Mobility Management and Control Protocol for Wireless ATM Networks

Alexandros Kaloxylos, Stathes Hadjiefthymiades, Lazaros Merakos

{agk | shadj | merakos}@di.uoa.gr

Communication Networks Laboratory

Department of Informatics, University of Athens

Tel: +301 7275334, Fax: +301 7252116

Panepistimioupolis Ilisia, Athens 15784, Greece

The introduction of wireless ATM (WATM) in customer premises networks (CPN) environments necessitates the design of mobility signaling protocols, since the existing versions of B-ISDN signaling do not support terminal mobility. Such protocols can be deployed either as extensions to the standard signaling capabilities, or as individual solutions that have little or no impact on existing infrastructures (switches, signaling software, etc.). A WATM architecture that adopts the latter approach is presented. After a discussion on the problems encountered in the integration of wireless networking and B-ISDN ATM technologies, a Mobility Management and Control (MMC) protocol is proposed. Finally, in the framework of the proposed MMC protocol, algorithms for implementing mobility procedures (handover and registration) are described.

Keywords: WATM, CPN, B-ISDN signaling, mobility, registration, handover

I. Introduction

The introduction of the Asynchronous Transfer Mode (ATM) in Wireless CPN environments (WATM) has led to the deployment of several pilot-experimental installations and the early stages of products ([1-3], [27], [29]). However, as the technology is not yet mature enough, many technical issues need to be resolved. Signaling is definitely one of the troublesome areas. Apart from the conventional signaling solutions encountered in wired networks, additional signaling is needed to cover the mobility requirements of terminals [4-9]. Wired ATM networks, which enjoy an impressive commercial growth, do not provide mobility of user terminal equipment. Contemporary B-ISDN signaling does not support handover, location updating, and (de-) registration for mobile terminals in the network.

A possible solution to this problem is the integration of the required mobility extensions with the standard signaling protocols to satisfy the identified requirements. Such an approach could lead to rather complex signaling protocols, whose complete range of functionalities is not required in fixed ATM networks. A more realistic approach suggests the introduction of new, completely independent, protocols, which handle only the mobility procedures (mobility control), while interacting (at some points) with conventional signaling (call control) [5].

The design of mobility protocols needs to take into account the problem of switching the signaling and data connections of a terminal, as the latter moves from the coverage area of one Base Station (BS) to that of a neighboring BS (handover). Mobility signaling and related procedures need to be designed appropriately to enable fixed network entities to render the signaling channels available to the mobile terminal in the new/target BS as fast as possible. Such procedures, despite the fact that they are uniformly applied in all handover cases, are mainly intended for those in which the current connection is abruptly lost. Such cases present substantial difficulties, which are mainly attributed to

- the current capabilities offered by ATM equipment (switches, software),
- the limited amount of time available for the switching of control and user plane connections, and finally,
- their unpredictable nature (especially in a CPN environment).

The main contribution of this paper is the design of a mobility signaling protocol for a Wireless ATM network, where the BSs have minimal functionality and are not directly interconnected. The protocol handles the required connection switching in a uniform way for both data and signaling connections for all mobility procedures, complies with existing ATM signaling standards, and its implementation leaves commercially available ATM components unaffected. This protocol has been implemented in the context of the Magic WAND (Wireless ATM Network Demonstrator) project [3,10] funded by the European Union in the framework of the “Advanced Communications Technologies and Services” (ACTS) program.

The paper is organized as follows. Section II proposes a generic network architecture based on the separation of call and mobility control (overlay approach). In this architecture, apart from the well-known signaling Virtual Channel (VC), one additional signaling channel is introduced at the user-network interface (UNI). Section III discusses the functional entities needed in the proposed WATM architecture as well as their inter-relationships in the context of the various protocol stacks. Section IV provides a brief overview of the handover types encountered in a CPN environment and provides an overview of relevant work on the subject. Section V proposes a solution for the switching of the signaling and data connections during the execution of a handover. VC switching - rerouting is accomplished through the Application Programming Interfaces (API) that modern switches offer. Section VI gives an insight of the various software modules developed in support of the protocol. Section VII elaborates on the proposed protocol by presenting the Message Sequence Charts [16] for the cases of Registration, Backward and Forward Handover. Finally, section VIII contains the conclusions.

II. Network architecture

The main components of the wireless network architecture under consideration are Mobile Terminals (MT), Base Stations (BS) and a Control & Switching Unit (CSU). MTs can move within the coverage area of BSs and exchange information with other MTs (in the case of MT-to-MT calls) or conventional terminals connected to the fixed part of the ATM infrastructure (MT-to-fixed terminal calls). BSs are attached to the CSU ports by means of high bandwidth links. Their primary role is the adaptation of ATM cells to radio packets and vice versa, and their transmission/reception over the radio link.

The CSU provides mobility related signaling (registration, de-registration, location update and hand-over) as well as routing of ATM cells. It is assumed that the CSU incorporates a typical, commercially available, ATM switch. The operation of the CSU is supported by a specially designed database (DB). The DB keeps track of the current location and status of MTs, and can be used for authentication and security procedures that need to be invoked upon registration. All MT originated signaling messages related to mobility are diverted to the CSU and processed there (the CSU constitutes a mobility signaling end-point). Standard signaling messages (e.g., SETUP, RELEASE) are also diverted to the CSU (to examine their potential local scope), but are subsequently forwarded towards the other terminal participating in the call/connection association.

BSs are controlled by the CSU by means of a specialized protocol (hereinafter referred to as BSMP - Base Station Management Protocol). BS management related messages are exchanged through a pre-reserved VC in the BS-CSU link.

A graphical overview of the considered network architecture is given in Figure 1.

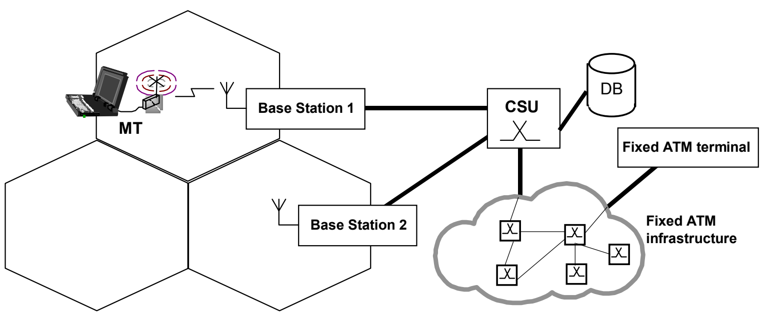

Figure 1: Wireless ATM network architecture

When porting signaling protocols from wired ATM systems to wireless environments, it is required for different MTs to transmit signaling information over the radio interface on the same VPI[1]/VCI

[1] Virtual Path Identifier

combination (VPI=0, VCI=5 for ATMF[2] UNI 3.1) [12]. Since BSs behave as traffic concentrators on the uplink and splitters on the downlink, a conflict is experienced due to the mandatory use of the same VPI/VCI values by different MTs on the same UNI at the multi-access radio link connecting MTs to a BS. To eliminate such a conflict, in the considered network architecture (limited MT population), one VP (with VPI=x, where x is calculated on the basis of the unique ATM address assigned to the terminal) is reserved for each mobile terminal in the MT-CSU logical interface. The mapping of VPI values is performed at the lower layers of the MT, transparently to the signaling entities that are positioned at the higher layers. For large-scale installations, other techniques can be found in [13].

Within this VP, a permanent VC is reserved for the purpose of exchanging standard signaling messages [11, 12, 17]. One permanent VC (PVC) is also allocated for the exchange of mobility related signaling messages. PVCs intended for standard signaling will be referred to as 'S-channels', while PVCs for mobility signaling will be termed "M-channels". This separation of signaling channels is adopted in order to minimize impact on the existing ATM infrastructure, which is one of the main objectives of this work. Other researchers have proposed the extension of conventional signaling protocols to accommodate mobility related signaling [25].

Figure 2 illustrates the VP/VC allocation in the BS-CSU fixed link. The VC allocation scheme described in the previous paragraph applies to all the BS-CSU fixed links where the link numbers differentiate individual connections.

[2] ATM Forum

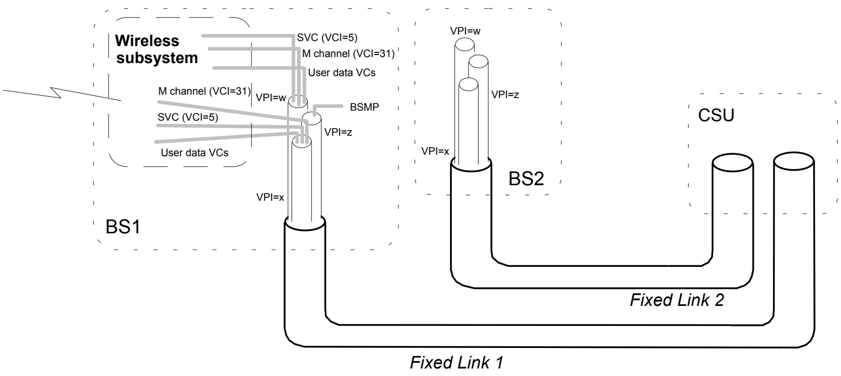

Figure 2: BS-CSU ATM link

III. Functional entities and signaling stacks

In this section, the functional entities for the considered WATM architecture are described. In the MT, a specialized entity performing mobility control is introduced. This entity is referred to as Mobility Management and Control (MMC). MMC is responsible for registering (de-registering) the MT in the network, and requesting handover or location update. MMC, upon notification by the lower layers on the signal strength degradation or complete signal loss experienced over the radio channel, is able to determine the type of handover (backward or forward), or location update that should be requested from the fixed network entities. Conventional signaling[3] is left to an ATMF UNI 3.1 [12] compatible entity. On top of this, a new entity, called Call Control and Signaling (CCS), is introduced to provide the information required by MMC (e.g., respond to queries for connection characteristics). Both the MMC and the ATMF UNI 3.1 protocols rely on Signaling ATM Adaptation Layer (SAAL) [14, 18] for assured transfer of signaling information.

In the MT, a wireless Medium Access Control (WMAC) entity [15] is introduced. WMAC helps obtaining control of the shared medium, performs association or de-association with BSs, routes ATM cells to the physical layer (and vice versa) and notifies MMC on the status of the radio link. Its counterpart is located in the BS. In the BS, apart from the MAC layer, a Radio Resource Manager (RRM)

[3] MT is a signaling end-point for both conventional and mobility signaling.

is also needed. Such entity retrieves long and short term traffic characteristics from the MAC entity and performs Connection Admission Control (CAC) for the wireless part of the network (Wireless CAC - WCAC).

The CSU incorporates conventional signaling entities (Q.2931 [11], NNI protocol) as well as a signaling entity intended for mobility management and control (MMC). The latter entity communicates with RRM by means of the BSMP. On top of the Q.2931 and NNI signaling modules there is a module called Resource Manager (RM) that is responsible for performing the necessary Call Admission Control (FCAC), Routing and Addressing procedures for the fixed part of the network. New or diverted (due to handover) connections are admitted in a specific BS, only if both the WCAC and the FCAC can accommodate the requests. MMC is responsible for coordinating both tasks to reach a combined decision.

In terms of module-entity instances, there is an one-to-one mapping between RRM and BSs (each BS has an RRM instance). There is also an one-to-one relationship between active MTs and MMC instances residing within the CSU (CS_MMC). The same applies to RM. In each MT, only one MMC (MT_MMC) and one CCS instance are needed.

Figure 3 presents the protocol stacks deployed in the various components of the network architecture. Gray lines denote logical interfaces between the higher layers of the architecture. In this figure, standard signaling is left unaffected. The only modifications to the existing infrastructure are the new interfaces with the controlling entities of standard signaling (i.e. CCS, RM). These entities receive signals from the WAND specific modules and translate them internally to the appropriate primitives on their interface with the standard signaling, and vice versa.

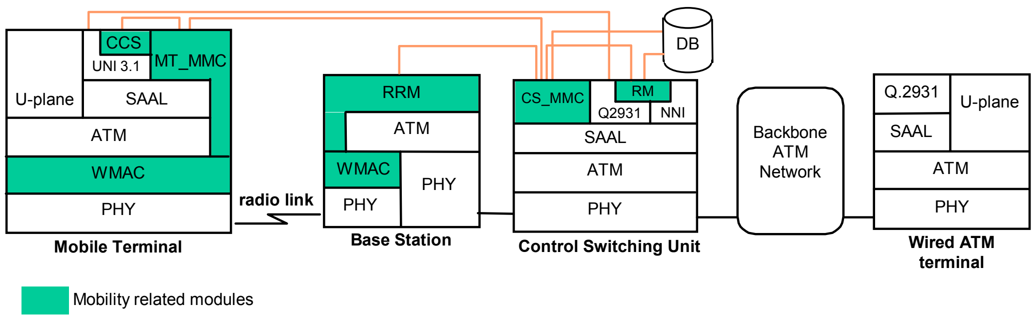

Figure 3: Protocol stacks

The User Plane (U-plane) in the considered WATM architecture supports LAN Emulation (LANE v.1) [24] in addition to Native ATM applications.

IV. Handover classification and prior work

In cellular environments, handovers can be classified as *intra-switch* or *inter-switch* [33] depending on whether the MT moves to a cell controlled by the same or different CSUs, respectively. Furthermore, two handover types can be identified: backward and forward. This distinction mainly refers to the BSs through which the handover signaling information is exchanged.

Σχόλιο:

Considerable work has been performed for the design and development of handover supporting protocols [34].

In [25], a detailed WATM architecture is presented including a classification of handover execution methods. Furthermore, [25] presents an innovative pilot implementation of a protocol that supports forward handovers. In the considered architecture, BSs act as standard signaling end-points. This approach may result in long processing time to complete the signaling tasks [26]. To accommodate mobility related signaling, conventional signaling messages are extended. Location management procedures are based on the Mobile-IP scheme [32].

In [1], a WATM pilot is also presented where connections are extended to the target BS each time the MT performs a handover. In this "path extension" technique, BSs need to be directly interconnected, and the resulting data paths may become sub-optimal. In [27], specialized core-network components, termed Interworking Devices (IWD) are introduced for the handling of mobility related procedures. The end-to-end ATM connection is always broken-bridged at the IWD to facilitate mobility management (location tracking, handovers, etc.).

V. Dynamic switching of connections

In our network architecture, there is only one data path at a time between the MT and the CSU, through which mobility or conventional signaling information could be exchanged (i.e., no macro-diversity is used). During the switching process, the existing SAAL instances should be cleared and new SAAL instances, between the MT and the CSU, should be spawned (Figure 4). Furthermore, the state of the old SAAL instances should be transferred to the new ones.

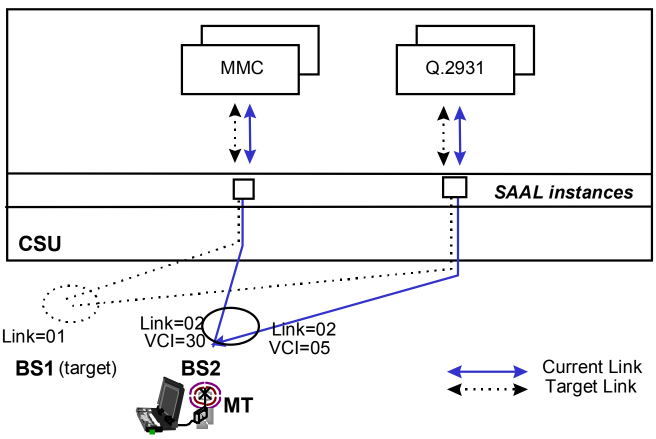

Figure 4: Switching of signaling connections

In order to avoid spawning and clearing of SAAL instances, the CS_MMC uses its interface with the switch API (Application Programming Interface) to reroute the M-channel connection in the ATM layer. Thus, the SAAL instances are left unaffected. The SAAL connection between the CSU and the

Διαγράφηκε: It is then, the responsibility of CS_MMC to determine what signaling connections (for the MMC protocol) need be rerouted and bring those changes into effect by issuing low level commands to the switch API. User plane VCs as well as the Q.2931 connection are rerouted at a later stage through the same approach.

BSs (VCC - Virtual Channel Connection) comprises two VCLs (Virtual Channel Links). A VC cross-connect is deployed by means of the switch API commands. This VCC is depicted in Figure 5.

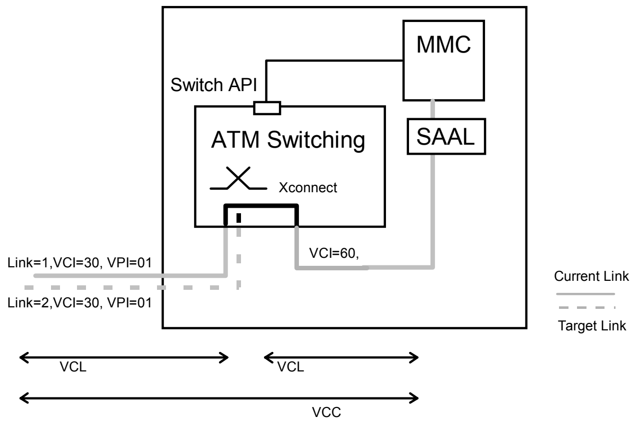

Figure 5: Switching of signaling connection using the switch API

Διαγράφηκε: 's

The inner VCL between the switching unit and the SAAL is established once, upon MT registration, and remains valid and unaffected until its de-registration. Outer VCLs are associated with the inner VCL each time the MT moves to a new BS. MMC triggers the VCL association (changes to the involved VC cross connect) according to the mechanism described below. Other researchers [25] have adopted GSMP [28] as an alternative mechanism to proprietary switch APIs.

In the case of handover or location update, CS_MMC faces a dilemma: where to switch the M-channel. The only network elements that store real-time information about the location of MT are the BSs and the MTs themselves. As the RRM entities are positioned in the forefront of the wired part of the network and have direct access to the WMAC data structures, it is relatively easy to obtain information on radio associations and de-associations of MTs. During forward handover the first action undertaken by a MT, is its association with the BS it can hear best. Such association is detected by RRM that subsequently notifies CS_MMC. This sequence of events is shown in Figure 6. Initially (step 1 in the figure) the mobile terminal communicates through BS1 (with RRM-old). In step 2, the mobile terminal crosses the cell boundary, which triggers a forward handover. In step 3, the MT associates with BS2. This association is detected by RRM-new (RRM within BS2) in step 4. MMC is notified in step 5, and proceeds with the required rerouting of signaling connections. The user plane connections are re-routed after the signaling channels become operational.

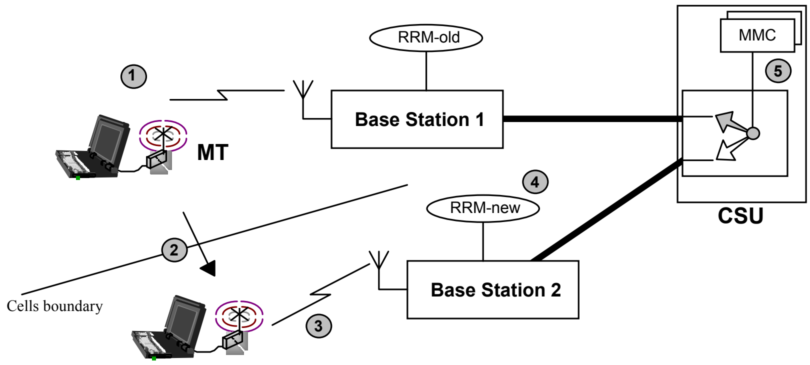

Figure 6: Forward handover steps

The re-routing of the signaling connections is performed at the ATM level, where the VC cross-connection is modified. Thus, the upper layer entities (signaling end-points) are left unaffected. A similar approach is proposed for the inter-switch handover scenario in [25].

VI. Internal structure of MMC entities

The CS_MMC module is responsible for handling all mobility related procedures (i.e., handover, registration, and location update) on the network side. Specifically, CS_MMC deals with the following tasks:

- the establishment of the M-channel through which the mobility related messages are exchanged,
- the coordination of Call Admission Control (CAC), of the wireless and the fixed resources, during the execution of mobility and standard signaling procedures,
- the switching of the signaling and the data connections (if any), whenever a MT crosses the boundaries of a cell, and
- the updating of the location of a MT in the CSU hosted DB.

CS_MMC has been formally specified and simulated using the Specification and Description Language (SDL [19], [20]). The corresponding SDL block consists of four processes (Figure 7). From those processes, only the ROUTER process has one instance. The other three processes, namely, Location_Update_Handler (LUH), Registration_Handler (RHC), and Mobility_Control_Function (MCF) may have N instances, where N is number of the active MTs in the system.

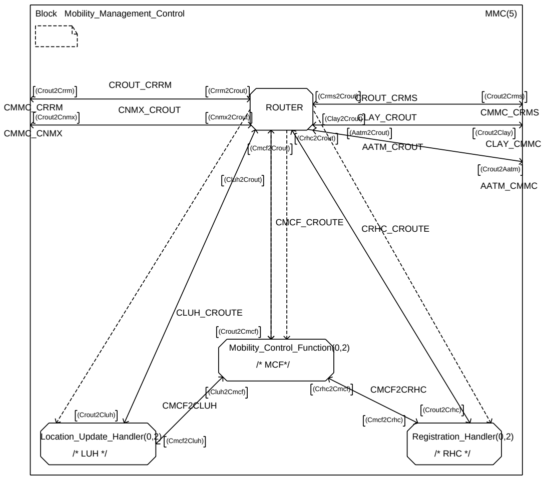

Figure 7: SDL block diagram of CS_MMC

The ROUTER process is responsible for the communication between the CS_MMC and all the other entities within the CSU. As shown in Figure 7, this process handles all incoming signals to the CS_MMC. The main task of this process is to send signals to the appropriate instances of MCF, RHC and LUH and spawn instances of these processes, as needed (dashed lines in Figure 7).

The LUH process is responsible for informing the DB whenever a MT changes location. This can happen either implicitly, whenever a MT performs a handover, or explicitly whenever a MT crosses the boundaries of a cell without any active data connections. In order to cope with the former case, LUH has a channel with MCF.

The RHC process is responsible for registering every MT that powers on within the network. This process is also responsible for the establishment of the signaling channel between the CSU and each MT.

The MCF process is responsible for handling MT handovers and standard call control procedures, by communicating with RM and RRM. One of the main tasks of this process is to guarantee that all mobility operations are performed in atomic steps that cannot be interrupted while in progress. This entity communicates with both LUH and RHC during implicit location update and the initial configuration of the signaling channels respectively. MCF, LUH and RHC have been implemented as Solaris threads ([21], [22]) of the CS_MMC process. The operating system, used in WAND for running the CSU functional entities, is SunOS 5.5.1 installed in a Ultra-Sparc I workstation.

The SDL block diagram of MT_MMC is shown in Figure 8.

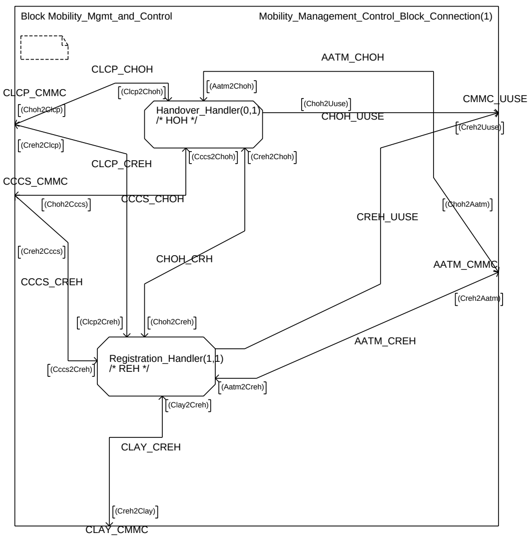

Figure 8: SDL block diagram of MT_MMC

In the SDL model, the following entities are specified as components of MT_MMC:

- **HOH** (HandOver Handler): HOH is signaled by the WMAC layer and may issue a Handover or Location Update request towards the CS_MMC. Prior to HOH's triggering by WMAC, no distinction is made between Handover and Location Update. HOH interacts closely with the CCS module of the MT with the purpose of determining whether user plane connections are active or not.
- **REH** (REgistration Handler): REH is responsible for instantiating - initializing HOH, requesting the set-up of a proper Q.SAAL instance and binding to it. For its communication with WMAC, REH (and HOH also) uses a protocol called LCP (Layer Control Protocol)[4]. REH transmits the signaling messages needed for the admission-registration of the mobile terminal in the WAND network but is also responsible for the de-registration procedure.

For the task of initializing other protocols within the MT stack, MT_MMC issues requests towards a Protocol Layer Manager. Its internal structure is strongly dependent on the implementation platform. In the WAND system, the Windows NT integrated Trillium stack ([21], [23]) will be used under Windows NTS ver.4.

VII. Mobility procedures

In this section, we give a detailed description of the *Registration, Backward and Forward Handover* algorithms.

Registration

Figure 9 gives a message sequence chart for the messages exchanged between the network elements involved in the registration algorithms described below.

Whenever a MT powers on within the network, it needs to register and then perform security and authentication procedures. The first step is to associate with the BS it can hear best. Upon successful association, resources are reserved in the wireless part by RRM. The CS_MMC is also notified on this event *(NEW_ASSOCIATION)*. CS_MMC checks if this is the first time that it receives a signal for the

[4] LCP has been developed by the University of Lancaster. LCP implements a stop-and-wait protocol. Messages are encapsulated in AAL5 PDUs.

specific mobile. In such a case, CS_MMC will check with RM if there are enough resources in the fixed part of the network to support the mobility signaling channel *(FR_STATUS)*. If there are sufficient resources, CS_MMC is notified *(CONN_SET)* and it performs the necessary VC configuration/management, using the switch API. When the configuration of the channel is completed CS_MMC requests the establishment of a SAAL connection with MT_MMC[5].

The MT receives notification of the SAAL connection establishment and the availability of the M-channel *(SIG_CHANNEL_READY)*. It then uses the M-channel, to start the registration procedure *(REGISTRATION_req)*. At this point no standard signaling channel is configured, since no security/authentication operations have taken place. This will happen when the DB is notified to create an entry for the specific MT *(CREATE_ENTRY_req/cnf)*. After the security actions are completed the MT will check if there are enough resources to support the signaling channel on the fixed part, and if there are it will notify both RRM *(CONN_SWITCHED)*, and MT_MMC *(REGISTRATION_cnf)*, about the result of the registration.

Forward Handover

Forward handover is initiated whenever the radio link of a MT with a BS is abruptly lost. In such a case, the MT which did not have the chance to pass signaling information to the CSU, pursues association with the BS it can hear best. The RRM entities of both the old and the new BS are aware of the current status of the MT as far as the radio link is concerned. The RRM of the new BS (RRM_new) is responsible for notifying the appropriate MMC instance of the CSU on the MT's recent radio association *(NEW_ASSOCIATION)*. As argued in Section V, this message is the external stimulus that triggers the switching of the signaling connections on the fixed part of the network. Prior to the transmission of the *NEW_ASSOCIATION* message, RRM_new performs the WCAC procedure for both the M-channel and the S-channel. If no resources are available for the signaling channels, then the association fails instantly and MT retries with another BS that it can listen to.

[5] CS_MMC has been previously bound to SAAL.

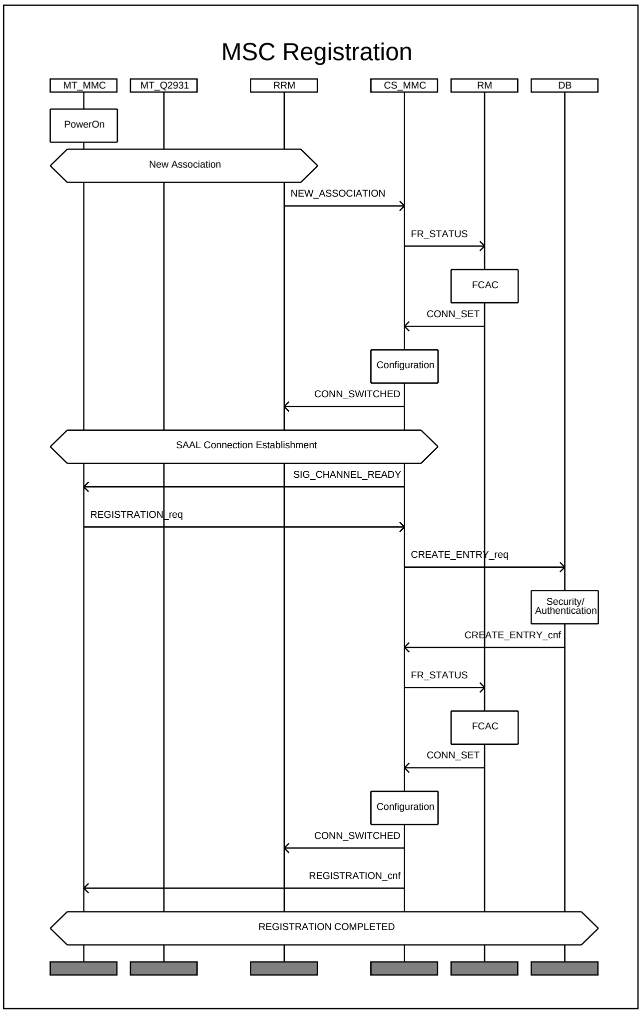

Figure 9: Message Sequence Chart for the Registration procedure

Upon reception of the *NEW_ASSOCIATION* signal by CS_MMC, the RM entity is invoked (*FR_STATUS*) to check if there are enough resources on the fixed part of the network, and to establish two new VCs (M & S-channels) towards the new BS. It then triggers CS_MMC (*CONN_SET*) to switch the MT signaling connections to the new BS (*CONN_SWITCHED*).

When the rerouting of the signaling channels is completed, CS_MMC informs the MT on the restoration of the signaling communication (*SIG_CHANNEL_READY*). At that point, the MT can initiate the handover procedure (*HO_REQUEST*) for the data connections.

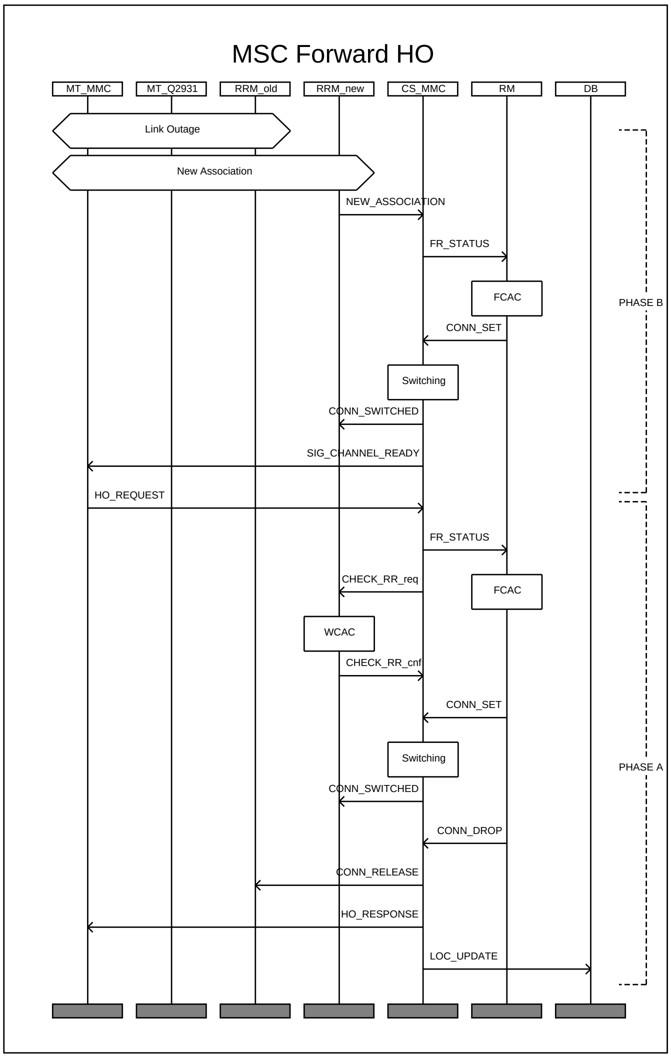

Figure 10: Message Sequence Chart for the Forward Handover procedure

The handshaking between CS_MMC & MT_MMC using the signal *SIG_CHANNEL_READY*, prior to the initiation of handover, is necessary in order to avoid potential race hazards (e.g. any attempts to transmit signaling information prior to the reconfiguration and the switching of the signaling connections).

CS_MMC is also responsible for checking the availability of both the fixed *(FR_STATUS)* and the wireless *(CHECK_RR_req/cnf)* resources for the u-plane connections. Should the CAC algorithm prove successful, the data channels are switched to the new BS (*CONN_SET, CONN_SWITCHED*). At the old BS the resources associated with the above channels are released (*CONN_DROP*, *CONN_RELEASE*). When the re-routing of the channels is completed, MT is notified accordingly on the result of the handover (*HO_RESPONSE*), and its new location is registered in the database (*LOC_UPDATE*).

In Figure 10, we provide the Message Sequence Chart of the forward handover algorithm described above[6]. As shown in this figure the handover procedure is broken up into two distinct phases (A and B). The first one involves the switching of the signaling connections, while the second one the switching of the data connections. In both phases, the same signals are applied although their parameters, which are not presented in the figure (e.g., VPI, VCI values), are different. This separation of switching phases enables the re-use of the same algorithm for the forward and backward HO cases.

Finally, one interesting point is that the *HO_REQUEST* signal passes to the CSU a list of all active data connections and a list of accessible, target BSs. The first list is prioritized and serves in the case where not all connections can be supported by the new BS. Thus, partially successful handover can be accomplished (connections with lower priority are dropped during the handover, if the resources in the new BS prove insufficient). The second list serves in those cases where the new BS is not the most appropriate one to handoff active connections. In order to make the best decision, CS_MMC requests RM (*FR_STATUS*) to examine the availability of the fixed resources for all the BSs that are identified in this second list. Such list is constructed (and sorted) by the MAC layer of the MT on the basis of the radio link quality that can be achieved. CS_MMC also triggers the corresponding RRMs to check the resources on the wireless side (*CHECK_RR_req*). The decision is based on both the results of the WCAC (*CHECK_RR_cnf*) and the Fixed CAC algorithms. If it is proven that the new BS (i.e., the one

[6] This is a simplified example, since all operations are considered to be successful.

where the MT is currently attached to) is not the best choice, the algorithm can be re-executed for the remaining elements of the second list.[7]

Backward Handover

Backward handover is performed when the quality of the radio channel fades gracefully and there is enough time for the MT to react promptly. All the signaling for the switching of the data connections is done through the current BS. When this task is completed, the MT will de-associate with the current BS, and will associate with the new one. At this point the switching of the signaling connections will be performed similarly to the case of forward handover.

As illustrated in Figure 11, in the proposed architecture, the backward and forward handover cases are similar. Their only difference is the execution sequence for the switching of the signaling and the data connections.

VIII. Conclusions

This article studied the issues for the design of mobility algorithms for wireless ATM CPN environments. The issues are mainly attributed to the incompatibility of conventional signaling with the peculiarities of a WATM installation, and refer to the required switching of the signaling connections during handover.

A solution has been proposed that has no impact on the existing ATM infrastructure. The implementation of this solution is quite straightforward. In our approach, the mobility procedures related to handovers are broken into two major phases: the switching of the signaling connections and the switching of the data connections. The same signals can be applied in both cases with different sequences. The solution only depends on the mechanisms/interfaces provided by contemporary ATM switches. Higher layer entities (like mobility and resource managers) are left unaffected.

[7] The algorithm for selecting the most appropriate BS can be also performed in parallel for all possible target BSs. The advantages and disadvantages of these two approaches are outside the scope of this paper.

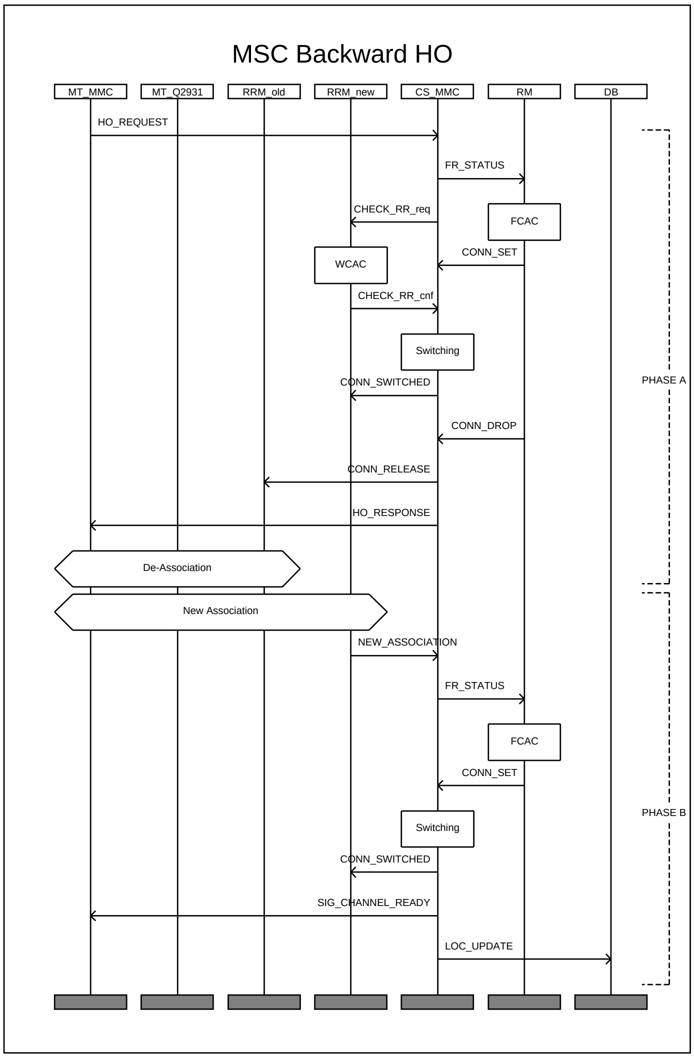

Figure 11: Message Sequence Chart for the Backward Handover procedure

We have shown how the presented switching approach can be applied to registration, and forward and backward handover algorithms tailored to the WATM installation. The proposed handover algorithm performs channel switching that involves handshaking between CS_MMC and MT_MMC to avoid potential race hazards.

In relation to prior work of other researchers in the WATM area, the proposed solution:

1. Covers both backward and forward cases

2. Does not impose modification to conventional signaling
3. Does not waste network resources, since the connection path is always optimum, and,
4. Limits the complexity of BSs

For the performance evaluation of the proposed protocol, a model, [30], has been developed in the Maisie simulation environment, [31]. The simulation study indicated that for low mobility the system is capable of supporting the required QoS, without compromises. Another observation was that the measured mean execution times for backward and forward handovers are identical because the only difference of the two algorithms is the switching sequence of the signaling and data connections (alternation of phases A and B described in the section VII).

Acknowledgments

This work has been performed in the framework of the project ACTS AC085 The Magic WAND, which is partly funded by the European Community and the Swiss BBW (Bundesamt für Bildung und Wissenschaft). The authors would like to acknowledge the contributions of their colleagues from Nokia Mobile Phones, Tampere University of Technology, Technical Research Center of Finland, Ascom Tech AG, Lucent Technologies WCND, University of Lancaster, Robert BOSCH GmbH, University of Ulm, Compagnie IBM France, IBM Zürich Research Laboratory, ETH Zürich, INTRACOM Hellenic Telecommunications and the University of Athens. Moreover, the authors would like to thank Professor Y.-B. Lin and the anonymous reviewers for their suggestions on this work.

References

[1] P. Agrawal, E. Hyden, P. Krzyzanowski, P. Misthra, M. Srivastava and J. Trotter, *SWAN: A mobile multimedia wireless network*, IEEE Personal Communications, April 1996.

[2] D. Raychaudhuri and N. Wilson, *ATM Based Transport Architecture for Multiservices Wireless Personal Communication Networks,* IEEE Journal on Selected Areas in Communications, October 1994.

[3] J. Mikkonen and J. Kruys, *The Magic WAND: A Wireless ATM Access System,* Proceedings of the ACTS Mobile Communications Summit '96, Granada, Spain, November 1996.

[4] M. Veeraraghavan, M.J. Karol and K.Y. Eng, *Mobility and Connection Management in a Wireless ATM LAN,* IEEE Journal on Selected Areas in Communications, January 1997.

[5] B. Akyol and D. Cox, *Signaling Alternatives in a Wireless ATM Network,* IEEE Journal on Selected Areas in Communications, January 1997.

[6] A.S. Acampora and M. Naghshineh, *An Architecture and methodology for mobile executed cell hand-off in wireless ATM networks,* IEEE Journal on Selected Areas in Communications, October 1994.

[7] C. Toh, *The Design and implementation of a Hybrid Handover Protocol for Multimedia Wireless LANs*, Proceedings of Mobicom'95, November 1995.

[8] H. Hansén, S. Hadjiefthymiades, J. Immonen and A. Kaloxylos, *Description of the handover algorithm for the Wireless ATM Network Demonstrator (WAND),* Proceedings of the ACTS Mobile Communications Summit '96, Granada, Spain, November 1996.

[9] A. Kaloxylos and S. Hadjiefthymiades, *Mobility Management in the Wireless ATM Network Demonstrator,* Proceedings of the International Workshop on Mobile Communications 1996 (IWMC'96).

[10] Magic WAND, Wireless ATM Network Demonstrator, http://www.tik.ee.ethz.ch/~wand/

[11] ITU-T Recommendation Q.2931*, B-ISDN Digital Subscriber Signaling System No 2 (DSS2) (UNI), Layer 3 Specification for Basic Call/Connection Control*, 1995.

[12] ATM Forum, *User-Network Interface (UNI) Specification - Version 3.1.*, 1994.

[13] N. Passas, N. Loukas, A. Kaloxylos, T. Kuehnel and Y-S. Wu, *Alternatives of Signaling Channel Allocation in Wireless ATM Networks*, Proceedings of the International Workshop on Mobile Communications 1996 (IWMC'96).

[14] ITU-T Recommendation Q.2130, *B-ISDN Signaling ATM Adaptation Layer - Service Specific Coordination Function for Support of Signaling at the User-to-Network Interface (SSCF at UNI)*, 1994.

[15] F. Bauchot, G. Marmigere, L. Merakos, N. Passas and S. Decrauzat, *MASCARA, A MAC protocol for Wireless ATM*, Proceedings of the ACTS Mobile Communications Summit '96, Granada, Spain, November 1996.

[16] ITU-T Recommendation Z.120, *Message Sequence Chart (MSC)*, 1993.

[17] B. Stiller, *A Survey of UNI Signaling Systems and Protocols for ATM Networks*, Computer Communication Review, ACM SIGCOMM, April 1995.

[18] ITU-T Recommendation Q.2110, *B-ISDN - ATM Adaptation Layer - Service Specific Connection Oriented Protocol (SSCOP)*, 1994.

[19] ITU-T Recommendation Z.100, *Specification and Description Language (SDL)*, 1996.

[20] F. Belina, D. Hogrefe and A. Sarma, *SDL with Applications from Protocol Specification,* Prentice Hall 1991, ISBN 0-13-785890-6.

[21] A. Kaloxylos and S. Hadjiefthymiades, *The Magic WAND Deliverable 4D6 Mobility Management and Control Module,* September 1996.

[22] Solaris Multithreaded Programming Guide, SunSoft Inc, ISBN 0-13-160896-7.

[23] *Trillium ATM Windows NT Platform White Paper*, Trillium Digital Systems, Inc., 1995.

[24] ATM Forum, *LAN Emulation over ATM - Version 1.0*, 1995.

[25] A. Acharya, J. Li, B. Rajagopalan and D. Raychaudhuri, *Mobility Management in Wireless ATM Networks*, IEEE Communications Magazine, November 1997.

[26] N. H. Loukas, N. Passas, L. Merakos and I. S. Venieris, *Design of Call Control Signaling in Wireless ATM Networks*, Proceedings of IEEE ICC'97, Montreal, Canada, June 1997.

[27] B. Rajagobalan, *Mobility Management in Integrated Wireless ATM Networks*, Proceedings of Mobicom'95, November 1995.

[28] P. Newman et al, *Ipsilon's General Switch Management Protocol Specification - Version 1.1*, RFC 1987, August 1996.

[29] G. Donis, D. Munoz-Rodriguez, and S. Tekinay, *A New Mobility Management Scheme for ATM based Wireless Networks*, Proceedings of the ICUPC 1996.

[30] A. Kaloxylos, G. Alexiou, S. Hadjiefthymiades and L. Merakos, *Design and Performance Evaluation of a Mobility Management Protocol for Wireless ATM Networks,* Technical Report TR98-0007, University of Athens, Dept. of Informatics, (also submitted to PIMRC' 98).

[31] R. Bagrodia and W. T. Liao, *MAISIE: A Language for the Design of Efficient Discrete-Event Simulations,* IEEE Transactions on Software Engineering, Vol. 20(4), April 1994.

[32] C. Perkins, *IP Mobility Support*, RFC 2002, IETF, Network Working Group, October 1996.

[33] A. Noerpel and Y.-B. Lin, *Handover Management for a PCS Network*, IEEE Personal Communications Magazine, Vol.4, No.6, pp.18-26, 1997.

[34] Y.-B. Lin, S. Mohan and A. Noerpel, *Channel Assignment Strategies for Hand-off and Initial Access for a a PCS Network*, IEEE Personal Communications Magazine, Vol.1, No.3, pp.47-56, 1994.