Universidade de Aveiro Departamento de Electrónica,
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Márcio Daniel Tavares de Melo

DESEMPENHO DE REDES WIMAX COM MOBILIDADE

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica da Prof. Dra. Susana Sargento, Professora auxiliar convidada do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro e do Prof. Dr. Francisco Fontes, Professor auxiliar convidado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

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Presidente

Prof. Dr. Nuno Miguel Gonçalves Borges de Carvalho
professor associado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Profª. Dra. Susana Isabel Barreto de Miranda Sargento
professora auxiliar convidada do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Profª. Dra. Marília Pascoal Curado
professora associada do Departamento de Engenharia Informática da Universidade de Coimbra

Prof. Dr. Francisco Manuel Marques Fontes
professor auxiliar convidado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

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palavras-chave

Handover, IEEE802.11, IEEE 802.16, IEEE 802.16e, IEEE 802.21, Inter-Tecnologia, Intra-Tecnologia, NS-2, Qualidade de Serviço, Mobilidade, UMTS, Wi-Fi, WiMAX.

resumo

Com a crescente evolução das tecnologias sem fios e a grande necessidade de estarmos sempre on(*line*) em qualquer lugar veio culminar com o desenvolvimento de uma nova norma a IEEE802.21, pelo grupo IEEE. Esta norma visa optimizar os *handovers* entre as diferentes tecnologias através de mecanismos e de eventos normalizados, com o objectivo de tornar as diferentes tecnologias transparentes para as camadas superiores.

Esta dissertação apresenta mecanismos de mobilidade independentes entre algumas tecnologias sem fios, em especial a tecnologia WiMAX com suporte para mobilidade e a tecnologia WiFi. É descrita a forma como se processam os *handovers* de redes heterogéneas com base na norma IEEE802.16 e IEEE802.21 e são propostas algumas modificações.

Posteriormente é analisado o simulador de redes, o qual foi utilizado para avaliar o desempenho dos *handovers* em redes heterogéneas através dos novos mecanismos definidos e propostos, e são efectuadas alterações para suportar a sinalização e funcionalidades especificadas.

Nesta Tese são simulados vários cenários com *handovers* de intra-tecnologia e de inter-tecnologia a fim de se obterem parâmetros de desempenho. Os resultados obtidos com as alterações produzidas no simulador mostram que esta nova norma e o mecanismo proposto de integração com as tecnologias 802.11 e 802.16, trazem melhorias significativas nos tempos de *handover*, assim como no suporte de *QoS*.

keywords

Handover, IEEE802.11, IEEE 802.16, IEEE 802.16e, IEEE 802.21, Inter-Technology, Intra-Technology, NS-2, Quality of Service, Mobility, UMTS, Wi-Fi, WiMAX.

abstract

With the growing trend of wireless technologies and the great need of being always on (line) and anywhere culminate with the development of a new standard the IEEE802.21, by the IEEE group. This standard is designed to streamline the *handovers* between different technologies through normalized mechanisms and events, with the purpose of making the different technologies seamless to the upper-layers

This thesis presents mobility mechanisms independent of the wireless technologies at this stage, particularly WiMAX technology with support for mobility and the WiFi technology. It is described how are processed heterogeneous handovers based on IEEE802.16 standard and the IEEE802.21 and are purposed some changes on it.

It is then analyzed the network simulator, which was used to assess the performance of the handovers in heterogeneous networks through the new mechanisms established and purposed, and changes are made to support the signalling and features specified.

On this Thesis are simulated several scenarios with handovers of intra-technology and inter-technology in order to obtain performance parameters. The obtained results with the changes produced in the simulator show that this new standard and the purposed mechanism of integration with the technologies 802.11 and 802.16, bring significant improvements on the time of handovers as well as on the support of QoS.

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Acronyms

	Acronym	Description
	3G	Third Generation
	3GPP	3rd Generation Partnership Project
	3GPP2	3rd Generation Partnership Project 2
A		
	ACK	Acknowledgement
	AP	Access Point
	AR	Access Router
B		
	BE	Best Effort
	BS	Base Station
	BW	Bandwidth
	BWA	Broadband Wireless Access
C		
	CID	Connection Identifier
	CN	Correspondent Node
	CoA	Care-of Address
	CoS	Class of Service
	CPS	Common Part Sublayer
	CS	Convergence Sublayer
D		
	DCD	Downlink Channel Descriptor
	DHCP	Dynamic Host Configuration Protocol
	DL	Downlink
	DL-MAP	Downlink Map
	DSA-REQ	Dynamic Service Addition Request
	DSA-RSP	Dynamic Service Addition Response
	DSA-ACK	Dynamic Service Addition Acknowledgment
E		
	ERTPS	Extended Real Time Polling Service
F		

	FA	Foreign Agent
	FBU	Fast Binding Update
	FMIPv6	Fast Mobile IPv6
	FNA	Fast Neighbour Advertisement
G		
	GPRS	General Packet Radio Service
	GSM	Global System for Mobile communications
H		
	HA	Home Agent
	HIP	Host Identity Protocol
	HO	Handover
I	IEEE	Institute of Electrical and Electronics Engineers
	IETF	Internet Engineering Task Force
	IPv4	Internet Protocol version 4
	IPv6	Internet Protocol version 6
L		
	LAN	Local Area Network
	LOS	Line of Sight
M		
	MAC	Medium Access Control
	MICS	Media Independent Command Services
	MIES	Media Independent Event Services
	MIIS	Media Independent Information Service
	MIH	Media Independent Handover
	MIHF	Media Independent Handover Function
	MIP	Mobile IP
	MN	Mobile Node
	MOB_BSHO-REQ	Mobility BS HO Request message
	MOB_BSHO-RSP	Mobility BS HO Response message
	MOB_HO-IND	Mobility HO Indication message
	MOB_MSHO-REQ	Mobility MS HO Request message
	MOB_NBR-ADV	Mobility Neighbour Advertisement message
	MOB_SCN-REQ	Mobility Scanning interval allocation Request message
	MOB_SCN-RSP	Mobility Scanning interval allocation Response message
	MOB_SCN-REP	Mobility Scanning result Report message
	MS	Mobile Station

	MT	Mobile Terminal
N		
	N2N	Network-to-Network
	NIST	National Institute of Standards and Technology
	NLOS	Non Line of Sight
	NRTPS	Non Real Time Polling Service
	NS	Network Simulator
	NS-2	Network Simulator version 2
	NS-2.29	Network Simulator version 2.29
	NS-3	Network Simulator version 3
	NWEST	National Wireless Electronics Systems Testbed
O		
	OFDM	Orthogonal Frequency Division Multiplexing
	OFDMA OTcl	Orthogonal Frequency Division Multiple Access Object Oriented Extension of Tcl
P		
	PDU	Protocol Data Unit
	PHY	Physical Layer
	PMP	Point-to-Multipoint
	PoA	point of attachment
	PoS	point of service
	PrRtAdv	Proxy Router Advertisement
	PS	Privacy Sublayer
	PTP	Point-to-Point
Q	QoS	Quality of Service
R		
	RA	Router Advertisement
	REG-REQ	Registration Request
	REG-RSP	Registration Response
	RNG-REQ	Ranging Request
	RNG-RSP	Ranging Response
	RS	Router Solicitation
	RtSolPr	Router Solicitation for Proxy Advertisement
S		

	SAP	Service Access Point
	SDU	Service Data Unit
	SF	Service Flow
	SS	Subscriber Station
T		
	TCL	Tool Command Language
	TCP	Transmission Control Protocol
U		
	UCD	Uplink Channel Descriptor
	UDP	User Datagram Protocol
	UGS	Unsolicited Scheduling Service
	UL	Uplink
	UL-MAP	Uplink Map
	UMTS	Universal Mobile Telecommunications System
W		
	Wi-Fi	Wireless Fidelity
	WiMAX	Worldwide Interoperability for Microwave Access
	WLAN	Wireless Local Area Network
	WMAN	Wireless Metropolitan Area Network
	WPAN	Wireless Personal Area Network

Chapter 1 – Introduction

1.1 Motivation

One of the areas of research in telecommunications, with growing interest, is the next generation of mobile communications systems. Those systems, with support for multiple wireless technologies, will support larger bandwidth than what is expected today, providing permanently high capacity of communication seamless to the users.

The growing need of users being connected at any time and anywhere has led to integrating the Internet with mobile networks. However, there are always areas of difficult coverage where the Internet access will be difficult to achieve.

The technology for metropolitan access IEEE 802.16 (commonly called WiMAX) is a technology for large wireless bandwidth, targeted for such scenarios, low cost compared to solutions of fibber, cable or copper. The IEEE802.16 group provides support for mobility, through the IEEE 802.16e standard, placing mobility in this scenario of metropolitan networks as seen in Figure 1.

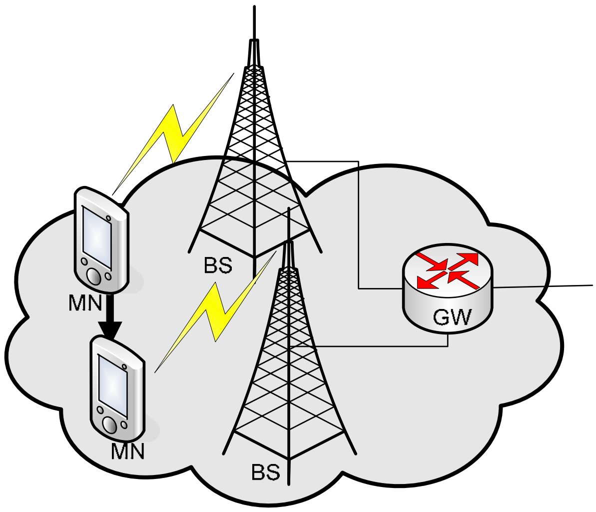

Figure 1 – WiMAX Mobility Scenario

Thus, this technology becomes very promising for use in environments of next generation. The IEEE 802.16 supports the modes of operation point-multi-point (PMP) and mesh as seen in Figure 2. In environments of next generation networks, users want access to all possible services, including multimedia in its various topological aspects (point-to-point, and diffusion), and operators need to support their requirements: support new services in real time with high quality, independent mobility of users.

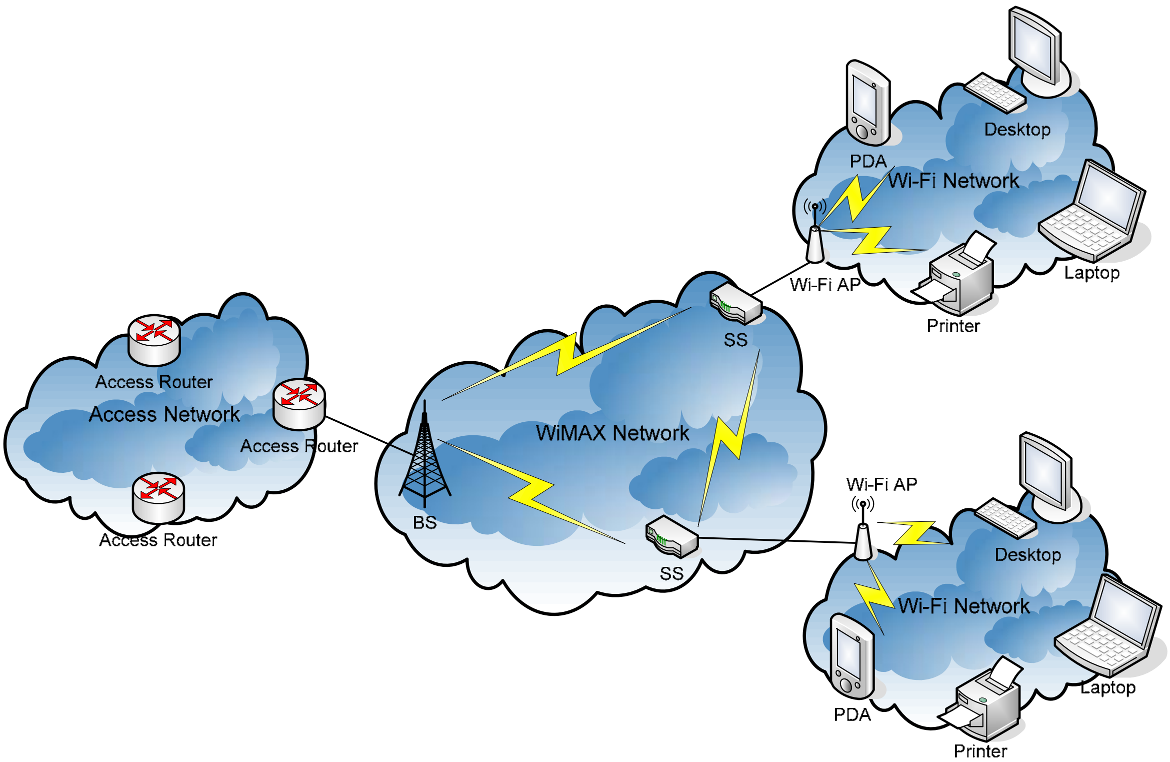

Figure 2 – WiMAX Applications

Despite this newest technology have many advantages, facing the existing wireless technologies, like Wi-Fi and UMTS, the purpose is not to compete with them or to eradicate them, but to cooperate with them since each one as different characteristics as you can see in Figure 3, WiMAX is in the middle of the existing ones, since it supports a huge bandwidth and as a nice range (coverage) per cell.

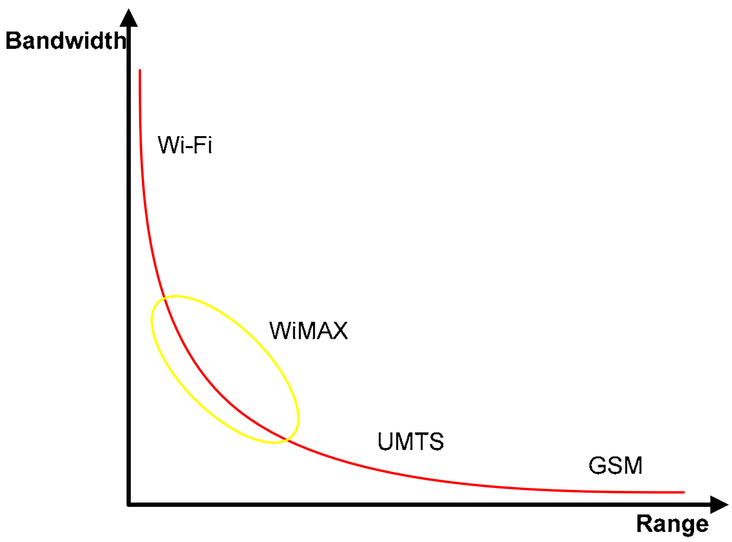

Figure 3 - Bandwidth vs. Range of wireless systems

Nowadays it is already possible to have more then one wireless interface, for connecting to the internet, in our laptop, pocket pc whatever; however, in the future this will be very common. Having more then one interface allows the users to be connected to the internet through 2 or more interfaces, and be able to increase the range of connectivity.

Considering the different requirements, more broadband (e.g. seeing a broadcast video) or more mobility (e.g. avoiding been offline), there is a need of having a media independent mobility mechanism to take advantage of having different interfaces, according to our needs or commands.

The IEEE 802.21 working group started the work in March 2004 for resolving this issue. More than 30 companies have joined the working group. The group produced a first draft of the standard including the protocol definition in May 2005. The letter ballot process began and subsequent revisions to the draft are in progress as of September 2006, with almost all comments resolved.

This emerging standard will support mechanisms that allow seamless handover between networks of the same type (horizontal handovers) as well as handover between different network types (vertical handovers). The standard provides information to allow the mobility to and from cellular, GSM, GPRS, WiFi, Bluetooth, 802.11 and 802.16 networks through different handover mechanisms.

1.2 Objectives

This thesis aims to evaluate the performance of IEEE 802.16 networks under mobility using IEEE802.21 as support. The assessment of the performance will focus on the aspects of mobility and support of multimedia services with requirements for high quality of transmission: it will be analyzed the features of mobility with Quality of Service (QoS) in those networks.

The analysis of performance will consist on the simulation of intra-technology and inter-technology handovers measuring some parameters, like jitter, packet delay, latency of handovers, packet loss.

The main goals of this thesis could be described through the following steps:

- Definition of performance metrics from the various networks;
- Familiarization with the existing modules to support the IEEE 802.16d, 802.16e and its integration with mobility (IEEE802.21);
- Development of the features for supporting networks architecture with IEEE 802.16e mobile;

- Carrying out tests and evaluating the performance.

1.3 Document Outline

The present Thesis is organized as follows:

- Chapter 2 provides a short overview of the 802.16 standard including the emend IEEE802.16e, and then follows an overview of IEEE 802.21 proposal for standard, through the explanation of the new defined framework the Media Independent Function (MIHF).
- Chapter 3 provides detailed information about the Integration proposed of IEEE802.16e with the IEEE802.21, through some diagrams of the process and their explanation as well.
- Chapter 4 provides an overview of the simulator used to obtain the results of handovers, describes what the simulator has implemented and what should be implemented for this purpose. Finally, it provides detailed information of the implementation done for filling those gaps.
- Chapter 5 shows the considered scenarios, experiences done and discusses the measurement results obtained for each considered scenario Intra-Technology Handover and Inter-Technology handover.
- Chapter 6 presents the conclusions of this work, as well as the envisaged future work.

Chapter 2 – Background

Recently, due to the exponential growth of intensive applications such as peer-to-peer (P2P) file sharing and tele-working, an increasing demand for higher bandwidth provisioning occurred. However, it is the bandwidth required by the next generation TV and video services, such as Video on Demand (VoD) and, more significantly, high definition TV (HDTV) which have recently begun increasing the pressure on bandwidth provisioning.

In general, broadband access technologies can be classified in two major groups: fixed line technologies or wireless technologies. The fixed line solution communicates via a physical network that provides a direct "wired" connection (e.g. Ethernet). Wireless solutions use radio or microwave frequencies to establish connectivity between the user and the network (e.g. Wi-Fi, WiMAX, UMTS).

The most important Broadband Wireless Access (BWA) technologies, such as Wi-Fi, WiMAX and UMTS, as well as their internal mechanisms, will be further described in this chapter. A special attention will be given to the WiMAX technology since it is a recent technology, with built in QoS, large throughputs and with a high coverage per cell. Thereafter, the IEEE802.21 draft standard for the optimization of handovers between heterogeneous wireless networks will be depicted, as well as the handover procedures defined in the IEEE802.16e amendment. At the end, the chapter conclusions will be presented.

2.1 Broadband Wireless Technologies

Wireless broadband technologies may support point-to-point (PTP) or point-to-multipoint (PTMP) topologies in the 2 – 43 GHz frequency spectrum in order to transmit signals between hub sites and an end-user receiver.

There is a wide range of frequencies within which wireless broadband technologies can operate, including licensed and unlicensed bands. Additionally, wireless technologies can be broadly categorized into those requiring line-of-sight (LOS) and those that can operate in non-line-of-sight (NLOS) conditions. The wireless technologies evaluated here are the following:

- Wi-Fi
- UMTS

- WiMAX

All these technologies can operate with NLOS, despite having better performances with LOS.

2.1.1 IEEE

The IEEE (Institute of Electrical and Electronics Engineers) is an international non-profit organization for the advancement of technology related to electricity. The IEEE is a leading developer of international standards that underpin many of today's telecommunications, information technology and power generation products and services.

Often the central source for standardization in a broad range of emerging technologies, the IEEE Standards Association has a portfolio of 900 active standards and more than 400 standards in development. This includes the prominent IEEE 802® standards for wireless networking. [ieee]

2.1.2 IEEE802.11

The first defined version of 802.11 standards was finished in 1999 [ieee802.11-99]. This primary version (802.11a) supports data rates up to 54Mbps at 5GHz. Recently, two new versions of the standard have been released, 802.11b and 802.11g, supporting data rates of 11Mps and 54Mbps, respectively, in unlicensed spectrum at 2.4GHz [ieee802.11e].

The IEEE802.11 group is now working on the specification of the 802.11n standard that will provide higher throughputs, compared to the existing 802.11a/b/g. The 802.11n standard is expected to deliver data rates up to 300 Mpbs.

The increased penetration of signals at these frequencies allows Wi-Fi transmitters to operate at low power and still achieve ranges up to 30 meters indoor and up to 450 meters outdoor. The main application of Wi-Fi is to provide local wireless radio links to end user communications equipment (e.g. PCs, VoIP Phones) within customer premises/residences.

2.1.3 Wi-Fi Alliance

The Wi-Fi Alliance is a global, non-profit industry association of more than 300 member companies devoted to promoting the growth of wireless Local Area Networks (WLANs). With the aim of enhancing the user experience for wireless portable, mobile, and home entertainment devices, the Wi-Fi Alliance's testing and certification programs help ensure the interoperability of WLAN products based on the IEEE 802.11 specification. Since the introduction of the Wi-Fi Alliance certification program in March 2000, more than 4,200 products have been designated as Wi-Fi CERTIFIED™, encouraging the expanded use of Wi-Fi products and services across the consumer and enterprise markets. [wifialliance]

2.1.4 UMTS

Universal Mobile Telecommunications System (UMTS) is one of the third-generation (3G) cell phone technologies, which is also being developed into a 4G technology. Currently, the most common form of UMTS uses W-CDMA as the underlying air interface. It is standardized by the 3GPP [3gpp] and is the European proposal to the ITU IMT-2000 requirements for 3G cellular radio systems.

To differentiate UMTS from competing network technologies, UMTS are sometimes marketed as 3GSM, emphasizing the combination of the 3G nature of the technology and the GSM standard.

2.1.5 IEEE802.16

At the ends of 90's many telecommunication equipment manufacturers were beginning to develop and offer products for Broadband Wireless Access (BWA). But at that time, the Industry was requiring an interoperable standard, for reducing the costs of those equipments and for allowing operators and users to use different equipments from different companies. With this need for a standard, the National Wireless Electronics Systems Testbed (NWEST) of the U.S and the National Institute of Standards and Technology (NIST) scheduled a meeting to discuss this issue [ieee802.16]. This effort was welcomed in IEEE 802, which led to the formation of the 802.16 Working Group (WG). Since then, the WG members have been working to develop standards for fixed and mobile BWA. IEEE Working Group 802.16 on BWA standard is responsible for the development of the 802.16 air interface, along with the associated standards and amendments.

The IEEE 802.16 standard contains the specification of Physical (PHY) and Medium Access Control (MAC) layer for BWA. The first version of the standard IEEE802.16-2001 [ieee802.16-01] was approved on December 2001 and it has gone through many amendments to accommodate new features and functionalities. The current version of the standard IEEE802.16-2004 [ieee802.16-04], approved on September 2004, consolidates all the previous versions of the standards. This standard specifies the air interface for fixed BWA systems supporting multimedia services in licensee and licensed exempt spectrum. The Working Group approved the amendment IEEE 802.16e-2005 [ieee802.16e-05] to IEEE802.16-2004 on February 2006.

For understanding the development of the standard to its current stage, the evolution of the standard is presented in the following subsections.

2.1.5.1 IEEE 802.16-2001

This first issue of the standard specifies the MAC and the PHY layer intended to provide fixed broadband wireless access in a point-to-point (PTP) or point-to-multipoint (PMTP) topology [ieee802.16-01]. The PHY layer uses single carrier modulation in the 10 – 66 GHz frequency range.

Transmission times, frames duration and modulation schemes are assigned by a Base Station (BS) and shared with all nodes in the network in the form of broadcast Uplink and Downlink maps.

Subscriber Stations (SS) have the ability to negotiate for bandwidth allocation on a burst to-burst basis, providing scheduling flexibility.

The standard employs Quadrature Phase-Shift Keying (QPSK), 16-State Quadrature Amplitude Modulation (16QAM) and 64QAM as modulation schemes. These can be changed from frame to frame and from SS to SS, depending on the robustness of the connection. The standard supports both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) as duplexing techniques. An important feature of 802.16-2001 is its ability to provide Quality of Service (QoS) in the MAC Layer. Service flows (SFs) are characterized by their QoS parameters, which can then be used to specify parameters like maximum latency and tolerated jitter. Service flows can be originated either from BS or SS side. 802.16-2001 works only in (Near) Line of Sight (LOS) conditions with outdoor Customer Premises Equipment (CPE).

2.1.5.2 IEEE 8020.16a-2003

This version of the standard amends IEEE 802.16-2001 by enhancing the MAC layer to support multiple PHY layer specifications. This was ratified by IEEE 802.16 WG in January 2003 [ieee802.16-03]. This amendment added physical layer support for 2-11 GHz. Both licensed and license exempt bands are included. Non Line of Sight (NLOS) operation becomes possible due to inclusion of frequency ranges below 11 GHz, extending the coverage of the network. Due to NLOS operation, multi-path propagation becomes an issue. To deal with multi-path propagation and interference mitigation, features like advanced power management and adaptive antenna arrays were included in the specification. The option of employing Orthogonal Frequency Division Multiplexing (OFDM) was included as an alternative to single carrier modulation.

Security was improved in this version; many of privacy layer features became mandatory while in 802.16-2001 they were optional. IEEE 802.16a also adds optional support for mesh topology in addition to PTMP.

2.1.5.3 IEEE 802.16c-2002

In December 2002, IEEE Standards Board approved amendment IEEE 802.16c [ieee802.16]. In this amendment detailed system profiles for 10-66 GHz were added and some errors and inconsistencies of the first version of the standard were corrected.

2.1.5.4 IEEE 802.16d-2004

The 802.16-2001, 802.16a-2003 and 802.16c-2002 were all together consolidated and a new standard was created which is known as 802.16-2004.

In the beginning, it was published as a revision of the standard under the name 802.16REVd, but due to the high number of changes, the standard was reissued under the name 802.16-2004, at September 2004.

In this version, the whole family of the standard is ratified and approved.

2.1.5.5 IEEE 802.16e-2005

This amendment was included in the current applicable version of standard IEEE 802.16-2004 in December 2005. This includes the PHY and MAC layer enhancement to enable combined fixed and mobile operation in licensed band.

A new entity was been defined – Mobile Station (MS) – similar to the SSs, previously defined in the 802.16d standard. The SSs could only move inside the coverage of the BS, while the MS can handover between different BSs. For supporting handovers, new procedures were implemented and new MAC management messages were defined. Table 1 has the main characteristics described on IEEE802.16d and this amendment (IEEE 802.16e).

	IEEE 802.16d	IEEE802.16e
Frequency	2 GHz -11GHZ	2GHz - 6Hz
Scheduling Services	UGS, rtPS, nrtPS, BE	UGS, rtPS, ertPS, nrtPS, BE
Subscribers	Fixed	Fixed/Mobile
Channel Conditions	LOS/NLOS	LOS/NLOS
Modulation	OFDM	S-OFDMA
Duplexing	TDD/FDD	TDD/FDD
Sub-carrier Modulation	QSPK, 16-QAM,64-QAM	QSPK,16-QAM,64-QAM
Data Rate	75 Mbps @ 20MHz 18Mbps @ 5 MHz	15Mps @ 5 MHz
Cell Range	50+Km @rural 15Km @ urban	3Km @ indoor 5Km @ outdour
Channel Bandwidth	1,25 MHz – 20 MHz	1,25 MHz -20 MHz

Table 1 – Comparison of IEEE standard for BWA

With respect to bandwidth, we have less bandwidth available for the mobile users. Four scheduling services are defined for the fixed version and five for the mobile version.

- **Unsolicited Grant Services (UGS)** supports data packets with fixed size and with a constant bit rate (CBR). The application that can be used with this type of service can be voice over IP (VoIP) with suppression of silence.
- **Real-time polling services (rtPS)** has been projected for supporting video flows that generate data packets with a variable bit rate (VBR).
- **Non-real-time polling service (nrtPS)** aims to support streams of data that need a special care with average delay, such as FTP, or flows that need a minimal data rate on downlink with variable size on the data packets.
- **Best-effort service (BE)**, this service was been projected for supporting data streams that don't need any special treatment at the level of QoS, such as web-browsing.
- **Extended real-time polling service (ErtPS)**, this service aims to support real time applications, like VoIP, that have VBRs with a maximum delay. This service is only defined for the mobile users (802.16e).

2.1.5.6 WiMAX Forum

The WiMAX Forum [wimax] is an industry-led, non-profit corporation formed to help promote and certify the interoperability of broadband wireless products compliant with the IEEE 802.16 and ETSI HiperMAN standards. The Forum's main goal is to accelerate global deployments of the IEEE 802.16 technology providing interoperable broadband wireless access (BWA) solutions. The economies of scale reachable throughout the value chain will result in cost points and performance levels unachievable by proprietary approaches. Computing history has shown that innovation occurs far more rapidly once a standards-based industry structure is in place, with consumers being the primary beneficiary. Reductions in equipment costs and consistent approaches to network design also vastly improve the business model for service providers.

WiMAX Forum Certified equipment is designed and configurable for a range of broadband wireless access deployment scenarios. These scenarios include the possibility for longer ranges (up to 50km) in low density, line-of-sight (LOS) outdoor conditions to shorter range NLOS deployments in cluttered urban environments (see Figure 4). Services can be fixed, portable or mobile, or some combination thereof. Over this range of conditions the common feature is the capability to reliably deliver broadband connectivity to the business and home users.

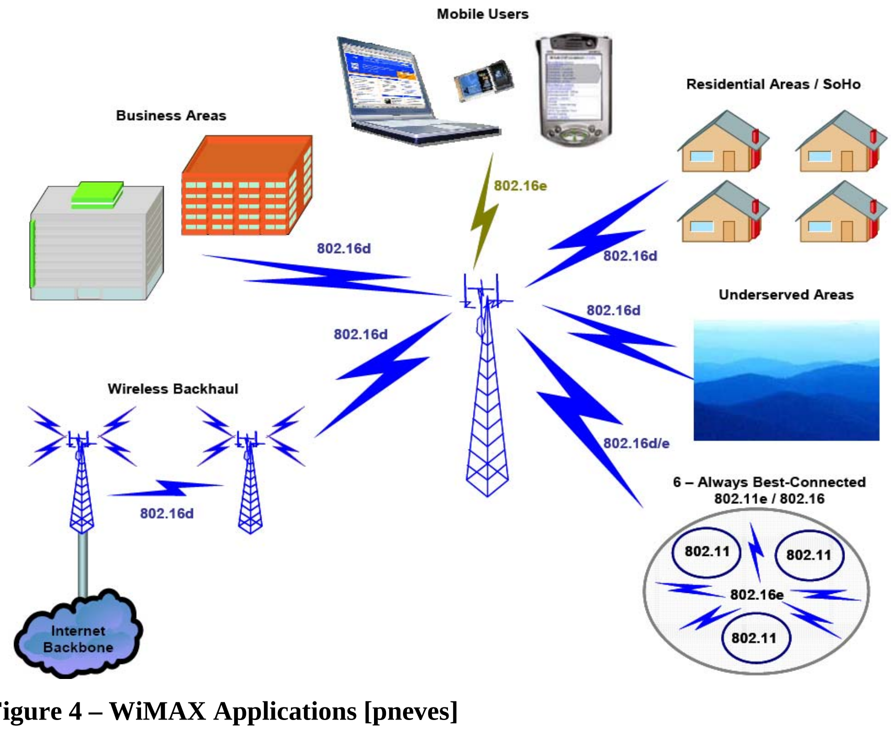

Figure 4 – WiMAX Applications [pneves]

2.2 IEEE802.21 Overview

2.2.1 Scope

The scope of the IEEE 802.21 (Media Independent Handover Services) standard [ieeeP802.21/D8.0] is to develop a specification that provides link layer intelligence and other related network information to upper layers to optimize handovers between heterogeneous media. This includes access technologies specified by 3GPP, 3GPP2 and both wired and wireless media in the IEEE 802 family of specifications.

2.2.2 Support

The proposal can support handovers for both mobile and stationary users. For mobile users, handovers may occur due to a change in wireless link conditions. Alternatively, handovers may occur due to a gap in radio coverage as a result of terminal movement. For a stationary user, handovers may become imminent when the environment around the user changes making one network more attractive than another. The user may choose an application which requires handover to a higher data rate channel, for example to stream an IPTV channel. Handovers should minimize any perceptible interruption in a video streaming during the handover process.

The IEEE802.21 standard supports cooperative use of both mobile terminals and network infrastructure. The mobile terminal is well-placed to detect available networks, and the infrastructure is in a good position to store overall network information, such as neighbourhood cell lists and the location of mobile devices. In general, both the terminals and the network point of attachments (PoAs) such as BSs or APs can be multimode, i.e. supporting different radio standards, and in some cases being capable of transmission on more than one interface simultaneously.

The network can have both micro cells (IEEE 802.11 or IEEE 802.15 coverage) and macro cells (3GPP, 3GPP2 or IEEE 802.16). The handover process is typically based on measurements and triggers supplied from link layers on the terminal. These measurements may include signal quality measurements, synchronization time differences, transmission error rates, etc.

The IEEE 802.21 framework facilitates the network discovery and selection process by exchanging network information that helps mobile devices to determine which networks are in their current neighbourhood. This network information could include information about the link type, the link identifier, link availability and link quality of nearby network links. This process of network discovery and selection allows a mobile to connect to the most appropriate network based on certain mobile policies.

As the mobile moves between different network Points of Attachment (PoA), it is essential to maintain proper security associations between the communicating end-points. These security associations can be obtained both via lower layer and higher layer mechanisms.

2.3 Framework

The IEEE802.21 defines the Media Independent Handover (MIH) framework to be implemented between the link layer (layer 2) and network layer (layer 3) – layer 2.5. See Figure 5.

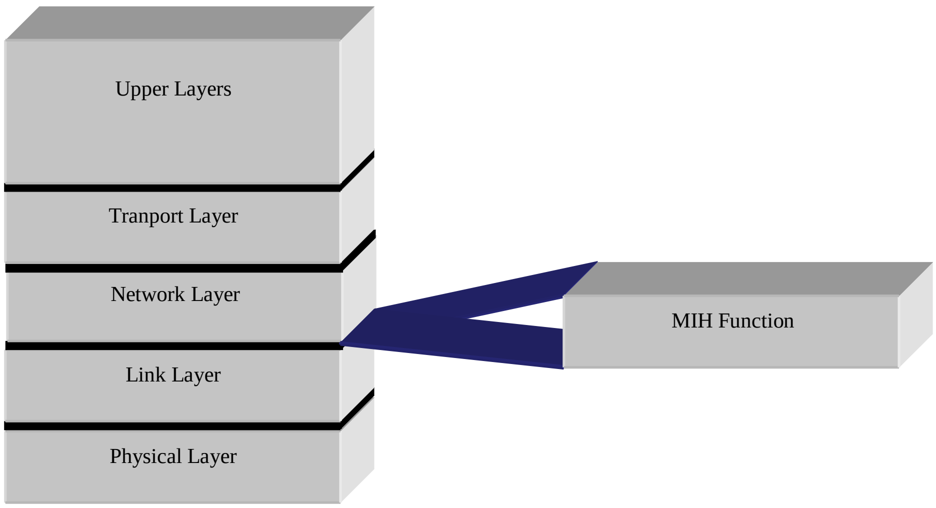

Figure 5 - TCP/IP Model plus MIHF block

MIHF operates using events, commands and information services. Therefore we can split this main block in three small ones:

- Service Management
- Event Service
- Command Service

The MIHF receives Link Events from the lower layers and sends them (as MIH Events) to the upper layers. The MIH commands are received from the upper layers and forwarded towards the lower layers as Link Commands. The information service is provided by either the upper layers or the lower layers to the MIHF, as seen in Figure 6.

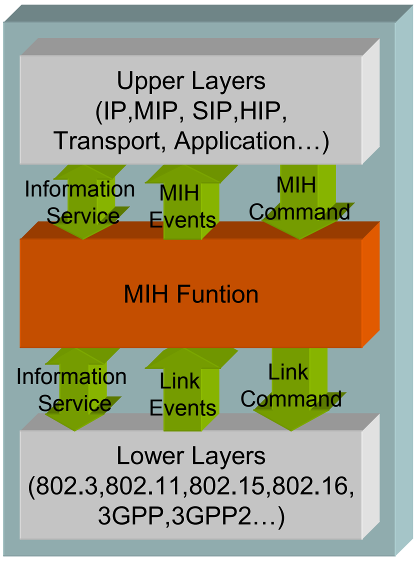

Figure 6 - MIHF Framework

A communication between peer MIHFs can also be established. For example, a MIHF entity can be installed in the MN and another one in the access network side. They can exchange remote commands and events using the MIH protocol (see Figure 7).

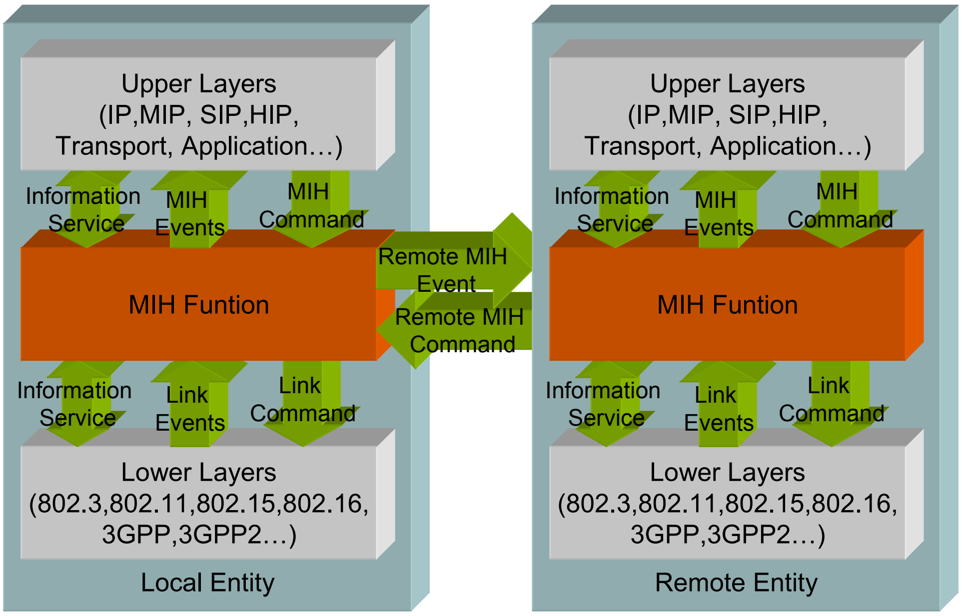

Figure 7 - Relationship with MIHF peers

2.3.1 MIHF services

The MIHF provides the Media Independent Event Service (MIES), the Media Independent Command Service (MICS), and the Media Independent Information Service (MIIS), facilitating the handover process across heterogeneous networks. This clause provides a general description of these services. These services are managed and configured through service management primitives.

2.3.1.1 Service Management

Prior to sending the MIH services from one MIHF to another, the MIH entities need to be configured properly.

This is done through the following service management functions:

- MIH Capability Discovery
- MIH Registration
- MIH Event Subscription

In order to know the services that are supported by a MIH peer, the MIH node performs MIH Capability Discovery. The MIH node may perform MIH Capability Discovery with different MIH peers in order to decide which one to register with.

Table 2 defines the set of service management primitives. A primitive is marked as local only (L), remote only (R), or local and remote (L, R), indicating whether it can be invoked by a local MIH User, a remote MIH User, or both, respectively.

Service Management Primitive	(L)ocal (R)emote	Comments
MIH_Capability_Discover	L,R	Discover the capabilities of a local or peer MIHF.
MIH_Register	R	Register with a peer MIHF.
MIH_DeRegister	R	Deregister from a peer MIHF.
MIH_Event_Subscribe	L,R	Subscribe for one or more MIH events with a local or remote MIHF.
MIH_Event_Unsubscribe	L,R	Unsubscribe for one or more MIH events from a local or remote MIHF.

Table 2 - Service management primitives

2.3.1.2 Media Independent Event Service

In general, handovers may be initiated either by the MN or by the network. Events that may be relevant to handover may originate from MAC, PHY or MIHF at the MN, at the network PoA, or at the PoS. Thus, the source of these events may be either local or remote. A transport protocol is needed for supporting remote events. Security is another important consideration in such transport protocols.

Multiple higher layer entities may be interested in these events at the same time. Thus these events may need to have multiple destinations. Higher layer entities may subscribe to receive event notifications from a particular event source. The MIHF may help in dispatching these events to multiple destinations.

These events are treated as discrete events. As such there is no general event state machine. However, in certain cases a particular event may have state information associated with it, such as the ***Link_Going_Down*** event. In such cases the event may be assigned an identifier and other related events, such as ***Link_Event_Rollback***, may be associated with the corresponding event using this identifier. Event notifications are generated asynchronously. Thus, all MIH Users and MIHFs that want to receive event notifications need to subscribe to particular events.

From the recipient's perspective these events are mostly “advisory” in nature and not “mandatory”. In other words, the recipient is *not* obligated to act on these events. Layer 3 and above entities may also need to deal with reliability and robustness issues associated with these events. Higher layer protocols and other entities may prefer to take a more cautious approach when events originate remotely as opposed to when they originate locally. These events may also be used for horizontal handovers. The Event Service is broadly divided into two categories, Link Events and MIH Events. Both Link and MIH Events may traverse from a lower to a higher layer. Link Events are defined as events that originate from event source entities below the MIHF and may terminate at the MIHF. Entities generating Link Events include, but are not limited to, various IEEE 802-defined, 3GPP-defined, and 3GPP2-defined interfaces. Within the MIHF, Link Events may be further propagated, with or without additional processing, to MIH Users that have subscribed for the specific events. MIH events are defined as events created within the MIHF, or Link Events that are propagated by the MIHF to the MIH Users. This relationship is shown in Figure 8.

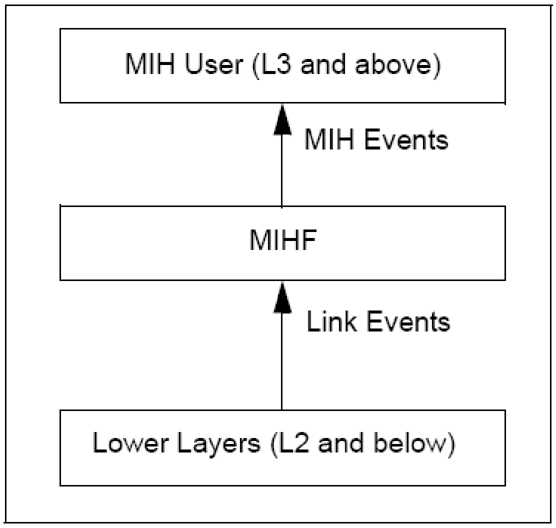

Figure 8 - Link events and MIH events [ieeeP802.21/D8.0]

All Link Events are local in nature and propagate from the local lower layer to the local MIHF. MIH Events may be local or remote. A remote MIH Event traverses the medium from a remote MIHF to the local MIHF and is then dispatched to local MIH Users that have subscribed to this remote event, as shown in Figure 9.

A Link Event that is received by the MIHF may also be sent to a remote MIH entity as a remote MIH Event.

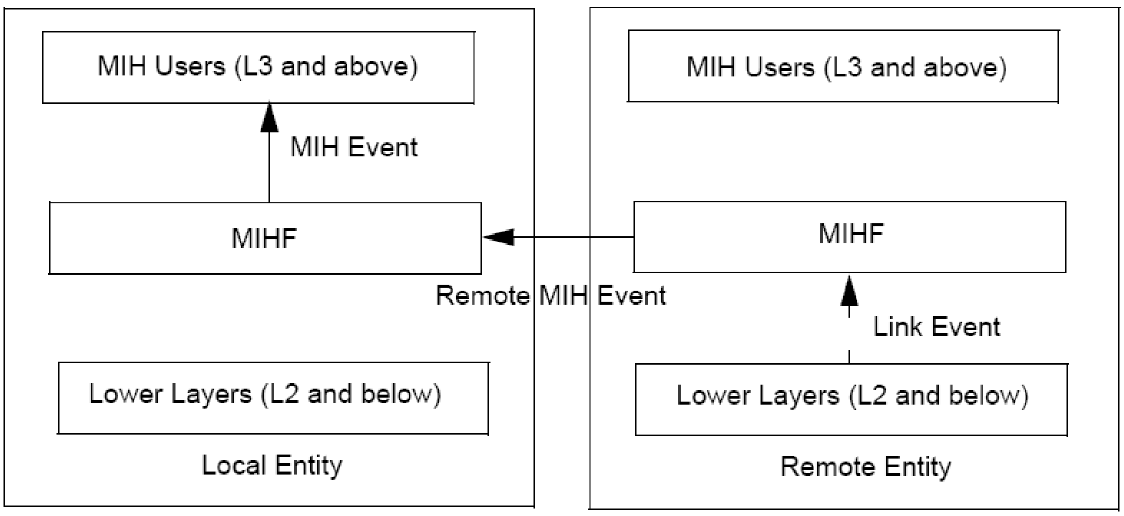

Figure 9 - Remote MIH events [ieeeP802.21/D8.0]

2.3.1.2.1 Link events

The Media Independent Event Service supports several categories of link events:

- **MAC and PHY State Change events**: These events correspond to changes in MAC and PHY state. For example ***Link_Up*** event is an example of a state change event.
- **Link Parameter events:** These events are due to changes in link layer parameters. For example, the primitive ***Link_Parameters_Report*** is a Link Parameter event.
- **Predictive events**: Predictive events convey the likelihood of a change in the link properties in the near future based on past and present conditions. For example, decay in signal strength of a WLAN network may indicate a loss of link connectivity in the near future. In case predictive events are incorrect they may be retracted.
- **Link Handover events**: These events inform upper layers about the occurrence of L2 handovers/link switches if supported by the given media type.
- **Link Transmission events**: These events indicate the link layer transmission status (e.g., success or failure) of upper layer PDUs. This information may be used by upper layers to improve buffer management for minimizing the upper layer data loss due to a handover. For example, the occurrence of a handover of an MN from one access network to another will result in the tear-down of the old link layer connection between the MN and the source Access network and the establishment of a new link layer connection between the MN and the target access network.

In general when a link event occurs due to a change in link condition it is not known at that instant if this would lead to intra-technology handover or inter-technology handover. That determination is done higher up in the protocol stack by the network selection entity based on variety of other factors. As such certain link layer events such as ***Link_Going_Down*** may lead to either intra-technology or inter-technology handovers.

The network selection entity may try to maintain the current connection, by first trying intra-technology handovers and only later on resort to inter-technology handovers

2.3.1.3 Media Independent Command Service

Media Independent Command Service (MICS) refers to the commands sent from MIH Users to the lower layers in the reference model. MIH Users may utilize command services to determine the status of links and/or control the multi-mode device for optimal performance. Command services may also enable MIH Users to facilitate optimal handover policies. For example, the network may initiate and control handovers to balance the load of two different access networks.

The link status varies with time and MN mobility. Information provided by MICS is dynamic information comprised of link parameters such as signal strength and link speed, whereas information provided by MIIS is less dynamic or static in nature and is comprised of parameters such as network operators and higher layer service information. MICS and MIIS information could be used in combination by the MN/network to facilitate the handover.

A number of commands are defined in the IEEE802.21 standard to allow the MIH Users to configure, control, and retrieve information from the lower layers including MAC, Radio Resource Management, and PHY. The commands are classified into two categories: MIH Commands and Link Commands. Figure 10 shows link commands and MIH commands.

The receipt of certain MIH command requests may cause event indications to be generated. The receipt of MIH command requests may indicate a future state change in one of the link layers in the local node. These indications notify subscribed MIH Users of impending link state changes. This allows MIH Users to be better prepared to take appropriate action.

Link Commands originate from the MIHF and are directed to the lower layers. These commands mainly control the behaviour of the lower layer entities. Link Commands are local only. Whenever applicable this standard encourages use of existing media-specific link commands for interaction with specific access networks. New link commands, if required, are defined as recommendations to different link layer technology standards. It is to be noted that although Link Commands originate from the MIHF, these commands are executed on behalf of the MIH Users. The MIH commands are generated by the MIH Users and sent to the MIHF. MIH commands can be local or remote. Local MIH commands are sent by MIH Users to the MIHF in the local protocol stack.

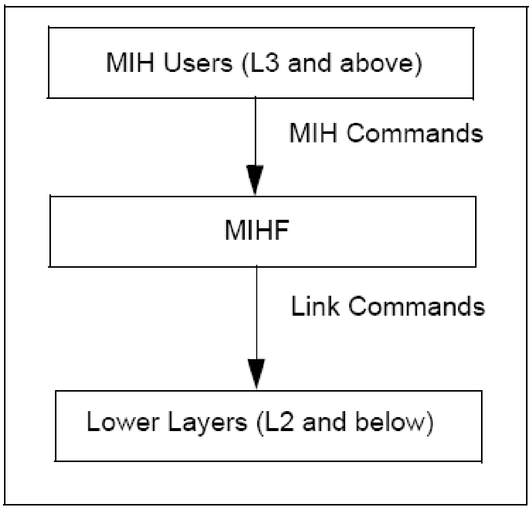

Figure 10 - Link commands and MIH commands [ieeeP802.21/D8.0]

Remote MIH commands are sent by MIH Users to the MIHF in a peer protocol stack. A remote MIH command delivered to a peer MIHF is executed by the lower-layers under the peer MIHF as a link command; or is executed by the peer MIHF itself as an MIH command (as if the MIH command came from an MIH User of the peer MIHF); or is executed by an MIH User of the peer MIHF in response to the corresponding indication. Often, an MIH indication to a remote MIH User may result from the execution of the MIH command by the peer MIHF. Figure 11 shows remote MIH commands.

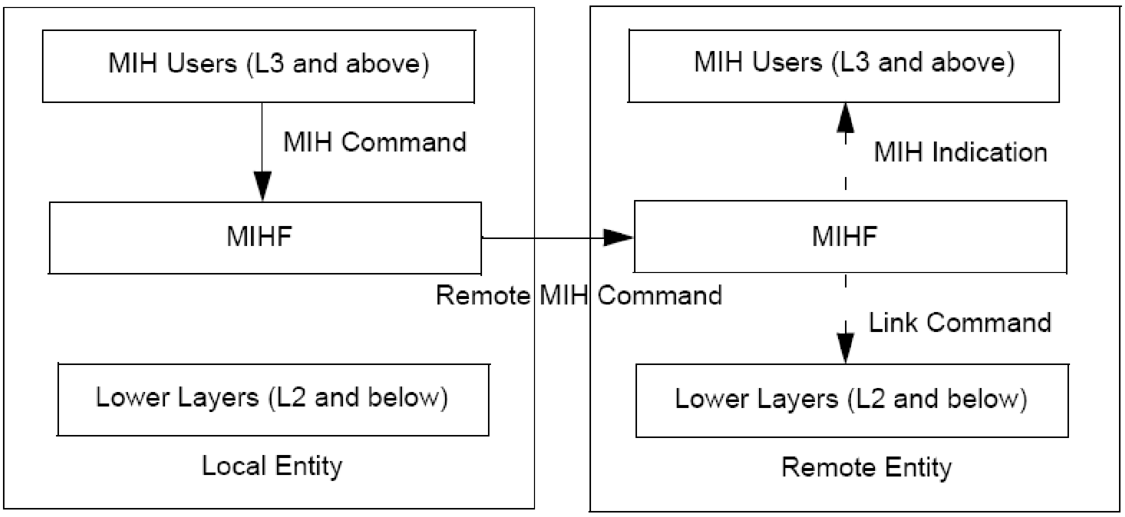

Figure 11 - Remote MIH command [ieeeP802.21/D8.0]

2.4 Handover Procedure

2.4.1 IEEEE802.16e

The handover procedure for mobile WiMAX, defined in the amendment IEEE802.16e, is represented in Figure 12. For helping understating this procedure (and matching it with Figure 12), the messages exchanged between the MN and the BS are on bold. In the figure the MN is represented by the Mobile Station (MS).

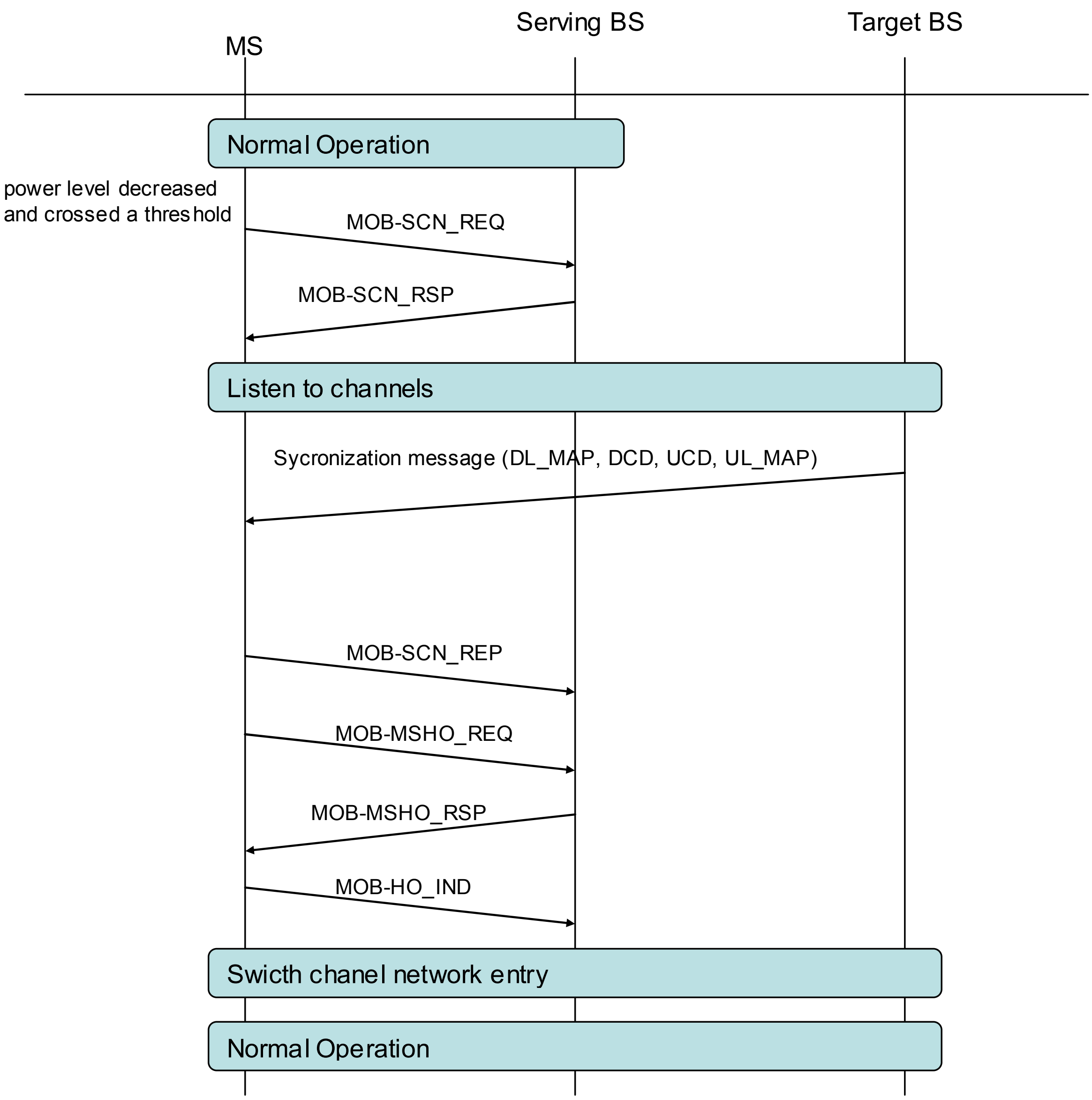

Figure 12 – Handover Procedure in WiMAX networks [nist802.16]

2.4.1.1 MS Scanning of Neighbour BS

A scanning interval is defined as the time during which the MN scans for an available BS [loutfi]. A BS may allocate time intervals to the MN for the purpose of MN seeking and monitoring suitability of neighbour BSs as targets for a handover. MN scanning of neighbour BSs is based on the following MAC Management messages: ***MOB_SCN-REQ***, SCaNning interval allocation REQuest, ***MOB_SCN-RSP***, SCaNning interval allocation Response, ***MOB_SCN-REP*** and SCaNning result REPort.

The ***MOB_SCN-REQ*** message is sent by the MN to request a scanning interval for the purpose of seeking available BSs and determining their suitability as targets for HO. In the MOB_SCN-REQ message the MN indicates a group of neighbour BSs for which only Scanning or Scanning with Association are requested by the MN. The Neighbour_BS_Index of the MOB_SCN-REQ message corresponds to the position of BSs in the MOB_NBR-ADV message. In this message, the MN may also request the scanning allocation to perform scanning or non contention Association ranging. Association is an optional initial ranging procedure occurring during the scanning interval with respect to one of the neighbour BSs.

Upon reception of the MOB_SCN-REQ message, the BS responds with a ***MOB_SCN-RSP*** message. The MOB_SCN-RSP message can also be unsolicited. The MOB_SCN-RSP Mobility, Handover and Power-Save Modes message either grants the requesting MN a scanning interval that is at least as long as that requested by the MN or denies the request. In the MOB_SCN-RSP message the BS indicates a group of neighbour BSs for which only Scanning or Scanning with Association are recommended by the BS.

Following reception of a MOB_SCN-RSP message granting the request, an MN may scan for one or more BSs during the time interval allocated in the message. When a BS is identified through scanning, the MN may attempt to synchronise with its downlink transmissions and estimate the quality of the PHY channel.

The BS may negotiate over the backbone with a BS Recommended for Association (in the MOB_SCN-REQ message) the allocation of unicast ranging opportunities. Then the MN will be informed on Rendez vous time to conduct Association ranging with the Recommended BS. When conducting initial ranging to a BS Recommended for Association, the MN uses an allocated unicast ranging opportunity, if available.

The serving BS may buffer incoming data addressed to the MN during the scanning interval and transmit that data after the scanning interval during any interleaving interval or after exit of the Scanning mode. When the Report mode is 0b10 (i.e. event-triggered) in the most recently received MOB_SCN-RSP, the MN scans all the BSs within the Recommended BS list of this message and then transmits a ***MOB_SCN-REP*** message to report the scanning results to its serving BS after each scanning period at the time indicated in the MOB_SCN-RSP message. The MN may transmit a MOB_SCN-REP message to report the scanning results to its serving BS at any time. The message will be transmitted on the Primary Management CID.

2.4.1.2 The Handover decision

The 802.16 standard refers that the handover decision algorithm is beyond its scope. The WiMAX Forum documents do not select a handover algorithm either. Only the framework is defined. The MN, using its current information on the neighbour BS or after a request to obtain such information (see the previous section), evaluates its interest in a potential handover with a target BS. Once the handover decision is taken by either the serving BS or the MN, a notification is sent over the ***MOB_BSHO-REQ*** (BS Handover REQuest) or the ***MOB_MSHO-REQ*** (MS Handover REQuest) MAC management messages, depending on the handover decision maker: the BS or MN.

2.4.1.3 Handover Initiation

A handover begins with a decision for an MN to make a handover from a serving BS to a target BS. The decision may be originated either at the MN or the serving BS. The handover decision results in a notification of MN intent to make a handover through the ***MOB_MSHO-REQ*** (MS HO REQuest) message (handover decision by the MN) or the ***MOB_BSHO-REQ*** (BS HO REQuest) message (handover decision by the BS).

The BS may transmit a MOB_BSHO-REQ message when it wants to initiate a handover.

This request may be recommended or mandatory. In the case where it is mandatory, at least one recommended BS must be present in the MOB_BSHO-REQ message. If mandatory, the MN responds with the MOB_HO-IND message, indicating commitment to the handover unless the MN is unable to make the handover to any of the recommended BSs in the MOB_BSHO-REQ message, in which case the MN may respond with the MOB_HO-IND message with proper parameters indicating HO reject. An MN receiving the MOB_BSHO-REQ message may scan recommended neighbour BSs in this message.

In the case of an MN initiated handover, the BS transmits an ***MOB_BSHO-RSP*** message upon reception of the ***MOB_MSHO-REQ*** message.

2.4.1.4 Termination of MN Context

This is the final step of a handover. The serving BS terminates all connections belonging to the MN and the discarding of the context associated with them, i.e. information in queues, ARQ state machine, counters, timers, header suppression information, etc. This is accomplished by sending the ***MOB_HO-IND*** message with the HO_IND_type value indicating a serving BS release.

2.4.2 IEEE802.21

This IEEE802.21 proposal [ieeeP802.21/D8.0] defines that the handover procedure can either be initiated by the mobile node or by the network; it will be described the procedure initiated by the mobile node, since the other procedure was not considered for obtaining practical results. This procedure can be split in 5 phases:

- Network Topology Acquisition
- Resources Availability Check
- Handover Preparation
- Handover Execution
- Handover Completion

2.4.2.1 Network Topology Acquisition

Initially Mobile Node is connected to the serving network via Current PoS and it has access to MIH Information Server.

Then MN queries information about neighbouring networks by sending the ***MIH_Get_Information Request*** to Information Server. Information Server responds with ***MIH_Get_Information Response*** as seen in Figure 13. This information query may be attempted as soon as Mobile Node is first attached to the network.

2.4.2.2 Resources Availability Check

Mobile Node *triggers* a mobile-initiated handover by sending ***MIH_MN_HO_Candidate_Query Request*** to Serving PoS. This request contains the information of potential candidate networks.

After receiving MIH_MN_HO_Candidate_Query Request from MN the Serving PoS queries the availability of resources at the candidate networks by sending ***MIH_N2N_HO_Query_Resources Request*** to one or multiple Candidate PoSs.

The Candidate PoSs respond with ***MIH_N2N_HO_Query_Resources Response*** and Serving PoS notifies the Mobile Node of the resulting resource availability at the candidate networks through ***MIH_MN_HO_Candidate_Query Response*** (Figure 13).

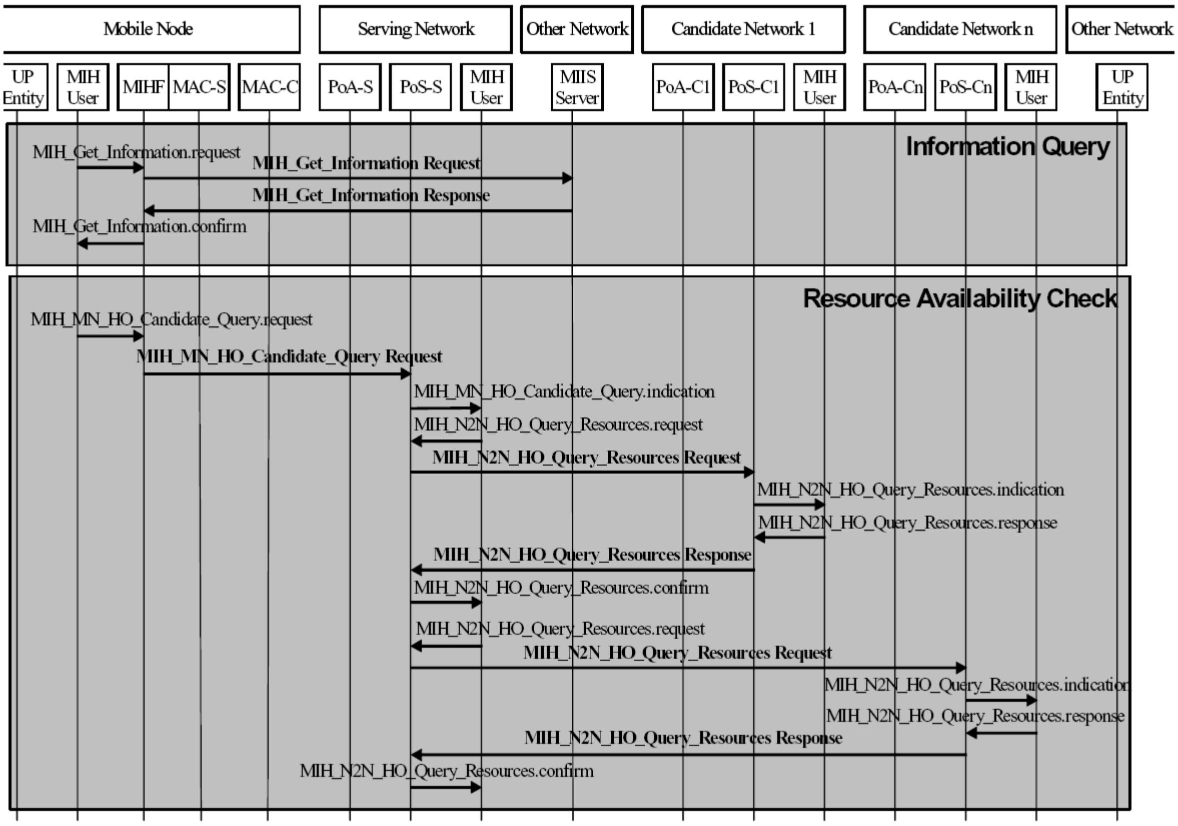

Figure 13 - Mobile-initiated handover procedure [ieeeP802.21/D8.0]

2.4.2.3 Handover Preparation

Mobile Node decides the target of the handover and requests resource preparation by sending the ***MIH_Link_Handover_Imminent*** Indication to Serving PoS.

Serving PoS sends ***MIH_N2N_HO_Commit Request*** to Target PoS to request resource preparation at the target network. Target PoS responds the result of the resource preparation by ***MIH_N2N_HO_Commit Response*** (Figure 14).

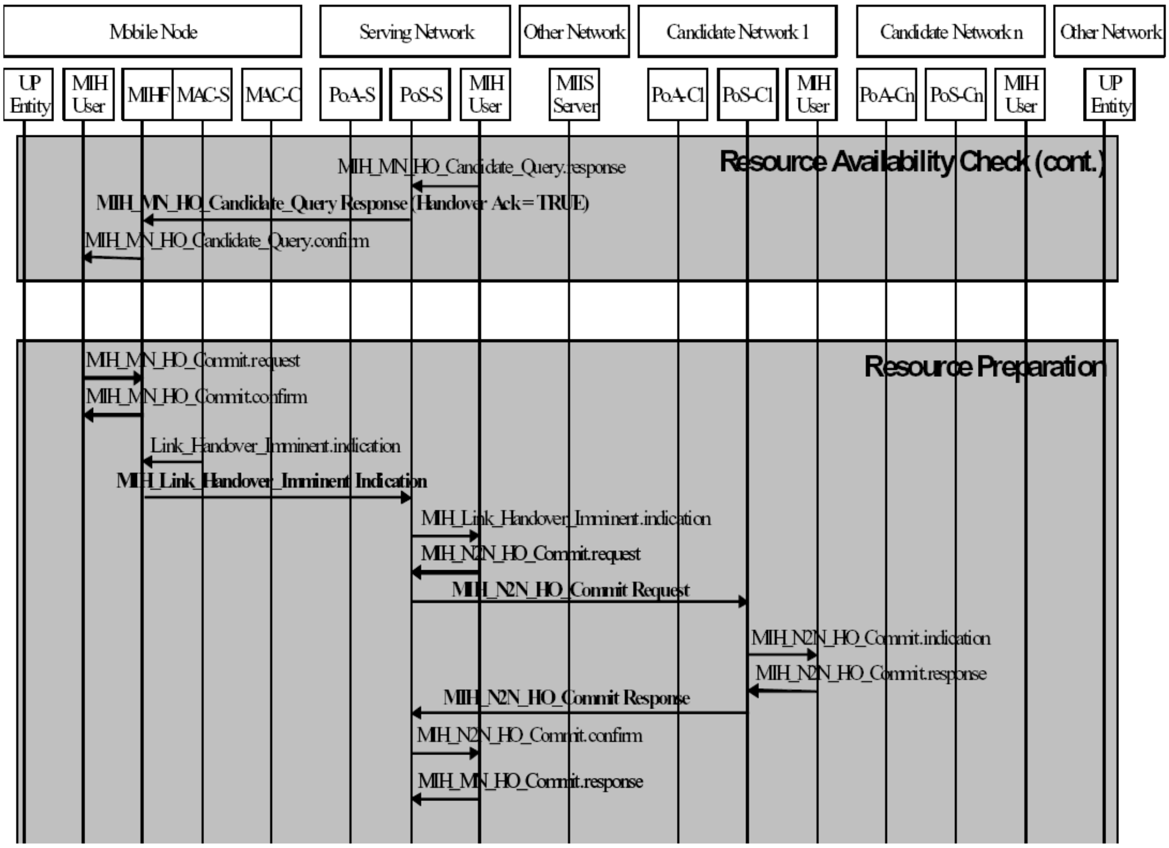

Figure 14 - Mobile-initiated handover procedure (cont.) [ieeeP802.21/D8.0]

2.4.2.4 Handover Execution

New layer 2 connection is established and a certain mobility management protocol procedures are carried out between the Mobile Node and target network.

2.4.2.5 Handover Completion

Mobile Node may send ***MIH_MN_HO_Complete Request*** to Target PoS. Target PoS sends ***MIH_N2N_HO_Complete Request*** to previous Serving PoS to release resource which was allocated to Mobile Node (Figure 15).

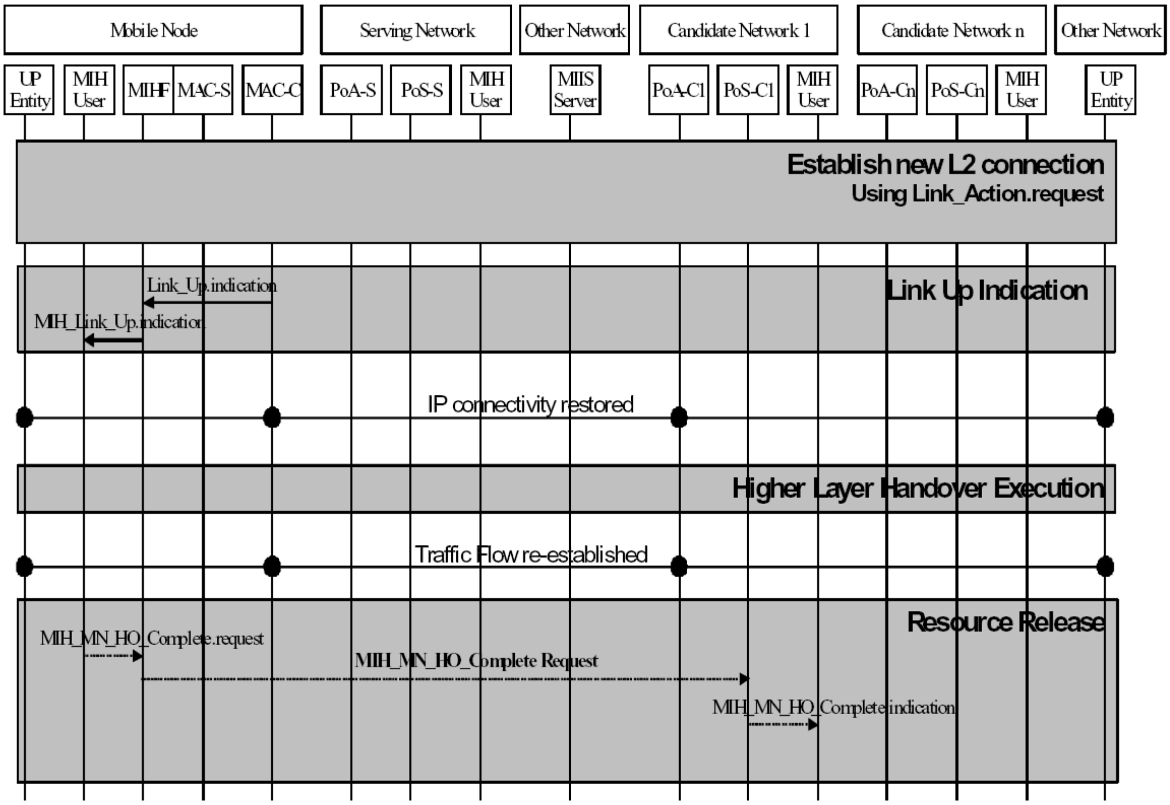

Figure 15 - Mobile-initiated handover procedure (cont.) [ieeeP802.21/D8.0]

After identifying that resource is successfully released, Target PoS may send ***MIH_MN_HO_Complete Response*** to Mobile Node (Figure 16).

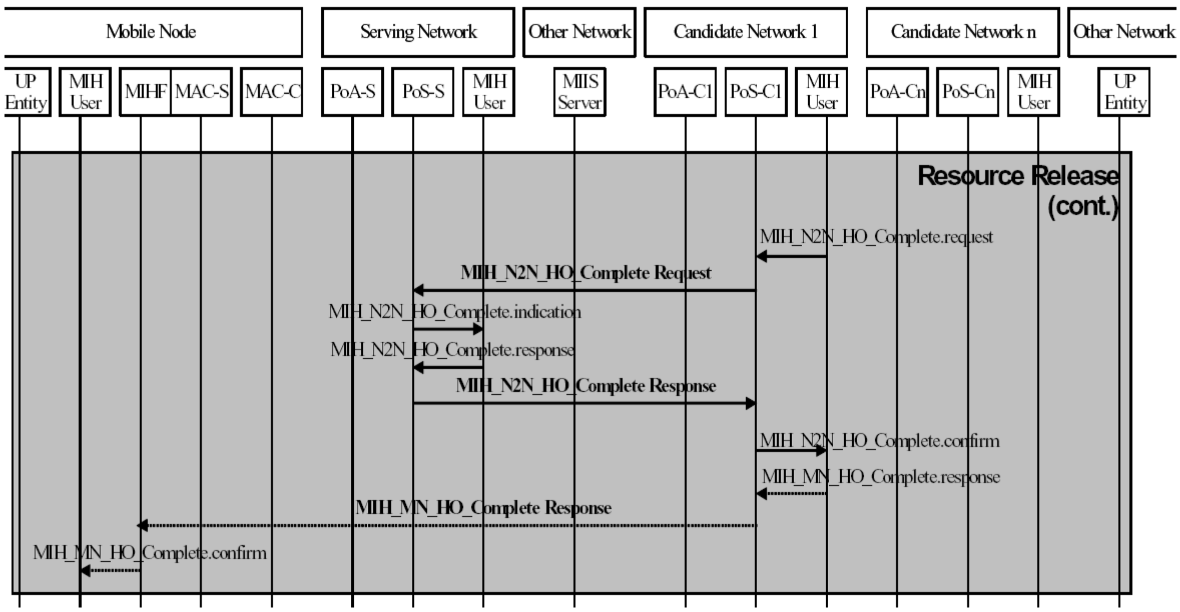

Figure 16 - Mobile-initiated handover procedure (cont.) [ieeeP802.21/D8.0]

2.5 Related work

2.5.1 IEEE802.16d+e

Developing a simulator that can support IEEE802.16d and IEEE.16e requires the interaction with many factors. We can have several modulations depending on the distance which implies different bit rates, different packet losses, delays and jitter.

At this stage, several simulators supporting IEEE802.16d and IEEE802.16e are available. One of them is the Network Simulator 2 (NS-2). - 36 -explains how the NS-2 simulator works and the reason to use it for obtaining practical results, in detriment of others.

The National Institute of Standards and Technology (NIST) created an add-on to NS-2 for allowing the simulation of IEEE802.16d and IEEE802.16e. Emanuel Marques, at the University of Aveiro (UA), has developed a patch to this add-on for supporting different types of scheduling on his final project entitled “Performance of WiMAX Networks”. Recently, this patch was modified by João Monteiro, researcher in Institute of Telecommunications (IT), for supporting NS-2.29.

2.5.2 IEEE802.21

At this point, the NS-2 has an add-on for supporting the IEEE802.21standard, released by NIST. This add-on is based on the draft 3 of the standard.

The modifications to this add-on were done based on the draft 8, since it was the latest version available on the beginning of this thesis.

2.6 Summary

An overview of Wi-Fi, UMTS and WiMAX broadband technologies has been provided in this chapter. The IEEE802.16 already defines a procedure for handovers in WiMAX networks. The IEEE802.21 defines mechanisms for heterogeneous handovers, which can be used for homogeneous handovers as well. Combining the WiMAX technology (WiMAX) with the new mechanisms defined by the IEEE802.21 standard it is possible to achieve handovers with less latency and less packet loss.

Chapter 3 – Integration

The IEEE802.16e amendment defines a procedure for handovers in IEEE 802.16 networks. Nevertheless, it only addresses the communication between the MN and the serving BS. The information exchanged between the serving BS and the candidate BSs is not under the scope of the IEEE 802.16 WG. The IEEE802.21 framework defines a procedure for optimizing the mobility process in heterogeneous access networks, which can be used in WiMAX networks as well.

On this chapter will be described how a multi-mode MN proceeds during a handover process, considering that he has two or more different wireless interfaces, in particul, one is Wi-Fi and another one is WiMAX. Initially, the MN is connected to the Wi-Fi AP and is under the coverage of the WiMAX network. A seamless handover mechanism will be presented in this chapter, using the IEEE802.16e standard, the IEEE802.21 draft standard (draft 8) [ieeeP802.21/D8.0] and the Fast Mobile IPv6 [rfc4068] protocol. Message sequence charts (MSCs) will be provided to clearly present the adopted solution.

This chapter is organized in 2 sections. Section 3.1 describes the proposed handover procedure and is further split into 5 sub-sections, corresponding to the number of the handover phases (Network Topology Acquisition, Resource Availability Check, Handover Preparation and Handover Completion. Section 3.2 provides the conclusions.

3.1 Handover Procedure

A seamless handover procedure can be split in the following five phases:

1. Network Topology Acquisition
2. Resources Availability Check
3. Handover Preparation
4. Handover Execution
5. Handover Completion

Each one of the previously mentioned phases will be explained in the following sub-clauses.

3.1.1 Network Topology Acquisition

Initially the Mobile Node (MN) is connected to the serving network (Wi-Fi) via an Access Point (AP) and is exchanging data with a Correspondent Node (CN). Since the terminal is multi-mode, it discovers a WiMAX network, using its WiMAX interface. This can be achieved with a ***DL_MAP*** messages (Figure 17). After receiving a DL_MAP in the WiMAX interface, the WiMAX MAC layer forwards this message to the MIHF in format of a Link Event with the type Link Detected. Then the MIHF replays it to the MIH User as a ***MIH Link Detected*** event. With such types of events the MIHU acquires the network topology and if the MN needs to do a handover, he already has the knowledge of one or more possible candidates for changing.

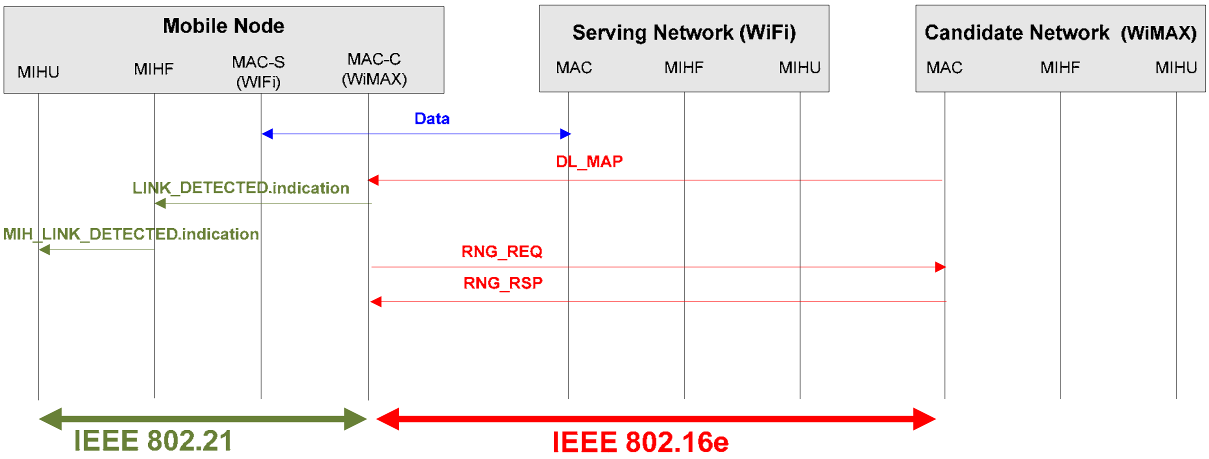

Figure 17 - Network Topology Acquisition (.21&.16e)

After receiving a MIH Link Detected event, the MIHU may decide to associate with the WiMAX BS or can simple ignore it.

If his decision is to associate, he sends a MIH Link Action Request to the MIHF. After receiving a MIH action request from the MIHU, the MIHF forwards it to the MAC layer of the WiMAX interface. Then the MAC layer performs the action by commanding the WiMAX interface to send Registration Request (***REG_REQ***) to the target BS (Figure 18).

After associating with the BS, the MIHU may send a router solicitation for proxy to his serving network, using the Fast Mobility IPv6 [rfc4068] protocol, with the purpose of discovering the prefix of this new network (WiMAX network).

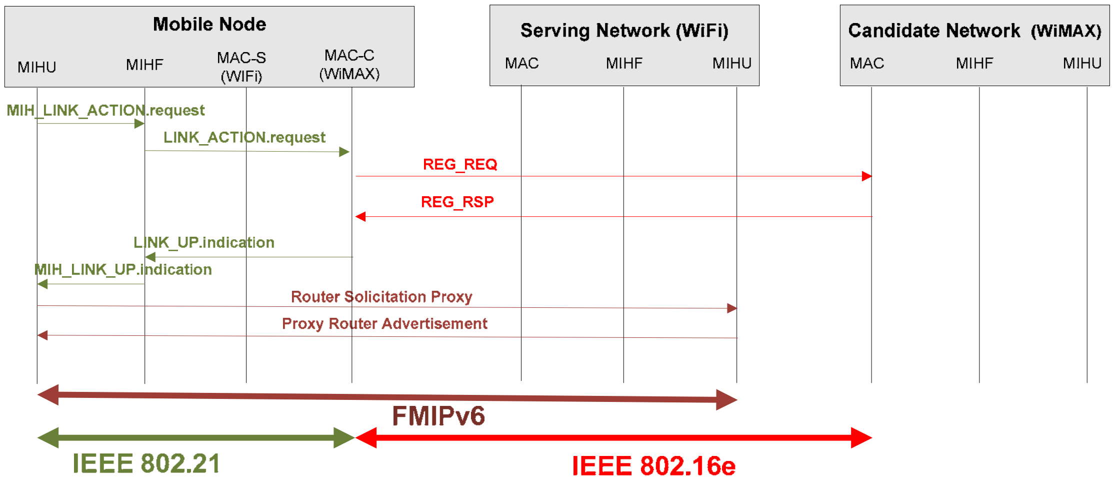

Figure 18 - Network Association (.21&.16e&FMIPv6)

If the gathered information through the ***DL_MAP*** messages is not enough, the MN can query information about different types of neighbouring networks by sending the MIH_Get_Information message.

The MN is connected with the serving network via the Wi-Fi AP. Therefore he has access to the MIH Information Server. This information query may be attempted as soon as Mobile Node is first attached to the serving network (Figure 19).

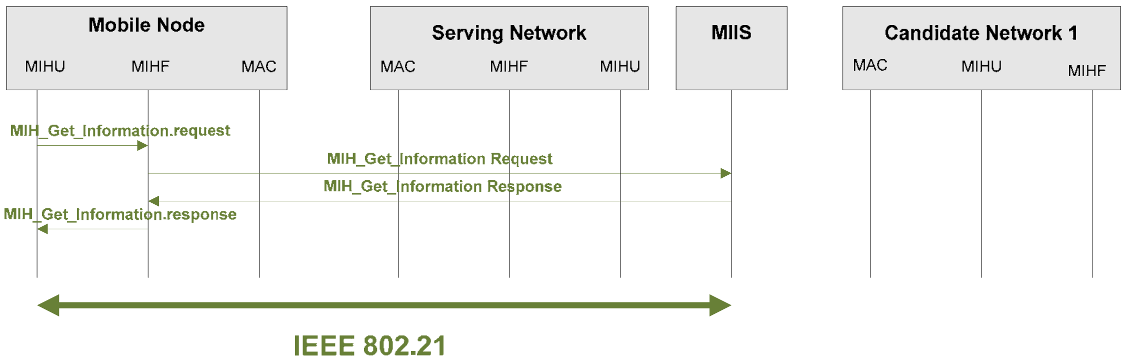

Figure 19 - Network Topology Acquisition (.21)

3.1.2 Resources Availability Check

The Mobile Node triggers a mobile-initiated handover by sending ***MIH_MN_HO_Candidate_Query Request*** to his serving PoS (Figure 20). This request contains the information of potential candidate networks. Serving PoS queries the availability of resources at the candidate networks by sending ***MIH_N2N_HO_Query_Resources Request*** to one or multiple Candidate PoS. Candidate

PoSs respond with ***MIH_N2N_HO_Query_Resources Response*** and Serving PoS notifies the Mobile Node of the resulting resource availability at the candidate networks through ***MIH_MN_HO_Candidate_Query Response***.

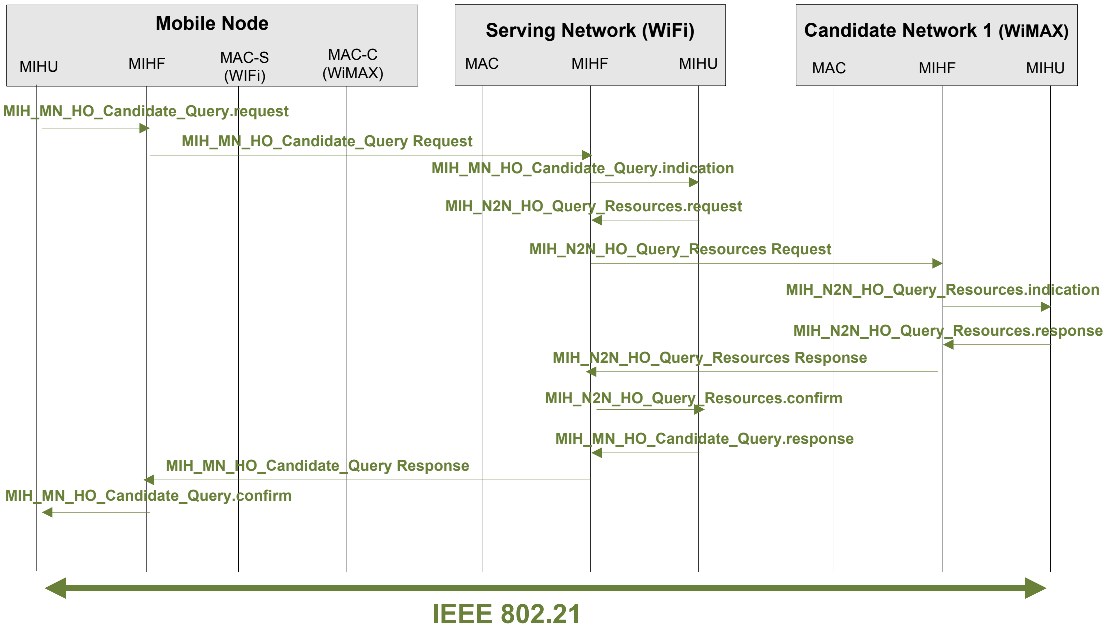

Figure 20 - Resources Availability Check (.21)

3.1.3 Handover Preparation

Mobile Node decides the target of the handover based on resource availability and some other selection criteria. After deciding the target access technology, the MN sends the ***MIH_MN_HO_Commit Request*** message to his serving PoS. The Serving PoS prepares the resources at the target network by sending ***MIH_N2N_HO_Commit Request*** to the target PoS. Target PoS respond with ***MIH_N2N_HO_Commit Response*** and Serving PoS notifies the Mobile Node of the resulting resource reservation at the target network through ***MIH_MN_HO_Commit Response*** (Figure 21).

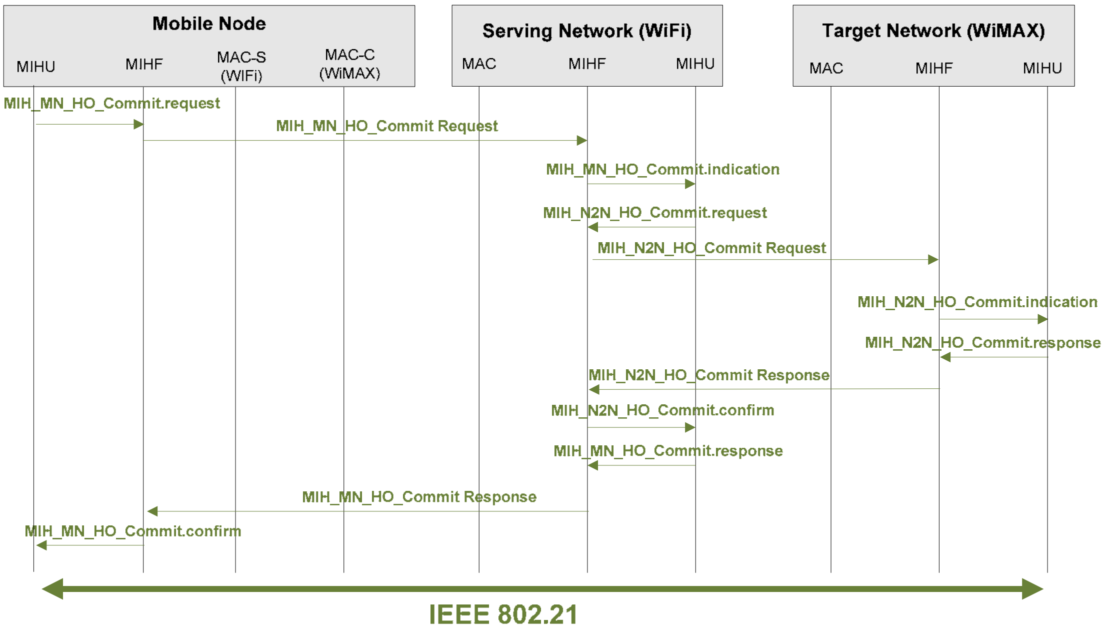

Figure 21 - Handover Preparation (.21)

3.1.4 Handover Execution

The MN starts by sending a ***Fast Binding Update*** (FBU) message instructing its Previous Access Router (PAR), on his serving network, to redirect its traffic towards the New Access Router (NAR).

The PAR sends a ***Handover Initiate*** message to the NAR. After receiving the HI message, the NAR sends a ***Handover Acknowledge*** (HA) message confirming that he received the HI message.

After receiving the ***Handover Acknowledge*** message, the PAR sends a ***Fast Binding Acknowledge*** (FBA) message to the MN and to the NAR warning them that he is already forwarding the MN packets to the NAR.

The MN receives an FBA on the previous link. This means that packet tunnelling is already in progress by the time the MN handovers to NAR. The MN send a ***Fast Neighbour Advertisement*** (FNA) immediately after attaching to the NAR, so that arriving and buffered packets can be forwarded to the MN right away (Figure 22).

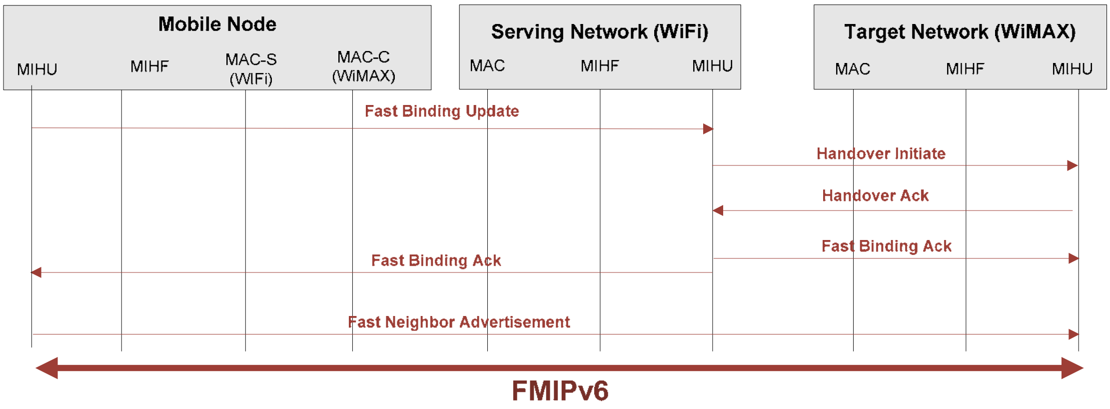

Figure 22 - Handover Execution (FMIPv6)

3.1.5 Handover Completion

The Mobile Node sends the ***MIH_MN_HO_Complete Request*** to the Serving PoS on the 802.16 network and that Serving PoS exchanges the ***MIH_N2N_HO_Complete*** messages with the previous PoS on the 802.11 network to release the resources that were reserved for the Mobile Node on that network (Figure 23).

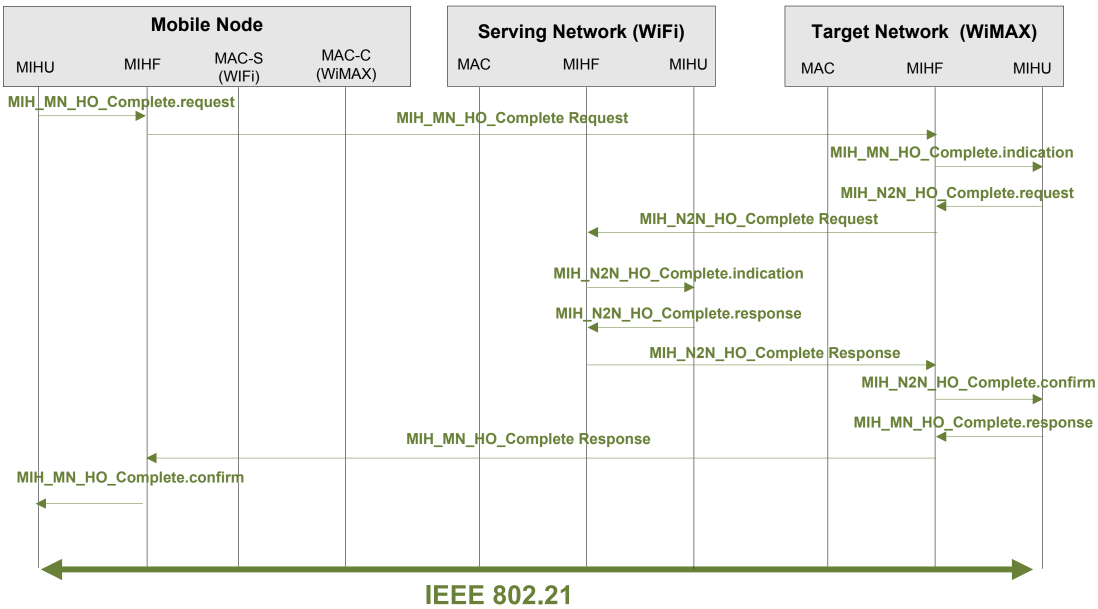

Figure 23 – Handover Completion (.21)

3.2 Summary

The main differences from this procedure to the procedure defined in the proposal IEEE802.21 are related with the ***MIH_MN_Commit*** messages. The proposal does not define these messages for the MN; they are only defined for the handovers started by the

Network (***MIH_NET_Commit***). With this type of messages the MN can command the serving network to commit the resources, queried before, on the target network (chosen by the MN). This topic had been discussed on the working group of the IEEE802.21 and has been decided to include these messages on the overcoming versions of the proposal.

Chapter 4 – Implementation

Telecommunications area is an ever growing area, due to today's needs and demands, and the evolvement of new technologies. In this sense, it takes time to get the technologies ready for experimentation. This is the case of IEEE 802.16e: although there are already some equipments available to experiment, at the start time of the Thesis, these equipments were not available yet. In this sense, we decided to perform all the extensions and integrations of IEEE 802.16 and IEEE 802.21 in the ns-2 simulator to evaluate its performance.

In this chapter, it will be described the simulator used for performing the handovers in heterogeneous networks, the reasoning for using it, and the functionalities missing according to IEEE802.21 proposal. Furthermore, it will be described the implementation performed in the simulator, to integrate 802.16 and 802.21 messages and functionalities, and for completing the missing functions (or part of it). At the end, it will be presented a summary of this chapter.

This chapter is split into 4 sections. Section 4.1 contains an overview of the simulator used for obtaining practical results. Section 4.2 describes the functionalities of the simulator in terms of mobility aspects, and section 4.3 describes the functions and messages added to the simulator to support the procedure described in the Chapter 3 – Section 4.4 concludes the implementation.

4.1 Network Simulator

For simulating heterogeneous handovers using the IEEE802.21 proposal, we have chosen the simulator "Network Simulator" (NS-2), since it already contained some messages that could be used to start the integration process.

The NS or the network simulator (also popularly called ns-2, in reference to its current generation) is a discrete event simulator targeted at networking research. NS provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks.

NS began as a variant of the REAL network simulator in 1989 and have been evolved substantially over the past few years. In 1995 NS development was supported by Defense Advanced Research Projects Agency (DARPA) through the VINT project at Lawrence Berkeley Laboratory (LBL), Xerox Palo Alto Research Center, Inc. (PARC), University of California in Berkeley (UCB), and the Information Sciences Institute (ISI) of the University of Southern California (USC). Currently NS development is supported through DARPA with SAMAN and through National Science Foundation (NSF) with CONSER, both in collaboration with other researchers including ACIRI. NS has always included substantial contributions from other researchers, including wireless code from the UCB Daedelus and CMU Monarch projects and Sun Microsystem [ns].

NS, the free open-source network simulator, is the de-facto standard for research over a wide variety of networking areas. NS version 2 is widely used across both academia and industry as a way of designing, testing and evaluating new and existing protocols and architectures, and has also proven a very useful tool for teaching purposes. NS version 3 is under active development.

4.1.1 NS-2 add-ons

The National Institute of Standards and Technology (NIST) is one of the groups that already performed large contributions to IEEE 802.16 and ns-2 [nist802.16]: this organization had released 2 important add-ons into NS-2, one that can simulate WiMAX networks, such as fixed (IEEE802.16d) and mobile (IEEE802.16e), and another one released recently for allowing the simulation of heterogeneous handovers. Those add-ons and their documentation could be achieved on the following website: http://w3.antd.nist.gov/seamlessandsecure.shtml#software_tools .

For practical purposes, when referring to this last add-on, we will refer it as the "Mobility add-on".

4.1.1.1 Mobility add-on

The modified version of NS-2.29 contains an implementation of MIHF based on the draft 3 of IEEE802.21 specifications. It is a platform to evaluate the performances and find problems that could arise due to the definition of the primitives. It also serves to evaluate different handover decision engines.

4.1.1.1.1 Design overview

Figure 24 represents a high level view of the MIHF interaction with the different components of the node. The MIHF is implemented as an Agent and therefore can send layer 3 packets to remote MIHF. The MIHF contains the list of local interfaces to get their status and control their behaviour. The MIH User is also implemented as an Agent and registers with the MIHF to receive events from local and remote interfaces.

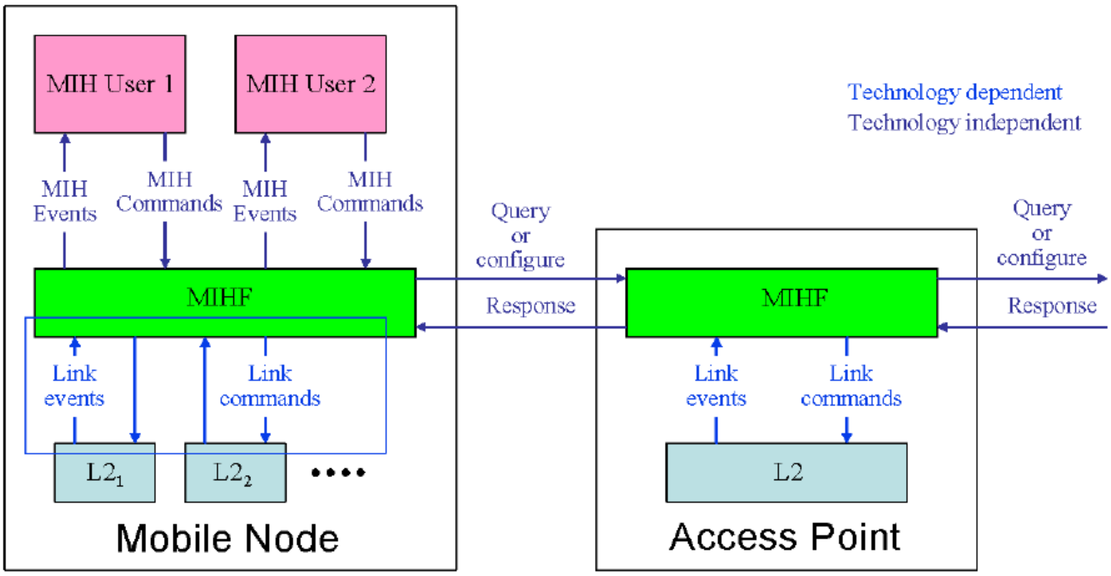

Figure 24 - MIH design overview [nist802.21]

The cross layer information exchange has been added to the NS-2 by modifying the MAC layer and linking the MAC layers via the script written in Tool Command Language TCL.

4.1.1.1.2 MIH Function

As mentioned earlier, the MIHF extends the class Agent defined in NS-2. This allows each instance to send and receive packets at layer 3. The files related to the MIH implementation are located in the *hsntg* subdirectory of the NIST distribution [nist802.21].

The MIHAgent is at the centre of the implementation. It communicates with both the lower layers (i.e. MAC) and the higher layers (i.e. MIH Users).

The MIHF class handles the list of MIH Users and their registration information. It also takes care of handling the communication with remotes MIHFs. Finally, it provides media dependent interface (MIH_LINK_SAP and media specific primitives).

Figure 25 represents a Unified Modelling Language (UML) of the MIHF implementation. As can be seen here, there are 6 functions that provide information to the MIHF. We have the *MIHInterfaceInfo* function responsible for the interfaces, the *MIHUserAgent* function that takes care of the MIHUsers, the *MIHScan* function.handles that scans requests, the *mihf_info* that contains the list of MIHF peers that have been discovered, the *session_info* that contains the current session that is being used for communicating with MIHF peer, and the *mih_pending_req* that contains the list of requests that are still waiting for a response.

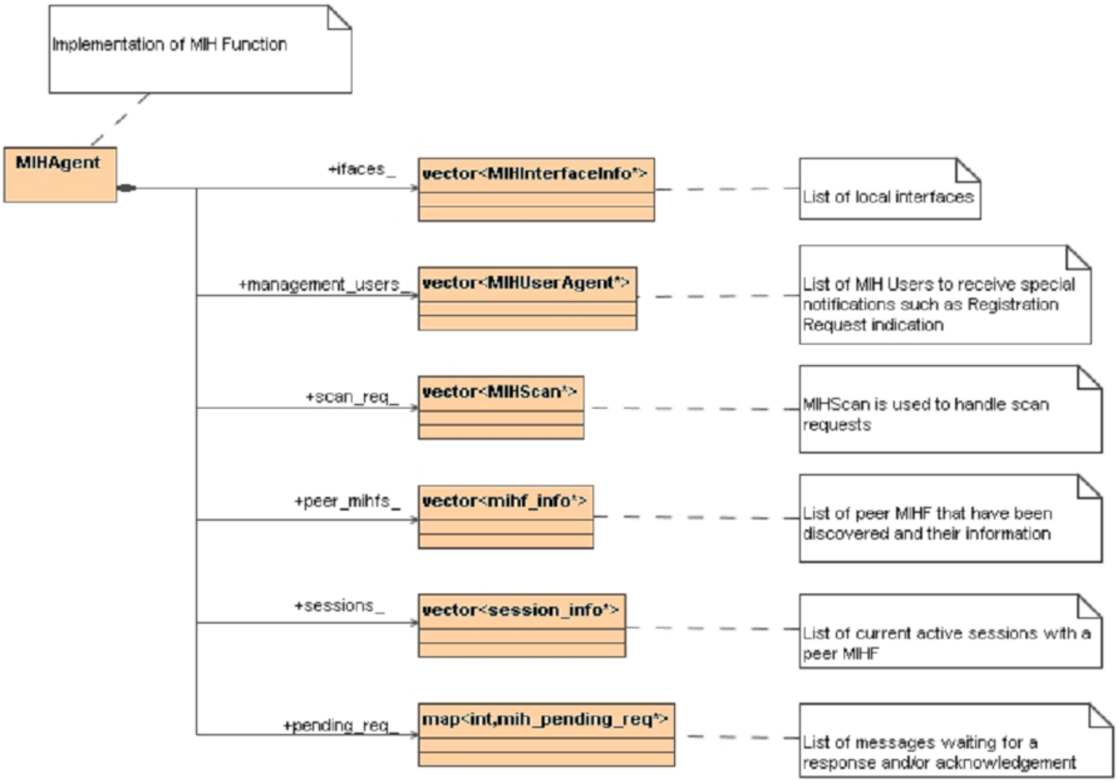

Figure 25 – MIHF design [nist802.21]

4.1.1.1.3 MIH User

MIH Users are entities that make use of the MIHF functionalities in order to enhance user performances by optimization handovers. Since there are an infinite number of implementations depending on the user preference or network policies, the implementation provides an abstract class MIH User that can be easily extended.

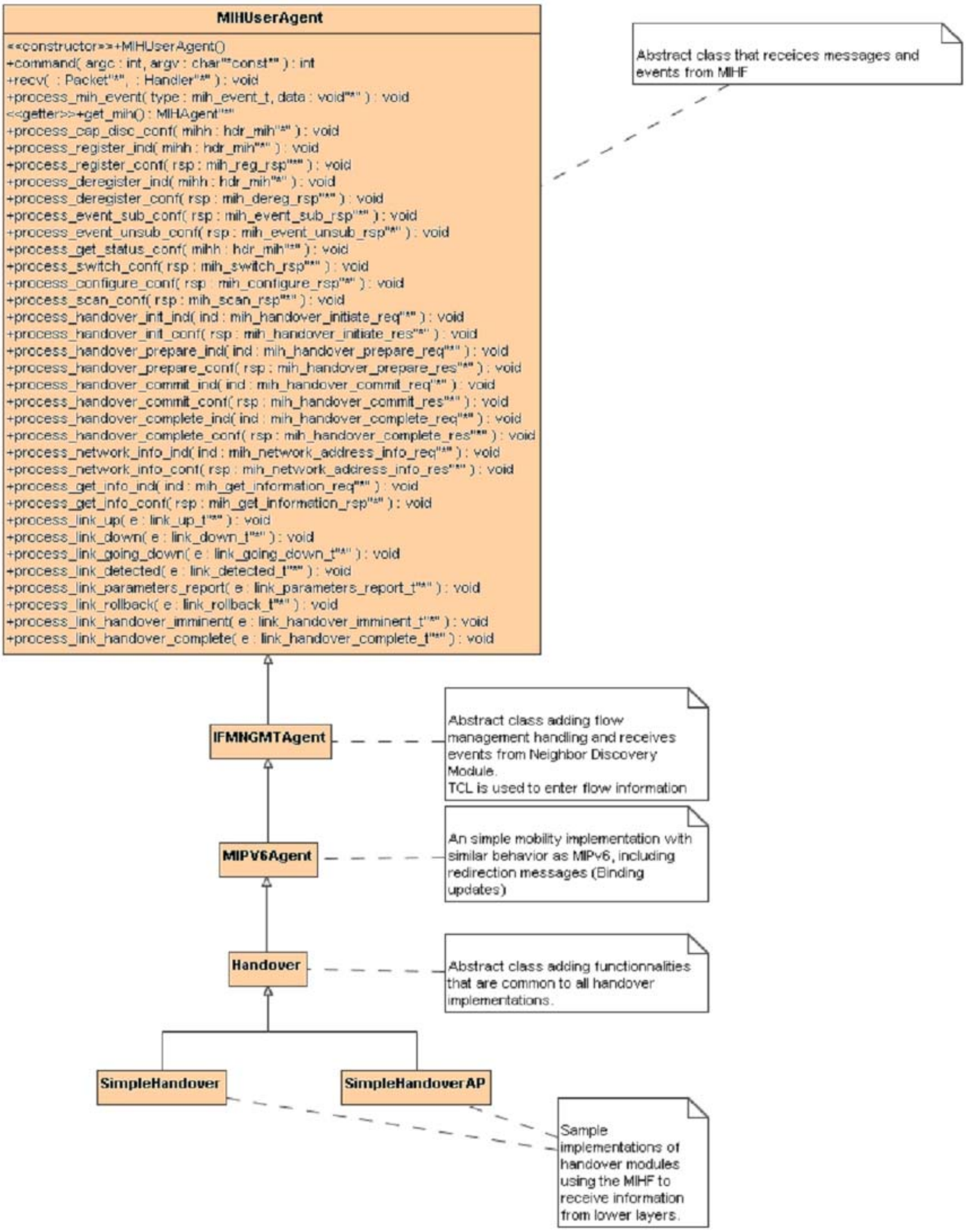

Figure 26 - MIH User class hierarchy [nist802.21]

As shown in Figure 26, the MIH User sends commands to and receives events/messages from the MIHF. To enhance usability, the implementation also provides a series of abstract classes that contain commonly used functionality.

The *IFMNGMT* Agent, as seen in Figure 26, provides flow management functions. Using the TCL, the user can register the flows that are being used in the node. This facilitates the handover module in finding the flows that need to be redirected. It also receives events from the node (*ND)* agent when a new prefix is detected or when it expires. The *MIPv6Agent* adds the redirection capability to the MIH User. When a flow needs to be redirected, a message can be sent to the source node to inform it of the new address or interface to use. Finally, the *Handover* class provides a template for handover modules and computes a new address after successful handover.

4.2 Analysis of the Simulator

The NS-2, with the mobility add-on, does not support all the functionalities defined in the IEEE802.21 proposal. Moreover, the mobility add-on was done based on a older version of the proposal (draft 3). For simulating heterogeneous handovers based on the procedure purposed in Chapter 3, some changes and extensions need to be performed into the simulator.

To have a clear idea of the extensions required in the simulator, a deep analysis (into the language code) of the simulator was performed, with special emphasis on the mobility add-on. In this section we present the supported/missed functions of the simulator for handling heterogeneous handovers, in particularly the MIHF functions.

4.2.1 Supported/Missed functions

Table 3 contains the meaning of each symbol used in following tables, addressing the status of implementation of each function/message.

√	Implemented
X	Not Implemented

Table 3 -Legend

We will show the functionalities provided on the simulator and the missing ones, according to the draft 8 of the proposal, for simulating handovers between WiFi and WiMax networks as a first stage.

4.2.1.1 Service management primitives

Table 4 presents the several service management primitives and its implementation status. The simulator already supports all the primitives of this type.

	Service Management Primitive	Comments
√	MIH_Capability_Discover	Discover the capabilities of a local or peer MIHF.
√	MIH_Register	Register with a peer MIHF.
√	MIH_DeRegister	Deregister from a peer MIHF.
√	MIH_Event_Subscribe	Subscribe for one or more MIH events with a local or remote MIHF.
√	MIH_Event_Unsubscribe	Unsubscribe for one or more MIH events from a local or remote MIHF.

Table 4 –Simulator: Service management primitives

4.2.1.2 MIH/Link events

The MIH events are grouped with Link events, because every link event has an MIH event as a match so they can be group together. It can be seen on Table 5 that the simulator does not support the transmission of PDU status. However, this type of event is not crucial on handovers.

	Event Name	Event Type	(L)ocal (R)emote	Description
√	Link_Up	State Change	L,R	L2 connection is established and link is available for use
√	Link_Down	State Change	L,R	L2 connection is broken and link is not available for use
√	Lin_Going_Down	Predictive	L,R	Link conditions are degrading and connection loss is imminent
√	Link_Detected	State Change	L,R	New link has been detected
√	Link_Param_Report	Link Parameters	L,R	Link parameters have crossed a specified threshold and need to be reported
√	Link_Event_Rollback	State Change	L,R	Previous link event needs to be rolled back
X	Link_PDU_Transmit_Status	Link Transmissions	L	Indicates transmission status of a PDU

√	Link_Handover_Imminent	Link Synchronous	L,R	L2 Handover is imminent based on either the changes in the link conditions or available information in the network.
√	Link_Handover_Complete	Link Synchronous	L,R	L2 link handover to a new PoA has been completed

Table 5 - Simulator: MIH/Link Event

4.2.1.3 MIH commands

Concerning the MIH commands, most of them are not supported, as can be seen on Table 6. Note that older versions of the 802.21 proposal had different names for the MIH commands, and some of them did not even exist before.

The simulator does not have the MIH SCAN command: this command is not defined in the new proposal, but a new one is defined, the MIH_Link_Actions, that incorporates the previous one and was the possibility to turn on or down the interfaces.

	MIH commands	(L) ocal, (R) emote	Comments
√	MIH_Get_Link_Parameters	L,R	Get the status of a link.
√	MIH_Link_Configure_Thresholds	L,R	Configure link parameter thresholds
X	MIH_Link_Actions	L,R	Control the behaviour of a set of links
X	MIH_Net_HO_Candidate_Query	R	Network may initiate handover and send a list of suggested networks and associated Points of Attachment.
X	MIH_MN_HO_Candidate_Query	R	Command used by MN to query and obtain handover related information about possible candidate networks.
X	MIH_N2N_HO_Query_ _Resources	R	This command is sent by the serving MIHF entity to the target MIHF entity to allow for resource query, context transfer (if applicable), and handover preparation.
X	MIH_Net_HO_Commit	R	In this case the network commits to do the handover and sends the choice of selected network and associated PoA.
X	MIH_MN_HO_Commit	L	Command used by MN to notify the network that a candidate has been committed for handover.

X	MIH_N2N_HO_Commit	R	Command used by a serving network to inform a target network that a mobile node is about to move toward that network.
X	MIH_MN_HO_Complete	R	Notification from MIHF of the MN to the target or source MIHF indicating the status of handover completion.
X	MIH_N2N_HO_Complete	R	Notification from MIHF of the MN to the target or source MIHF indicating the status of handover completion.

Table 6 - Simulator: MIH commands

4.2.1.4 Link commands

Concerning the link commands (Table 7), the current implementation misses the Link Action command. This command is very important because it is the one that allows MIHF to command the interfaces, and therefore, it needs to be implemented.

	Link Command	Comments
X	Link_Capability_Discover	Query and discovery list of supported link layer events and link layer commands
√	Link_Event_Subscribe	Subscribe to one or more events from a link
√	Link_Event_Subscribe	Unsubscribe from a set of link layer events
√	Link_Configure_Treshold	Configure threshold for Link Parameters Report event
√	Link_Get_Parameters	Get parameters measured by the active link (SNR…)
X	Link_Action	Request actions on a link layer connection

Table 7 - Simulator: Link commands

4.2.1.5 MIH information

Concerning the MIH Information, the simulator does not support the MIIS primitives as shown in Table 8, since the entity MIIS is not implemented. This can be due to lack of definition on draft 3 [ieeeP802.21/D3.0].

	MIH Information	Comments
X	MIH Get Information	Get information from the database

Table 8 -Simulator: MIH information

4.3 New Functions

The following table enumerates the commands added and implemented for executing the procedure for handovers as proposed before in Chapter 3. The FMIPv6 has not been added to the simulator, since the *mobility add-on* does not support MIPv6.

The MIIS entity has not been added also, since the MN can acquire the network topology from the Mobility Neighbour Advertisement (MNA) message used in WiMAX networks for warning the MN of new surrounding BSs.

	MIH Command
√	MIH_MN_HO_Candidate_Query
√	MIH_MN_HO_Commit
√	MIH_MN_HO_Complete
√	MIH_N2N_HO_Query_Resources
√	MIH_N2N_HO_Commit
√	MIH_N2N_HO_Complete

Table 9 – MIH Commands added

	Protocol
X	FMIPv6

Table 10 – FMIPv6

	Entity
X	Media Independent Information Service (MIIS)

Table 11 - Media Independent Information Service (MIIS)

The simulator does not have an implementation of the MIH Users on the network, as could be confirmed through Figure 24. Therefore, the MIH Users on the Mobile Node cannot interact with MIH Users of the network (since they do not exist). In this sense, the MIH Users on the Network need to be implemented on the simulator.

In the following sections, we will explain the implementation performed into the NS-2, starting by referring the implementations in each element, and then the functions added or modified.

4.3.1 MIHF

The MIHF is implemented in the file *mih.cc* and *mih.h* (header file), where the class denoted as *MIHAgent* is placed. The following functions were added to this class in *mih.cc* file.

The main functions added are required for sending/receiving the following (remote) messages:

- MIH_MN_HO_Candidate_Query request
- MIH_MN_HO_Candidate_Query response
- MIH_N2N_HO_Query_Resources request
- MIH_N2N_HO_Query_Resources response
- MIH_MN_HO_Commit request
- MIH_MN_HO_Commit response
- MIH_N2N_HO_Commit request
- MIH_N2N_HO_Commit response
- MIH_MN_HO_Complete request
- MIH_MN_HO_Complete response
- MIH_N2N_HO_Complete request
- MIH_N2N_HO_Complete response

These messages are used to proceed with a handover. The first four messages are used with the purpose of knowing which resources are available on each candidate network. The four at the middle are used for reserving the resources needed by the MN at the target network. The last ones are used for releasing the resources reserved on the serving network for the MN.

4.3.2 MIH User

4.3.2.1 Mobile Node

In order to build a new MIHU for the MN compatible with the original implementation and with support of the enhanced functionalities, it was been created a new MIHU for the

MN taking as a base the existing one (implemented in the file *handover-1.cc*; this new MIHU is implemented in the file *Handover_MN.cc*).

The main functions added are enumerated as follows:

- process_mn_ho_candidate_query_req
- process_mn_ho_candidate_query_conf
- process_mn_ho_commit_conf
- process_mn_ho_complete_conf

The first function is used to initiate the handover, and the last 3 are used to process the response messages (i.e. MIH_MN_HO_Candidate_Query response) sent by the serving network in order to a request message sent previously (i.e. MIH_MN_HO_Candidate_Query request) by the MN.

4.3.2.2 Network

In the network, the same process was performed, similar to the one of the MN side.(the base file was the *HandoversimpleAp.cc* and the new one was the *Handover_PoA.cc*).

The main functions added are enumerated as follow:

- process_mn_ho_candidate_query_ind
- process_n2n_ho_query_resources_ind
- process_n2n_ho_query_resources_conf
- process_mn_ho_commit_ind
- process_mn_ho_commit_conf
- process_mn_complete_ind
- process_n2n_complete_conf

These functions are used by the network to process the request messages previously sent by the MN (i.e. MIH_MN_HO_Candidate_Query request).

4.3.3 MAC Layer

In the MAC layer, several functions were added to each different type of interface to obtain the current data rate (the bandwidth). The MAC layer of the WiMAX was modified to avoid that the Mobile Station associates with the Base Station after a Ranging Response without getting the order from the MIHU through a Link Action Request.

4.3.4 MIH_Link_Going_Down.indication

After receiving the MIH Event, from the MIHF, the MIH User verifies its type: if the type is *MIH Link Going Down*, the MIH User knows that the conditions of this link are getting worst (e.g. due to getting out of coverage). Then, the MIH User needs to check if the MN is using this link or another one. If the MN is using it, it knows that it should initiate the handover procedure soon, because this link will go down in the near future. If it is not using this link, there is no problem, since this link is not being used to establish communication with the network (Figure 27).

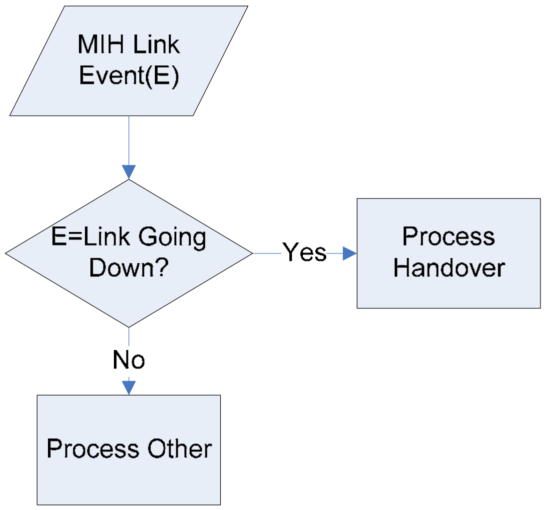

Figure 27 - MIH_Link_Going_Down.indication

After knowing that it should initiate the handover procedure, the MIH User verifies if the Mobile Node has more then one interface that can be used. If so, then it verifies the status of each link on the respective interface. It does this with the purpose of knowing if it has at least one Link Up available that can be used for the handover, since the current one is going down. If it has only one interface or the others are all down, it requests the MIHF to perform a link scan on each interface including the one that sends this event (Link Going Down) (Figure 28).

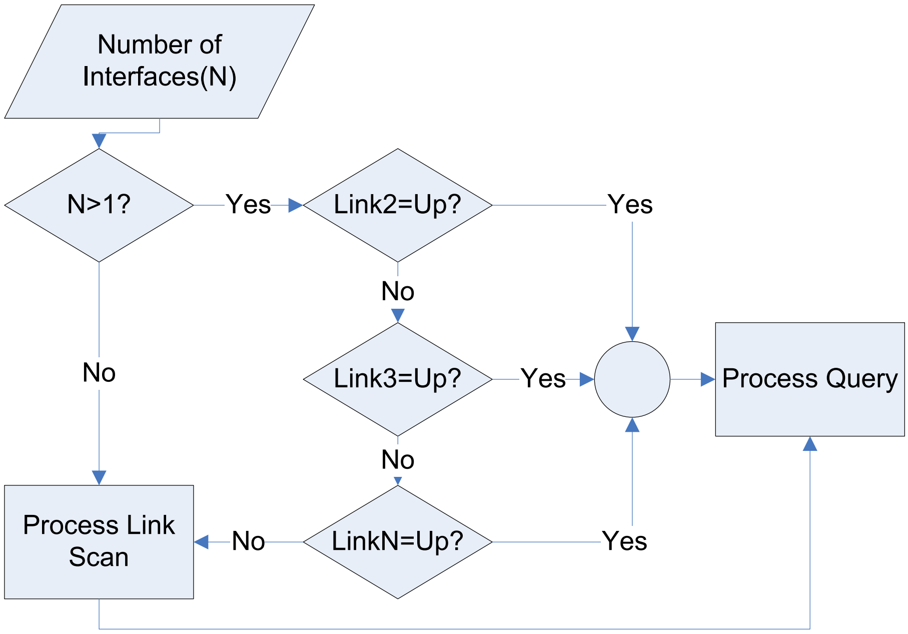

Figure 28 - MIH_Link_Going_Down.indication (cont.)

After performing a scan or having one link up available, the MIH User fills up the list of the candidates with the information gathered before (if at least one Link Up was available) or scanned meanwhile (if only one interface was available).

The MIH User verifies which resources are needed (due to limitations of the simulator, it only verifies the needed bandwidth) for each class of service (flow), according to the flows that are being used at the moment. After having the information about the resources that should be queried and the list of possible (network) candidates for handover, it sends a *MIH_MN_HO_Candidate_Query Request* message to its serving network, with the purpose of knowing which candidate network has the queried (better) resources available (Figure 29).

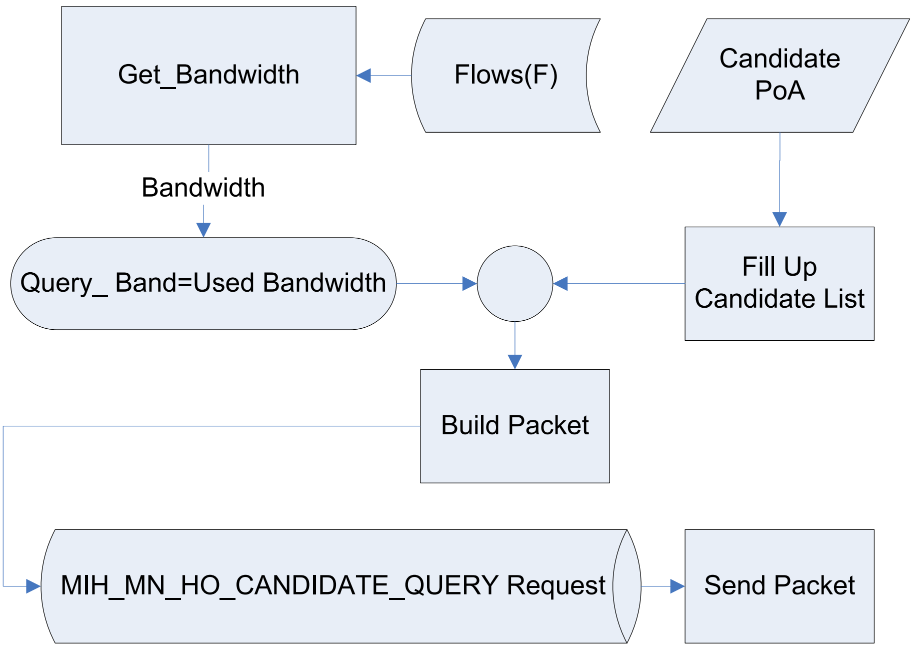

Figure 29 - MIH_Link_Going_Down.indication (cont.)

4.3.5 MIH_MN_HO_Candidate_Query Request

After receiving a *MIH_MN_HO_Candidate_Query Request* message from the MIHF in the MN, the MIHU in the serving Network checks if the MN has already sent a query request. If so, it ignores this request because it is still waiting for a response; if not, it sends a *MIH_N2N_HO_Query_Resources Request* message to each candidate network that is in the list provided by the MN through the *MIH_MN_HO_Candidate_Query Request* message, with the purpose of querying the resources specified by the MN (Figure 30).

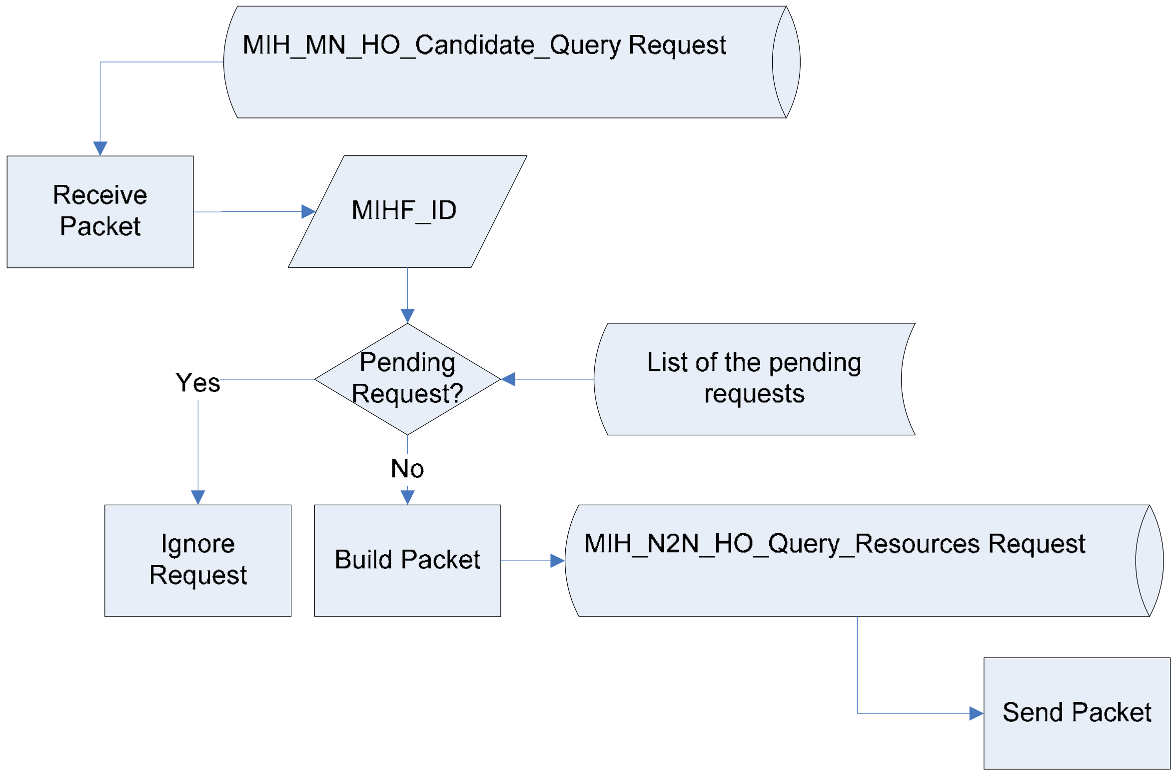

Figure 30 - MIH_MN_HO_Candidate_Query Request

4.3.6 MIH_N2N_HO_Query_Resources Request

After receiving a *MIH_N2N_HO_Query_Resources Request* message from the serving network of the MN, each candidate fills up the *Available Resource Set* list, according to its Available Resources for each Class of Service (CoS) specified by the MN. Each candidate also verifies if its available resources for each CoS are larger than the resources queried by the MN. If so, then they put the flag *LinkResourceStatus* at True; if not, this flag is False. After that, they reply to the serving network with a *MIH_N2N_HO_Query_Resources Response* message, where the *Available Resource Set* goes inside the packet (Figure 31).

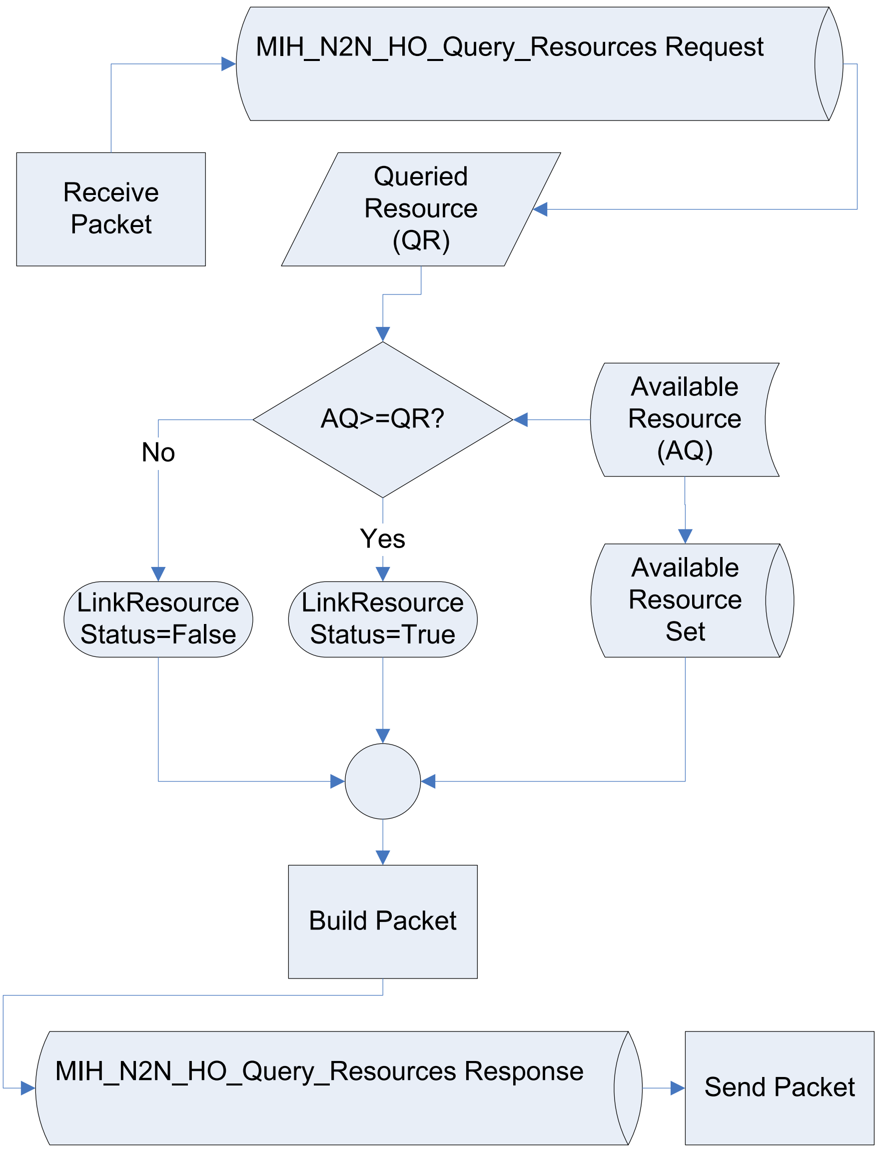

Figure 31 - MIH_N2N_HO_Query_Resources Request

4.3.7 MIH_N2N_HO_Query_Resources Response

Every response message, from the serving network or candidate, has a field called *Status* which indicates the status of the given response. If the status is different from *Success*, it means that it should be processed an error handling for that response and the rest of the fields in the message should be ignored. Due to time constraints, this *Error Handling* is not implemented yet. Therefore, the program will only check if the status is success; if so, it continues with the normal process (Figure 32).

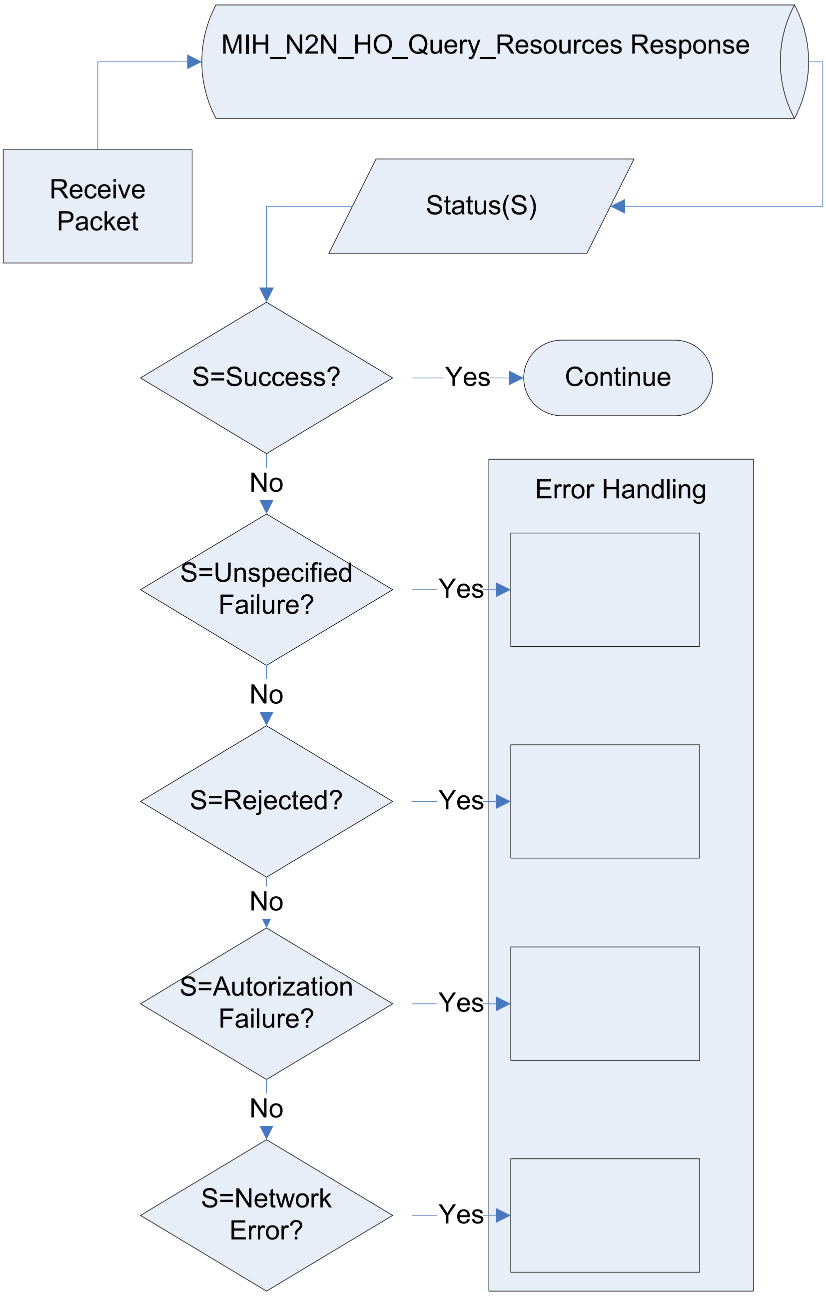

Figure 32 - MIH_N2N_HO_Query_Resources Response

The Serving network receives *MIH_N2N_HO_Query_Resources* response messages from all candidates (or part of them) and it verifies the status of the responses: if the status is equal to Success, it accepts the response message; if not, it ignores it.

After verifying this field, the serving network checks which candidate network has the higher resources available and orders the list by these criteria, the candidate with the best resources in the first place and so on (Figure 33).

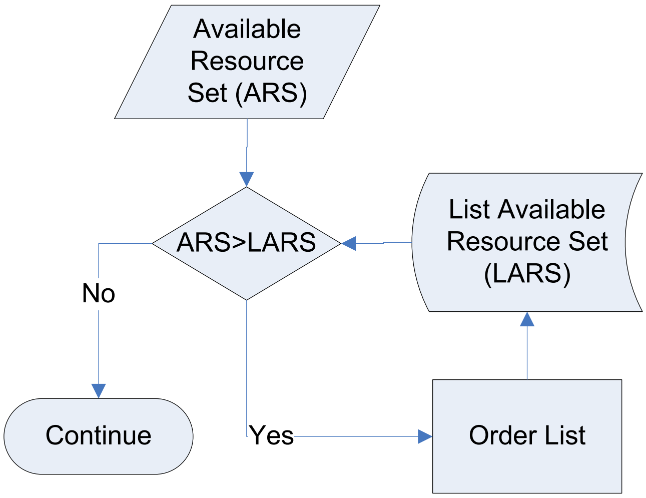

Figure 33 - MIH_N2N_HO_Query_Resources Response (cont.)

After ordering the list, it verifies if the number of responses given is equal to the number of requests sent: if it is equal, it sends a *MIH_MN_HO_Query_Resources Response* message to the MN, with the list ordered (Figure 34). If not, it waits a defined timeout for the rest of the responses. This timeout should not be very high, because it can increase the time of processing a handover, and should not be very small, because some responses could be ignored (Figure 35).

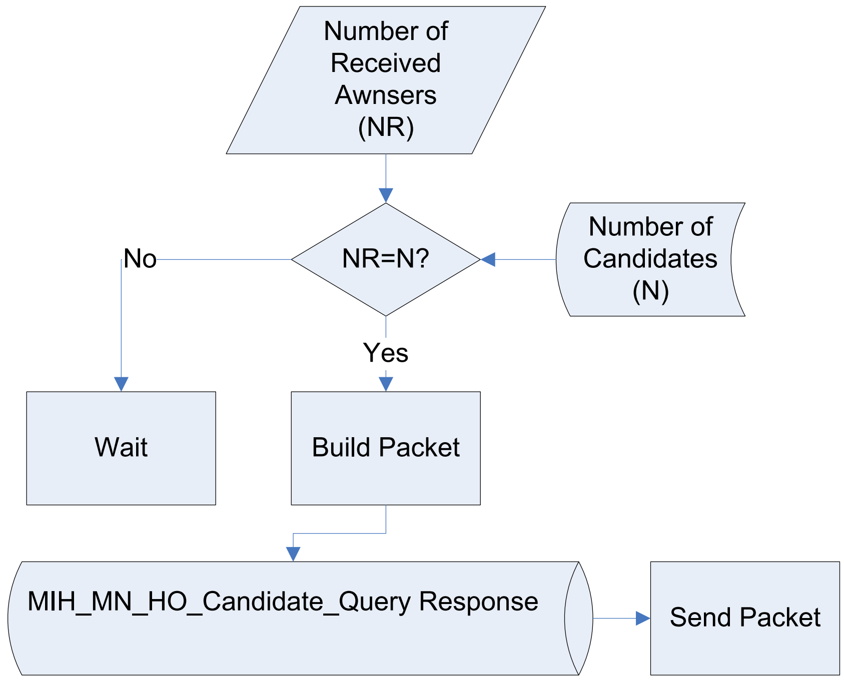

Figure 34 - MIH_N2N_HO_Query_Resources Response (cont.)

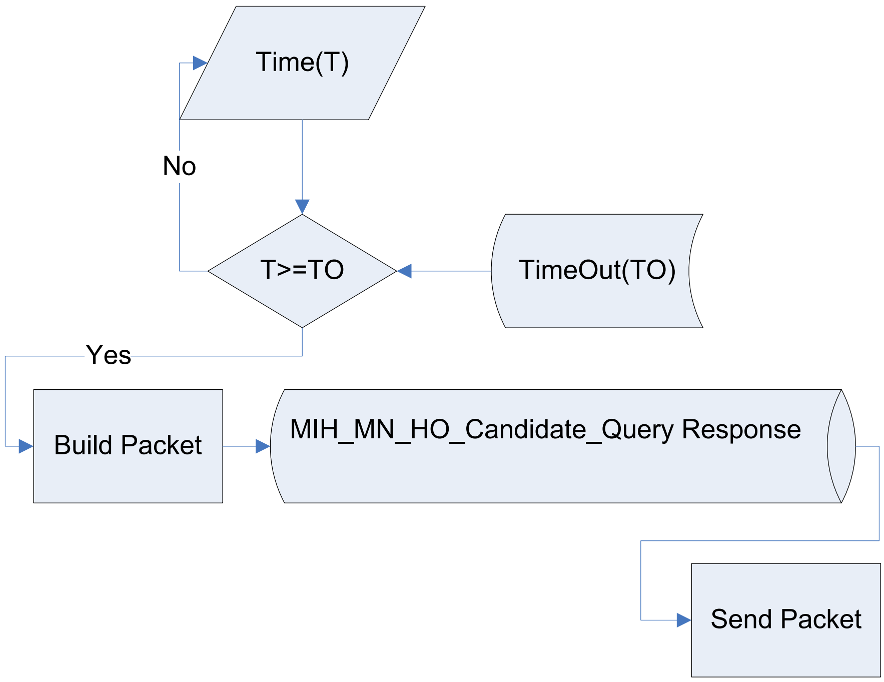

Figure 35 - MIH_N2N_HO_Query_Resources Response (cont.)

4.3.8 MIH_MN_HO_Candidate_Query Response

After receiving a *MIH_MN_HO_Candidate_Query Response* message from it previous request, the MN verifies which candidate has the larger resources available attending to the different CoS, and sends a *MIH_MN_HO_Commit Request* message to its serving PoS, with the purpose of requesting the reservation of resources in the chosen candidate (target network), by the available resource set.

4.3.9 MIH_MN_HO_Commit Request

The serving network then forwards the *MIH_MN_HO_Commit Request* message as a *MIH_N2N_HO_Commit Request* message to the target network.

4.3.10 MIH_N2N_HO_Commit Request

The target network reserves the resources and then replies to the serving network with a *MIH_N2N_HO_Commit Response*, referring the status (result) of the operation (reservation) done (Figure 36).

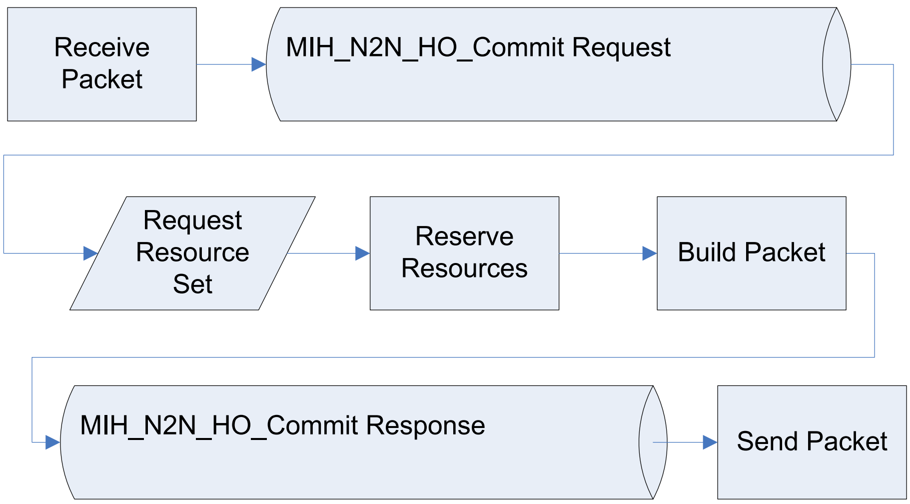

Figure 36 - MIH_N2N_HO_Commit Request

4.3.11 MIH_N2N_HO_Commit Response

The serving network forwards this message to the MN, with the result of the request, with a *MIH_MN_HO_Commit Response.*

4.3.12 MIH_MN_HO_Complete Request

When the MN receives the *MIH_MN_HO_Commit Response* message to its request for committing resources, it checks if the status of the operation was "Success". If the result is successful, it switches interface for connecting to the network, changing from the current interface to the target interface. After performing this operation, it sends a

MIH_MN_Complete Request message to the target network through the new interface (Figure 37).

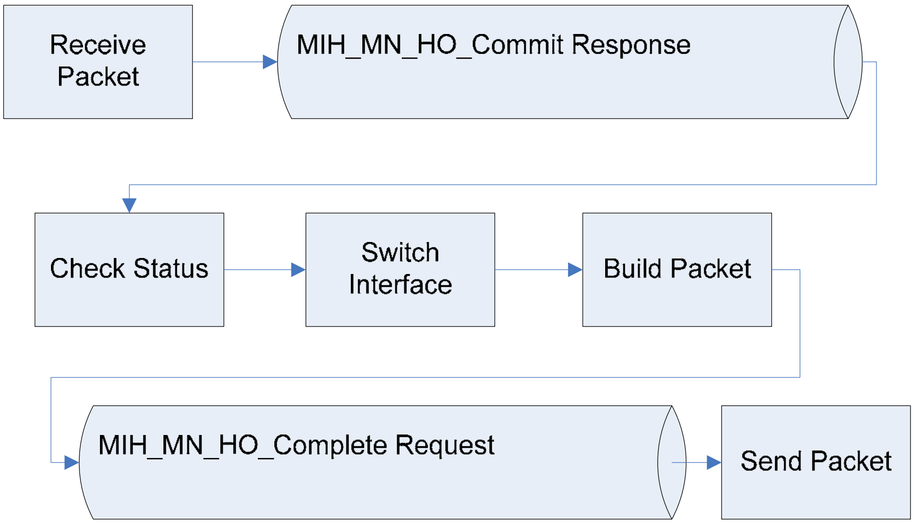

Figure 37 - MIH_MN_HO_Complete Request

4.3.13 MIH_N2N_HO_Complete Request

The new serving network receives the *MIH_MN_HO_Complete Request* message from the MN and sends a *MIH_N2N_HO_Complete Request* message to the old serving network of the MN, since the MN is now using this new network (it is its serving network).

4.3.14 MIH_N2N_HO_Complete Response

The old serving network of the MN receives the packet from the new serving one, frees the previous allocated resources, and replies to the new serving network with the status of the operation performed. Note that some technologies (i.e. WiFi) do not allocate resources, and therefore they do not need to perform this operation.

4.3.15 MIH_MN_HO_Complete Response

The new serving network receives the response from the old serving network and replies to the MN with the status of the operation done in the old serving network. The MN receives the response message from the new serving network, checks if the status of the previous operation was “Success”, and if so, this procedure ends: the MN is now communicating with the CN through the new network.

4.4 Summary

This chapter presented the network simulator (NS) used and the *mobility add-on* functionalities already available to perform the integration of 802.21 with 802.16 and

802.11. It also described the functionalities that were not present in this mobility package, according to the standard (draft 8). Finally, it included and described the several functions and messages that were added to perform the complete handover process.

Chapter 5 – Results

To test the proposed procedure for heterogeneous handovers, described in Chapter 3 – we consider two different scenarios, with inter-technology (vertical) handovers from WiFi to WiMAX and intra-technology handovers from WiMAX to WiMAX (horizontal) handovers.

This chapter will present and describe the considered scenarios, the measured parameters and the obtained results. Each scenario has been simulated with the NS-2 with the new changes carried on the mobility package for supporting the proposed procedure. At the end of each scenario, a short conclusion on the obtained results is presented.

This chapter is organized in 4 sections. The section 5.1 describes each measured parameter on the different scenarios. The section 5.2 presents the simulated scenario for intra-technology handovers and its obtained results. In section 5.3 we evaluate the scenario for inter-technology handovers. Finally, section 5.4 contains the main conclusions.

5.1 Measured Parameters

The measured parameters in each simulation comprise the latency of the handovers, the delay of the packets, the jitter and the packets lost.

The latency of the handover is the time interval between the redirect message sent to the correspondent node until the first packet is received on the target interface. According to the recommendation of the International Telecommunication Union's (ITU-T's G.114), for VoIP calls, the delay between packets should not be higher then 150 msec in each direction, which means that the latency of the handover must be less then this value.

The delay is the time interval between the instant the correspondent node sends a packet for the mobile and the instant when the mobile node receives it. The jitter is the variance of the packet delay.

All the simulations were run between 10 times. The values included in the following graphics contain the mean of these runs.

5.2 . Intra-Technology Handover

Figure 47 represents the simulated scenario for intra-technology handovers. As can be seen, there are 3 different networks, 2 are WiMAX and another one is an Ethernet

Network. They are all connected through the GateWay (GW). The users (U1-U3) in the WiMAX networks are exchanging data with the users (CN1-CN5) in the Ethernet Network. The WiMAX network 1 contains a mobile user (Mobile Node) that is, in the beginning, in its serving network (network 1). The MN and other nodes in the WiMAX networks 1 and 2 are receiving a video stream, with a rate of 512Kbps, from their correspondent nodes (CN) on the Ethernet network.

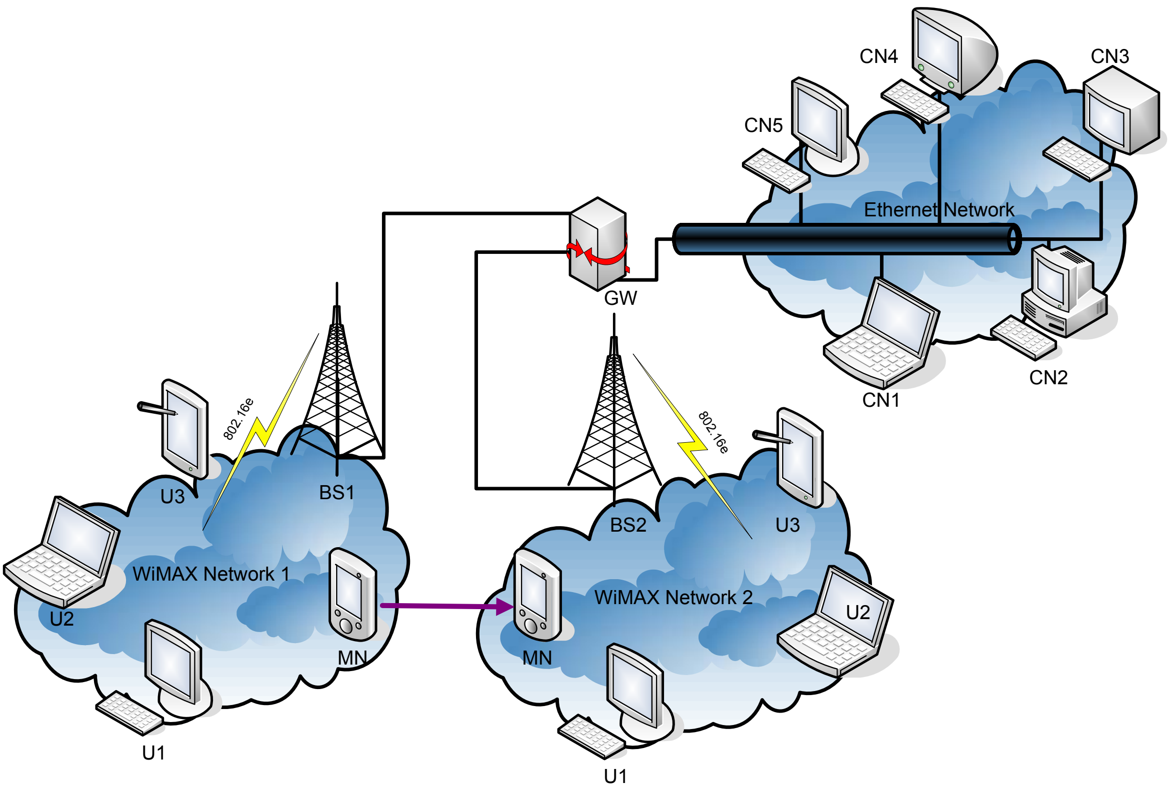

Figure 38 - Scenario with Intra-Tech Handover

At certain instant in time, the MN decides to move towards the WiMAX network 2. When the conditions on the WiMAX link from the Base Station 1 (BS1) are getting worse, since the MN is getting out of coverage from BS1, the MIH User receives a Link Going Down and decides to initiate the handover procedure; after concluding the procedure, the MN will be connected with BS2 and exchanging data packets with its correspondent node (CN) in the Ethernet Network.

The simulation time in each run is 100 seconds. The MN starts moving after 10 seconds. The handover occurs once and it happens at around 40 seconds. The MN is moving at 1 meter per second. We have a 16QAM3/4 modulation on the WiMAX network. The data packets have a size of 1500 Bytes. Each WiMAX network contains the same number of users, where 10 users correspond to 10*512Kbps, and the MN also has a data flow of 512Kbps.

5.2.1 Obtained Results

In Figure 39 we have presented the average delay on the WiMAX link of the MN for its data packets before the handover. As can be seen, this delay increases with the number of (static) users, where more users in the network means more traffic, which implies larger delays. This graphic contains 2 curves: one in red that represents the delay obtained with the previous mobility package (NIST model), and on in blue that represents the delay with the new enhanced mobility proposal (with integrated 802.21). The packet delays are similar, since our modifications do not affect the normal packets delay.

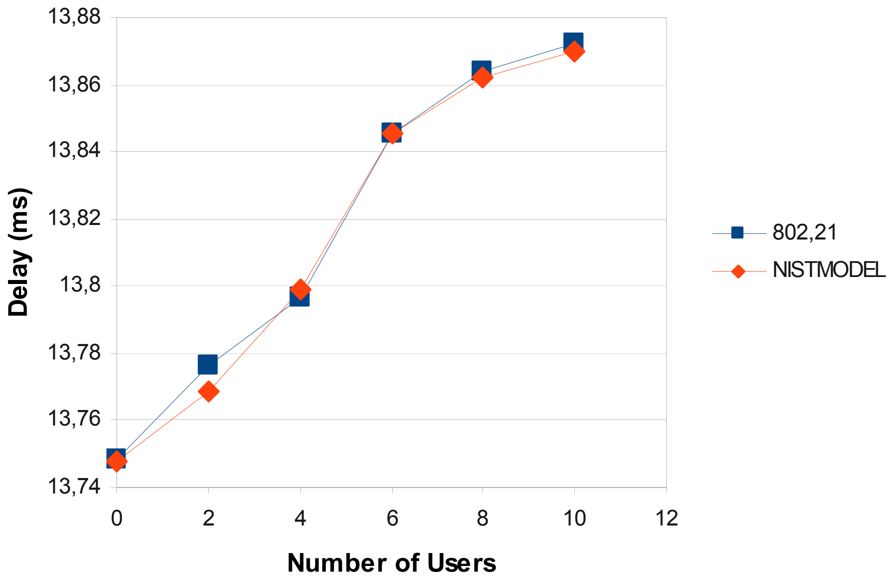

Figure 39 – Intra-Tech: Delay before Handover versus Number of Users (512Kbps)

Figure 40 represents the data packets delay during the handover. We can see here that the 802.21 model causes more delay on the data packets during the handover. In our proposal, data packets are buffered on the serving network, when the MN is switching from its serving network, causing a large delay. The NIST model does not perform this action and packets are lost instead of being delayed.

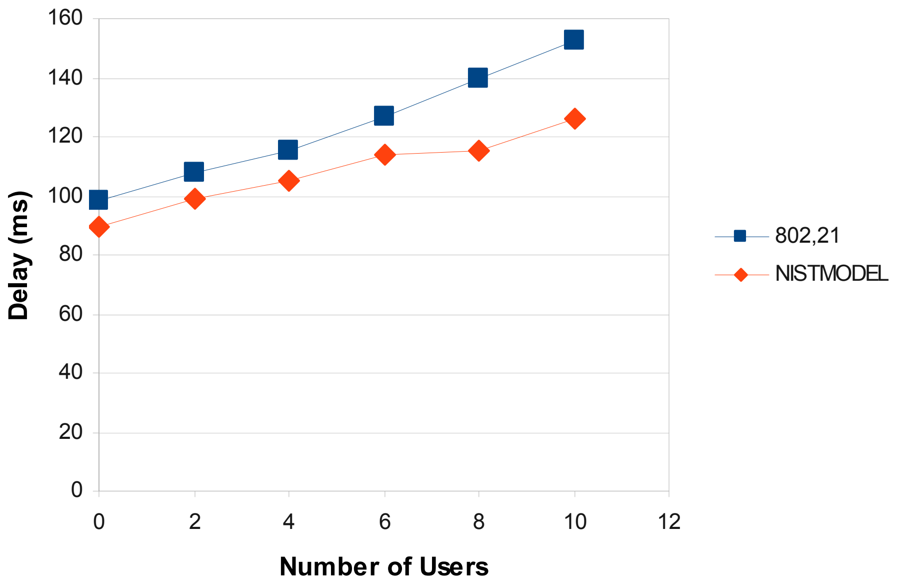

Figure 40 - Intra-Tech: Delay during Handover versus Number of Users (512Kbps)

Figure 41 presents the delay of data packets after handover, which does not contain main differences between previous and proposed model.

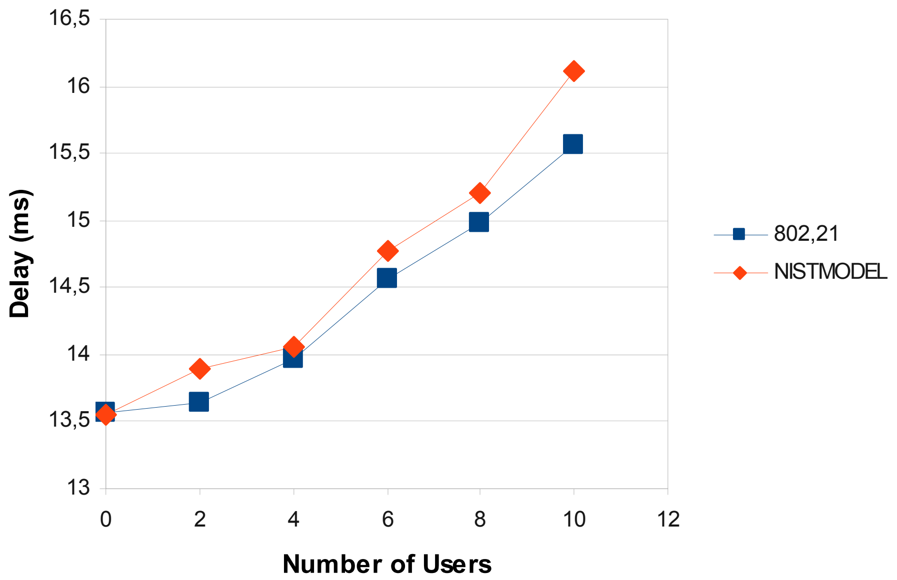

Figure 41 - Intra-Tech: Delay after Handover versus Number of Users (512Kbps)

Figure 42 presents the average jitter for the data packets of the MN before starting the handover. It increases with the number of users (background traffic) and, similarly to the delay, there are no significant differences in each model.

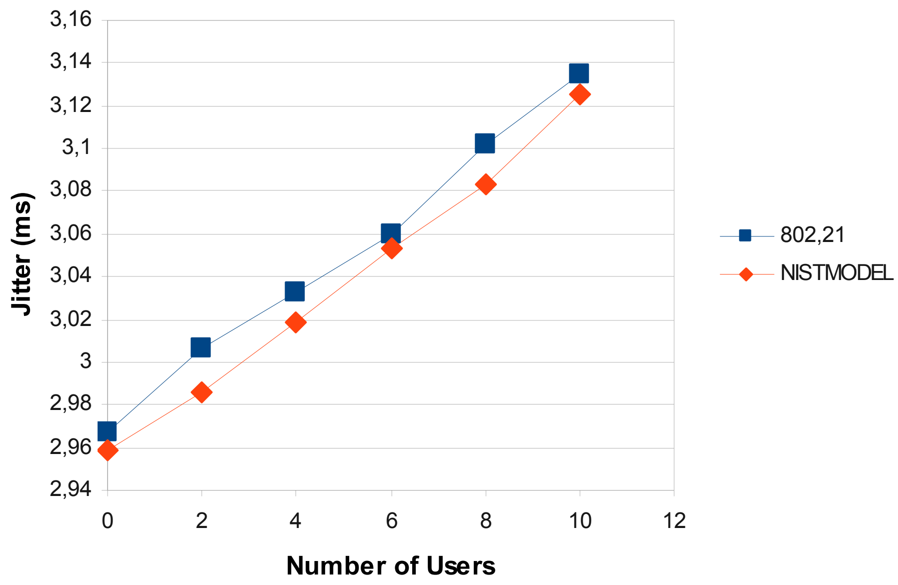

Figure 42 – Intra-Tech: Jitter before Handover versus the Number of Users (512Kbps)

Figure 43 presents the jitter during the handover. The jitter is larger in our proposed model, due to the same reason explained for delay.

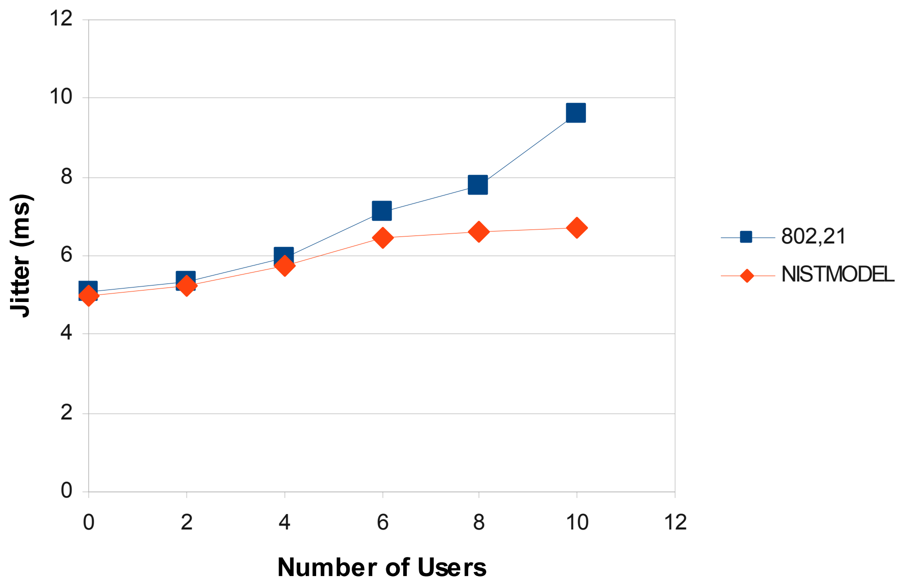

Figure 43 - Intra-Tech: Jitter during Handover versus the Number of Users (512Kbps)

Figure 44 presents the jitter after the handover, which does not contain main differences between previous and proposed model.

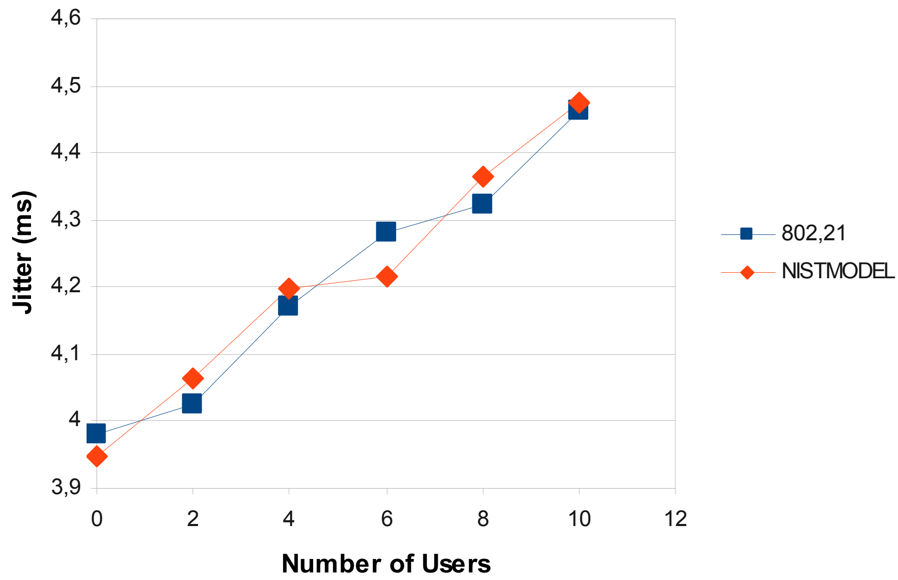

Figure 44 - Intra-Tech: Jitter after Handover versus the Number of Users (512Kbps)

Figure 45 represents the handover delay. Without users and active sessions in each network, both models achieve the same handover delay. However, when we increase the number of users, there is a small difference between the delays, around 30 msec, with our 802.21 proposed model achieving the best results. This difference on results is due to the reservation of resources performed in the commit phase of the 802.21 model, where we assure the required bandwidth for the MN, queried before on the query resources phase, providing QoS for the MN.

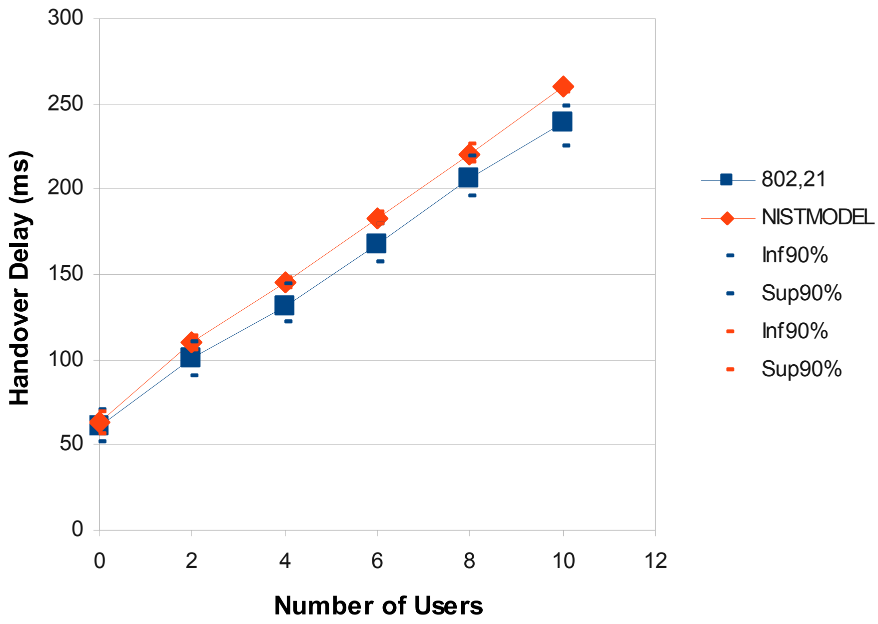

Figure 45 – Intra-Tech: Handover Delay versus Number of Users (512Kbps)

Figure 46 represents the percentage of dropped packets during handover. With the NIST model, 90% of the packets are lost during handover when 10 users are active in the network. With the 802.21 proposed approach, there are no packet losses because they are buffered in the serving network during the handover, and after concluding, they are forward to the new serving network and then received by the MN.

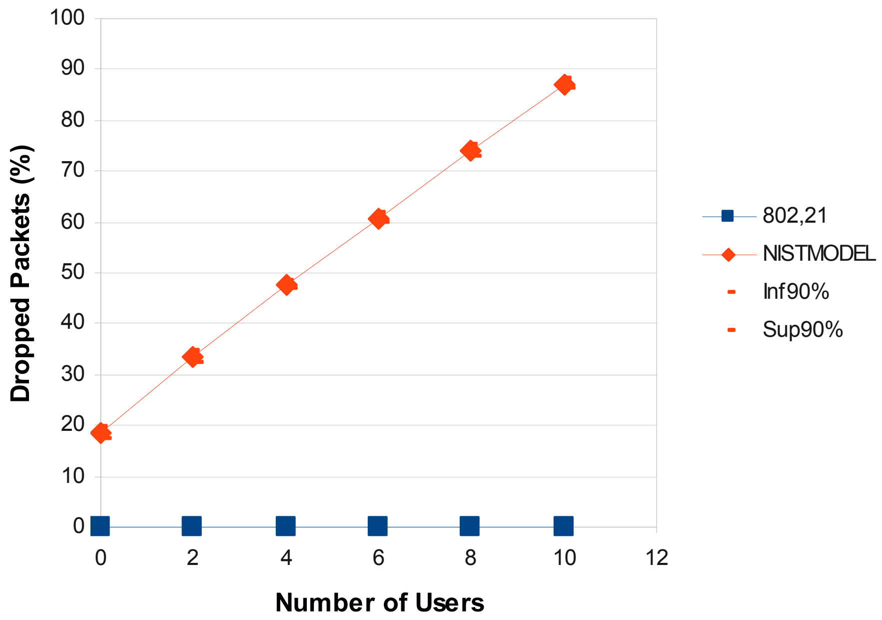

Figure 46 – Intra-Tech: Dropped Packets during Handover versus Number of Users

5.3 . Inter-Technology Handover

Figure 47 depicts the simulated scenario for inter-technology handovers. There are 3 different types of networks, a WiFi network, a WiMAX network and an Ethernet Network. They are all connected through the GateWay (GW). The users in the WiFi network have coverage from Access Point 1 (AP1) and from Base Station 1 (BS1) also. The users in the WiMAX and WiFi network are exchanging data with the users in the Ethernet Network. In the WiFi network there is a particularly user, a mobile user (Mobile Node) that has two wireless interfaces, one WiMAX and another one WiFi. At the beginning of the simulation this MN is stationary and is using the WiFi network only.

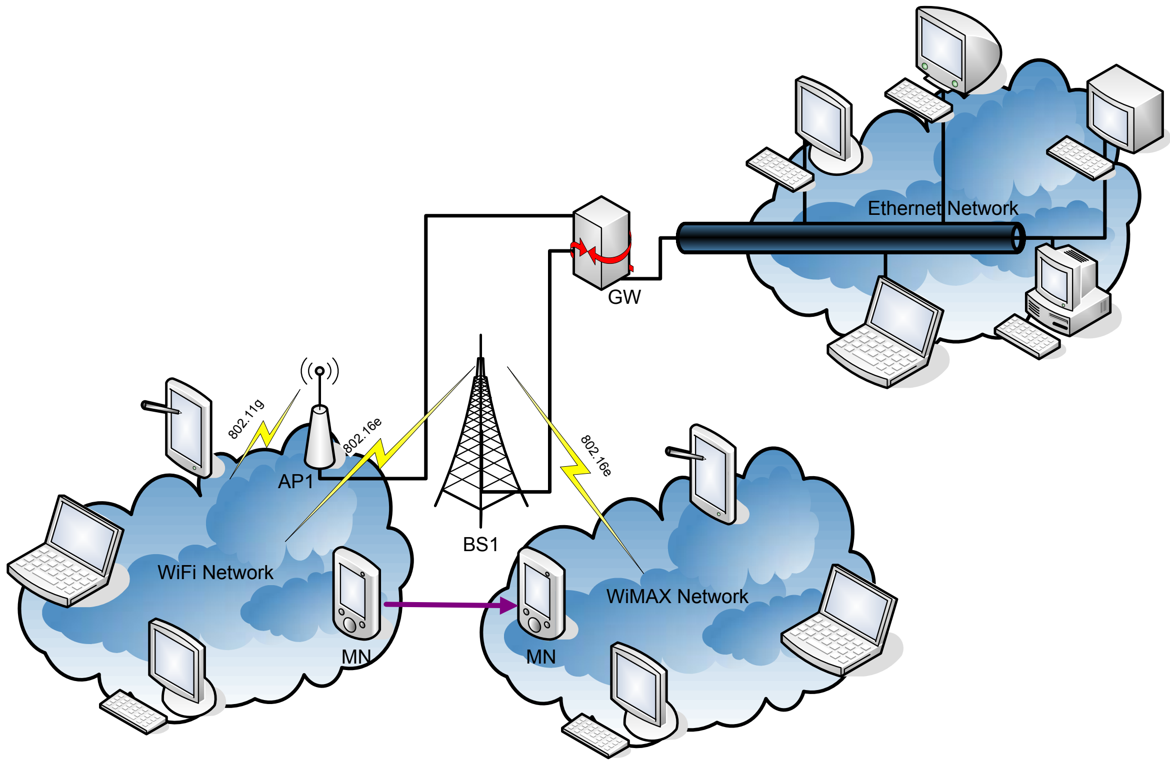

Figure 47 – Scenario with Inter-Tech Handover

At certain instant in the simulation, the MN decides to move and to go towards the WiMAX network. When the conditions on the WiFi link are getting worse, when the MN is getting out of coverage from the AP1, the MIH User receives a Link Going Down and decides to initiate the handover procedure. After concluding the procedure, the MN will be connected with BS1 and exchanging data packets with its correspondent node (CN) on the Ethernet Network through the WiMAX interface.

The conditions of the simulation are similar to the ones in intra-technology handovers. The MN is moving at 1 meter per second, unless in the scenarios with different mobility speed. We have a 16QAM3/4 modulation on the WiMAX network, unless in the scenarios with different modulations. The data packets have a size of 1500 Bytes. There is the same number of users in each network (WiMAX and WiFi) during the simulations, where 10 users correspond to 10*128Kbps, and the MN also has a data flow of 512Kbps.

5.3.1 Obtained Results

Figure 48 represents the delay for the data packets of the MN before handover. As in the previous scenario, the two models have the same behaviour. Notice that the delay is lower when compared to the previous scenario, since now we are using the WiMAX network.

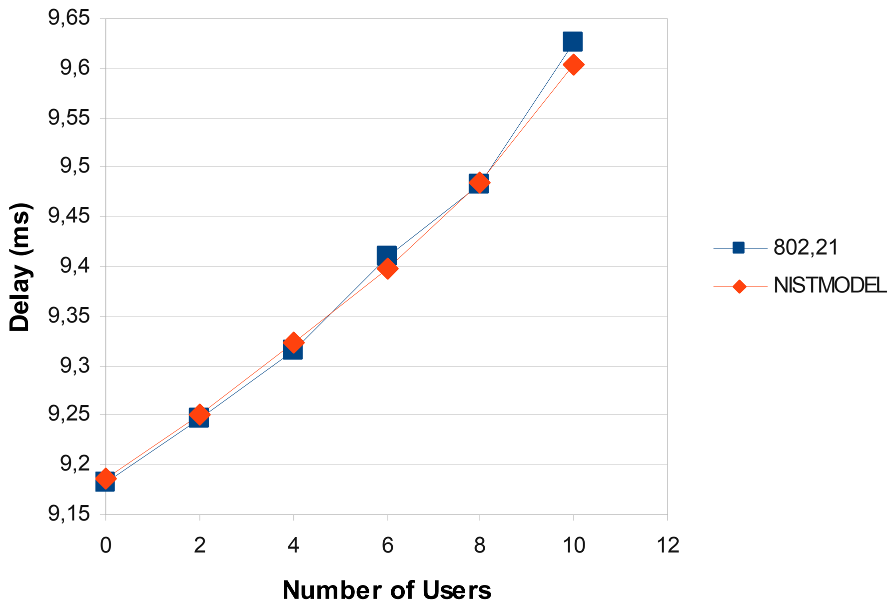

Figure 48 - Inter-Tech: Delay before handover versus Number of Users (128Kbps)

Figure 49 presents the delay during the handover. The 2 models have the same behaviour, but the 802.21 causes more delay during the handovers, since it buffers the data packets on the serving network allowing the MN to change from network without loosing packets.

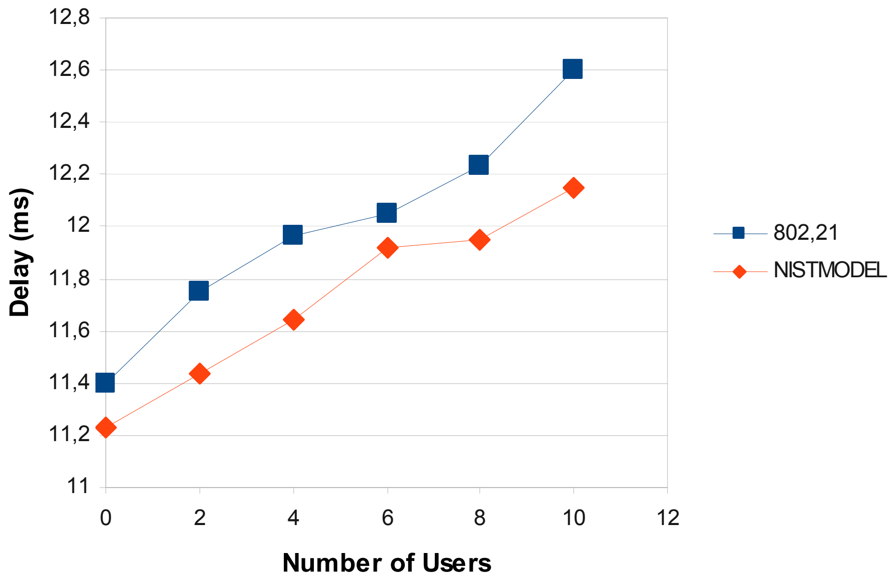

Figure 49 - Inter-Tech: Delay during handover versus Number of Users (128Kbps)

Figure 50 presents the delay after handover, which is similar in both models.

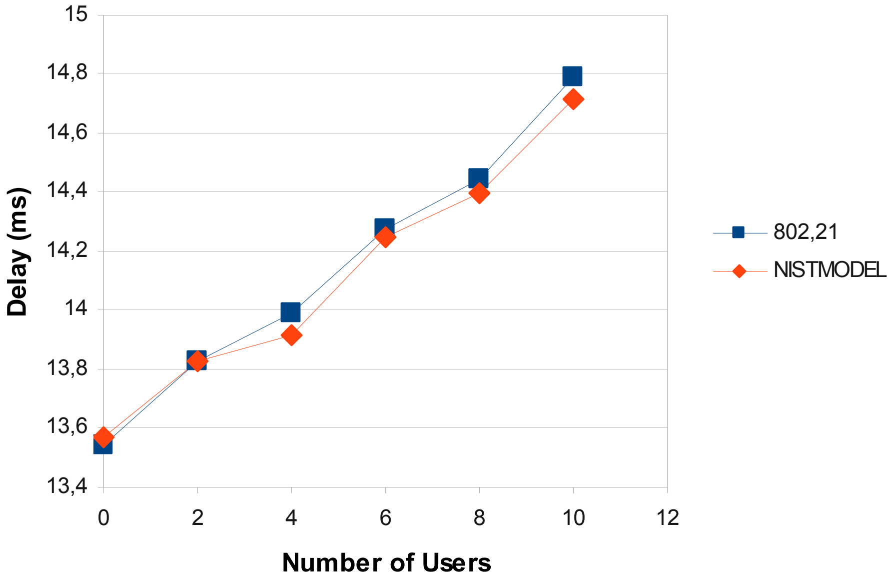

Figure 50 - Inter-Tech: Delay after handover versus Number of Users (128Kbps)

Figure 51 presents the jitter during handover. The 802.21 causes a higher jitter then the NIST model, due to the same reason as explained for delay.

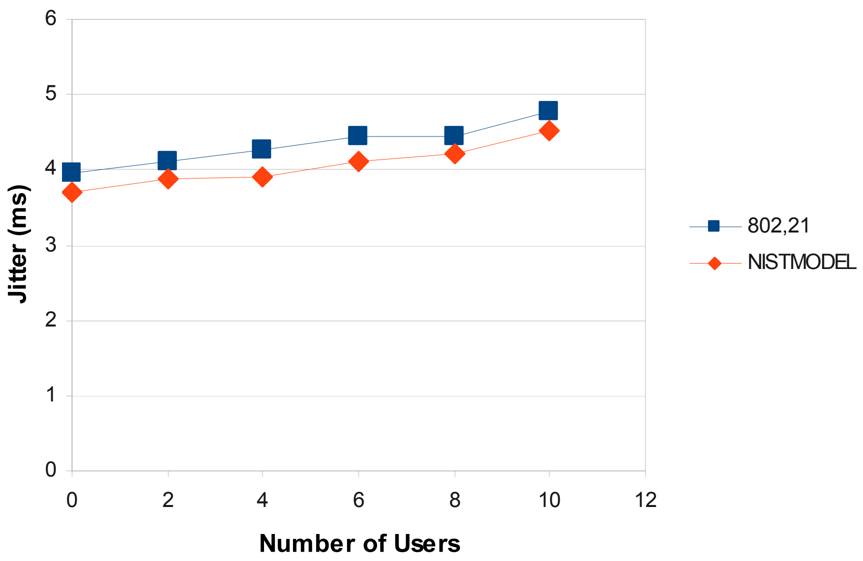

Figure 51 - Inter-Tech: Jitter during handover versus number of Users (128Kbps)

Figure 52 represents the handover delay from WiFi to WiMAX, having flows of 128Kbps on the background traffic. In a small number of users both models have the same values. However, when increasing the background traffic (number of users), the 802.21 integration model achieves better results, again due to the reservation of resources. When comparing this delay with the one of intra-technology handovers, we can see the lower delay in this case (always lower than 100 msec), since the MN has two different interfaces being active simultaneously.

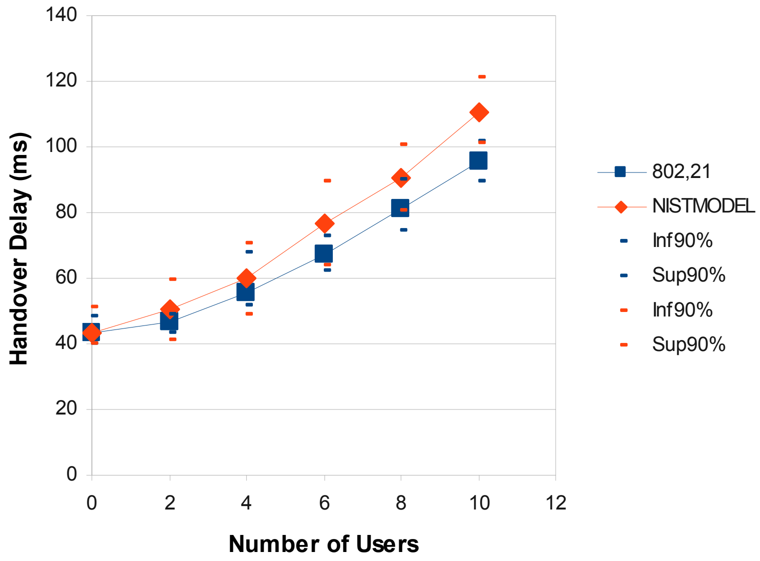

Figure 52 – Inter-Tech: Handover Delay versus Number of Users (128Kbps)

Figure 53 illustrates the percentage of dropped packets for inter-technology handovers. The dropped packets increase in the NIST model only, since the 802.21 integration model buffers the packets on the serving network.

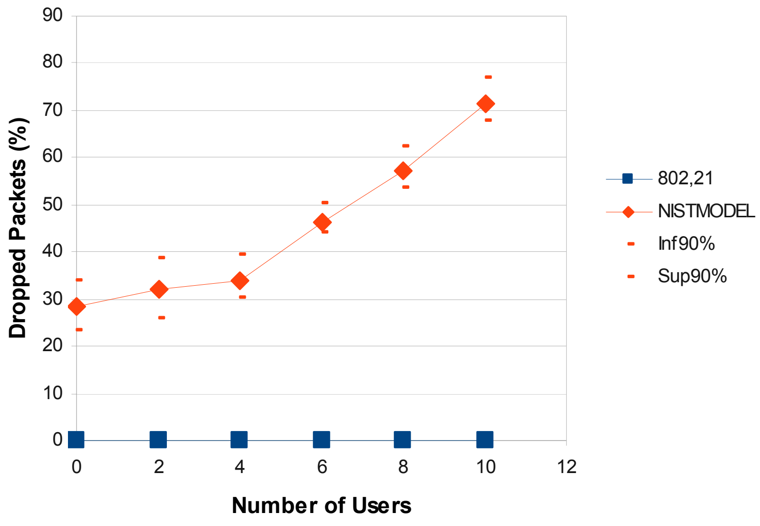

Figure 53 - Inter-Tech: Dropped Packets on Handover versus Number of Users (128Kbps)

To compare the influence of background traffic, we have increased the rate of each flow to 512kbps, maintaining the rate of the flow running in the MN. In Figure 54 we show the handover delay for this rate. Here we have the same behaviour mentioned on Figure 52, but with higher delay on the handovers for the same number of flows. This figure only contains a maximum of 6 users, since for more users there are already dropped packets before starting the handover, due to bandwidth limitations on the WiFi network.

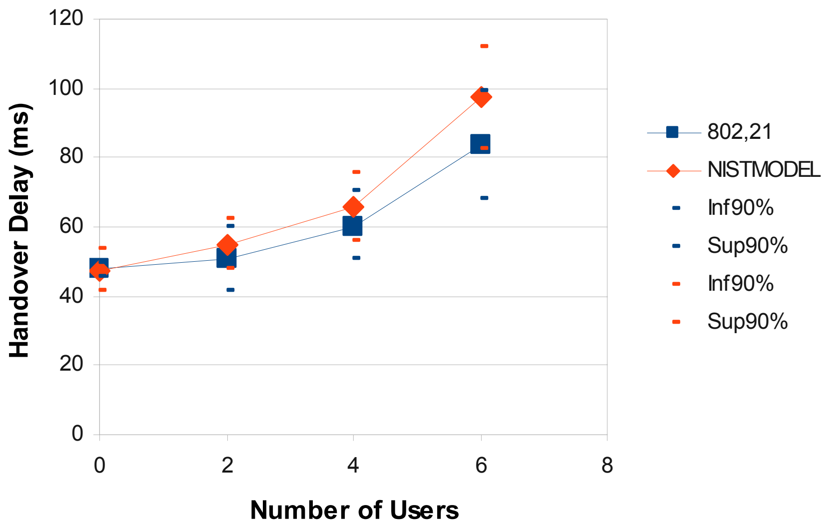

Figure 54 – Inter-Tech: Handover Delay versus Number of Users (512Kbps)

Figure 55 contains the percentage of dropped packets during the handover, with flows of 512kpbs on the background traffic. The behaviour is similar to the one of 128kbps of background traffic.

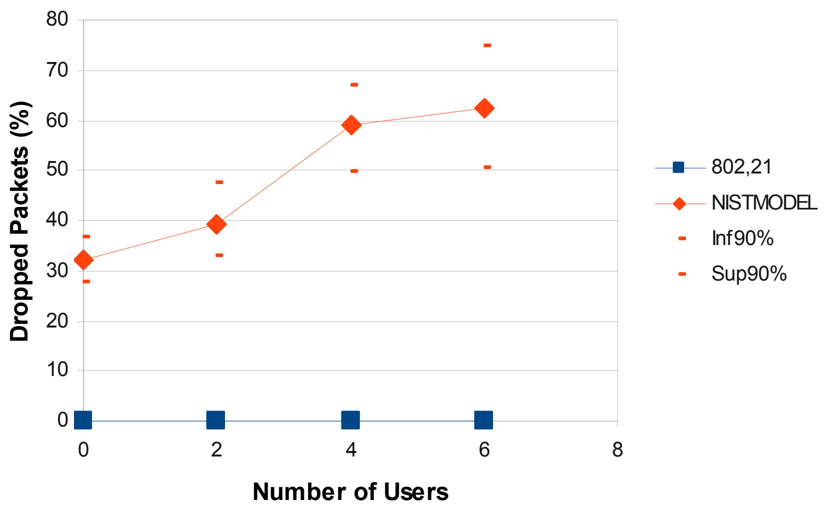

Figure 55 - Inter-Tech: Dropped Packets on Handover versus Number of Users (512Kbps)

To compare the effect of mobility, we consider the same performance metrics for different mobility speed.

Figure 56 represents the percentage of dropped packets, using the NIST model, for 3 different speed (1, 2 and 5 m/sec). When the MN increases its speed there are more dropped packets, since the handover procedure takes the same time in each different speed: with less time to process the handover the MN will loose more packets. In the 802.21 integration model there were no dropped packets.

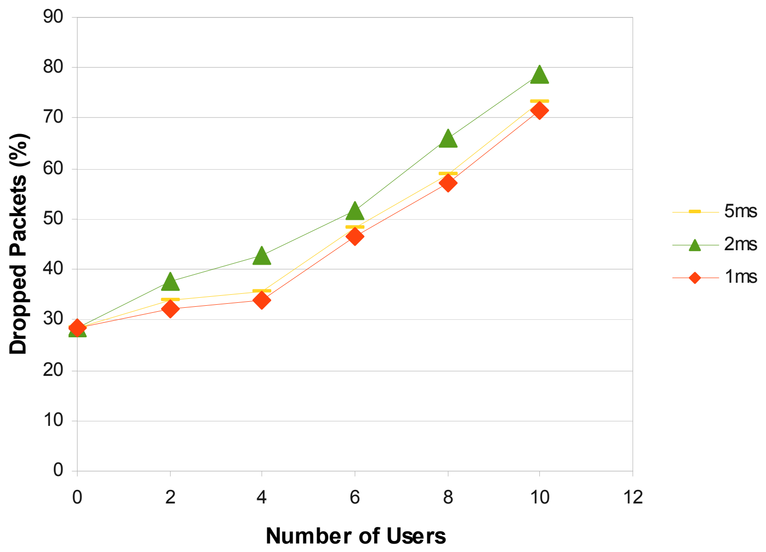

Figure 56 - Inter-Tech: Dropped Packets using NIST model versus Number of Users (128Kbps)

Figure 57 and Figure 58 represents the handover delay for the NIST model and for the 802.21 integration model, respectively, with different values of mobility speed. This delay increases in each model with the MN speed, with larger delays for the NIST model. The increase in the mobility speed increases the time to perform the ranging and registration in the L2 technology.

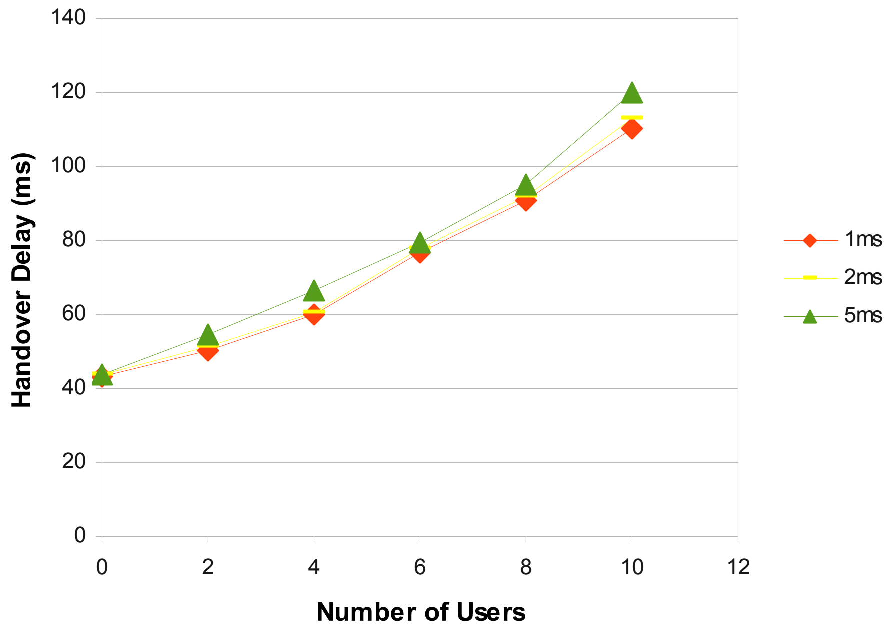

Figure 57 - Inter-Tech: Handover Delay using NIST model versus Number of Users (128Kbps)

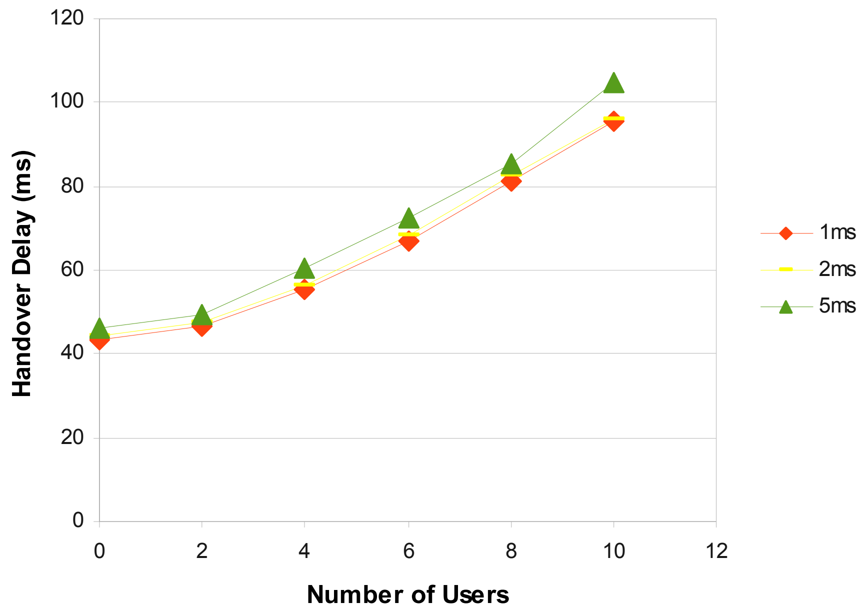

Figure 58 - Handover Delay using 802.21 model versus Number of Users (128Kbps)

Figure 59 depicts the handover delay using different modulations on the WiMAX network. Each user has a flow of 128Kbps and the MN has a flow of 512Kbps. For a small number of users the different modulations have the same behaviour. With more users the handover delay on the QPSK1/2 modulation increases more than in other modulations (with more then 8 users, there are dropped packets before the handover and during it). This is due to limitations of this modulation.

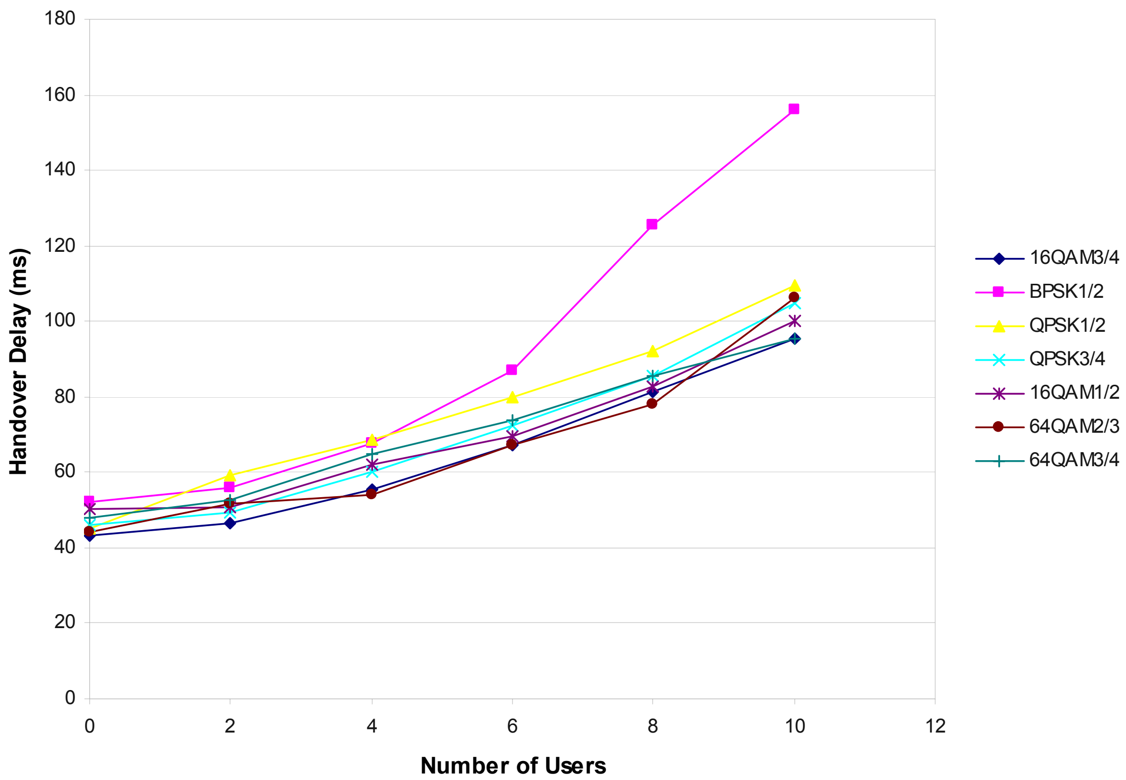

Figure 59 - Inter-Tech: Different Types of Modulations versus Number of Users (128Kbps)

5.4 Summary

We have presented the obtained results for each type of handover using the new modifications (802.21 integration) and with the NIST model. We have demonstrated that we have better results with these new modifications: lower handover delays and no packets lost. The handover delay and percentage of dropped packets were minor for inter-technology handovers. This is due to the support of more then one interface to be used simultaneously (multi-homing).

Chapter 6 – Conclusions

6.1 Final Conclusion

This thesis presented an evaluation of the integration of IEEE 802.21 with broadband wireless technologies, namely with IEEE 802.16.

The procedures for heterogeneous handovers defined in the proposal were described, and a new procedure to support inter-technology and media independent handovers has been proposed. The Thesis also includes a deep analysis of the network simulator used and the new modifications carried on it, with an explanation of the new functions added and modifications performed.

The simulator now supports 4 phases of the 5 phases of the proposed procedure for heterogeneous handovers: the new phases added were the query, commit and the resource release.

Two different types of handovers were simulated, intra-technology and inter-technology, to evaluate the performance of the wireless networks using IEEE802.21. The obtained results are very relevant, in special for inter-technology handovers, in terms of handover delays and packet losses during handover.

We can conclude that the IEEE802.21 improves the user experience of mobile devices by facilitating handover between 802 networks whether or not they are of different media types.

6.2 Future Work

For future work different parts still need to be performed. One of the parts would consider the modification of our extension for mobility with the purpose of integrating it on the new version of NS, the NS-3 that is still under construction, since NS-2 was not built initially for wireless networks.

For making use of the Media Independent Information Service MIIS and its primitives defined in the proposal, this entity needs to be implemented allowing the Mobile Node to acquire the Network Topology when it is firstly connected to its serving network, instead of finding the candidates when are moving.

The Fast Mobile IPv6 protocol should also be implemented with the purpose of getting more realistic results, with the overall handover process.

The simulator has already an implementation for UMTS networks, which could be modified to work with the new functions added and therefore for simulating heterogeneous handovers with this technology as well.

Finally, only a basic admission control mechanism was implemented; a better integration of QoS according to the IEEE802.21 is required.

Annex

Annex A MIHF

This annex includes all the types of events and commands, such as link or MIHF, defined in the draft 8 of the standard.

Annex A1 - Link Event

On Table 12 are described the Link Events defined in the standard:

Event Name	Event Type	Description
Link_Up	State Change	L2 connection is established and link is available for use
Link_Down	State Change	L2 connection is broken and link is not available for use
Lin_Going_Down	Predictive	Link conditions are degrading and connection loss is imminent
Link_Detected	State Change	New link has been detected
Link_Param_Report	Link Parameters	Link parameters have crossed a specified threshold and need to be reported
Link_Event_Rollback	State Change	Previous link event needs to be rolled back
Link_PDU_Transmit_Status	Link Transmissions	Indicates transmission status of a PDU
Link_Handover_Imminent	Link Synchronous	L2 Handover is imminent based on either the changes in the link conditions or available information in the network.
Link_Handover_Complete	Link Synchronous	L2 link handover to a new PoA has been completed

Table 12 - Link events

Annex A2 - MIH Event

Table 13 describes the MIH Events. A event is marked as local only (L), remote only (R), or local and remote (L, R), indicating whether it can be subscribed by a local MIH User, a remote MIH User, or both, respectively.

MIH Event Name	(L)ocal (R)emote	Description
MIH_Link_Up	L,R	L2 connection is established and link is available for use
MIH_Link_Down	L,R	L2 connection is broken and link is not available for use
MIH_Link_Going_Down	L,R	Link conditions are degrading and connection loss is imminent
MIH_Link_Detected	L,R	New link has been detected
MIH_Link_Param_Report	L,R	Link parameters have crossed a specified threshold and need to be reported
MIH_Link_Event_Rollback	L,R	Previous link event needs to be rolled back
MIH_Link_PDU_Transmit_Status	L	Indicates transmission status of a PDU
MIH_Link_Handover_Imminent	L,R	L2 handover is imminent based on either the changes in the link conditions or additional information available in the network. For example, the network may decide that an application requires a specific QoS that can be best provided by a certain access technology.
MIH_Link_Handover_Complete	L,R	L2 link handover to a new PoA has been completed

Table 13 - MIH events

Annex A3 - Link Command

Table 14 has the Link commands.

Link Command	Comments
Link_Capability_Discover	Query and discovery list of supported link layer events and link layer commands
Link_Event_Subscribe	Subscribe to one or more events from a link
Link_Event_Subscribe	Unsubscribe from a set of link layer events
Link_Configure_Treshold	Configure threshold for Link Parameters Report event
Link_Get_Parameters	Get parameters measured by the active link (SNR…)
Link_Action	Request actions on a link layer connection

Table 14 – Link Command

Annex A4 - MIH Command

Table 15 defines MIH Commands. An MIH command is marked as local only (L), remote only (R), or local and remote (L, R), indicating whether it can be issued by a local MIH User, a remote MIH User, or both, respectively.

MIH commands	(L) ocal, (R) emote	Comments
MIH_Get_Link_Parameters	L,R	Get the status of a link.
MIH_Configure_Link	L,R	Configure a link.
MIH_Scan	L,R	Scan a list of links.
MIH_Net_HO_Candidate_Query	R	Network may initiate handover and send a list of suggested networks and associated Points of Attachment.
MIH_MN_HO_Candidate_Query	R	Command used by MN to query and obtain handover related information about possible candidate networks.
MIH_N2N_HO_Query_ _Resources	R	This command is sent by the serving MIHF entity to the target MIHF entity to allow for resource query, context transfer (if applicable), and handover preparation.
MIH_Net_HO_Commit	R	In this case the network commits to do the handover and sends the choice of selected network and associated PoA.
MIH_MN_HO_Commit	R	Command used by MN to notify the network that a candidate has been committed for handover.
MIH_N2N_HO_Commit	R	Command used by a serving network to inform a target network that a mobile node is about to move toward that network.
MIH_MN_HO_Complete	R	Notification from MIHF of the MN to the target or source MIHF indicating the status of handover completion.
MIH_N2N_HO_Complete	R	Notification from MIHF of the MN to the target or source MIHF indicating the status of handover completion.

Table 15 – MIH Command

Annex B – Symbols used in the diagram block

This annex includes the symbols used in Chapter 4 –and their meaning as well.

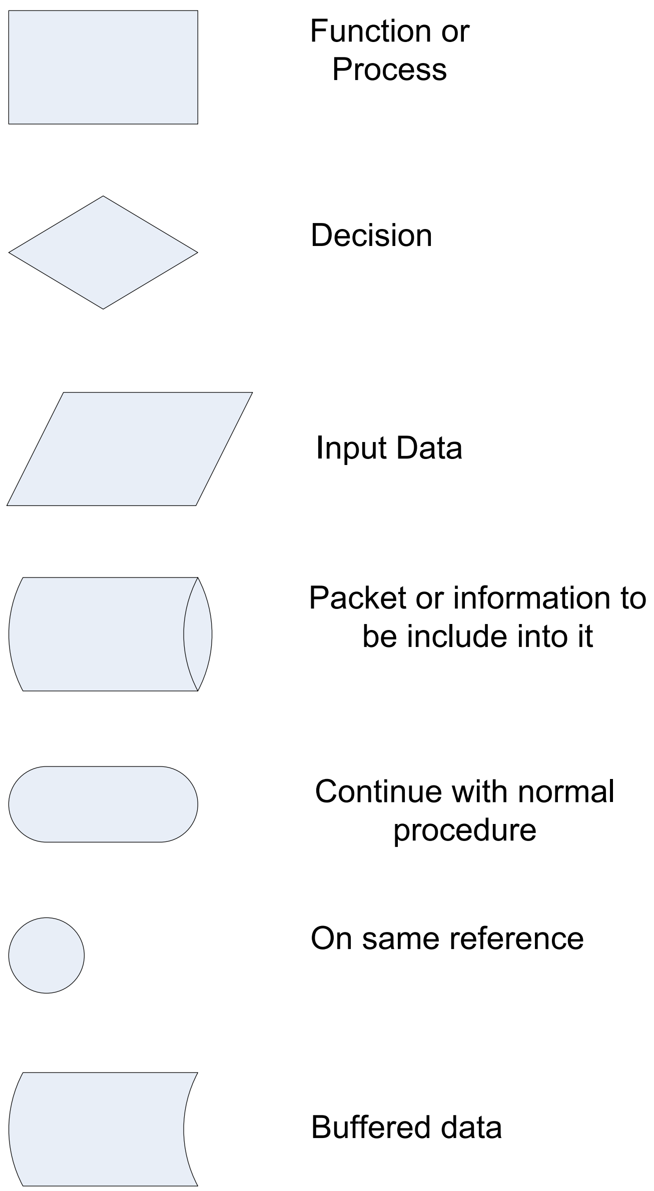

Figure 60 – Symbols used in the diagrams

SInBAD

Estes anexos só estão disponíveis para consulta através do CD-ROM.
Queira por favor dirigir-se ao balcão de atendimento da Biblioteca.

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