbitrary multicast routers. In the worst case, the branching point of the multicast tree is in the gateway.

The signaling costs are comprised of the components listed in table 5.2.

For better understanding of the analytical expressions, we make the following notes.

- The number of wireless cells, MEPs and links between MEPs and routers in the assumed topology is 7^3, the number of links between routers of first and second hierarchical level is 7^2 and between routers of the second and third level 7^1.

Signaling type	**Expression**
MEP advertisements	$7^3\ r_{Adv}\ \omega_w\ L_{Adv}$
Inter-MEP advertisements	$7^3\ (\ 5 + S_{MEPGr}\ )\ r_{IMEPAdv}\ \omega_c\ L_{IMEPAdv}$
Re-registrations	$7^3\ m\ r_{Rereg}\ \omega_w\ L_{Rereg}$
IGMP membership query/response	$7^3\ r_{MQR}\ \ \omega_c\ (L_{MQ}\ +\ (\ m\ +\ 6\ )\ L_{MR})$
PIM hello messages	$(7^2\ +\ 7^1)\ r_{PIMH}\ \omega_c\ L_{PIMH}$
PIM state refreshes	$7\ (7^2\ +\ 7^1)\ (\ m\ +\ 6\ )\ r_{PIMR}\ \omega_c\ L_{PIMR}$
Handover signaling	$mr_{cc}[7^3(\omega_w L_{HOR} + 6\omega_c L_{MS}) + 7(7^2 + 7^1)\omega_c L_{PIMR}]$

Table 5.2: Analytical expression of signaling operations without paging support

- Signaling messages sent over wireless links are more *expensive* than that sent over wire-line links. This is taken into account by weight factors ω_c and ω_w.
- Inter-MEP advertisements are first sent up-link to the gateway and then distributed down-link to the MEPs of the correspondent group. Finally, they are duplicated on the last wired hop and distributed to the MEPs. This results in the sub-term $(5 + S_{MEPGr})$ in above term.
- IGMP membership refreshes are triggered by IGMP membership queries by the multicast router to all hosts (224.0.0.1). The MEPs answers with an IGMP membership report for each multicast channel the MEP belongs to: one per directly registered mobile host (m), per indirectly registered host $m\ S_{MEPGr}$ (TBD) and one per MEP group (6) the MEP belongs to. Therefore $m + 6$ IGMP membership response messages are sent.
- Signaling message of the multicast routing protocol (PIM subscribe and un-subscribe messages) are sent to the gateway as the root of the multicast tree.
- Handover signaling consists of two components: a) signaling on the wireless links and on the links between MEPs and router (IGMP) (first addend in above term). b) signaling between the multicast routers – including gateway (second addend).
- For simplification in analysis we neglect that a multicast router sends a IGMP membership query after a IGMP leave operation to check if there other hosts are subscribed to the multicast channel.

Next, we sum up the terms in table 5.2 and substitute $m = \delta\ \frac{3}{2}R^2\sqrt{3}$, $r_{cc} = \eta\frac{v}{R}$ and we get

$$
\begin{aligned}
C_{\text{w/o paging}} = \\
343\,\omega_w \left[\, r_{Adv}\, L_{Adv}\ +\ \tfrac{3}{2}\sqrt{3}\,\delta\, R^2\, r_{Rereg}\, L_{Rereg}\ +\ \eta\tfrac{v}{R}\, L_{HOR} \right] \\
+\, 343\,\omega_c \Big[\, (\, S_{MEPGr}\ +\ 5\,)\, r_{IMEPAdv}\, L_{IMEPAdv} \\
+\, r_{MQR}\,(\, L_{MQ}\ +\ (\, \tfrac{3}{2}\sqrt{3}\,\delta\, R^2\ +\ 6\,)\, L_{MR})\ +\ 9\sqrt{3}\,\delta\, R^2\, L_{MS} \Big] \\
+\, 56\,\omega_c \left[\, r_{PIMH}\, L_{PIMH}\ +\ (\, \tfrac{21}{2}\sqrt{3}\,\delta\, R^2\ +\ 56\,)\, r_{PIMR}\, L_{PIMR} \right]
\end{aligned} \tag{5.6}
$$

5.2.2 Signaling costs with paging support

The signaling costs for mobility *with* paging support is composed of the same components as without paging (section 5.2.1) and additionally *paging updates* and *paging requests*. Clearly, the number of registration refreshes and handover signaling operations is reduced by the number of inactive mobile hosts. This in turn reduces the number of IGMP membership responses, PIM state refreshes and PIM subscribe/un-subscribe messages.

The total cost of signaling for mobility *with* paging [1] is a function of

$$\begin{aligned} C_{\text{w/ paging}} = \\ & f(\omega_c, \omega_w, r_{In}, r_{Out}, r_{Adv}, r_{IMEPAdv}, r_{MQR}, r_{PIMR}, r_{Rereg}, r_{PU}, \\ & \alpha, S_{MEPGr}, s_{PA}, \delta, \alpha, R, v, L) \end{aligned} \tag{5.7}$$

using the same notation as in section 5.2.1 and additionally the following variables

r_{In} Rate of incoming data sessions for a mobile host, equals the paging rate; $[\frac{1}{s}]$
r_{Out} Rate of outgoing data session for an idle mobile host; $[\frac{1}{s}]$
r_{PU} Rate of paging updates for an idle mobile host where $r_{PU} = r_{cc}/(s_{PA} + \frac{1}{2})$; $[\frac{1}{s}]$
s_{PA} Paging area size where the number of cells in the PA is $n_{PA} = 3s_{PA}(s_{PA} - 1) + 1$; [ ]
α Proportion of active mobile hosts to the overall number of mobile hosts; [ ]
L_{PU} Length of a paging update message; $[byte]$
L_{PR} Length of a paging request message; $[byte]$

Signaling type	**Expression**
MEP advertisements	$7^3\ r_{Adv}\ \omega_w\ L_{Adv}$
Inter-MEP advertisements	$7^3\ (\ 5 + S_{MEPGr}\ )\ r_{IMEPAdv}\ \omega_c\ L_{IMEPAdv}$
Re-registrations	$7^3\ m\ \omega_w\ [\ \alpha\ r_{Rereg}\ +\ (\ 1-\alpha\ )\ (\ r_{In} + r_{Out}\ )\ ]\ L_{Rereg}$
Paging updates	$7^3(\ 1\ -\alpha\ )\ m\ r_{PU}\ [(\ \omega_w\ +\ 3*\omega_c\ ) + 3(r_{In} + r_{Out})\omega_c]\ L_{PU}$
Paging requests	$7^3\ (\ 1\ -\ \alpha\ )\ m\ [\ (\ 2\ + n_{PA}\ )\ w_c\ + n_{PA}\ w_w\ ]\ r_{In}\ L_{PR}$
IGMP membership query/response	$7^3\ r_{MQR}\ \omega_c\ (L_{MQ}\ +\ (\ \alpha\ m\ +\ 6\ +\ 1)\ L_{MR})$
PIM hello messages	$(7^2\ +\ 7^1)\ \omega_c\ r_{PIMH}\ L_{PIMH}$
PIM state refreshes	$7\ (7^2\ +\ 7^1)\ (\ \alpha\ m\ +\ 6\ +\ 1)\ r_{PIMR}\ \omega_c\ L_{PIMR}$
Handover signaling	$\alpha\ m\ r_{cc}\ [\ 7^3(\omega_w L_{HOR} + 6\omega_c L_{MS}) + 7(7^2 + 7^1)\ \omega_c\ L_{PIMR}\ ]$

Table 5.3: Analytical expression of signaling operations *with* paging support

Again, we sum up all terms in table 5.3 and substitute m, r_{cc}, and additionally $n_{PA} = 3s_{PA}(s_{PA} - 1) + 1$ and $r_{PU} = r_{cc}/(s_{PA} + \frac{1}{2}) = \eta\frac{v}{R}/s_{PA}$.

[1]For analysis we consider only non-overlapping paging areas.

$$
\begin{aligned}
C_{\text{w/ paging}} =& \\
& 343\omega_w\Big[r_{Adv}L_{Adv} + \tfrac{3}{2}\sqrt{3}\alpha\delta R^2 r_{Rereg}L_{Rereg} + (1-\alpha)(r_{In}+r_{Out})L_{Rereg} \\
& \quad +\tfrac{3}{2}\sqrt{3}(1-\alpha)\delta R^2((r_{In}+r_{Out})L_{Rereg} + r_{In}L_{PU} + \eta\tfrac{v}{R}L_{HOR})\Big] \\
& +343\omega_c\Big[(\,S_{MEPGr}+5)r_{IMEPAdv}L_{IMEPAdv} + r_{MQR}(L_{MQ} + (\tfrac{3}{2}\sqrt{3}\alpha\delta R^2+7)L_{MR}) \\
& \quad +9\sqrt{3}\eta\tfrac{v}{R}\alpha\delta R^2 L_{MS} + \tfrac{3}{2}\sqrt{3}(1-\alpha)\delta R^2(\,s_{PA}+\tfrac{1}{2})w_c\eta\tfrac{v}{R}L_{PU}\Big] \\
& +56\omega_c\Big[r_{PIMH}\,L_{PIMH} + (\tfrac{21}{2}\sqrt{3}\alpha\delta R^2+49)r_{PIMR}L_{PIMR} + \tfrac{21}{2}\sqrt{3}\alpha\delta R^2\eta\tfrac{v}{R}L_{PIMR}\Big] \\
& \quad +(1-\alpha)[(3s_{PA}(s_{PA}-1)+3\,)w_c + (3s_{PA}(s_{PA}-1)+1)w_w]r_{In}L_{PR} \qquad (5.8)
\end{aligned}
$$

5.3 Results

We estimate the signaling costs in an access network with basic multicast-based mobility support and with the paging enhanced scheme. The parameters are set to typical values for analyzing cellular systems and listed in table 5.4.

Notation	**Value**
ω_w	5
ω_c	1
r_{Adv}	1 [1/s]
$r_{IMEPAdv}$	0.2 [1/s]
r_{MQR}	0.00833 [1/s]
r_{PIMR}	0.01666 [1/s]
r_{PIMH}	0.03333 [1/s]
r_{Rereg}	0.1 [1/s]
S_{MEPGr}	6 [cells]
δ	0.01([mobiles$/m^2$]
R	10 [m]
v	1 [m/s]
η	1
L	50 [byte]
r_{In}	0.001666 [1/s]
r_{Out}	0.001666 [1/s]
s_{PA}	2
$alpha$	0.1

Table 5.4: Parameters for performance evaluation

In figure 5.4 we plot the signaling costs in $\left[\frac{\text{weighted hops * bytes}}{s}\right]$ versus the number of mobiles per cell. We set the parameter α to 0.1 – 10% of the mobiles are active – and it can be seen that paging reduces

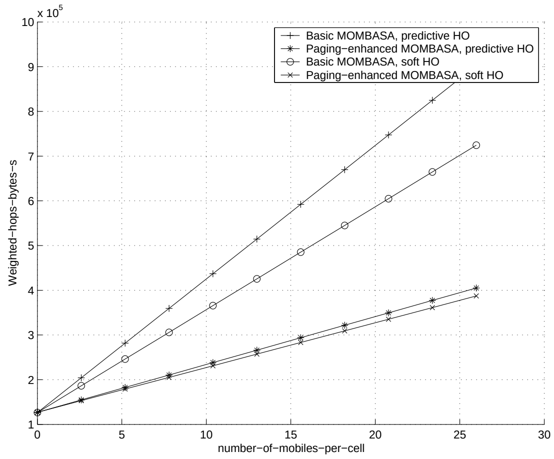


Figure 5.2: Signaling costs versus number of mobile hosts per cell

the signaling overhead considerably: With 5 mobiles per cell, the signaling costs in the basic approach are two times higher than in the paging-enhanced scheme and the relation is growing with the number of mobiles. A similar reduction of the signaling costs can be observed for soft handover. The impact of α – the proportion of the number of active mobile hosts – is shown in figure 5.3.

To find the optimum between paging and tracking, we change the parameter s_{PA}. As it can be seen in figure 5.4, the optimal paging area size is 2.

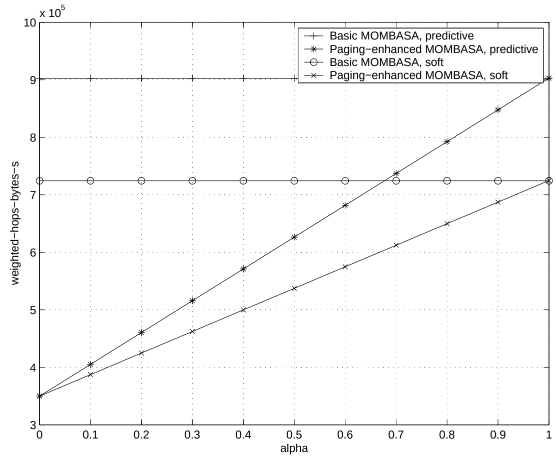


Figure 5.3: Signaling costs including paging versus proportion of active mobile hosts α

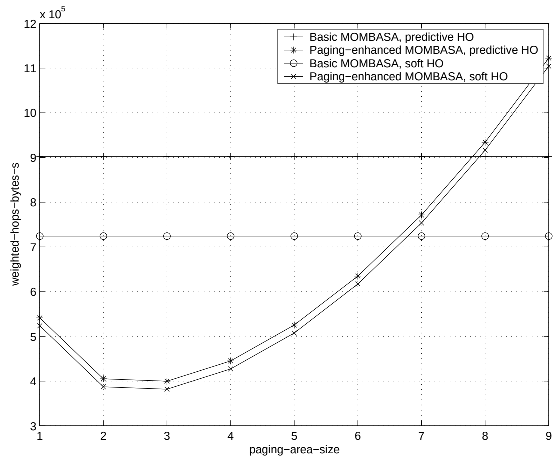


Figure 5.4: Signaling costs including paging versus size of the paging area

Chapter 6

Related Work and Conclusions

6.1 Related Work

The problem of reducing the cost of tracking mobile users has been addressed by many studies, e.g. [14, 17, 18] and others. The focus of these studies are on paging algorithms. The algorithms discussed in this report are partially based on the proposed schemes. Recently, there has been new efforts in the context of IP-based mobile networks, such as *Cellular IP*, *HAWAII* and *Paging Extensions of IETF Mobile IP*.

Cellular IP [12] and HAWAII [19] are micro-mobility protocols that utilize paging. The basic principles of paging in these approaches and in our approach are similar: They differentiate between active and inactive mobile hosts. An active mobile host registers each time it enters a new cell, whereas an inactive mobile host sends paging updates less often than re-registrations. An inactive mobile host is located by paging in a paging area grouped of several cells.

In Cellular IP, network nodes (access points or routers) have a routing cache and selected network nodes are provided with a paging cache. Both caches are separated from each other. This facilitates efficient management of the tables: The paging cache is expected to be much larger as the routing caches, but is updated less often. This is more efficient than a single cache. Moreover, in Cellular IP, the states are distributed in the access network and no single point of failure exists. But, in Cellular IP the number, size and population of paging areas are determined by the access network topology and the placement of paging caches. The MOMBASA approach allows to create paging areas fully independent of the topology. This feature eases the introduction of new paging mechanism, reconfiguration, etc.

In HAWAII, multicast-based paging is proposed. The main difference is that HAWAII is a micro-mobility protocol which is *not* based on multicast. The HAWAII protocol is extended by paging. This paging can be based on multicast (see [20]). We believe that this duplicates functionality and increases protocol complexity. MOMBASA is less complex, since the same multicast mechanisms are used for active (addressing, routing, handover) and for passive mobile hosts (paging, etc.).

In P-MIP [21], the basic IETF Mobile IP is extended by paging functionality. Two methods are proposed: home agent and foreign agent paging. To send paging requests to multiple foreign agents, replicated unicast packets are sent. Clearly, this wastes resources. Multicast can reduce the overhead of distributing paging requests to the Mobile IP foreign agents of a paging area. However, the same argument as for multicast-based paging in the HAWAII scheme is valid.

6.2 Conclusions

In this report we have proposed a paging extension for MOMBASA – a multicast-based mobility approach for cellular access networks. With paging the costs of mobility can be reduced and paging provides power savings at mobile hosts through reducing the registration signaling. The usage of multicast for paging offers a number of advantages: flexibility to create paging areas, ease of network management, efficient distribution of paging requests in the access network, and flexibility to introduce paging policies. We have presented analytical results: Assuming a small number of active mobile hosts and low data session rates, paging reduces signaling costs significantly. To minimize the signaling costs we have determined the optimal paging area size. The multicast-based paging approach has been implemented. Based on this implementation and the described testbed setup we will evaluate the performance of active and inactive handover by measurements.

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