Cross Layer Designs in WLAN Systems
by Nizar Zorba, Charalambos Skianis and Christos Verikoukis

Book Chapter

Advanced Cross-Layer Mobility Mechanisms in a Heterogeneous WLAN Scenario

Vitor Bernardo, Marilia Curado, Edmundo Monteiro

Laboratory of Communications and Telematics
Center for Informatics and Systems
University of Coimbra
Polo II, Pinhal de Marrocos, 3030-290 Coimbra, Portugal

{vmbern, marilia, edmundo}@dei.uc.pt

Table of contents

1. Introduction

The IEEE 802.11 standard [1][2] has become very popular as access technology in multiple scenarios, such as schools, commercial public areas, and homes. Originally, this Wireless Local Area Network (WLAN) standard was conceived to provision devices with wireless network connectivity and did not provide mechanisms for Quality of Service (QoS) support. As multimedia applications such as Voice over IP (VoIP), Video Streaming and Video Conferencing have become widely used, IEEE 802.11 has been extended to support QoS provisioning mechanisms.

The combination of WLAN as end-user access network with broadband-wired access technologies, such as Digital Subscriber Line (DSL), as a backhaul connection, is a common deployment scenario, which is able to fulfill the major requirements of almost all typical Internet applications. Recently broadband wired access technologies are being complemented with broadband wireless access technologies to support end-user mobility and to enable faster deployment in remote areas. However, the integration of IEEE 802.11 access with backhaul connections using broadband wireless technology creates new challenges concerning the innate resource reservation and mobility mechanisms of these technologies that must be addressed to successfully fulfill user requirements.

Worldwide Interoperability for Microwave Access (WiMAX) [3] is one of the technologies facing the challenges of 3G and beyond broadband wireless access technologies. As frequency licensing is becoming commercially available throughout the world, it is still unclear whether WiMAX will be better positioned than its main competitors, such as High Speed Packet Access (HSPA) and Long Term Evolution (LTE). All these technologies can be used in diverse network scenarios, namely as a real end-user access technology or in the backhaul using, for instance, IEEE 802.11 as access technology. Concerning the later scenario, it is critical to evaluate the behavior of both IEEE 802.11 and WiMAX technologies within the foreseen all-IP communications world and taking into account the management of a seamless mobility scenario between different IEEE 802.11 access networks.

In the challenging environment described above two types of mobility can be considered, namely micro and macro mobility. Micro mobility is usually handled by the technology. However, when there is mobility between different networks, there is a need to perform mechanism at the IP layer, which is known as macro-mobility. One of the possibilities to enable the macro-mobility support is to use a technique named *make-before-break*, where the future connection and possible resource reservations are handled before the current connection is broken. The mobile version of WiMAX has native support for micro mobility. However it does not support, by itself, Internet Protocol (IP) Layer-3 mobility mechanisms, which need to be included in order to handle macro mobility.

Even though WiMAX is a natural candidate for the last mile wireless broadband access due to the innate quality of service capabilities and the higher bandwidth supported when compared with the third generation of mobile telecommunications standards (3G) competitors, there are a few problems regarding the technology deployment and costs. WiMAX systems have the potential to offer a good tradeoff cost/benefit solution to cover inaccessible and isolated areas within an all-IP network. However, in many cases end-users equipments are not yet able to support WiMAX, which increases the deployment cost. To accomplish a better cost/benefit tradeoff, a possible solution is to use WiMAX as a backhaul solution and IEEE 802.11 as access technology for the end-users. The challenge is how to achieve an IEEE 802.11 seamless handover support within a WiMAX backhaul network using the information gathered within the WLAN.

To overcome this challenge, this work proposes a seamless mobility schema between different IEEE 802.11 networks, when WiMAX is used as the backhaul technology. The proposal includes the configuration of the QoS mechanisms, mobility management and resource reservation modules as well as the cross-layer approach employed. Moreover, the Media Independent Handover (MIH) [4] and an extension to the Next Steps in Signalling Framework (NSIS) [5] for mobility management support was designed and integrated in the mentioned scenario.

The chapter is organized as follows: Section 2 describes the WiFi and WiMAX technologies, as well as the mobility handover assistance mechanisms, within the cross-layer design principle. Section 3 presents a detailed description of the proposed seamless mobility approach. The results of the experimental validation of the proposal on a testbed are discussed in Section 4. Finally, Section 5 presents the main conclusions of the work.

2. Cross-layer mechanisms for horizontal and vertical handover

This section provides a brief introduction to the IEEE 802.11 standard, as a widely used Wireless Local Area Network technology, and WiMAX, an emergent Broadband Wireless Network technology. Then, the main mechanisms for horizontal and vertical handover are presented with emphasis on cross-layer strategies that have the potential to improve the handover between different WLANs.

2.1 IEEE 802.11

IEEE 802.11 [1][2] is the most well deployed standard to support Wireless Local Area Network links. It is used in different places, such as homes, small offices, and public areas. The IEEE 802 LAN/MAN Standards Committee (LMSC) maintains the WLAN Working Group which is responsible for the IEEE 802.11 standards. Additionally, the Wi-Fi Alliance[1] is responsible for the certification of the IEEE 802.11 equipment.

The IEEE 802.11-2007 standard [1] enables the wireless access in the frequencies of 2.4 GHz with a peak data rate of 54 Mb/s. Recently, the IEEE 802.11-2009 standard [2] has been released, specifying a theoretical throughput up to 600 Mb/s [9], working at the 2.4 GHz or 5.0 GHz frequencies and using 40 MHz channels. The usage of Multiple-Input and Multiple-Output (MIMO) [10] technology in the antennas has also offered an important contribution to the performance and range improvements [11].

QoS mechanisms in IEEE 802.11 were firstly introduced by the IEEE 802.11e amendment [7]. Besides the Point Coordination Function (PCF) and Distributed Channel Function (DCF) Media Access Control (MAC) layer coordination functions, the Hybrid Coordination Function (HCF) was developed. This new function encompasses two new channel access modes, namely the Enhanced Distributed Channel Access (EDCA) and the HCF Controlled Channel Access (HCCA).

The QoS provisioning mechanisms implemented in the IEEE 802.11e standard are the QoS parameterization and the QoS prioritization. When using the QoS prioritization mechanisms, the MAC layers provides differentiated channel access to the frames based on the user priority defined in the higher layers. The EDCA channel access mode implements this method, doing the correct traffic classification and using queues to manage the priorities. In the QoS parameterization approach, a virtual connection, named traffic stream, is firstly

[1] http://www.wi-fi.org/

established between the transmitter and the receiver. This virtual flow includes the QoS requirements (e.g. throughput) of the desired connection, being exchanged between the requesting clients and the supporting station. If the supporting station is able to satisfy the connection requirements, the QoS connection flow is installed. The HCCA channel access mode uses this parameterization schema. However, the reservation information used in this scheduler considers only the average values of the application characteristics (e.g. mean throughput), which means that this channel mode is not efficient for applications with Variable Bit Rate (VBR) [14][15].

2.2 The WiMAX technology

WiMAX is a potential technology for the integration of WLAN scenarios in an end-to-end communication system and thus it is presented in this section.

2.2.1 IEEE 802.16

IEEE 802.16, also known as WirelessMAN, is a standard that aims at the development and deployment of broadband wireless metropolitan area networks [3]. The IEEE 802.16-2001 [16] standard was originally released in 2001, and it only supported Line of Sight (LOS) propagation, point-to-multipoint topology, single-carrier at the physical layer and Time Division Duplexing (TDD) mechanism. Several amendments to the standard were released in order to support new features such as Non Line of Sight (NLOS) propagation, Frequency Division Duplexing (FDD) and Orthogonal Frequency Division Multiplexing Access (OFDMA) technology. These revisions were included in a new standard named IEEE 802.16-2004 [19], which was frozen in 2004.

The IEEE 802.16-2004 standard was conceived to work in fixed scenarios. A new standard called IEEE 802.16e-2005 [20] has been defined to support mobile communication requirements. Although the two major releases of IEEE 802.16 are the IEEE 802.16-2004 and the IEEE 802.16e-2005 for the fixed and mobile scenarios, respectively, amendments with focus on management issues such as the IEEE 802.16f [17] and the IEEE 802.16g [18] were also developed. Currently, the working group is focusing on the specification of IEEE 802.16m, which aims at higher data rates and improved mobility performance. This new version will be the IEEE 802.16 candidate to the IMT-Advanced, a certification of 4G systems of the International Telecommunication Union Radiocommunication Sector (ITU-R), which requires 1Gb/s for the fixed scenarios and 100Mb/s with mobility.

Inherent Quality of Service support is one of the most important features of IEEE 802.16. In the IEEE 802.16-2004 standard there are four classes of service: Unsolicited Grant Service

(UGS), Real-time Polling Service (rtPS), Non-realtime Polling Service (nrtPS) and Best Effort (BE). Later, the IEEE 802.16e-2005 standard introduced a new class of service named Extended Real-time Polling Service (ertPS). Table 1 summarizes these classes of service.

Table 1 – IEEE 802.16 scheduling services

Name	Mandatory QoS Parameters	Applications
Unsolicited Grant Service (UGS)	Maximum sustained traffic rate; Maximum latency; Tolerated jitter and Request/Transmission policy.	Real-time applications with fixed-size data packets at periodic intervals. Ex: VoIP with silence suppression
Real-time Polling Service (rtPS)	Minimum reserved traffic rate; Maximum sustained traffic rate; Maximum latency and Request/Transmission policy.	Real-time applications with variable data packets at periodic intervals. Ex: MPEG video
Non-realtime Polling Service (nrtPS)	Minimum reserved traffic rate; Maximum sustained traffic rate; Traffic priority and Request/Transmission policy	Delay-tolerant data streams with variable packet size which requires a minimal data rate. Ex: FTP
Best Effort (BE)	Maximum sustained traffic rate; Traffic priority and Request/Transmission policy.	Data streams with no minimum service level required. Ex: HTTP
Extended Real-time Polling Service (ertPS)	Maximum sustained traffic rate; Minimum reserved traffic rate; Maximum latency and Request/Transmission policy	Real-time applications with variable-size data packets at periodic intervals. Ex: VoIP

2.2.2 WiMAX Forum Network Reference Model

The WiMAX Forum [23] is a non-profit organization which has as main objectives the promotion, certification and interoperability between the IEEE 802.16 and the ETSI HiperMAN [24] standards. The WiMAX Forum Network Working Group has the mission of creating the higher-level network specification for both Fixed and Mobile WiMAX. Thus, the Network Working Group created the Network Reference Model (NRM), in order to integrate WiMAX into an all-IP based network. The NRM, illustrated in Figure 1, defines the key functional entities and the interfaces needed to enable interoperability between different entities, named reference points.

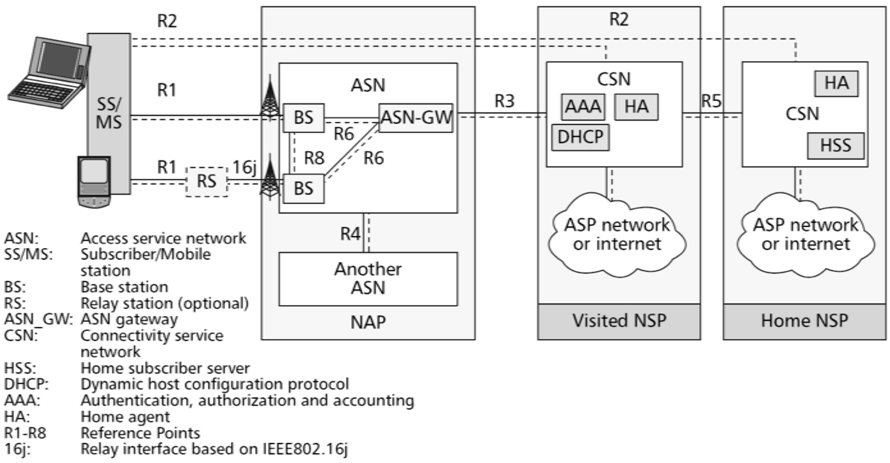

Figure 1 – WiMAX Network Reference Model [25]

The Network Access Provider (NAP) is the entity that provides WiMAX radio access to the Network Service Provider (NSP) and controls the Access Service Network (ASN). The IP connectivity and the WiMAX services are provided by the NSP, which also manages the Connectivity Service Network (CSN). The communication between the different entities is performed through the following reference points:

- R1 - Protocols and procedures between the Mobile Station (MS) and the ASN;
- R2 - Protocols and procedures between the MS and the CSN associated with Authentication, Services Authorization and IP host Configuration management;
- R3 - Control plane protocols between the ASN and the CSN to support Authentication, Authorization and Accounting (AAA), policy enforcement and mobility;
- R4 - Control and bearer planes protocols between ASN-GWs to coordinate the MS mobility; interoperability between ASNs;
- R5 - Control and bearer planes protocols for internetworking between the CSN operated by the home NSP and the visited NSP;
- R6 - Control and bearer plane protocols for communication between BS and ASN-GW;
- R7 - Optional reference point, which defines the control plane procedures between the Policy Decision Point (PDP) and the Policy Enforcement Point (PEP);
- R8 - Reference point defined by the IEEE 802.16e and IEEE 802.16g to enable the seamless handover. It specifies the control plane messages and bearer plane data flows between different BSs.

The ASN provides radio access to the subscriber/mobile stations (SS / MS) and includes features such as Authentication, Authorization and Accounting (AAA) transfer, NSP discovery and selection, as well as CSN and ASN anchored mobility. The ASN comprises the

Base Station, entity that provides radio access to the SS/MS, and the ASN-GW, entity responsible for the mobility and security at the control plane and for handling IP forwarding.

The CSN provides IP connectivity and all the network functions to the MS/SS. The key features of the CSN are IP address management, AAA proxy or server, Inter-ASN tunneling, CSN anchored mobility and Inter-ASN mobility. Moreover, the CSN is also capable of providing connectivity to the Internet and managing other services such as IP Multimedia Services [26] and location based services.

Employing the WiMAX Forum NRM presented before, two types of mobility based on the IEEE 802.16e-2005 standard are supported, namely, the ASN anchored mobility and the CSN anchored mobility. Figure 2 illustrates these two mobility types.

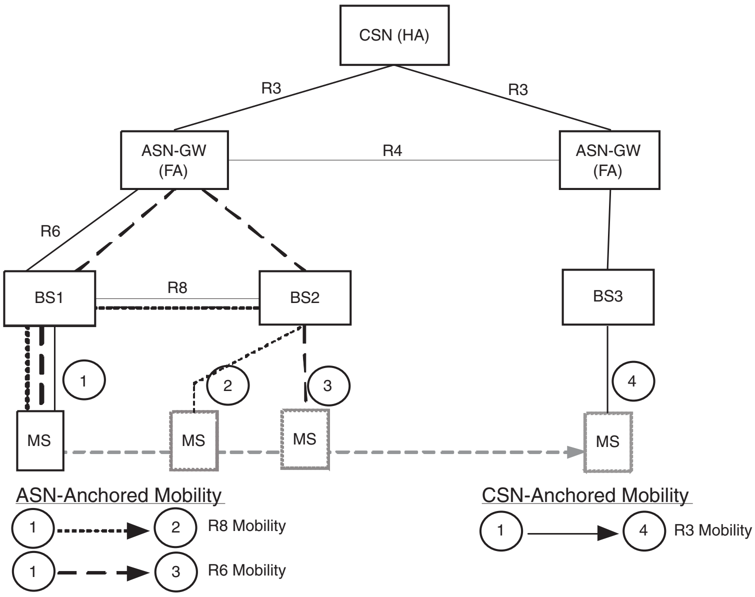

Figure 2 – Handover methods supported in Mobile WiMAX [22]

The ASN anchored mobility, also known as micro-mobility or intra-ASN mobility, is the mobility of a Mobile Station where a Care of Address (CoA) update is not involved. The reference points used in this case can be R6 or R8.

The CSN anchored mobility, also known as macro-mobility or inter-ASN mobility, is IP based mobility between the ASN and CSN across the R3 reference point. The Mobile IP (MIP) [27] protocol is responsible for the mobility management at the IP layer. The macro-mobility mechanisms presented above do not use information from the technology dependent layers to support the handover, which could provide a better experience level to the end-users. Cross-layer approaches have the potential to fill this gap, as described in the next sub-section.

2.3 Cross-layer issues

The Open System Interconnected (OSI) model [28] is a conceptual representation of the layer-oriented communication protocol design. Each of the seven layers represented in the model are able to provide information to the adjacent layers. One of the main characteristics of this architecture is that it does not permit the communication between nonadjacent layers. The cross-layer design is known as the violation of the referenced layered communication architecture, which means that the communication between nonadjacent layers is possible in a certain way. The cross-layer communication can be performed in several ways, which enable numerous cross-layer designs [29].

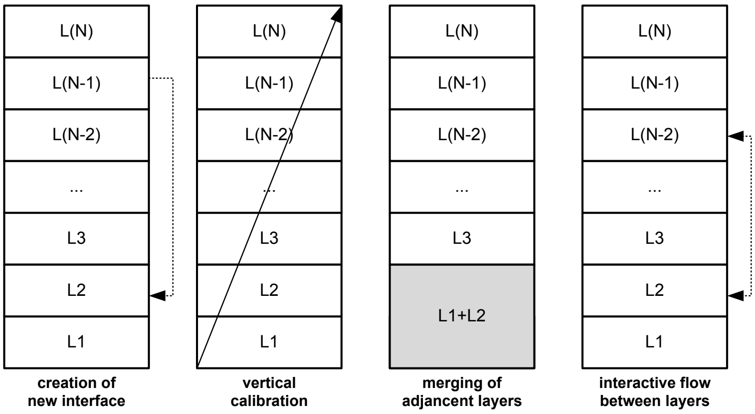

Figure 3 - Cross-layer design schemas

Figure 3 illustrates some cross-layer design schemas in within *N* layers of the protocol stack. These representations can be defined as follows:

- *Creation of new interfaces*: an explicit communication interface between two non-adjacent layers is created with the aim to set a parameter;
- *Vertical calibration across layers*: adjust a parameter that spans across non-adjacent layers;
- *Merging of adjacent layers*: two or more adjacent layers are designed together;
- *Interactive flows between layers*: communication between two non-adjacent layers. It can be a two-way communication or one-way in descending or ascendant order.

Cross-layer design assumes a particular importance in all wireless networks (e.g. WLANs), largely due to the variation in time and space of these communication technologies. The environment where the system is being used associated with the natural movements of the users (i.e. the mobile devices) create problems in the wireless systems. However, as stated in [30], these errors cannot be eliminated merely using strong forward error correction, because such approach will reduce the communication spectral efficiency. Whilst the employment of novel techniques such as OFDMA and MIMO in WLANs technologies will enable higher throughput (e.g. IEEE 802.11n [11]), the challenge to maintain a suitable level of end-user experience remains unsolved, especially in mobility scenarios. Therefore, the employment of cross-layer techniques to support mobility decisions can contribute to an enhanced network performance.

The fourth generation of mobile telecommunications standards (4G) enabled networks are concerned in granting a good quality of service and quality of experience to the end-users, through the usage of advanced resource reservation techniques and protocols such as Resource ReSerVation Protocol (RSVP) [34] or Next-Steps in Signalling (NSIS) [5]. In these systems, the make-before-break decision is very important, because it will allow a new reservation of the resources before the user changes to the next network. This is particularly important due to the timings associated with channel reservation in OFDM-like systems [35].

Currently, one of the big issues in the design of network architectures is how to exchange cross-layer information between different entities. There are some protocols being proposed to solve this transport issues, namely the Media Independent Handover (MIH) [4] and a new application for the Next Steps in Signalling framework. The next-subsections will present these approaches.

2.3.1 Media Independent Handover (MIH) – IEEE 802.21

The Media Independent Handover (MIH) standard, identified as IEEE 802.21 [4], aims to enable the seamless handover between heterogeneous technologies, known as vertical handover. The handover operation can be performed to and from any cellular network, such as Global System for Mobile communications (GSM), General Packet Radio Service (GPRS), Bluetooth, IEEE 802.11 and IEEE 802.16, as well as between the same technology, known as horizontal handover.

One of the main goals of MIH is to support the handover decisions based on information collected from the lower layers. MIH supports both station and network initiated handovers. The handover policies as well as the network selection procedures are not part of the IEEE 802.21 standard.

The MIH standard defines the Media Independent Handover Function (MIHF), which must be supported by all the entities involved in the handover operations, such as clients and network elements. MIHF is used as a channel to exchange information between the lower and upper layers, as shown in Figure 4.

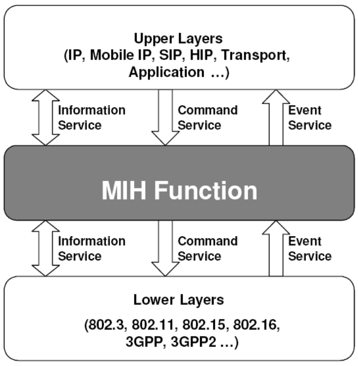

Figure 4 – MIH architecture [4]

MIH provides different services primitives as illustrated in the MIHF reference model (Figure 5). In particular, the MIH event service is used to deliver event triggers and the MIH command service aims to provide a set of standard commands for the handover control. The MIH information service is employed when the goal is to provide information, for instance, to support seamless handovers.

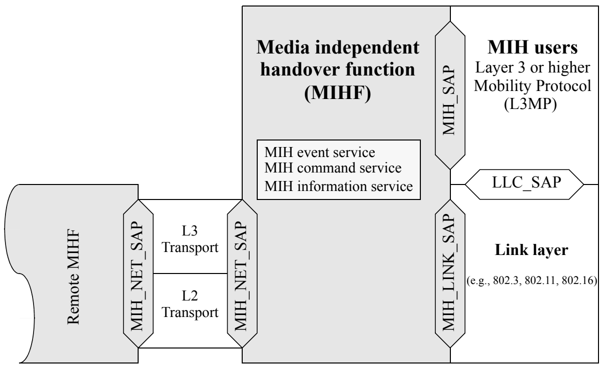

Figure 5 – MIH Services [4]

All the MIHF service primitives are grouped in Service Access Points (SAPs) used to provide the communication between all the MIHF entities. The MIH_SAP is the interface with the upper layers of the stack, while the MIH_LINK_SAP is the interface with the lowers layers. The interface that supports the information exchange between MIHF entities is named MIH_NET_SAP and it can transport messages over both Layer-2 and Layer-3.

The MIH standard specifies a Media Independent Information Service (MIIS), which provides detailed information about the neighboring networks. This information is essential to take some handover decisions in macro-mobility scenarios and it can be accessed by specific queries or using broadcast messages.

2.3.2 Next Steps in Signalling (NSIS)

The Next Steps in Signalling (NSIS) [5] framework is being defined in the NSIS Working Group of the IETF. This group is responsible for the standardization of IP signalling, having QoS signalling as the first use case [36]. The NSIS framework is composed by two layers:

NSIS Transport Layer Protocol (NTLP) that is a generic layer and a NSIS Signalling Layer Protocol (NSLP) that is specific to each application, as depicted in Figure 6.

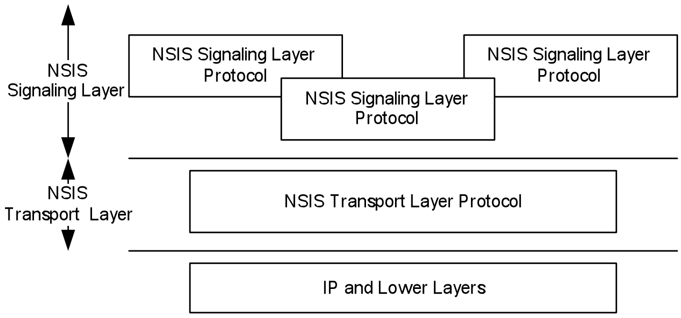

Figure 6 - NSIS framework structure

The NTLP layer is a lower layer responsible for the communication between all the peers in the network. NTLP functionalities are fulfilled by the General Internet Signalling Transport (GIST) component [40]. The main function of GIST is the transport of signalling messages sent by NSLPs through the network, and their delivery to the correct application. Moreover GIST is also responsible for managing the routing state of the network entities. The installation and refresh of the routing state tables is done through a 3-way handshake process. Figure 7 shows the basic operation of the NSIS two-layer framework using the NTLP and three different NSLPs.

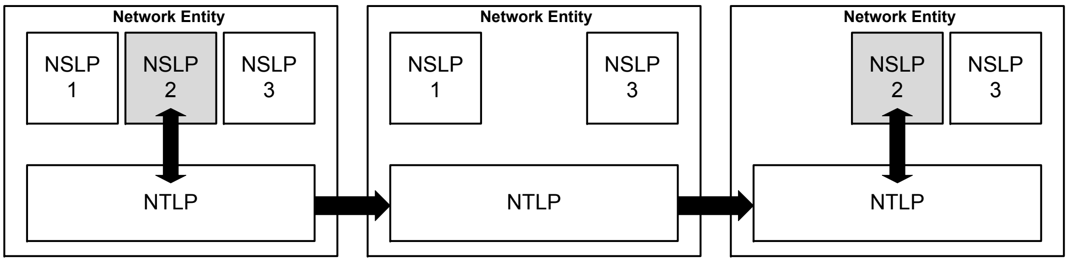

Figure 7 - NSIS signalling example

In the previous example, the application named “NSLP 2” starts the signalling sending a message to the local NTLP. Then, the NTLP forwards the message to the next network entity in the path, until the message reaches the destination. In the second network entity, as the application “NSLP 2” does not exist, the message is forwarded to the next entity without being processed by the NTLP. When the target NSLP exists, the NTLP delivers the message so it can be processed.

GIST was defined to be an extensible protocol, where new features can be included without changing the actual specification. For instance, the GIST Extension for Hybrid On-path Off-path Signalling (HyPath) is an extension to the NSIS framework (that natively only supports path coupled signalling), which provides both on-path and off-path signalling [41].

The NSLP layer is specific to each application, which means that a new NSLP should be defined when a new application is required. The NSLP designed to provide resource reservation is named Quality of Service NSIS Signalling Layer Protocol (QoS-NSLP) [42]. QoS-NSLP is responsible for the establishment and maintenance of the states between network entities, following a soft-state approach. QoS-NSLP starts the signalling procedure when an application requests a reservation between two network entities, the sender and the receiver, with particular QoS requirements. The application must send the QoS requirements to the local QoS-NSLP, which will question the decision control modules, such as Admission Control. Later, if the request is accepted, QoS-NSLP must contact the local Resource Management Function (RMF) in order to install the resources in the network.

The interoperability of the QoS model used by NSIS entities is achieved through the QoS-NSLP specification (QSPEC) template [49]. Whilst this template defines a set of QSPEC parameters, additional parameters may be used as specified in ITU-T Recommendation Y.1540 [50] and RDM-QOSM [51].

Recently, the Media Independent Handover Network Signalling Layer Protocol (MIH-NSLP) [44] was proposed to the NSIS working group. The MIH-NSLP is used for the transport of IEEE 802.21 [4] messages within the NSIS framework. As in most situations, mobility is associated with QoS reservations where NSIS should be widely used, all the transport mechanism provided in the framework can be easily reused.

The next section presents the proposed seamless mobility scenario between two different WLANs integrated with a wireless backhaul.

3. A cross-layer and seamless approach for macro-mobility

Wireless Local Area Networks based on the IEEE 802.11 standard are extensively deployed, and it is common to find more than one WLAN in public zones, such as schools, shopping areas and airports. The ever-increasing availability of wireless access is changing the end-user behavior and, as a result, applications like VoIP, online gaming, and Video Streaming are becoming very popular. Since these applications have stringent QoS requirements, the IEEE 802.11 standard was improved to enhance the support of such applications. In addition, the end-users are constantly in movement, which emphasizes the need to support seamless handovers between IEEE 802.11 networks. Whilst the handover between IEEE 802.11 enabled access points is transparent when the WLAN is integrated with a wired backhaul, new issues arise when the backhaul consists on wireless technologies, since resource reservations are mandatory to enable a proper end-user experience.

WiMAX is one of the candidates for wireless backhauls, providing broadband connection to isolated or impervious areas. For instance, the deployment of cabled solutions, such as DSL, to provide broadband connection to isolated villages is not feasible due to the high costs associated with the installation of the infrastructure. Although WiMAX has the potential to be the natural technological answer for these scenarios, most user devices are not yet WiMAX ready. To offer the best cost/benefit trade-off for both users and network operators, IEEE 802.11 WLAN can be used to grant end-user access to the network, which will then use WiMAX as the backhaul. In these situations, a seamless handover between the IEEE 802.11 access points needs to be complemented by resource reservation mechanisms in the WiMAX backhaul, which create new challenges that to be addressed.

3.1 Related work

This section presents the related work review for the environment previously described, by analyzing and comparing the current solutions with this work.

One of the most challenging goals in wireless networks is the integration of all the systems in the end-to-end IP schema, also known as all-IP network. The TCP/IP, as the most well deployed layer-oriented stack, is definitely a candidate to ensure the full compatibility and interoperability between all communication networks in the world. The interaction among layers has been studied in the literature, taking into account different targets. For instance, the cross-layer design optimization proposal for the wireless protocol stacks [31] aims to provide certain QoS levels and also to maximize the perceived end-user quality, also known as Quality of Experience (QoE). The cross-layer interaction takes up an important role to reach these goals, because it will enable a deeper idea of the system to the upper layers, which can then act accordingly.

The connection between 3G and WiMAX has been studied in [52], where an architecture for mobility management is presented. This architecture uses MIP to enable IP mobility and Session Initiation Protocol (SIP) [53] to enable session mobility, introducing thus support for the IMS architecture. Despite the interworking between different technologies, cross-layer information is not employed to improve the handover performance. Instead the architecture relies on Layer-3 protocols to enable heterogeneous handovers. In [54] a seamless handover architecture for heterogeneous networks using the IEEE 802.21 has been proposed. The proposal encompasses different seamless mobility mechanisms that are not originally supported in the IEEE 802.21 standard, namely the resource reservation. The main drawback is that it does not provide any validation or evaluation work to demonstrate the practical feasibility of the solution.

Bess et al. [55] introduce an architecture for QoS signalling for IP mobile networks, combining resource management with mobility management procedures, resorting to reservation before performing the handover. Despite the support of anticipated handover and technology independence, the detection of new access points is solely based on Layer-3 data. By employing cross-layer information, namely MIH facilities, the handover could be reduced and QoS signalling could be anticipated.

An integrated QoS-aware mobility architecture for seamless handover in IEEE 802.16e is presented in [56], where a new cross-layer mobility scheme has been developed with the help of information from the lower layers. Nevertheless, this proposal lacks a mechanism to enable the handover notification from the upper layers, for instance, by an entity responsible for the mobility management. Dutta et al. [57] present an architecture for seamless handovers across heterogeneous access networks. This architecture is based on the facilities of MIH and the Media Independent Pre-Authentication (MPA) framework. This last one allows performing authentication at Layer-2 and Layer-3, independently of the technology. Besides introducing the design of the architecture, the proposal is evaluated in a testbed based on the IEEE 802.11 and CDMA technologies. Despite the improved handover performance with the assistance of MIH and MPA, the transport of MIH messages between MIHF entities is based on the HTTP protocol, which introduces delay in event propagation, due to its connection-oriented nature.

MIH has been extended in various ways to achieve different goals, namely allowing QoS provisioning and mobility optimization through new algorithms that improve handoff decisions. Neves et al. [58] propose an extension to MIHF named enhanced Media Independent Handover Function (eMIHF), which aims to improve IEEE 802.21 by enabling the efficient QoS resource reservation in the target radio access technology. By implementing and testing the eMIHF proposal in the ns-2 simulator using an IEEE 802.11 / WiMAX handover integrated with the Fast Mobile IPv6 (FMIPv6) mobility management protocol, the authors have concluded that eMIHF has several benefits within a make-before-break handover approach. The evaluation performed in the ns-2 simulator demonstrates the importance of doing the QoS reservation in the handover preparation phase, since the results show that 30-80% of the packet will be lost if a proper QoS reservation is not done before the handover execution. Nonetheless, this work lacks the evaluation in real scenarios, which bring additional challenges not represented by a simulation setup.

Another enhanced MIH version has been proposed in [59], using information from the upper-layer (e.g. application layer) to support the handover decision. The main goal of this proposal is to use network and client information to support the handover decision, by collecting data from both. The data collected can be categorized in four main types, namely the link layer information, the QoS application details, and the user and network context. In addition, the work also proposes two algorithms to select the best candidate network, which are based on a weighted Markov chain (WMC) approach. The main contribution of this work is the new ranking mechanism for the handover network selection using the information of various parameters from network to application layers. Although both [58] and [59] aim to guarantee the proper resource reservation in the target access radio access network when a heterogeneous handover occurs, it not able to manage a scenario where the resource reservation must be done in the backhaul connection (e.g. using WiMAX as a backhaul of a IEEE 802.11 access).

A user-centric cross-layer approach for vertical handover decision based on the MIH has been investigated in [60], where the authors propose a new algorithm, named Vertical Handover Decision (VHOD). The algorithm takes also into account the MIH User information in the handover decision, which aims to enable a better handover decision. This proposal is an extension of MIH framework and does not improve the performance in the macro-mobility scenario, but only increases the decision quality during the handoff process.

By analyzing the current state-of-the-art and from the best of our knowledge, our approach fills a gap within the integration of WLAN in all-IP environments. The proposal described consists of a novel set of seamless cross-layer handover mechanisms in heterogeneous WLAN scenarios that use a broadband wireless technology as the backhaul.

3.2 Scenario description

Figure 8 illustrates the deployment environment envisaged. The macro-mobility scenario encompasses two different IEEE 802.11 networks (i.e. WLAN-1 and WLAN-2) using WiMAX backhaul connections. One of the WiMAX subscriber stations is in a school serving hundreds of people (i.e. WLAN-1) and the other is a home subscription (i.e. WLAN-2). The scenario aims to show a real deployment situation where a student is connected to the school network and is moving to a zone near his home, where the network link conditions are becoming better.

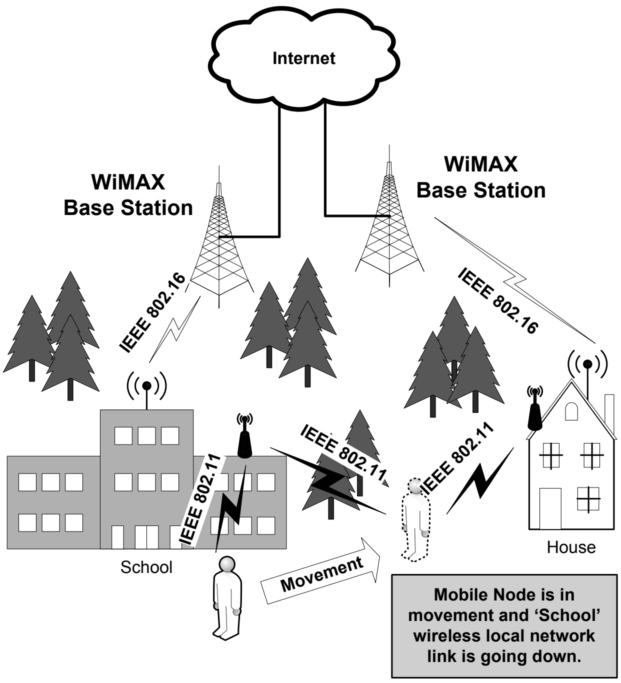

Figure 8 - WiMAX backhaul deployment scenario

As the backhaul connections are WiMAX networks, Figure 9 shows the mapping between the scenario presented in Figure 8 and the WiMAX Forum NRM entities described before. The scenario follows strictly the architecture proposed in the network reference model, as the early version defined in [45]. ASN-1 and ASN-2 are serving the WLAN-1 and WLAN-2, respectively.

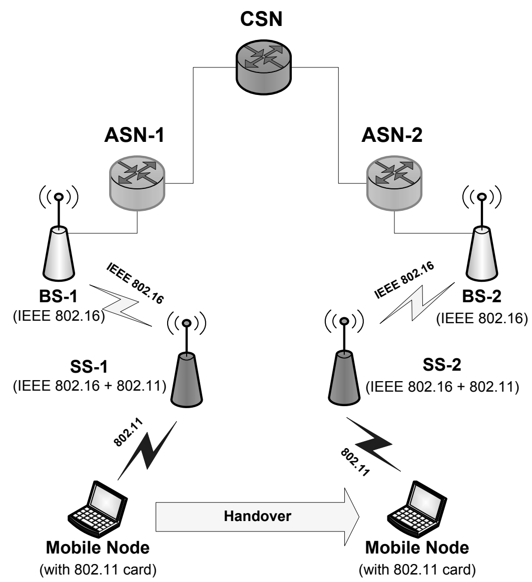

Figure 9 – Relationship between the proposed scenario and WiMAX Forum NRM

The home network is the school network (i.e. WLAN-1) and the foreign network is the house network (i.e. WLAN-2). The handover will occur from the school to the foreign network, as expected.

In this scenario the Mobile Node (MN) is physically connected to the core network through an IEEE 802.11 ready device and the mobility process takes place within the same technology (i.e. horizontal handover). In these cases the typical approach for a make-before-break handoff resorts to MAC layer handoff techniques [46][47]. However, even though quite effective, these techniques are technology dependent and do not consider the core network type or topology, which is a clear problem when the core network is using WiMAX or an equivalent wireless broadband access technology, where the time needed to establish a connection between the base station and the subscriber station is important.

Additionally, after the handoff, the context and the QoS parameters must be the same as before. Thus, the handover process must take into account not only the movement of the mobile node, but also the resource reservation over the WiMAX technology.

Seamless handover is crucial to fulfil real time application requirements, such as those of Voice Over IP (VoIP) and Video Streaming. For instance, an end-user will notice service degradation in a VoIP call, if the one-way delay is larger than 150ms [48]. Therefore it is not feasible to use a hard handover approach due the resource reservation time in the WiMAX segments.

In the next section, the detailed process to perform a seamless handover between IEEE 802.11 networks using WiMAX as a backhaul technology is described.

3.3 Seamless handover process description

The physical handover process of the scenario under study will occur between the IEEE 802.11 access points of the WLAN-1 and the WLAN-2. This handover matches the situation described in Figure 9 with the Inter NAP R3 mobility case defined by the WiMAX Forum, where the mobile node moves between two different ASNs (each WLAN is connected to a different IEEE 802.16 subscriber station). The seamless handover process will be enabled through a make-before-break technique, where the mobile node stays connected to the home ASN until all the reservations and signalling processes in the new ASN are successfully completed.

The mobile node may itself cause the handoff, but it will not be a seamless handover due to the time needed to perform all the reservations in the WiMAX segment. Therefore, the ASN network must have an entity to control the handover process. In the proposed schema, the network entity responsible for the control and management of mobility is named Mobility Manager (MM). The handover decision can be based on various parameters, such as the quality of service required by each flow, user preferences and end-user link quality. In this context, the information from lower-layers such as end-user link quality enables the creation of cross-layer mobility schema where the MM plays an important role at the decision point. Besides the importance in the handover decision, the MM must also start the signalling process needed to perform the resource reservation in the core and access networks.

The communication between non-adjacent layers such as the physical and application layers (e.g. Mobility Manager) can be done using several cross-layer design approaches, for instance with the creation of a new interface. However, this solution is not flexible as the new interface will be very dependent of the technology used. The previously presented MIH framework aims to solve this problem, creating a generic interface for the communication between lower and upper layers and it will be use in the proposal. The NSIS framework will be used for both QoS signalling, using QoS-NSLP, and to transport MIH messages between different networks through the MIH-NSLP.

Detailed sequence diagrams representing the major messages exchanged in the handover process are presented in the next sections. All diagrams are focused on the most important messages exchanged and there is an assumption that all the reservations performed in the

WiMAX equipment were successfully completed and that no signalling message retransmission occurs. The MIH standard decomposes the handover process in three different phases: initialization, preparation and execution. The proposed seamless handover schema uses a make-before-break technique, follows the MIH standard approach, and thus it divides the handover process into three phases, namely initialization, preparation and execution.

3.3.1 Initialization phase

Figure 10 shows the message sequence exchange between all entities to perform the handover initialization phase.

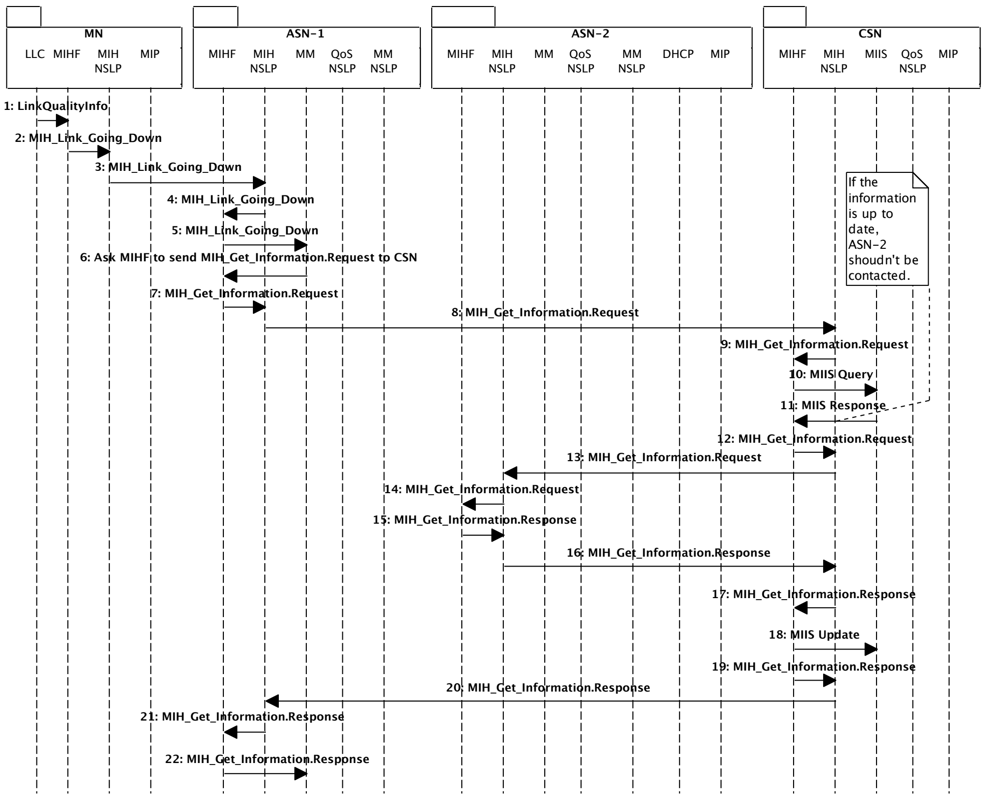

Figure 10 – Seamless handover initialization phase

Initially, the Mobile Node (MN) is connected to WLAN-1 through ASN-1. While connected to this network, the MN will detect a new network, WLAN-2, controlled by ASN-2 through the information gathered by the Logical Link Control (LLC). When the LLC detects that the actual connection (i.e. WLAN-1) is losing quality and perceives a better one (i.e. WLAN-2), it sends a trigger to MIHF. Then, the MIHF will generate an event reporting this information (Figure 10, Message nº3), which is sent towards the Mobility Manager (MM) of ASN-1, through the MIH-NSLP protocol (Section 2.3.1).

Upon receiving the event notification, the MM of ASN-1 needs to contact the ASN responsible for the newly detected network WLAN-2, i.e., the ASN-2. There are two ways to perform this communication, one through the Reference Point R4 and the other through Reference Point R3. In this scenario, ASNs are controlled by different entities and therefore the communication between ASN-1 and ASN-2 is through the Reference Point R3.

The signalling between ASN-1 and ASN-2 must precede the resource provisioning need in the ASN-2, to guarantee the same QoS in the new access network, WLAN-2, For that purpose, the ASN that is controlling the WLAN-1, ASN-1, needs to know the IP address of ASN-2. This information is obtained from the MIIS database in the CSN, by sending a MIHF event (Figure 10*, message nº5*), which includes, among other, information about the new network. Upon receiving this request, the CSN will make a query to the MIIS database. If the information is not available or is deprecated, the CSN will redirect the request towards ASN-2. Then, the required information will be encapsulated in a MIHF message (Figure 10*, messages nº6 to nº8*). When receiving this message, the CSN will update the MIIS database (Figure 10*, message nº18*) and then it will send a response back to ASN-1.

At this point (Figure 10*, message nº*22), the MM in the ASN-1 has information about ASN-2, and is therefore able to request a new reservation on ASN-2, before prompting the MN to perform the handover.

A make-before-break approach is possible, because the cross-layer information (e.g. the link status information) collected through MIHF is made available to the mobility manager application. Therefore, a seamless handover between the two access networks is achieved.

The preparation phase, which encompasses the resource reservation process, is presented in the next sub-section.

3.3.2 Preparation phase

The preparation phase, shown in Figure 11, is fundamental for the success of the seamless handover, since all the resource reservation operations as well as the context transmission between both ASN networks is performed at this moment.

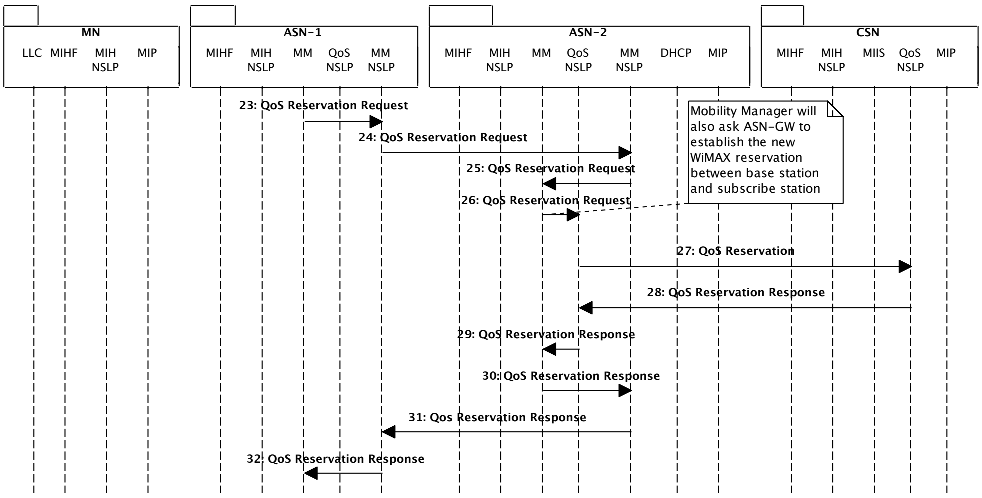

Figure 11 - Seamless handover preparation phase

After successfully completing the initialization phase, the MM of ASN-1 should contact the related entity of ASN-2 to start the QoS signalling via QoS NSLP across the ASN-2 domain. The communication must be done between the two Mobility Managers and not directly between the QoS NSLP entities since QoS NSLP does not provide support remote reservations. Thus, the MM in the ASN-2 must parse all the data received from ASN-1 (i.e. QSPEC information from each established session) and act as a normal reservation application, asking the QoS NSLP to perform the new reservations (Figure 11*, message nº26*).

The signalling between MM entities is done through a new NSLP, called Mobility Manager NSLP (MM-NSLP), specifically designed for the communication between these MM entities. According to the NSIS extensibility document, new NSLP Protocols can be created to work in parallel or to replace the applications already defined by the working group [37]. The MM-NSLP will use GIST (Section 2.3.2**Error! Reference source not found.**) as transport layer taking advantages of all already implemented security and reliability mechanisms. In addition, the MM-NSLP can reuse the associations established between adjacent GIST nodes already created by any other NSLP (e.g. QoS NSLP) avoiding thus the time need to create new connections.

The MM of ASN-2 starts the local signalling and necessary procedures to guarantee the seamless handover. In this way, when the MN moves from WLAN-1 to WLAN-2, controlled, by ASN-1 and ASN-2, respectively, the resource reservation will be already established. The MM should perform all QoS reservations with the IP address that the MN will have in the foreign network. Then, the MM communicates with the ASN-GW and with QoS-NSLP to achieve the signalling needed for QoS Reservation, both in the WiMAX link between base station and subscriber stations of the ASN-2 network, and between ASN-2 and CSN. In case of success, the MM of ASN-2 will inform its homologous of ASN-1 accordingly, using the

MM-NSLP. If the reservation fails, an error message is sent and all the process may be either restarted or cancelled.

Until now, the mobile node stays connected to the home network, WLAN-1, and then in the execution phase it will effectively move to the new network, WLAN-2. This process is presented in the following sub-section.

3.3.3 Execution phase

Finally, in this phase the mobility manager asks the Mobile Node to perform the handover to the new network, WLAN-2, as illustrated in Figure 12.

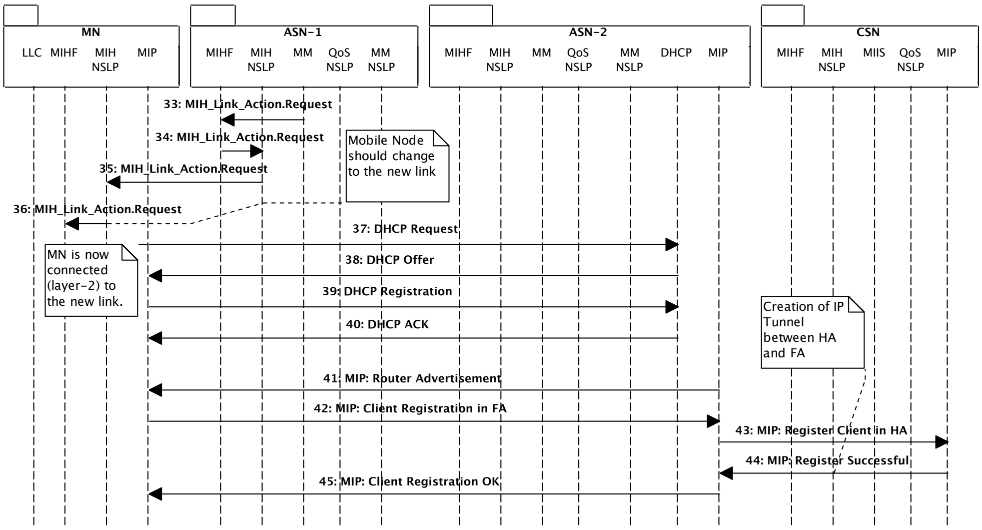

Figure 12 - Seamless handover execution phase

Given that the resources are provisioned on the foreign network, the MN must be informed that is must change to the new network. To accomplish this, the ANS-1 MM asks MIHF to send an event (Figure 12, *message nº33*) to the MN. This event will then force the MN to move to the new network. When the MN shifts to the new network, it will send a DHCP Request and the normal DHCP negotiation will occur.

After the MN has moved to the Foreign Network, WLAN-2, it will start to receive Router Advertisements of the Foreign Agent (FA) present in the ASN-2 network. Upon the reception of these advertisements, MIP in the MN will send a registration request to the FA. This registration will force the creation of the new IP Tunnel between this FA and the Mobile Node Home Agent, which is in the CSN. This tunnel, and the respective registration in the CSN, will allow that the messages for the MN may be re-directed to its FA, and later on delivered to the mobile node itself. The testbed was conceived using IPv4 to demonstrate the most complex situation in terms of signalling. However all the specified mechanisms will also work with IPv6, which is simpler, since the usage of an FA is not required.

The next section shows the experimental testbed validation of the proposed seamless handover process.

4. Experimental testbed validation

This section presents the results of the experimental testbed validation of the components developed to support the IEEE 802.11 seamless macro-mobility scenario using WiMAX as a backhaul.

The main goal of this study is to evaluate the proposed approach for seamless IEEE 802.11 mobility using WiMAX as a backhaul, employing a make-before-break technique. The focus of the validation will be on the overhead introduced by the mechanisms of the mobility architecture described in the previous section, with emphasis on the performance of the mobility manager. Additionally, the performance of the modules involved in QoS and mobility signalling will be assessed.

4.1 Validation scenario setup

Figure 13 depicts the testbed configuration, composed by two WLANs, namely WLAN-1 and WLAN-2, and each one controlled, respectively, by ASN-1 and ASN-2. Both base stations used in the testbed were compliant with IEEE 802.16d (Fixed WiMAX). The access technology does not affect the specified mobility approach, since it is independent of the WiMAX version used. Moreover, since almost all the deployed systems still employ IPv4, the testbed will also use this IP version. Nevertheless the proposed scheme could be easily adapted to be used with IPv6, with minor changes related to the enhanced mobility features. In order to evaluate the scalability of the proposed approach, the tests were performed with an increasing amount of simultaneous reservations, which included 1, 2, 4, 8, 16, 32, 64 and 128 simultaneous reservations.

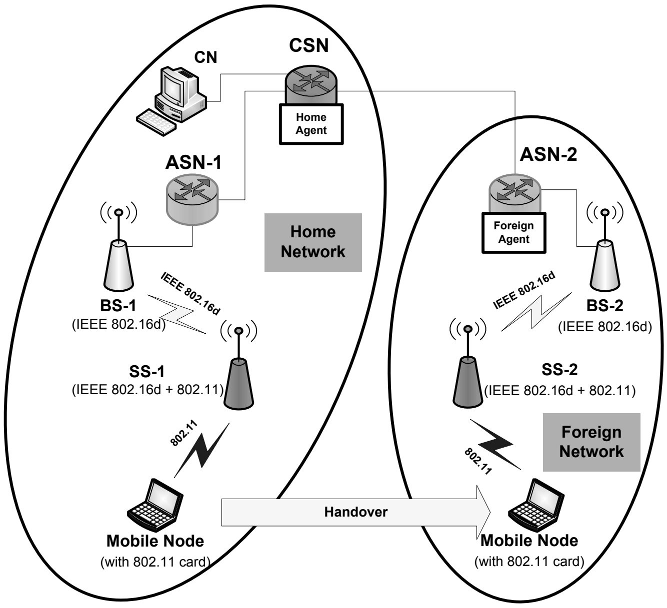

Figure 13 – WiMAX testbed configuration

As the performance of the WiMAX equipment was not in the evaluation scope, further details regarding the cost of using IEEE 802.16 dynamic channel configuration can be found in [35]. All the results, depicted with greater detail in the next subsections, are based on average values.

4.2 Results

This section presents the results of the experimental study performed to assess the overall system performance with the procedures required to enable the seamless handover. The study encompasses the measurement of the messages exchanged between the two ASN domains, which control both WLANs, and the performance of the modules involved in the reservation in the new domain.

The messages between the two ASN domains are transported by the MM-NSLP. Figure 14 shows the size of the messages exchanged between ASN-1 and ASN-2, for the different number of simultaneous reservations. Each message contains all the required information for the handover process, such as source address, destination address and direction.

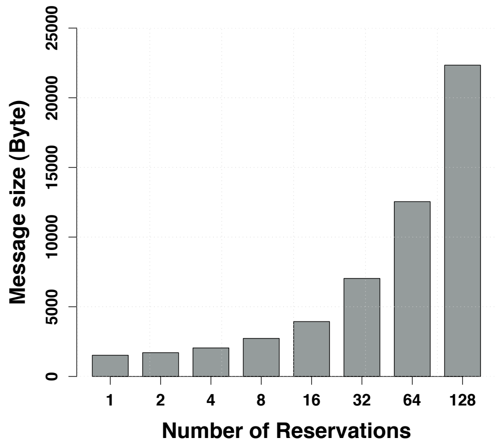

Figure 14 - Context transfer message size

Besides the payload information, each message also contains the overhead due to the information introduced by MM-NSLP. As expected, the message size increases with the number of reservations, due to the QSpec data, AAA credentials and Session Identification information associated with each reservation. Nonetheless, the message overhead introduced through MM-NSLP message headers is not directly affected by the number of reservations to be transferred, since the message header size is the same, independently of the number of reservations. This behaviour is confirmed by the negligible difference between transferred messages containing information of one, two and four reservations, as shown in Figure 14.

The processing time of the mobility manager is illustrated in Figure 15. The results comprise all the time needed to process messages inside this module including operations such as message serialization and deserialization. The time needed to perform the resource reservation in the WiMAX segment in not considered in these measurements. Figure 15 also shows that the processing overhead introduced by the MM is within acceptable bounds (bellow 80 ms) and, for up to 64 simultaneous reservations, the number of reservations does not significantly affect its performance.

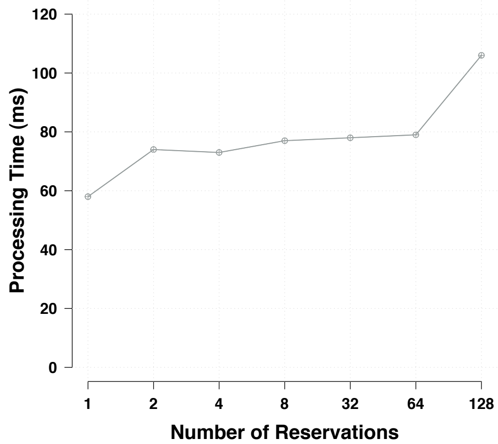

Figure 15 - Mobility Manager processing time

The duration of the handover preparation phase is shown in Figure 16, detailing the processing time associated with the main modules involved in mobility related mechanisms, namely, QoS signalling and AAA functions. The handover preparation time includes the interval between the instant when the MM in ASN-1 receives the cross-layer information about the IEEE 802.11 link conditions (Figure 10, *message nº5*) and the arrival of the response from ASN-2 acknowledging the success of the reservation (Figure 11, *message nº32*). Therefore, during this period the mobile node stays connected to the home network.

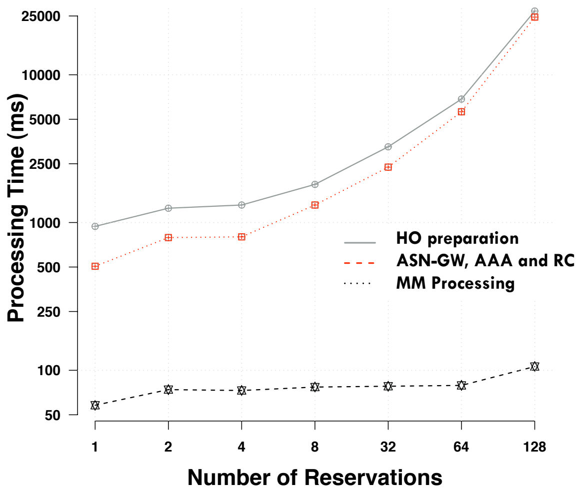

Figure 16 - Handover preparation time

The time spent in the ASN-GW, the interaction with AAA, the resource management function and the Resource Control (RC) processing time are also evaluated. The length of the handover preparation phase is mainly influenced by the ASN-GW+AAA+RC processing time, due to the complexity of the RMF function of the ASN-GW. Namely, the ASN-GW is responsible for policy and admission control functions, such as QSpec deserialization and communication with the RC to perform resource reservation in the WiMAX segment, as presented in [35].

The MM processing time is the sum of the processing time of each message in the module plus the handover decision time. The processing time of this core module is always bellow 110ms, even for the highest number of reservation. Almost all the time spent in the handover preparation phase is due to the resource reservation in the WiMAX segment. In short, the results show that the proposed solution, as well as the modules developed, has the potential to achieve a seamless handover with a limited overhead, by employing a make-before-break technique.

The general conclusions about this work are presented in the next section.

5. Conclusions

Wireless mobile network access has become, more than a requirement, a fundamental element of nowadays lifestyle. In this context, the WLAN together with a last mile wireless broadband access technology (e.g. WiMAX) have the potential to play an important role in all-IP networks, supporting different levels of service for applications with stringent quality of service requirements, such as voice and video.

This work has explored and enhanced the IEEE 802.11 and WiMAX capabilities integrated in an end-to-end IP architecture, proposing a macro-mobility seamless handover approach using the WiMAX technology as a backhaul and IEEE 802.11 as end-user access technology. The proposed cross-layer schema has been specified through sequence diagrams and evaluated in a real tested, employing all the specified modules. To support the communication of the MM modules between different domains, as well as the MIHF communication, the NSIS framework was employed. A new NSIS NSLP was developed to support the communication between MM modules and the state-of-the-art MIH-NSLP, to transport MIHF messages between distinct networks, was also used.

The testbed validation of the proposed scheme showed that the modules designed to support seamless mobility using cross-layer information introduce a negligible impact on the system performance, despite the number of simultaneous reservations. Moreover, the employment of the cross-layer techniques was crucial for the success of the proposed schema, since it provides the capability to predict the link quality degradation as well as the mechanisms to inform the end-user that it should move to a new network.

By employing the proposed cross-layer macro-mobility approach within a heterogeneous network comprising WLAN with IEEE 802.11 access and WiMAX as the wireless backhaul, this work demonstrated the feasibility to deploy broadband connections for isolated or impervious areas using these technologies. The integration of WLAN and WiMAX allows a promising cost/benefit result for both end-users and network operators, enabling also good mobility experience using advanced mobility mechanisms.

Acknowledgement

This work was partially funded by the Portuguese Ministry of Science (scholarship contract SFRH/BD/66181/2009) and supported by the FCT UBIQUIMESH project (PTDC/EEATEL/

105472/2008).

References

[1] IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999), vol., no., pp.C1-1184, June 2007

[2] IEEE Std 802.11n-2009 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, and IEEE Std 802.11w-2009), vol., no., pp.c1-502, Oct. 29 2009

[3] IEEE Std 802.16-2009 (Revision of IEEE Std 802.16-2004) , vol., no., pp.C1-2004, 29 May 2009.

[4] IEEE Std 802.21-2008 "IEEE Standard for Local and metropolitan area networks- Part 21: Media Independent Handover", 21 January 2009

[5] R. Hancock, G. Karagiannis, J. Loughney, S. Van den Bosch "Next Steps in Signalling (NSIS): Framework", IETF, RFC 4080, June 2005

[6] IEEE Std 802.11g-2003 (Amendment to IEEE Std 802.11-1999), vol., no., pp.c1-68, 2006

[7] IEEE Std 802.11e-2005 (Amendment to IEEE Std 802.11, 1999 Edition (Reaff 2003), vol., no., pp.0_1-189, 2005

[8] IEEE Std 802.11n-2009 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, and IEEE Std 802.11w-2009), vol., no., pp.c1-502, Oct. 29 2009

[9] J. Wall, J. Khan, "Towards Optimal Multimedia Packet Bursting for IEEE 802.11 Wireless LANs" Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE, vol., no., pp.2149-2154, 11-15 March 2007

[10] A. Pauraj, A. Gore, R. Nabaar, H. Bolcskei, "An overview of MIMO communications - a key to gigabit wireless," Proceedings of the IEEE, vol.92, no.2, pp. 198-218, Feb 2004

[11] P. DeBease, "802.11n: Enterprise Deployment Considerations", White Paper, 2008

[12] R. Braden, D. Clark, S. Shenker, "Integrated Services in the Internet Architecture: an Overview", IETF, RFC 1633, June 1994

[13] Blake, et. al., "An Architecture for Differentiated Services", IETF, RFC 2475, December 1998

[14] H. Zhu, M. Li, I. Chlamtac, B. Prabhkaran, "A survey of quality of service in IEEE 802.11 networks" Wireless Communications, IEEE, vol.11, no.4, pp. 6-14, Aug. 2004

[15] L. Romdhani, Q. Ni, T. Turletti, "Adaptive EDCF: Enhanced Service Differentiation for IEEE 802.11 Wireless Ad Hoc Networks", IEEE Wireless Communication and Network Conference, New Orleans, LA, 2003.

[16] IEEE Std. 802.16-2001 IEEE Standard for Local and Metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems," *IEEE Std 802.16-2001*, 2002

[17] IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems- Amendment 1: Management Information Base," *IEEE Std 802.16f-2005 (Amendment to IEEE Std 802.16-2004)*, 2005

[18] IEEE Standards for Local and metropolitan area networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems - Amendment 3: Management Plane Procedure and Services," *IEEE Std 802.16g 2007 (Amendment to IEEE Std 802.16-2004)*, 2007

[19] IEEE 802.16 Working Group, editor. "IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems. IEEE Std". 802.16-2004, October 2004

[20] IEEE 802.16 Working Group, editor. "IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems. Amendment 2: Physical and Medium Access Control Layer for Combined Fixed and Mobile Operation in Licensed Bands." IEEE Std.802.16e-2005, December 2005.

[21] H. Yin, S. Alamouti, "OFDMA: A Broadband Wireless Access Technology" Sarnoff Symposium, 2006 IEEE , vol., no., pp.1-4, 27-28 March 2006.

[22] J. Andrews, A. Ghosh, R. Muhamed, Fundamentals of WiMAX Understanding Broadband Wireless Networking. Prentice Hall. ISBN 0-13-222552-2. 2007

[23] WiMAX Forum, WiMAX Forum site. http://www.wimaxforum.org/home/. Last visit: 12 April 2010

[24] ETSI, Broadband Radio Access Networks (BRAN); HiperMAN; Physical (PHY) layer.V1.3.2.

[25] K. Etemad "Overview of Mobile Wimax technology and evolution", Communications Magazine, IEEE, 46(10), 31–40, Oct 2008

[26] G. Camarillo, M. Garcia-Martin, "3g IP Multimedia Subsystem (IMS): Merging the Internet and the Cellular Worlds", ISBN 978-0470871560, November 2008

[27] C. Perkins, "IP Mobility Support for IPv4", IETF RFC3344, 2002

[28] ITU, Information Technology – OSI – Basic Reference Model, X.200, July 1994

[29] V. Srivastava, M. Motani, "Cross-layer design: a survey and the road ahead," *Communications Magazine, IEEE* , vol.43, no.12, pp. 112-119, Dec. 2005

[30] S. Shakkottai, T.S. Rappaport, P.C. Karlsson, "Cross-layer design for wireless networks," *Communications Magazine, IEEE* , vol.41, no.10, pp. 74-80, Oct 2003

[31] V. T. Raisinghan, S. Iyer, "Cross-layer design optimizations in wireless protocol stacks", Elsevier Computer Communications, Volume 27, Issue 8, pp. 720-724, May 2004

[32] D. D. Clark, D. L. Tennenhouse, Architectural considerations for a new generation of protocols. ACM *SIGCOMM Comput. Commun. Rev.* 20, 4, pp. 200-208, Aug. 1990

[33] J. L. Burbank, W.T. Kasch, "Cross-layer design for military networks," *Military Communications Conference, 2005. MILCOM 2005. IEEE* , vol., no., pp.1912-1918 Vol. 3, 17-20 Oct. 2005

[34] R. Braden (Ed.), "Resource ReSerVation Protocol (RSVP)", RFC 2205: The version 1 functional specification was described in RFC 2205 (Sept. 1997) by IETF. Version 1 describes the interface to admission (traffic) control that is based "only" on resource availability. Later RFC2750 extended the admission control support.

[35] B. Sousa, P. Neves, G. Leao, D. Palma, J. Silva; S. Sargento, F. Fontes, M. Curado, F. Boavida, "The Cost of Using IEEE 802.16d Dynamic Channel Configuration," *Communications, 2008. ICC '08. IEEE International Conference on* , vol., no., pp.383-390, 19-23 May 2008

[36] Internet Engineering Task Force Next Steps in Signalling Working Group. http://www.ietf.org/html.charters/nsis-charter.html

[37] J. Manner, R. Bless, J. Loughney, E.B. Davies, "Using and Extending the NSIS Protocol Family", draft-ietf-nsis-ext-05, December 2009

[38] E. Kohler, M. Handley, S. Floyd, "Datagram Congestion Control Protocol (DCCP)", RFC 4340, IETF, March 2006

[39] R. Stewart, "Stream Control Transmission Protocol", RFC 4960, September 2007

[40] H. Schulzrinne, R. Hancock, "GIST: General Internet Signalling Transport", draft-ietf-nsis-ntlp, IETF, October 2008

[41] L. Cordeiro, V. Bernardo, M. Curado, E. Monteiro, "HyPath: An Approach for Hybrid On-Path Off-Path End-to-End Signalling," *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE* , vol., no., pp.1-6, Nov. 30 2008-Dec. 4 2008

[42] J. Manner, G. Karagiannis, A. McDonald, "NSLP for Quality-of-Service Signalling", draft-ietf-nsis-qos-nslp, IETF, February 2008

[43] M. Stiemerling, H. Tschofenig, C. Aoun, E. Davies, "NAT/Firewall NSIS Signalling Layer Protocol (NSLP)", draft-ietf-nsis-nslp-natfw, IETF, February 2008

[44] L. Cordeiro, M. Curado, P. Neves, S. Sargento, G. Landi, X. Fu, "Media Independent Handover Network Signalling Layer Protocol (MIH NSLP)", draft-cordeiro-nsis-mih-nslp, IETF, February 2008

[45] V. Bernardo, L. Cordeiro, I. Caramelo, B. Sousa, M. Curado, E. Monteiro, "A Seamless Mobility Scenario for IP over WiMAX", FMN 2009, 60-71, June 2009

[46] A. Mishra, M. Shin, W. Arbaugh, "An empirical analysis of the IEEE 802.11 MAC layer handoff process" *SIGCOMM Comput. Commun. Rev.* 33, 2, Apr. 2003

[47] S. Shin, A. G. Forte, A. Rawat, H. Schulzrinne, "Reducing MAC layer handoff latency in IEEE 802.11 wireless LANs." In *Proceedings of the Second international Workshop on Mobility Management & Wireless Access Protocols,* Philadelphia, PA, USA, Oct 2004

[48] WiMAX Forum, “WiMAX System Evaluation Methodology”, 2008

[49] G. Ash, A. Bader, C. Kappler, D. Oran, "QoS NSLP QSPEC Template", draft-ietf-nsis-qspec-22, November 2009

[50] ITU-T Recommendation Y.1540, "Internet Protocol Data Communication Service - IP Packet Transfer and Availability Performance Parameters," December 2002

[51] A. Bader, et al., "RMD-QOSM - The Resource Management in Diffserv QOS Model," draft-ietf-nsis-rmd-15, July 2009

[52] K. Kumudu .S. Munasinghe, A. Jamalipour, “An architecture for mobility management in interworked 3G cellular and WiMAX Networks,” in Wireless Telecommunications Symposium, 2008. WTS 2008, 2008, 291-297.

[53] J. Rosenberg, H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M. Handley, E. Schooler“SIP: Session Initiation Protocol”, IETF, RFC 3261, June 2002

[54] G. Lampropoulos, A.K. Salkintzis, N. Passas, "Media-independent handover for seamless service provision in heterogeneous networks," Communications Magazine, IEEE , vol.46, no.1, pp.64-71, January 2008

[55] R. Bless, J. Hillebrand, C. Prehofer, M. Zitterbart, “A quality-of-service signalling architecture for seamless handover support in next generation, IP-based mobile networks,” Wirel. Pers. Commun. 43, no. 3 (2007): 817-835..

[56] H. Yao, G. Kuo, “An Integrated QoS-Aware Mobility Architecture for Seamless Handover in IEEE 802.16e Mobile BWA Networks”, Military Communications Conference, 2006. MILCOM 2006, 23-25 Oct. 2006.

[57] A. Dutta, S. Das, D. Famolari, Y. Ohba, K. Taniuchi, V. Fajardo, R. Lopez, T. Kodama, H. Schulzrinne, “Seamless proactive handover across heterogeneous access networks,” Wirel. Pers. Commun. 43, no. 3 (2007): 837-855.

[58] P. Neves, S. Sargento, M. Melo, F. Fontes, K. Pentikousis, Enhanced Media Independent Handover Framework, IEEE Vehicular Technology Conference-(VTC-Spring), Pages: Vol. N/A, pp. N/A - N/A

[59] W. Ying, P. Zhang, Y. Zhou, J. Yuan, F. Liu, G. Li, “An Enhanced Media Independent Handover Framework for Heterogeneous Networks”, in Proc. IEEE Vehicular Technology Conference (VTC Spring), pp. 2306-2310, May 2008.

[60] M. Rehan, M. Yousaf, A. Qayyum, S. Malik, “A Crosslayer User Centric Vertical Handover Decision Approach based on MIH Local Triggers”, Second IFIP WG 6.8 Joint Conference, WMNC 2009, Gdansk, Poland, September 9-11, 2009