

Technical University Berlin  
Telecommunication Networks Group

---

Protocol Specification of the  
MOMBASA Software Environment

A. Festag, L. Westerhoff  
{festag|westerhoff}@ee.tu-berlin.de

Berlin, October 2001  
Version 1.3

TKN Technical Report TKN-01-014

---

TKN Technical Reports Series  
Editor: Prof. Dr.-Ing. Adam Wolisz

# Contents

<b>1</b>	<b>Introduction</b>	<b>5</b>
<b>2</b>	<b>System Overview</b>	<b>7</b>
<b>3</b>	<b>Protocol Description</b>	<b>11</b>
3.1	Addressing . . . . .	11
3.2	Multicast . . . . .	12
3.3	Tables for Paging, Registration and Routing . . . . .	13
3.4	Timers . . . . .	14
3.5	Policies . . . . .	15
3.6	Buffer Management . . . . .	15
3.7	Overview of Protocol Operations . . . . .	15
3.7.1	Initial Registration and Address Allocation . . . . .	15
3.7.2	Packet Transport . . . . .	16
3.7.3	Handover . . . . .	16
3.7.4	Transition from Active to Inactive Mode . . . . .	17
3.7.5	Transition from Inactive to Active Mode . . . . .	17
3.7.6	Paging . . . . .	18
3.8	Protocols . . . . .	18
<b>4</b>	<b>Message Formats</b>	<b>20</b>
4.1	LHP Message Formats . . . . .	20
4.1.1	MEP Advertisements . . . . .	20
4.1.2	MEP Solicitation . . . . .	21
4.1.3	MH Registration Request . . . . .	21
4.1.4	MH Registration Reply . . . . .	23
4.2	IMP Message Formats . . . . .	24
4.2.1	Inter-MEP Advertisement . . . . .	24
4.3	MEP-GWP Message Formats . . . . .	24
4.3.1	Paging Request . . . . .	24
4.3.2	Paging Update . . . . .	25
4.4	IGMP Message Formats . . . . .	26
4.4.1	IGMP . . . . .	26
4.4.2	IGMP Membership Query Message . . . . .	26
4.4.3	IGMPv3 Membership Report Message . . . . .	27

4.4.4	IGMPv2 Leave Group Message . . . . .	28
4.5	PIM Message Formats . . . . .	30
4.5.1	PIM Hello Message . . . . .	30
4.5.2	PIM Register Message . . . . .	31
4.5.3	PIM Register-Stop Message . . . . .	32
4.5.4	PIM Join/Prune Message . . . . .	32
4.5.5	Other PIM Messages . . . . .	33
<b>5</b>	<b>Protocol specification</b>	<b>34</b>
5.1	Mobile Agent State Machine . . . . .	48
5.2	MEP State Machine . . . . .	59
5.3	Gateway Proxy State Machine . . . . .	65
5.4	Multicast Router State Machine . . . . .	73
<b>6</b>	<b>Simulation Trace</b>	<b>76</b>
<b>7</b>	<b>Acronyms</b>	<b>91</b>

# List of Figures

2.1	System architecture . . . . .	8
2.2	Paging Area: Non-overlapping (left) and Overlapping (right) . . . . .	9
3.1	Address translation by means of encapsulation/decapsulation . . . . .	12
3.2	Address translation by means of NAT . . . . .	13
3.3	MOMBASA protocols involved in signaling for handover . . . . .	19

# Chapter 1

## Introduction

<sup>1</sup> In general IP multicast supports location-independent addressing and routing. This ability of multicast is similar to the requirements of mobility support in IP-based networks, though in a different context. **MOMBASA** stands for **M**obility support – **A** **M**ulticast-**B**ased **A**pproach. MOMBASA intends to utilize multicast for network-level mobility support. Contrary to the classic mobility approach of address translation and indirect routing (e.g. IETF Mobile IP [16, 22]), MOMBASA eliminates the need for IP address translation. Therefore MOMBASA has three main advantages:

- Rerouting for handover is executed in a network node where the path to the old and the new access point diverge (and not in a mobility agent on the mobile's home network which might be distant to the current location of the mobile).
- As a matter of principle, a (possibly future) multicast infrastructure and signaling is reused for handover. The multicast is complemented by *handover-specific* functionality (such as paging, last-hop-signaling etc.). Nevertheless it is not required to replace the multicast by a handover-specific infrastructure and signaling at all.
- Multicast offers flexible mechanisms to control the service interruption. In the utmost case packets can be distributed efficiently to potential new access points which buffer the packets and the handover latency is reduced to an absolute minimum.

The MOMBASA software environment is a generic platform to investigate the utilization of multicast for host mobility in IP-based networks. This document specifies protocols for this environment. The specification is the basis for the implementation.

The MOMBASA software environment provides the following features:

- The MOMBASA software environment provides mobility support in an access network. Multicast is used for *micro-mobility*<sup>2</sup> support.
- Even though multicast might be used as a sole mechanism for routing of packets in mobile networks (see e.g. [20]), typical mobility-specific functionalities are added complementing the basic multicast to support location management, handover initiation, paging, indirect registration and other functionalities.

---

<sup>1</sup>This work has been partly supported by SIEMENS.

<sup>2</sup>Handover between cells of an access network. Micro-mobility is transparent to the *macro-mobility* protocol.

- The software environment provides a generic interface to the multicast protocol. The interface can be adapted to support certain classes of multicast approaches. At this stage, the implementation of the MOMBASA software environment employs IGMPv2 / PIM-SM [12, 13]; IGMPv3 and SSM [3, 4] will be examined at the coming stage. However, the specification is independent of the particular multicast routing and access protocols as much as possible.
- The MOMBASA software environment works consequently with soft states.
- Policies grant a high degree of freedom (e.g. for rerouting, paging, interface selection, etc.)

The outline of the document is as follows: In the second chapter, the overall system is described and important terms defined. In chapter three, the overall protocol is explained. Message formats are specified in chapter four. Finally, the protocol specification can be found in chapter five and a simulation trace described by Message Sequence Charts (MSCs) in chapter six.

## Chapter 2

# System Overview

The system consists of the following core elements, as shown in figure 2.1. These include:

- *Mobile User (MU)*. Person equipped with a single or several communication devices and using communication services. A Mobile User traverses the coverage of a cellular network while on the move. A Mobile User is identified by a unique personal identifier.
- *Mobile Host (MH)*. An IP-based communication device equipped with a single or multiple wireless network interfaces. Multiple interfaces usually support different technologies.<sup>1</sup> With the success of software radio an interface might adapt to different wireless technologies. A Mobile Host may vary from a dumb terminal to a powerful stand-alone machine.
- *Access Point (AP)*. Stationary network node with a single or multiple down-link interfaces and a wire-line interface. It can be considered as a router which routes packets between the wireless and the wire-line network part. An Access Point performs Network Address Translation between multicast and unicast addresses. Additionally mobility-related tasks are performed by means of signaling. With respect to the Multicast Routers in the Handoff Domain, the Access Points act as multicast receivers. Access Points cooperate to support seamless handover.
- *Multicast Router (MR)*. Stationary network node with multiple wire-line interfaces between which packets (both multicast and unicast) are routed. It is assumed that a Multicast Router is a standard device and has no specific mobility-related functionality.
- *Gateway (GW)*. A stationary network node with multiple wire-line interfaces. A Gateway interconnects the Handover Domain with the global Internet. A Gateway performs Network Address Translation between unicast and multicast addresses. It acts as a Multicast Router and has additional mobility-related tasks.

Additionally the following terms are important:

- *Handover Domain*. An IP network under the control of a single authority. It consists of Access Points, Multicast Routers and Gateways. It may consist of multiple subnets.

---

<sup>1</sup>In this document it is assumed that the last hop between MH and AP is wireless though this is not a not necessary for mobility.

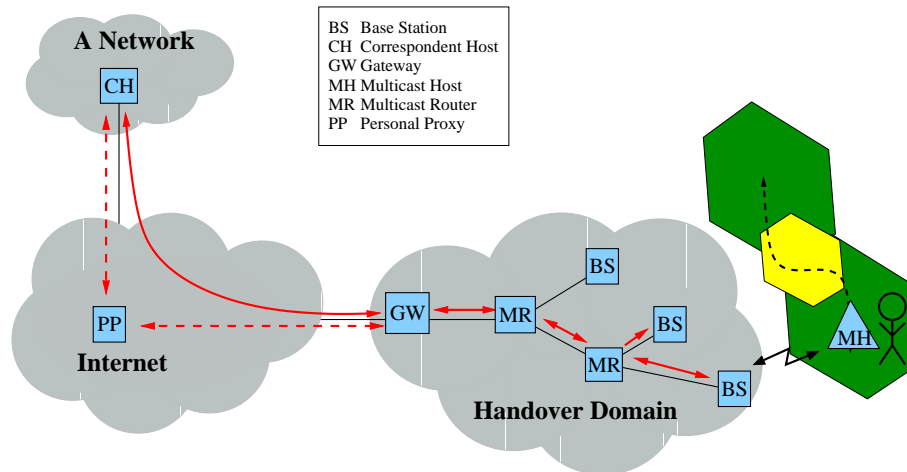


Figure 2.1: System architecture

- *Paging Area.* Set of wireless cells with a specific geographic coverage. When the exact location of the Mobile Host is not known, the Mobile Host is located by *Paging* within a Paging Area. Paging avoids locating a Mobile Host by broadcast.
- *Access Point Group.* Access Points which are potential candidates for handover form an Access Point group. When a Mobile Host registers with the actual Access Point the other Access Points belonging to the group will also subscribe to the multicast channel. The current Access Point is called *active*, the other Access Points *passive*. A group of Access Points is usually formed of adjacent and/or overlapping wireless cells.

Hosts and servers in the Internet communicating with Mobile Hosts in the Handover Domain are usually characterized as *Corresponding Hosts*.

It is assumed that a Mobile User can be identified by a unique personal identifier. Moreover, an Internet-wide location service is assumed which resolves the unique personal identifier of the Mobile User into IP addresses identifying the Mobile Host. Future mobility-aware applications will be able to communicate with the Mobile User directly (via the shortest path). Non-mobility-aware applications can communicate with the Mobile User via a Personal Proxy. Routing via a Personal Proxy causes indirect routing with all the disadvantages known from Mobile IP. Nevertheless a Personal Proxy can convert media (fax to email, voice to email, etc.) and preserves the location privacy of the Mobile User. Details of this architecture are beyond the scope of this document and it is referred to [18, 23].

The software components of the system are executed on the Mobile Hosts, Access Points, Multicast Routers and Gateways. The components are:

- *Mobile Agent.* A Mobile Agent is executed on the Mobile Host and performs mobility-related tasks.
- *Mobility-Enabling Proxy.* A MEP is executed on the Access Point. A MEP advertises its services in the wireless cell(s), manages registration tables, initiates and controls handoffs, exchanges routing informations with the Gateway Proxy and with other MEPs and controls



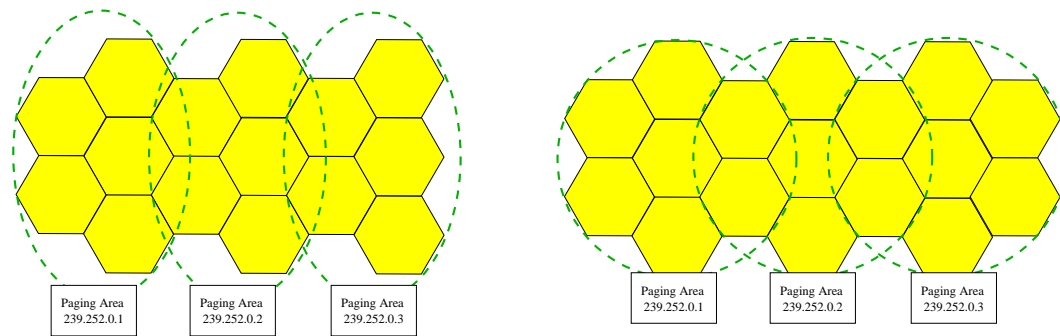


Figure 2.2: Paging Area: Non-overlapping (left) and Overlapping (right)

traffic between the wired and wireless networks part. A MEP executes address translation between the Mobile Host's multicast and unicast address.<sup>2</sup>

- *Multicast Router demon.* A Multicast Router demon is executed on the Multicast Router. The type of demon depends only on the supported multicast protocol and need not be mobility aware.
- *Gateway Proxy (GWP).* The GWP is executed on the Gateway. The Gateway Proxy (or Paging demon) performs mobility-related tasks, such as location management and paging.

A Mobile Host may move freely through the coverage of wireless cells, while being associated with an Access Point and communicating. When it crosses cell boundaries a handover to the new Access Point is executed.

The main features of the system are:

- Addressing and routing based on IP- and IP-style multicast
- Multicast proxies in access points to disburden the mobile host from multicast group management for mobility support,
- Advertisements/Solicitations to advertise the availability of Mobility-Enabling Proxies (MEPs),
- Inter-MEP advertisements to register mobile hosts in advance,
- Packets can be distributed in advance to candidate Access Points by means of multicast. These *passive* Access Points buffer the packets. When the Mobile Host registers with one of the Access Points, it becomes *active* and the buffered packets will be forwarded to the Mobile Host. The other Access Points drop the buffered packets. This method reduces the handover latency to a minimum.
- The system supports heterogeneous wireless technologies, in particular multiple interfaces in the Mobile Host are supported.

<sup>2</sup>The term MEP group and Access Point group is used interchangeable.

- The system differentiate between active and inactive mobile hosts. Inactive Mobile Hosts may have passive connectivity, where the frequency of re-registrations is decreased. This reduces the energy consumption of Mobile Hosts and signaling load on the wireless link.
- *Paging* is used to determine the exact location of a Mobile Hosts before delivering packets destined to an inactive Mobile Host. Paging allows the Mobile Host to update its location information less frequently at the cost of providing the network with only approximate location information. For paging in MOMBASA, wireless cells are grouped to Paging Areas and are identified by a multicast channel (see figure 2.2 for Paging Areas with non-overlapping and overlapping wireless cells). When locating a Mobile Host by paging, a paging request is sent via the paging channel. The usage of multicast facilitates a flexible and dynamic composition of Paging Area. In particular, the Paging Areas are not tied to the wired network topology in the Handover Domain.
- In principle, the system facilitates policies to provide flexibility and efficiency and to control system behavior. The policies separate decision making from algorithms. In particular, policies are used to select the *optimal* access point among several possible ones and when to handover, and for control of buffering, forwarding and paging algorithms.
- The system facilitates soft-state of the location-management tables as well as of the multicast routing tables. Whereas the soft-state is an inherent feature of the multicast routing protocol, its consequent application for the location management allows the storage of network state in a distributed manner across various nodes and protocols.

## Chapter 3

# Protocol Description

### 3.1 Addressing

It is assumed that a Mobile User is identified by a permanent and unique *Personal Identifier*, which can be resolved to application-specific addresses and to IP addresses, respectively. We do not constrain to a specific address format; a Network Access Identifier (NAI) [1] might be reasonable. This address type is widely used as a *userID* (e.g. *user@realm.com*) submitted by the client during PPP authentication.

Moreover, it is assumed that a Mobile Host is identified by two addresses: *multicast channel* and a *unicast IP address*. A multicast channel is a combination of a unicast IP source address  $S$  and the SSM destination address  $G$ , which form a  $(S, G)$  pair. In the described architecture the source address  $S$  is usually the Gateway's unicast IP address. For  $G$  the address realm 232/8 (232.0.0.0 - 232.255.255.255) is reserved<sup>1</sup>.

When a Mobile Host enters the Handover Domain the first time, a *multicast channel* and a *unicast IP address* is assigned to the Mobile Host. Both addresses are quasi-permanent: they are assigned once and remain unchanged as long as the Mobile Host is registered within the Handover Domain. Within the handover domain, the multicast channel is used to transport *down-link* data packets, the unicast IP address is used for *up-link* data packets. Outside the Handover Domain the unicast IP address is used for both up-link and down-link packets. Therefore the unicast address must be a globally valid IP address. The multicast channel is regarded as a private address and valid inside the Handover Domain, only.

In the MOMBASA software environment a specific addressing concept is used: Suppose, for the Handover Domain a pool of unicast IP addresses is reserved which can be assigned to Mobile Hosts. Then, each unicast IP address has a corresponding IP address in the multicast address realm (232/8 addresses). Both the unicast and multicast address pools are continuous thus the multicast address of a Mobile Host can be simply determined by address mapping. See table 3.1 for an example.

---

<sup>1</sup>Designated as Source-Specific Multicast (SSM) destination addresses [2]

Unicast IP address	Multicast channel (S,G)
130.149.49.1	(S,232.149.49.1)
130.149.49.2	(S,232.149.49.2)
.	.
.	.
130.149.255.254	(S,232.149.255.254)

Table 3.1: Address mapping between unicast addresses and multicast channels

The use of multicast addresses in the Handover Domain requires an address translation by IP encapsulation [21] or by Network Address Translation (NAT) [9]. See figures 3.1 and 3.2 for examples.

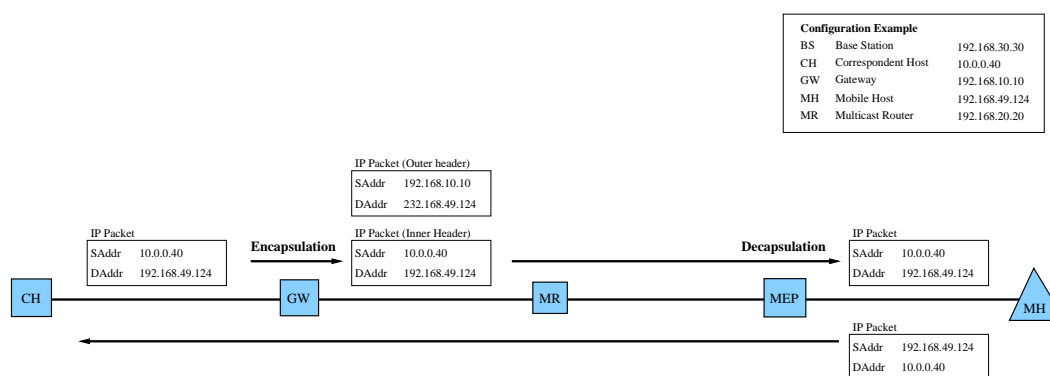


Figure 3.1: Address translation by means of encapsulation/decapsulation

One part of the multicast address space is reserved for signaling operations, i.e. for

- MEP groups
- Paging Area

### 3.2 Multicast

Multicast is an essential part of the system. Multicast is provided for:

- Transport of data packets in the down-link direction from the Gateway Proxy towards the MEPs. (In particular multicast provides efficient data distribution to a group of MEPs in order to support seamless handover),
- Transport of signaling packets to locate inactive Mobile Hosts with paging,
- Management of multicast groups, such as paging areas and MEP groups,

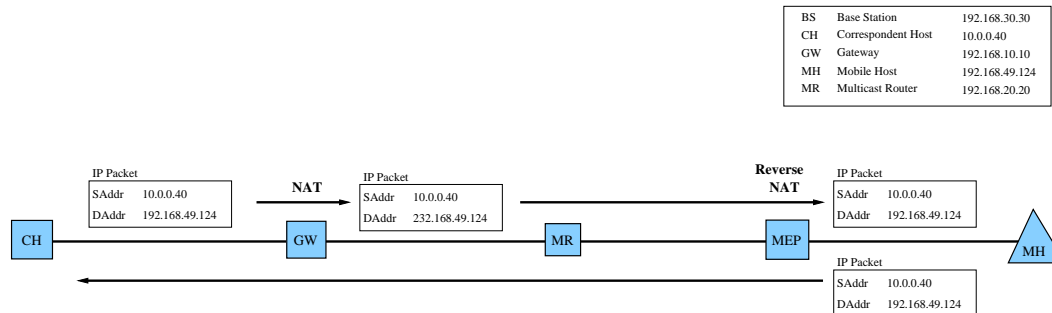


Figure 3.2: Address translation by means of NAT

### 3.3 Tables for Paging, Registration and Routing

It is distinguished between paging, registration and routing tables. All network nodes in the Handover Domain make use of their standard *routing tables* MRIB and RIB (multicast and unicast routing information base). Additionally each MEP manages a *registration table* and the Gateway Proxy a *paging table*. The paging and registration tables have *soft states*. They require a periodic refresh to keep network state alive. Moreover a multicast routing protocol uses soft state mechanisms to adapt to the underlying network conditions and to dynamics of multicast group membership.

The *registration table* of a MEP has an entry for each active Mobile Host registered directly and additionally entries for Mobiles which have been pre-registered by other MEPs.<sup>2</sup> An entry consists of:

- Link-level address of the Mobile Host,
- Interface of the last received registration,
- Unicast IP address of the Mobile Host,
- Flag if the Mobile Host has registered directly or was indirectly pre-registered via another MEP,
- Requested registration lifetime,
- Remaining registration lifetime of a pending or current registration.

A new entry is inserted in the registration table when a Mobile Host registers directly with a MEP or is indirectly pre-registered by another MEP. An entry is updated when an entry already exists: Three cases can be distinguished:

1. The Mobile Host was directly registered and re-registers.
2. The Mobile Host was directly registered and is pre-registered by another MEP.
3. The Mobile Host was indirectly pre-registered by another MEP and registers directly.

<sup>2</sup>Note that inactive Mobile Hosts do not have an entry.

When the remaining lifetime is less than zero or a registration message with lifetime zero is received, the entry will be removed from the registration table.

The *paging table* of the Gateway Proxy has an entry for each Mobile Host in the Handover Domain. An entry consists of:

- Unicast IP address of the Mobile Host,
- Paging Area id of last paging-update,
- Requested paging-update lifetime,
- Remaining lifetime of the current paging-update.
- Registration identification for reordering detection.

A new entry is inserted into the paging table and the entry is updated when a paging update is sent by a Mobility-Enabling Proxy (MEP) for an inactive Mobile Host. When the remaining lifetime of the current paging table entry is less than zero or a paging update with lifetime zero is received, the entry is removed from the paging table.

For routing of packets, the standard routing tables are used. Unicast packets are routed by means of the standard unicast routing table (RIB); multicast packets use the standard multicast routing table (MRIB).

For a Mobile Host two cases have to be considered, whether the Mobile Host is *active* or *inactive*. For an *active* Mobile Host, entries in registration tables and entries for the Mobile Host's multicast channel in the multicast routers exist. For an *inactive* Mobile Host, the multicast routing table entries of the multicast routers and the registration table entries are timed out, whereas the paging table entry still exists. The re-establishment of the multicast routing table entries can be triggered by paging.

For efficiency reasons the multicast router provides a multicast forwarding cache (MFC) at kernel level and additionally a multicast routing table (MRIB) at user space level in the multicast routing daemon. However, here the paging functionality is realized in a paging demon and requires an interaction with the multicast functionality.

### 3.4 Timers

Timers are used to realize soft-state in a distributed manner across the network nodes. In general two types of timers are distinguished: Timers that control the sending of signaling messages for registration and advertisements and timers for aging out state in registration and paging tables. In table 3.2 the MOMBASA-specific timers are listed. Note that table 3.2 does not include timers which control states in multicast routing tables (MRIB) or multicast forwarding caches (MFC).

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

Table 3.2: Timers in the MOMBASA software environment

### 3.5 Policies

In general policies are a set of rules to administer, manage, and control access to network resources [19]. In MOMBASA policies are used to

- select the interface in order to determine the optimal network access,
- determine *when* to handover (including hysteresis),
- allocate the optimal buffer space in passive Access Points buffering packets,
- select the optimal rerouting policies: *break-before-make*, *make-before-break* or *predictive handover*.

### 3.6 Buffer Management

For predictive handover, passive Access Points buffer packets. The buffer is allocated when the Mobile Host is pre-registered with the MEP and de-allocated when the Mobile Host's entry is removed from the registration list or the Mobile Host registers directly with the Mobility-Enabling Proxy. Determining the allocated buffer size is policy-controlled and for further study.

### 3.7 Overview of Protocol Operations

The next section provides a rough overview of the protocol operations. It is divided into initial registration and address allocation, packet transport, handover and paging.

#### 3.7.1 Initial Registration and Address Allocation

1. MEPs advertise their availability on each link for which they provide service. Alternatively, a Mobile Host may solicit a MEP Advertisement from a MEP through a MEP solicitation.
2. When a Mobile Host enters the Handover Domain, it associates a unicast IP address with its interfaces. The address may be dynamically acquired by the Mobile Host through a protocol

such as DHCP [8] or may be owned as a long-term address for its use only in the Handover Domain. This step should be tied with authorization and authentication.<sup>3</sup>

3. The Mobile Host sends a registration request to the MEP indicating an active state.
4. The MEP processes the registration request and inserts a new entry in its registration table, sends a reply to the Mobile Host, determines the multicast channel assigned to the mobile host's IP address and subscribes for the multicast channel on behalf of the mobile host. Additionally the MEP triggers the other MEPs in its group to likewise subscribe for the multicast channel.

Alternatively, a Mobile Host may go immediately into inactive state after acquiring the unicast IP address. In this case the Mobile Host sends an inactive registration to the MEP which sends a paging update to the Gateway Proxy on behalf of the Mobile Host.

As long as the Mobile Host remains in the active state, a re-registration to the MEP is sent frequently. This, in turn triggers the MEP to send a paging update to the Gateway Proxy.

### 3.7.2 Packet Transport

At first it is assumed that the Gateway and MEP applies IP-IP encapsulation and decapsulation, respectively (see figure 3.1). The case where the Gateway performs NAT (see figure 3.2) is similar.

- Downstream traffic directed to the Mobile Host:
  1. A CH may send packets to the unicast IP address of the Mobile Host.
  2. The Gateway Proxy intercepts the packets and performs IP-IP encapsulation. If an entry in the multicast forwarding cache (MFC) for the channel exists, the packet is forwarded directly towards the multicast channel. Otherwise the Gateway Proxy is informed and packets are queued. If no entry exists in the paging table the multicast routing demon is notified. If an entry in the multicast routing table in the demon exists, the queued packets are forwarded. In the case that an entry in the paging table exists, the packets are buffered in the Gateway Proxy and the Mobile Host will be paged. (The paging case will be considered separately. See section 3.7.6)
  3. Intermediate multicast routers forward the packet along the multicast channel.
  4. When the active MEP receives a multicast packet, the MEP decapsulates the packet and forwards it to the Mobile Host's link local address. A passive MEP buffers the packet.
  5. Finally, the Mobile Host receives the packet.
- Upstream traffic is originated by the Mobile Host and is sent via unicast.

### 3.7.3 Handover

- Mobile Host initiated handover
  1. The need for handover is detected by one of the algorithms for link availability detection: monitoring of layer-2 parameters, advertisements-based or polling.

---

<sup>3</sup>Details of address allocation, authorization and authentication are out of scope.



2. If the Mobile Host is in active state, it sends an active registration request to the MEP.
3. The MEP processes the registration request and updates its registration table. If an entry in the MEP's registration table was already existing due to a pre-registration by another MEP then buffered packets (if any) will be forwarded to the Mobile Host. Additionally the MEP triggers the other MEPs in its group to likewise subscribe for the multicast channel.
4. When the Mobile Host's entry in the registration table of the old MEP times out then the entry is removed and the MEP triggers other MEPs in its group to un-subscribe the Mobile Host's multicast channel. The Mobile Host may also send an explicit de-registration message (registration message with lifetime zero).
5. When a MEP has both a direct and an indirect registration, the direct registration has higher priority than the indirect one. However the indirect registration is not discarded but noted in the registration entry. When the direct registration expires (or is deleted by a de-registration) and the indirect one is still valid the MEP becomes a *passive* MEP. This avoids certain race conditions after handovers.

Alternatively, a handover can be initiated by the MEP.

### **3.7.4 Transition from Active to Inactive Mode**

The transition from active to inactive mode happens as follows:

1. The Mobile Host detects that for some time data was neither sent nor received.
2. The Mobile Host sends a registration request denoting inactive to a MEP.
3. If the MEP has a registration entry for the Mobile Host this entry is deleted and MEPs in the same MEP group are notified. The MEP un-subscribes from the corresponding multicast channel. A paging update is generated and sent to the Gateway Proxy.
4. The Gateway Proxy receives the paging update and generates an entry in the paging table.
5. When the Mobile Host's entry in the registration table of the old MEP times out then the entry is removed and the MEP triggers other MEPs in its group to un-subscribe the Mobile Host's multicast channel. The Mobile Host may (and should if possible) send an explicit de-registration message (registration message with lifetime zero) to the old MEP.

### **3.7.5 Transition from Inactive to Active Mode**

Wakeup (the transition from inactive to active mode) is performed when the inactive Mobile Host wants to send data or when it is paged (see next section).

1. The Mobile Host sends a registration request indicating active state and that the registration is a wakeup to a MEP of its choice.
2. The MEP processes the registration request and inserts a new entry in its registration table, sends a reply to the Mobile Host, determines the multicast channel assigned to the mobile host's IP address and subscribes for the multicast channel on behalf of the mobile host. Additionally

the MEP triggers the other MEPs in its group to likewise subscribe for the multicast channel. Finally the MEP sends a paging update with lifetime zero to the Gateway Proxy.

3. The Gateway Proxy receives the paging update and removes its entry in the paging table.

### 3.7.6 Paging

For paging it is assumed that all MEPs belonging to a specific paging area have subscribed to the corresponding multicast channel.

1. When a Gateway Proxy receives a packet and has an entry for the destination Mobile Host in its paging table the Gateway Proxy buffers the packet. It sends a paging request to the paging area. For this the Gateway Proxy determines the IP multicast address corresponding to the paging area and forwards the paging request on the multicast channel.
2. The MEPs receive the paging request and forwards it on their wireless interface.
3. When the Mobile Host finds its unicast IP address in the paging request, the Mobile Host performs the wakeup procedure as described in the previous section.

## 3.8 Protocols

Consider a typical MOMBASA network which uses IGMP and PIM-SSM as multicast protocols. Then the overall network uses five protocols

- *Last-Hop Protocol (LHP)*. Defined protocol between Mobile Host and MEP.
- *Inter-MEP Protocol (IMP)*. Defined protocol between MEPs.
- *MEP-GWP protocol*. Defined protocol between MEP and GWP.
- *IGMP*. Internet Group Management Protocol(IGMP). Standard management protocol for IP multicast. Actual versions are IGMPv2 [13] and IGMPv3 [4]. IGMPv3 adds support for single source multicast. IGMPv1 [5] is considered for backward compatibility only. The implementation of IGMPv3 is based on [14, 15]
- *PIM-SSM*. Protocol Independent Multicast-Single Source Mode (PIM-SSM). Standard multicast routing protocol based on explicitly subscribe- and un-subscribe-operations [12]. The implementation is based on [7, 11, 12]

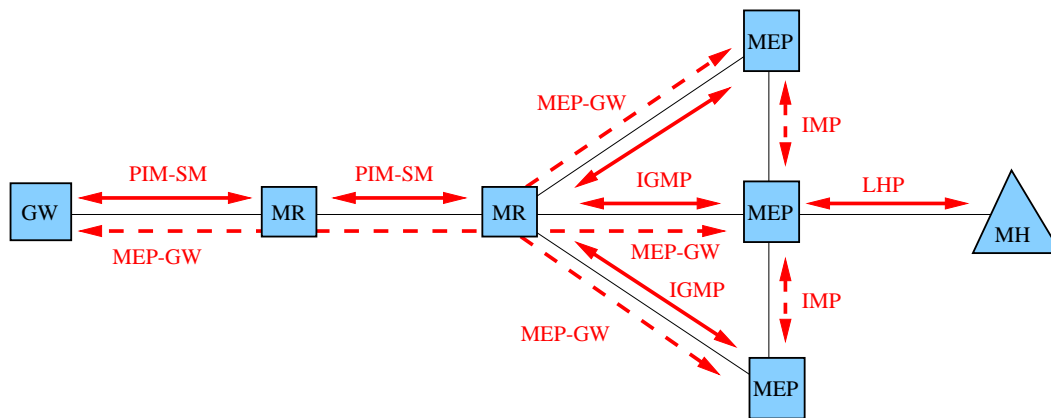


Figure 3.3: MOMBASA protocols involved in signaling for handover



<i>Type</i>	17 (MEP Advertisement)
<i>Length</i>	Length of this extension (6).
<i>Sequence Number</i>	Count of MEP Advertisement sent since the MEP was initialized. Wrap-around as in RFC2002[22] to enable reboot detection.
<i>Registration Lifetime</i>	Longest lifetime (in seconds) the MEP is willing to accept.
<i>R</i>	Not used (Registration required, for IETF Mobile IP only)
<i>B</i>	Busy. The MEP will not accept registrations from additional Mobile Hosts.
<i>H</i>	Not used (Home Agent, for IETF Mobile IP only)
<i>F</i>	Not used (Foreign Agent, for IETF Mobile IP only)
<i>M</i>	Not used (Minimal encapsulation, for IETF Mobile IP only)
<i>G</i>	Not used (GRE encapsulation, for IETF Mobile IP only)
<i>V</i>	Not used (VanJacobson Header Compression, for IETF Mobile IP only)
<i>P</i>	Indicates if the MEP supports paging or not (Not available in IETF Mobile IP).
<i>R</i>	Reserved. Zeroed.
<i>Reserved</i>	Zeroed.

#### 4.1.2 MEP Solicitation

A MEP solicitation is sent by a Mobile Host to solicit a MEP Advertisement from a MEP. A MEP solicitation is identical to a ICMP Router Solicitation with the restriction that the IP TTL field is set to 1.

#### 4.1.3 MH Registration Request

A registration request is sent by a Mobile Host to the MEP. A Mobile Host registers when a Mobile Host

- is in the initial or active state and detects that it has moved to a new MEP,
- detects that its registration-request timeout is about to expire, indicating that an expected reply to a sent registration-request is missing,
- detects that its re-registration timer is about to expire,
- is in active state and detects that its current MEP has rebooted,
- transits from active to inactive state or vice versa.

When the Mobile Host is in active state it sets the appropriate flag in the registration request message.

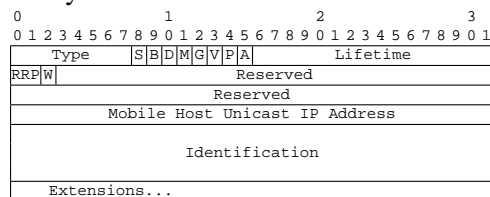
IP fields:

Source Address	Mobile Hosts unicast IP address.
Destination Address	MEP IP address from the corresponding MEP Advertisement.
TTL	Set to 1.

UDP fields:

Source Port      Variable  
 Destination Port   434

The UDP header is followed by:



<i>Type</i>	2 (Registration Request)
<i>S</i>	Not used (Simultaneous Binding, for IETF Mobile IP only)
<i>B</i>	Broadcast datagrams
<i>D</i>	Not used (Decapsulation by Mobile Host, for IETF Mobile IP only)
<i>M</i>	Not used (Minimal encapsulation, for IETF Mobile IP only)
<i>G</i>	Not used (GRE encapsulation, for IETF Mobile IP only)
<i>V</i>	Not used (VanJacobson Header Compression, for IETF Mobile IP only)
<i>P</i>	Indicates if the Mobile Host supports Paging or not (Not available in IETF Mobile IP).
<i>A</i>	Indicates that the Mobile Host is active. (Not available in IETF Mobile IP).
<i>Lifetime</i>	Number of seconds remaining before the registration is considered expired. The lifetime for the inactive mode should be larger than for the active mode. Zero indicates a de-registration request. 0xffff indicates infinity.
<i>RRP</i>	Rerouting Policy. 0 Break-before-make 1 Make-before-break 2 Predictive
<i>W</i>	The Mobile Host is just waking up ( <i>A</i> must be also set).
<i>Reserved</i>	Zeroed.
<i>Mobile Host Unicast IP Address</i>	IP Address of the Mobile Host.
<i>Identification</i>	Used for matching registration requests with registration reply, and for protecting against replay attacks of registration messages [22].
<i>Extensions</i>	Optional Mobile Host - Gateway authentication extension (Prefix Length Extension, One-byte Padding Extension).

### 4.1.4 MH Registration Reply

A registration reply is sent by the MEP to reply to a registration request.

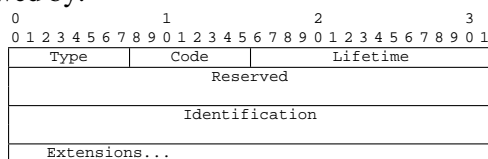
IP fields:

Source Address Copied from the MEP registration request destination field.  
 Destination Address MEP IP address.

UDP fields:

Source Port Variable.  
 Destination Port Copied from Source Port of the MEP registration request.

The UDP header is followed by:



*Type* 4 (Registration Reply)  
*Code* Indicates the result of the Registration Request.  
*Lifetime* Number of seconds remaining before the registration is considered expired.  
*Reserved* Zeroed.  
*Identification* Used for matching registration Requests with registration Reply, and for protecting against replay attacks of registration messages [22].  
*Extensions* Mobile Host - Gateway authentication extension (optional)

The following Codes are defined:

- 0 Registration accepted
- 64 Reason unspecified
- 65 Administratively prohibited
- 66 Insufficient resources
- 67 Mobile Host failed authentication
- 69 Requested lifetime too long
- 70 Poorly formed Request
- 80 GW host unreachable (ICMP error received)
- 81 GW port unreachable (ICMP error received)
- 82 GW unreachable (other ICMP error received)

## 4.2 IMP Message Formats

### 4.2.1 Inter-MEP Advertisement

An inter-MEP advertisement is sent by a MEP to other MEPs to advertise its availability and to pre-register Mobile Host with other MEPs of its MEP group. Therefore the group of MEPs form a IP multicast group with a pre-defined IP multicast address whereas the currently active MEP acts as a multicast sender.

IP fields:

Source Address      IP address from which the message is sent.  
Destination Address    Multicast IP address for the MEP group.

UDP fields:

Source Port      Variable  
Destination Port    434

0						1						2						3													
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
Type						Length						Sequence Number																			
Hold-time						Reserved																									
Unicast IP address of Mobile Host 1						..						Unicast IP address of Mobile Host N																			
Extensions...																															

*Type*                                    6 (Inter-MEP Advertisement)  
*Length*                                 Length of the extension excluding type and length fields.  
*Sequence Number*                    Count of Inter-MEP Advertisement sent since the MEP was initialized.  
*Hold-time*                             Number of seconds remaining until the pre-registration is considered expired.  
*Reserved*                               Zeroed.  
*Unicast IP address ...*              Unicast IP address of the Mobile Host to pre-register.

## 4.3 MEP-GWP Message Formats

### 4.3.1 Paging Request

A paging request is sent by the Gateway Proxy to a Paging Area which is identified by a multicast channel. The MEPs broadcast the paging request in their wireless cells or send them to the unicast IP address of the paged Mobile Host.

IP fields:

Source Address      Address from which the message is sent.  
Destination Address    Multicast address of the paging area.

UDP fields:

Source Port      Variable  
Destination Port    434



The UDP header is followed by:

										1										2										3									
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Type										Length										Sequence Number																			
Unicast IP address of Mobile Host																																							
Extensions...																																							

- Type*                      8 (Paging Request)
- Length*                    Length of the extension (6 Bytes).
- Sequence Number*      Count number of paging requests. Used to distinguish the paging request messages.

### 4.3.2 Paging Update

A paging update is sent by the Mobile Host to refresh the Gateway Proxie’s paging cache. It is sent frequently if the Mobile Host is in inactive state.

IP fields:

- Source Address            Unicast address of the Mobile Host.
- Destination Address    Address of the Gateway Proxy.

UDP fields:

- Source Port                Variable
- Destination Port        434

The UDP header is followed by:

										1										2										3									
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Type										Length										Lifetime																			
Unicast IP address of Mobile Host																																							
Identification																																							
Current Paging Area Id																																							

- Type*                                      10 (Paging Update)
- Length*                                    Length of the message.
- Lifetime*                                  Number of seconds remaining before the lifetime is considered expired. Copied from registration request.
- Identification*                          Identification copied from registration request.
- Current Paging Area ID*                Multicast Address of the Paging Area. Set by the current MEP.

## 4.4 IGMP Message Formats

### 4.4.1 IGMP

IGMP version 1 [5], version 2 [13] and version 3 [4] provide a method through which a host can join or leave a multicast group. IGMP version 3 adds support for *Single Source Multicast (SSM)*: a host or router may report interest in receiving packets *only* from specific source addresses, or from *all but* specific source addresses sent to a specific multicast address.

IGMP messages are encapsulated in IP datagrams, with an IP protocol number of 2. The IGMP messages are sent with a TTL of 1. They carry an IP Router Alert Option [17] in its IP header.

The following types are defined:

0	Hello
0x11	Membership Query (General Query or Group-Specific Query or Group-and-Source-Specific Query)
0x12	Version 1 Membership Report
0x16	Version 2 Membership Report
0x22	Version 3 Membership Report
0x17	Leave Group

In MOMBASA II only IGMPv3 is provided.

### 4.4.2 IGMP Membership Query Message

Sent by Multicast Routers to query the multicast reception state of neighboring interfaces of MEPs or other Multicast Routers.

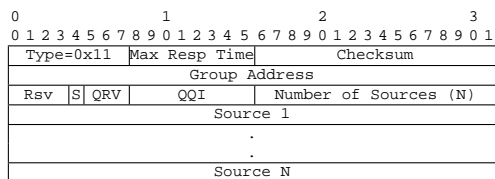
There are three variants:

- *General Query*. Sent by a multicast router to learn the complete multicast reception state of the neighboring interfaces. General Queries are periodically sent. The *Group Address* field and the *Number of sources* are zero.
- *Group-Specific Query*. Sent by a multicast router to learn the reception state for a *single* multicast address of the neighboring interfaces. The *Group Address* field contains the multicast address of interest, the *Number of sources* field contains zero.
- *Group-and-Source-Specific Query*. Sent by a multicast router to learn if any neighboring interface desires reception of packets for a specific multicast address from any address of the list of sources. The *Group address* field contains the multicast address of interest and the *Source Address* fields contain the source address(es) of interest.

IP fields:

Destination Address	224.0.0.1 for General Query (All-hosts multicast group) Multicast address of interest for Group-Specific and Group-and-Source-Specific Query.
TTL	1

IGMP Membership Query message format:



<i>Type</i>	0x11 (IGMP Membership Query)
<i>Max Resp Time</i>	Maximum allowed time before sending a responding report, in units of 1/10s.
<i>Checksum</i>	Checksum of the whole IGMP message (entire IP payload).
<i>Group Address</i>	Multicast group address. Zeroed in a General Query. Multicast address in a Group-Specific or Group-and-Source-specific query.
<i>Rsv</i>	Zeroed.
<i>S</i>	Suppress Router-Side Processing (S-Flag). It indicates to a multicast router to suppress the normal timer updates upon hearing a request.
<i>QRV</i>	Querier's Robustness Variable. It allows tuning for the expected packet loss. If a network is expected to be lossy, the Robustness Variable may be increased. Default:2
<i>QQI</i>	Querier's Query Interval in seconds. If a Multicast Router is not the current querier adopt the value from the most recently received Query. Default: 135 sec.
<i>Number of Sources</i>	Number of sources present in the Query. The field is zero in a General Query or a Group-Specific Query.
<i>Source address</i>	IP unicast addresses.

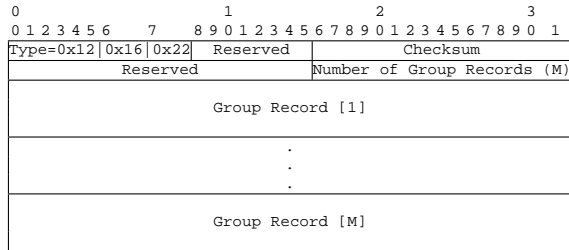
### 4.4.3 IGMPv3 Membership Report Message

Sent by a MEP or Multicast Router to report the current multicast reception state of their interfaces.

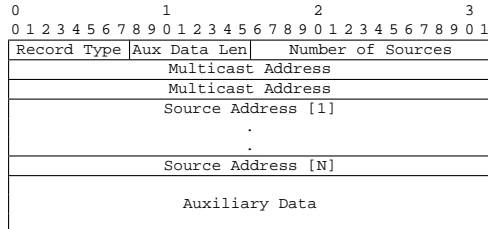
IP fields:

Source Address	IP address of the corresponding interface in the MEP or Multicast Router.
Destination Address	224.0.0.13 (All IGMPv3-capable routers) (for IGMPv1 and v2 the multicast group address specified in the Group Address field of the Membership Query message).
TTL	1

IGMP Membership Report message format:



Each Group Record consists of



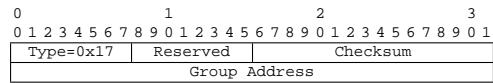
<i>Type</i>	0x12 IGMPv1 Membership Report, 0x16 IGMPv2 Membership Report, 0x22 IGMPv3 Membership Report,
<i>Reserved</i>	Zeroed
<i>Checksum</i>	Checksum of the whole IGMP message (entire IP payload).
<i>Number of Group Records</i>	Number of records present in the message.
<i>Group Record</i>	Contains information about the sender's membership in a multicast group on the interface from which the Report is sent.
<i>Record Type</i>	Current state of record or change of the filter mode. In INCLUDE mode, reception of packets is requested only for those IP parameters listed in the source list. In EXCLUDE mode, reception of packets is requested from all IP source addresses <i>except</i> those listed in the source-list. 1 MODE_IS_INCLUDE 2 MODE_IS_EXCLUDE 3 CHANGE_TO_INCLUDE_MODE 4 CHANGE_TO_EXCLUDE_MODE 5 ALLOW_NEW_SOURCES 6 BLOCK_OLD_SOURCES
<i>Aux Data Len</i>	Length of the Auxiliary Data field (units of 32-bit words).
<i>Number of sources</i>	Number of sources present in the report.
<i>Auxiliary Data</i>	Not used.

#### 4.4.4 IGMPv2 Leave Group Message

A IGMPv2 Leave Group message is sent by a MEP to un-subscribe from a multicast channel.

Source Address	IP address of the corresponding interface in the MEP.
Destination Address	224.0.0.2 (All routers).

IGMPv2 Leave Group message format:



- Type*            0x17 (IGMPv2 Leave Group)
- Reserved*        Zeroed
- Checksum*        Checksum of the whole IGMP message (entire IP payload).
- Group Address*   Multicast group address to leave.

## 4.5 PIM Message Formats

All PIM control messages have protocol number 103.

The following PIM-types are defined:

- 0 Hello
- 1 Register
- 2 Register-Stop
- 3 Join/Prune
- 4 Bootstrap
- 5 Assert
- 6 Graft (for PIM-DM only)
- 7 Graft-Ack (for PIM-DM only)
- 8 Candidate-acsRP-Advertisement

### 4.5.1 PIM Hello Message

A PIM Hello message is sent periodically by the Gateway and Multicast Routers on each PIM-enabled interface. They allow to learn the neighboring PIM router.

IP fields:

Source Address            IP address of the corresponding interface in the MEP or Multicast Router.  
 Destination Address    224.0.0.13 (All PIM routers)

PIM Hello message format:

0	1	2	3
Version	Type=0	Reserved	Checksum
Option Type		Option Length	
Option Value			
.			
Option Type		Option Length	
Option Value			

<i>Version</i>	Version of PIM 2
<i>Type</i>	0 (Hello).
<i>Reserved</i>	Zeroed.
<i>Checksum</i>	Standard IP checksum.
<i>Option Type</i>	Type of the option given in the <i>Option Value</i> field. 1 Hold-time 2-16 reserved for future use 17-18 deprecated, not to use 19 DR Priority 20 Generation ID 21 State Refresh Option for PIM DM 22-65000 To be assigned by IANA 65001-65535 Reserved for private use.
<i>Option Length</i>	Length of the <i>Option Value</i> field in bytes. For
	<i>Option Type</i> <i>Option Length</i>
	1                    2
	19                   4
	21                   4
<i>Option Value</i>	See <i>Option Type</i> field

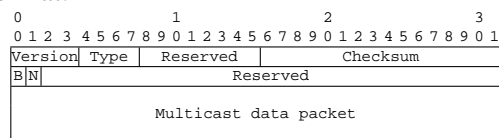
#### 4.5.2 PIM Register Message

Sent by a DR to the RP when a multicast packet needs to be transmitted on the multicast distribution tree.

IP fields:

Source Address	IP Address of the DR.
Destination Address	IP address of the RP.

PIM Register message format:



<i>Version</i>	Version of PIM 2
<i>Type</i>	1 (Register).
<i>Reserved</i>	Zeroed.
<i>Checksum</i>	Checksum is calculated only for the first 8 bytes, excluding the data packet.
<i>B</i>	Border bit. Set to 0, if a source is directly connected to the router. Set to 1, if a source is in a directly connected cloud.
<i>N</i>	Null-Register bit. Set to 1 by a DR that is probing the RP before expiring its local Register-Suppression timer.
<i>Multicast data packet</i>	The original packet sent by a source.

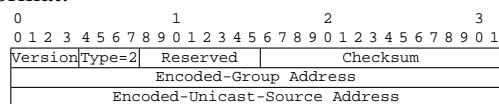
### 4.5.3 PIM Register-Stop Message

Sent by a RP to the DR (sender of the *Register*-message).

IP fields:

Source Address	Address to which the <i>Register</i> message was addressed.
Destination Address	Source address of the <i>Register</i> message.

PIM Register message format:



<i>Version</i>	Version of PIM 2
<i>Type</i>	2 (Register-Stop).
<i>Reserved</i>	Zeroed.
<i>Checksum</i>	IP checksum.
<i>Encoded-Group Address</i>	Encoded multicast group address
<i>Encoded-Unicast-Source Address</i>	Address of source from multicast data packet in <i>Register</i> -message

### 4.5.4 PIM Join/Prune Message

Sent by Multicast Routers towards upstream sources and RPs.

IP fields:

Source Address	Address of the Multicast Router.
Destination Address	Address of upstream router or RP.

PIM Join/Prune message format:



0				1				2				3											
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3
Version				Type				Reserved				Checksum											
Encoded-Unicast-Upstream Neighbor Address																							
Reserved				Num Groups				Hold-time															
Encoded-Multicast Group Address-1																							
Number of Joined Sources												Number of Pruned Sources											
Encoded-Joined Source Address-1																							
.																							
.																							
Encoded-Joined Source Address-n																							
Encoded-Pruned Source Address-1																							
.																							
.																							
Encoded-Pruned Source Address-n																							
Encoded-Multicast Group Address-n																							
Number of Joined Sources												Number of Pruned Sources											
Encoded-Joined Source Address-1																							
.																							
.																							
Encoded-Joined Source Address-n																							
Encoded-Pruned Source Address-1																							
.																							
.																							
Encoded-Pruned Source Address-n																							

<i>Version</i>	Version of PIM 2
<i>Type</i>	3 (Register).
<i>Encoded-Unicast-Upstream Neighbor Address</i>	Encoded IP address of the upstream neighbor.
<i>Hold-time</i>	Amount of time in seconds a receiver must keep the Join/Prune state alive.
<i>Number of Groups</i>	Number of multicast group sets contained in this message.
<i>Encoded-Multicast Group Address</i>	A wild card group (*,*,acsRP) join is represented by a 224.0.0.0 in the group address and '4' in the mask length field.
<i>Number of Joined Sources</i>	Number of Joined Sources listed for a specific multicast group.
<i>Join Source Address-1..n</i>	List with addresses of sources. The sending router will forward multicast datagrams for these sources.
<i>Number of Pruned Sources</i>	Number of prune source addresses listed for a group.
<i>Prune Source Address-1..n</i>	List with addresses of sources. The sending router does not want to forward multicast datagrams for these sources.

### 4.5.5 Other PIM Messages

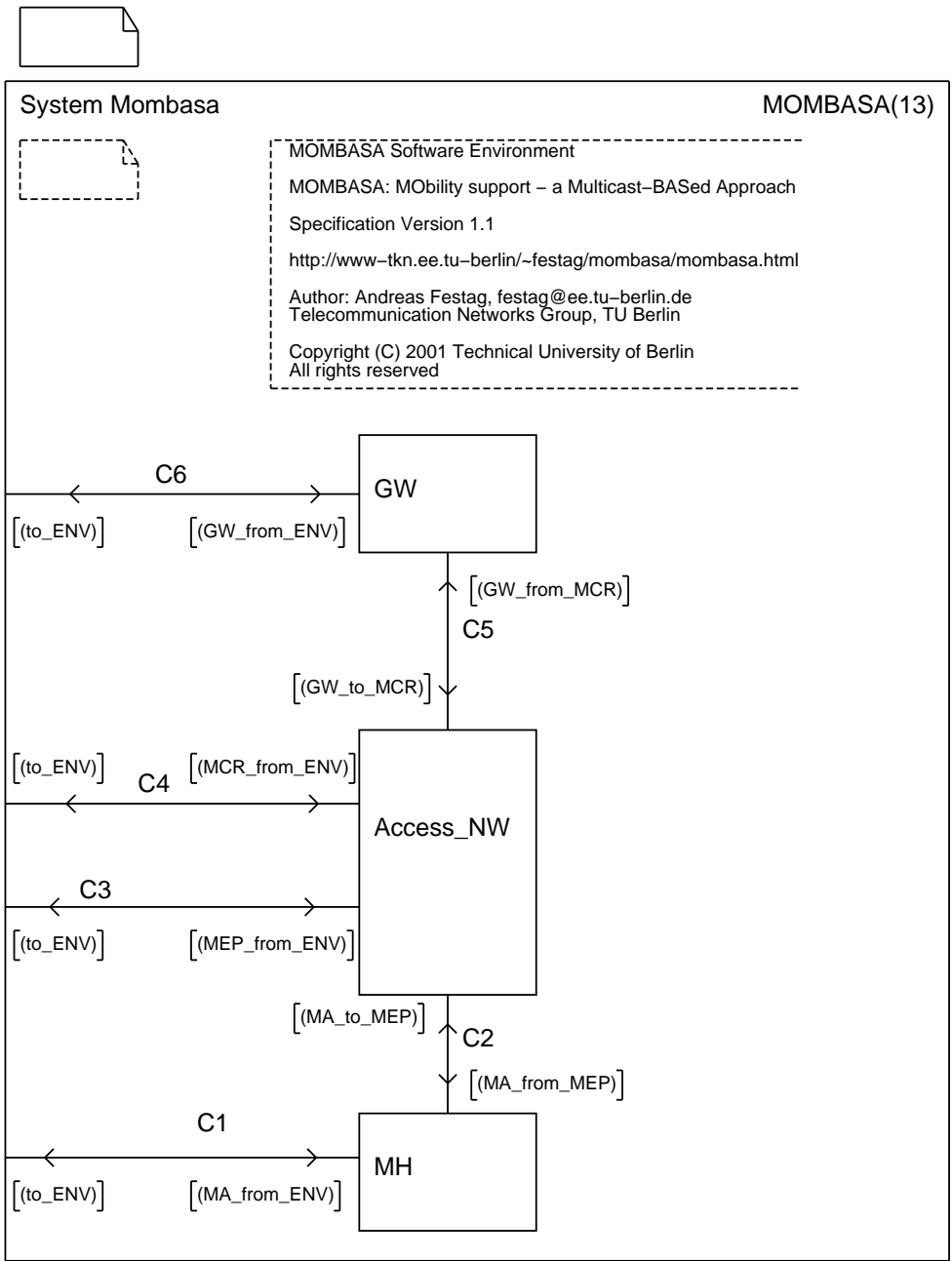
*Bootstrap-, Assert-, Graft-, Graft-Ack-, and Candidate-acsRP-Advertisement* messages are beyond the scope of this document.

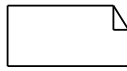
## Chapter 5

# Protocol specification

The MOMBASA system is formally specified using SDL [10], a general-purpose specification language for communication systems. The system is modeled as communicating processes of the components described in section 2 and their environment. Each process is regarded as an Extended Finite State Machine (EFSM). Communication is represented by signals and can take place between the processes and the environment of the system. The environment generates signals (such as handover) which are considered as *external* events of the MOMBASA system.

In the following, the major parts of the specification are listed. At first, an overview of the SDL blocks, definitions of signals, message types, and data types used in the particular processes (registration tables, paging tables, etc.) is given. Then, the state machine of each process is shown. Due to space limitations, the procedure specifications are not included in this report.

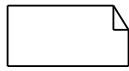




System Mombasa Signal\_Definitions(13)

SIGNAL

```
env_MA_Restart,
env_MA_Stop,
env_MEP_Restart,
env_MEP_Stop,
env_MCR_Restart,
env_MCR_Stop,
env_GW_Restart,
env_GW_Stop,
env_Wakeup,
env_Act_TO,
env_Pag_Trig,
env_HO_Trig(uint8_t),
env_Warning(CharString),
MEP_Advert(MEP_Advert_Packet),
MCR_IMEP_Advert(IMEP_Advert_Packet),
IMEP_Advert(IMEP_Advert_Packet),
MEP_Solicit(MEP_Solicit_Packet),
MEP_Subscribe_MCC(MB_MC_Channel),
MEP_Unsubscribe_MCC(MB_MC_Channel),
MEP_stopBuffer(MB_Buffer),
MEP_buffer_stopped(uint32_t),
MEP_startFlush,
MEP_stopFlush,
MEP_flush_stopped(uint32_t),
MCR_Subscribe_MCC(MB_MC_Channel),
MCR_Unsubscribe_MCC(MB_MC_Channel),
MA_RegReq(MA_RegReq_Packet),
MA_RegReply(MA_RegReply_Packet),
GW_PagReq(GW_PagReq_Packet),
MCR_PagReq(GW_PagReq_Packet),
MEP_PagReq(GW_PagReq_Packet),
MEP_PagUpd(MA_PagUpd_Packet),
MCR_PagUpd(MA_PagUpd_Packet),
GW_stopBuffer(MB_Buffer),
GW_buffer_stopped(uint32_t),
GW_startFlush,
GW_stopFlush,
GW_flush_stopped(uint32_t);
```



System Mombasa Signal\_List\_Definitions(13)

```
SIGNALLIST
MA_from_ENV = env_MA_Restart,env_MA_Stop,env_Wakeup,env_Act_TO,env_HO_Trig;

SIGNALLIST
MA_from_MEP = MEP_Advert,MA_RegReply,MEP_PagReq;

SIGNALLIST
MA_to_MEP = MEP_Solicit,MA_RegReq;

SIGNALLIST
MEP_from_ENV = env_MEP_Restart,env_MEP_Stop;

SIGNALLIST
MEP_from_MCR = MCR_PagReq,MCR_IMEP_Advert;

SIGNALLIST
MEP_to_MCR = MEP_Subscribe_MCC,MEP_Unsubscribe_MCC,IMEP_Advert,MEP_PagUpd;

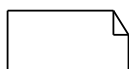
SIGNALLIST
MCR_from_ENV = env_MCR_Restart,env_MCR_Stop;

SIGNALLIST
GW_from_ENV = env_GW_Restart,env_GW_Stop,env_Pag_Trig;

SIGNALLIST
GW_to_MCR = GW_PagReq;

SIGNALLIST
GW_from_MCR = MCR_Subscribe_MCC,MCR_Unsubscribe_MCC,MCR_PagUpd;

SIGNALLIST
to_ENV = env_Warning;
```



System Mombasa

MOMBASA\_Data\_Types(13)



```

/* MB_Data_Types I */
newtype MB_IPHdr struct
  proto uint16_t;
  src IP_Addr_t;
  dest IP_Addr_t;
endnewtype MB_IPHdr;

newtype IP_Addr_t
  Array(uint2_t, uint8_t)
endnewtype IP_Addr_t;

/* newtype MA_Regldent struct
  high uint32_t;
  low uint32_t;
endnewtype MA_Regldent; */

newtype MB_Interface struct
  name CharString;
  index uint8_t;
  addr IP_Addr_t;
  netmask IP_Addr_t;
  broadcast IP_Addr_t;
endnewtype MB_Interface;

newtype RRP_t
  literals HARD,SOFT,PREDICTIVE,NO_RRP;
endnewtype RRP_t;

newtype MB_Tunnel_t
  literals MC_NAT,MC_ENCAPS;
endnewtype MB_Tunnel_t;

newtype MB_Route struct
  dest IP_Addr_t;
  src IP_Addr_t;
  iif uint8_t; /* Input interface index */
  oif uint8_t; /* Output interface index */
  gateway IP_Addr_t;
endnewtype MB_Route;

newtype MB_Buffer struct
  mb_size size_t;
  empty Boolean;
endnewtype MB_Buffer;

```

```

/* MB_Data_Types II */
newtype MB_MC_Channel struct
  s_addr IP_Addr_t;
  g_addr IP_Addr_t;
endnewtype MB_MC_Channel;

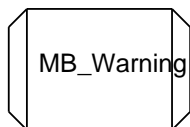
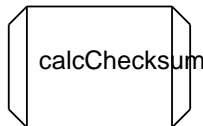
newtype MRT_Entry_t struct
  ch MB_MC_Channel;
  subscribed Boolean;
endnewtype MRT_Entry_t;

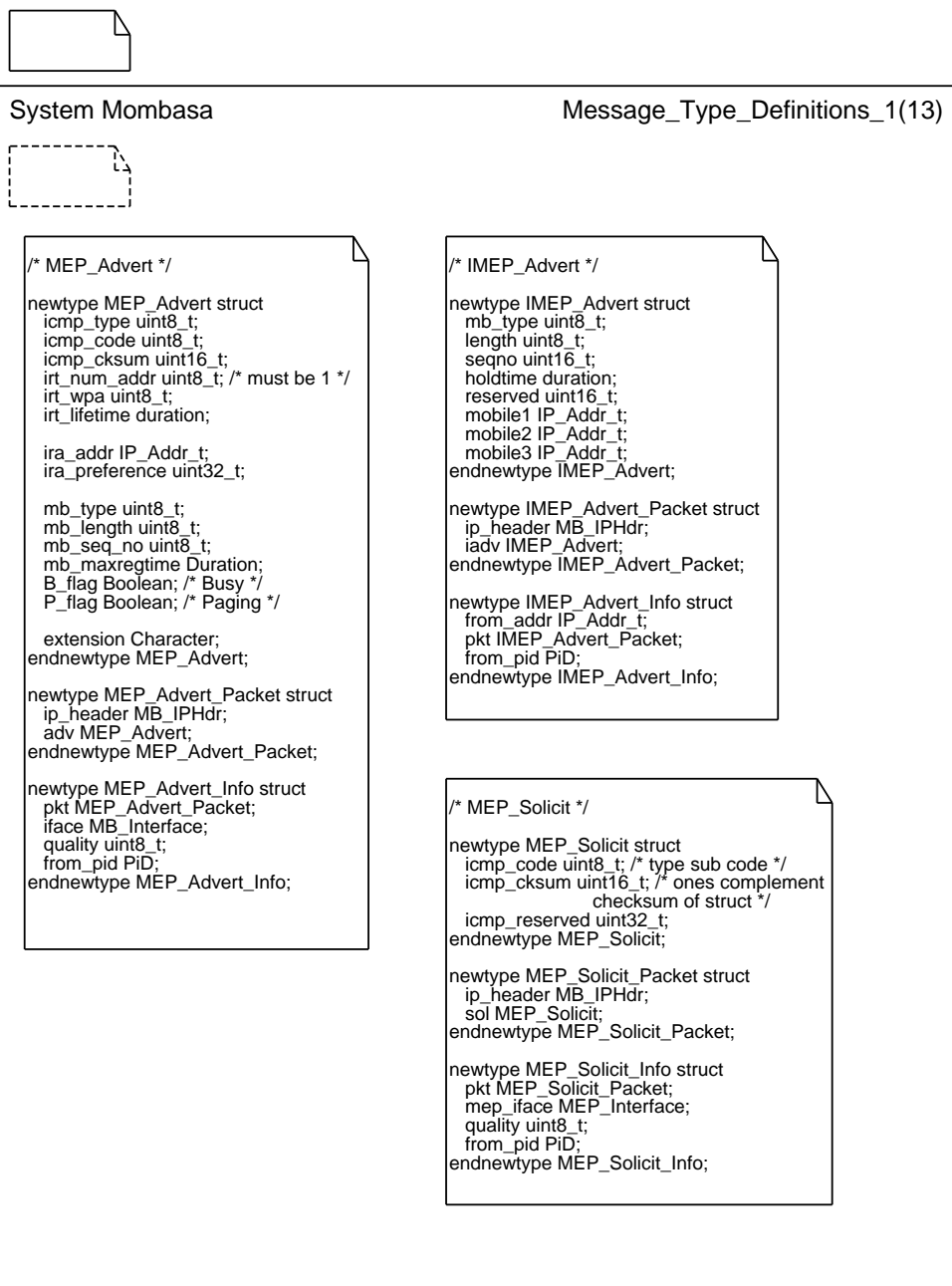
newtype MB_MRT_t
  Array(uint2_t, MRT_Entry_t)
  /* Array(uint32_t, MRT_Entry_t) */
endnewtype MB_MRT_t;

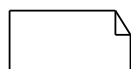
newtype MB_PAT_Entry_t struct
  g_addr IP_Addr_t;
  mep_pid1 PiD;
  mep_pid2 PiD;
  mep_pid3 PiD;
endnewtype MB_PAT_Entry_t;

newtype MB_PAT_t
  Array(uint2_t, MB_PAT_Entry_t)
endnewtype MB_PAT_t;

```

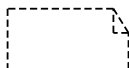






System Mombasa

Message\_Type\_Definitions\_2(13)



```

newtype MA_RegReq struct /* MA_RegReq */
  mb_type uint8_t;
  send_PagUpd Boolean; /* Paging update
                        is sent when the mobile wakes up */
  B_flag Boolean; /* Broadcast datagrams */
  P_flag Boolean; /* Mobile supports paging */
  A_flag Boolean; /* Mobile is active */
  lifetime duration;
  RRP RRP_t;
  reserved uint32_t;
  mh_addr IP_Addr_t;
  id uint32_t;
  extension Character;
endnewtype MA_RegReq;

newtype MA_RegReq_Packet struct
  ip_header MB_IPHdr;
  regreq MA_RegReq;
endnewtype MA_RegReq_Packet;

newtype MA_RegReq_Info struct
  pkt MA_RegReq_Packet;
  mep_iface MEP_Interface;
  quality uint8_t;
  bs MA_BaseStationEntry;
  port uint16_t;
  from_pid PiD;
endnewtype MA_RegReq_Info;

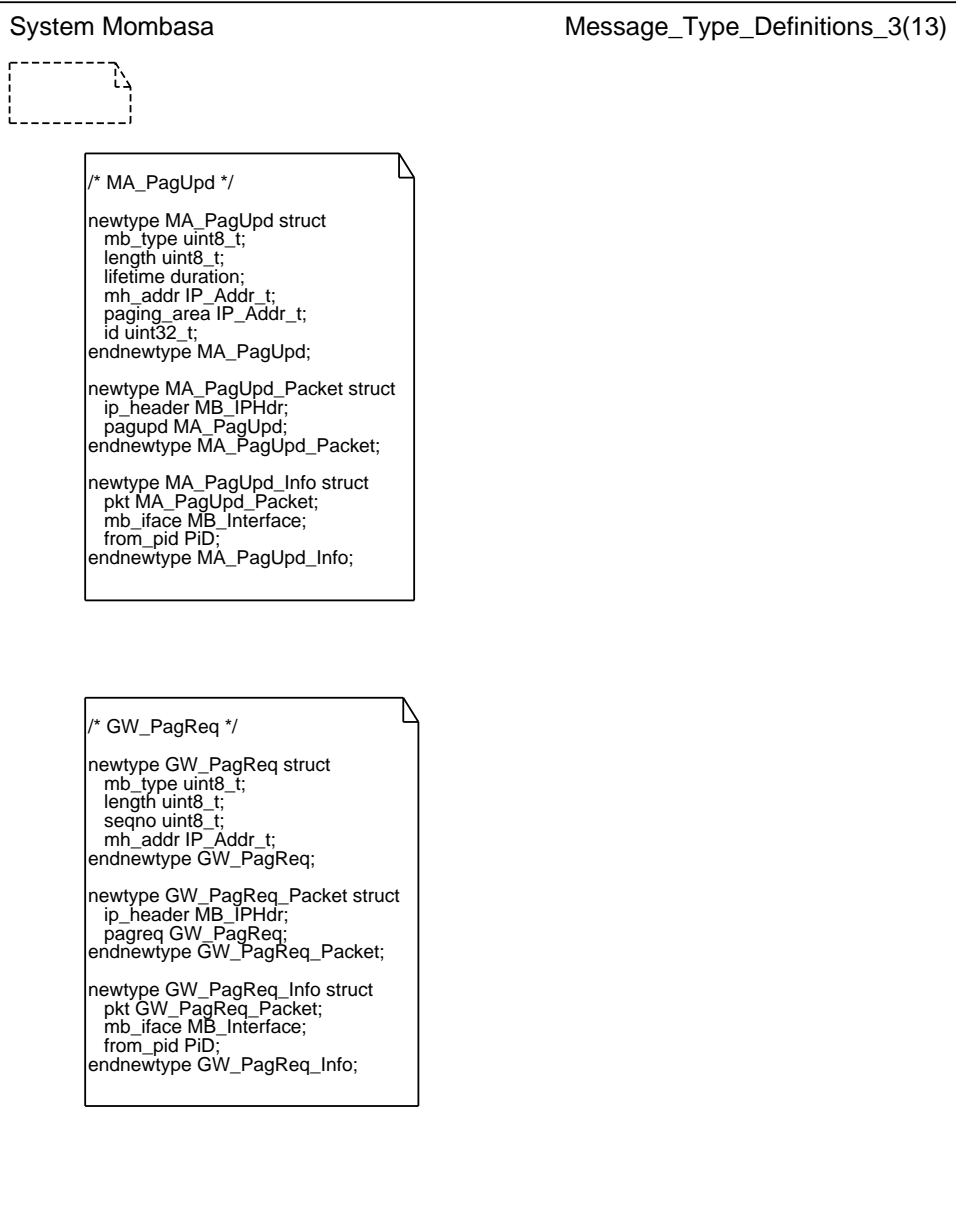
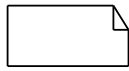
/*****
newtype MA_RegReply struct /* MA_RegReply */
  mb_type uint8_t;
  code uint8_t;
  lifetime DURATION;
  /*reserved uint64_t;*/
  id uint32_t;
  extension Character;
endnewtype MA_RegReply;

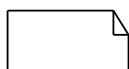
newtype MA_RegReply_Packet struct
  ip_header MB_IPHdr;
  regreply MA_RegReply;
endnewtype MA_RegReply_Packet;

newtype MA_RegReply_Info struct
  pkt MA_RegReply_Packet;
  MA_iface MA_Interface;
  quality uint8_t; /* quality of received advertisement
                  (0: worst, 100: best)*/
  addr IP_Addr_t;
  port uint16_t;
  pending_reg_info MA_RegReq_Info;
  from_pid PiD;
endnewtype MA_RegReply_Info;

```

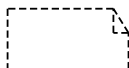






System Mombasa

GW\_Data\_Type\_Definitions(13)



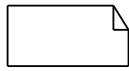
```
/* Gateway type definitions */
newtype GW_Config struct
  upstream GW_Interface;
  downstream GW_InterfaceMap;
  mobile_uc uint32_t; /* mobile unicast address range */
  mobile_mc uint32_t; /* mobile multicast address range */
  mobile_mask uint32_t;
  mobile_mask_len uint8_t;
  tunnel_type MB_Tunnel_t;
  paging_port uint16_t; /* PAGING disabled
                        if paging_port = 0 */
  paging_source IP_Addr_t;
  paging_areas uint32_t;
  paging_areas_mask uint32_t;
  paging_areas_masklen uint8_t;
  max_mobiles uint8_t;
  max_cachetime Duration;
  mobile_buffer_size uint32_t;
endnewtype GW_Config;

newtype GW_Interface struct
  mb_iface MB_Interface;
  force_addr IP_Addr_t;
endnewtype GW_Interface;

newtype GW_InterfaceMap
  Array(iface_index, GW_Interface);
endnewtype GW_InterfaceMap;

newtype GW_MobileEntry struct
  addr IP_Addr_t; /* Unicast IP address of MH */
  location IP_Addr_t; /* Last known paging area */
  gw_iface GW_Interface; /* Interface from which */
  /* last paging update was heard */
  lifetime Duration;
  lastid uint32_t;
  paging Boolean;
  flushing Boolean;
endnewtype GW_MobileEntry;

newtype GW_MobileMap
  /* Array(uint32_t, GW_MobileEntry); */
  Array(uint2_t, GW_MobileEntry);
endnewtype GW_MobileMap;
```

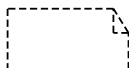


System Mombasa	MEP_Data_Type_Definitions_1(13)
<pre data-bbox="319 571 782 1276">/* MEP type definitions 1 */ newtype MEP_Config struct upstream US_Interface; downstream MEP_InterfaceMap; send_paging_updates Boolean; mobile_uc uint32_t; /* mobile unicast address range */ mobile_mask uint32_t; mobile_mc uint32_t; /* mobile multicast address range */ mobile_mask_len uint32_t; tunnel_type MB_Tunnel_t; reg_port uint16_t; imep_port uint16_t; paging_port uint16_t; primary_paging_area MB_MC_Channel; secondary_paging_area MB_MC_Channel; primary_mep_group MB_MC_Channel; secondary_mep_group MB_MC_Channel; gw_addr IP_Addr_t;  max_direct_mobiles uint32_t; max_indirect_mobiles uint32_t; mobile_threshold uint32_t; /* number above which to send shortage warnings */ max_regtime Duration; mobile_buffer_size uint32_t; sent_mepadv Boolean; sent_imepadv Boolean;  pseudo_seed Duration; /* for pseudo random number */ endnewtype MEP_Config;</pre>	



System Mombasa

MEP\_Data\_Type\_Definitions\_2(13)



```
/* MEP type definitions 2 */
newtype MEP_Interface struct
  mb_iface MB_Interface;
  force_addr IP_Addr_t;
  adv_interval duration; /* in msec */
  adv_lifetime duration; /* in msec */
  adv_seqno uint8_t;
endnewtype MEP_Interface;

newtype MEP_InterfaceMap
  Array(iface_index,MEP_Interface);
endnewtype MEP_InterfaceMap;

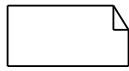
newtype US_Interface struct
  mb_iface MB_Interface;
  force_addr IP_Addr_t;
  imep_interval duration; /* in msec */
  imep_lifetime duration; /* in msec */
  imep_seqno uint32_t;
endnewtype US_Interface;

newtype MEP_BaseStationEntry struct
  addr IP_Addr_t; /*IP address of other base station */
  seqno uint8_t;
  holdtime duration;
endnewtype MEP_BaseStationEntry;

newtype MEP_MobileEntry struct
  addr IP_Addr_t; /*Unicast IP address of MH*/
  is_direct Boolean;
  mb_iface MB_Interface;
  lifetime duration;
  quality uint8_t;
  B_flag Boolean; /* Broadcast datagrams */
  P_flag Boolean; /* Paging */
  A_flag Boolean; /* Active */
  RRP RRP_t;
  mb_channel MB_MC_Channel;
endnewtype MEP_MobileEntry;

newtype MEP_MobileMap
  /* Array(.MEP_MobileEntry); */
  Array(uint2_t,MEP_MobileEntry);
endnewtype MEP_MobileMap;

newtype MEP_BaseStationMap
  Array(uint32_t,MEP_BaseStationEntry);
endnewtype MEP_BaseStationMap;
```



System Mombasa MA\_Data\_Type\_Defintions(13)

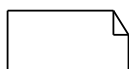
```
/* Mobile Agent type definitions */
newtype MA_Config struct
  ma_iface MA_InterfaceMap;
  regid uint32_t;
  paging_enabled Boolean;
  rrp RRP_t;
  broadcast Boolean;
  paging_port uint16_t;
  reg_port uint16_t;
  idle_timeout Duration;
  config_file CharString;
endnewtype MA_Config;

newtype MA_Interface struct
  mb_iface MB_Interface;
  force_addr IP_Addr_t;
  preference uint32_t;
  active_regtime duration;
  idle_regtime duration;
  regreq_timeout duration;
  send_solicit Boolean;
  send_dereg Boolean;
endnewtype MA_Interface;

newtype MA_InterfaceMap
  Array(iface_index.MA_Interface);
endnewtype MA_InterfaceMap;

newtype MA_BaseStationEntry struct
  addr IP_Addr_t;
  registered Boolean;
  busy Boolean;
  stale Boolean;
  quality uint8_t;
  ma_iface MA_Interface;
  adv_seqno uint16_t;
  adv_lifetime duration;
  maxregtime duration;
  P_flag Boolean;
  mep_pid PId;
endnewtype MA_BaseStationEntry;

newtype MA_BaseStationMap
  Array(uint32_t,MA_BaseStationEntry);
endnewtype MA_BaseStationMap;
```



System Mombasa

Synonym\_Types(13)



```

/* General data types */
syntype uint2_t = Integer constants 0:3 /* 2^2 */ endsyntype;
syntype uint8_t = Integer constants 0:256 /* 2^8 */ endsyntype;
syntype uint16_t = Integer constants 0:65535 /* 2^16 */ endsyntype;
syntype uint32_t = Integer constants 0:65535 /* 4294967296 */ /* 2^32 */ endsyntype;
/* syntype uint64_t = Integer constants 0:4294967296 2^64 endsyntype; */
syntype size_t = Integer constants 0:1024 endsyntype;
syntype iface_index = Integer constants 0:1 endsyntype;
syntype reg_retry_counter_t = Integer constants 0:DEFAULT_REGRETRY endsyntype;

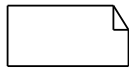
/* MEP message types */
synonym MB_MEP_ADVERT uint8_t = 17;
synonym MB_REG_REQ uint8_t = 2;
synonym MB_REG_REPLY uint8_t = 4;
synonym MB_IMEP_ADVERT uint8_t = 6;
synonym MB_PAGING_REQ uint8_t = 8;
synonym MB_PAGING_UPDATE uint8_t = 10;

/* ICMP message types RFC1256 */
synonym ICMP_ROUTERADVERT uint8_t = 9;
synonym ICMP_ROUTERSOLICIT uint8_t = 10;

/* Protocol types RFC1060 */
synonym ICMP_PROTO uint16_t = 1;
/* synonym IGMP_PROTO uint16_t = 2; */
synonym UDP_PROTO uint16_t = 17;

/* Replay codes for registration requests */
synonym REGISTRATION_ACCEPTED Integer = 0;
synonym REASON_UNSPECIFIED Integer = 64;
synonym ADMINISTRATIVELY_PROHIBITED Integer = 65;
synonym INSUFFICIENT_RESOURCES Integer = 66;
synonym MOBILE_HOST_FAILED_AUTHENTICATION Integer = 67;
synonym REQUESTED_LIFETIME_TOO_LONG Integer = 69;
synonym POORLY_FORMED_REQUEST Integer = 70;
synonym GW_HOST_UNREACHABLE Integer = 80; /* ICMP error received */
synonym GW_PORT_UNREACHABLE Integer = 81; /* ICMP error received */
synonym GW_UNREACHABLE Integer = 82; /* other ICMP error received */

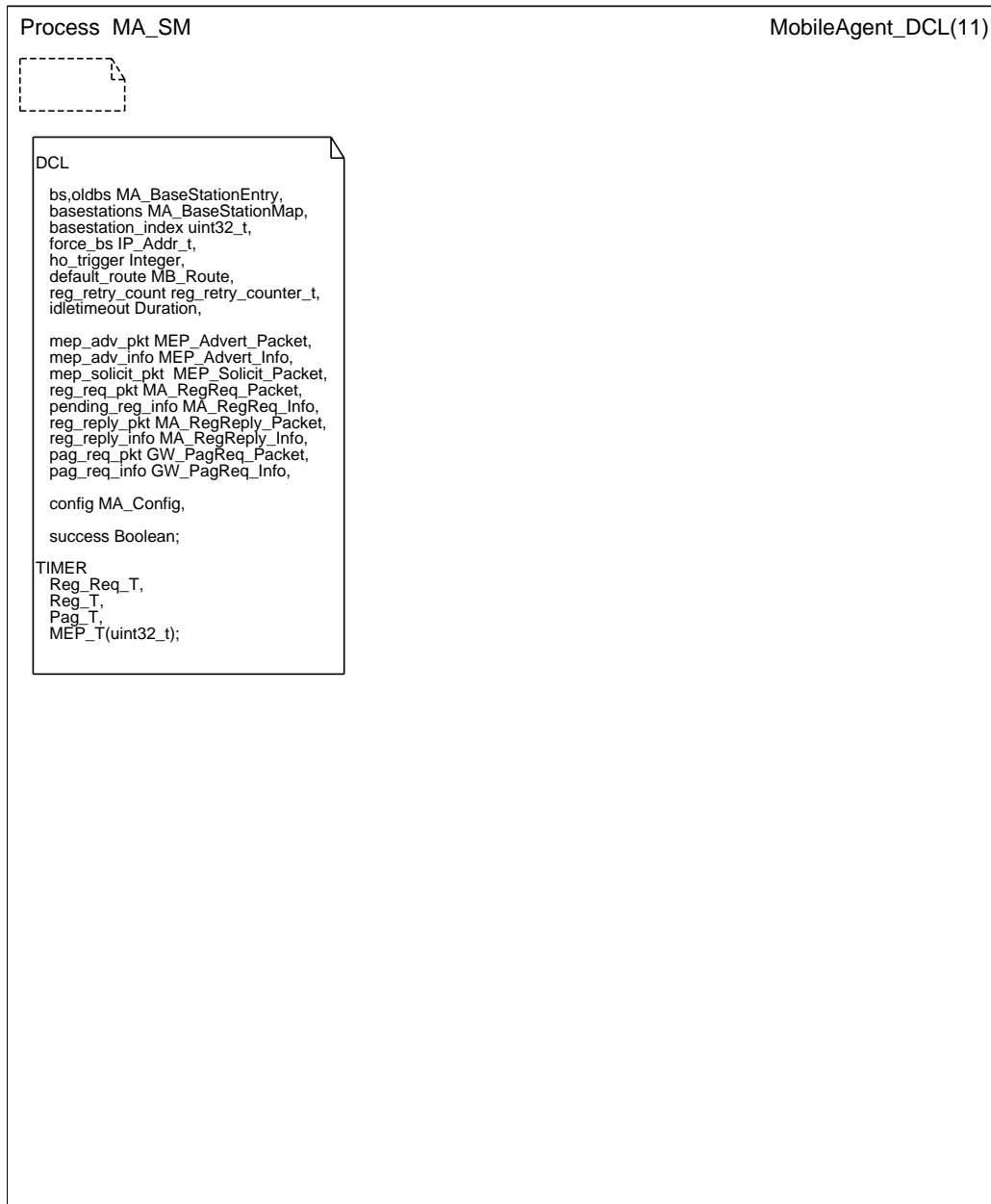
```



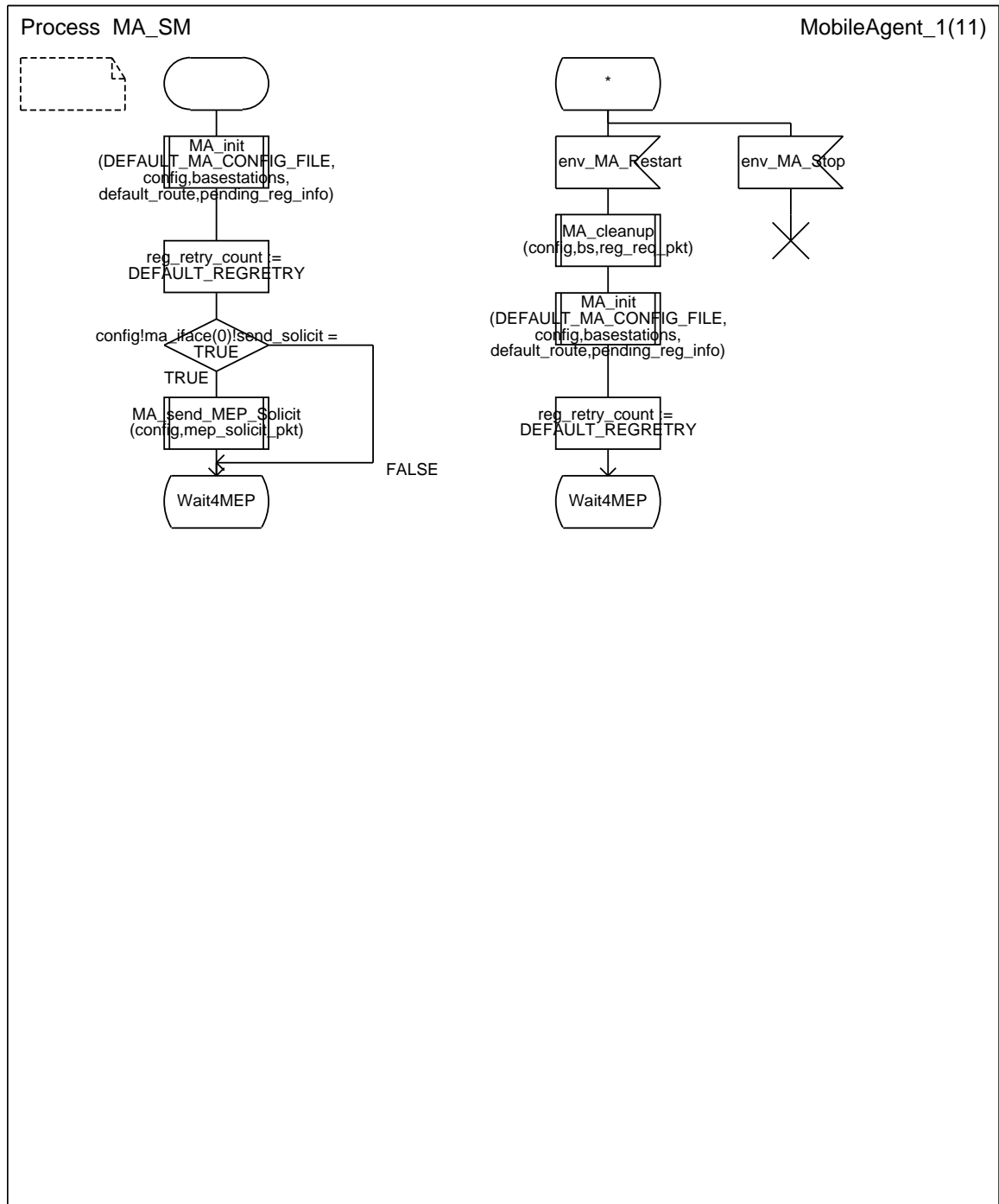
System Mombasa Synonym\_Defaults(13)

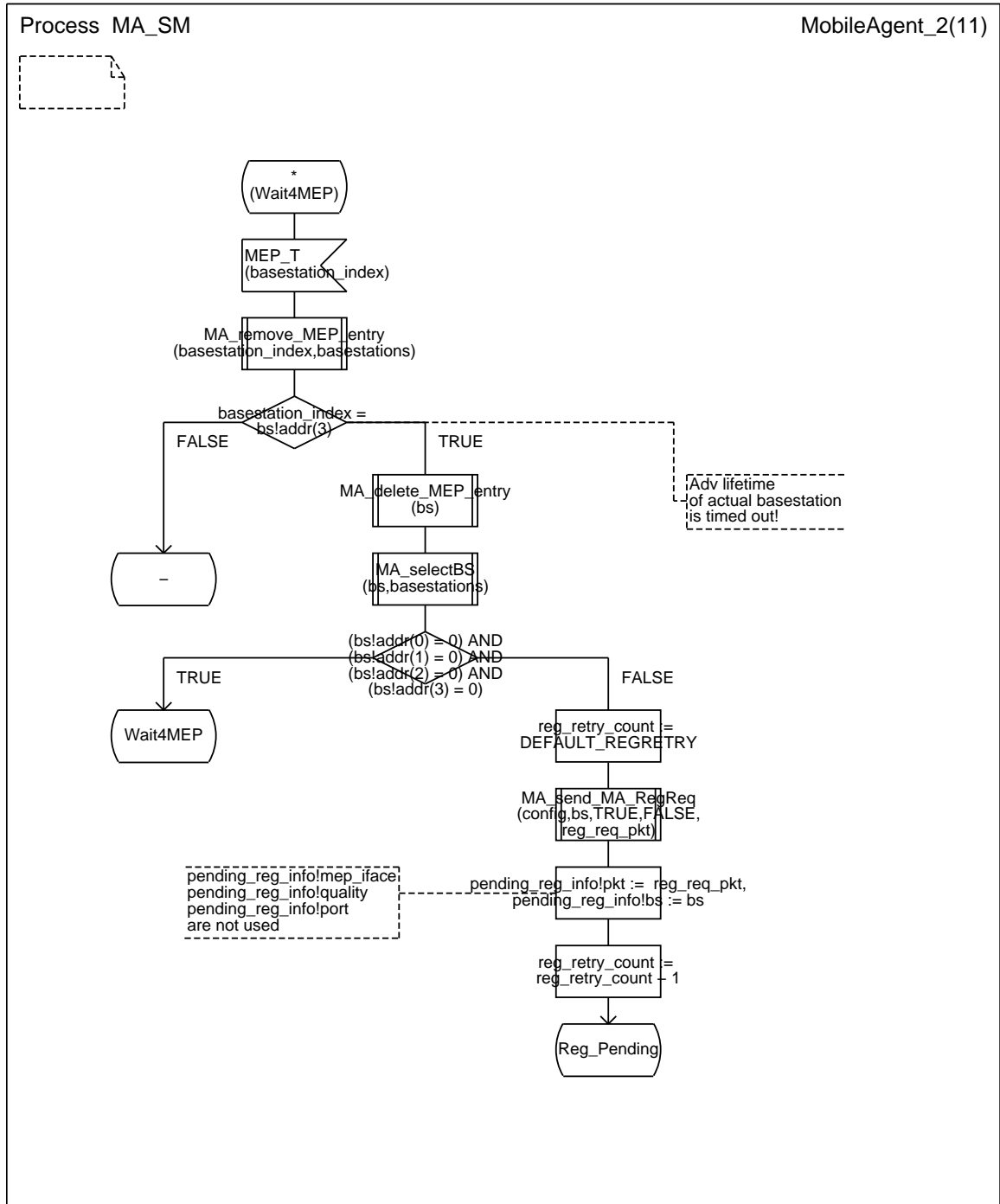
```
/* Defaults */  
synonym DEFAULT_PAGING_PORT Integer = 434;  
synonym DEFAULT_REG_PORT Integer = 434;  
synonym DEFAULT_IMEP_PORT Integer = 434;  
synonym DEFAULT_MAX_MOBILES Integer = 2;  
synonym DEFAULT_MAX_GATEWAY_MOBILES Integer = 2;  
synonym DEFAULT_MOBILE_THRESHOLD Integer = 20;  
synonym DEFAULT_MAX_REGTIME Duration = 3600;  
synonym DEFAULT_MAX_PAGINGCACHE_TIME Duration = 3600;  
synonym DEFAULT_FLUSH_TIME Duration = 3.1416;  
synonym DEFAULT_REGRETRY Integer = 3;  
synonym DEFAULT_MOBILE_BUFFER_SIZE Integer = 262144; /* 256 * 1024 */  
synonym DEFAULT_GATEWAY_BUFFER_SIZE Integer = 262144; /* 256 * 1024 */  
synonym DEFAULT_ACTIVEREG_TIMEOUT Duration = 60;  
synonym DEFAULT_IDLE_TIMEOUT Duration = 300;  
synonym DEFAULT_ADV_INTERVAL Duration = 10;  
synonym DEFAULT_ADV_LIFETIME Duration = 20;  
synonym DEFAULT_IMEP_INTERVAL Duration = 10;  
synonym DEFAULT_IMEP_LIFETIME Duration = 20;  
synonym DEFAULT_RRP RRP_t = PREDICTIVE;  
synonym DEFAULT_MEP_CONFIG_FILE CharString = 'mep_conf_file';  
synonym DEFAULT_MA_CONFIG_FILE CharString = 'MA_conf_file';  
synonym DEFAULT_GW_CONFIG_FILE CharString = 'gw_conf_file';
```

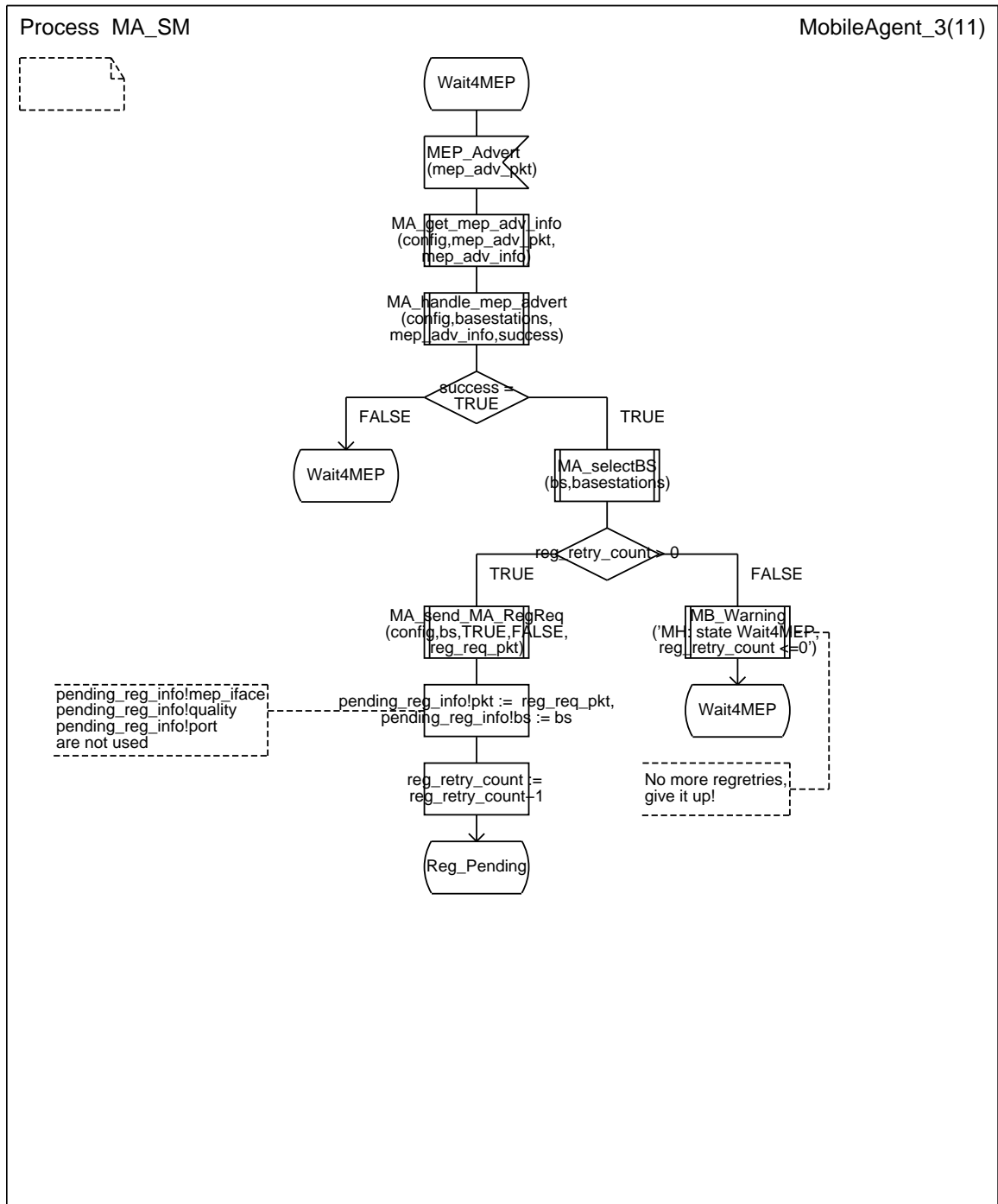
## 5.1 Mobile Agent State Machine

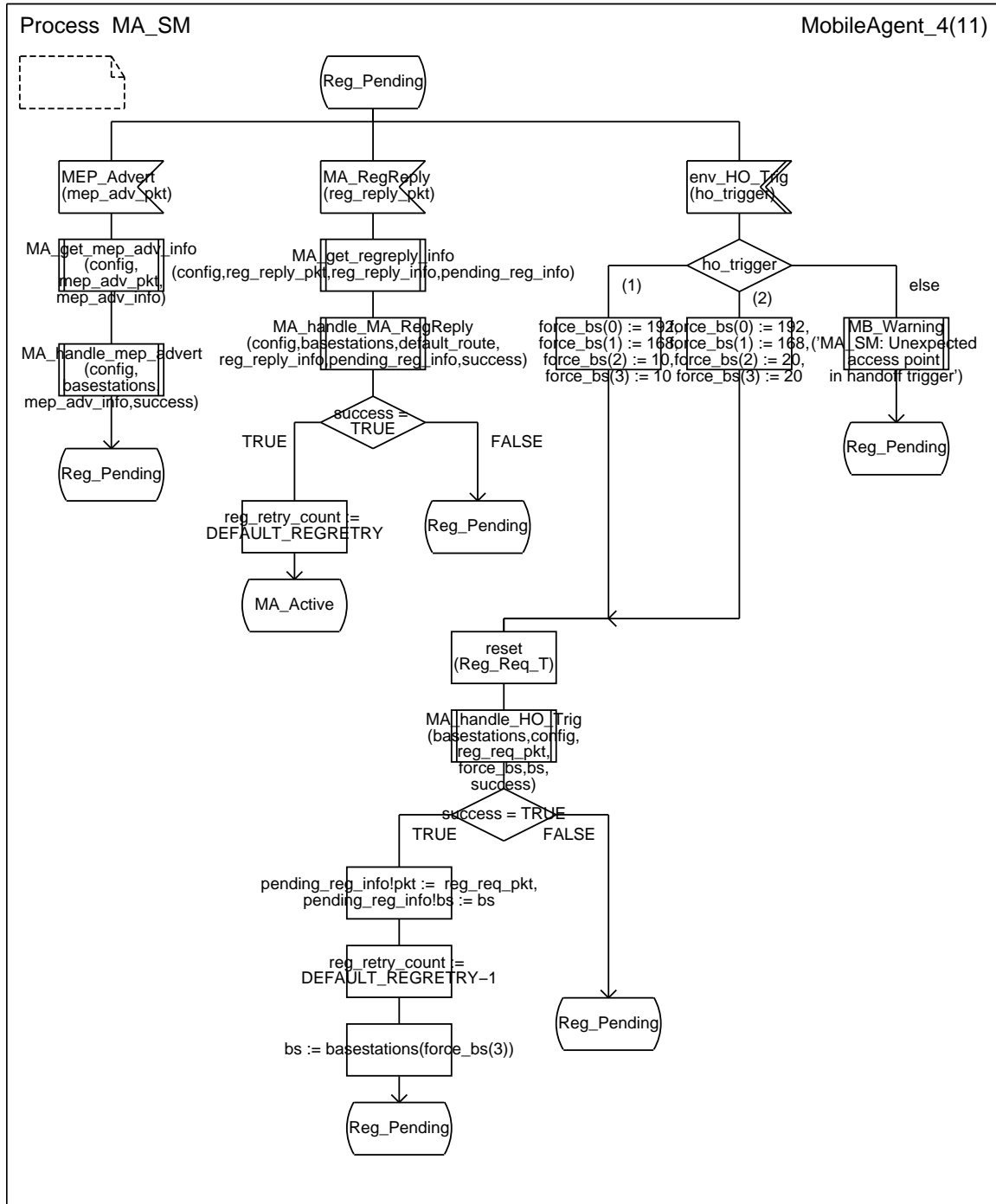


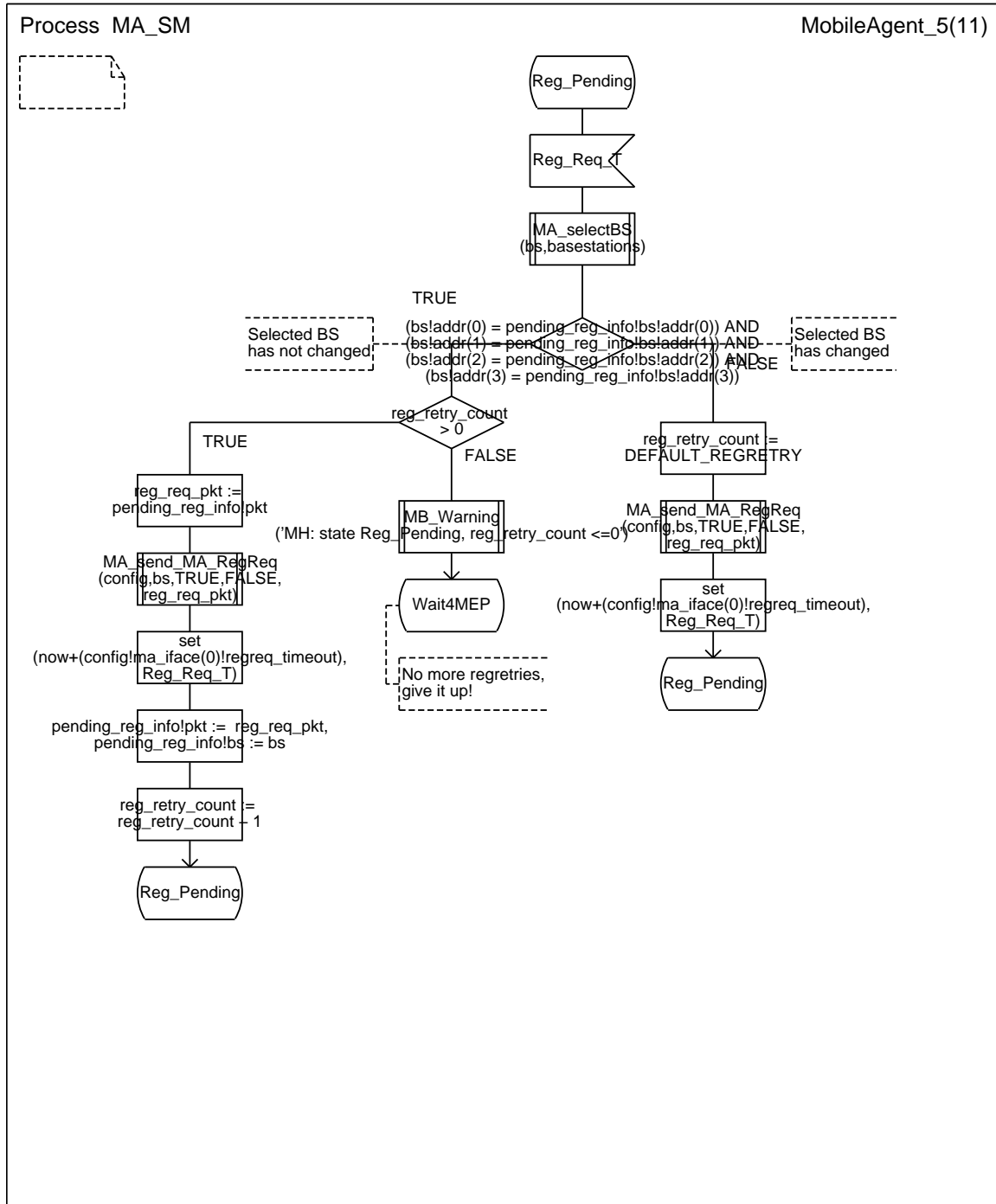


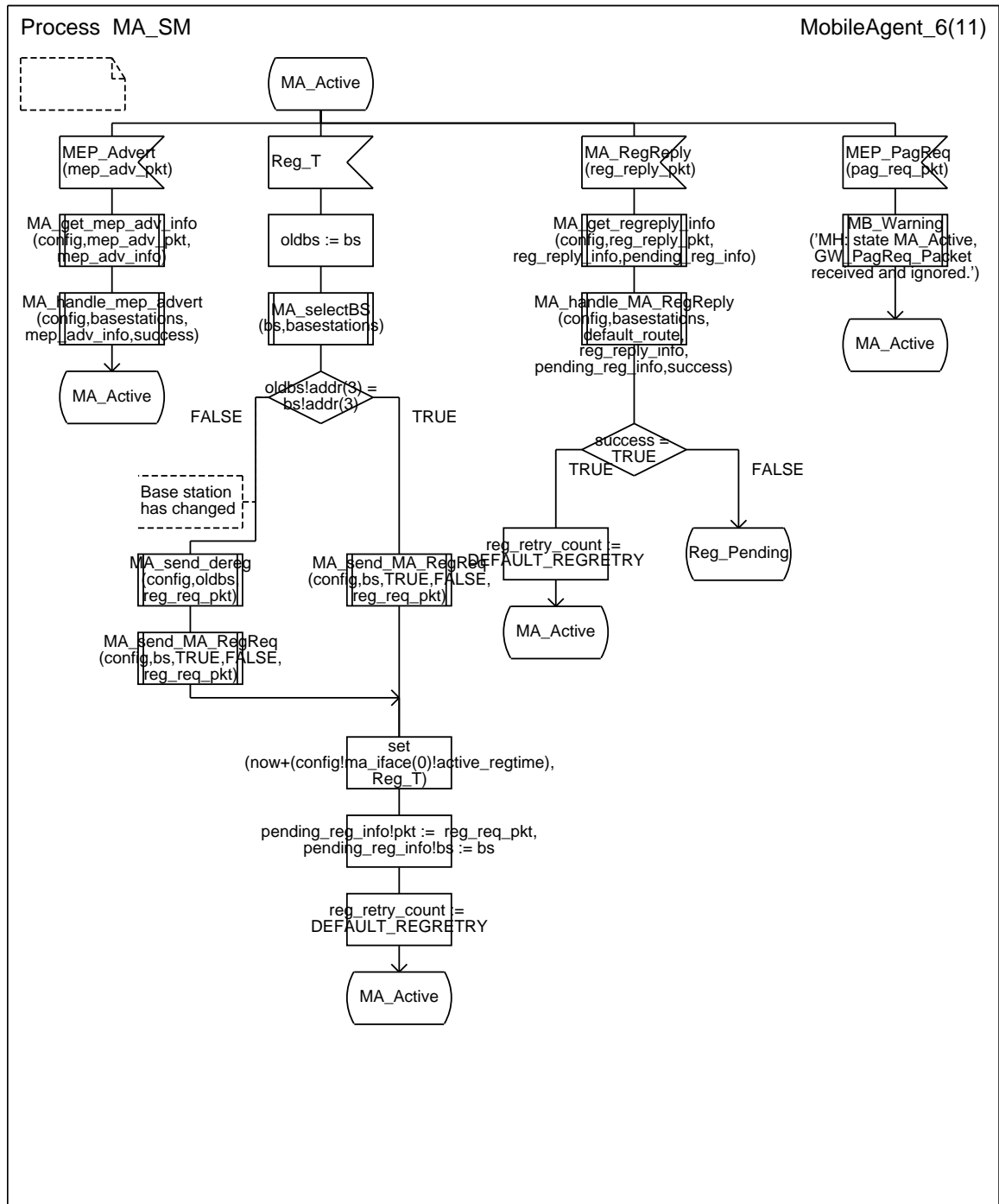


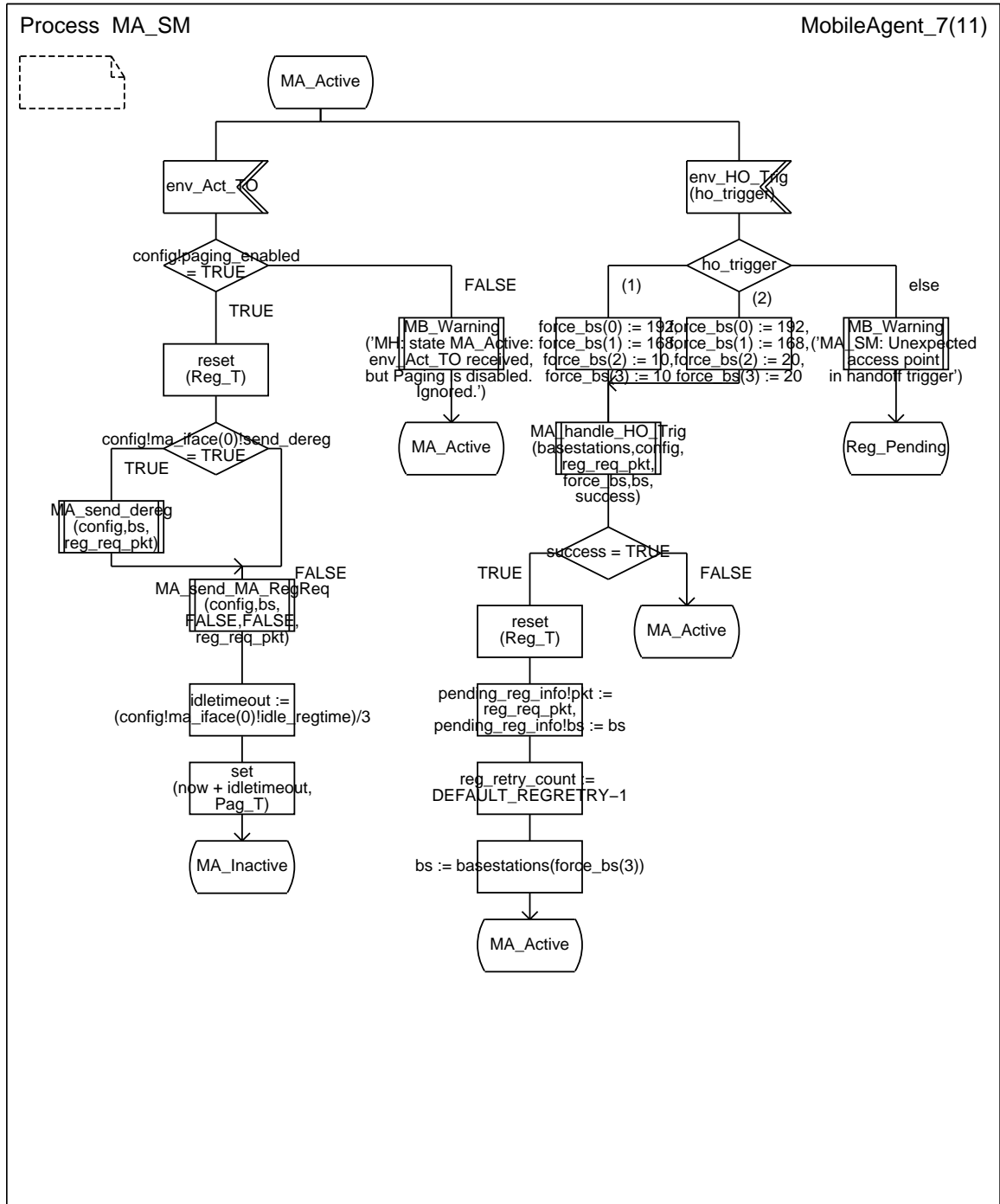


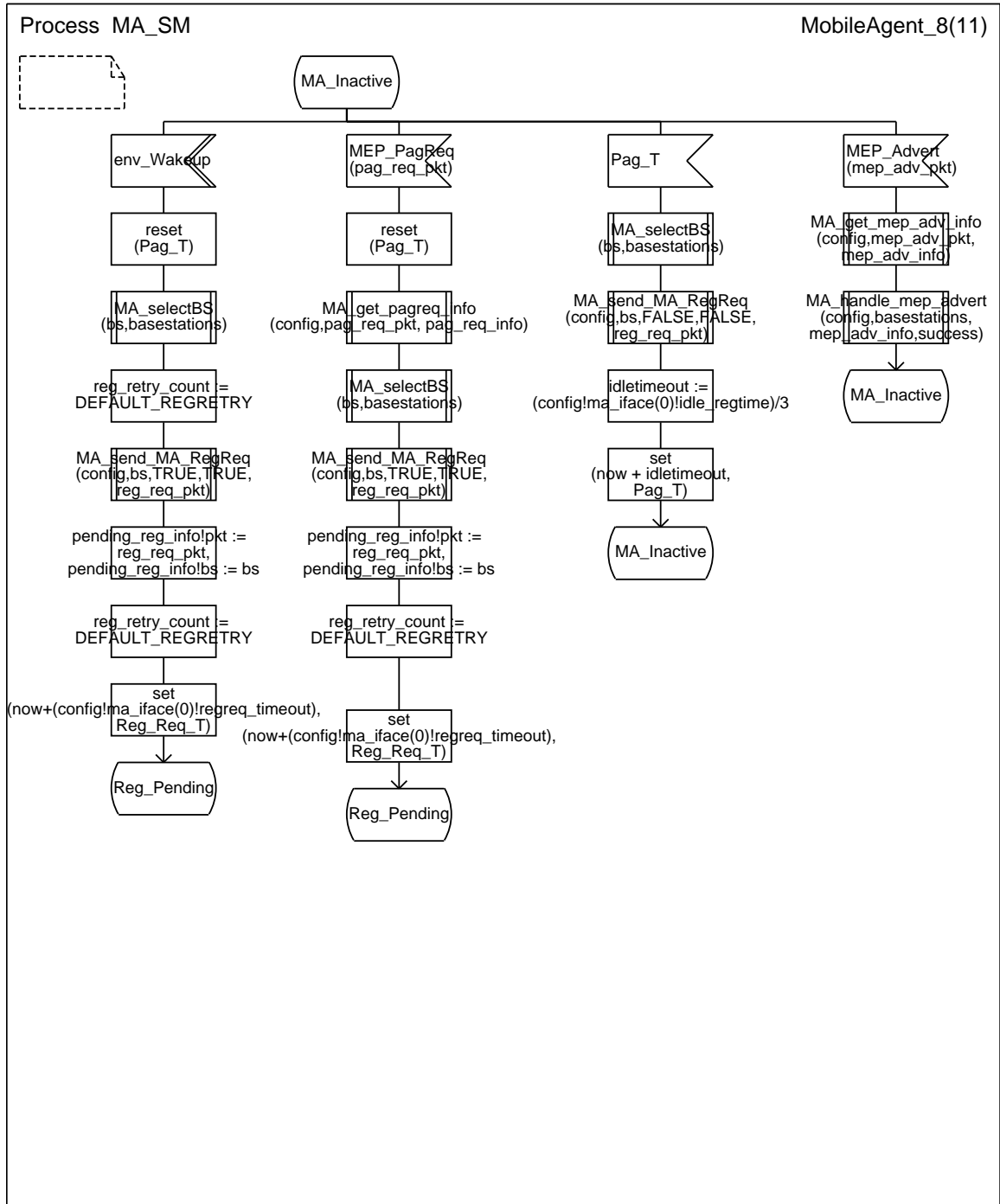




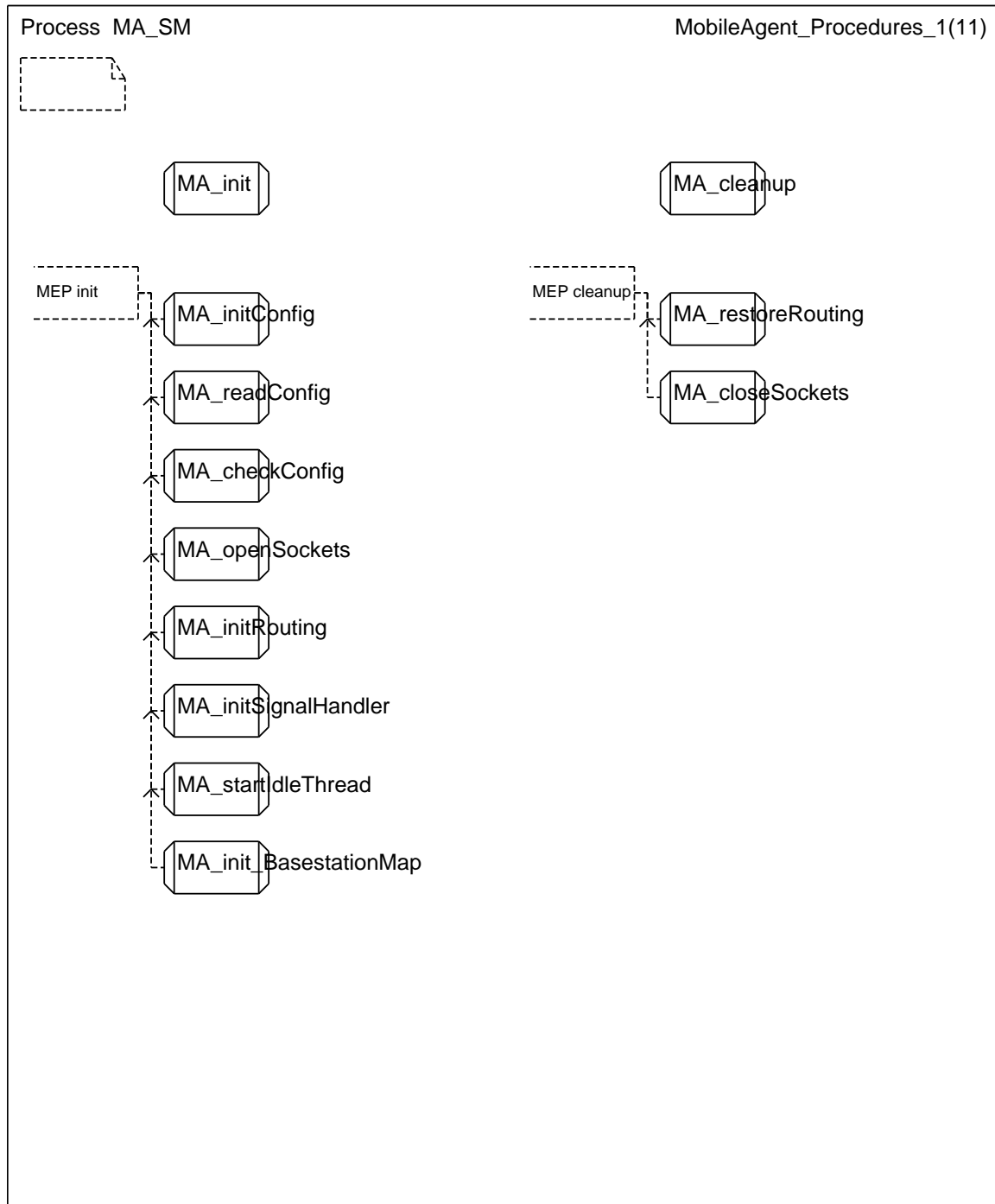


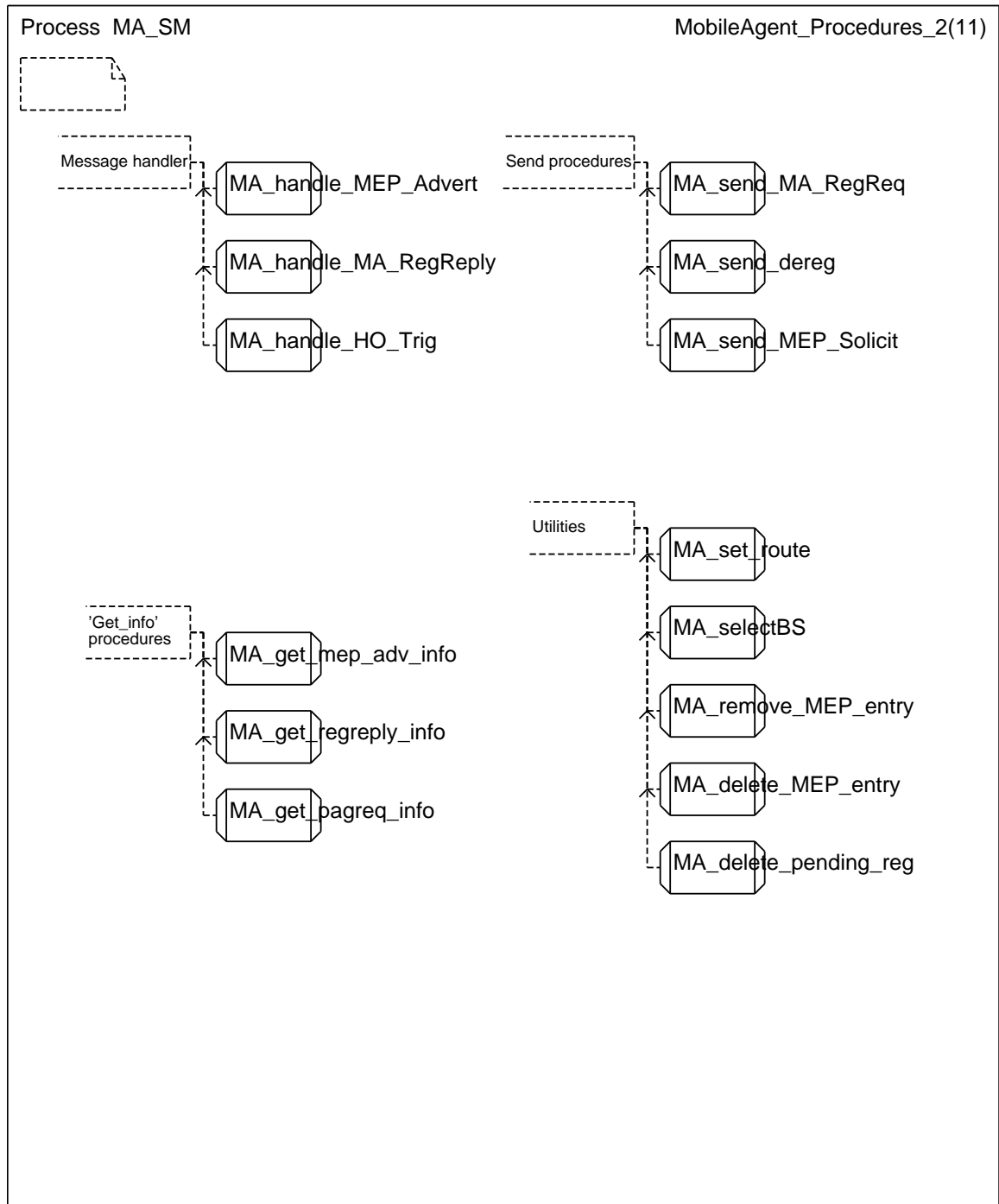




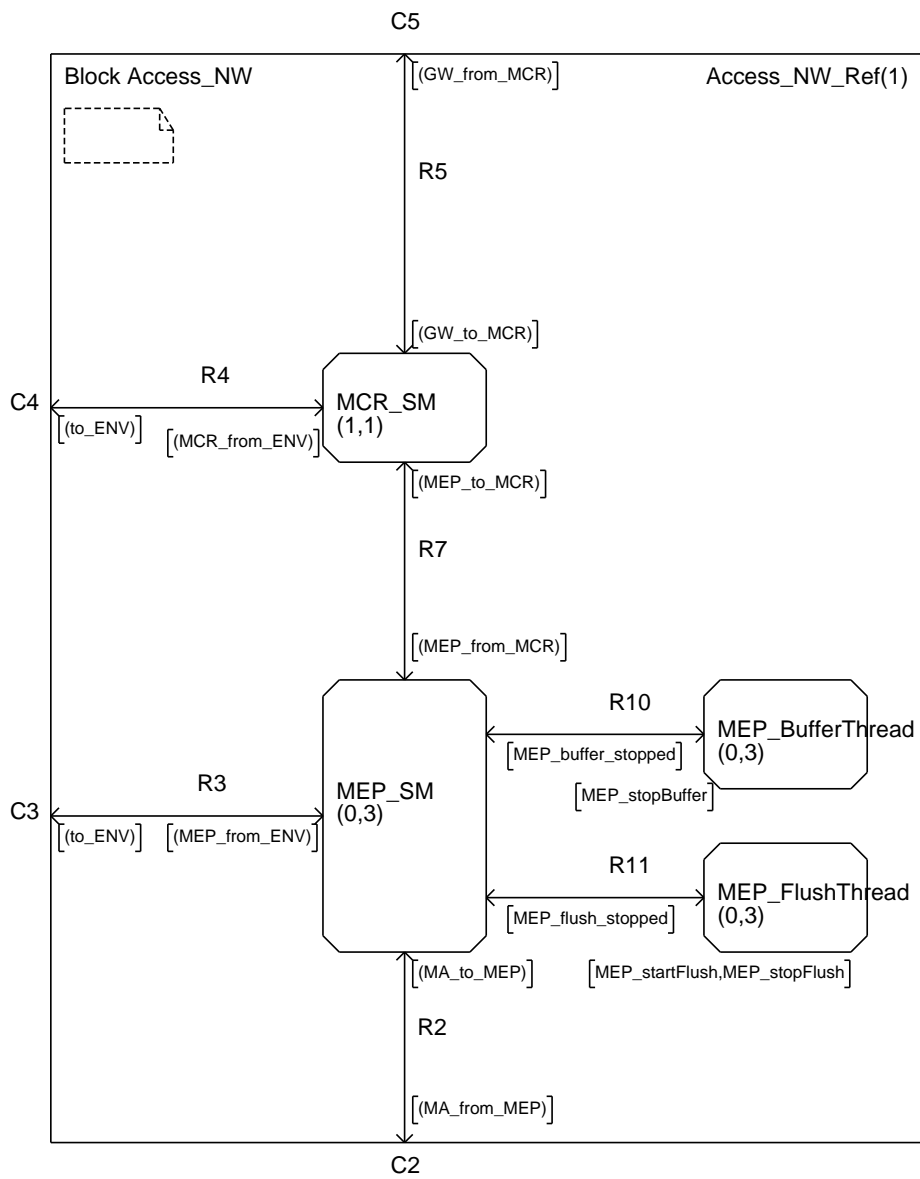








## 5.2 MEP State Machine



Process MEP\_SM

MEP\_DCL(5)

```
FPAR  
mep_id uint2_t;
```

DCL

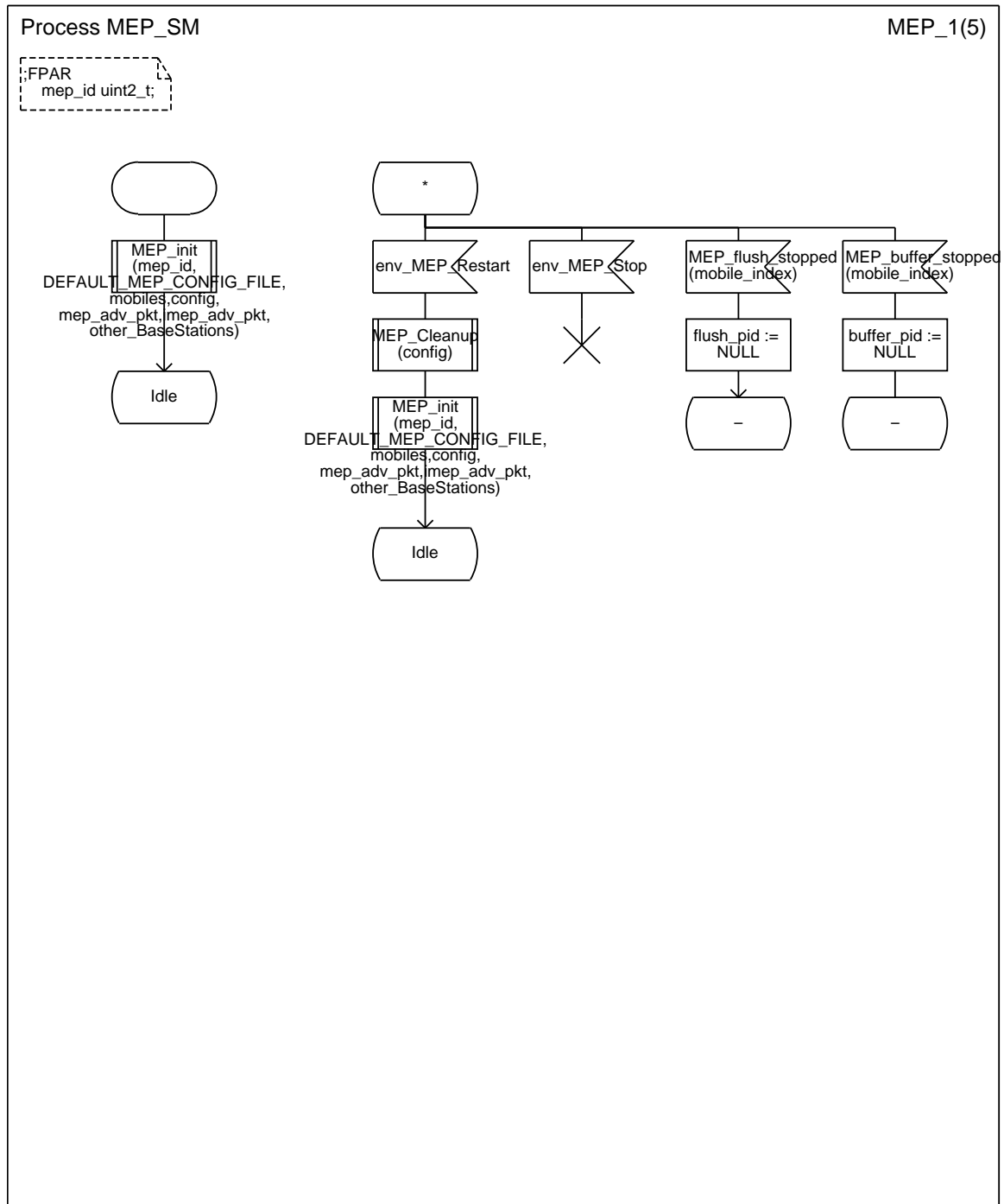
```
config MEP_Config,  
mobiles MEP_MobileMap,  
other_basestations MEP_BaseStationMap,  
mep_buffer MB_Buffer,  
buffer_pid PId,  
flush_pid PId,
```

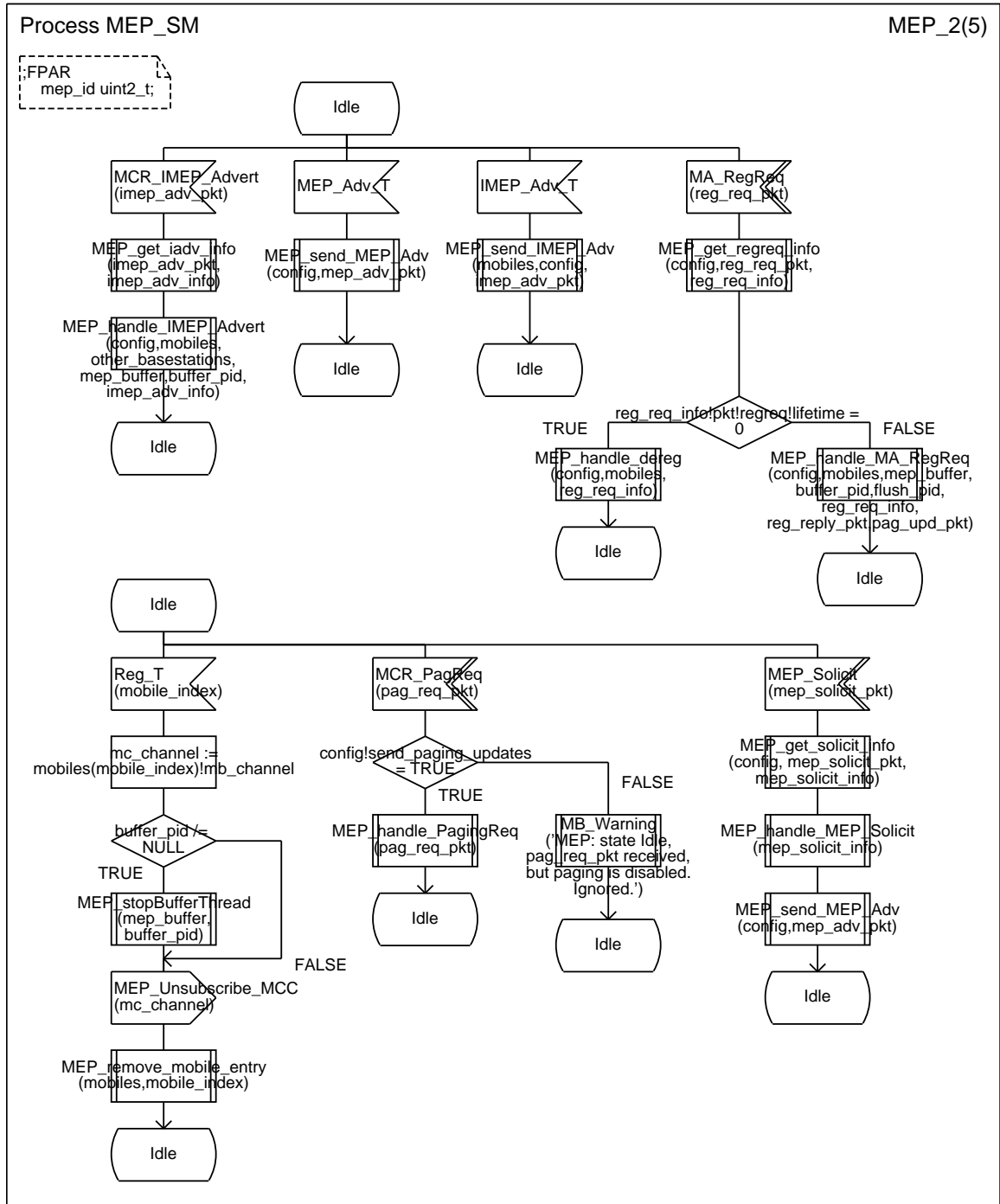
```
reg_req_pkt MA_RegReq_Packet,  
reg_req_info MA_RegReq_Info,  
reg_reply_pkt MA_RegReply_Packet,  
pag_upd_pkt MA_PagUpd_Packet,  
pag_req_pkt GW_PagReq_Packet,  
mep_adv_pkt MEP_Advert_Packet,  
imep_adv_pkt IMEP_Advert_Packet,  
imep_adv_info IMEP_Advert_Info,  
mep_solicit_pkt MEP_Solicit_Packet,  
mep_solicit_info MEP_Solicit_Info,
```

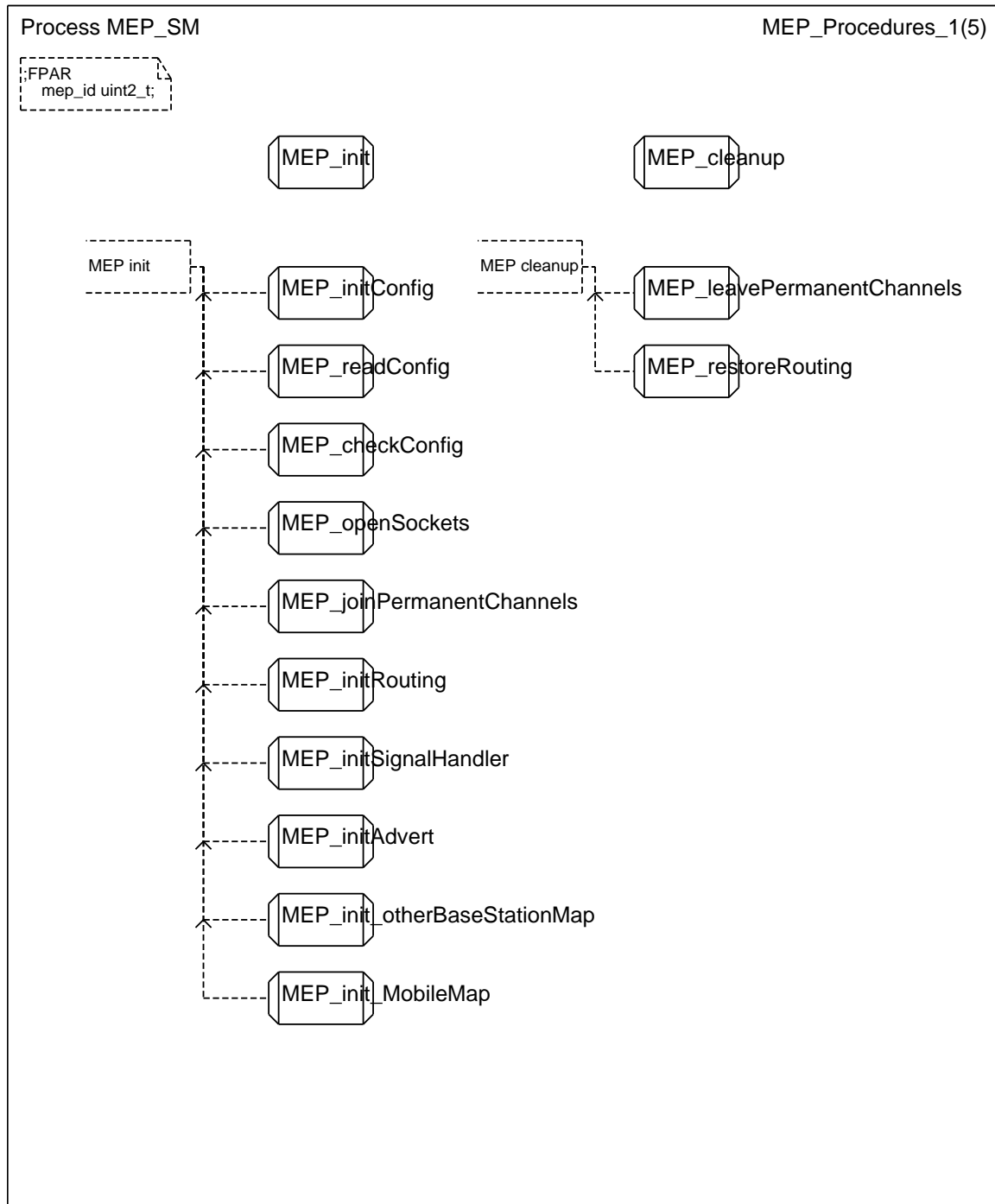
```
mobile_index uint32_t,  
mc_channel MB_MC_Channel;
```

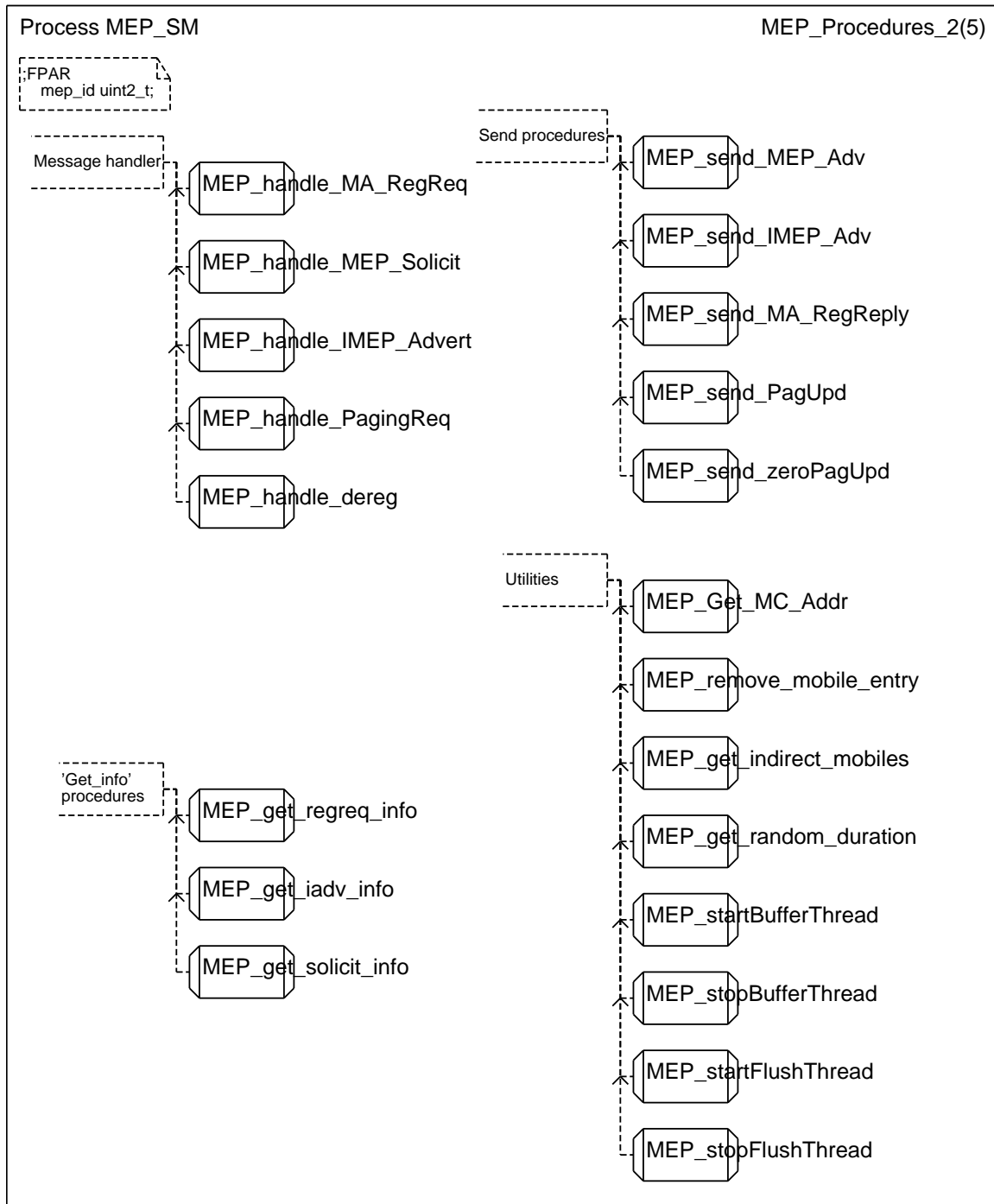
TIMER

```
MEP_Adv_T,  
IMEP_Adv_T,  
Reg_T(uint32_t);
```



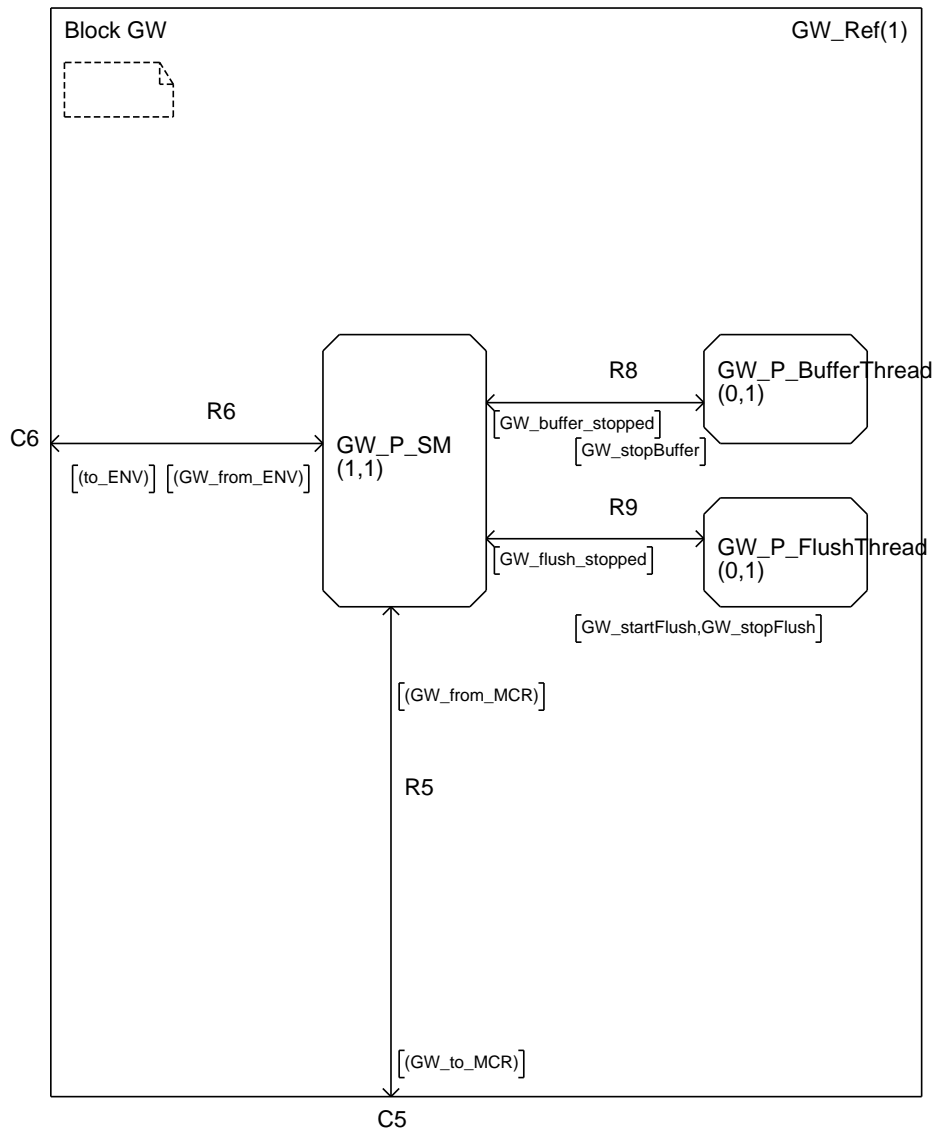








### 5.3 Gateway Proxy State Machine



Process GW\_P\_SM

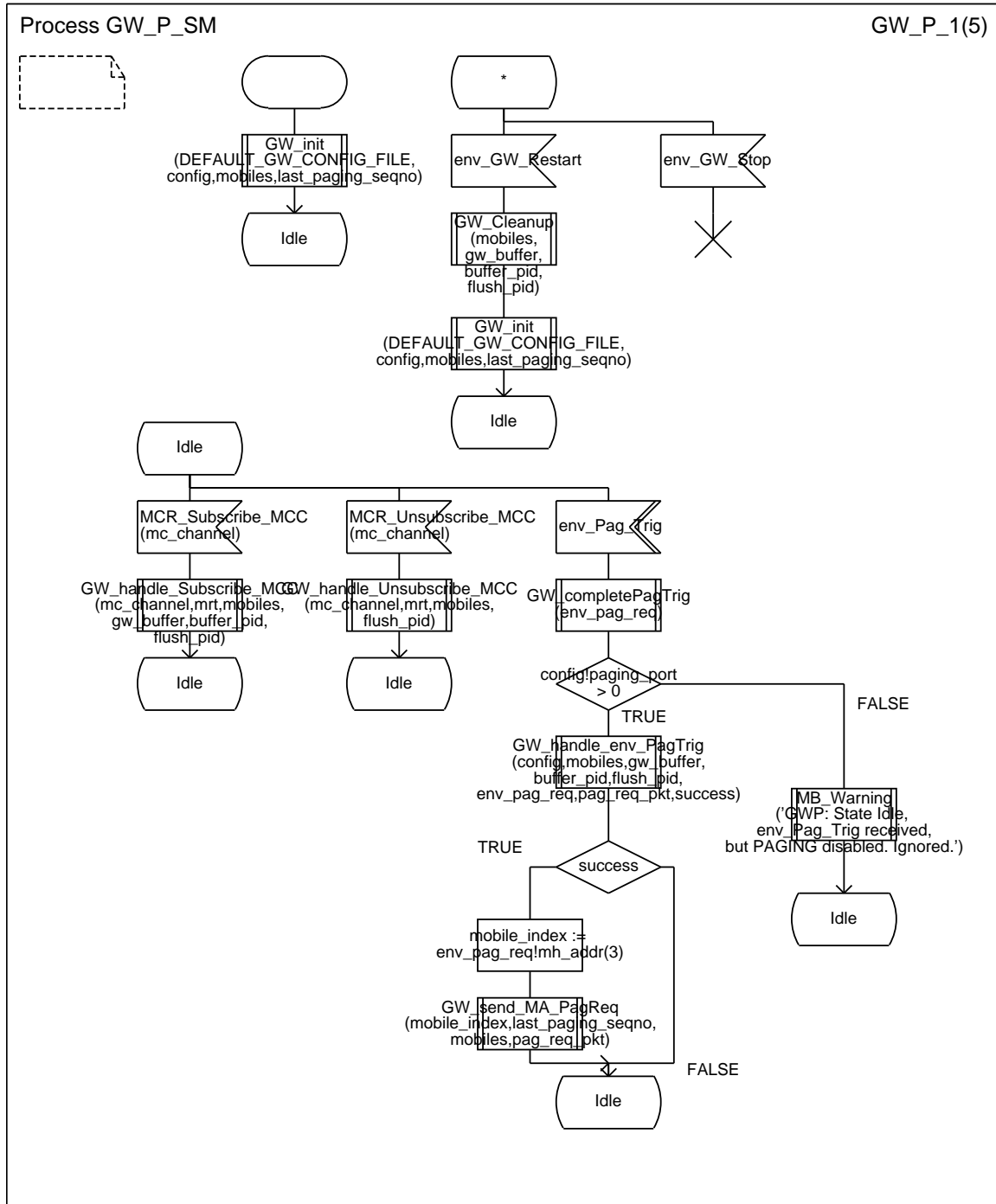
GW\_P\_DCL(5)

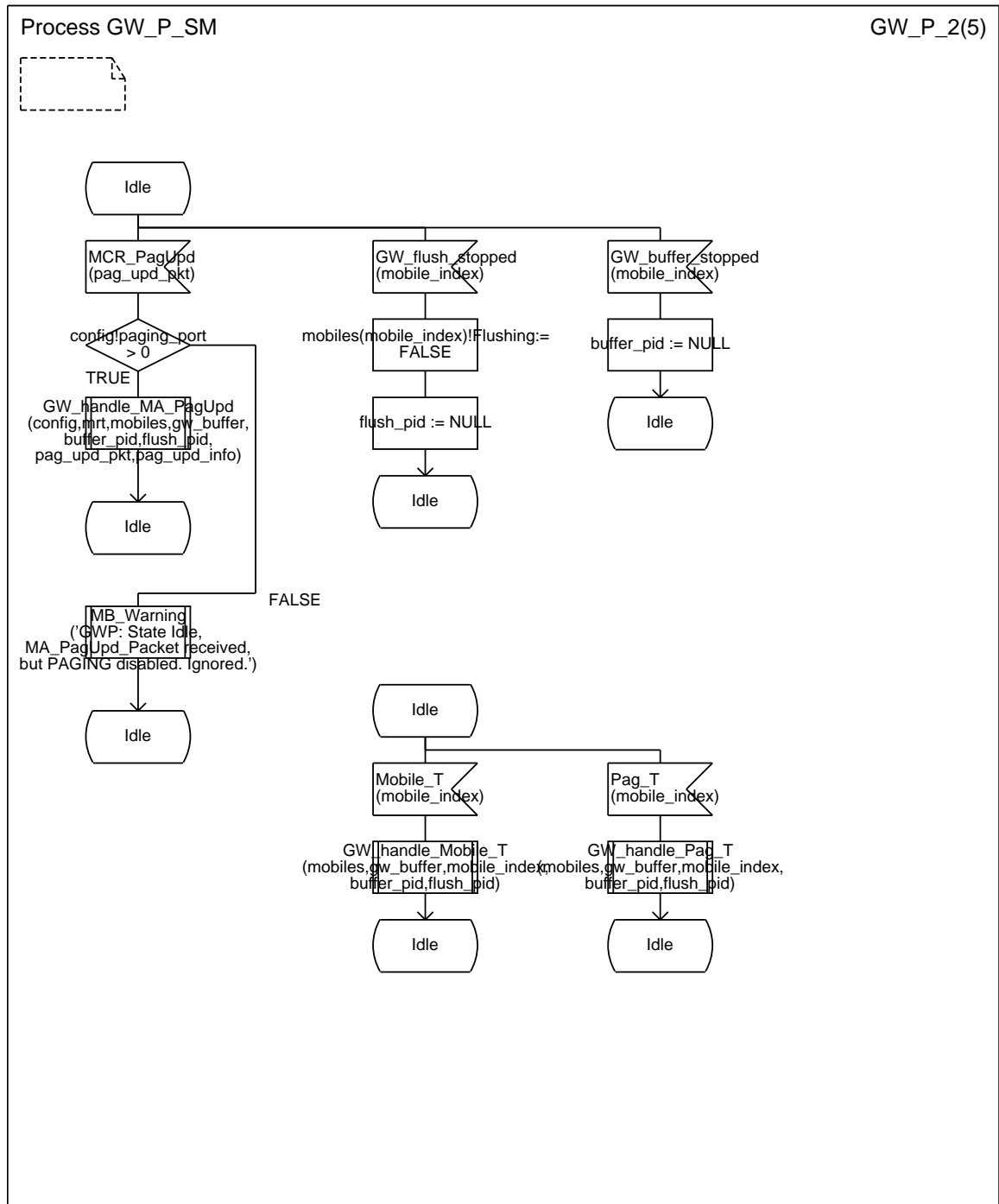


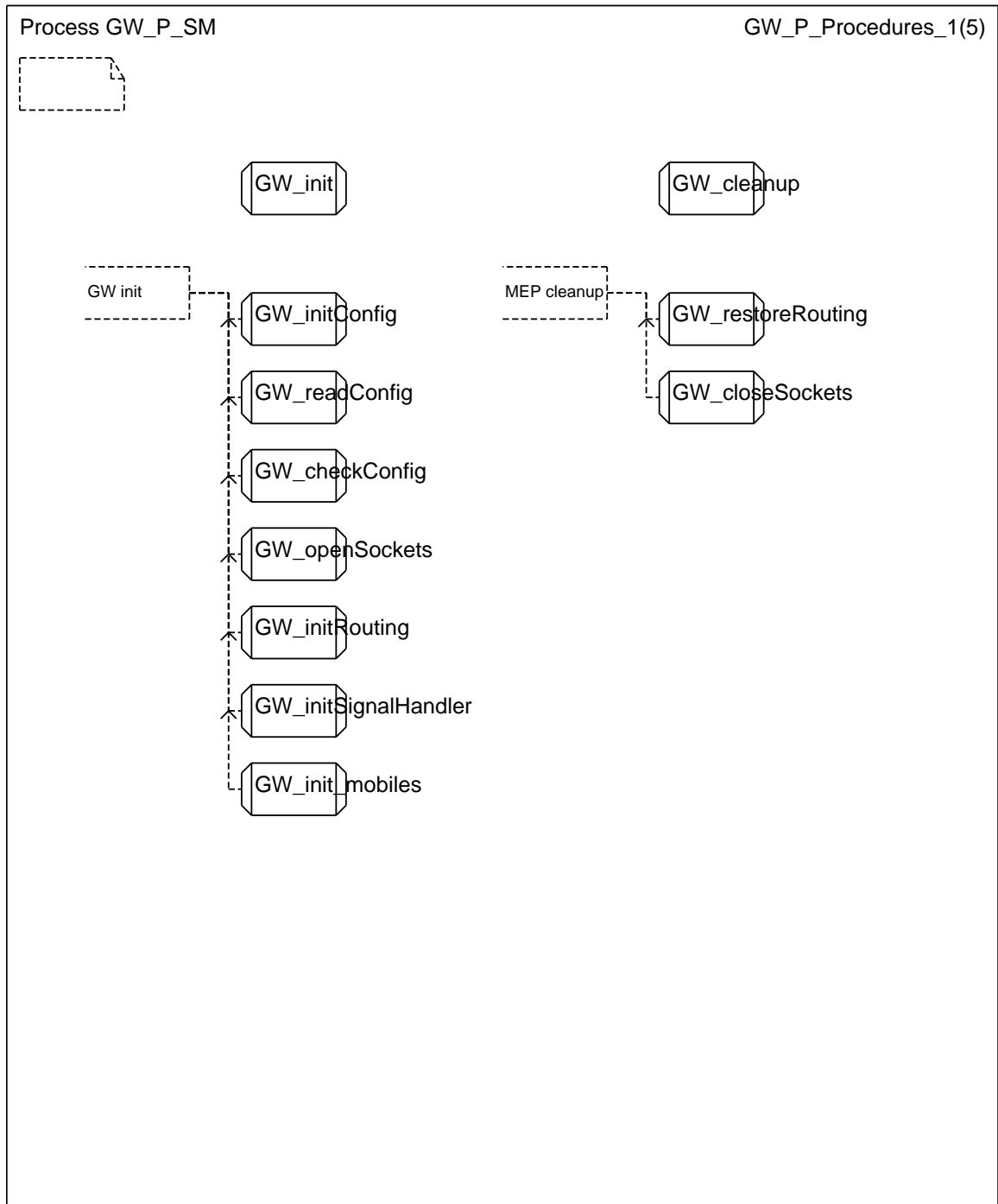
```
DCL
config GW_Config,
mobiles GW_MobileMap,
mrt MB_MRT_t,
mc_channel MB_MC_Channel,
gw_buffer MB_Buffer,
buffer_pid PId,
flush_pid PId,
last_paging_seqno uint32_t,
mobile_index uint32_t,
success Boolean,

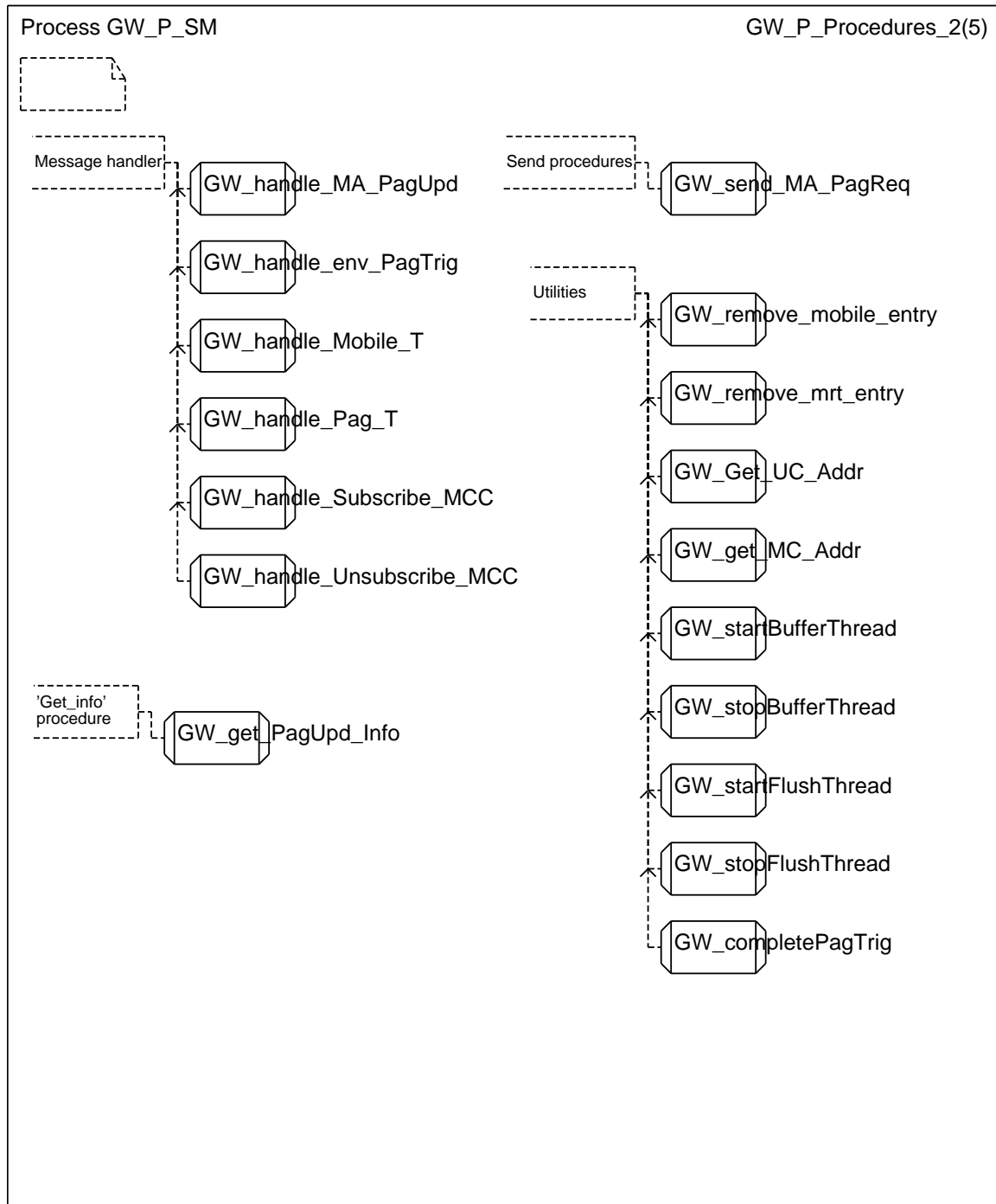
env_pag_req GW_PagReq,
pag_req_pkt GW_PagReq_Packet,
pag_upd_pkt MA_PagUpd_Packet,
pag_upd_info MA_PagUpd_Info;

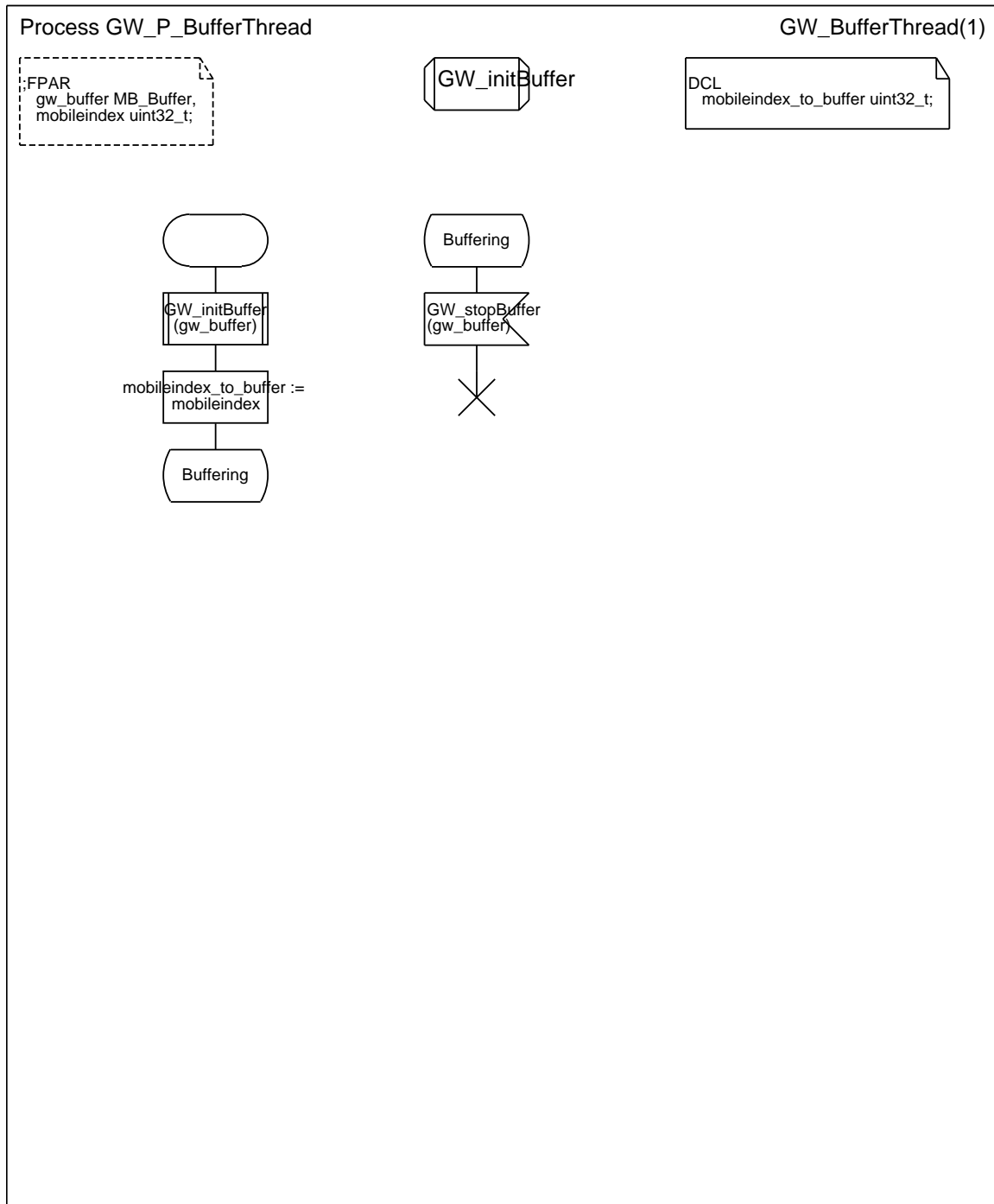
TIMER
Mobile_T(uint32_t),
Pag_T(uint32_t);
```

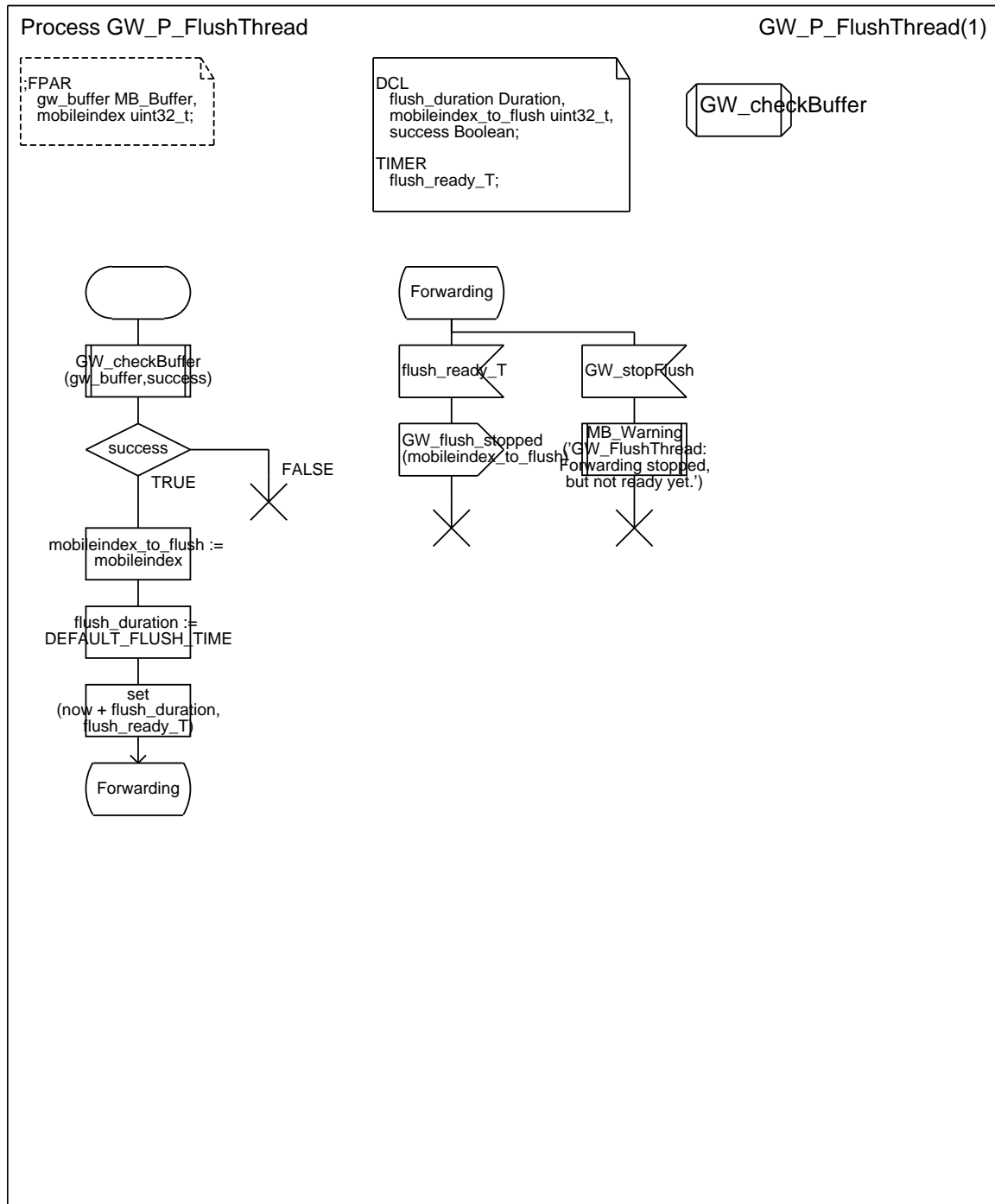






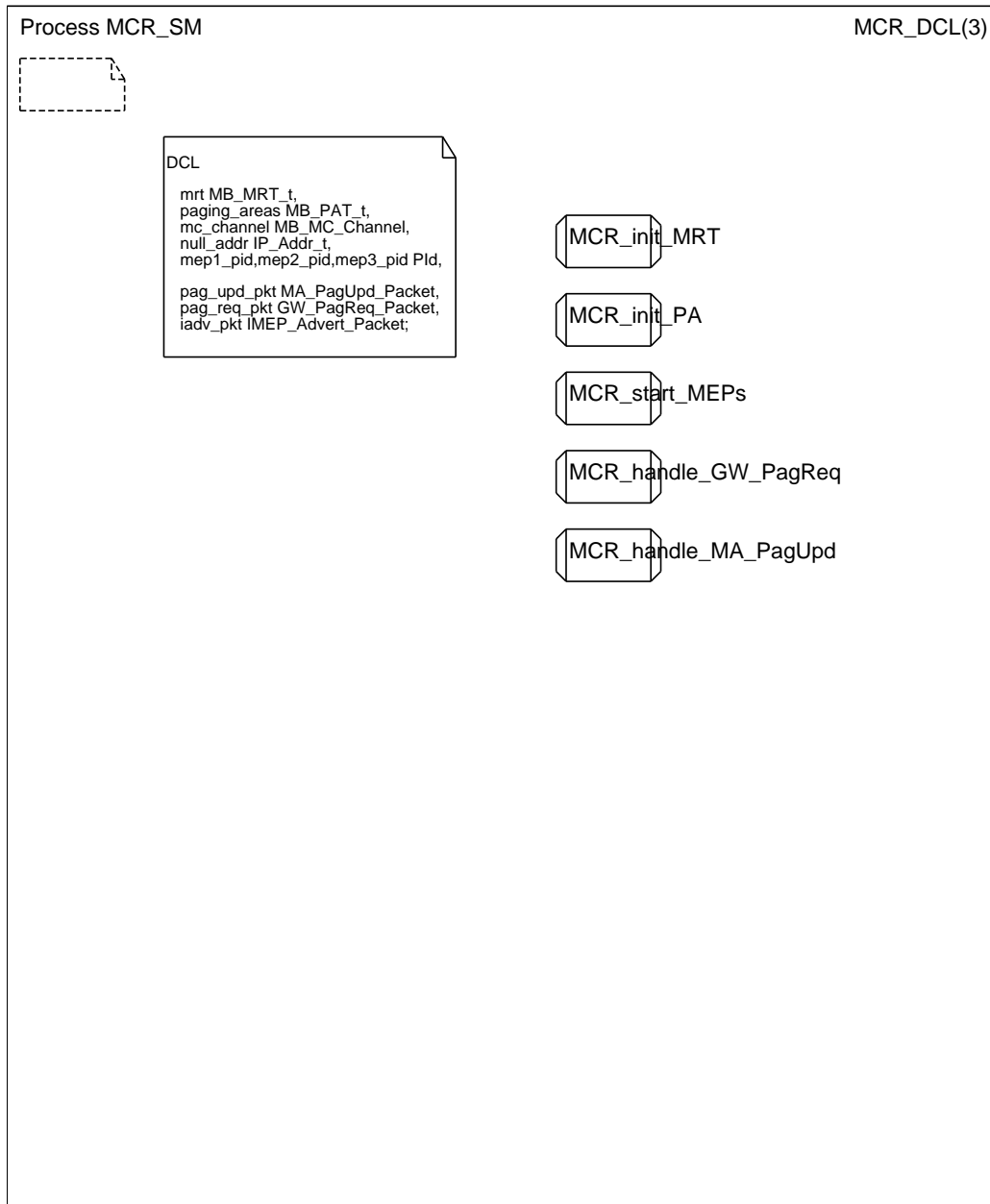


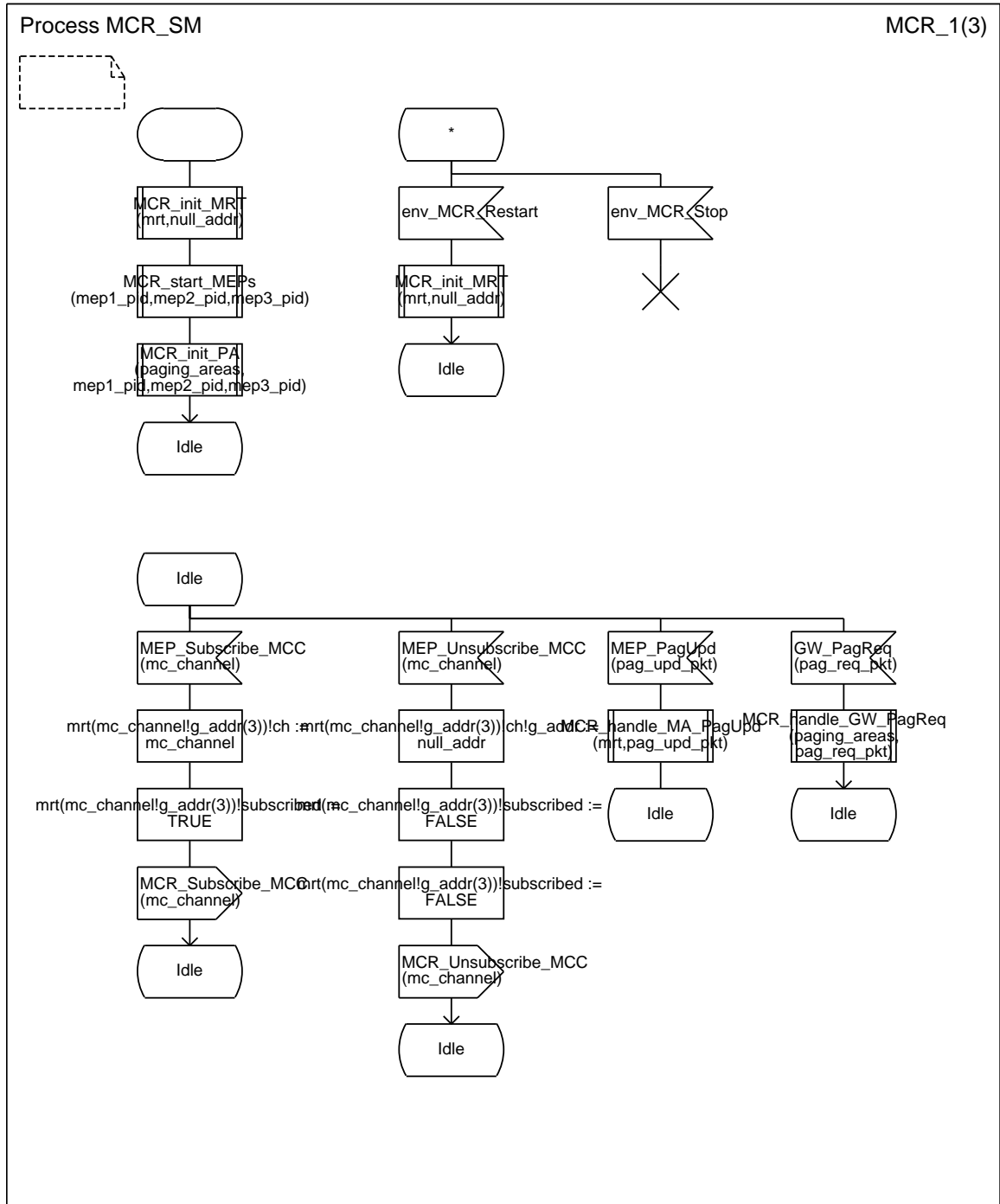


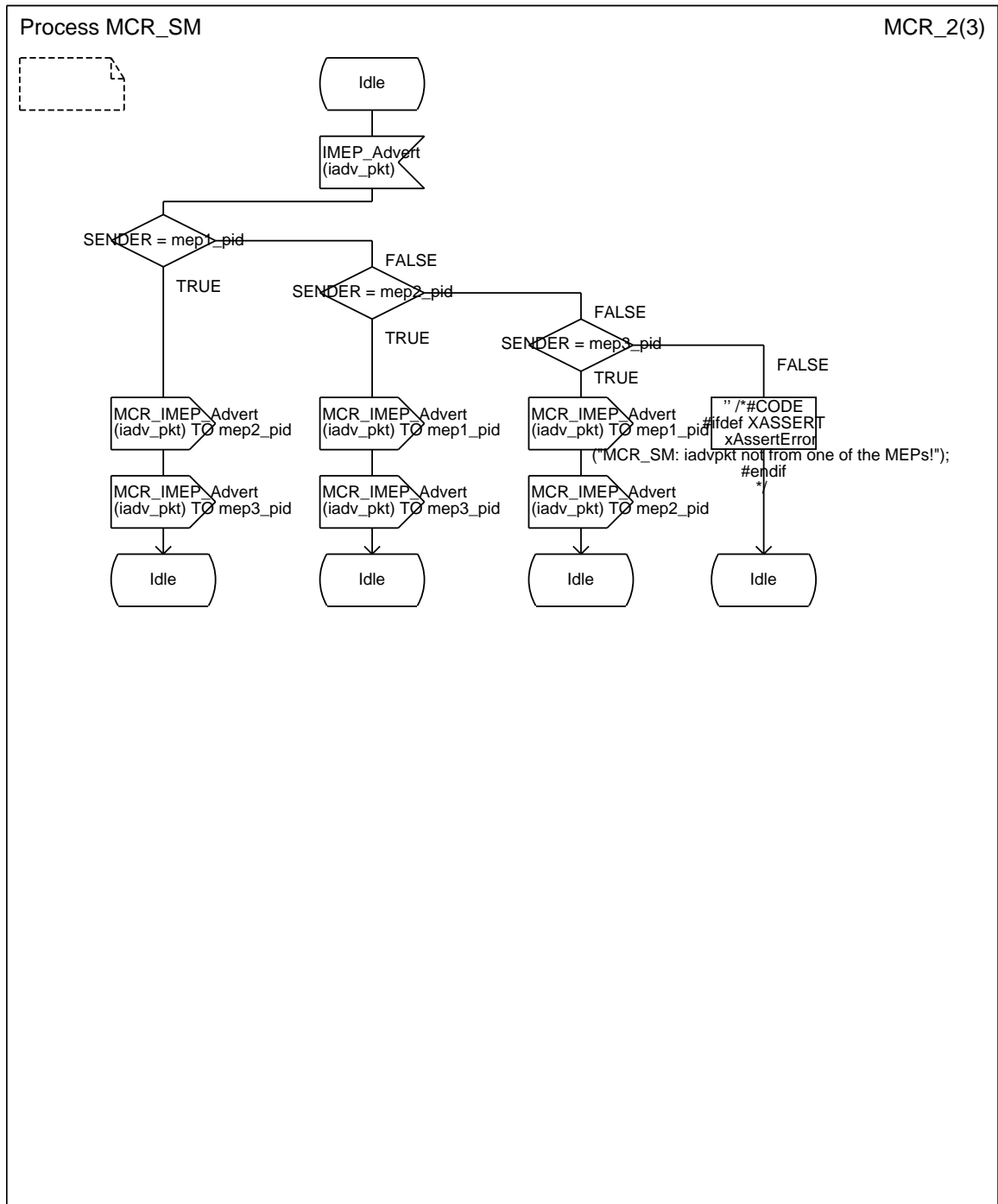




## 5.4 Multicast Router State Machine







## Chapter 6

# Simulation Trace

In order to give an intuitive understanding of the system behavior, the following figures show typical protocol operations by means of a simulation trace (*Message Sequence Charts*), i.e.

1. *Initial registration*: The mobile host is in its INIT state and registers with a MEP.
2. *Activity Timeout*: The mobile host goes into the state INACTIVE,
3. *Wakeup*: The mobile host wakes up and goes into state ACTIVE,
4. *Handover*: The mobile host executes a handover,
5. *Activity Timeout*: The mobile host goes into the state,
6. *Paging*: The mobile host is paged by the gateway proxy.

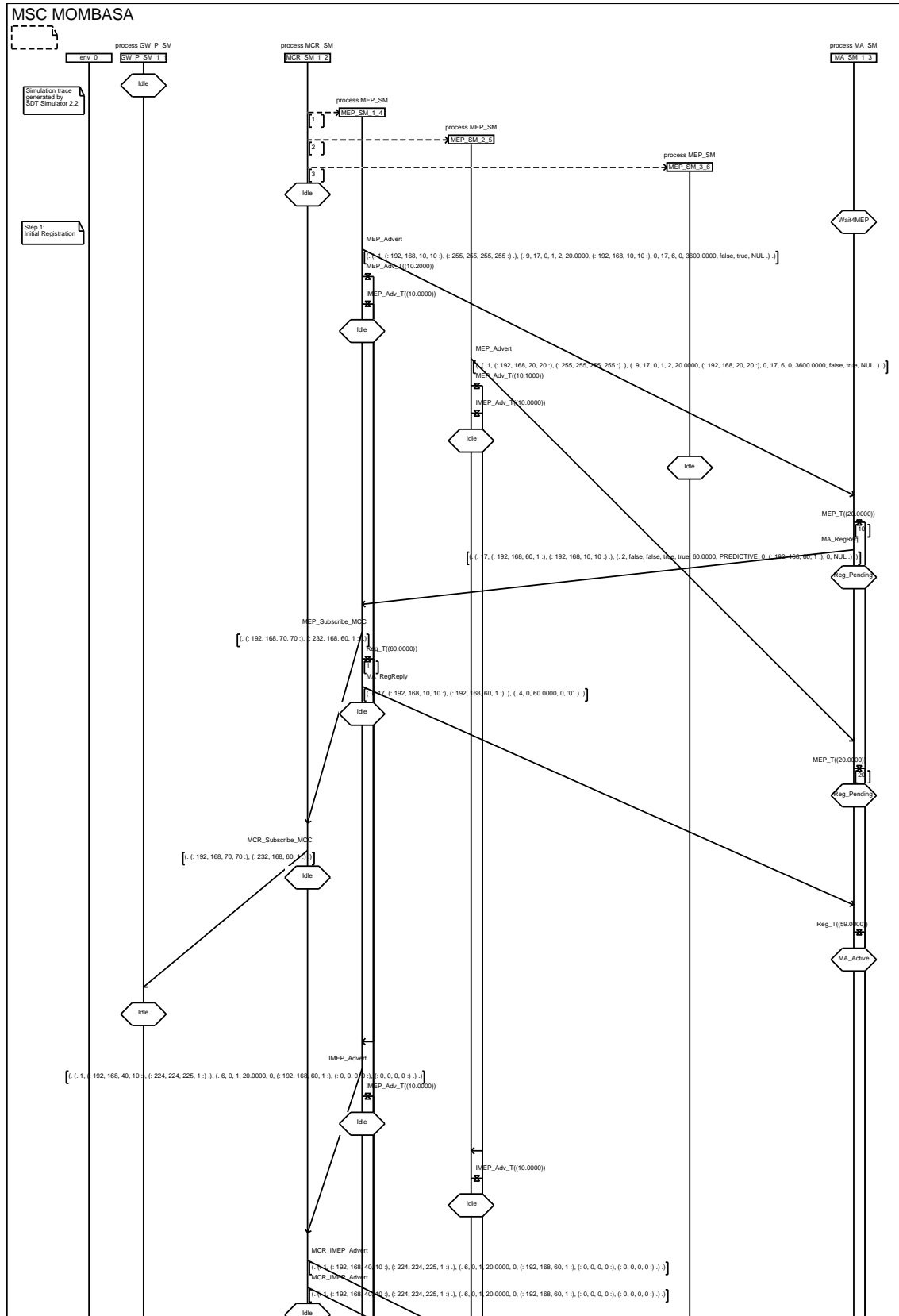
To generate the MSCs, the SDL code was transformed into a number of C source files that are compiled and linked with a SDT runtime library. This process has resulted in an executable program which is used to simulate the system.

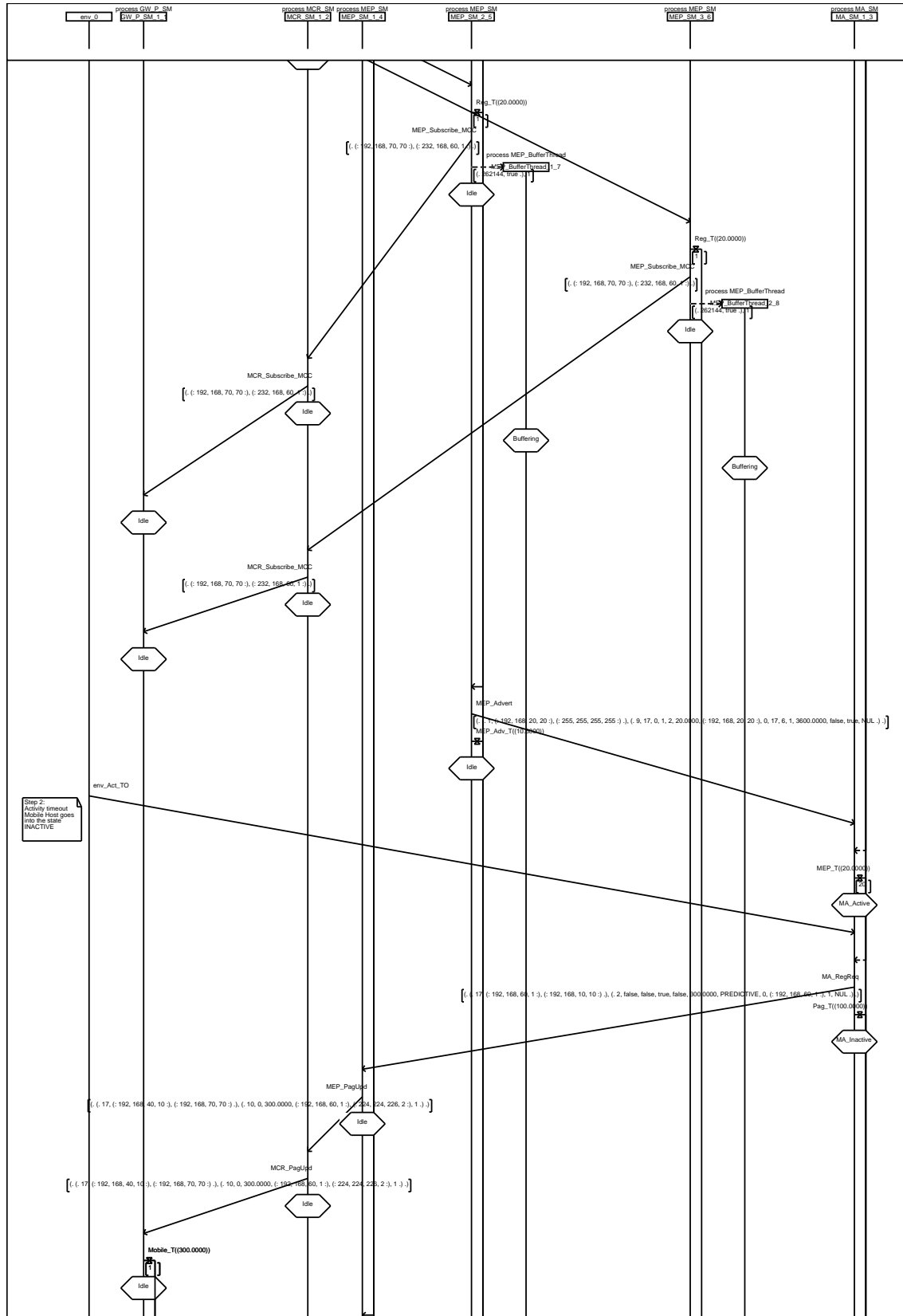
In the simulated scenario, the system consists of

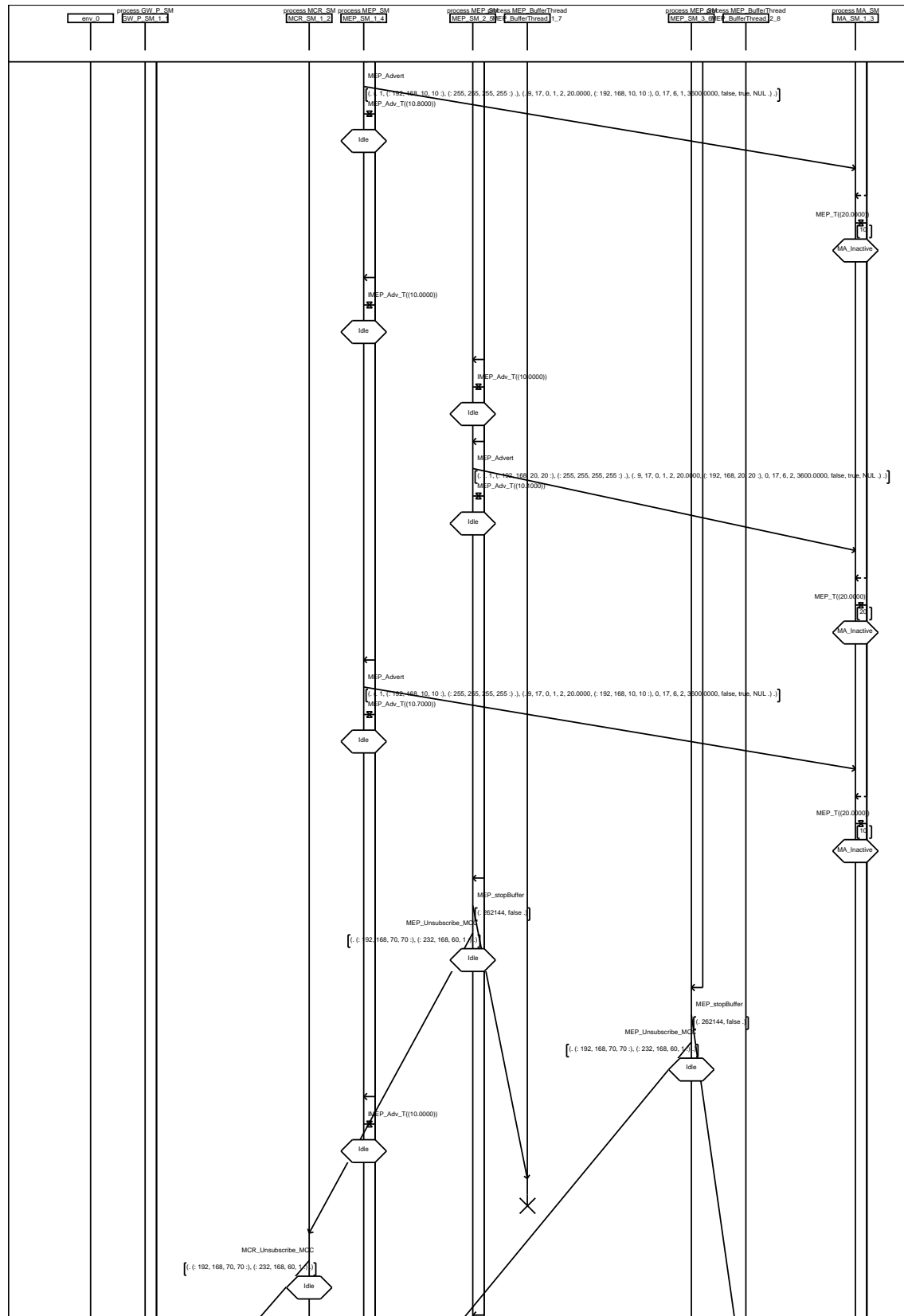
- a single mobile host which executes a mobile agent process,
- an access network, which is composed of three access points executing mobility-enabling proxies (MEPs) and a multicast router which executes a simplified multicast routing demon,
- a gateway proxy (GWP)

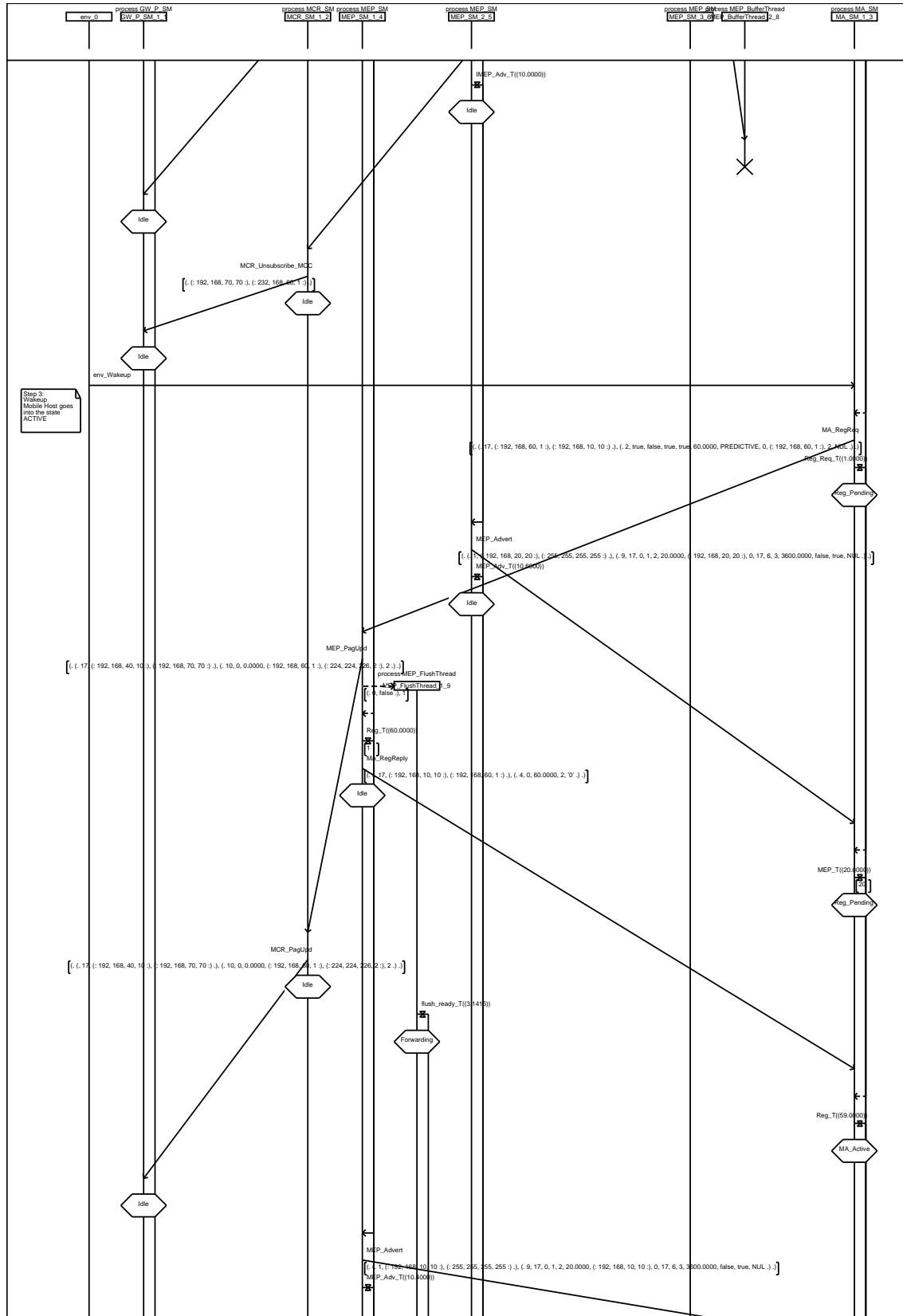
The three MEPs in the access network are configured that only MEP1 and MEP2 are actively involved in handover. MEP3 plays only a passive role, i.e. it does not send any MEP advertisements and IMEP advertisements. To simulate different cases of grouping access points to MEP groups, we differentiate between primary and secondary MEP groups: A MEP sends IMEP advertisements to the multicast channel of the primary MEP group and receives the IMEP advertisements from the multicast channel of the secondary MEP group. Moreover, in the simulated scenario MEP2 and MEP3 form a paging area, where MEP1 is the only access point in another paging area.

To improve the readability of the MSC, some minor details are not shown, such as IMEP Advertisement, when no mobile host is registered with the particular MEP and subscription to static multicast channels (e.g. MEP groups).





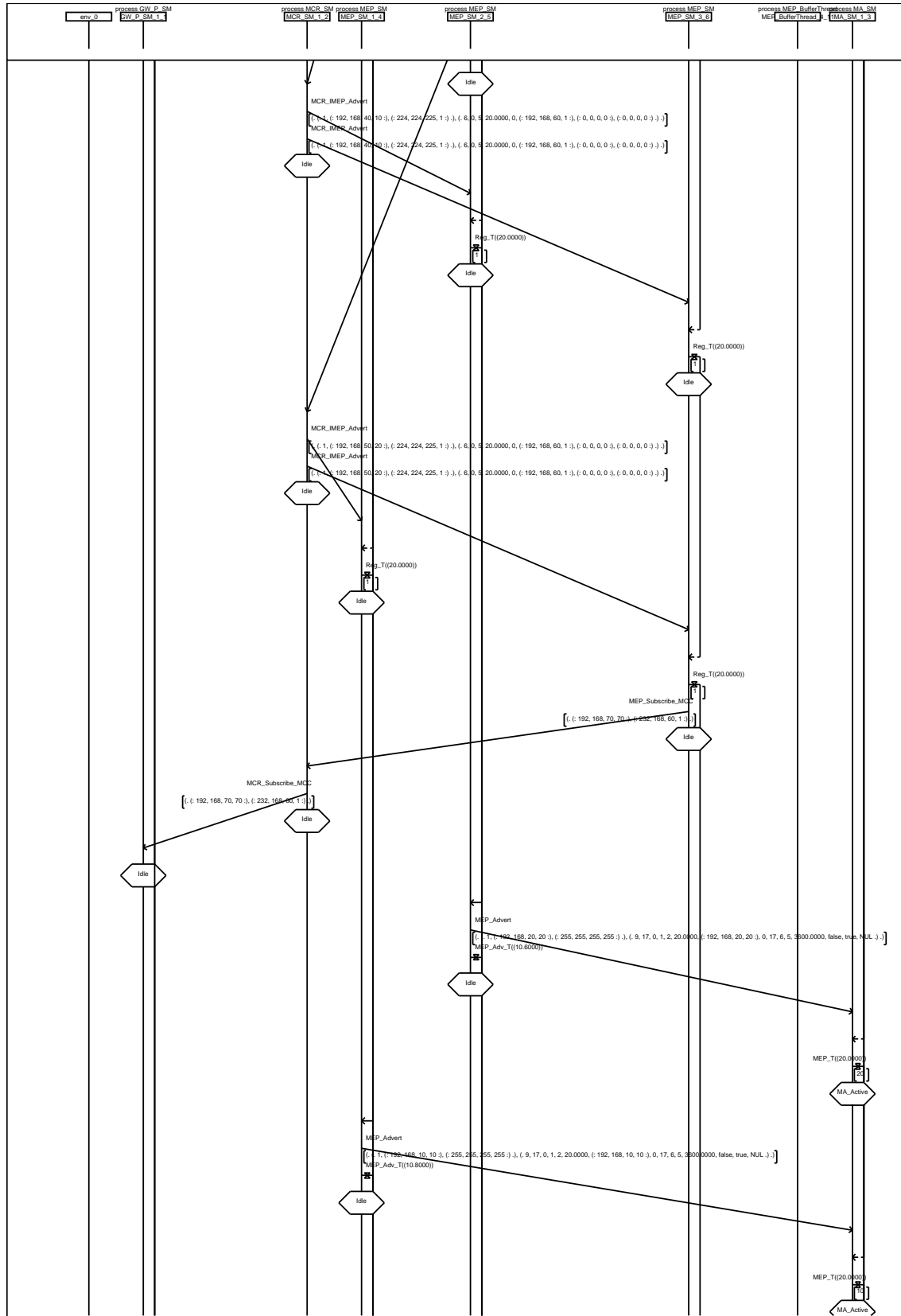


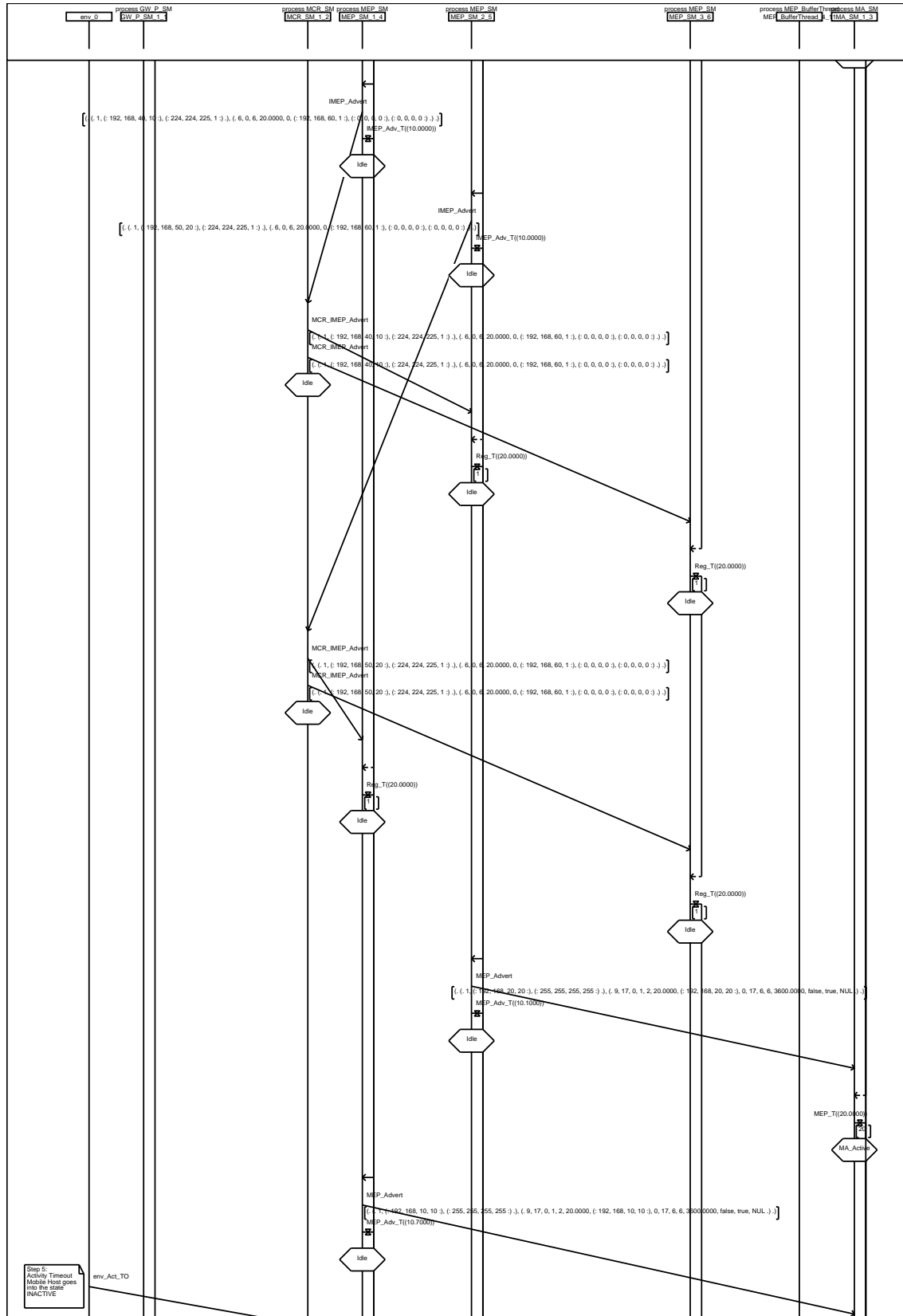


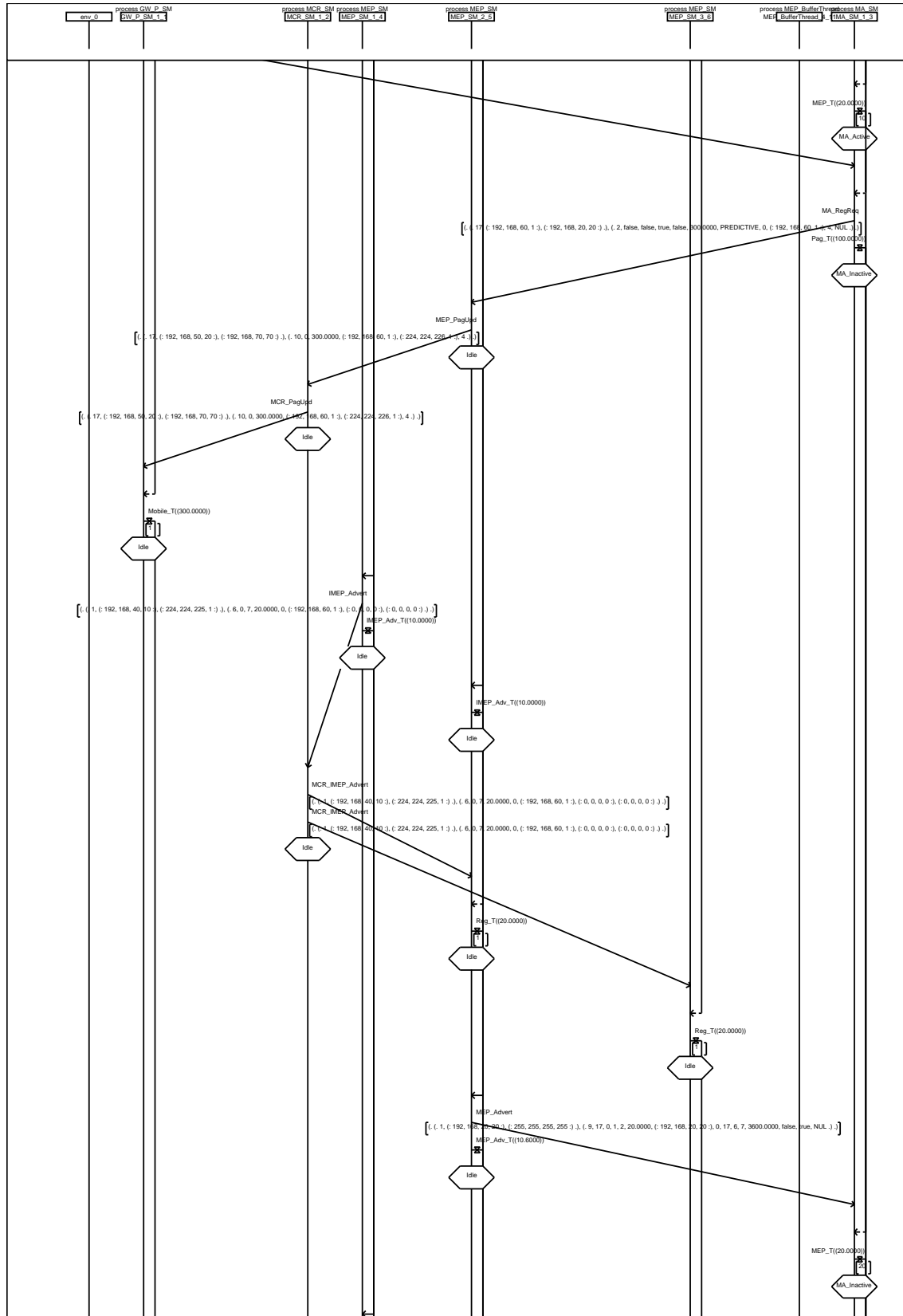






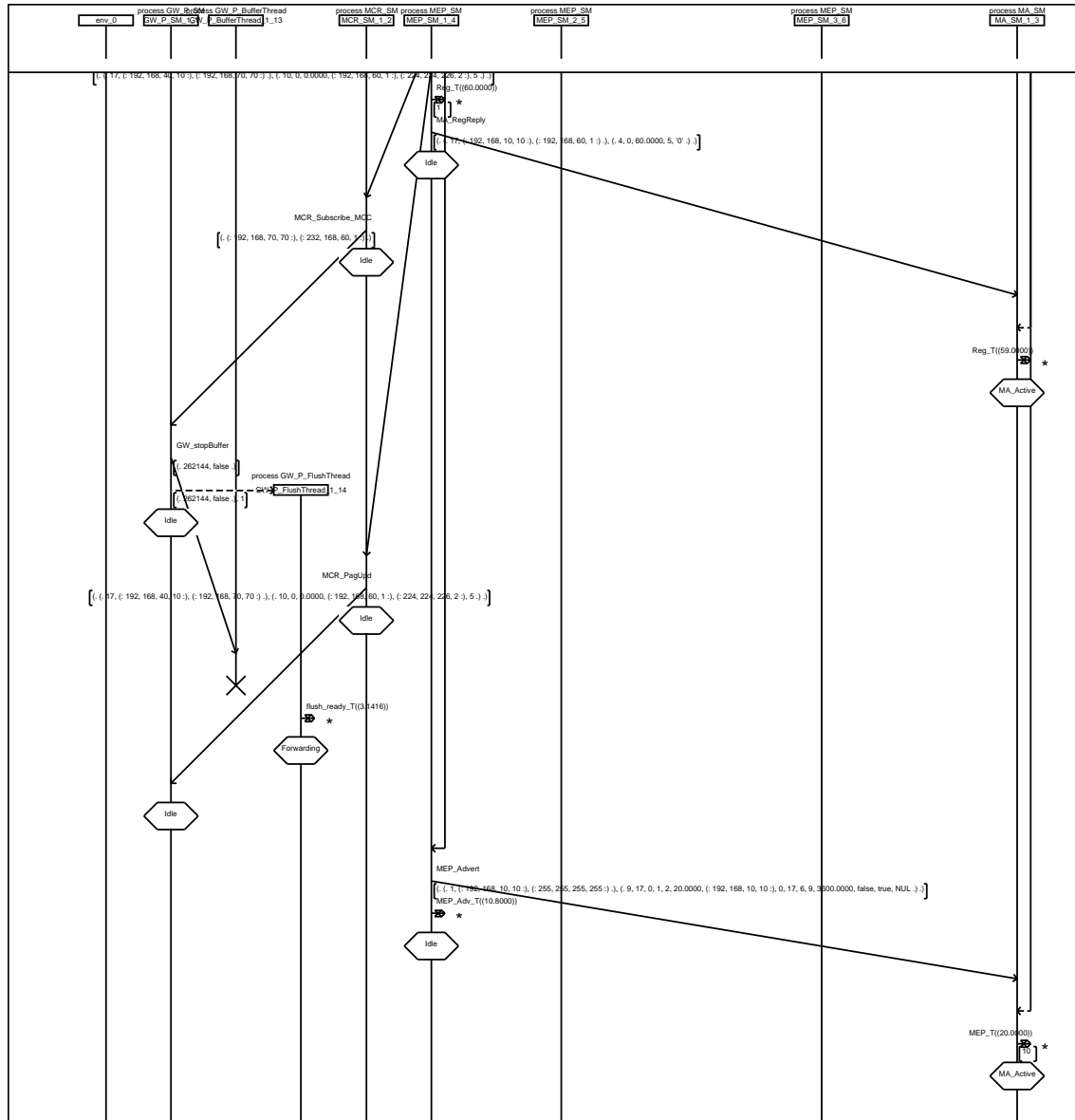














# Bibliography

- [1] B. Aboba and M. Beadles. The Network Access Identifier. RFC 2486, January 1999. <http://www.ietf.org/rfc/rfc2486.txt>.
- [2] Internet Assigned Numbers Authority. Internet multicast addresses. <http://www.isi.edu/in-notes/iana/assignments/multicast-addresses>.
- [3] S. Bhattacharyya, C. Diot, L. Giuliano, R. Rockell, J. Meylor, D. Meyer, G. Shepherd, and B. Haberman. An Overview of Source-Specific Multicast(SSM) Deployment. Internet Draft work in progress, May 2001. <http://www.ietf.org/internet-drafts/draft-ietf-ssm-overview-01.txt>.
- [4] B. Cain, S. Deering, A. Denner, I. Kouvelas, and A. Thyagarajan. Internet Group Management Protocol, Version 3. Internet Draft work in progress, March 2001. <http://www.ietf.org/internet-drafts/draft-ietf-idmr-igmp-v3-07.txt>.
- [5] S. Deering. Host Extensions for IP Multicasting. RFC 1112, August 1989. <http://www.ietf.org/rfc/rfc1112.txt>.
- [6] S. Deering and Editor. ICMP Router Discovery Messages. RFC1256, September 1991. <http://www.ietf.org/rfc/rfc1256.txt>.
- [7] S. Deering, D. Estrin, D. Farinacci, M. Handley, A. Helmy, V. Jacobson, L. Wei, P. Sharma, and D. Thaler. Protocol Independent Multicast-Sparse Mode (PIM-SM): Motivation and Architecture. Internet Draft work in progress, October 1994. <http://citeseer.nj.nec.com/373495.html>.
- [8] R. Droms. Dynamic Host Configuration Protocol. RFC 1541, October 1993. <http://www.ietf.org/rfc/rfc1541.txt>.
- [9] K. Egevang and P. Francis. The IP Network Address Translator (NAT). RFC 1631, May 1994. <http://www.ietf.org/rfc/rfc1631.txt>.
- [10] J. Ellsberger, D. Hogrefe, and A. Sarma. *SDL Formal Object-oriented Language for Communication Systems*. Number ISBN 0-13-621384. Prentice Hall, 1997.
- [11] D. Estrin, D. Farinacci, A. Helmy, D. Thaler, S. Deering, M. Handley, V. Jacobson, C. Liu, P. Sharma, and L. Wei. Protocol Independent Multicast-Sparse Mode (PIM-SM): Protocol Specification. RFC 2362, June 1998. <http://www.ietf.org/rfc/rfc2362.txt>.
- [12] B. Fenner, M. Handley, H. Holbrook, and I. Kouvelas. Protocol Independent Multicast - Sparse Mode (PIM-SM): Protocol Specification (Revised). Internet Draft work in progress, March 2001. <http://www.ietf.org/internet-drafts/draft-ietf-pim-sm-v2-new-03.txt>.
- [13] W. Fenner. Internet Group Management Protocol, Version 2. RFC 2236, November 1997. <http://www.ietf.org/rfc/rfc2236.txt>.
- [14] C. Gkantsidis. Design and Implementation of IGMPv3 for Linux. Technical Report TR00-ATL-111501, Sprint Labs, 2000. <ftp://ftp.sprintlabs.com/Pub/supratik/IGMPv3-TR.ps>.
- [15] C. Gkantsidis, S. Bhattacharyya, and W. DeGraaf. Testing IGMPv3 Implementations. Technical Report TR00-ATL-111502, Sprint Labs, 2000. <urlftp://ftp.sprintlabs.com/Pub/supratik/IGMPv3-testing.ps>.
- [16] D. Johnson and C. Perkins. Mobility Support in IPv6. Internet Draft work in progress, November 2000. <http://search.ietf.org/internet-drafts/draft-ietf-mobileip-ipv6-13>.

txt.

- [17] D. Katz. IP Router Alert Option. RFC 2113, February 1997. <http://www.ietf.org/rfc/rfc2794.txt>.
- [18] P. Maniatis, M. Roussopoulos, E. Swierk, M. Lai, G. Appenzeller, X. Zhao, and M. Baker. The Mobile People Architecture. *ACM Mobile Computing and Communications Review (MC2R)*, July 1999. <http://mosquitonet.stanford.edu/publications.html>.
- [19] B. Moore, E. Ellesson, J. Strassner, and A. Westerinen. Policy Core Information Model – Version 1 Specification. RFC 3060, February 2001. <http://www.ietf.org/rfc/rfc3060.txt>.
- [20] J. Mysore and V. Bharghavan. A New Multicast-based Architecture for Internet Mobility. In *ACM MOBICOM 97*, October 1997. <http://www.acm.org/pubs/articles/proceedings/comm/262116/p161-mysore/p1%61-mysore.pdf>.
- [21] C. Perkins. IP Encapsulation within IP. RFC 2003, October 1996. <http://www.ietf.org/rfc/rfc2003.txt>.
- [22] C. Perkins. IPv4 Mobility Support. Request for Comments 2002, October 1996.
- [23] H.J. Wang, B. Raman, C. Chuah, R. Biswas, R. Gummadi, B. Hohlt, X. Hong, E. Kiciman, Z. Mao, J.S. Shih, L. Subramanian, B.Y. Zhao, A.D. Joseph, and R.H. Katz. ICEBERG: An Internet-core Network Architecture for Integrated Communications. *IEEE Personal Communications*, (Special Issue on IP-based Mobile Telecommunication Networks.), 2000. <http://iceberg.cs.berkeley.edu/publications.html>.

## Chapter 7

# Acronyms

**AP** Access Point

**CH** Correspondent Host

**DR** Designated Router

**GW** Gateway

**GWP** Gateway Proxy

**IGMP** Internet Group Management Protocol

**IMP** Inter-MEP Protocol

**LHP** Last-Hop Protocol

**MEP** Mobility-Enabling Proxy

**MFC** Multicast Forwarding Cache

**MOMBASA** MObility support - a Multicast-BAsed Approach

**MH** Mobile Host

**MU** Mobile User

**MR** Multicast Router

**MRIB** Multicast Routing Information Base

**NAT** Network Address Translation

**PA** Paging Area

**PIM** Protocol-Independent Multicast

**PIM-DM** Protocol-Independent Multicast - Dense Mode

**PIM-SSM** Protocol-Independent Multicast - Single Source Mode

**PIM-SM** Protocol-Independent Multicast - Sparse Mode

**PPP** Point-to-Point Protocol

**RIB** Routing Information Base

**RP** Rendezvous Point