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Scalable and Efficient Vertical Handover Decision Algorithms in Vehicular Network Contexts

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Dum in Altum

Acknowledgments

To G.

To my wife Mary and my daughter Naira, because they are the engine of my soul. Thanks for the time you have lent me; for those busy days without sun, husband and father that you have suffered. To my parents and siblings, because they taught me the most important things in life... they made who I am.

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I wish to all of you nothing but the best.

"Good friends we have had, oh good friends we've lost along the way. In this bright future you can't forget your past." (Bob Marley).

Abstract

In the late nineties, and at the beginning of the new millennium, wireless networks have evolved from being just a promising technology to become a requirement for everyday activities in developed societies. The transportation facilities have also evolved, offering on-board communication to improve safety and access to infotainment content.

End-user requirements have become technology dependent, meaning that their connectivity needs have increased due to the different requirements for applications running on their portable devices such as tablets, smartphones, laptops or even On-Board Units (OBUs) within vehicles. To fulfill those connectivity requirements while considering different available wireless networks, Vertical Handover (VHO) techniques are required in order to seamlessly and transparently switch between networks without requiring user intervention.

In this thesis we aim at developing scalable and efficient Vertical Handover Decision Algorithms (VHDAs) optimized for Vehicular Network (VN) contexts. In that sense, we have proposed, developed, and tested different VHDAs, based on the facilities available in the current, and probably in the future, wireless and vehicular networks,

and combining different techniques, such as computational and mathematical methods, in order to guarantee appropriate connectivity by handing over to the networks that better fit the application and user requirements.

In order to evaluate the surrounding context, we have used different tools to obtain information, such as network availability, status of the network, geolocation of the vehicle, service provider features and user preferences. Based on the information gathered, the VHDAs perform the decision-making process to choose the most suitable candidate network to handover to. Therefore, the information must be gathered in an accurate way, and the decision making process must evaluate it in a fair manner, allowing the OBU to seamlessly disconnect from the old network and connect the new one. The algorithms that we present consider the availability and capacity of candidate Points of Attachment (PoAs), combining different data sources at the OBUs, taking advantage of Global Positioning System (GPS) information, maps, geolocation and navigation information, surrounding context information and routes in order to guarantee the Quality of Service (QoS) and the Quality of Experience (QoE).

To support the development and testing of the VHDAs proposed, we have performed several works including a thorough overview of the VHDAs available in the literature. Moreover, we analyze and present the IEEE 802.21 standard, which was developed in the last couple of years. This standard provides a homogeneous middleware for heterogeneous networks that allows improving the handover processes among different wireless access networks, as well as a service to collect not only network status information, but also service provider information.

We have also extended and developed the Network Simulator (ns-2) and the *Seamless and Secure* add-on (developed by the National Institute of Standards and Technology (NIST)) to be able to test our VHDA proposals. Additionally, we have tested the performance of different wireless networks, such as Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX), and Universal Mobile Telecommunications System (UMTS) in order to determine their performance limits, and we tested the viability of a content delivery framework for VNs based on Vehicular *Ad-hoc* Networks (VANETs).

The proposed algorithms are empowered not only by the IEEE 802.21 standard, but also by the multiple features available on the OBU at the vehicles, such as GPS, high resources (processor and memory), and no power supply constrains. Moreover, the algorithms have been tested under different network conditions within heterogeneous wireless networks such as Wi-Fi, WiMAX, and UMTS. The most promising contribution of our VHDAs is to guarantee the QoS and the continuous connectivity due to the full integration of the heterogeneous wireless networks within the vehicular network context.

The resulting algorithms present novelties concerning heterogeneous networks and the use of the IEEE 802.21 standard. Moreover, advanced geolocation is used to improve the VHDA. The algorithms introduce new concepts about QoS guarantees supported by the combination of geolocation, network, and context information, improving the decision-making process by considering multiple criteria in order to fairly evaluate the candidate networks to switch into. The algorithms are evaluated on well thought-out simulation environments, obtaining results that offer useful insights concerning VHO processes and VHDAs.

Resumen

DESDE finales de los años noventa, las redes inalámbricas han evolucionado y ganado protagonismo, pasando de ser una tecnología prometedora para convertirse en tecnología referente para las actividades cotidianas en las sociedades desarrolladas. Por otra parte, los Sistemas de Transporte Inteligente también han evolucionado, ofreciendo comunicación a bordo para mejorar la seguridad vial y el acceso a contenidos de información y entretenimiento.

Los requisitos de los usuarios finales se han hecho dependientes de la tecnología, lo que significa que sus necesidades de conectividad han aumentado debido a los diversos requisitos de las aplicaciones que se ejecutan en sus dispositivos móviles, tales como tabletas, teléfonos inteligentes, ordenadores portátiles o incluso ordenadores de abordo (*On-Board Units (OBUs)*) dentro de los vehículos. Para cumplir con dichos requisitos de conectividad, y teniendo en cuenta las diferentes redes inalámbricas disponibles, es necesario adoptar técnicas de Vertical Handover (VHO) para seleccionar y utilizar la red mas adecuada de forma transparente y sin necesidad de intervención del usuario.

El objetivo de esta tesis es desarrollar algoritmos de decisión (*Vertical Handover Decision Algorithms (VHDAs)*) eficientes y escalables, optimizados para el contexto

de las redes vehiculares. En ese sentido se ha propuesto, desarrollado y evaluado diferentes algoritmos de decisión basados en la infraestructura disponible en las actuales, y probablemente en las futuras, redes inalámbricas y redes vehiculares. Para ello se han combinado diferentes técnicas, métodos computacionales y modelos matemáticos, con el fin de garantizar una conectividad apropiada, y realizando el *handover* hacia las redes más adecuadas para cumplir tanto con los requisitos de los usuarios como los requisitos de las aplicaciones.

Con el fin de evaluar el contexto, se han utilizado diferentes herramientas para obtener información variada, tales como la disponibilidad de la red, el estado de la red, la geolocalización del vehículo, las características de los proveedores de servicios y de las preferencias del usuario. En base a la información recopilada, el VHDA realiza el proceso de toma de decisiones para elegir la red candidata más adecuada de cara a realizar el cambio hacia ella. Por lo tanto, la información debe ser recogida de una forma precisa, y la toma de decisiones debe evaluar las distintas redes de manera justa, para permitir a la OBU desconectarse de manera transparente de la antigua red, y conectarse a la nueva. Los algoritmos que se presentan consideran la disponibilidad y capacidad de los puntos de red (*Points of Attachment (PoAs)*) candidatos, y la combinación de diferentes fuentes de datos en las OBUs, aprovechando la información del sistema de posicionamiento global (*Global Positioning System (GPS)*), mapas, geolocalización y la información de navegación, información del entorno y las rutas, para garantizar la calidad de servicio (*Quality of Service (QoS)*) y la calidad de experiencia (*Quality of Experience (QoE)*).

Para desarrollar y probar los VHDAs propuestos, se ha llevado a cabo varios trabajos, incluyendo una amplia revisión de los VHDAs disponibles en la literatura. Además, se ha analizado y presentado el estándar IEEE 802.21, que se desarrolló en el último par de años. Esta norma proporciona un *middleware* homogéneo para redes heterogéneas que permite mejorar los procesos de *handover* entre las diferentes redes de acceso inalámbrico, así como un servicio para recolectar no sólo información sobre el estado de la red, sino también la información del proveedor de servicios.

En este trabajo de Tesis también se ha mejorado, desarrollado y extendido el simulador *Network Simulator (ns-2)*, además del complemento *Seamless and Secure* (desarrollado por el National Institute of Standards and Technology (NIST)) para poder evaluar los VHDAs propuestos. Además, se ha probado el rendimiento de las diferentes redes inalámbricas, como Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX), y Universal Mobile Telecommunications System (UMTS) a fin de conocer sus límites de rendimiento, y se ha probado la viabilidad de una arquitectura para la entrega de contenidos en entornos vehiculares basado en Vehicular *Ad-hoc* Networks (VANETs).

Los algoritmos propuestos utilizan la funcionalidad proporcionada por el estándar IEEE 802.21, asi como las múltiples funciones disponibles en el OBU de los vehículos, tales como GPS, amplios recursos (procesador y memoria), y la no limitación de energía. Por otra parte, los algoritmos se han probado bajo diferentes condiciones de red en redes inalámbricas heterogéneas, tales como Wi-Fi, WiMAX y UMTS. La contribución más prometedora de los VHDAs presentados es garantizar la QoS y una conectividad continua, debido a la integración plena de las redes inalámbricas heterogéneas dentro de las redes vehiculares.

Los algoritmos resultantes presentan novedades referentes a la integración de redes heterogéneas mediante el uso de la norma IEEE 802.21. Por otra parte, la geolocalización avanzada se utiliza para mejorar las prestaciones de los VHDA. Los algoritmos introducen nuevos conceptos que permiten garantizar la QoS en base a la combinación de la información de geolocalización, de la red y del contexto, mejorando el proceso de toma de decisiones teniendo en cuenta múltiples criterios con el fin de evaluar, de manera ecuánime, las redes candidatas. Los algoritmos propuestos se han evaluado en entornos de simulación complejos, obteniendo resultados que ofrecen información útil sobre los procesos de VHO y los VHDAs.

Resum

DES de finals dels anys noranta, les xarxes sense fils han evolucionat i han guanyat protagonisme, en passar de ser una tecnologia prometedora a esdevenir una tecnologia referent per a les activitats quotidianes en les societats desenvolupades. Per una altra banda, els sistemes de transport intel·ligent també han evolucionat, i ofereixen comunicació a bord per a millorar la seguretat vial i l'accés a continguts d'informació i entreteniment.

Els requisits dels usuaris finals s'han fet dependents de la tecnologia, cosa que significa que les seues necessitats de connectivitat han augmentat a causa dels diversos requisits de les aplicacions que s'executen en els dispositius mòbils, com ara tauletes, telèfons intel·ligents, ordinadors portàtils o fins i tot ordinadors de bord *(On-Board Units [OBU])* dins dels vehicles. Per a complir aquests requisits de connectivitat, i tenint en compte les diferents xarxes sense fils disponibles, cal adoptar tècniques de Vertical Handover (VHO) per a seleccionar i utilitzar la xarxa més adequada de forma transparent i sense necessitat d'intervenció de l'usuari.

L'objectiu d'aquesta tesi és desenvolupar algorismes de decisió *(Vertical Handover Decision Algorithms [VHDA])* eficients i escalables, optimitzats per al context de les

xarxes vehiculars. En aquest sentit s'han proposat, desenvolupat i avaluat diversos algorismes de decisió basats en la infraestructura disponible en les actuals, i probablement en les futures, xarxes sense fils i xarxes vehiculars. Per a fer-ho s'han combinat diverses tècniques, mètodes computacionals i models matemàtics, amb la finalitat de garantir una connectivitat apropiada, i realitzant el *handover* cap a les xarxes més adequades per a complir tant els requisits dels usuaris com els requisits de les aplicacions.

Amb la finalitat d'avaluar el context, s'han utilitzat diferents eines per a obtenir informació variada, com ara la disponibilitat de la xarxa, l'estat de la xarxa, la geolocalització del vehicle, les característiques dels proveïdors de serveis i de les preferències de l'usuari. Sobre la base de la informació recopilada, el VHDA realitza el procés de presa de decisions per a triar la xarxa candidata més adequada de cara a fer el canvi cap aquesta. Per tant, la informació ha de ser recollida d'una forma precisa, i la presa de decisions ha d'avaluar les diferents xarxes de manera justa, per a permetre a l'OBU desconnectar-se de manera transparent de l'antiga xarxa, i connectar-se a la nova. Els algorismes que s'hi presenten consideren la disponibilitat i la capacitat dels punts de xarxa *(Points of Attachment [PoA])* candidats, i la combinació de diferents fonts de dades en les OBU, aprofitant la informació del sistema de posicionament global *(Global Positioning System [GPS])*, mapes, geolocalització i la informació de navegació, informació de l'entorn i les rutes, per a garantir la qualitat de servei *(Quality of Service [QoS])* i la qualitat d'experiència *(Quality of Experience [QoE])*.

Per a desenvolupar i provar els VHDA proposats, s'han dut a terme diversos treballs, inclosa una àmplia revisió dels VHDA disponibles en la literatura. A més, s'ha analitzat i s'ha presentat l'estàndard IEEE 802.21, que s'ha desenvolupat en els darrers dos anys. Aquesta norma proporciona un programari intermediari (middleware) homogeni per a xarxes heterogènies que permet millorar els processos de *handover* entre les diverses xarxes d'accés sense fil, i també un servei per a recol·lectar no solament informació sobre l'estat de la xarxa, sinó també la informació del proveïdor de serveis.

En aquest treball de tesi també s'ha millorat, desenvolupat i estès el simulador *Network Simulator (ns-2)*, a més del complement *Seamless and Secure* (desenvolupat pel National Institute of Standards and Technology [NIST]) per a poder avaluar els VHDA proposats. A més, s'hi ha provat el rendiment de les diferents xarxes sense fils, com ara Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX), i Universal Mobile Telecommunications System (UMTS), a fi de conèixer-ne els límits de rendiment, i s'ha provat la viabilitat d'una arquitectura per al lliurament de continguts en entorns vehiculars basada en Vehicular Ad-hoc Networks (VANET).

Els algorismes proposats utilitzen la funcionalitat proporcionada per l'estàndard IEEE 802.21, com també les múltiples funcions disponibles en l'OBU dels vehicles, com ara GPS, amplis recursos (processador i memòria), i la no limitació d'energia.

D'altra banda, els algorismes s'han provat sota diferents condicions de xarxa en xarxes sense fils heterogènies, com Wi-Fi, WiMAX i UMTS. La contribució més prometedora dels VHDA presentats és garantir la QoS i una connectivitat contínua, a causa de la integració plena de les xarxes sense fils heterogènies dins de les xarxes vehiculars.

Els algorismes resultants presenten novetats referents a la integració de xarxes heterogènies mitjançant l'ús de la norma IEEE 802.21. Per una altra banda, la geolocalització avançada s'utilitza per a millorar les prestacions dels VHDA. Els algorismes introdueixen nous conceptes que permeten garantir la QoS sobre la base de la combinació de la informació de geolocalització, de la xarxa i del context, i milloren el procés de presa de decisions tenint en compte múltiples criteris amb la finalitat d'avaluar, de manera equànime, les xarxes candidates. Els algorismes proposats s'han avaluat en entorns de simulació complexos, en què s'han obtingut resultats que ofereixen informació útil sobre els processos de VHO i els VHDA.

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Part I

Background

Chapter 1

Introduction

In developed countries the user demand for mobile services is increasing due to the need to access information *anywhere, anytime.* The ever-growing communications infrastructure allows offering connectivity through diverse wired and wireless technologies in different environments.

The adoption of wireless technologies is increasing at a very fast rate. This trend is basically due to factors including (i) the miniaturization of devices such as laptops, Personal Digital Assistant (PDA), tablets, smartphones, and netbooks, (ii) the multiple networking interfaces available in most devices, (iii) the availability of several wireless technologies such as Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX), Universal Mobile Telecommunications System (UMTS), and Long Term Evolution (LTE), and (iv) the emerging mobile applications, such as those based on the Web 2.0 paradigm, car navigation, and location based services.

In addition, it is well known that most individuals spend a few hours every day in their vehicles or in public transportation. Under the *"always-on"* paradigm, users expect network availability at any time to satisfy their connectivity needs. Currently, available infrastructures do not offer total coverage, thus preventing users from reaching contents such as news, weather, video and information at all times. Nowadays, vehicles are continuously being improved in order to boost safety and to offer enhanced comfort features. The automotive industry is taking advantage of the latest developments of the different embedded systems and communication technologies, thus building fully featured On-Board Units (OBUs) powered by fast and reliable processor units, Global Positioning System (GPS) based navigation systems, Wi-Fi, UMTS, LTE and even WiMAX interfaces to reinforce the communication system of the vehicles [LL10]. Since there are different alternatives for communication among vehicles, and between the vehicles and the infrastructure, on both highways and metropolitan areas, the industry must face the downside issues when heterogeneous wireless technologies are used in highly dynamic environments such as Vehicular Networks (VNs). The integration of different wireless network technologies is needed to provide a "seamless" interoperability, integration and convergence among these heterogeneous technologies and, therefore, the use of *Vertical Handover (VHO)* techniques is required.

A handover event is a process of transferring a mobile station from one channel or base station to another. When a handover occurs within the domain of a single wireless access technology the process is known as *Horizontal Handover* ; in contrast, *Vertical Handover* is a term that refers to handover among heterogeneous wireless access network technologies [Rap02].

The research community has been making significant efforts towards the convergence of the different wireless networking technologies. As a consequence, there are different proposals addressing heterogeneous scenarios, protocols, handover techniques and algorithms, network technologies, metrics, and procedures. In addition, since 2004, the IEEE 802.21 Working Group has been working in the Media Independent Handover Services Protocol [80209] whose purpose is to provide a homogeneous function-interface between heterogeneous network technologies, offering standard handover services between lower and upper layers. The IEEE 802.21 standard was finally approved in November 2008.

1.1 Motivation

Wireless communications have improved at a fast rate during the last decade, changing the way people interact. Nowadays, users demand for continuous connectivity on their personal mobile devices in order to access the Internet to accomplish a wide-range of every-day activities such as work, entertainment, information, and social networking.

Currently, there are many works in both literature and industry covering VHO among diverse technologies such as Wi-Fi, Wireless Broadband (WiBro), WiMAX, UMTS, LTE, Bluetooth (BT), ZigBee (ZigBee), and Low Earth Orbit (LEO) satellite communications. Due to the wide variety of solutions for these technologies, no single

VHO strategy embraces them all, but most of them only take into account a few processes and parameters, and merely consider two wireless technologies as candidate networks to switch to.

To make an accurate decision, a well designed Vertical Handover Decision Algorithm (VHDA) must find the optimal trade-off between parameters such as network discovery, network selection, service continuity, security, mobility management, and Quality of Service (QoS) issues [CHL09, MBCCM11a], being the latter a priority.

1.2 Objectives

This thesis aims to collect relevant information related to VHO within VN contexts, thereby offering a solid background to researchers interested in the VHO and VN research areas. Moreover, the main goal is to deploy VHDAs capable of handling multiple underlying wireless networks, evaluating different parameters from many sources (*i.e.*, geolocation information, networking information, user preferences, network provider preferences) to optimize the decision-making process of the VHO.

In order to achieve the main goal of this thesis, a set of objectives have been proposed. We proceed to enumerate them:

- A review, concerning VHO techniques, must be performed in order to evaluate the current solutions up to date found in the literature, including both particular proposals and standards. Moreover, this review should focus on the VHO process from a VN perspective, highlighting those techniques and algorithms that fit better to this type of networks.

- For simulation purposes, the Network Simulator (ns-2) [KK09a] in conjunction of third-parties add-ons such as the *NIST mobility package for the ns-2* [Adv], the Enhanced UMTS Radio Access Network Extensions (EURANE) [ET] must be extended and improved, to be able to simulate VN contexts, Wi-Fi, WiMAX and UMTS underlying wireless technologies, GPS geolocation and geonavigation, thus performing seamless VHO powered by the IEEE 802.21 standard and its services.

- Finally, to reach our main goal, we must develop and validate smart and efficient VHDAs considering the surrounding context within the VN. Therefore, an increasing development of the VHDAs must be done in order to power-up the algorithms by considering Geolocation, Geonavigation, multiple wireless underlying networks, IEEE 802.21 context information.

1.3 Structure of the thesis

This manuscript is organized in five main parts, including chapters which describe related information. We proceed to describe each part briefly:

Background. Includes this introductory chapter, as well as two chapters covering, on the one hand, the basic concepts and the proposals found in the literature concerning VHO, and the IEEE 802.21, and, on the other hand, the basics of the VNs, Wi-Fi, WiMAX and UMTS technologies.

Contributions. This part presents the different contributions associated with this Ph.D. thesis. We introduce the theoretical model and the concept of each VHDA that we have developed in order to improve the VHO process.

Experimentation and results. This part presents all the experimentation framework and schemes used to prove, test, validate and evaluate each proposed VHDA, that was presented in the previous part.

Conclusions. The conclusions of this thesis are presented in the final chapter. Also, a list of the publications related to the thesis as well as the open research issues that can be derived from the work accomplished in this thesis are also presented.

Appendices and references. Finally, the appendices such as the acronyms, glossary, and the bibliography are presented in this complementary part.

Chapter 2

Wireless Technologies and Vehicular Networks (VNs) Overview

During the last two decades, wireless networks have been evolving towards high data rates, larger communication ranges and more efficient use of the radio spectrum, thereby triggering novel changes in the offered services, their management and their usability.

Figure 2.1 presents the evolution of the wireless access networks along with the different data rates. As observed, since the beginnings of wireless communications, data rates have been boosted from a few Kbps up to several Mbps nowadays. Moreover, Figure 2.2 presents a trade-off between the data rates offered by the different wireless technologies and the coverage distance that each of them can achieve. In this chapter we will describe the basics of the wireless technologies that we have considered (*i.e.*, Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave

Access (WiMAX), and Universal Mobile Telecommunications System (UMTS)) to develop smart Vertical Handover Decision Algorithms (VHDAs) within the VN context. Moreover, an overview of VNs will also be presented in this chapter.

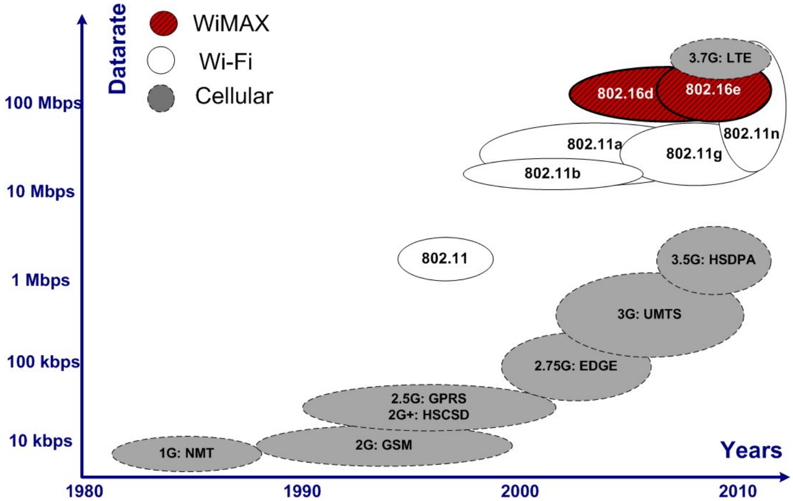


Figure 2.1: Wireless evolution.

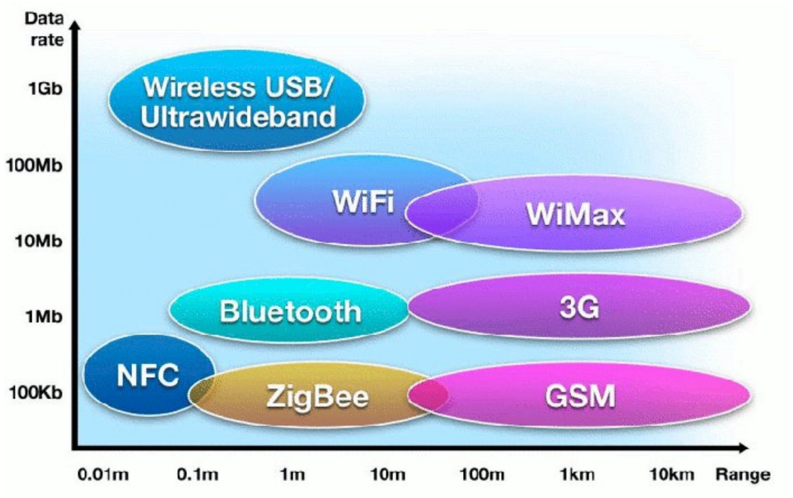


Figure 2.2: Wireless technologies coverage distance (source:cnx-software.com).

Table 2.1: IEEE 802.11 protocols.

Protocol	**Date**	**Data rate (Mbps)**	**Modulation**	**Radio frequency (GHz)**	**Channel width (MHz)**
802.11a	1999	54	Orthogonal Frequency Division Multiplexing (OFDM)	5	20
802.11b	1999	11	Complementary Code Keying (CCK), Direct Sequence Spread Spectrum (DSSS)	2.4	20
802.11g	2003	54	CCK, DSSS, OFDM	2.4	20
802.11n	2009	300	CCK, DSSS, OFDM	2.4 & 5	24, 40

2.1 Wireless technologies overview

2.1.1 Wireless Fidelity (Wi-Fi)

The IEEE 802.11 [IEEa] is a communications standard for Wireless Local Area Network (WLAN) environments. It is commonly named as Wi-Fi due to the compatibility certification among devices by the Wi-Fi Alliance. Successive amendments to the original standard have appeared in the last decade, currently achieving a theoretical data rate of up to 300 Mbps. Table 2.1 presents the data rate features of the most popular protocols that extend the original standard. There are also other interesting protocol extensions that improve the performance of 802.11, such as 802.11i - security, 802.11e - Quality of Service (QoS), etc.

Architecture

A WLAN is based on cells, and every Access Point (AP) controls a cell, which is called a Basic Service Set (BSS). A WLAN may be composed by only one BSS or by many.

In the latter, a set of many BSS is called an Extended Service Set (ESS). However, there is a third network configuration, called Independent Basis Service Set (IBSS) and commonly known as *ad hoc*, which allows nodes to communicate among them without any infrastructure support (*i.e.*, AP and Distribution System (DS)). Figure 2.3 shows a generic 802.11 architecture. As shown, every AP is connected to the Local Area Network (LAN) via the DS, and every node under the cell coverage communicates via the AP. Moreover, nodes in different cells are able to communicate among them via the ESS.

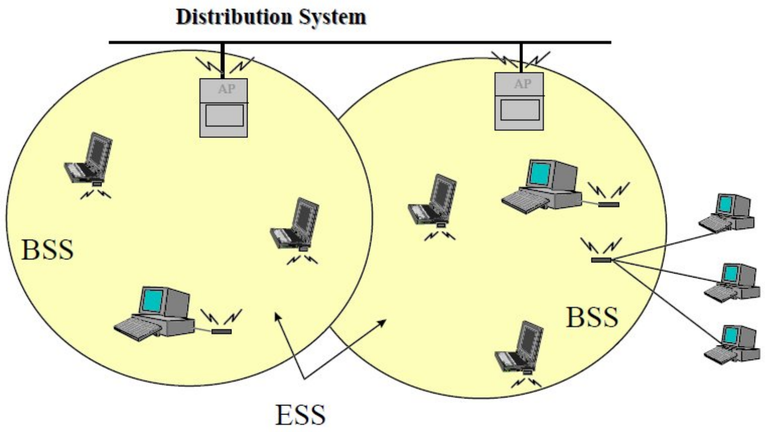


Figure 2.3: Wi-Fi generic architecture (source: [Bre97, Cal06]).

Physical (PHY) layer description

When the IEEE 802.11 standard was approved, it was designed to be used with three different PHYs: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and InfraRed (IR). Figure 2.4 presents the interaction among the different layers in the IEEE 802.11.

Concerning the IEEE 802.11a standard, it uses the basic concepts of the IEEE 802.11. It operates in the worldwide license free band Industry, Scientific and Medical (ISM). IEEE 802.11a uses OFDM, being able to transmit at rates up to 54 Mbps; nevertheless, it can be adjusted to 48, 36, 24, 18, 12, 9 or 6 Mbit/s, depending on channel conditions. IEEE 802.11a uses 12 non-overlapped channels, 8 and 4 for indoor and point-to-point use, respectively.

Regarding IEEE 802.11b, it uses CCK, a variation of Code Division Multiple Access (CDMA) which is based on the DSSS, and reaching from 1 and 2 up to 5.5 and 11 Mbps. IEEE 802.11b works on the 2.4 GHz band, similarly to 802.11g. Concerning

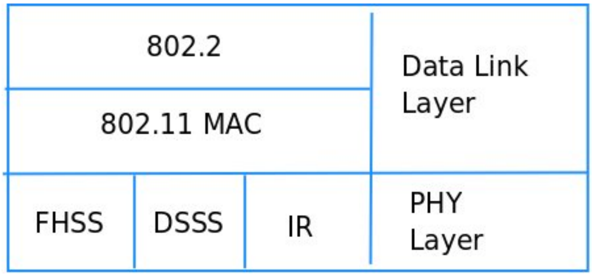


Figure 2.4: 802.11 layers interaction.

IEEE 802.11g, the maximum data rate offered is 54 Mbps. However, IEEE 802.11g due to its variety of modulation methods, supports the same data rates as IEEE 802.11b, achieving full compatibility between both standards. For data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps it uses OFDM, while for 5.5 and 11 Mbps it uses CCK.

The IEEE 802.11n is the most recent specification available with the IEEE 802.11 standard. This specification achieves higher performance due to changes to the OFDM implementation, and to the introduction of Multiple Input-Multiple Output (MIMO) mechanisms by using a new antenna technology for transmission and reception, achieving data rates up to 300 Mbps.

Medium Access Control (MAC) layer description

The 802.11 uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism to access the medium in order to transmit. In order to transmit, a node listens (*i.e.*, *carrier sensing*) for a clear channel and then transmits. It then listens for an acknowledgement (ACK) and, if it does not receive it, backs off for a random period of time (*i.e.*, *contention period*), and then listens for a clear channel before retransmiting again. Since the retransmission is based on a random time, all the nodes within the BSS have a high probability of accessing the channel at the same time (on average). Figure 2.5 illustrates the CSMA/CA mechanism, showing the different periods to access the medium.

2.1.2 Worldwide interoperability for Microwave Access (WiMAX)

Similarly to Wi-Fi, the term WiMAX comes from a Certification Alliance: the WiMAX Forum. The protocol family that determines the rules and specifications of this technology is the IEEE 802.16 [IEEb]. This set of protocols allows transmitting at high rates and long distances using a wireless link. Depending on the specific protocol

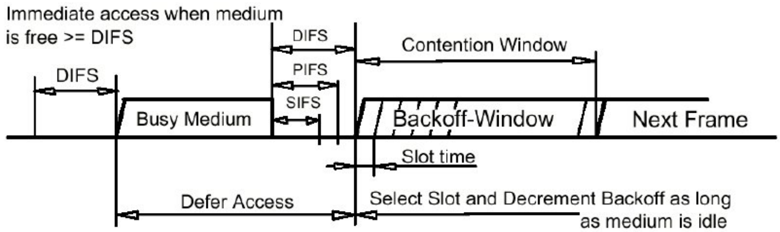


Figure 2.5: 802.11 layers interaction (source: [Cal06]).

Table 2.2: IEEE 802.16 protocols.

Protocol 802.16	**Date**	**Data rate (Mbps)**	**Frequency (GHz)**
d - Fixed	2004	70	10 - 66
e - Mobile	2005	70	2 - 11
2009(d+e)	2009	70	2 - 66

used, the data rate could vary from 2 up to 144 Mbps within a 70 km radius when in clear line of sight. Table 2.2 presents the features of the main protocols in the 802.16 family. Currently, the 802.16m standard is being developed in order to offer data rates of up to 1 Gbps for fixed stations, and 100 Mbps for mobile ones. WiMAX offers flexibility by operating in both license and unlicensed bands.

Nowadays, WiMAX is one of the most successful broadband wireless access technologies, being expected to deliver broadband access services to residential and enterprise customers in an economical and efficient way. WiMAX is able to provide service even in areas that are difficult or inaccessible for wired infrastructure to reach, having the ability to overcome the physical limitations of traditional wired infrastructure. WiMAX changes the last mile issue for broadband in the same way as Wi-Fi has changed the last one hundred meters of LANs. It can satisfy diverse access needs, extending broadband capabilities to fulfill subscribers needs, filling gaps in cable, Digital Subscriber Line (DSL) and T1 services, Wi-Fi and cellular back-haul.

Architecture

The WiMAX network architecture envisions a model able to support fixed and mobile deployments based on an Internet Protocol (IP) model. Figure 2.6 illustrates the most important entities of the WiMAX network architecture model. The overall network is divided into:

Mobile Station (MS). Mobile device used by the end-user to access the network.

Subscriber Station (SS). Fixed device used by the end-user to access the network.

Base Station (BS). Responsible of handling the connectivity to the MS. Moreover, it is in charge of the micromobility management functions (*e.g.*, handover issues, tunneling management, QoS policies, radio resource management, session and mobility management).

Access Service Network (ASN). Composed by one or more BS and one or more Access Service Network Gateways (ASN-GWs) that build the radio access network at the edge.

Access Service Network Gateway (ASN-GW) It usually acts as a Layer 2 traffic aggregation element. Some other functions might be performed by the ASN-GW (*e.g.*, admission control, caching of SS profiles).

Connectivity Service Network (CSN). Provides IP connectivity and all the IP core network functions, connecting to the Internet, other public networks, and corporate networks. The CSN includes Authentication, Authorization, and Accounting (AAA) servers that support authentication for devices and users. It also provides per user policy management of QoS and security. The CSN is also responsible for IP address management, support for mobility and roaming.

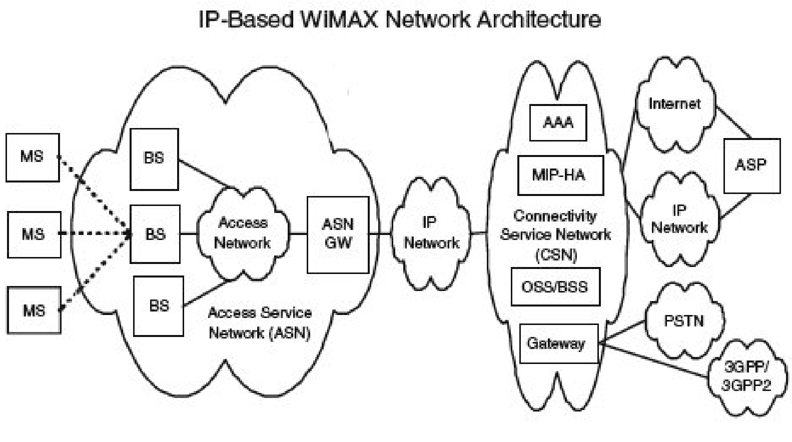


Figure 2.6: WiMAX generic architecture (source: *intel.com*).

PHY layer description

WiMAX supports a variety of modulation and coding schemes which can be changed on a burst-by-burst basis per link, depending on channel conditions. Using the chan-

Table 2.3: IEEE 802.16 modulation and coding.

Parameter	Downlink	Uplink
Modulation	Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (QAM), 64 QAM; BPSK optional for OFDMA-PHY	QPSK, 16 QAM; 64 QAM optional
Coding	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition codes at rate 1/2, 1/3, 1/6, Low Density Parity Check (LDPC), Reed–Solomon Codes (RS-Codes) for OFDM-PHY	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition codes at rate 1/2, 1/3, 1/6, LDPC

nel quality indicator, the MS can provide the BS with feedback on the downlink channel quality. For the uplink, the BS estimates the channel quality based on the Received Signal Strength (RSS) quality. However, 802.16d uses OFDM, while 802.16e uses Orthogonal Frequency-Division Multiple Access (OFDMA) for the PHY mode. However, WiMAX can also be deployed as Time Division Duplex (TDD), Frequency Division Duplex (FDD) and half duplex FDD. The most common mode is TDD since it allows a greater efficiency in spectrum usage than the FDD mode. By using TDD, MS, SS and BS are able to transmit at the same frequency, but using time slots in order to avoid interfering with each other. Table 2.3 presents the modulation and coding schemes that WiMAX is able to support. Moreover, Table 2.4 presents the obtainable data rates for different combinations of modulation and coding in WiMAX.

MAC layer description

The WiMAX MAC offers several important types of applications within different mobility degree levels, such as:

- Security and Privacy.
- Multi-point and single-point connectivity.
- Improved handovers and mobility support.

Table 2.4: IEEE 802.16 data rates based on modulation and coding.

Channel Bandwidth	3.5 MHz		1.25 MHz		5 MHz		10 MHz	
PHY mode	256 OFDM		128 OFDMA		512 OFDMA		1,024 OFDMA	
Oversampling	8/7		28/25		28/25		28/25	
Modulation & Code Rate	**PHY-Layer Data Rate (kbps)**							
	DL	UL	DL	UL	DL	UL	DL	UL
BPSK, 1/2	946	326	NOT APPLICABLE					
QPSK, 1/2	1,822	653	504	154	2,520	653	5,040	1,344
QPSK, 3/4	2,822	979	756	230	3,780	979	7,560	2,016
16 QAM, 1/2	3,763	1,306	1,008	307	5,040	1,306	10,080	2,688
16 QAM, 3/4	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032
64 QAM, 1/2	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032
64 QAM, 2/3	7,526	2,611	2,016	614	10,080	2,611	20,160	5,376
64 QAM, 3/4	8,467	2,938	2,268	691	11,340	2,938	22,680	6,048
64 QAM, 5/6	9,408	3,264	2,520	768	12,600	3,264	25,200	6,720

- Efficient use of the spectrum by applying header suppression, packing and fragmentation.
- Five QoS classes: Unsolicited Grant Service (UGS), Real-Time Polling Service (rtPS), Non-Real-Time Polling Service (nrtPS), Best Effort (BE), and Extended Real-Time Variable Rate (ERT-VR).

These BSs use the MAC layer allocating uplink and downlink bandwidth to subscribers as per their individual needs. This is basically done on a real-time need basis.

For the different formats: IEEE 802.16-2004 and IEEE 802.16e-2005, the WiMAX MAC layer design (see Figure 2.7) includes a convergence sublayer to operate with different higher-layer protocols, such as Ethernet, IP, Asynchronous Transfer Mode (ATM), and other protocols that may be developed in the future. The Privacy layer supports the Extensible Authentication Protocol (EAP), as well as the Privacy Key Management (PKM) protocol to offer security at the MAC level.

2.1.3 Universal Mobile Telecommunications System (UMTS)

UMTS addresses the ever-growing demand of mobile applications to improve the transmission speed and establish global handover rules. The third generation of mobile communications introduces important features such as intelligent network

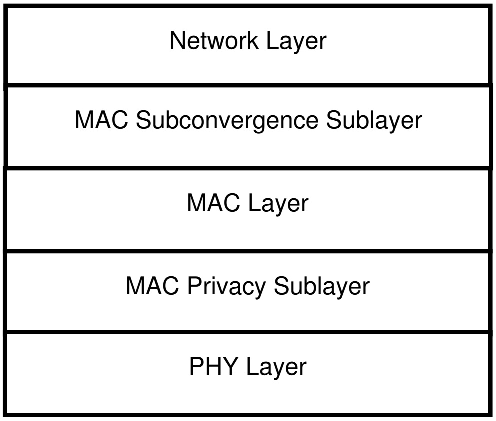


Figure 2.7: WiMAX MAC layers.

Table 2.5: 3GPP standards.

Protocol	**Date**	**Data rate (Mbps)**	**Frequency (MHz)**
GPRS	1997	0.8	
EDGE	2003	0.15	
UMTS	2005	2	850 /900 /1700 /1900 /2100
HDSPA	2007	7.2	
LTE	2010	> 100	

services, enhanced speech compression/decompression, and high data rates up to 7.2 Mbps (downlink) and 2 Mbps (uplink), depending on factors such as mobility, speed, available throughput and UMTS version [3GP06]. UMTS uses CDMA in order to access the medium; nevertheless, Time Division Multiple Access (TDMA) is still required to provide backwards compatibility with the General Packet Radio System (GPRS). Table 2.5 presents the evolution of the different Third Generation Partnership Project (3GPP) protocols.

Architecture

Basically, as shown in Figure 2.8, the UMTS architecture is mainly composed by:

Correspondent Node (CN). The core network architecture of UMTS is deployed on top of the GPRS architecture. There are two different domains: i) the Circuit Switching (CS) domain and ii) Packet Switching (PS) domain. Circuit switching is composed by the Mobile Switching Center (MSC), the Visitor Locator

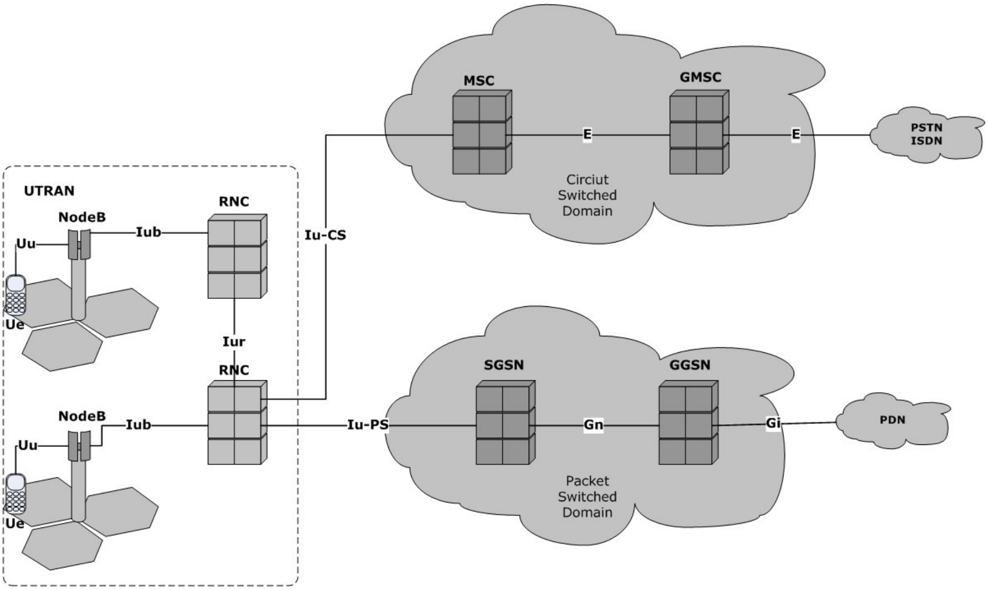


Figure 2.8: UMTS architecture (source: *Telecom*).

Register (VLR) and the gateway MSC. Regarding packet switching, it offers backwards compatibility with GPRS; it is composed by the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN).

UMTS Terrestrial Radio Access Network (UTRAN). It is composed by the Node B and by the Radio Network Controller (RNC). UTRAN manages the access to the radio mobility and resource allocation. The RNC builds the logical connection between the User Equipment (UE) and the CN. UTRAN uses internal and external interfaces in order to connect the different elements: Uu, Iub and Iur.

User Equipment (UE). The UE is the mobile radio terminal used by the subscriber to access to the UTRAN. This can be a mobile phone, a Personal Digital Assistant (PDA) or any type of radio communication device. The UE is connected to the node B (BS), and it is usually identified by the Subscriber Identity Module (SIM).

Node B. It provides communication to the radio cells. Node B is the radio transceiver unit, and it connects the UE via Wide-band Code Division Multiple Access (WCDMA); the node B also provides TDD and FDD.

2.2 Vehicular Networks (VNs) overview

Within VNs a vehicle is considered as a node of the network, being equipped with multiple interfaces that provide access to different technologies such as Global Positioning System (GPS), Wi-Fi, WiMAX, UMTS and Long Term Evolution (LTE). Vehicles are able to communicate among them and with their Point of Attachments (PoAs) (APs or BSs) under the *Ad-hoc* or the infrastructure mode [BF08], respectively. Figure 2.9 illustrates the manner that vehicles are able to communicate among them and between the different technology BSs.

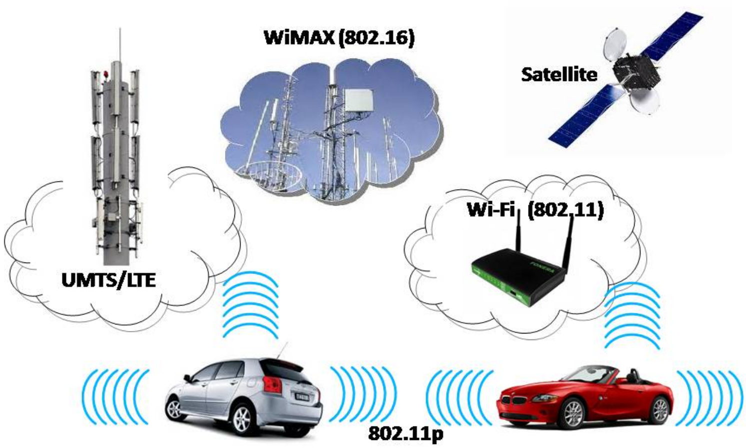


Figure 2.9: Vehicular Network (VN).

VNs offer many application branches, which can be classified into two main categories:

- ***safety***, such as emergency warning systems for vehicles, transit or emergency vehicle priority signaling, etc.
- ***non-safety***. As examples, we have cooperative adaptive cruise control, electronic parking and toll payments, infotainment services, and content delivery, among others.

Vehicular *Ad-hoc* Networks (VANETs) are a class of VNs that rely on direct communication between vehicles [CG07]. VANETs are becoming an important area for research and development since they allow creating a fully functional network when no support infrastructure is available. In an *Urban scenario* multiple short and wide range wireless technologies are available covering different areas. Regardless of the wireless technologies used, the specific characteristics of VANETs can be summarized in terms of:

- *topology restrictions.*
- *mobility patterns.*
- *power consumption.*
- *scalability.*
- *node reliability.*
- *speed.*

In a generic VANET scenario every vehicle behaves as a node in the network, being equipped with an On-board Unit device (OBU) able to receive and relay messages of other vehicles through the ad-hoc wireless network. Vehicles can also communicate with fixed communication elements, called Roadside Units (RSU), to reach an infrastructure. Figure 2.10 shows a generic VANET architecture, where vehicles are equipped with on-board units and some buildings or street furniture have embedded roadside units.

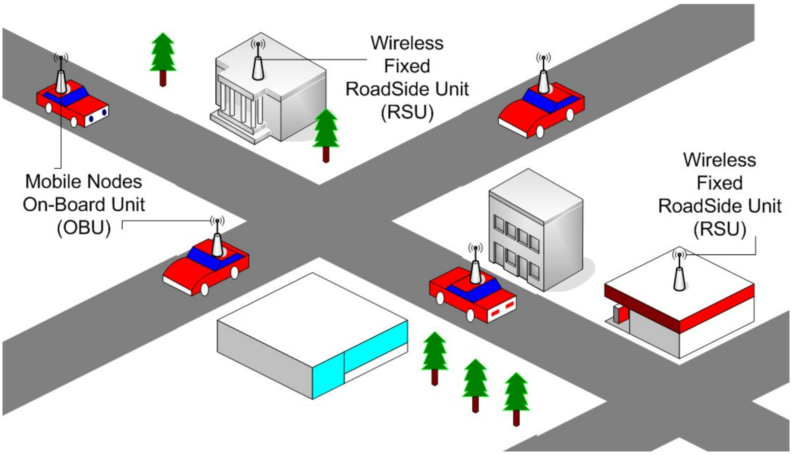


Figure 2.10: Vehicular *Ad-hoc* Network (VANET).

Notice that we use the acronym VN referring to wide area networks where vehicles are interconnected through a base station, and not referring to VANETs where the vehicles are connected among them using a short-range wireless technology.

Several worldwide projects are being developed and promoted in order to provide solutions to reinforce safety and to extend the use of non-safety applications on cars and highways through the use of wireless technologies. Industry, researchers and governments are working towards a standardization for those solutions: Europe, through projects and consortiums such as Car2Car Communication Consortium, Network on Wheels, and Safespot; USA, through the Vehicle Safety Consortium (VSC), Vehicular Infrastructure Integration (VII) and Intelligent Vehicle Highway Systems (IVHS); finally, Japanese projects Advanced Safety Vehicle (ASV) and Advanced Highway Systems (AHS) focus their efforts on setting common issues such as frequency allocation, protocol definition and infrastructure deployment [JK08, MD10].

Wireless Access in Vehicular Environments (WAVE) [IEE06b] is a standard developed for Vehicular Networks to satisfy the communication needs of a large class of applications. The WAVE protocol architecture results from the combination of the IEEE P802.11p standard [IEE06a], for layers PHY/MAC and, the IEEE P1609 [IEE06b] family of protocols, for the application layers. These protocols must be efficient and reliable in order to provide safety and comfort services to passengers via context sensitive applications, as well as low latencies to deliver contents within acceptable time bounds.

The International Organization for Standardization (ISO) is also working towards a seamless connectivity solution for a wide variety of wireless access technologies. This proposal, called Continuous Air Interface for Long and Medium Range (CALM M5), has been specifically designed to reduce the end-to-end communication latency in mobile environments such as VNs [San09], and also works on top of IEEE 802.11p.

2.3 Summary

Wireless technologies are being applied in different areas of the science and the industry. Currently, there are different wireless technologies available characterized by heterogeneous capabilities and performances. In the case of VNs, the most common underlying technologies used are Wi-Fi, WiMAX and UMTS. Concerning VANETs, different standards are being promoted depending on the consortium that leads the project. However, in both types of networks, their goals converge into reinforcing the passengers' safety, and powering the access to infotainment contents.

Chapter 3

Vertical Handover (VHO) Overview

3.1 Introduction

The integration of different wireless network technologies is needed to provide a "seamless" interoperability, integration and convergence among heterogeneous technologies and, therefore, the use of *VHO* techniques are required.

Concerning *Horizontal and Vertical handover*, Figure 3.1 illustrates both horizontal and vertical handover events. Akyildiz *et al.* [AXM04] refer to the horizontal handover as *intrasystem handover*, and to vertical handover as *intersystem*; other authors [CMSM04] prefer the terms *intradomain* and *extradomain*, respectively. Nevertheless, considering IP-Based networks, when the handover occurs within the same domain it is called *micromobility*, while *macromobility* denotes that the mobile device has reached a Point of Attachment (PoA) of a different domain.

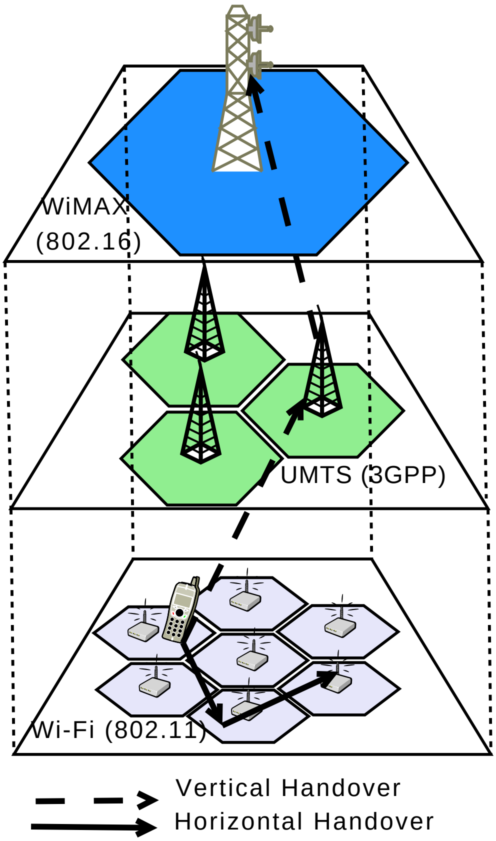


Figure 3.1: Illustration of the horizontal and vertical handover processes.

Handover techniques have been widely studied in the cellular communications domain, and their popularity is increasing among IP-based wireless networks [CSYG06]. Handover is considered "seamless" when it is able to maintain the connectivity of all applications running on the mobile device, providing a continuous end-to-end data service within the same session during the switchover, offering both low latency and minimal packet loss.

One of the first approaches in order to provide seamless connectivity among heterogeneous networks appeared during the late nineties. Stemm and Katz [SK98] presented an implementation that gathered Mobile IP and routing aspects, together in an application developed to manage the handover process. This implementation was based on the technology available in those days that considered the IBM Infrared Wireless LAN, the AT&T WaveLAN and the Metricom Ricochet Network as in-building, campus, and wide area underlying wireless technologies, respectively. These first studies evidenced that vertical handover is a must when dealing with a variety of technologies.

More recently, various works appeared covering the VHO among heterogeneous technologies including: Universal Mobile Telecommunications System (UMTS) and Wireless Fidelity (Wi-Fi) [LC08], Long Term Evolution (LTE) and Wi-Fi [BCS11], Wi-Fi and Wireless Broadband (WiBro) [KKL+08a], Wi-Fi and Worldwide interoperability for Microwave Access (WiMAX) [Wri07], WiMAX and UMTS [JC08], WiBro and UMTS [JH07], WiMAX and ZigBee [LC10d], Wi-Fi and ZigBee [LC10b], UMTS and ZigBee [CTK10] ,WiMAX, Wi-Fi and UMTS [AIJ08], WiMAX and Radio Frequency Identification (RFID) [LC10c], Wi-Fi and RFID [LC10e], Bluetooth (BT) and Wi-Fi [Cor06, LC10a], broadcast communication technologies like Digital Video Broadcasting (DVB) and Multimedia Broadcast/Multicast Service (MBMS) [BMM+07b, YUL12, SAMFJ12], or even UMTS and Low Earth Orbit (LEO) satellite [NZ09, ARG10]. Considering networking technologies, Table 3.1 shows the technologies used by the different proposals. As observed, most proposals (75.21%) evaluate the VHO using only two technologies, being that the remaining 24.79% of the proposals have considered three technologies instead. In addition, about 44.44% of the proposals focus on evaluating the VHO viability between Wi-Fi and UMTS. The main drawback of this broad variety of solutions stands in the fact that none proposes a unique homogeneous approach that can be adapted to all the available wireless technologies.

Table 3.1: Networking technologies used in VHO studies.

Proposals	**%**	**Networking Technologies**										
		Wi-Fi	WiMAX	WiBro	UMTS	GPRS	Bluetooth	Ethernet	Zigbee	Satellite	RFID	LTE
Two Technologies												
[LZ05, AMA07, YMP05, LSL08, TYKO08, KYPV08, IVNC08, KKL08b, FHS+09, LSK+09, SS05, LCX07, KKP07, KKP08a, KKP08b, KP07, YGQD07, MC05, XLGCHW08, HBG07, LC08, LVV08, Qiu11, CMSC10, JSHS10, EVMN10, ZZXZ10, CSZ+10, KT10, ASS10, NAST10, COP10, WSS+10, QDlB+10, QBYSz10, He10a, CWHN10, HCZ10, LPM+10, CZC+10, He10b, TYW10, DEBEH10, CTXC10, Pil10, KGG10, MAHAA+10, LYS+10, BUA10, GSZS10, EGB12, SP12]	44.44	★			★							

Table 3.1: Networking technologies used in VHO studies.

Proposals	**%**	**Networking Technologies**										
		Wi-Fi	WiMAX	WiBro	UMTS	GPRS	Bluetooth	Ethernet	Zigbee	Satellite	RFID	LTE
[BCS11]	0.85	★										★
[CYS^{+}05, UPHA11, UPHA11]	2.56	★						★				
[Cor06, LC10a]	1.71	★					★					
[JC08, AIJ08, NOT10, JZH12]	3.42		★		★							
[PHK^{+}08]	0.85			★	★							
[KKL^{+}08a]	0.85	★		★								
[PFMM07]	0.85	★				★						
[LC10b]	0.85	★							★			
[LC10d]	0.85		★						★			
[CTK10]	0.85				★				★			
[LC10c]	0.85		★								★	
[LC10e]	0.85	★									★	
[CHL09, IJL^{+}10, LRO^{+}10, PMBJ10, MFC10, YSK^{+}10, VOF10, MCF10, MFC10, CKM10, AAMBG10, TKG10, NKT^{+}10, RG10, SC10a, ASWGT12, SAMFJ12, MM12]	15.38	★	★									
Three Technologies												
[BN08, LBHB08, CC08, YJY^{+}08, Wri07, NH09, SHTW09, TP10, Baz10, FK12, Lu10, TB10, CC10a, KS10, MMPRSN10, DEN^{+}10, SV10, Mit10, DDBR12]	16.24	★	★		★							
[GS08, SNW06, APFH10a]	2.56	★			★	★						
[CSYG06]	0.85	★					★	★				
[JH07]	0.82	★	★	★								
[LORG10, WGMaV10]	1.71	★			★			★				
[BCI04]	0.85	★				★		★				
[ARG10]	0.85	★	★							★		
[RPR12]	0.85	★	★									★

The research community has been making significant efforts towards the convergence of the different wireless networking technologies. As a consequence, there are different proposals addressing heterogeneous scenarios, protocols, handover techniques and algorithms, network technologies, metrics, and procedures. In addition, since 2004, the IEEE 802.21 Working Group has been working in the Media Independent Handover Services Protocol [80209] whose purpose is to provide a homogeneous function-interface between heterogeneous network technologies, offering standard handover services between lower and upper layers. The IEEE 802.21 standard was finally approved in November 2008. Nevertheless, there have been early proposals and studies addressing the performance of 802.21 and offering improvements in terms of VHO effectiveness [DLOMV+07, BN08, DDF+07]. Recently, there are few studies and proposals concerning the IEEE 802.21 standard and its performance [VOF11, VF11, DLOEB+11] as well as real implementation on operation systems, smartphones devices [ITKK11, APF+11, CGSA11] and tablet devices [SGC+12].

In this chapter we survey the most significant proposals found in the literature concerning VHO techniques, including both independent proposals and standards. In addition, we emphasize on the VHO process from a Vehicular Networks (VNs) perspective , highlighting those techniques and algorithms that better fit to this type of networks. This survey can be useful to the research community since most proposals in the literature merely evaluate specific VHO techniques *per se*. Notice that we use the acronym VNs referring to wide area networks where vehicles are interconnected through a Base Station (BS) or Access Point (AP), and not referring to Vehicular *Ad-hoc* Networks (VANETs), where the vehicles are connected among them using a short-range wireless technology (please refer to Section 2.2).

3.2 IEEE 802.21 Protocol: Media Independent Handover Services

3.2.1 Media Independent Handover Function (MIHF)

The MIHF protocol defined by the IEEE 802.21 standard establishes the messages exchanged between peer Media Independent Handover (MIH) entities for handover, offering a common message payload across different media (802.3, 802.11, 802.16, Cellular). The standard refers as *lower layers* to the technology dependent components, and as *upper layers* to the requesting modules. These lower layers can be accessed by different functions to retrieve information to detect, prepare and execute the VHO, while the upper ones demand that information; therefore, the latter are also referred to as *Media Independent Handover User (MIHU)*. The MIHF offers a Service Access Point (SAP) to both lower and upper layers in order to exchange the service messages. Figure 3.2 shows the basic 802.21 architecture.

The general design principles of the standard are based on [80209]:

- MIHF is a logical entity that facilitates handover decision-making. MIH users make handover decisions based on inputs from the MIHF.

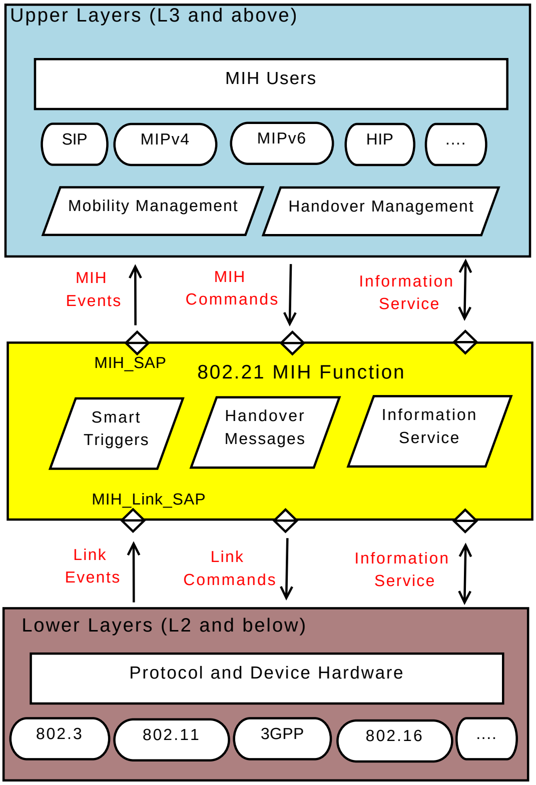


Figure 3.2: IEEE 802.21 architecture.

- MIHF provides abstracted services to higher layers. The service primitives defined by this interface are based on the technology-specific protocol entities of the different access networks. The MIHF communicates with the lower layers of the mobility-management protocol stack through technology-specific interfaces. Figure 3.3 presents the reference model showing the position of the MIHF in a protocol stack, and the interaction of the MIHF with other elements of the system. All exchanges between the MIHF and other functional entities occur through service primitives, grouped in SAPs [80209].

- Higher layer mobility management protocols specify handover signaling mechanisms for vertical handovers. Additionally, different access network technologies have defined handover signaling mechanisms to facilitate horizontal handovers. The definition of such handover signaling mechanisms is outside the scope of the standard. The role of the IEEE 802.21 is to serve as a handover facilitating service, and to maximize the efficiency of such handovers by providing appro-

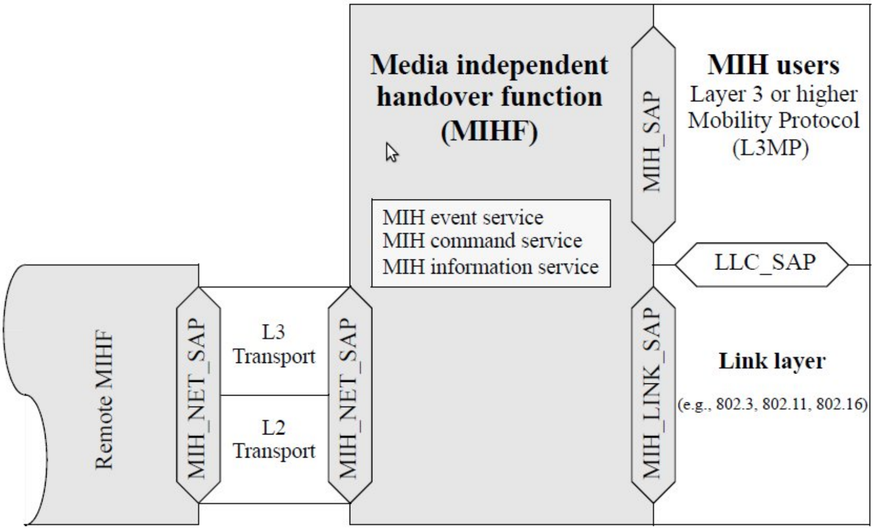


Figure 3.3: MIHF reference model (source:[80209]).

priate link-layer intelligence and network information. Figure 3.4 presents the interaction and relationship among the different link layers. The gray arrows show the MIH signaling over the network; black arrows show local interactions between the MIHF and lower/higher layers in the same network.

- The standard provides support for remote events. Events are *advisory* in nature. The decision whether to cause a handover or not based on these events is outside the scope of this standard.

The basic services offered by the MIHF are briefly described below:

Media Independent Event Service (MIES)

This service detects the changes on the lower layers, *e.g.*, changes on the physical and data link layer. The MIHF notifies events occurring in the lower layers to the MIHUs as they have requested. The MIES covers events such as:

- State change events (link up, link down, link parameter changes).
- Predictive events (link going down).
- Network initiated events (load balancing, operator preferences).

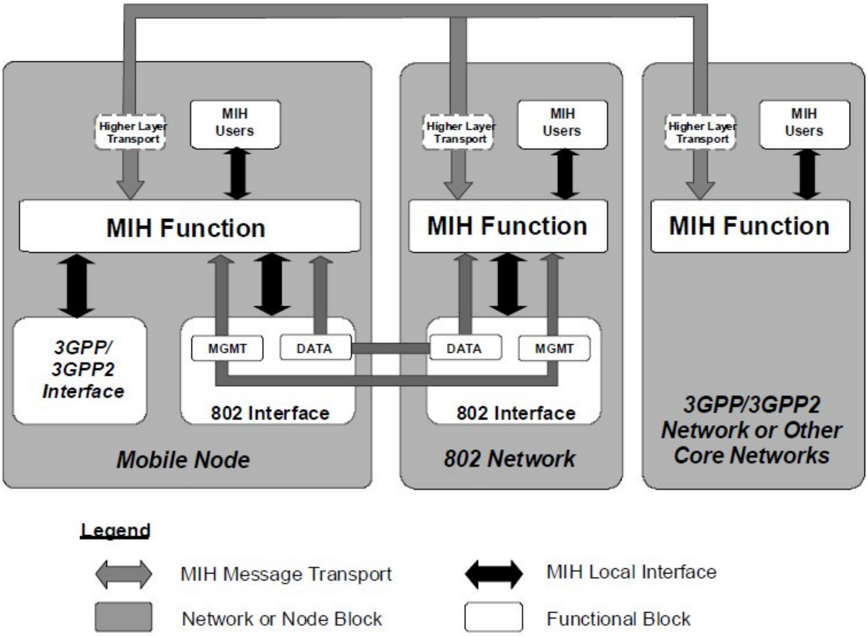


Figure 3.4: MIHF relationship (source:[80209]).

Media Independent Information Service (MIIS)

The MIIS allows the MIHF to discover its network environment by gathering information that the upper layers use to make decisions. The information elements refers to the list of available networks, location of PoA, operator ID, roaming partners, cost, security, QoS, PoA capabilities, and Vendor specific information, among others.

Media Independent Command Service (MICS)

The MICS allows the MIHU to take control over the lower layers through a set of commands. With the information gathered by the MIES and MIIS, the MIHU decides whether to switch from one PoA to another. The commands allow not only to execute the handover, but also to set different parameters in the lower layers elements. Depending on which entity has the handover control, some services are more useful than others. The following commands are typically used by the MICS:

MIH Handover Initiate. Used between network and mobile device.

MIH Handover Prepare. Used between the old network (PoA) and the new network.

MIH Handover Commit. Used between network and mobile device.

MIH Handover Complete. Used between network and mobile device and network to network.

Amendments

In order to fully provide handover services, the 802.21 must be implemented into network devices and mobile devices. The media specific amendments required by MIHF are defined as follows:

- Container for MIH messages for 802.11 are defined in the 802.11u [IEE04].
- Container for MIH messages for 802.16 are defined in the 802.16g [IEE07].
- The 3GPP-SAE (System Architecture Evolution) is working for 3GPP [3GP06].
- The IEFT MIPSHOP (Mobility for IP: Performance, Signaling and Handoff Optimization) produces the required enhancements and/or specifications for IP-based support of the MIH Protocol [MIP04].
- 802.3 is desired.
- 802.21a-2012 provides security mechanisms to protect media independent handover services, based on proactive authentication (Extensible Authentication Protocol (EAP)). [Gro12a].
- 802.21b-2012 is an extension for supporting handovers with downlink only technologies [Gro12b].

MIHF network model

A reference network model is presented in Figure 3.5, which includes MIH services. As observed, the model includes Mobile Nodes (MNs) capable to operate with the MIH primitives. MNs are powered by multiple wired and wireless interfaces to be able to access different technologies (also known as *multihomed devices*). The serving network is able to operate with multiple underlying technologies or permits users to roam into different networks when there is a Service Level Agreement (SLA) among providers offering MIH services in their access networks in order to facilitate heterogeneous handovers.

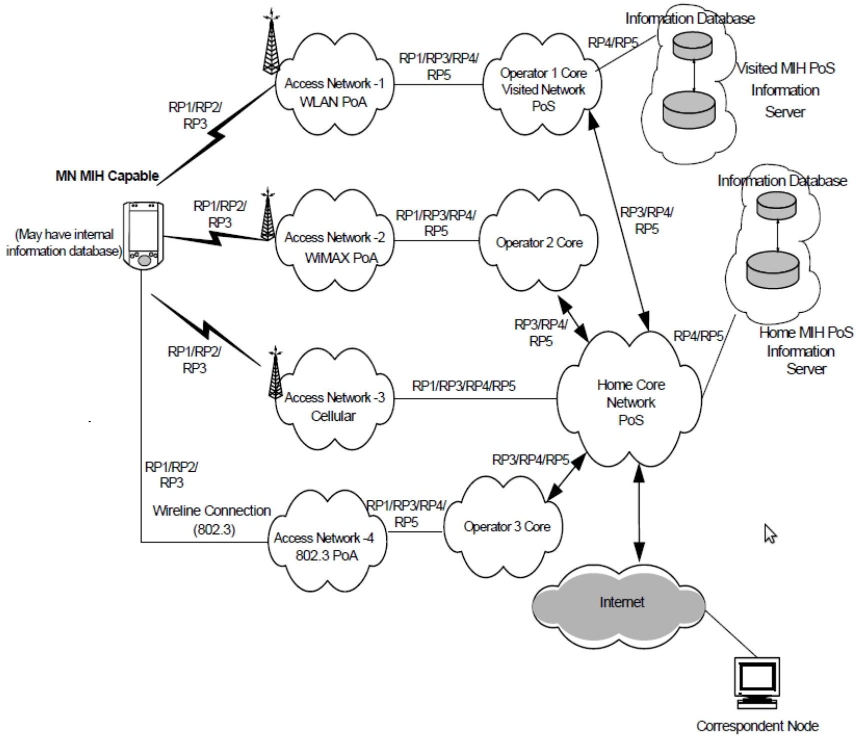


Figure 3.5: IEEE 802.21 network example (source:[80209]).

Finally, Figure 3.6 illustrates a VHO among UMTS and Wi-Fi based on the MIHF functionalities. It shows the signaling flow among the different elements of the network model.

3.3 Vertical handover overview

An accurate VHO process should take into account and care about the service continuity, network discovery, network selection, security, device's power-management and Quality of Service (QoS) issues [Cor06, CYS+05, CHL09], focusing mostly on the latter. Several proposals [KKP08a, KKP08b, SNLW08] split the VHO process into three parts: i) Handover information gathering, ii) Handover decision, and iii) Handover execution. Figure 3.7 shows the interactions among the three phases required to implement handover in heterogeneous networks.

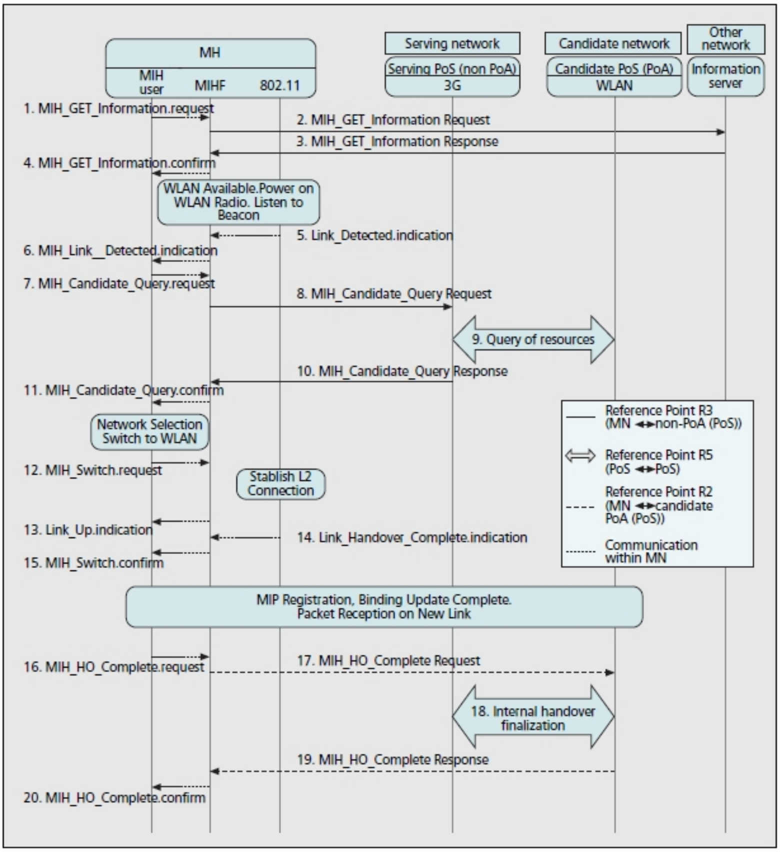


Figure 3.6: IEEE 802.21 VHO example (source:[DLOBS+08]).

3.3.1 Handover information gathering

The handover information gathering phase collects not only network information, but also information about the rest of the components of the system such as network properties, mobile devices, access points, and user preferences. For that reason this phase receives different names: *Handover information gathering* [KKP07], *System discovery* [SP07], *System detection* [CSC+04], *Handover initiation* [Gup06, IVNC08], *Information discovery* [OK10] or simply *Network discovery* [SZ06, DDF+07, GS08, LZ10]. In this phase, the information is collected to be used and processed for making decisions in the handover decision phase. The information typically collected is the following:

- Availability of neighboring network links by offering information such as through-

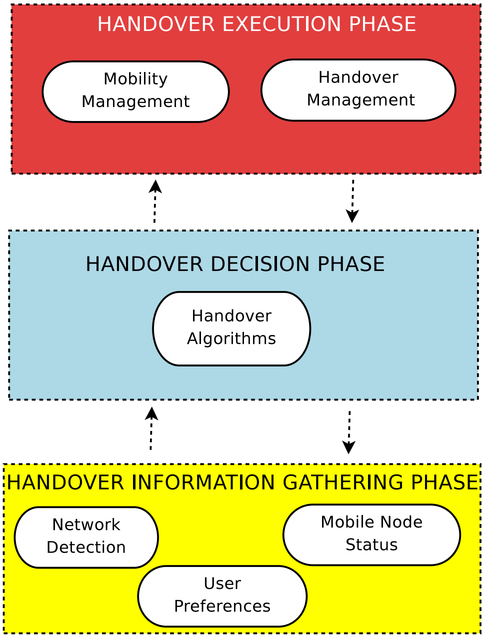


Figure 3.7: Handover management procedure.

put, cost, packet loss ratio, handoff rate, Received Signal Strength (RSS), Noise Signal Ratio (NSR), Committed Information Rate (CIR), Signal to Interference Ratio (SIR), Bit Error Ratio (BER), distance, location, and QoS parameters.

- The mobile device's state by gathering information about battery status, resources, speed, and service class.
- User preferences information such as budget and services required.

Section 3.4 describes this phase along with the techniques used by the different proposals to perform the data gathering task.

3.3.2 Handover decision

The handover decision phase is one of the most critical processes during the handover. This phase is also know as *System selection* [KKP08b], *Network selection* [KKP08a, GS08] or *Handover preparation* [Gup06]. Based on the gathered information, this phase is in charge of deciding *When* and *Where* to trigger the handover. The *When* decision refers to the precise instant in time to make an optimal handover, while the *Where* refers to selecting the best network fulfilling our requirements for the switching.

In a homogeneous network environment, deciding *When* to handover usually depends on RSS values, while the *Where* is not an issue since we use the same networking technology (horizontal handover). In heterogeneous networks the answer to these questions is quite complex. To make the best decision the information gathered must be evaluated taking into account many parameters obtained from the different information sources, *i.e.*, network, mobile devices, and user preferences. Vertical Handover Decision Algorithms (VHDAs) are used to weight up and evaluate the parameters involved under each specific criteria. As examples of algorithms allowing to evaluate cross-layer multi-parameters we have techniques such as fuzzy logic, neural networks, and pattern recognition, among others. Section 3.5 presents a brief description and a taxonomy of the VHDA found in the literature.

3.3.3 Handover execution

This phase performs the handover itself; besides performing the handover, it should also guarantee a smooth session transition process. In order to perform the VHO different handover strategies cooperate with control signaling, and the IP management protocols. This phase is usually known as *Handover execution* [SP07, KKP07, SNLW08], but it also receives the name of *VHO assessment* [IVNC08], *Handoff Implementation* [SZ06] or *Handoff performing* [LZ10]. A detailed description of the execution phase is presented in Section 3.6.

Concerning VNs, the performance of each phase must be focused on the distinctive characteristics and features of such type of networks. The information gathering phase must consider the dynamism of the available information at the devices and the network. Making decisions based on highly dynamic information with a given degree of the device's mobility requires a quick and reliable decision algorithm. Finally, the execution of the VHO must be carefully controlled to achieve accuracy by considering the geographical location, the selected network and the precise time.

3.4 Handover information gathering phase

In order to perform an *"always best connected"* handover [GJ03], a full set of information is gathered and provided to the decision phase. To collect the available information from different sources, the mobile device surveys the surrounding networks in order to discover services, data rates, and power consumption. As a complement to the information gathered through scanning, networks may also advertise their supported services and QoS parameters, while the device information is also collected, *i.e.*, speed, battery status, features, and so on. Finally, information concerning user preferences is also a relevant element to the decision-making process, mostly due to its impact on the end-user's satisfaction.

Table 3.2: Information parameters pertinent to the VHO process.

Layers	**Parameters**
Application	User preferences (*e.g.*, cost, provider)
	Context information (*e.g.*, speed)
	Location information (*e.g.*, geolocation)
	QoS parameters (*e.g.*, bw offered, delay, jitter)
	Security alerts (*e.g.*, notifications)
Transport	Network load (*e.g.*, bw available)
Network	Available foreign agents
	Network pre-authentication
	Network configuration
	Network topology
	Routing information
Data-link	Radio access network conditions
	Link parameters
	Link status
Physical	Available access media

Gathering information reliably is crucial for the VHO process since the decision-making procedure relies on that data. Table 3.2 presents the information that should be taken into account in order to maximize the benefits of decision-making. It clearly shows that information should be collected at each and every layer of the protocol stack in order to cover all the possible information sources. Moreover, Table 3.3 presents diverse parameters used by different authors in their proposals and works (see Section 3.7.1).

Different proposals addressing this phase are based not only in monitoring different layers, but also by implementing events and triggered notifications. Attaullah *et al.* [AIJ08] present a trigger management system that monitors and collects multi-level parameters. Similarly, works [TYKO08] and [KKL+08a] present modules called "Link Layer State" and "Network Connection Module", respectively, where both perform the same monitoring task. An xml-based process is used by a CORBA communication middleware to gather information and to notify events in [OLSK04]. Seigneur *et al.* [STM10] use different operating system's Application Programming Interfaces (APIs) to monitor the device and the network in order to evaluate the electrosmog exposure to trigger the VHO.

Several proposals [DDF+07, SNLW08, LSK+09, JS10, WMPB10, MW10, JKPP10, JCYS10, WZZ+10, GRG10, DLOEB+11] rely on the MIIS mechanism offered by the IEEE 802.21 standard for this phase, which allows interaction with a wide set of wireless technologies in a unified manner. The 802.21 addresses the optimization of both network detection and selection by providing a source of extensible and semantically defined information to facilitate optimized handover decision-making [Gup06]. As shown in Figure 3.2, the IEEE 802.21 offers a middleware protocol called *MIHF* that is able to encapsulate the different underlying network technologies (*e.g.*, 802.3, 802.11, 802.16, 3GPP, and 3GPP2) to the upper layers, allowing the handover management process to operate independently of the physical and data link layers.

In heterogeneous vehicular networks it is important to consider the environmental conditions when performing the VHO. A high mobility degree, as well as the mobility patterns, will significantly affect the reliability of measurements and the decision-time. Therefore, vehicular mobility patterns and speed must be carefully taken into consideration. Additionally, context and location information are also important to perform an accurate handover in vehicular networks. This information can be retrieved from the vehicle's On-Board Unit (OBU).

3.5 Handover decision phase

The decision phase can be considered as the core phase of the VHO since it is in charge of evaluating and deciding the most appropriate network choices in order to fulfil both system and user requirements, thus providing the desired seamless communications.

To make an accurate decision, this phase takes advantage of algorithms that, considering the information available, perform an evaluation process in order to obtain the best choice for handover execution. These algorithms are usually called Vertical Handover Decision Algorithm (VHDA), or simply Vertical Handover Algorithms. In the literature we can find several VHDA proposals. Some of them take into account, in a straightforward manner, the handover decision task by considering only the lower layers' information given by the media independent information service; most of the proposals combine the metrics and parameters of the diverse components to build an accurate cross-layer handover algorithm.

The decision phase basically consists of three steps:

1. Parameter selection.
2. Parameter processing.
3. Parameter aggregation.

The parameter selection step takes into account only those parameters that the algorithm uses to evaluate and weight a candidate network. The parameter processing step allows to normalize all the parameters; parameter values with diffuse information are merged using several techniques such as fuzzy logic, neural networks and specific functions, to extract relevant data. Finally, to make a decision, an algorithm aggregates and evaluates the weight of each parameter and, based on some decision

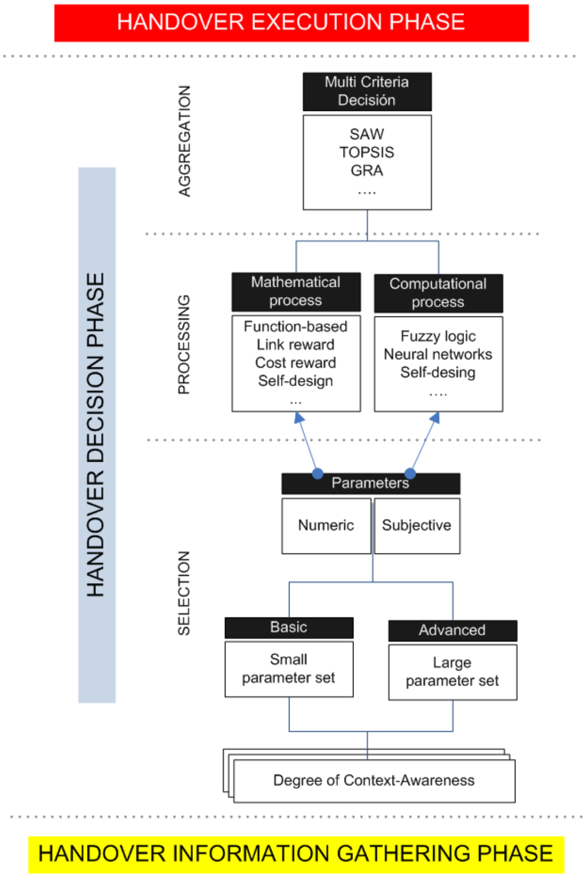


Figure 3.8: Vertical handover algorithms taxonomy.

criteria, selects the best candidate. Although the process described applies to most proposals, authors typically modify this process slightly to fit their needs.

Based on the decision strategies and algorithms analyzed in the literature, we classified the algorithms according to the taxonomy shown in Figure 3.8. We now proceed to describe each of these algorithms in detail.

3.5.1 Parameter selection algorithms

This type of algorithms takes advantage of the context information, generating knowledge to perform an accurate decision. Any changes in the mobile and network context trigger events and processes, which are notified to the VHO decision phase by the information gathering phase. Depending on the number of parameters selected for processing, these algorithms can be considered as: *basic* or *advanced*.

Concerning advanced algorithms, Pawar *et al.* [PWvB+08] present a mobile service platform with a context-aware middleware. It takes as context-source parameters the user trip information, the device services, the network services, the user preferences, the device specifications, and the time. Once the information is collected, a QoS predictor performs a path prediction to ensure the end-to-end QoS. The whole information gathered and predicted is evaluated under the Analytic Hierarchy Process (AHP) algorithm (an algorithm of the multiple criteria decision-making family. This type of algorithms will be described in section 3.5.3). Similarly, other works [KKP07, KKP08a] present an autonomic architecture that evaluates the context information through a combination of multiple criteria and policy-based algorithms in order to perform the best decision. Lassoued *et al.* [LBHB08] present a VHO evaluation methodology which combines different algorithms to tune the decision. Despite of the diverse algorithms used, this methodology has a context-aware core to collect and process the information.

Location-Aware algorithms are a basic type of context-aware algorithms [LBHB08, PWvB+08, GSZS10]. These algorithms take as primary information sources the events triggered by changes in the context, focusing on location changes alone. The work in [IVNC08] presents a location-based VHDA approach that combines mobile location information and network information in order to avoid the *ping-pong effect* related to performing predictions at wireless cells' boundaries, thus improving the VHO latency. With this purpose the authors introduce a hysteresis cycle in the decision process, evaluating the mobile device's location through the network *goodput*, a metric based on the allocated bandwidth to the device for the serviced requested. Joe and Hong [JH07] present a mobility prediction VHDA solution based on two location schemes: i) a sector and zone scheme, which consists in dividing the zones into several sectors and predicting the mobility based on statistics to decide the best network candidate, and ii) a scheme based on Global Positioning System (GPS) location information. Finally, the decision is made based on the mobile device's speed and mobility pattern regardless of the scheme used to determine the pattern. Similarly, the work in [LCX07] takes into account the device's location information based on the packet arrival time and the RSS, a typical metric for horizontal handover. Once the information is collected, it is processed by a multiple criteria algorithm. A framework for location-aware VHO based on GPS location management and wake-up procedures is presented in [YMP05]. This framework also allows evaluating cross-layer VHDA combining location-aware and power-based algorithms or dwell-timer based algorithms. The work in [CC08] presents an adaptive VHO technique based on predictive RSS patterns. Finally, Kwon *et al.* [KYPV08] present a classification of location-aware algorithms based on RSS, movement extrapolation, history data, mobility pattern and distance to the access point.

3.5.2 Parameter processing algorithms

The parameter processing algorithms are in charge of processing the chosen parameters and provisioning of the input information to the parameter aggregation algorithms. The evaluated works use diverse functions to process the information depending on its nature; therefore, the functions used could vary from pure mathematical to computational algorithms.

Mathematical algorithms

Most mathematical algorithms are self-designed algorithms. Some authors propose their own self-design decision algorithms in order to satisfy their VHO needs based on the information available in their systems.

Stevens *et al.* [SNLW08] present an algorithm based on a Markov Decision Process (MDP) using two types of functions: there is a link-reward function associated with the QoS received by the connection, and a signaling-cost function associated with the signaling overhead and latency when the handover execution is performed. They have evaluated the performance of the algorithm using voice and data traffic. This algorithm can work in conjunction with the 802.21 framework. A work also based on MDP is presented by Sharna *et al.* [SM10] focusing on estimate link rewards. An advanced proposal based on Weighted Markov Chain (WMC) is proposed by Martinez *et al.* [MMPRSN10]. The work in [YJY+08] proposes two Markov decision approaches based on rank aggregation, where the top weighted network is selected. This selection process is similar to the MCDM Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [SNLW08], but obviates the *ideal network* comparison. This proposal also works in conjunction with IEEE 802.21. Hasswa *et al.* [HNH05] present a decision function algorithm which allows users to prioritize the available networks based on network performance, user preferences and monetary costs. Based on routing issues, Liao *et al.* in [LC08] present a VHO cost-function in order to optimize the VHO latency. Works such as [CC08, MC06, RV10] also present a *cost-based optimal network selection function* based on a cross-layer adaptive scheme, that takes into account parameters from different layers. A framework with a normalized function in its decision module is presented in [KKL+08a], which normalizes the incoming values in terms of the RSS, QoS, and user preferences to select the best candidate network. A score function is used in a Smart Decision Model to decide the best network interface and the best time to perform the handoff. This decision-making model performs a smart decision based on various factors, such as the properties of available network interfaces, the system information, and the user preferences [CSC+04, CSYG06].

Computational algorithms

Computational algorithms use Fuzzy Logic and Neural Networks techniques to interpret imprecise information, although authors usually apply their own self-designed algorithms to perform the interpretation task. The above algorithms require precise data in order to weight attributes and to perform an accurate decision. Nevertheless, the gathered information is often imprecise; to handle this issue, fuzzy control theory and neural networks techniques are applied [KKP08b, SNLW08, CMSC10, HIMH10, SM10, RG10, CC10a, KS10, He10a, HCZ10, He10b, RV10, VMMK11, IR11, SP12]. Usually, these algorithms are applied first in order to convert imprecise data into precise data. Afterwards, a Multiple Criteria Decision-Making (MCDM) algorithm is fed with these data to determine the best choice. Kassar *et al.* [KKP07, KKP08b, KKP08a] combine fuzzy logic procedures with classical MCDM procedures. Similarly, the work in [XLGCHW08] combines *fuzzyfication* processes with Grey Relational Analysis (GRA) techniques. A fuzzy-based algorithm is presented in [LTD06] which combines fuzzy logic and a cost function-based algorithm in order to make the best decision. The work in [SP07] presents an evaluation and review of fuzzy-based algorithms taking into account parameters such as RSS, Cost and Bandwidth. In order to improve the QoS of a real-time application, the proposal in [AIJ08] combines a fuzzy-based algorithm with a rule-base algorithm to make an accurate decision. Finally, Horrich *et al.* [HBG07] present a neural networks knowledge based algorithm that fuzzyfies imprecise information in order to score the alternatives.

These methods may be helpful at combining the different information sources to extract relevant information, since in mobile environments, such as VNs, high speeds make the gathered information to have low reliability. However, the applicability of this type of algorithms can be reduced if computational times involved become too high.

3.5.3 Parameter aggregation algorithms

Since VHO mechanisms take into account diverse metrics and parameters to evaluate the best candidate networks, there is a need for algorithms that are able to jointly handle multiple parameters and metrics, as shown in Table 3.2. Consequently, ***Multiple Criteria Decision-Making (MCDM)*** algorithms are adopted to fulfill this requirement by aggregating all these processed parameters.

MCDM algorithms include algorithms based on multiple attributes or multiple goals. *Multiple Attribute Decision-Making (MADM)* algorithms evaluate the different alternatives based on their attributes, while *Multiple Objective Decision-Making (MODM)* algorithms focus on diverse objectives that can not be reached simultaneously [KKP08b]. Both types of algorithms are generally called MCDM. We now proceed to briefly describe the most popular algorithms:

Analysis Hierarchy Process (AHP)

This type of algorithms is based on the *divide-and-win* (*a.k.a. divide-and-conquer*) paradigm. The main decision problem is divided into sub-problems, where each sub-problem is evaluated as a decision factor. From the set of alternative solutions, AHP finds the most optimal solution [KKP08b, LCX07, Sun07, TP10, SC10b].

Grey Relational Analysis (GRA)

This mathematical algorithm builds a grey relationship between elements (networks), one of them with the *ideal quality values*. So, the rest of the elements are compared and evaluated against the ideal solution. The option that better approaches this ideal solution receives the highest score [KKP08b, LCX07, LBHB08, SNW06, AMBG10, MMPRSN10].

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Similarly to GRA algorithms, TOPSIS algorithms consider and *ideal solution* for performance comparison, considering as the best alternative the one nearest to the ideal solution, and as worst the one furthest from such solution [SNLW08, LBHB08, KKP08b, SmSMh10, MMPRSN10, SM10].

Simple Additive Weighting (SAW)

SAW algorithms are frequently used when MCDM is applied. This technique consists in scoring each alternative by adding the attribute values multiplied by its weight, in order to score the overall alternative, being the highest score the most optimal choice [SNW06, LBHB08, KKP08b, KHH10, TP10, MMPRSN10, SM10].

Multiplicative Weighting Exponent (MWE)

MWE works similarly to SAW algorithms. To score the overall alternative, it uses the weighted product of all attributes. Since this product does not have an upper-bound, it is advisable to compare the score against an *ideal solution* [SNW06, LBHB08, MMPRSN10].

ELimination Et Choix Traduisant la REalité (french)[Elimination and Choice Translating Priority] (ELECTRE)

The basics of the ELECTRE method is to use a reference attribute vector in order to adjust the raw attribute values for the alternative networks before they are compared. The value of each of the attributes in the decision matrix is compared with a corresponding reference attribute value. Then a set of recommendations is obtained. The nature of the recommendation depends on the problem being addressed: choosing, ranking or sorting [MMPRSN10].

Vlsekriterijumska optimizacija I KOmpromisno Resenje (serbian) [multi-criteria optimization and compromise solution] (VIKOR)

The VIKOR method is based on the compromise solution approach, assuming that each alternative is evaluated on the basis of a separate criterion function; the compromise ranking can be achieved by comparing the measure of closeness to the ideal alternative [MMPRSN10, DEN$^+$10].

An interesting comparison and evaluation of MCDM algorithms and their performance is presented in [SNW06]. This evaluation takes into account basic network parameters such as BER, delay, jitter and bandwidth, suggesting that most of the algorithms have a similar performance, depending heavily on the weight assigned to each parameter or attribute. Yan *et al.* in [YAcN10], present also a comprehensive comparison study of the most representative algorithms evaluating trade-offs between their complexity of implementation and efficiency.

3.5.4 Comments on algorithm applicability to VNs

In the context of VNs, information about location and mobility patterns are of utmost importance due to the high speeds involved. Thus, any handover decision scheme proposed should account for this information.

The most appropriate VHDA scheme for vehicular networks must include advanced context information and particularly location-aware information. It is important to consider location and also location predictions in order to choose the best network candidate in the area. Nevertheless, context information adds valuable information to the VHDA. To combine the different information sources, a fast MCDM algorithm is recommended, being in charge of weighting the set of parameters and providing a fast decision on how to perform the VHO at the best time and place. Nevertheless, a self-designed algorithm, defined according to the special characteristics of VNs, can also be used to make decisions.

3.6 Handover execution phase

The third phase of the VHO process focuses on execution. This phase is in charge of committing the VHO itself. So, once the information is collected in phase one and processed in phase two by selecting the *network candidate*, the execution phase will trigger a network binding update. With this purpose this phase is concerned with control, security, session and mobility, among other issues, in order to perform a seamless handover.

We now briefly describe the main processes participating in this phase:

3.6.1 Handover management

In the handover process there must be an entity in-charge of controlling the VHO process. Usually, the handover can be either *Network controlled* or *Mobile controlled*. In the former case it is initiated and controlled by the network, a solution that is typically adopted by operators to achieve load balancing duties and traffic management, among others [KYS+10]. In the latter case (Mobile controlled) the VHO is initiated and controlled by the mobile device. This type of control is the most common case, usually based on user preferences [PWvB+08, IVNC08, SU10]. Also, the VHO can be *Network assisted*, referring to the VHO initiated by the mobile device but assisted by the network making use of the information services, or *Mobile assisted* when it is initiated by the network but assisted by the mobile device [Gup06, Yli05].

During the handover process, when a mobile device reaches a new Point of Attachment (PoA), the system might execute procedures to manage the connections. These procedures usually perform *Registration*, *Association*, *Re-association*, and *Dissociation* tasks [Yli05, CSC07, Per02, JPA04].

3.6.2 Mobility management

One of the key issues of the seamless handover concept is mobility management. In IP-based networks, the standard protocols designed for mobility become an important solution to maintain the session alive when targeting a seamless handover. These protocols usually work on the intermediate layers of the TCP/IP protocol stack. The most common protocols used for mobility in VHO are the Mobility support for Internet Protocol v.4 (MIPv4) [Per02], Mobility support for Internet Protocol v.6 (MIPv6) [JPA04], Session Initiated Protocol (SIP) [RSC+02], Network Mobility Basic Support Protocol (NEMO) [DWPT05] and Host Identity Protocol (HIP) [MNJH08].

A study of the different techniques for mobility management in IP-based wireless networks is presented in [AXM04] and [ACC+09]. These works cover different cross-layer methods, as well as particular solutions depending on the layer and the wireless technology.

The work in [KKL+08a] evaluates a VHO architecture covering Wi-Fi and WiBro wireless technologies, achieving low handover latencies through an improved implementation of the Mobile IP (MIP) protocol. Similarly, the proposal in [FHS+09] appeals to MIP to manage the mobility in a new VHO proposal in boundary conditions for UMTS and Wi-Fi. Moreover, works [MFC10, MCF10, CKM10] appeal to Proxy Mobile IP (PMIP) or Fast Proxy Mobile IP (FPMIP) [ZZXZ10] to deal with mobility issues. In the same manner, Minghai *et al.* propose a solution for mobility proxy-based session continuity control [XG10]. The handover management among different IP versions is studied in [JSK07], presenting a scheme to support IPv4-IPv6 traversal between domains considering routing issues as well as IP-related details. In contrast, Andersson *et al.* [AGEr10] present a mobility management scheme which avoids tunneling by maintaining the same IP while moving across different subnets.

A proactive seamless handover scheme based on 802.21 features and SIP is evaluated in [DDF+07]. This scheme offers a proactive authentication in order to early obtain an IP and, thanks to SIP management, maintain the session alive during a seamless handover. Considering SIP, Uddin *et al.* [UPHA11] also present a solution taking into account ethernet and Wi-Fi technologies [UPHA11]. Moreover Park *et al.* [PCCL12] also base their proposal on the use of SIP. The work [AMA07] combines the use of SIP and the Stream Control Transmission Protocol (SCTP) in order to maintain the session in a multihoming environment, taking advantage of the multithreading features of the SCTP, despite of the redundant retransmission that the latter implies [MYLR03, LSL08, KK09b, SGC+12, EGB12]. Howie *et al.* [HYHS04], as well as Boutabia *et al.* [BAEA10], combines the use of SIP at the application layer and MIP at the network layer to provide a supernetworking mobile application able to perform fast handovers. An identification middleware layer is proposed by Wong *et al.* [WGMaV10] decoupling the host identification from the location, thus allowing the host to move across domains without interrupting the sessions. A broad comparison study of the VHO performance based on the SIP, MIP and Mobile Stream Control Transmission Protocol (mSCTP) is presented by Mahmound *et al.* [MAHAA+10].

Concerning security, the work in [PSAC08] performs an analysis of HIP based mobility and triggering using a hardware/software testbed to evaluate VHO techniques; the authors also study how mobility triggers affect latency. Several works also consider HIP for both mobility and security issues [Wu10, Qiu11, WY11, SW08]. Latvakoski *et al.* [LVV08] evaluate the VHO focusing on VoIP in an *Ad-hoc* environment under HIP and SIP protocols to provide continuously secure communication.

When operating in vehicular environments, both latency and security issues must be addressed. Due to the characteristics of VNs in terms of speed and node reliability, the execution of the VHO must not add excessive latency. Although solutions based on Mobile IP seem to be the most natural and adequate, further scrutiny is required to assess which solution is able to offer the best trade-off.

3.7 VHO evaluation strategies

In this section we briefly describe the most representative VHO evaluation methodologies found in the literature. Moreover, simulators and testbeds frequently used in the different proposals are also described. As mentioned before, most proposals do not evaluate VHO techniques from a VN's perspective; therefore, most of the following works and tools evaluate the VHO in environments other than VN ones. Nevertheless, in this section we also point out how some of them are able to evaluate the VHO in a VN environment by modifying or adapting their components to VN characteristics.

3.7.1 Evaluation methodology

The VHO evaluation done by different authors follows their specific research objectives, and so the input parameters, methodologies and metrics adopted are quite heterogeneous. Such drawback impedes a fair comparison between proposals, thus limiting their usefulness and hindering research in this field. As an evidence of the heterogeneity of metrics found in the literature, Table 3.3 shows a collection of metrics gathered from different works in the VHO-related literature. As can be observed, the metrics and parameters are classified by information source (*i.e.*, network, user preferences, mobile terminal and VHO itself) and also by the domain of usage (*e.g.*, coverage, security, location, etc). However, some metrics are used not only as an evaluation metric, but also as input parameters. Moreover, different metrics are used for the evaluation of the same parameters, or simply the same parameters receive different names. After an extensive review of the current literature, we conclude that there is a lack of evaluation methodologies considering homogeneous metrics and methods. As far as we know, only Lassoued *et al.* [LBHB08] present an attempt of an evaluation methodology. Their methodology takes into account parameters and metrics related to both upper and lower layers of the vertical handover architecture, such as the current context, the user mobility models, the user preferences, along with wireless access technologies specificities and QoS parameters. Nevertheless, in order to avoid all the undesired issues, and to unify and clarify concepts, we now propose a set of metrics to harmonize evaluations in this field.

Table 3.3: Parameters and metrics used for VHO.

Source	**Domain**	**Metric**	**Description**	**Used as: Input Parameter**	**Used as: Evaluation Metric**
Network	Latency	Latency e2e, Average Delay	End-to-end latency, from packet generation to packet reception	[NZ09, LBHB08, SNW06, SNLW08, LRO+10]	[LBHB08, DDF+07, SNW06, JC08, YJY+08, HBG07, FHS+09, LRO+10, AMBG10, FA10, SC10a]
		Network Delay	Time taken to deliver a packet	[KKP07, SNW06, YJY+08, KKP08a, KO05, Wri07, SZ06, SAAS10, CC10b, SZBK09, Mit10, SM10, ZJZ10, RG10, QDlB+10, JZH12, RPR12, MM12]	[Cor06, CHL09, BI04, LC10e, LC10b, OK10, MMPRSN10, RV10, EVMN10, VOF10, LORG10, LC10d, LC10a, LC10c, SGC+12]
	Coverage	Network availability, coverage	Related to the area covered by the network	[DDF+07, KKP07, BCI04, KKL+08a, PWvB+08, SAAS10, SU10, JKPP10, KT10]	
	Performance	RSS	Received Signal Strength	[BN08, CSYG06, SNLW08, SS05, KKP07, KYPV08, LCX07, SNW06, CC08, MC05, XLGCHW08, HBG07, JH07, GS08, YMP05, BCI04, MC06, PFMM07, LSK+09, FHS+09, IVNC08, KKL08b, AIJ08, SP07, JS10, KHH10, SU10, JCYS10, CSPL10, SZBK09, JSHS10, EVMN10, CWHN10, HCZ10, LZ10, DEBEH10, CZS10, HIMH10, LORG10, VOF10, KTJ10, AAMBG10, Baz10, CSZ+10, AMBG10, ASS10, HGKQ10, NAST10, KS10, CLCC12, DDBR12]	
		CIR	Carrier Interference Ratio	[SS05, SNW06, KYII10, NKT+10]	

Table 3.3: Parameters and metrics used for VHO.

Source	Domain	Metric	Description	Used as: Input Parameter	Used as: Evaluation Metric
		RTT	Round Trip Time	[SS05, SNLW08, SNW06, CC08, TYKO08, KO05, SAAS10, SU10, NKT+10, VHST10, LS10, SLLZ10]	[CTK10]
		PRTX	Packets retransmitted	[SNW06, TYKO08]	
		BER	Bit Error Rate	[LBHB08, KKP07, SS05, SNW06, Cor06, MC06, KKP08a, Wri07, PMBJ10, QDlB+10, RG10, RPR12]	
		SINR	Signal to Interference and Noise Ratio	[YGQD07, Cor06, MC06, IVNC08, SU10, SZBK09, LPM+10, RG10, NOT10, SmSMh10, KT10, IYK+10, LRO+10, PMBJ10]	
		Security	The security level deployed in the network	[LBHB08, SNW06, HNH05]	
		Packet Loss	Packets unsuccessfully delivered	[KKP07, SNW06, YJY+08, KO05, SZ06, SU10, KT10, JZH12]	[JC08, KO05, CHL09, SNSMW10, CC10b, SZBK09, BI04, MFC10, MCF10, KTJ10, TKG10, CSZ+10, AMBG10, QCL+10, STH10, OK10, BAEA10, UPHA11, PCCL12, ASWGT12]
		Throughput, Data rate	Throughput in the network	[NZ09, THM06, AIJ08, Wri07, NH09, LRO+10]	[CSYG06, YGQD07, CC08, XLGCHW08, Cor06, HBG07, LVV08, YMP05, MC06, TYKO08, KO05, CHL09, IVNC08, LSL08, SU10, EVMN10, LORG10, HIMH10, WGMaV10, ZZXZ10, TP10, AAMBG10, SmSMh10, LC10a, NOT10, FA10, WSS+10, SC10a, LPM+10, BUA10, CWY10]

Table 3.3: Parameters and metrics used for VHO.

Source	**Domain**	**Metric**	**Description**	**Used as: Input Parameter**	**Used as: Evaluation Metric**
		Bandwidth available	The bandwidth available at a precise instant in the network	[SNLW08, LBHB08, NZ09, XLGCHW08, LTD06, YJY+08, HBG07, KKP08a, LSK+09, AIJ08, SP07, SZ06, SU10, CC10b, SZBK09, KT10, CCHL07, Mit10, JZH12, MM12]	[LSK+09, JKPP10, MMPRSN10, RV10]
		Bandwidth offered, link capacity	The bandwidth offered by a candidate network	[KKP07, CYS+05, YJY+08, GS08, KKL08b, SM10, ZJZ10]	[MMPRSN10]
		Network Jitter	Jitter introduced by the network	[KKP07, SNW06, HNH05, YJY+08, KKP08a, KO05, AIJ08, Wri07, SU10, LRO+10, KT10, ZJZ10, QDlB+10, RPR12]	[CHL09, BI04, EVMN10, LC10d, LC10a, LC10c, LC10b, LC10e, MMPRSN10]
		Network Overhead	Extra management packets in the network		[LC08, CSZ+10]
	Billing	Cost/Money	The price for using the network	[LBHB08, KKP07, SNW06, HNH05, XLGCHW08, Cor06, LTD06, YJY+08, GS08, KKP08a, SP07, NH09, SZ06, PMBJ10, AMBG10, MZ04]	[LBHB08, YJY+08, LZ05, TP10, LPM+10]
	Other	Number of users	Amount of users connected in the network	[NZ09, LZ05]	
		Reputation	Colaborative reputation	[PMBJ10, ZJZ10, JZH12]	
User Preferences		Budget	User budget to spent in using networks	[KKP07, KKP08a, SZ06, AAMBG10, CTXC10]	
		Preferred Network	User choice	[KKP07, DDF+07, NZ09, KKP08a, PWvB+08, SZ06, SU10, AAMBG10, PMBJ10]	
Mobile Terminal	Location	Mobility, Location	Geolocation or AP-based location	[KKP07, KYPV08, CC08, MC05, JH07, IVNC08, PWvB+08, SZ06, JS10, JCYS10, EVMN10]	
		Movement	The change of movement direction	[JH07, KYPV08, SZ06, JS10, EVMN10]	

Table 3.3: Parameters and metrics used for VHO.

Source	Domain	Metric	Description	Used as: Input Parameter	Used as: Evaluation Metric
	Capabilities	Speed, Velocity	The speed while moving the mobile terminal	[KKP07, JH07, NZ09, HNH05, HBG07, GS08, SZ06, JS10, SU10, SZBK09, EVMN10, RG10, CTXC10]	
	Capabilities	Network Interfaces	Technologies available in the device	All proposals referred	
	Capabilities	Battery Consumption	Power consumption	[KKP07, NZ09, SNW06, HNH05, LTD06, GS08, KKP08a, LSK+09, PWvB+08, SZ06, SZBK09, KYII10, CTXC10]	[LSK+09, KYII10]
Vertical Handover	Occurrence	Number of VHO	VHO events performed		[SNLW08, JH07, CC08, THM06, MC05, XLGCHW08, Cor06, LTD06, JH07, GS08, BCI04, MC06, IVNC08, KHH10, EVMN10, KYII10, SmSMh10, RG10, KS10, He10b, Pil10, CLCC12, SP12]
Vertical Handover	Occurrence	VHO success rate	The ratio of VHO events successfully performed	[BN08]	[SZBK09]
Vertical Handover	Latency	VHO Latency	Time associated with the VHO process		[CSYG06, BN08, KP07, YMP05, AMA07, PHK+08, KKL+08a, JS10, CSPL10, CC10b, YCG10, OYNK10, IJL+10, MCF10, MFC10, ZZXZ10, CKM10, TKG10, SLLZ10, STH10, BAEA10, ARG10, He10a, TYW10, VHST10, UPHA11, PCCL12, ASWGT12]
Vertical Handover	Latency	Gathering Latency	Time associated with the VHO Gathering phase alone		[BN08, KP07, PHK+08]
Vertical Handover	Latency	Decision Latency	Time associated with the VHO Decision phase alone		[BN08, KP07, PHK+08, AMBG10]

Table 3.3: Parameters and metrics used for VHO.

Source	Domain	Metric	Description	Used as: Input Parameter	Used as: Evaluation Metric
		Execution Latency	Time associated with the VHO Execution phase alone		[BN08, KP07, PHK+08]
		Dwell Time	The period during which a VHO process remains halted in order to allow another process to take place	[SS05, SNLW08, YMP05, FHS+09]	
	Network	VHO Packet Loss	Undelivered packets during the VHO process		[DDF+07, LCX07, CSPL10, JZH12]

End-to-end switching latency

The end-to-end latency refers to the time taken to deliver a data packet from the source to the destination upon the VHO. This latency implies the *network latency* and the *VHO handover latency*, as shown in Equation 3.1. Through this metric we are able to compare proposals considering not only the decision algorithm's performance, but also the conditions and performance of the chosen candidate network.

$$Latency_{e2e} = Latency_{Network} + Latency_{VHO} \tag{3.1}$$

VHO latency

This metric only takes into account the time associated with the VHO process itself, considering the three phases of the VHO: information gathering, decision and execution phases. It is defined as follows:

$$Latency_{VHO} = Latency_{Gathering} + Latency_{Decision} + Latency_{Execution} \tag{3.2}$$

VHO packet loss

Merely comparing the time consumed by the VHO is not enough. In fact, it is also important to compare the amount of packets that are dropped during the VHO process. This metric is described by Equation 3.3

$$PacketLoss_{VHO} = \frac{1 - Packets_{received}}{Packets_{sent}} \tag{3.3}$$

Notice that packet loss should be calculated solely for the VHO time period.

VHDA cost

The metrics shown above can be used when performing simulations or executing implementations on real frameworks. Thus, they can be applied *a posteriori* in order to evaluate a proposal. However, *a priori* metrics are also required in order to pre-evaluate or compare proposals. To do so, we propose the use of metrics based on the degree of complexity in terms of memory and time consumed, where complexity is represented in the $O(f(n))$ format (*e.g.*, $O(log_2 n)$, $O(n)$, $O(n^2)$, etc).

3.7.2 Simulation tools

For evaluation purposes, the proposals use diverse simulation/emulation tools, as well as specific and self-designed testbeds and hardware/software implementations. Most of the authors rely on widely used simulators, especially network simulators, in order to reproduce network conditions and schemes. Nevertheless, there are no simulators specifically designed for VHO evaluation; therefore, most proposals make some adjustments or develop modules to mitigate this shortage. According to Table 3.4, the research community is adopting several tools to aid them in their endeavors.

The aforementioned proposals evaluate the VHO by using network simulators indirectly. Consequently, simulators such as the Network Simulator (ns-2) [KK09a], Network Simulator (ns-3) [ns-12] and OPNET [OPN12] are used to simulate the network environment, although none of them offers tools to evaluate the VHO itself. To do so, authors modify the code or configure the simulators to reach their goals. Referring to VHO models, MATLAB [Mat] is used to evaluate mathematical models that describe the VHO process, usually VHDA performance. Finally, some authors build their own framework to fit their needs and interests, as shown in Table 3.4.

Nevertheless, in order to provide a heterogeneous environment to study the VHO process, only a few modules, testbeds and architectures have been developed. We briefly describe the most popular ones:

Seamless and Secure Mobility [Adv]. This simulation framework is being developed for ns-2 in order to provide modules for several wireless and wired technologies such as IEEE 802.3, IEEE 802.11b, IEEE 802.15.1, and UMTS to simulate heterogeneous environments. This free and opensource tool is a powerful solution to evaluate the VHO in VN environments since ns-2 is able to model multiple network topologies and mobility protocols. This module provides VHO management based on 802.21, as well as wide area wireless technologies and protocols. When combined with ns-2, the *Seamless and Secure Mobility* solution, in addition to the flexibility and freedom of open source, provides a wide set of simulation possibilities within VN environments.

ns2-Miracle [BMM+07a]. As its name shows, this simulation framework is also designed to work with the ns-2. The *Muli-InteRfAce Cross Layer Extension (MIRACLE)* is a set of dynamic libraries which, in conjunction with the ns-2, offer support for multi-technologies and cross-layering. Although the first implementation only considered UMTS and Wi-Fi, currently a set of plugins have been developed to offer WiMAX support.

SHINE [BPG06] is a simulation framework able to simulate heterogeneous networks and perform vertical handovers within overlapped coverage areas. This framework uses a main server which acts as the *upper layers* in charge of the mobility and users management, transport protocols, etc; it also uses clients for each simulated access technology. These clients represent the lower layers. The framework is able to simulate General Packet Radio System (GPRS), UMTS, Wi-Fi and WiMAX. The main features of this framework are that it allows reproducing the transport protocol behavior and start an instance for each new traffic session originated by the client.

Universal Seamless Handoff Architecture (USHA) [CSC+04, CSYG06] is a simple, fast and reliable handover solution to perform seamless VHO. It is based on a two part software component (USHA client and USHA server) that uses MIP tunneling to maintain the session open. This solution was fully tested in a real implementation.

Y-Comm [MSC+07] presents a new architecture for mobile heterogeneous networking. This architecture is based on two frameworks: the first one is called *Peripheral framework*, and the second one *Core framework*. The Peripheral framework interacts with the peripheral wireless network, and it is implemented in the mobile devices. It is in charge of controlling the VHO and doing policy management, among other tasks. The second framework runs in a distributed manner throughout the infrastructure providing configuration services, as well as network management and QoS. The Y-Comm testbed is being developed for the Android mobile operating system [Ope12].

Reconfigurable Interoperability of Wireless Communications System (RIWCoS) [ARG10, FPH10, FBGP11, LOR+11]. This scheme enables network providers and their users to choose between alternative heterogeneous access networks. It is compatible with the IEEE 802.21 standard, exploiting the synergy between heterogeneous access technologies. It is composed by an *Interoperability module*, which is in charge of handling the mobility, and by the *Distributed resource management* module that manages de resource allocation. This framework was initially design for military communications.

Table 3.4: Evaluation tools used in the literature.

Type	Tool/Scale	%	Proposals
Simulator	Network Simulator (ns-2)	20.75	[BN08, FHS+09, CYS+05, JC08, CHL09, KKUR08, MCF10, MFC10, KTJ10, TKG10, CSZ+10, KT10, LC10d, LC10a, LC10b, LC10e, LC10c, COP10, GSZS10, BD11, PCCL12, SAMFJ12]
	Network Simulator (ns-3)	0.94	[CMH11]
	OPNET	4.72	[HBG07, JH07, AMA07, OK10, CC10a]
	MATLab	11.32	[YGQD07, THM06, MC05, NZ09, IVNC08, AMBG10, HGKQ10, NOT10, CC10a, DDBR12, JZH12, SP12]
	Self design	1.89	[GS08, EVMN10]
	Others	20.75	Qualnet [KYPV08, LRO+10, VOF10, NKT+10, VOB+10, OFV10, ARG10, MM12], Seamless and Secure Mobility [CHL09, MFC10, MCF10, KTJ10, TKG10, CSZ+10, KT10], CanuMobiSim [LBHB08], Simulink [DDBR12], RIWCoS [ARG10, FPH10, FBGP11, LOR+11],KauNet [EGB12]
Testbed	Short Scale	29.25	[SNW06, SNLW08, LCX07, XLGCHW08, YJY+08, KKL08b, AIJ08, KKL+08a, LSL08, TYKO08, Wri07, DDF+07, MC06, OCP+09, RFFA10, IJL+10, FQM+10, LORG10, WGMaV10, APFH10a, APFH10b, APFH10c, Lu10, CTK10, TYW10, VHST10, CZS10, UPHA11, ASWGT12, LOR+11, SGC+12]
	Medium Scale	10.38	[SS05, KKP08b, KYPV08, Cor06, LVV08, LSK+09, PHK+08, NH09, KKP08b, JSK07, LZ05]

Table 3.4 presents the use of the different evaluation tools, including the references to the proposals that have used each of the tools. We have surveyed the main conferences and journals on VNs and VHO research areas, mostly in the last decade. This table clearly shows the trend towards testbed usage. Short scale testbeds are typically used to evaluate the performance of VHDA, while Medium scale ones are used to evaluate the whole VHO process within networks with several mobile devices.

To the best of our knowledge, there are very few proposals of VHO techniques designed and implemented in VN environments. Lee *et al.* in [LSK+09] present VHDA controllers to optimize the overall VHO performance; these controllers take into account a route-selection algorithm considering wireless *Ad-hoc* networks, as well as VANET environments. Datta *et al.* [DDBR12] present a VHO for vehicular communications based on Analytic Network Process (ANP) that adopts the Continuous Air Interface for Long and Medium Range (CALM M5) and takes into account mobility parameters such as velocity and initial network delay. Zhu *et al.* [ZNW+09] present a recompilation of different solutions for mobility management combining simultaneous Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2V) routing in order to perform VHO using multi-homed mobile routers. A specific proposal for VHO in a VANET scenario is presented in [OCP+09]. The authors propose a simple VHO architecture - *VANET Backup Communications (VANBA)* - as an alternative to the IEEE 802.21 standard and to the Communication Access for Land Mobiles (CALM) architecture. The key issue is the simplicity offered through its 2.5 layer and its function-based decision (monetary cost and bandwidth available). This architecture has been evaluated over the DRIVE testbed [PSL+08], achieving low latencies in the execution of the VHO among Wi-Fi and UMTS in a VN environment. Considering the IEEE 802.21 standard along the GeoNET project's V2V communication system, Widhiasi *et al.* [WMPB10] present an interesting VHO scheme for V2V communication called FANSCI: Fast handover scheme for Car-2-car communication. This proposal consists of two main components: tower component and car component, where both components are based on the current GeoNET implementation, although enhanced with the features offered by the IEEE 802.21 for heterogeneous networks.

3.8 Open research issues

Although VHO techniques have been significantly improved in the last years, there are still several issues requiring further scrutiny concerning VHO in VNs environment. Summarizing, we suggest the main issues to be addressed.

3.8.1 Quality of Service (QoS)

The applications being executed on the mobile device require different levels of QoS. However, providing the required QoS across the different wireless networks is a major issue. In addition, high levels of mobility introduce more challenging issues. In order to guarantee the QoS, VHO techniques must carefully consider vehicular mobility and network conditions in order to choose the best candidate network and perform a fast handover.

3.8.2 Quality of Experience (QoE)

Guaranteeing the QoS is not enough in order to provide the best possible service to users. Quality of Experience (QoE) is a concept related to the users' satisfaction, and QoE assessment sometimes evidences that good networking performance is not a synonym of total satisfaction to the end users. Hence, issues related with the user preferences and mobile equipments must be taken into account in order to design VHO strategies and techniques.

3.8.3 Security

Security is one of the most important issues in many technological areas. In networking, security has always been a primary concern. Unfortunately, the IEEE 802.21 standard does not consider security in the main standard leaving this area to be handled by other protocols such as MIP, which places a strong emphasis on security. So, in order to improve the VHO techniques, robust security solutions must be adopted that can be used in heterogeneous networks, thus allowing security anytime and anywhere. However, recently the IEEE 802.21a [Gro12a] amendment has standardized the mechanisms to improve the security issues when the IEEE 802.21 is being applied.

3.8.4 Industry standardization effort and alliances

The design and implementation of the IEEE 802.21 standard is a great step towards seamless VHO among heterogeneous wireless networks. However, issues related to the operators are not solved by this standard. The billing and pricing for the use of the networks owned by the operators, the management of these issues among them and between operators and users, must be solved at least partially in order to facilitate the VHO and to guarantee the QoE as well as the QoS.

3.8.5 Homogeneous VHO evaluation

As mentioned above, there is a lack of a homogeneous evaluation methodology. This issue is a barrier when comparing different proposals. Therefore, a common methodology is required in order to permit researchers, developers and users to easily compare and evaluate the diverse VHO techniques found in the literature. Hence, the VHO-related research community should join efforts to release a standard or guidelines on good practices for VHO evaluation.

3.9 Summary

In this chapter we described the VHO process, the different phases that are part of this process, as well as the procedures triggered at each phase. Additionally the Media Independent Handover Services Protocol (IEEE 802.21) designed for VHO is briefly described. Moreover, we analyzed the VHO from the Vehicular Networks (VNs) perspective to evaluate the branch of solutions that the conjunction of wireless technologies and VHO techniques is able to offer in order to satisfy the connectivity needs on the road. Furthermore, we classified the most widely used Vertical Handover Decision Algorithm (VHDA) in the literature into different sets of algorithms, depending primarily on the information used to make decisions, and the techniques employed. Concerning VNs, we consider that the MIHF protocol must be taken into account when designing the VHO architecture. Multiple-parameters-based algorithms should be used to select the information, in order to the take the most of the context environment.

Different tools are presented in order to compare the multiple VHO possibilities and to evaluate the most appropriate VHO techniques to be applied in VN environments. Moreover, the most suitable tools for the study of VHO and VNs have been presented. When evaluating a VHO proposal in a testbed, DRIVE offers a fully function car-framework. When simulating VHO systems in VNs, diverse tools might be used; nevertheless, we consider that ns-2, in conjunction with *Seamless and Secure Mobility*, as a fast and flexible tool that allow correctly evaluating VHO processes in VNs environments.

When gathering information in VNs we must take into account the vehicular mobility prediction and the vehicular speed in order to improve the selection effectiveness in the presence of highly dynamic channel conditions. In addition, the decision-making process must rely on a fast MCDM algorithm to perform an accurate decision, and to switch to the best candidate network within a very short period of time. Finally, when executing a seamless VHO, low latencies and high security levels must be achieved. To do so, we consider Mobile IP as one of the candidate solutions offering the best trade-off.

Part II

Contributions

Chapter 4

Proposed IEEE 802.21-based Vertical Handover Decision Algorithms (VHDAs)

4.1 Introduction

Several Vertical Handover Decision Algorithms (VHDAs) have been proposed by different authors and, as described on Chapter 3, most of them were designed to meet the user and application requirements based on different techniques. In this chapter we discuss our proposals, which are based on the IEEE 802.21 protocol and powered by the context information offered by vehicular networking technologies.

The different VHDAs proposed in this chapter consider the use of the same three underlying wireless access technologies: Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX), and Universal Mobile Telecommunications

System (UMTS). Moreover, as mentioned before, the use of the IEEE 802.21 protocol is a must in the design of these VHDAs, in order to maximize the benefits that the different technologies are able to offer. In particular, we will propose four different VHDAs:

- A simpler algorithm that, as a decision criteria, takes into account the capacity offered by the different technologies.
- An algorithm that not only considers the capacity offered, but also, depending on the path followed by the car, considers the time under the cell coverage.
- An advanced version of the previous algorithm is presented, which also considers the surrounding context and the vehicle's geolocation to decide whether the Quality of Service (QoS) at the current position is good enough to switch to the evaluated network.
- Finally, an advanced multi-criteria algorithm is presented. In order to make the decision, several factors, such as bandwidth, price, latency, geolocation, and packet loss, are taken into account and weighted to choose the candidate network to switch to.

4.2 Description of the Technology-Aware VHDA

The Technology-Aware VHDA is a solution that, based on the services defined by the IEEE 802.21 framework, takes into account not only the Received Signal Strength (RSS), but also the capacity offered by the different technologies as the main decision parameters in any scenario where Wi-Fi, WiMAX, and UMTS technologies appear concurrently.

Figure 4.1 shows the state diagram of the VHDA when selecting a candidate network to switch to. As observed, the Media Independent Handover Function (MIHF) set at the User Equipment (UE) is continuously sensing the interfaces. When an event is triggered, and depending on the type of event (*e.g.* link up, link down, link parameter changes, link going down), the VHDA performs different routines and subroutines based on the Media Independent Command Service (MICS) and Media Independent Event Service (MIES) in order to select the best candidate network. The UMTS network is chosen by default, since it assumes full UMTS coverage. Finally, considering the execution phase of the Vertical Handover (VHO) process, we use Mobility support for Internet Protocol v.6 (MIPv6) to manage the mobility issues.

It is important to emphasize that the 802.21 events: LINK UP and LINK DOWN, determine the behavior of the VHDA. When a LINK DETECTED event occurs, the user equipment will trigger other events, such as LINK UP, if the technology detected is able to offer more bandwidth, negotiating with the new base station for

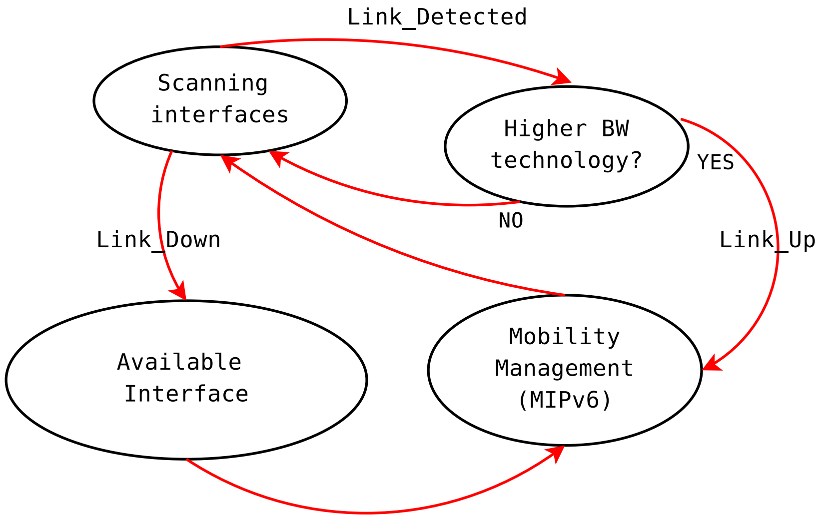


Figure 4.1: VHDA state diagram.

the IP address; MIPv6 is in charge of this negotiation and notification to different components of the system. All these negotiation and notifying processes require complex actions, which implies latency. On the other hand, when a LINK DOWN event is detected, only a notification is performed by the MIPv6 agent (see Figure 4.2, since the interface was already configured in a previous LINK UP. So, there is no added latency to these processes.

4.2.1 Mobility support for Internet Protocol v.6 (MIPv6)

We consider that is important to describe the basics of the MIPv6, in order to clarify the mobility management within the VHDAs proposed. To do so, Figure 4.2 shows an overview of the Internet Engineering Task Force (IETF) MIPv6 working process. We now proceed to briefly describe the process :

A. The Mobile Node (MN), through the Home Agent Discovery (HAD) mechanism, discovers its Home Agent (HA).

B. The MN moves towards the Foreign Link-A living its home network.

C. A new Care-Of-Address (CoA) is obtained by the MN; it sends Binding Update (BU) notification messages to its HA and to the Correspondent Node (CN).

D. The packets sent by the CN to the MN are forwarded by the HA to the MN using the CoA.

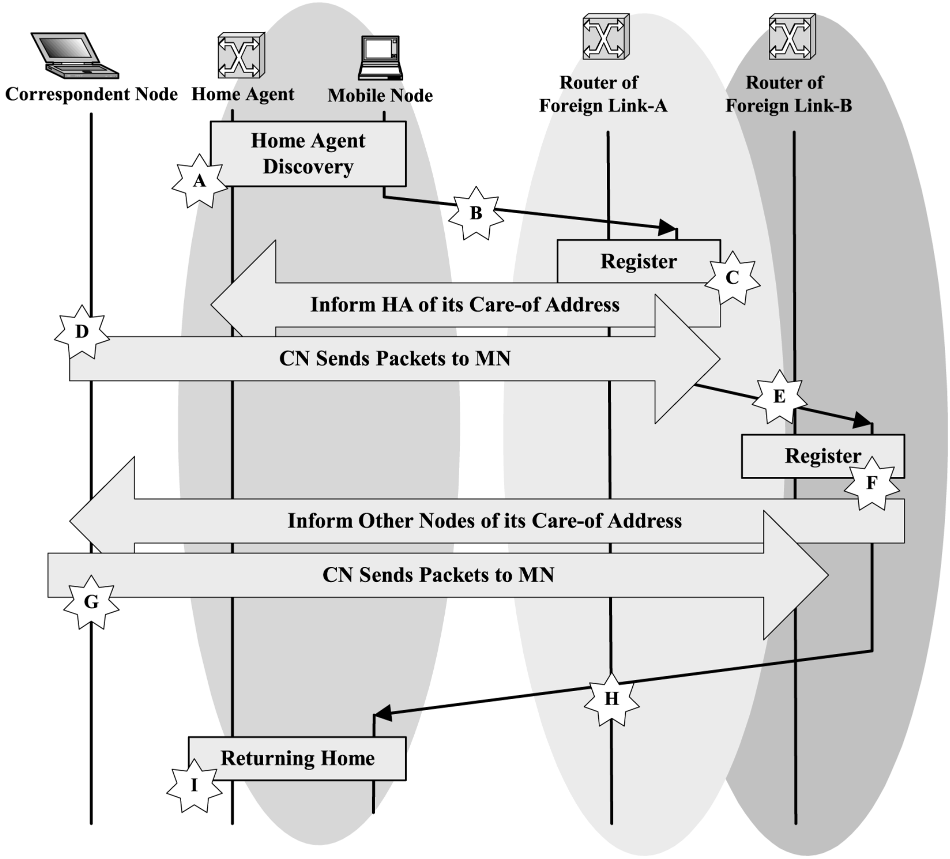


Figure 4.2: Overview of the MIPv6 (source [Cha01]).

E. MN moves away from Foreign Link-A to reach Foreign Link-B.

F. The MN obtains the CoA from the Foreign Link-B and it notifies this update by using BU messages.

G. When the BU message has been received, the CN updates its Binding Cache (BC) and sends a Binding Acknowledgement (BA) message to the MN.

H. The MN returns back to its home network.

I. The MN notifies to its HA that it is not attached to a Foreign Network anymore.

4.2.2 Mobile IP (MIP) within Vehicular Network (VN) contexts

The mobility is an extremely matter when considering continuous connectivity in VNs, due to several handoff events performed in the On-Board Unit (OBU) while crossing different technology coverage areas, changing not only from one wireless access technology to another, but also changing from one Internet Protocol (IP) domain to another, thus obtaining different network identify address. Therefore, MIPv6 is used in our algorithm proposals in order to guarantee the correct IP management when switching from one network to another.

Every time the vehicle reaches a new coverage area, the VHDA used might decides to switch to the new network, if it does, then the OBU at the vehicle performs the VHO process. As an important part of the VHO process, the IP management is done by the MIPv6 protocol. That way, the notification of the new address is made in order to maintain the session alive and to redirect the flows to the new address destination.

4.3 Description of the MACHU VHDA

In this section we propose a novel VHDA, called Multi-ACcess network Handover algorithm for vehicUlar environments (MACHU), which combines Global Positioning System (GPS)-based geolocation, map information, surround context information and route calculation, with the functionality of the IEEE 802.21 standard. For the decision-making process, MACHU takes advantage of both the current and the future geolocation of the vehicle (within the route and map layout), along with the networking information provided by the different services of the IEEE 802.21 standard. The purpose is to choose the most suitable access network along the route when following the pathway from one location to another. Figure 4.3 shows a car following a pathway and reaching different wireless networks along the way.

Horizontal handovers assisted by GPS information have been already studied and proposed by different authors [DMC+03, MN06] presenting the advantages of geolocation in the scope of a single type of wireless network. Recently, works considering GPS support for the decision-making process when performing VHO among multiple access technologies were presented. Ylianttila *et al.* [YMP05] proposed using the GPS in order to manage the current location of the mobile device to hand over among Wi-Fi and UMTS cells, performing the decision-making based on the RSS. Inzerilli *et al.* [IVNC08] present a decision-making process aided by the GPS in order to avoid the ping-pong effect when performing VHO at the boundaries of the cells.

Concerning network information, as far as we know, none of the previous proposals collects the networking information using the Media Independent Information Service (MIIS) offered by the IEEE 802.21 standard. The MIIS offers very powerful and

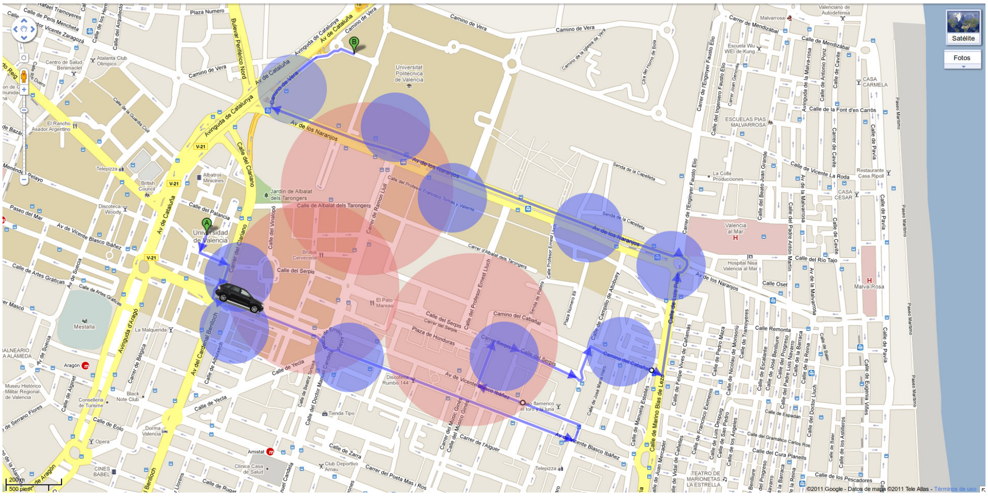


Figure 4.3: Example of a pathway with different wireless network coverage areas.

detailed information about the Points of Attachment (PoAs) (*i.e.* Base Stations (BSs) and Access Points (APs)), network preferences, billing information, and handover policies.

In our proposal, we not only use GPS-based coordinates, but also combine coordinates, maps, surrounding context information and routes to dynamically calculate and recommend the optimal pathway from one place to another. Based on the calculated pathway to follow, the VHDA requests to the IEEE 802.21 services the surrounding context information in order to select the best network to hand over to while following the pathway.

Concerning Vehicular Networks (VNs), when a vehicle passes through different PoAs along the route, a VHDA could decide to join/leave different coverage areas for a very short period of time due to the speed and route chosen to reach the destination. Thus, an adequate VHDA for vehicular environments must evaluate all the surrounding PoAs (cell information and coverage) not only to choose the one whose performance best fits the applications' requirements, but also the one which offers a more reasonable coverage within the route to make the VHO worthwhile.

Our proposal (MACHU) takes the most of the current OBUs, such as continuous power supply, multiple networking interfaces, GPS information, maps and routes, combining the different data sources with the network information provided by the IEEE 802.21 standard. Figure 4.4 presents the flow diagram of the MACHU Algorithm, which is mainly divided into three parallel components: Networking, Neighborhooding, and Decision-making branches. We now proceed to describe each branch.

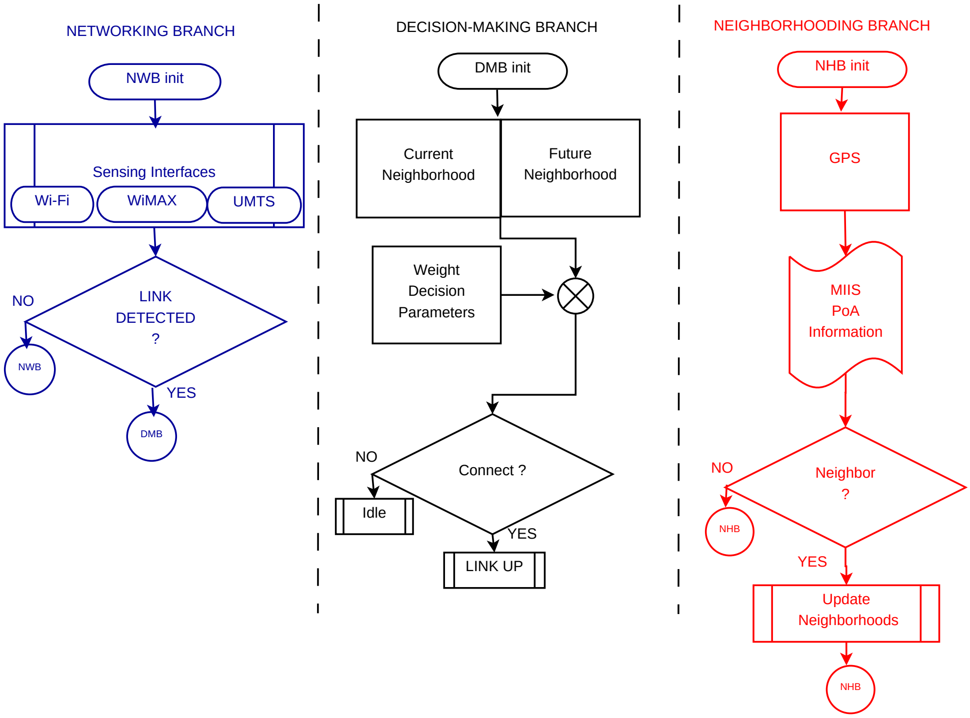


Figure 4.4: MACHU algorithm.

4.3.1 Networking

The networking branch is in charge of sensing the different wireless network interfaces available at the OBU. This process is done by a process that periodically sends and receives information about the network status (*e.g.* Router Advertisement (RA) and Router Solicitation (RS)). To interact with the interfaces, MACHU uses the IEEE 802.21 services, *i.e.* Media Independent Event Service (MIES) and Media Independent Command Service (MICS) to check the link status and received reports. When an event occurs in the physical/link layer, the interfaces receive a trigger event (LINK DETECTED) launching different sequence processes (decision-making, VHO execution); through the MIES, different events are notified to the upper layers in order to execute the different actions associated with a VHO process. Moreover, any further actions defined by the upper layers are executed by the lower layers using the primitives stated by the MICS.

4.3.2 Neighborhooding

The Neighborhooding branch introduces novel features by considering surround context information. All the surrounding information is gathered into two data storage elements: Current Neighborhood and Future Neighborhood. Each of these storage elements are periodically filled-in with information about the current and future PoAs available (cell information and coverage), respectively. Every $SensingPeriod$ seconds, the branch executes a query to the GPS module requesting the current geolocation and the future geolocation within the next $PredictionWindow$ seconds. The response contains a geolocation within the map with the route that the vehicle is taking to reach the destination. Based on those geolocations a request is performed to the PoA information database, powered and made available by the Media Independent Information Service (MIIS) of the IEEE 802.21. A list of current and future available PoAs is retrieved and locally stored at the OBU to be used by the decision-making branch. The MIIS PoA information database offers information such as the ID of the network, the ID of the PoA, its geolocation, coverage, monetary cost per MB, and BW offered. The local data storage containing current and future neighborhood information is filled-in with the PoAs' information only if the current and future geolocations, within $PredictionWindow$ seconds, are inside the coverage area described in every PoA registry. To determine the coverage condition Equation 4.1 is used, which considers the geolocation of a vehicle at a certain time, and the PoA's geolocation described at the MIIS PoA information database. Moreover, the local storage not only retrieves the MIIS information, but it also calculates the useful coverage time under each PoA coverage by combining the GPS information about the route on the map and the MIIS information. The useful coverage is affected by different issues such as whether the route tangentially crosses the coverage area, the times for reaching/leaving a coverage area, or the existence of overlapping coverage areas along the path, as shown in Figure 4.5.

$$d = \sqrt{(X_{vehicle} - X_{PoA})^2 + (Y_{vehicle} - Y_{PoA})^2} \tag{4.1}$$

A major parameter to take into account when performing a VHO is the latency taken by whole VHO process, since a high latency could be a symptom of packet loss and service disruption, thus downgrading the application performance. Equation 4.2 describes the different latencies that are implied in a VHO process, where VHO_{L2} is the latency referred to the association process at the link layer, while VHO_{L3} is related to the IP level processes (*i.e.* IP address negotiation between the interface and the PoA). Finally, VHO_{MIP} is the time taken by the Mobility for IP (MIP) protocol for notifying and upgrading the home and foreign IP addresses when managing mobility.

$$VHOLat = VHO_{L2} + VHO_{L3} + VHO_{MIP} \tag{4.2}$$

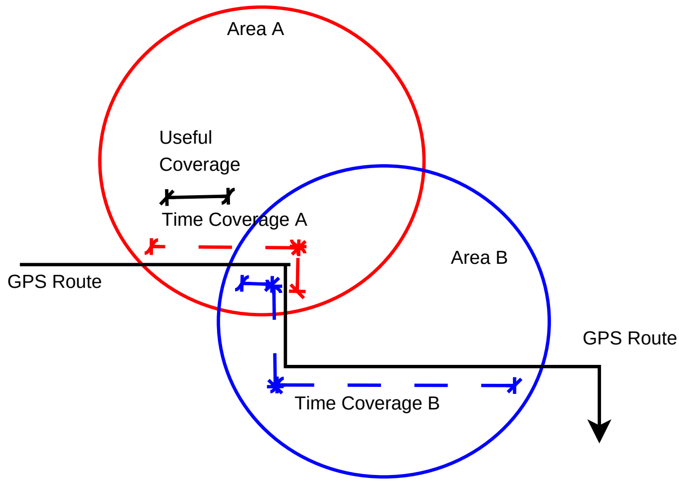


Figure 4.5: GPS route & coverage area considerations example.

The MACHU algorithm takes $VHOLat$ into account as a main decision parameter. In order to perform an adequate neighborhood discovery task, the most adequate values for the $SensingPeriod$ and the $PredictionWindow$ variables must be selected. Therefore, based on Equation 4.2, we made the following considerations:

i) To guarantee an accurate decision-making process, MACHU must gain awareness of, at least, some minimum future neighborhood information within the amount of time defined by Equation 4.3, where α is the relative percentage of the Useful Coverage Time (see Figure 4.5) during which the system is able to tolerate the adverse effects of VHO (which implies both packet loss and latency).

$$CellCoverageTime_{min} = \frac{VHOLat_{max}}{\alpha} \tag{4.3}$$

ii) An optimum $SensingPeriod$ must be smaller than the $CellCoverageTime$, as show in Equation 4.4. This means that, before the current neighborhood information becomes deprecated upon reaching the $CellCoverageTime$, the $SensingPeriod$ must assure fresh information about the future neighborhood. This parameter is related to how often the information must be collected.

$$SensingPeriod_{opt} < CellCoverageTime_{min} \tag{4.4}$$

iii) Based on the $SensingPeriod$, Equation 4.5 presents a minimum $PredictionWindow$ which guarantees an accurate process of Neighborhooding. This parameter is related to how much information must be collected; therefore, an adequate window size must double the amount of $SensingPeriod$ time in terms of future information.

$$PredictionWindow_{min} = 2 \cdot CellCoverageTime_{min} \tag{4.5}$$

However, depending on the features and performance of the OBU, the optimum $PredictionWindow$ can be determined according to the Equation 4.6, where β is a multiplier that can be tuned according to the OBU and the system performance, expected to take values in the range of 1 to 2 (*i.e.* $1 < \beta \leq 2$).

$$PredictionWindow_{opt} = \beta \cdot PredictionWindow_{min} \tag{4.6}$$

By taking all the aforementioned parameters into account, the Current and Future Neighborhood shall offer precise and coherent information.

4.3.3 Decision-making

Finally, the selection of the destination network (by choosing a PoA to hand over to) is made at the decision-making branch. This process evaluates all the gathered information and, based on the useful coverage area criteria, the candidate PoA which best fits the application requirements is chosen. For testing purposes, MACHU currently considers the cell coverage information (stored locally as the Current and Future Neighborhoods) in order to allow or deny the VHO execution (*i.e.* LINK UP IEEE 802.21 primitive). The main MACHU's decision logic, which considers the cell coverage time, allows handovers to take place only when the $VHOLat$ time is less than α percent of the Useful Coverage time. Remember that α, as mentioned before, is the maximum relative time during which the system supports handover-related losses. Considering the scenario of Figure 4.5, when a vehicle arrives to the coverage area A, the wireless network interface triggers a LINK DETECTED event, starting the whole MACHU process. If we based the decision on the Time Coverage A, not considering the immediate future, we could make a mistaken decision, since the vehicle will leave the coverage area A almost immediately to join the coverage area B, and so the VHO would be worthless. Therefore, a decision must be taken considering the Useful Coverage Time, instead of the mere coverage area advertised by the IEEE 802.21 MIIS.

Finally, when a VHO process takes place, the new address is notified to the network elements by using MIPv6, which manages the mobility issues.

4.4 Description of the Geo-MACHU VHDA

When VHO processes are performed within a VNs context, many mobility and location issues must be considered. The intrinsic characteristics of the VNs, such as dynamism, speed, and very changing contexts, turn the VHO into a very challenging process.

Other features of the VNs, such as availability of geolocation through the GPS, and the lack of power restrictions due to the continuous energy supply, allow the devices to improve the gathering of context information in order to perform an accurate switching decision, thus improving the VHO process. Based on this, we present a novel VHDA called Geolocation-based Multi-ACcess network Handover algorithm for vehicUlar environments (Geo-MACHU). In this proposal we combine GPS information (both geolocation and navigation), underlying network information (realistic propagation models), as well as network architecture information, in order to optimize the network selection process, a critical element of the VHO process.

Before describing the proposed algorithm and its working process, we present some underlying network considerations which are taken into account when the VHDA is performing the decision-making process.

4.4.1 Underlying network considerations

In order to design a VHDA able to perform the handoff not only considering the most adequate candidate network to switch to, but also considering the precise time to leave the previous PoA and join the new one, we must estimate the packet loss conditions associated with the different networks at different distances between vehicle and PoA. The VHDA could evaluate the performance along the route followed by the car by calculating the distance to the PoA and assessing the network conditions, thus improving the VHO process.

To obtain a valid model for the channel behavior we have performed several measurements within the Polytechnic University of Valencia campus and the University of Murcia campus, obtaining real Wi-Fi and WiMAX results, respectively. For measurement purposes, a 1500 bytes packet size was used. Figure 4.6 presents the Packet loss as a function of distance to the PoA for both Wi-Fi and WiMAX technologies. It is important to point out that the measurements where taken at the MAC level, to model the phy/mac behavior. Equations 4.7 and 4.8 present the distance reception probability based on the model.

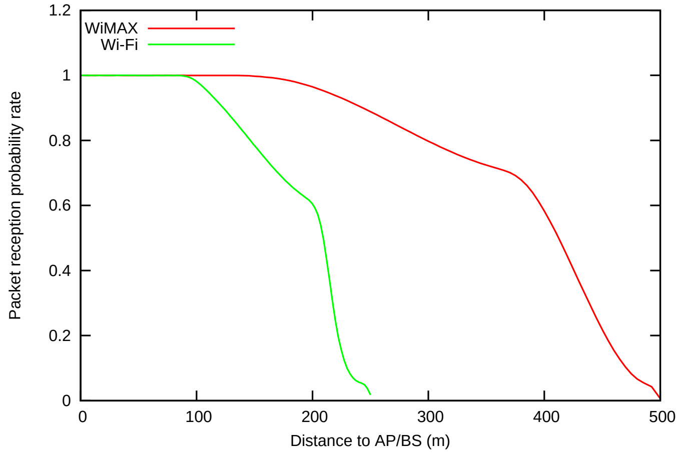


Figure 4.6: Wi-Fi & WiMAX packet loss model.

$$DRP_{Wi-Fi} = \begin{cases} 1 & \text{if } d <= 100 \\ 2.912e^{-07} * d^3 - 0.00012 * d^2 + 0.0138 * d + 0.571 & \text{if } d > 100 \ \& \ d <= 210 \\ -1.139e^{-05} * d^3 + 0.00833 * d^2 - 2.0342 * d + 165.489 & \text{if } d > 210 \ \& \ d <= 250 \\ 0 & \text{if } d > 250 \end{cases} \quad (4.7)$$

$$DRP_{WiMAX} = \begin{cases} 1 & \text{if } d <= 150 \\ 4.258e^{-08} * d^3 - 3.485e^{-05} * d^2 + 0.00765 * d + 0.4889 & \text{if } d > 150 \ \& \ d <= 375 \\ 6.222e^{-05} * d^3 - 0.000798 * d^2 + 0.333 * d - 44.908 & \text{if } d > 375 \ \& \ d <= 500 \\ 0 & \text{if } d > 250 \end{cases} \quad (4.8)$$

4.4.2 Geo-MACHU main tasks

In this Section we will briefly describe the basics of the Geo-MACHU since it is based on the previous one presented in Section 4.3 (MACHU). Both VHDAs take advantage of advanced car features, such as powerful OBUs, GPS (geolocation and navigation information), different networking interfaces, and networking/context information provided by the IEEE 802.21 standard. Geo-MACHU, similarly to MACHU, is composed of 3 asynchronous branches: Networking, Neighborhooding, and Decision-making branches. Figure 4.7 presents the flow diagram of the algorithm.

For the Networking task, Geo-MACHU takes into consideration not only the Detection via RA and RS level-3 network packets, but also through level-2 network packets (*i.e.* link scan and link response), thus obtaining an accurate network status.

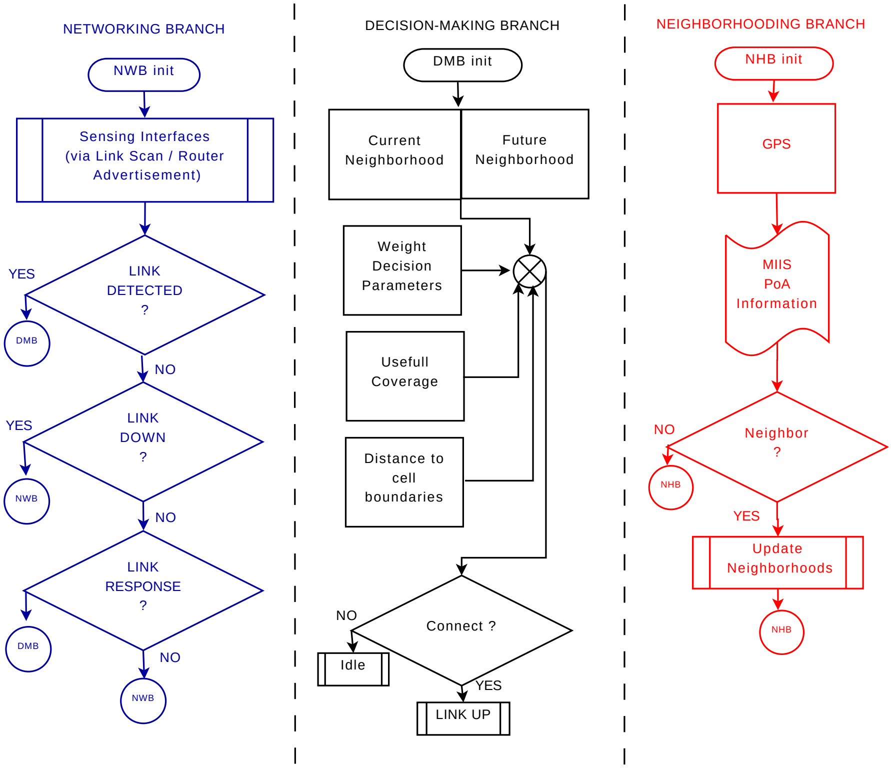


Figure 4.7: Geo-MACHU algorithm.

Concerning the Neighborhooding task described in Section 4.3.2, we have added a new GPS-based parameter into consideration: The QoS cell borderline, which guarantees the required QoS based on the considerations presented in the model described in Equations 4.7 and 4.8. By taking into account the QoS cell borderline, the Current and Future Neighborhoods can be built with different surrounding information, thus offering a different PoA availability to the decision branch. Figure 4.8 illustrates the concept of the GPS route, cell overlapping and QoS cell borderline.

The main decision logic (decision-making task) of our proposed Geo-MACHU algorithm, whose aim is to guarantee the QoS, considers the cell coverage time and guaranteed QoS borderline of the cell, allowing handovers to take place only when there is a worthy Useful Coverage available considering also the distance to the QoS cell borderline of the PoA involved in the decision process. As shown in Figure 4.8, when a vehicle arrives to the coverage area A, the wireless network interface triggers a LINK DETECTED event, starting the VHDA process. If we based the decision on the Time Coverage A, considering neither the immediate future nor the QoS borderline,

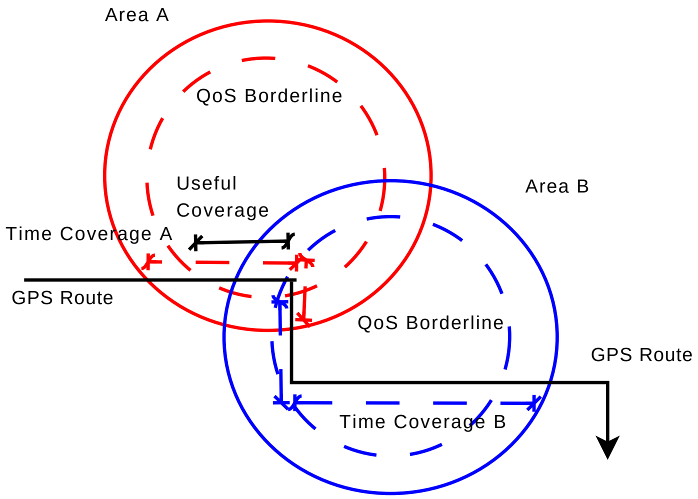


Figure 4.8: GPS route, coverage area and QoS borderline example.

we could make a mistaken decision, since the vehicle would soon leave the coverage area A to join the coverage area B, and so the VHO would be worthless. Therefore, a decision must be taken considering the Useful Coverage Time and the distance to the guaranteed QoS borderline, instead of just the coverage area offered by the IEEE 802.21 MIIS.

Once the whole VHO has been performed, similarly to MACHU, different notification-update processes are exchanged with the server to handle the mobility issues by using MIPv6, OBU's wireless interfaces, and networking elements, redirecting the flows so as to maintain the connection alive.

4.5 Description of the MCDM-MACHU VHDA

The Multiple Criteria Decision-Making based Multi-ACcess network Handover algorithm for vehicUlar environments (MCDM-MACHU) is also based on the combined use of the IEEE 802.21 standard and OBU features. For its decision-making process, MCDM-MACHU collects information from multiple sources and applies the Simple Additive Weighting (SAW) algorithm (presented in Section 3.5.3) to evaluate the multiple criteria, achieving a fair evaluation of all the candidate networks. This algorithm, similarly to its predecessors (MACHU and GEO-MACHU) takes into account network and context information, such as technology availability, coverage areas, useful coverage, QoS borderline, GPS routes, and map layouts. However, the MCDM-MACHU algorithm also takes into consideration the user preferences and the application requirements. We now proceed to describe both sets of requirements:

4.5.1 User preferences

We have defined *User Profiles* in order to classify the user preferences into self defined sets. Each profile is based on requirements, and considers both application requirements and the user budget. The defined profiles are:

Maximum Performance. Under this profile, the VHDA always selects the best performing network among all the possible choices, irrespectively of the associated cost.

Guaranteed Video. The video profile is optimized to choose those networks that offer not only a high throughput, but also a low packet loss ratio. A trade-off between performance and cost is also sought.

Guaranteed VoIP. Similarly to the Video profile, this profile considers that having a low packet loss ratio is an important factor, but in this profile a low latency per packet is also critical when choosing a candidate network. Throughput is not so significant, neither is cost.

Minimum Cost. This profile is based on the user budget, and it considers the price that user is willing to pay as the most important factor for the decision making process. If this value is low, the cheapest network available will be always the best choice.

4.5.2 Application requirements

The application requirements are a set of parameters that the VHDA, in conjunction with the user preferences, takes into account for evaluating the best candidate network. These parameters are evaluated by a Multiple Criteria Decision-Making (MCDM) algorithm. That way, all of them are considered and weighted by the decision-making process when selecting the most suitable network. We now proceed to describe each parameter:

Throughput. This parameter describes the throughput requirement that the application is demanding.

Latency per packet. The latency that the application is able to tolerate in order to guarantee its performance.

Packet loss ratio. The losses on the channel that the application tolerates before decreasing its performance.

Price per Mb. The price that the user is willing to pay for the connectivity service.

4.5.3 Proposed SAW-based network assessment function

As we mention before, an MCDM algorithm was used to evaluate the multiple criteria. The algorithm is based on the SAW algorithm. Equation 4.9 presents the ratio among the network parameters and the application requirements. The ratio of each parameter (*i.e.* Throughput, Latency per packet, Packet loss, and Price per Mb) must be normalized and maximized; therefore, Equation 4.9 presents two different cases, depending on the parameter evaluated. In order to achieve different optimization objectives, this equation can be tuned by applying different multiplier factors, usually called *weights*. We have set, as optimization objectives, the user profiles described in Section 4.5.1.

$$ParametersRatio_i = \begin{cases} \frac{RequirementParam_i}{CandidateNetworkParam_i} & \text{if i=\{PriceMb,LatencyPacket,PacketLoss\}} \\ \\ \frac{CandidateNetworkParam_i}{RequirementParam_i} & \text{if i=Throughput} \end{cases} \tag{4.9}$$

In order to adjust the importance (weight) of the requirements, as a function of the user profile, a β multiplier is required. Factors β_i are profile-specific, and allow modifying the weight of each *ParametersRatio* element, as shown in Equation 4.10, where i is an element of the Application requirements list.

$$CandidateNetwork_{MCDMValue} = \sum_{i=0}^{n} \beta_i \left(ParametersRatio_i\right) \tag{4.10}$$

4.5.4 Calibration of the β_i values

In order to calculate the most appropriate weight (β_i) for each parameter for the different user profiles, we have adopted a 2-step Monte Carlo process. The Monte Carlo process is fed by training cases, based on a set of 10 different networks with different performance and characteristics (among Wi-Fi, WiMAX and UMTS). We have defined a training set with a total of 270 VHO decisions, combining the different networks at different utilization states. We must take into account that the decisions where done from a subjective point of view, considering all the requirement parameters and the candidate network parameters.

The first step of the Monte Carlo process was to determine the best β values out of three million runs. The success rate is measured in terms of similitude to the

Table 4.1: β values optimized for the user profiles.

Requirement Parameter	**Minimum Cost**	**Guaranteed Video**	**Guaranteed VoIP**	**Maximum Performance**
PriceMb	0.4637620	0.4218970	0.2578700	0.0469420
LatencyPacket	0.1068350	0.4216220	0.1638400	0.0617170
PacketLoss	0.0339010	0.1348730	0.2269100	0.3986950
Throughput	0.3955020	0.0216080	0.3513700	0.4926470

decisions used as input to the process. Once the β_i values were chosen, we proceed to the second step of the Monte Carlo process, adding other three million runs to refine the β_i values obtained in the first step. In particular, the variation interval for the β_i values was of 1%. By doing this second step we can obtain even more accurate β values. Table 4.1 presents the β values optimized for each user profile. These sets of values guarantee a success ratio of about 82% of success at the VHO decision process when the MCDM-MACHU is applied.

4.5.5 MCDM decision process

As mentioned earlier, the development of the different VHDAs proposed was done in a progressive and incremental manner. Therefore, MCDM-MACHU stands on the basis of the Geo-MACHU algorithm. So, considering Figure 4.8, when a vehicle reaches the QoS borderline, and once all the filters used by the previous algorithms (Tech-aware, MACHU and Geo-MACHU) have been used to select feasible networks, the MCDM process is then executed to introduce additional criteria to the decision-making process. The MCDM-MACHU process calculates the $CandidateNetwork_{MCDMValue}$ (as shown in Equation 4.10) for each candidate network, obtaining a positive value (*i.e.* $CandidateNetwork_{MCDMValue} > 0$). Once all the values are obtained, they are compared, and the MCDM process chooses the network with the highest value. It means that the chosen network is the most suitable network when attempting to fulfill the application requirements under a certain user profile.

When the decision-making process finishes, the VHO execution process performs its tasks and seamlessly switches from the old network to the chosen candidate network, executing the MIP notification process and redirecting the traffic flows.

4.6 Summary

In this Chapter we have presented the evolution of our Vertical Handover Decision Algorithms (VHDAs) proposed. All of them work according to the IEEE 802.21 standard, considering Wi-Fi, WiMAX, and UMTS as underlying wireless access technologies.

Our main contributions can be summarized in function of VHDA algorithms:

Technology-Aware VHDA. Considers availability and capacity of candidate PoAs.

MACHU VHDA. Based on the Technology-Aware VHDA, also combines different data sources at the OBUs used in vehicular environments, taking advantage of GPS information, maps, surrounding context information and routes.

Geo-MACHU VHDA. Based on the MACHU VHDA, it takes into account context network, geolocation and navigation information to guarantee the QoS.

MCDM-MACHU VHDA. Based on the Geo-MACHU VHDA, it adds to its predecessors a multi-criteria decision making process, attempting to meet the application requirements from a user preferences perspective.

Part III

Experimentation and results

Chapter 5

Simulation Frameworks and Experimentation

In order to evaluate the algorithms proposed in Chapter 4, we have developed a simulation framework able to reproduce, via simulation, heterogeneous network schemes. Moreover, in this Chapter, we not only present the Vertical Handover Decision Algorithms (VHDAs) performance evaluation, but also the previous experimentation to support the aforementioned algorithms. Therefore, we have initially evaluated the viability of the content delivery over Vehicular Networks (VNs), and then we have studied the performance of each wireless network to be used in the VHDA experimentation (*i.e.*Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX), and Universal Mobile Telecommunications System (UMTS)). Based on the information collected on those experiments, we were able to evaluate the proposed VHDAs under appropriate context and scheme.

5.1 Content delivery approach in Vehicular *Ad-hoc* Networks (VANETs)

In this section we present a multi-layer performance evaluation of a content delivery framework over multi-hop vehicular networks by focusing not only on the application layer, but also on the transport and routing layers. The framework is evaluated using the Network Simulator (ns-2) [KK09a], where contents on remote servers are accessed through the HiperText Transfer Protocol (HTTP)/1.1. We rely on the *Ad-hoc* On-demand Distance Vector (AODV) routing protocol to discover and maintain routes in the VANET, and model the IEEE 802.11p assuming a 20 MHz band for the PHY/-MAC communications. To evaluate the performance of the proposed framework we performed several experiments varying different parameters affecting VANET performance, such as vehicle speed, density of vehicles, the user request rate, and the pattern of these requests.

Results show the viability of the content delivery framework over VANETs. We find that performance is improved when vehicular density and speed is increased since the user perceived latency is reduced.

5.1.1 VANET-based delivery framework overview

Our proposed content delivery framework for VANETs is based on a VANET scenario where only a limited number of vehicles is within the range of a RoadSide Unit (RSU). These vehicles advertise themselves as gateways to other vehicles, allowing to extend the coverage area of RSUs seamlessly, thereby reducing the costs associated to the deployment of a full coverage infrastructure. Every vehicle equipped with an On-Board Unit (OBU) is able to demand infotainment contents from the infrastructure by relying on VANET communication. These requests are handled by a main server, accessible through the RSU. It is important to point out that vehicles benefit from the multi-channel framework proposed by IEEE 802.11p in order to communicate with the RSUs and with other vehicles simultaneously.

To evaluate the viability of the proposed content delivery framework, we envision a scenario where content requests coming from vehicles are handled by a main server (*i.e.* Webserver or Proxy). Basically, vehicles behave as web clients that make requests to a web server. We propose using the HTTP protocol to access contents at the application level since it is the most widely used protocol for content delivery in the Internet. We rely on the AODV routing protocol for topology maintenance due to its well-known performance in environments with a high degree of mobility [LF03]. AODV is a reactive protocol classified as a pure on-demand route acquisition system. It minimizes the control traffic by avoiding any control traffic when no data traffic is flowing through the network.

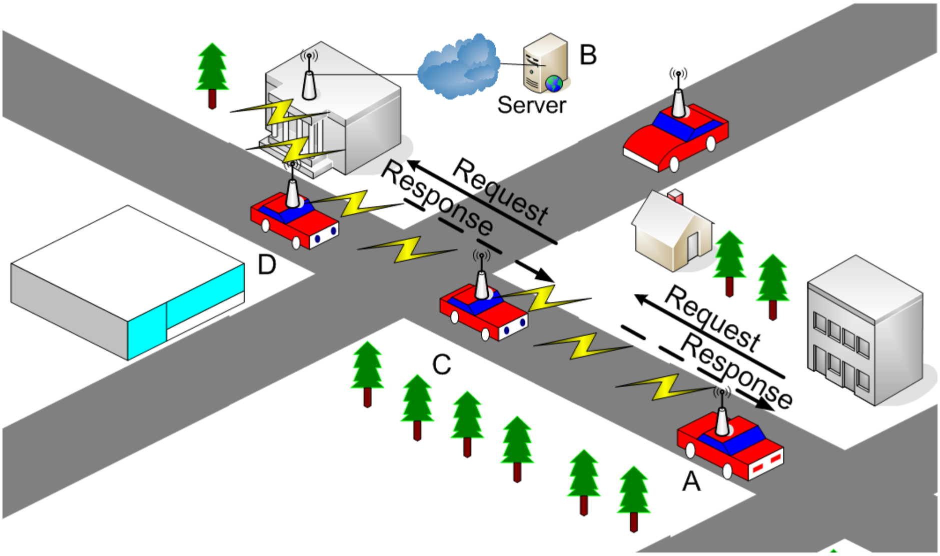


Figure 5.1: Content delivery scheme.

Figure 5.1 shows the parameters adopted for the content delivery scheme considered in our framework. In this example vehicle A is requesting contents from server B by using the HTTP protocol. Although vehicle A is located far away from the server, the AODV routing protocol triggers a request message to establish a multi-hop path where vehicles C and D participate in the content delivery process as traffic forwarders. Notice that the same procedure could be used to send information from the vehicles to the server, in order to advertise information related to traffic conditions, collisions, accidents, etc.

5.1.2 Simulation set-up

One of the most widely used simulators in the literature is the ns-2 simulator [KK09a], which allows testing with several protocols and architectures. ns-2 allows us to simulate *Ad-hoc* and vehicular environments in a straightforward way, requiring the latter only some minor adaptations.

The different mobility scenarios were defined using the Citymob tool [FJCP08]. This tool was developed by the Networking Research Group (GRC) at the Polytechnic University of Valencia (UPV), and consists of a mobility pattern generator for VANETs that allows to easily create urban mobility scenarios, including the possibility to model car accidents. Citymob is designed to be used in conjunction with the ns-2 simulator.

Thanks to the flexibility offered by Citymob along with ns-2, we have evaluated multiple scenarios based on a Manhattan grid in a 2000 by 2000 meters area with 80 meters between the median strips of consecutive streets, resembling the distribution in Figure 5.1. In order to perform a fair evaluation we used various randomly generated scenarios to obtain consistent results.

To evaluate the content delivery framework under different conditions we define two sets of experiments:

A) In the first set we vary the vehicular density from 100 to 400 vehicles with a granularity of 50. Only one hundred vehicles demand the workload, behaving the rest merely as forwarding nodes.

B) In the second set we vary the content workload demanded by vehicles from low to high rates. We set the total number of vehicles to 250, where one hundred of them demand for contents.

In both sets of experiments, considering a urban scenario, the speed varies among slow, intermediate, and fast *i.e.* 20, 50 and 75 km per hour, respectively.

Every vehicle is equipped with an IEEE 802.11p enabled OBU, having one channel reserved for communication in the *Ad-hoc* mode, which is used for VANET-based content delivery, and another channel reserved for communicating with the RSUs (whenever available). The wireless data rate is set to 54 Mbps, and the radio range is set to 250 meters on both channels.

To generate traffic we used a tool called *WebTraff* [KK09a], included within the ns-2, that allowed us to model HTTP traffic. The characteristics of the traffic representing contents accessed by the different VANET participants is presented in Table 5.1. Sets #1 and #2 present the workload used for the first and the second group of experiments, respectively. As observed in the second set, we basically increase the workload by varying the page size and the object size parameters.

5.1.3 Performance evaluation

We have evaluated the following performance metrics: i) latency, ii) throughput, iii) and packet loss. In a VANET, results are strongly related to the specific scenario used. Hence, in order to improve the reliability of the results presented, we performed several experiments varying the scenarios, assuring that the mean values obtained were within strict confidence intervals.

Notice that, to measure the effectiveness of the content delivery process, we take into account the user perceived latency. This value is measured at the OBU considering the amount of time required to completely fulfill the user request, being therefore

Table 5.1: User access description.

Set of experiments	**Set #1**	**Set #2**
Metric	**Function/Value**	**Function/Value**
Time between content requests	Exponential (Avg. 1 sec.)	Exponential (Avg. 1 sec.)
Time between related object requests	Exponential (Avg. 0.01 sec)	Exponential (Avg. 0.01 sec)
Page size	Constant (10 Objects)	5 to 30 objects (granularity: 5)
Object size	Constant (10 KB)	5 to 80 KB (granularity: 15)
Sessions	100	100
Pages per Session	300	300

an application-layer metric that significantly differs from the traditional end-to-end delay metric (routing layer).

Impact of vehicle density on performance

We evaluate the impact that the vehicle density has over the content delivery performance.

Figure 5.2 depicts the average throughput and average latency per request. As shown, throughput increases when vehicular density increases; speed variations have only a minimal impact on throughput. Increasing the vehicular density within the VANET also increases the number of alternative routes, offering not only more but also better routes, thus improving performance. The user perceived latency is also improved, reaching lower values when vehicular density increases. We also observe that the vehicles' speed has a significant impact on latency.

Packet loss partially reveals the state of the VANET connectivity. This metric clearly shows the performance of the VANET due to several factors such as route updating, lack of routes, errors and collisions at the physical layer, and queue dropping. Figure 5.3 shows that, for moderate/high speeds, the packet loss ratio decreases as the number of vehicles increases. This fact confirms that a higher vehicular density increases the overall network performance.

The intimate relationship between packet losses and latency can be observed in Figure 5.3 (bottom). This figure shows that latency deteriorates with higher losses in a linear manner. Through regression we obtained a linear function relating both magnitudes. We found the root mean squared error for the curve fitting process to be below 0.0920.

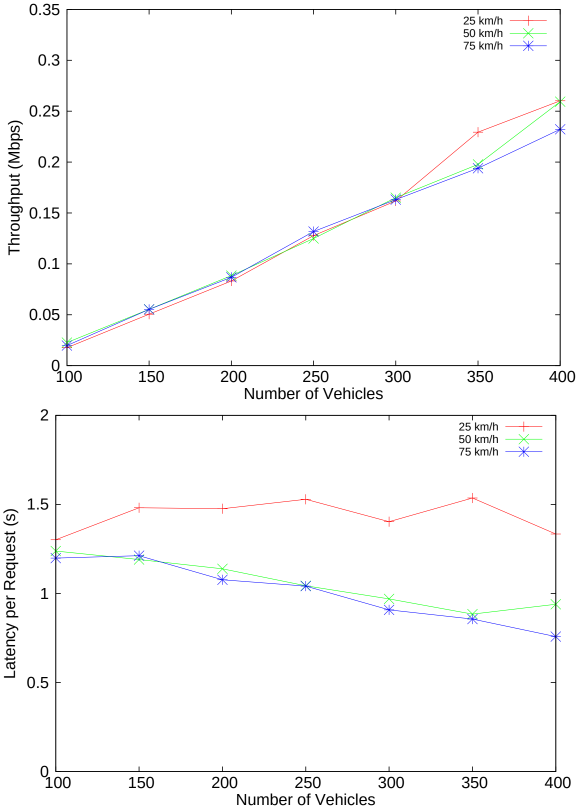


Figure 5.2: Average throughput (top) and latency (bottom) when varying the vehicular density.

All the results shown above evidence that a high vehicular density improves the performance of the content delivery within the VANET. Nevertheless, to perform a fair evaluation, it is also important to measure the overload that routing messages cause to the VANET. Figure 5.4 (top) shows the routing overhead per vehicle when the number of vehicles increases. We can see that, as the VANET density increases, the total amount of routing packets per source actually tends to decrease. This means that, the more vehicles are implicated in the routing process, the less each of them has to participate in topology control tasks.

A metric that better explains the relationship between routing packets and data packet delivery ratio is the *Normalized routing overhead*. Figure 5.4 (bottom) shows that this latter metric increases when the number of vehicles also increases. This is expected since the amount of control traffic is proportional to the number of vehicles in the VANET.

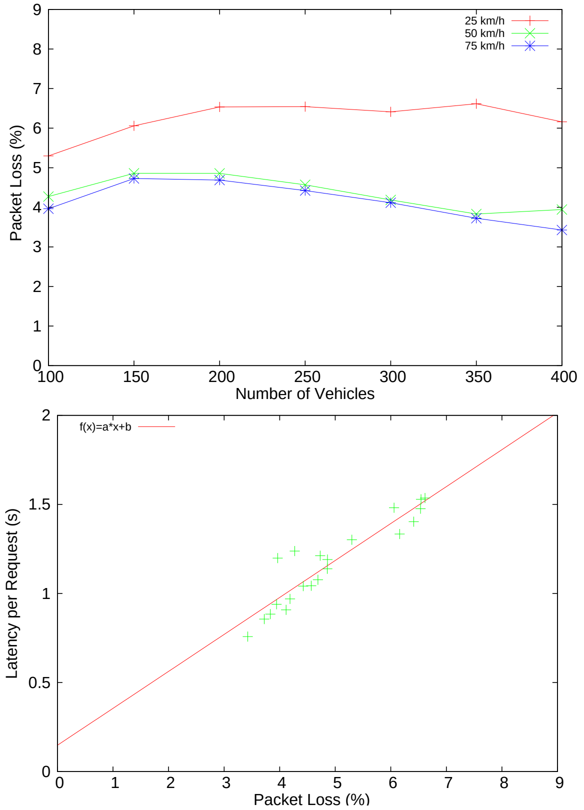


Figure 5.3: Average packet loss when varying the vehicular density (top) and latency as a function of packet loss (bottom).

Impact of the offered workload on performance

We now evaluate the impact that the offered workload has on the overall performance.

We evaluate performance of the content delivery framework over the VANET when varying the workload demand rate from 1.5 Mbps to 4.5 Mbps. Figure 5.5 (bottom) shows that, independently of the vehicle speed, latency strongly increases when there is an increment in the workload demand rate. As expected, the throughput also increases, though the increase is not linear (see Figure 5.5, top). When measuring the latency, we observe that latency decreases when vehicular density increases (see Figure 5.2, bottom). On the other hand, for a fixed number of vehicles, when the workload increases, the latency also increases (see Figure 5.5, bottom), thus degrading the performance.

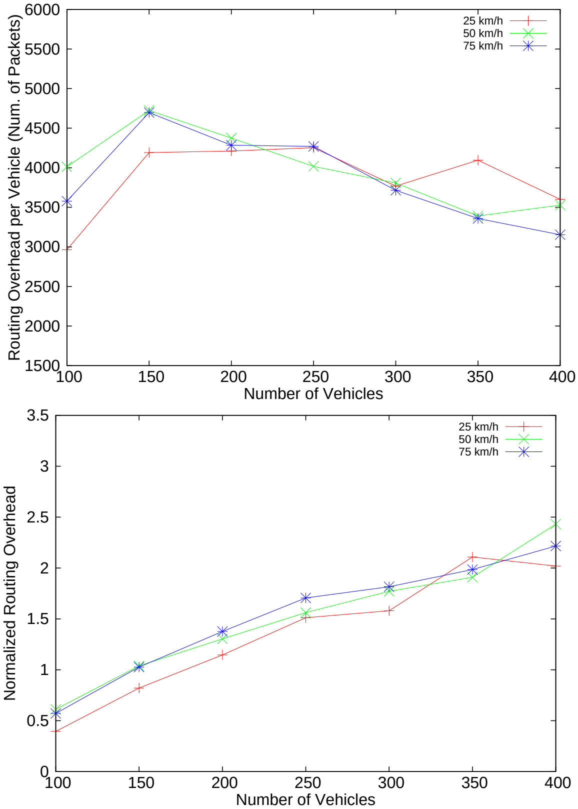


Figure 5.4: Routing overhead per vehicle (top) and normalized routing overhead (bottom) when varying the vehicular density.

Figure 5.6 (top) presents the packet loss when varying the workload demand rate. We observe that packet loss increases when the workload demand increases in a more-than-proportional manner. As we mentioned before, the Transmission Control Protocol (TCP) packet loss partially reflects the overall performance of the VANET. Figure 5.6 (bottom) shows the relationship between latency and packet loss. As shown in this figure, latency exponentially increases when packet loss surpasses the 10% threshold. To confirm this trend, we adjust function $g(x) = a \cdot e^{b \cdot x} + c$ to the set of results (see Figure 5.6, bottom), obtaining a root mean squared error of only 2.77. The effect shown should be taken into account when proposing content delivery schemes for VANETs considering workload and bandwidth related issues.

Finally, Figure 5.7 presents the routing overhead per vehicle (top) and the normalized routing overhead (bottom). We observe that this metric does not increase

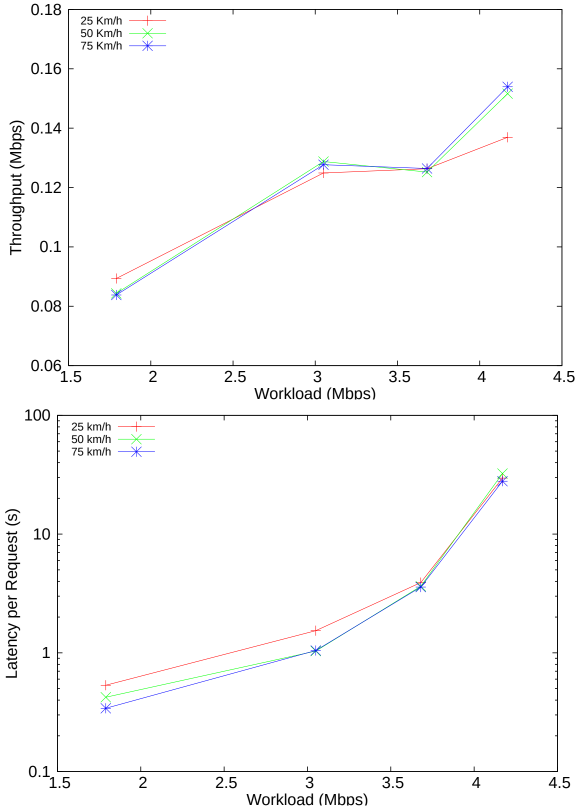


Figure 5.5: Average throughput and latency when varying the workload.

compared to the other metrics. This occurs because the routing overhead mostly depends on the number of the vehicles that participate in the process and their degree of mobility, rather than on the amount of traffic transmitted in the VANET.

5.2 Wireless technologies performance

In this section we evaluate the performance of different underlying wireless access networks. We aim to study the performance of each wireless network under stress conditions in order to evaluate their boundaries performance.

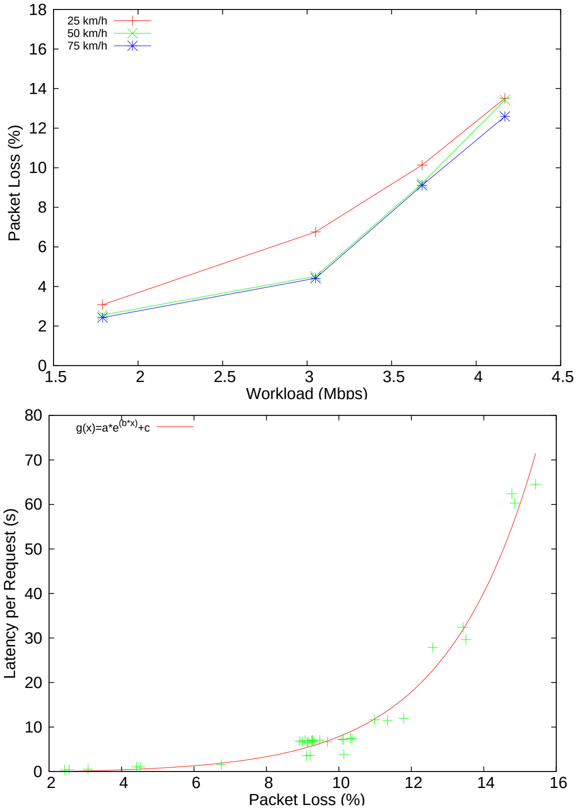


Figure 5.6: Average packet loss when varying the workload and latency as a function of packet loss.

5.2.1 Simulation framework and tools

There are several tools for network simulation. One of the most complete simulators for wireless networks is the ns-2. This tool allows simulating 802.11-based networks and, thanks to the *Enhanced UMTS Radio Access Network Extensions (EURANE)* [ET] and the *National Institute of Standards and Technology (NIST)* [Adv] extensions, it also allows simulating UMTS and WiMAX technologies. Since our main research goal is to study and develop Vertical Handover (VHO) strategies, we used the *NIST mobility package for the ns-2*. This package already offers the 802.11, 802.16 and UMTS (EURANE) modules modified to perform a seamless VHO among these wireless technologies.

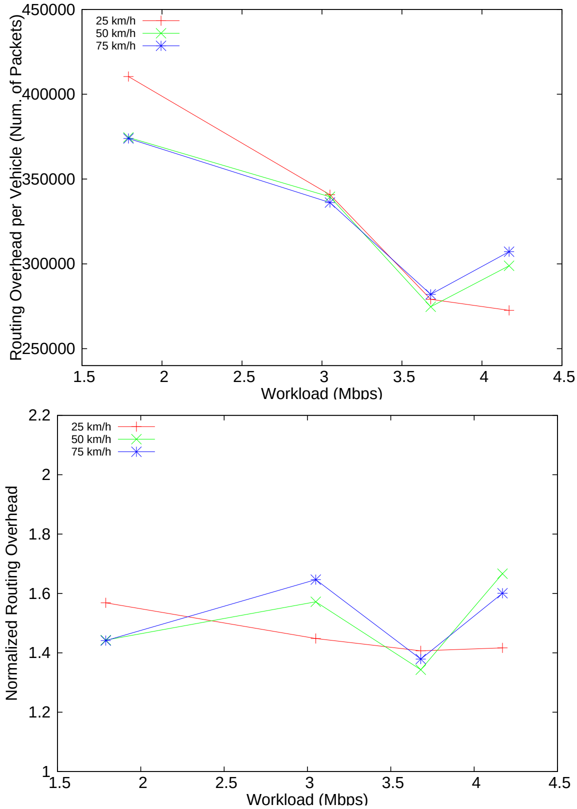


Figure 5.7: Routing overhead per vehicle (top) and normalized routing overhead (bottom) when varying the workload.

802.11

We simulate a scenario based on an access point and up to 10 nodes downloading/uploading packets to/from a server at a Constant Bit Rate (CBR), as shown in Figure 5.8. The protocol used is the 802.11g with a specific fading model designed to enable VHO triggering. It is important that the nodes request and inject data at maximum rate in order to stress the network.

802.16

Similarly to Wi-Fi, we set up the 802.16 scenario (see Figure 5.9) considering 1 access point and up to 10 nodes that are able to request and send CBR packets to/from a

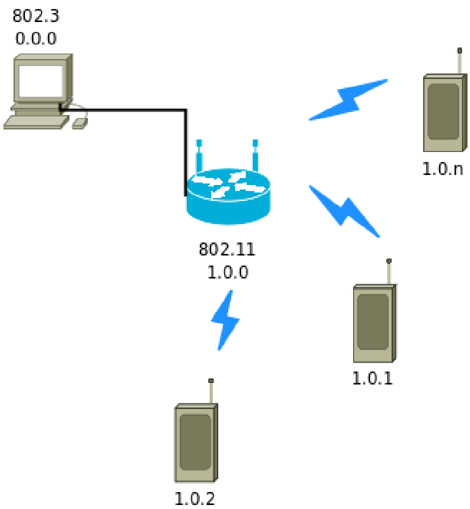


Figure 5.8: Wi-Fi simulation framework.

server at a very high data rate. The 802.16e amendment is used in order to support node mobility. Moreover, different types of modulation have been used in order to evaluate a wide range of WiMAX alternatives.

UMTS

Finally, the UMTS scenario has been set up taking into account the main components of the UMTS and General Packet Radio System (GPRS) core, as the one presented in [DGL11]. Figure 5.10 shows the scenario used: 1 nodeB (base station), 1 Radio Network Controller (RNC) unit, 1 Gateway GPRS Support Node (GGSN) unit, 1 Serving GPRS Support Node (SGSN) unit, up to 10 User Equipment (UE) units and 1 server. To maintain the trend of the experiments we have evaluated uplink and downlink CBR traffic with a high data rate.

5.2.2 Performance evaluation

To evaluate the performance of each wireless technology we used throughput as the main performance metric. In simulations, results are strongly related to the specific selected seed. Therefore, in order to obtain reliable results, we performed several experiments with different seeds. This way we assure that the mean values obtained were within strict confidence intervals.

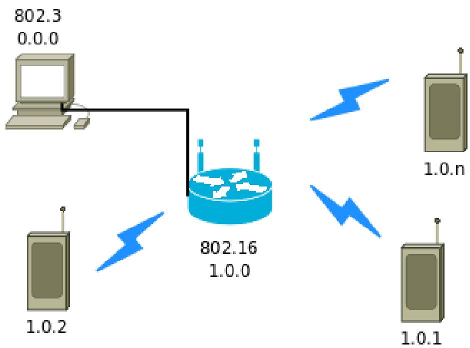


Figure 5.9: WiMAX simulation framework.

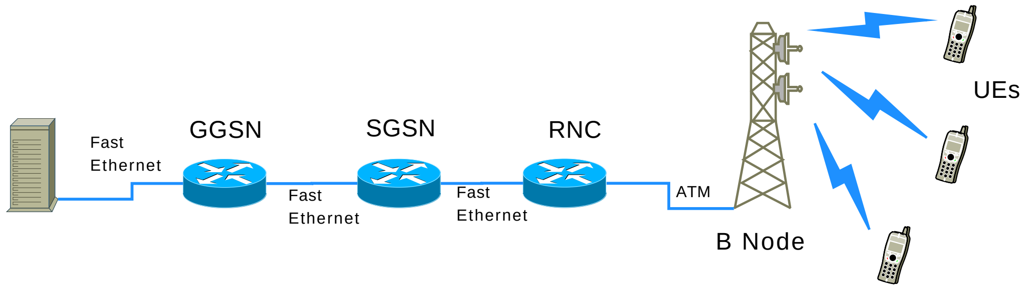


Figure 5.10: UMTS simulation framework.

Wi-Fi performance

In terms of Wi-Fi performance, Figure 5.11 shows the average throughput achieved per node, as well as the total throughput achievable in the channel. Our tests reveal that only up to 24.09 Mbps could be achieved from the 54 Mbps theoretical maximum offered by 802.11g. The channel's throughput remains close to 24 Mbps, and the nodes sharing the channel do not always receive a fair share of bandwidth, as experimental results show that some Wi-Fi nodes monopolize the channel due to their proximity to the access point. It is important to point out that this throughput is a best-case value that is only reached within a very short coverage range (less than 5 meters) in real environments.

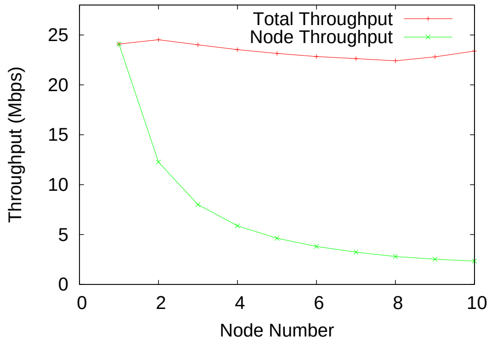


Figure 5.11: Wi-Fi maximum experimental throughput.

WiMAX performance

In our second set of experiments we have assessed the performance of WiMAX under different configurations. Figure 5.12 shows the different data rates reached when varying the cyclix prefix and the modulation strategy. The WiMAX standard states that using modulations which offer low data rates allows reaching greater distances, while high data rates can only be achieved for shorter distances. This means that the system does not cover wide areas while transferring at high data rates. Additionally, Figure 5.13 presents the total channel throughput achievable, as well as the per-node throughput reached in a simulation based on 64QAM 3/4 modulation with a cyclix prefix of 0.0625. Unlike Wi-Fi, WiMAX shares the channel bandwidth equally among the nodes due to its multiplexing feature. In particular, we find that every WiMAX node receives the same bandwidth share.

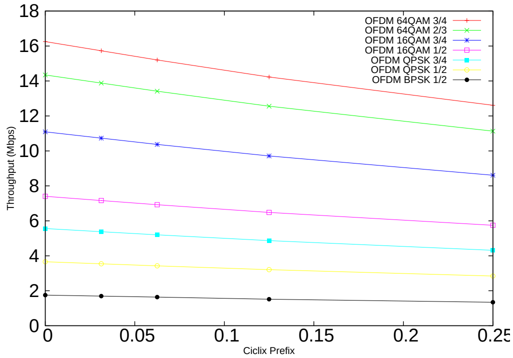


Figure 5.12: WiMAX maximum experimental throughput varying modulation and cyclix prefix.

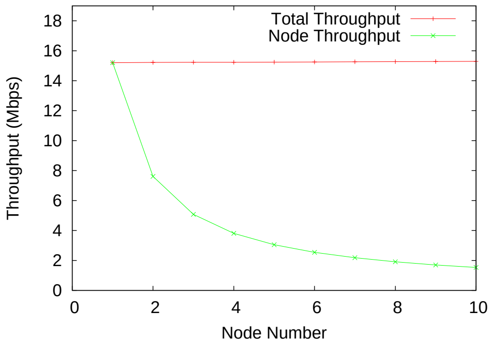


Figure 5.13: WiMAX maximum experimental throughput.

UMTS performance

Similarly to Wi-Fi and WiMAX, we performed several sets of experiments to determine the maximum throughput reachable in a stressed environment using UMTS. Figure 5.14 reveals that a User Equipment (UE) can achieve up to 2.7 Mbps when downloading data using a 5 Mbps channel. For uploading activity, as shown in Figure 5.15, a data rate up to 1.8 Mbps in a 2 Mbps channel can be achieved. Similarly to WiMAX, UMTS allows UEs to access the channel through multiplexing. Therefore, the bandwidth used by the UEs is fairly shared among them.

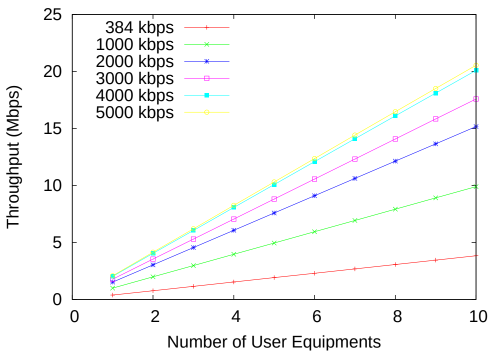


Figure 5.14: UMTS maximum experimental downlink throughput.

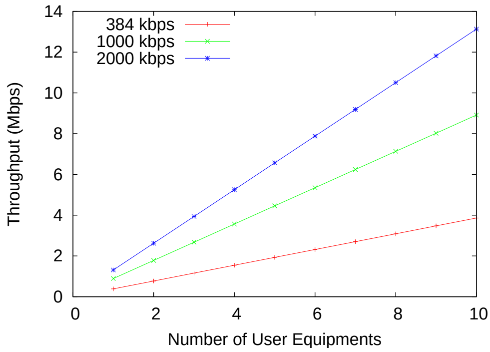


Figure 5.15: UMTS maximum experimental uplink throughput.

Technology evaluation summary

Table 5.2 presents the data rates obtained, as well as the main features of each type of wireless network. Wi-Fi offers the highest achievable data rate using a contention-based shared channel. This means it will be the technology of choice when channel occupation is low. WiMAX also reaches high data rates, but relies on a multiplexing-based shared channel instead. The lowest data rate is achieved by UMTS, which offers a dedicated channel that guarantees Quality of Service (QoS) under stable channel conditions. Nevertheless, considering the coverage area offered by these wireless technologies, UMTS offers the most stable data rate for a large coverage area, while the other two suffer from both distance-dependent data rates and high bandwidth variability associated to the number of users.

Table 5.2: Simulation results.

Wireless Technology	**Channel Type**	**Uplink (Mbps)**	**Downlink (Mbps)**	**Coverage Area**	**Medium Access**
Wi-Fi	Shared	24.09	24.09	small	Carrier Sense Multiple Access with Collision Avoidance (CS-MA/CA)
WiMAX	Shared	16.03	16.03	medium	Orthogonal Frequency-Division Multiple Access (OFDMA)
UMTS	Dedicated	5	2	large	Code Division Multiple Access (CDMA)

Table 5.3: VHO scheme components.

Component	**Wi-Fi**	**WiMAX**	**UMTS**
Access Point	2	2	1
Theoretical Bw (Mbps)	54	70	5
Bw offered (Mbps)	28.2	16.3	2.7
Advertisement Interval (ms)	100	5000	-
Coverage (m)	250	500	1000

5.3 Technology-aware VHDA evaluation

After assessing the performance of each wireless access network, we now proceed to evaluate each of the proposed algorithms in Chapter 4. To do so, we have developed a framework which will be used for evaluation purposes. However, the scheme is slightly modified for every VHDA evaluation due to need of more complex scenarios in order to evaluate the different features of each of the VHDAs.

5.3.1 Evaluation framework

To perform wireless networking experiments there are different techniques and tools that are currently used among researchers. One of those techniques is simulation. Through simulation researchers are able to reproduce a specific environment in order to evaluate performance under different parameters or configurations. Considering networking in general, there are several tools for simulation. Nevertheless, considering VHO in particular, there are only a few simulation tools available. To address this shortage, the National Institute of Standards and Technology (NIST) has developed a tool for seamless mobility [Adv] based on a widely used simulator for wired and wireless networks: the ns-2. The *NIST mobility package for the ns-2* allows simulating Wi-Fi, WiMAX, and UMTS technologies, as well as performing handovers among these technologies in a seamless manner. Moreover, it allows operating under the IEEE 802.21 standard offering most of its features.

For our experiments we have evaluated the VHDA by setting up a scheme considering three wireless technologies: Wi-Fi, WiMAX, and UMTS. Our scenario is a square area of 3000 m^2 area where 5 access points (1 node B for UMTS, 2 base stations for WiMAX, and 2 access points for Wi-Fi) have been deployed. Each element of the network has an MIH entity to manage the 802.21 protocol directives. Table 5.3 presents the elements and the configuration used. Moreover, Figure 5.16 shows the scenario used for our studies where the UE demands CBR traffic. The mobile terminal has permanent UMTS connectivity and, while moving, it discovers new wireless

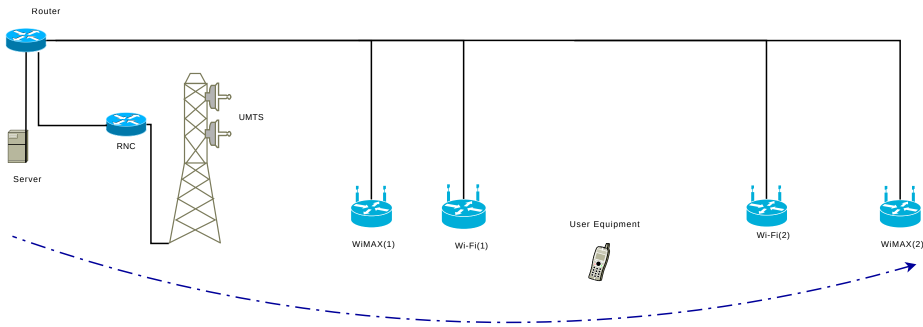


Figure 5.16: VHO scheme.

networks; it performs a VHO if any of the new networks offers a higher performance, or if the network being used disappears. Since our work focuses on VHO itself, the coverage areas of each technology do not extend over a very large area to avoid long periods of time where only one technology is used. Figure 5.17 presents the position of each access point and its coverage area. The initial position for the user equipment is represented by point A; the user equipment moves to the right in a straight line across the different coverage areas at a constant speed of 3 meters per second.

5.3.2 Performance evaluation under best-case conditions

To evaluate the performance of the VHO scheme we used the following metrics: i) latency, ii) throughput, iii) and packet loss. In order to obtain reliable results, we performed several experiments varying the seed randomly. By obtaining several simulation results per test we assure that the obtained mean values are within strict confidence intervals.

Concerning VHO performance, there are different points of view about the evaluation metrics to be used in order to perform an accurate analysis. However, it is important to establish two evaluation lines: the underlying wireless technologies and the VHO itself.

Underlying wireless technologies performance

In order to evaluate the performance of each wireless network, we evaluated the performance experienced by a mobile terminal throughout the simulation time. Figure 5.18 shows the network being used when moving along the scenario at a speed of 3 m/s. For the period of time that the user equipment is connected to a network, the throughput reached is the maximum for each technology. Figure 5.19 clearly shows the throughput reached by each network within a certain period of time. Wi-Fi offers

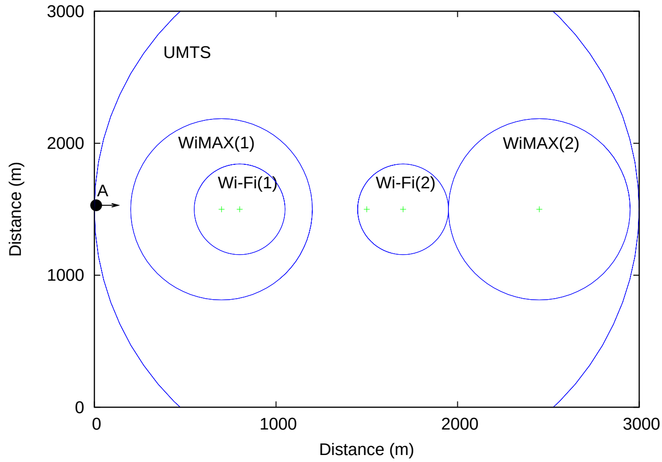


Figure 5.17: Wireless technologies coverage areas in the scenario under analysis.

the highest bandwidth, achieving up to 28.2 Mbps. Then WiMAX offers up to 11 Mbps, while UMTS offers a 2.04 Mbps data rate. These values confirm the trend of the results obtained in Section 5.2.2. Concerning latency, Figure 5.20 presents the trend of each wireless network during the simulation time. As observed, UMTS takes an average of 29.96 ms to deliver one packet, while WiMAX and Wi-Fi offer lower latencies: 0.81 and 0.23 ms, respectively.

VHO performance

Finally, we have performed several simulations to evaluate the performance of the VHO itself. We evaluate VHO latency and the undelivered packets. Table 5.4 shows the latency we obtained for every VHO process. When it is done trough a LINK UP event, the latencies vary between 1.71 and 8.40 milliseconds depending on the technologies involved. Concerning the VHO latency associated with LINK DOWN events, we can observe that the latencies achieved by the latter processes are between 0.04 and 0.11 milliseconds. The difference among these latencies is due to the different sequence of actions performed, as mentioned before. Concerning packet loss, Table 5.4 also presents the number of packets that have not been delivered while the VHO process was being performed. The amount of undelivered data is related to the bandwidth available at the new network. As shown in the referred table, VHO processes that switch from a network with higher bandwidth to a network with lower bandwidth experience a higher amount of packet losses.

The results were obtained under "best-case" conditions, since there are no other

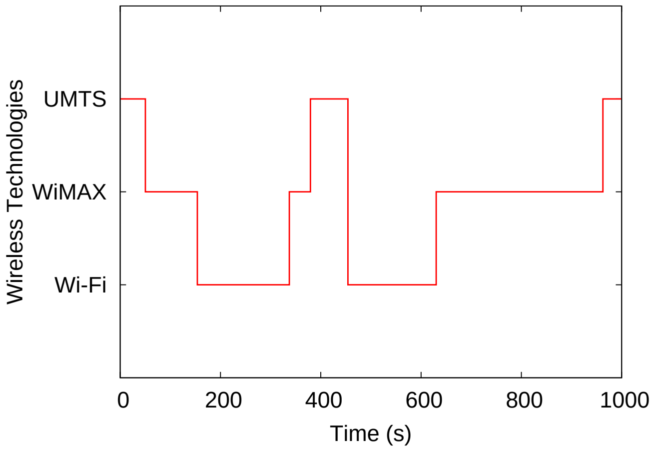


Figure 5.18: Wireless technologies usage.

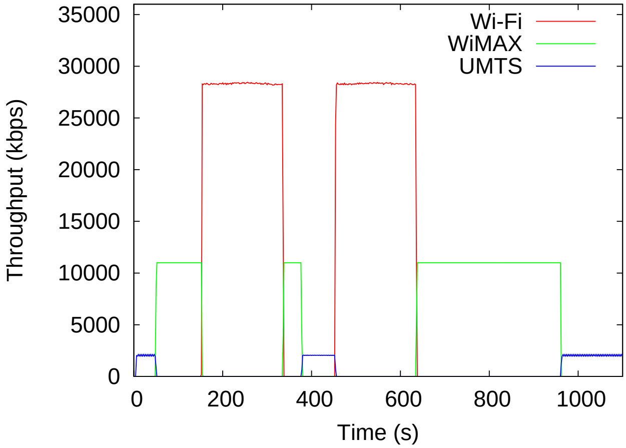


Figure 5.19: Wireless technologies throughput.

user equipments requesting services or decreasing the performance of the available networks. Therefore, the resulting mean values of the different metrics measured must be considered as optimistic results, in order to avoid any erroneous decision.

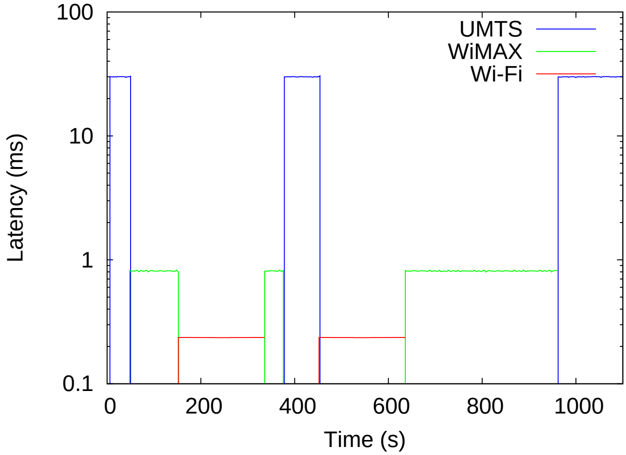


Figure 5.20: Wireless technologies latency.

Table 5.4: Simulation results.

VHO Event	Type of Event	VHO Latency (ms)	Undelivered Packets
UMTS-WiMAX(1)	Link Up	6.51043	0
WiMAX(1)-WiFi(1)	Link Up	1.71175	0
WiFi(1)-WiMAX(1)	Link Down	0.04578	81
WiMAX(1)-UMTS	Link Down	0.11723	679
UMTS-WiFi(2)	Link Up	1.75597	0
WiFi(2)-WiMAX(2)	Link Up	8.40820	0
WiMAX(2)-UMTS	Link Down	0.10205	664

5.3.3 Performance evaluation under stress conditions

Evaluation framework

To evaluate the performance under different condition we have used the framework presented in Section 5.3.1. However we have added an extra Wi-Fi Point of Attachment (PoA) as shown in Figure 5.21. Concerning traffic evaluation, the UE will cross the scenario following a straight path, passing through the coverage areas of each technology while demanding bandwidth for a 1.48 Mbps video streaming session. Video transmission allows performing a fair evaluation since it requires constant throughput and low latencies, important issues when evaluating VHO solutions [PBG+11]. The main features of each technology are shown in Table 5.5. All the values were taken

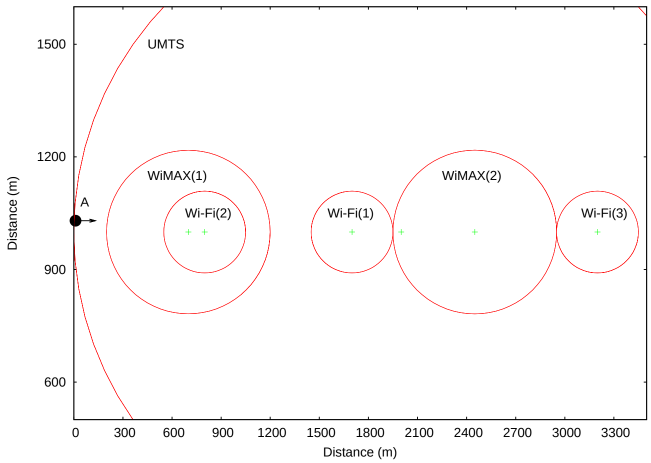


Figure 5.21: Wireless technologies coverage areas.

within a best-case configuration when there is no background traffic decreasing the performance of the networks. To reach our goal, in our experiments we defined different levels of background traffic to decrease the Wi-Fi and WiMAX performance. The goal is to demonstrate that a VHDA which only considers the capacity of the network, avoiding context information, does not always choose the best candidate to switch to, becoming even counterproductive.

Table 5.5: VHO scheme components.

Component	**Wi-Fi**	**WiMAX**	**UMTS**
Protocol	802.11g	802.16e	HSDPA
Access point	3	2	1
Theoretical Bw (Mbps)	54	70	5
Bw offered (Mbps)	28.2	16.3	2.7
Latency per UDP packet (ms)	0.307	2.766	26.92
Advertisement interval (ms)	100	5000	-
Coverage (m)	250	500	1000
Background sources	0-20	0-20	0
Background traffic (Mbps per source)	8	8	0

Underlying wireless technologies performance

To assess the performance of each wireless technology, we have focused on throughput and latency metrics, while increasing the number of sources, generating background traffic. Figure 5.22 presents the best-case scenario when no background traffic is present in any network. Therefore, when switching from one network to another, we find that those networks able to offer a better bandwidth (*e.g.*, Wi-Fi compared to UMTS) also excel at fulfilling the delay requirements for the video stream (see Figure 5.23). As observed in Figure 5.22, the trajectory followed by the UE promotes that it can often switch to higher capacity networks. Also, since networks are not degraded by background traffic, the UE receives all the bandwidth demanded for the video stream. On the other hand, Figures 5.24 and 5.25 present the throughput and latency performance, respectively, of each wireless network when there is background traffic. As shown, when switching from one technology to another in an attempt to achieve a higher performance (*e.g.*, from UMTS to WiMAX or Wi-Fi), we could not maintain performance; in fact, QoS demanding applications, as in the case of the video stream, experience a worse performance after the switching. This demonstrates that not assuming all the context information for the decision making process can result in choosing the worst candidate network, which is just opposite to the seamless VHO objectives.

Finally, Figures 5.26 and 5.27 present a summary of the throughput and latency performance of the wireless networks under study when the number of background-traffic sources increases. As observed, while the amount of background data increases, the performance exponentially decreases, as is the case of the latency.

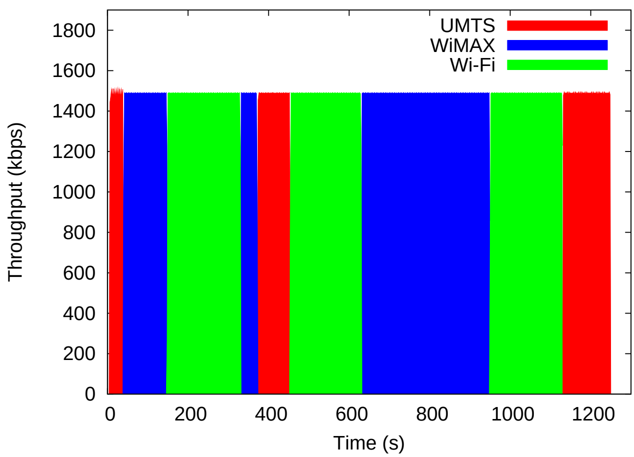


Figure 5.22: Mean throughput with no background traffic.

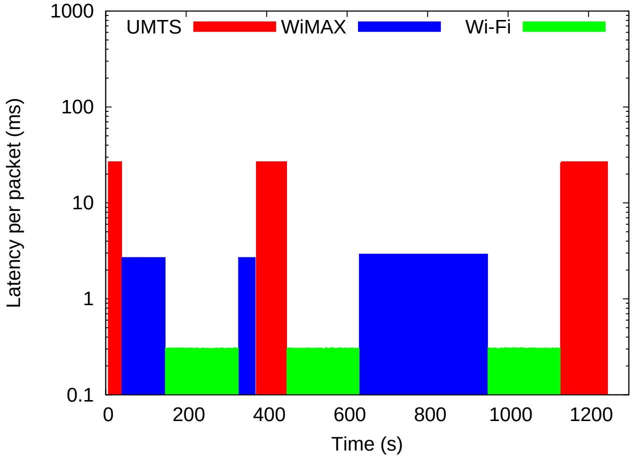


Figure 5.23: Mean latency per packet with no background traffic.

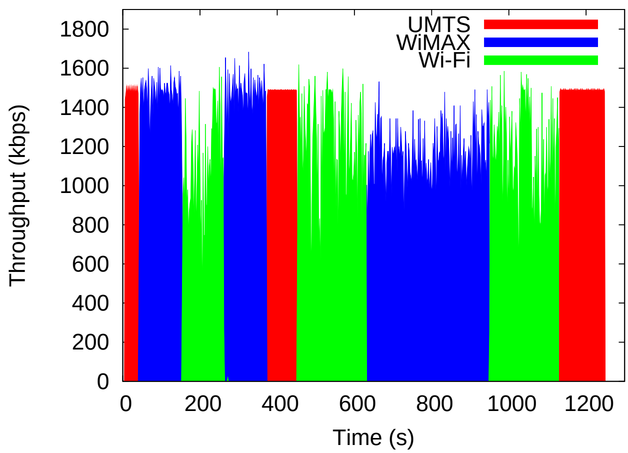


Figure 5.24: Mean throughput under 14 background-traffic sources.

VHO performance

Concerning VHO events and their performance, we have evaluated the dwell-time usage per technology and the VHO time, which is the time that a VHO process takes to complete the handover. Figure 5.28 shows the percentage of the simulation time that each wireless technology is being used. As observed, when the number of background sources is low (*i.e.*, 0 to 2), the usage of Wi-Fi, WiMAX, and UMTS is the expected one for that configuration. Nevertheless, when the number of sources increases, we

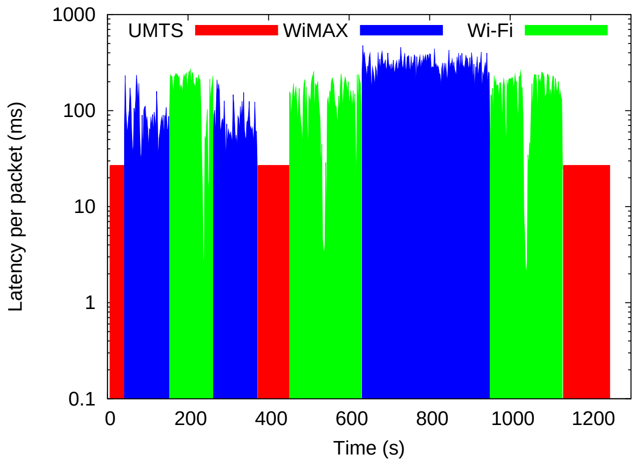


Figure 5.25: Mean latency per packet under 14 background-traffic sources.

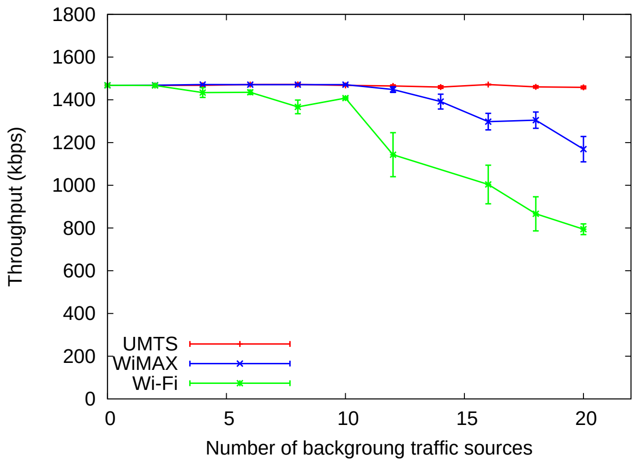


Figure 5.26: Mean throughput of each wireless technology.

can observe that the use of UMTS and WiMAX also increases. This effect is due to the Wi-Fi interface connectivity losses, since the medium is congested and the UE switches to the next available technology, most of the times to UMTS since it has a complete scenario coverage. Concerning the 802.21 events, Figures 5.29 and 5.30 show the latencies for Link Up an Link Down events, respectively. As mentioned in Section 4.2, when the UE detects the availability of a new wireless network, it triggers different events such as registration and negotiation with the Base Stations (BSs) or Access Points (APs), and mobility notifications via Mobility support for Internet

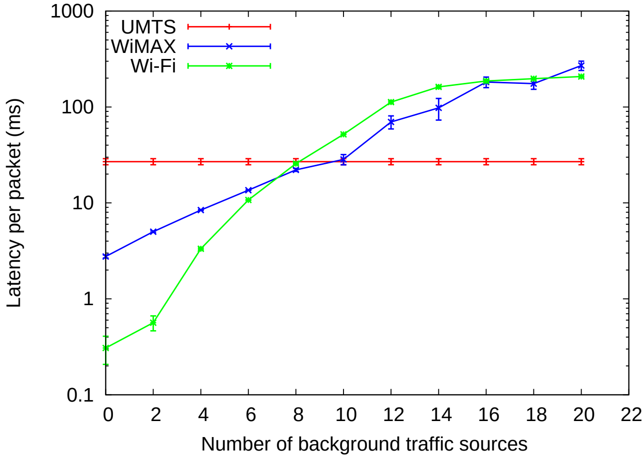


Figure 5.27: Mean latency per packet of each wireless technology.

Protocol v.6 (MIPv6) services to the rest of the network components. We present the latency accumulated by these processes under the Link Up latencies (Figure 5.29). We observed, in the case of leaving WiMAX and joining Wi-Fi coverage areas, that when increasing the number of background traffic sources, the latencies also increase due to the underperformance of the congested Wi-Fi network. In addition, concerning leaving UMTS and getting attached to Wi-Fi networks, the latency also increases, achieving more than 3 seconds for a Link Up event, which is a considerable amount of time for a seamless VHO. Nevertheless, if the VHO event occurs when leaving UMTS and joining WiMAX, the effect of the underperformance of WiMAX in comparison to UMTS is of about 500 ms, which is still an acceptable value for seamless VHO. When the VHO is produced by a signal loss, a Link Down event is triggered, switching to the next available network. In this process there are less events implicated in the VHO process. Therefore, the latencies are low in comparison with the Link up ones. As shown in Figure 5.30, when joining UMTS via Link Down event, the latencies are not higher than 0.12 seconds, being of just 0.056 seconds in the case of joining WiMAX, which is desirable for a seamless VHO.

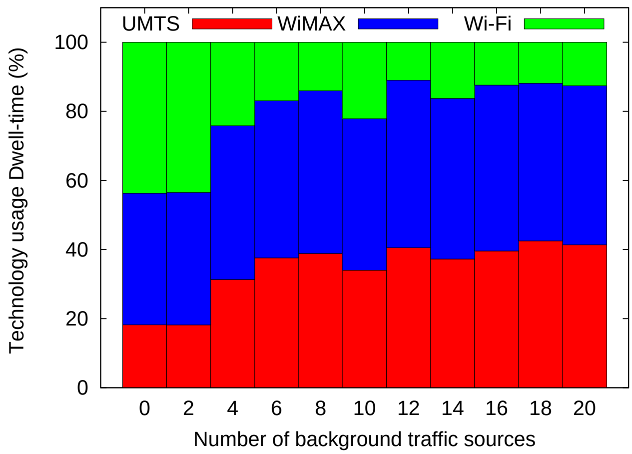


Figure 5.28: Dwell-time technology usage.

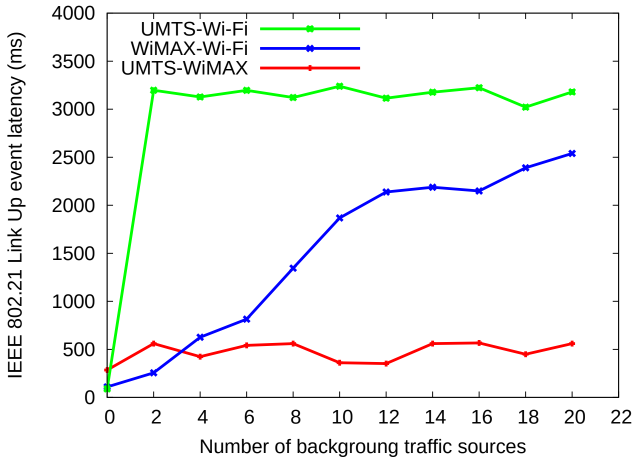


Figure 5.29: 802.21 Link Up event latency.

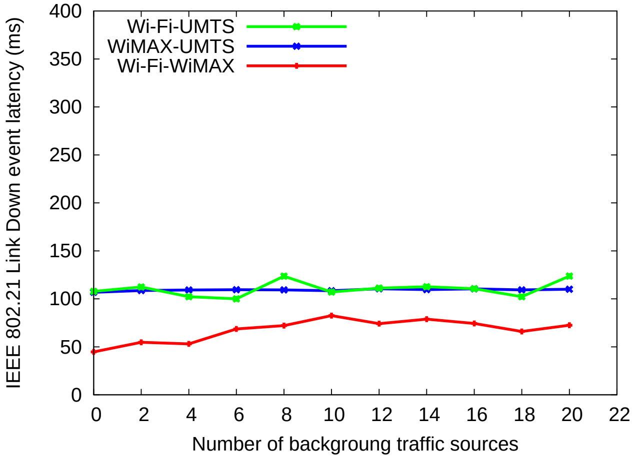


Figure 5.30: 802.21 Link Down event latency.

5.4 Multi-ACcess network Handover algorithm for vehicUlar environments (MACHU) VHDA evaluation

5.4.1 Simulation tools

As mentioned in Section 5.2.1, the NIST has developed an ns-2 [KK09a] add-on for seamless mobility [Adv]. The *NIST mobility package for the ns-2* in conjunction with EURANE [ET] offers many capabilities and features to simulate Wi-Fi, WiMAX, and UMTS technologies performing VHO among them. Furthermore, the NIST add-on also enables the Media Independent Event Service (MIES) and the Media Independent Command Service (MICS) of the IEEE 802.21 standard to interact with heterogeneous network interfaces under homogeneous standard primitives.

Since our different proposals require the third IEEE 802.21 service: the Media Independent Information Service (MIIS), we have developed (extending the NIST add-on) a MIIS considering local and remote databases which store the PoA container information, being able to read and write information via XML files, strictly following the IEEE 802.21 standard. Our proposal also considers the capability of updating the status of the PoA container via notifications performed by the vehicles, as suggested by Andrei *et al.* in [APFH10b].

We have also implemented a Global Positioning System (GPS) add-on module for the ns-2 which manages the GPS coordinates, maps, and routes, to select a pathway

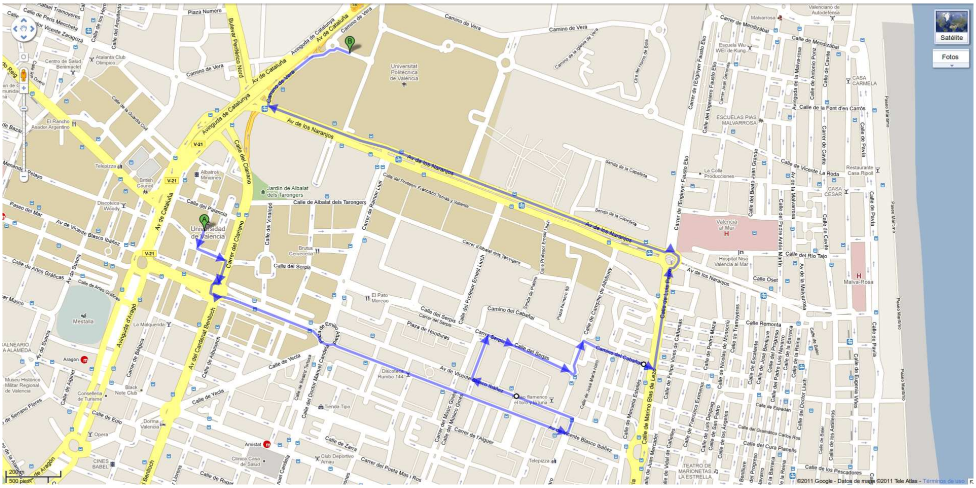


Figure 5.31: Map and route layout.

to travel from the current geolocation to any destination. The GPS module also translates the geolocation coordinates into traveling time, in order to allow the MACHU algorithm to know *where* the vehicle is expected to be at any moment in the future.

5.4.2 Simulation scheme

For our experiments we have devised a simulation scheme considering vehicles moving at 32 Km/h from Universitat de Valencia Campus (Source) to Universitat Politecnica de Valencia Campus (Destination) in the city of Valencia, Spain. Figure 5.31 shows the route from one geolocation to another, taking a distance of 5.5 km in a 3.75 km^2 area. Our GPS module manages all the coordinates of the route. Moreover, the MIIS provides information about the available networks and its respective PoAs within the simulated area, as shown in Figure 5.32. Table 5.6 summarizes the main configuration set for the experiments. As observed, there are 1 UMTS, 8 Wi-Fi, and 3 WiMAX PoAs covering different areas with distinct bandwidth capacity. It is important to point out that UMTS covers the whole scenario, meaning that the UMTS technology is always the backup connectivity technology for this set of experiments. The $VHOLat$ considered for each technology has been extracted from real measurements of Wi-Fi handovers done at the Universitat Politecnica de Valencia Campus, while the WiMAX handovers have been done at the Universidad de Murcia Campus; these measurements agree with the ones presented in [TCC10, YCG09]. For the α value, we have set the system to allow up to a 5% of the *Useful Coverage Time* to be associated with handover-related losses, and β is set to 1 to verify whether the

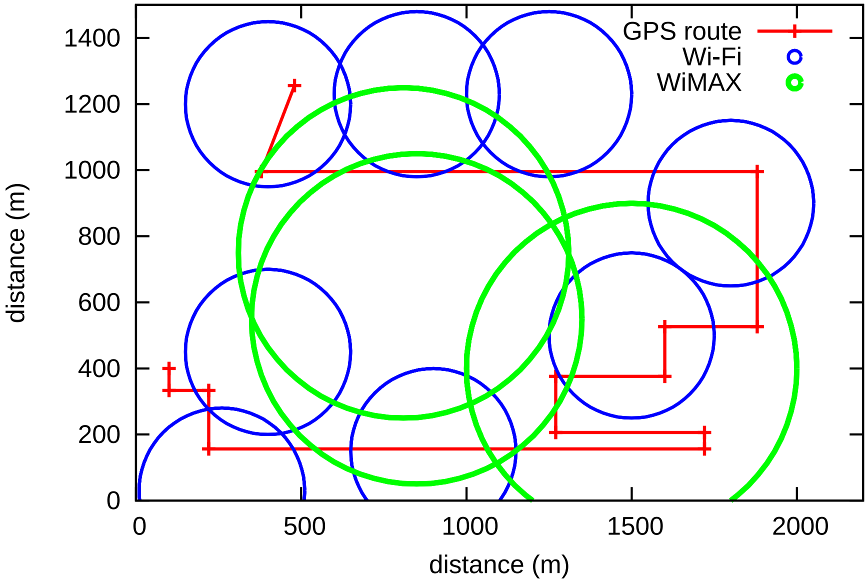


Figure 5.32: Wireless technologies coverage areas.

minimum $PredictionWindow$ is good enough to guarantee the correct functionality of MACHU. The OBU demands a 1.48 Mbps CBR video traffic stream. We consider video streaming traffic since it allows performing a fair evaluation when considering the different evaluation parameters during VHO events due to the characteristics of such type of traffic. For evaluation purposes, the available networks are working under "best-case" conditions, so there is no other traffic in the network that could interfere or compromise our evaluation of the MACHU algorithm. So, the purpose of this set of experiments is to evaluate the performance of the MACHU algorithm rather than evaluating the network performance itself.

5.4.3 Performance evaluation

To evaluate MACHU, we have performed several experiments in order to confirm its performance improvements. For comparison purposes, we also have performed experiments evaluating the simulation scheme under a different VHDA. In particular, we have used the Technology-aware VHDA describe in Section 4.2.

Results show that the experiment with the Technology-aware VHDA performs a VHO every time a new coverage area offering higher bandwidth is detected, since its decision-making process does not consider the surrounding context nor the useful

Table 5.6: VHO scheme components.

Component	Wi-Fi	WiMAX	UMTS
Access Point	8	3	1
Theoretical Bw (Mbps)	54	70	5
Bw offered (Mbps)	28.2	16.3	2.7
VHO latency (ms) [TCC10, YCG09]	1080	2665	-
Advertisement Interval (ms)	100	5000	-
Coverage (m)	500	1000	5000

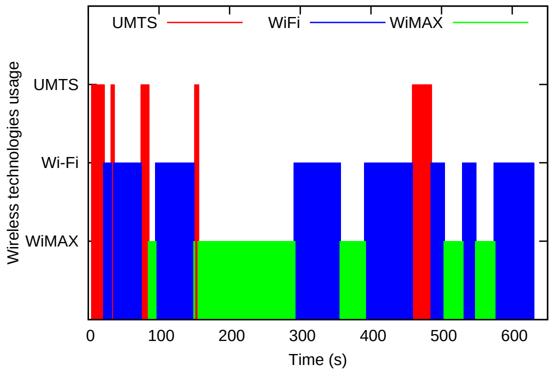


Figure 5.33: Wireless technologies usage when Tech-aware VHDA applied.

coverage areas. Thus, it often joins PoAs that are abandoned after a very brief period of time, performing unnecessary VHO processes with their inherent latency and packet loss. Missing context information may lead to wrong decisions, as demonstrated in [MBCCM11d]. Table 5.7 shows that the experiment adopting the Technology-aware VHDA performed 18 VHO events, which resulted in 64816 lost packets. Figure 5.33 presents the active wireless interfaces at the OBU of the vehicle while moving within the pathway (during simulation time). Figure 5.34 presents the active interfaces under the MACHU algorithm for comparison. We can clearly observe that there are less VHO events performed with MACHU than with the Technology-aware VHDA, avoiding to join worthless PoAs due to their reduced *Useful Coverage Time*, thus reducing unnecessary VHO events and their adverse effects. Table 5.7 presents a summary of the main performance results for both VHO decision algorithms. As observed, MACHU introduces less VHO processes, reducing up to 55% the VHO events required, and achieving an improvement of up to 32% in terms of packet loss, while maintaining the QoS demanded by the video streaming session. Finally, Figure 5.35 presents the technology dwell usage time, describing the amount of time that every type of wireless interface has been active during the experiments. We can

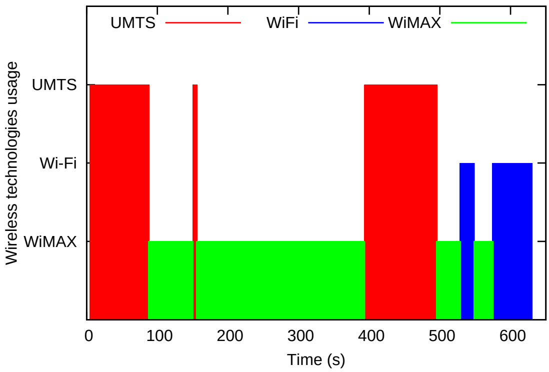


Figure 5.34: Wireless technologies usage when MACHU VHDA applied.

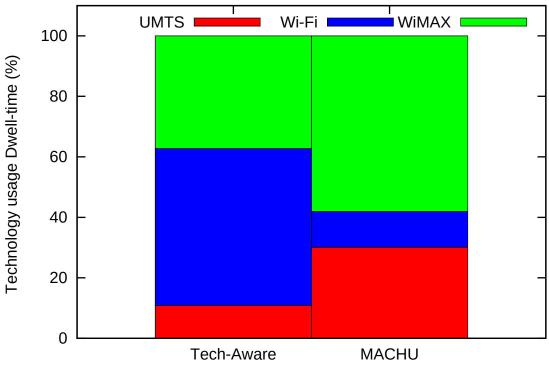


Figure 5.35: Wireless technologies usage.

observe that, when using the Technology-aware VHDA, the UMTS, WiMAX and Wi-Fi interfaces are active the 12.5%, 37.14%, and 50.3% of the time, respectively; however, the MACHU VHDA, their activity changes to the 30.21%, 54.3% and 12.44% of the time, respectively. The differences detected highlight the different choices made; in particular, we find that MACHU avoids unnecessary VHO events when reaching Wi-Fi hotspots that, due to their small useful coverage areas, will cause only adverse effects rather than improve the overall performance through higher bandwidth capacity.

Table 5.7: VHO results.

Parameters	Tech-aware	MACHU
VHO events	18	8
Packet loss	64816	21348
Throughput (Mbps)	1.471	1.477
Unnecessary VHO events	10	0

5.5 Geolocation-based Multi-ACcess network Handover algorithm for vehicUlar environments (Geo-MACHU) VHDA evaluation

5.5.1 Simulation scheme

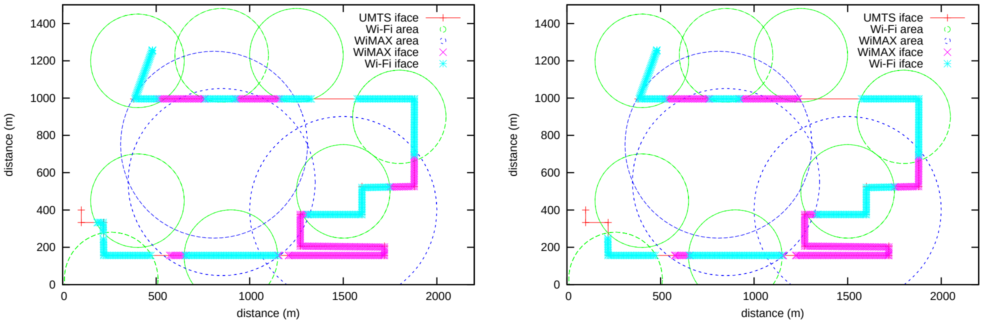
In order to perform a fair evaluation and comparison among the proposed VHDAs we have use the same simulation scheme presented in Section 5.4.2. The scheme offers a set of several VHO combinations among different technologies, being an adequate scenario for our studies.

5.5.2 Performance evaluation

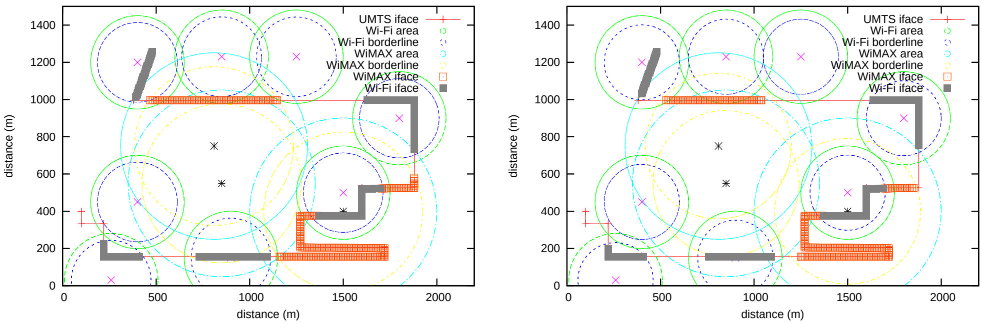
To evaluate and compare the performance of the Geo-MACHU VHDA, we have also evaluated the performance of the two different VHDAs studied in previous Sections: Tech-aware and MACHU VHDAs.

The performance of these algorithms is compared in terms of the VHO events performed, packet loss, packet latency and dwell time per technology. In order to obtain accurate results we have performed several runs obtaining a 95% confidence interval.

Figure 5.36 presents the connectivity behavior of the evaluated VHDAs. As we can observe, Figure 5.36(a) shows the Tech-aware VHDA and MACHU VHDA performance, respectively. The Tech-aware VHDA, performs up to 18 VHO events due to its decision-making policy. On the other hand, the MACHU VHDA performed about 15 VHO events, being more selective when switching from one network to another. In Figure 5.36(b), Geo-MACHU set to minimum packet delivery thresholds of 40% and 60% behaves the same manner in both cases, switching network up to 11 times. The main difference is on the geolocation (QoS borderline) where the handoff has occurred, always in pro of the QoS. Table 5.8 summarizes this set of results, and Figure 5.37 presents the technology use dwell-time per VHDA. As we can observe,



(a) Tech-aware and MACHU



(b) Geo-MACHU (40%) and Geo-MACHU (60%)

Figure 5.36: VHDAs Handover connectivity comparison.

the interfaces connect to the available PoAs in different manners depending on the decisions made by the VHDA.

Concerning the performance of the underlying networks, through the Packet loss metric we are able to evaluate the performance of the network. Figure 5.38 presents the Packet loss evaluation during the simulation for the studied algorithms. We can observe that, while the car is crossing the different PoAs, the network offers a certain QoS (based on packet loss and packet probability reception); therefore, when Geo-Machu under 40% and Geo-Machu under 60% loss is applied at the QoS borderline within the PoA coverage (guaranteeing the packet reception), there are lower Packet loss values than for the simulations under the rest of VHDAs. Table 5.9 presents the comparison of Packet loss per technology globally reached by each VHDA, clearly showing that the overall performance increases when considering the distance reception probability. By comparing the Tech-aware VHDA performance against the Geo-Machu VHDA, we find that packet loss improves from 47.1 % of packet loss down to 16.5%. Following the same trend, as shown in Table 5.10, the mean throughput per technology is also increased when applying more sophisticated

Table 5.8: VHO events.

	Tech-aware	**MACHU**	**Geo-MACHU 40%**	**Geo-MACHU 60%**
VHO events	18	15	11	11

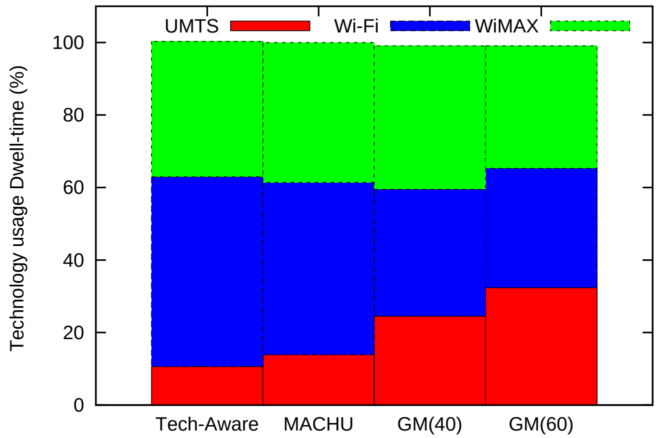
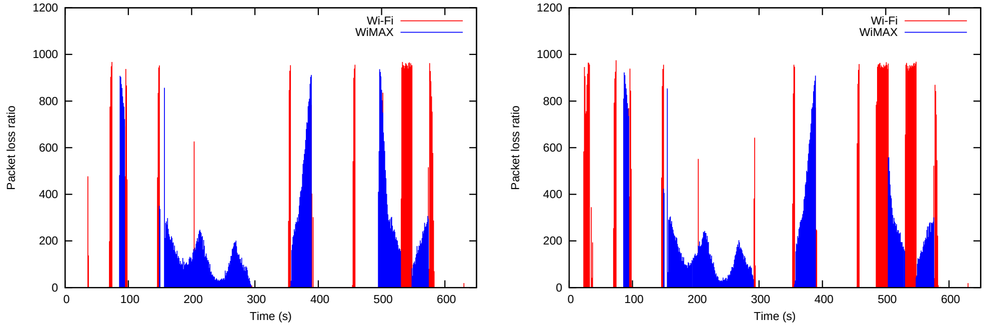


Figure 5.37: Dwell-time comparison.

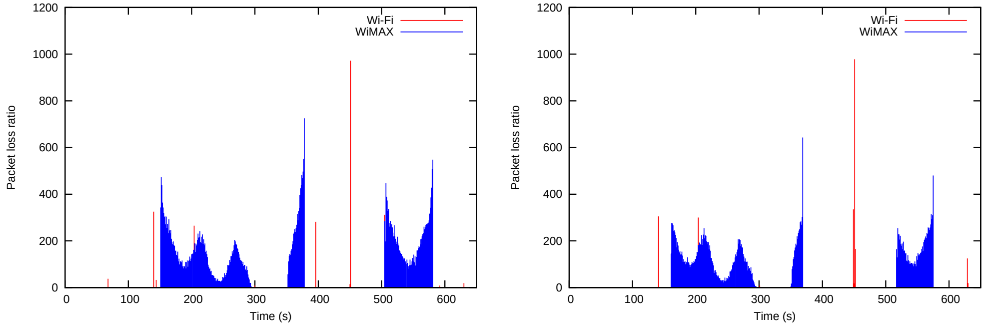
VHDAs; this occurs because the switching to a new network only occurs when the QoS is guaranteed by taking into account the QoS borderline, as considered by Geo-MACHU algorithm. On the other hand, Table 5.11 presents the mean latency per packet during simulation; since the underlying networks are in an "ideal case", there is only a slight improvement in terms of the VHDAs latency performance.

Table 5.9: Mean packet loss comparison.

	Tech-aware	**MACHU**	**Geo-MACHU 40%**	**Geo-MACHU 60%**
Wi-Fi	21.072	14.508	1.194	1.178
WiMAX	24.238	25.66	18.17	14.848
UMTS	1.883	1.405	0.762	0.482
Global	47.193	41.573	20.126	16.508



(a) Tech-aware and MACHU



(b) Geo-MACHU (40%) and Geo-MACHU (60%)

Figure 5.38: VHDAs packet loss comparison.

Table 5.10: Mean throughput comparison.

	Tech-aware	**MACHU**	**Geo-MACHU 40%**	**Geo-MACHU 60%**
Wi-Fi	1.1436	1.239	1.446	1.441
WiMAX	1.090	1.072	1.181	1.232
UMTS	1.406	1.407	1.411	1.421

Table 5.11: Mean latency per packet comparison.

	Tech-aware	**MACHU**	**Geo-MACHU 40%**	**Geo-MACHU 60%**
Wi-Fi	17.216	16.856	15.22	15.204
WiMAX	17.664	17.643	17.54	17.251
UMTS	52.54	52.544	52.55	52.553

5.6 Multiple Criteria Decision-Making based Multi-ACcess network Handover algorithm for vehicUlar environments (MCDM-MACHU) VHDA evaluation

5.6.1 Simulation scheme

For comparison purposes, we maintain the same simulation scheme presented in Section 5.4.2 for our simulations. By simulating under the same scheme, we are able to fairly evaluate the performance of the proposed algorithms. However, for the evaluation of the MCDM-MACHU, we have configured the performance of each network of the scheme (see Figure 5.32) with different performance parameters. By doing this, we generate different alternatives to evaluate the candidate networks. Table 5.12, presents the parameter set for each network. In the scheme, the vehicle moves from position A to position B, as shown in Figure 5.31, within the pathway defined, reaching the different coverage areas while performing a video streaming session. A VHO algorithm is used in order to choose the candidate network that best fits the video session requirements. Table 5.13 presents the minimum requirements for the video session that must be fulfilled by the chosen networks during the simulation.

Table 5.12: Network parameters.

Parameter	**PoA-1**	**PoA-2**	**PoA-3**	**PoA-4**	**PoA-5**	**PoA-6**
Technology	UMTS	Wi-Fi	Wi-Fi	WiMAX	Wi-Fi	WiMAX
Price per Mb	0.9000	0.0800	0.0400	0.1500	0.0513	0.0200
Latency per packet	52.5500	15.2200	30.4400	17.5400	23.7432	60.8800
Packet loss ratio	0.7600	1.1900	2.3800	2.7400	1.8564	4.7600
Throughput (Mbps)	1.4100	1.4400	0.7200	1.1800	0.9231	0.3600
Parameter	**PoA-7**	**PoA-8**	**PoA-9**	**PoA-10**	**PoA-11**	**PoA-12**
Technology	Wi-Fi	Wi-Fi	Wi-Fi	WiMAX	Wi-Fi	Wi-Fi
Price per Mb	0.0750	1.2000	0.8000	0.0375	0.7692	0.5128
Latency per packet	35.0800	0.5500	0.7500	70.1600	0.8580	1.1700
Packet loss ratio	3.1510	0.8600	0.9800	3.5606	1.3416	1.5288
Throughput (Mbps)	0.5900	1.8100	1.6900	0.2950	1.1603	1.0833

Table 5.13: Application requirements for a video on demand session.

Parameter	**Value**
Price per Mb	0.05
Latency per packet	100
Packet loss ratio	2
Throughput (Mbps)	1

Table 5.14: VHO events.

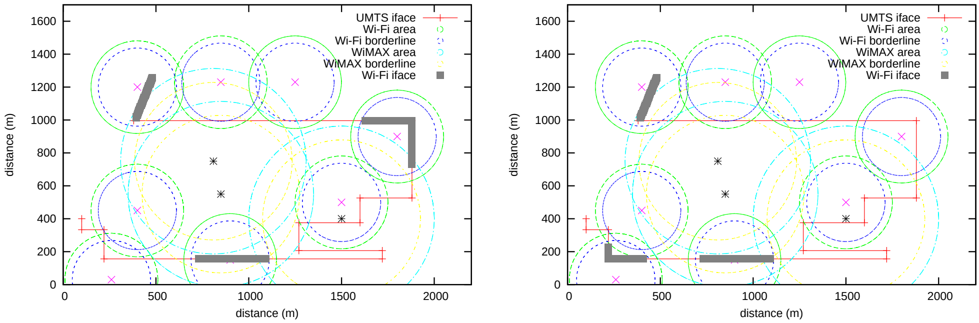
	Geo-MACHU 40%	**MCDM Maximum Performance**	**MCDM Guaranteed VoIP**	**MCDM Guaranteed Video**	**MCDM Minimum Cost**
VHO events	11	5	5	3	9

5.6.2 Performance evaluation

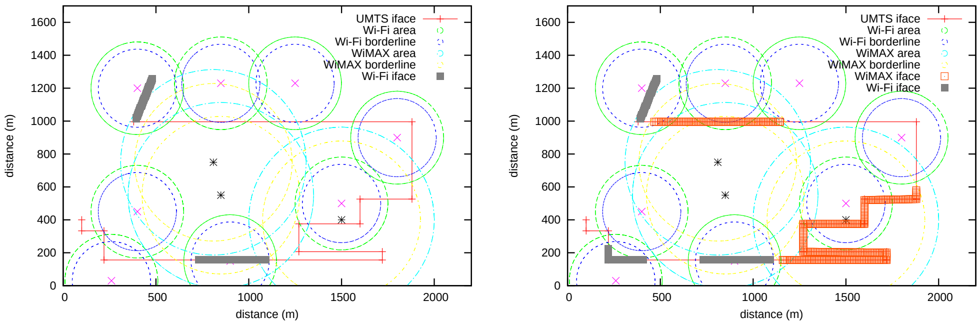
To evaluate the MCDM-MACHU performance we have performed different simulations varying the user profile. Moreover, we have also simulated the Geo-MACHU with a packet delivery threshold of 40% on the QoS borderline to compare the developed algorithms, since we consider that Geo-MACHU 40% is representative of the mean performance of the different algorithms proposed. Once again, a 95% confidence interval was obtained for all the simulations performed.

Depending on the user profile applied, the MCDM-MACHU behaves in a different manner. Figure 5.39 shows the connectivity adopted by the MCDM-MACHU for each user profile for the same application requirements mentioned in Section 5.6.1. As we can observe, different networks have been chosen depending on the chosen profile. In order to compare the performance levels associated with the different algorithms, Figure 5.36(b) left, presents the connectivity behaviour of the Geo-MACHU 40%, showing the active network interfaces, and performing 11 VHO events. Table 5.14 summarizes the connectivity behaviour by presenting the number of VHO events. As shown, a different number of events took place depending on the user profile. Despite the VoIP and Maximum performance profiles perform the same amount of VHO events, the chosen networks are different, thus reaching different performances. To reinforce this profile dependency, Figure 5.40 presents the dwell-time per technology, that is, the total time each interface has been active during the simulation.

With respect to price cost, we can observe in Figure 5.41 that the different user profiles are also associated with different costs. We can confirm that the minimum cost profile was able to meet the original goal by choosing the networks in an accurate manner, thereby reducing the total cost of the video session. However, this profile is



(a) Maximum Performance and VoIP profiles



(b) Video and Minimum Cost profiles

Figure 5.39: Video demand connectivity profile comparison.

intended to optimize the cost in detriment of the rest of the application requirements. In fact, we can observe in Figures 5.42, 5.43, and 5.44 that the minimum cost profile achieves a poor performance, having a packet delivery ratio of only 65%. We observe anyway that the maximum performance profile achieves the highest performance (*i.e.* low latency, high throughput, and low packet loss rate) by choosing the candidate networks with better performance, but paying the highest price cost for those high quality services.

Figure 5.42 presents the throughput achieved by each user profile and Geo-MACHU 40%. We can observe that the Video, VoIP and Maximum performance almost obtain the 1 Mbps demanded, while the Minimum Cost and Geo-Machu 40% profiles achieve about 640 Kbps since their priority is not the performance, but rather the cost and geolocation, respectively. Concerning Latency and Packet loss, we observe the same trend: Video, VoIP, and Maximum Performance profiles achieve different trade-offs between performance and cost. We can observe that those profiles achieve better performance in Figures 5.43 and 5.44, while the Minimum Cost and Geo-Machu 40% do not optimize these parameters.

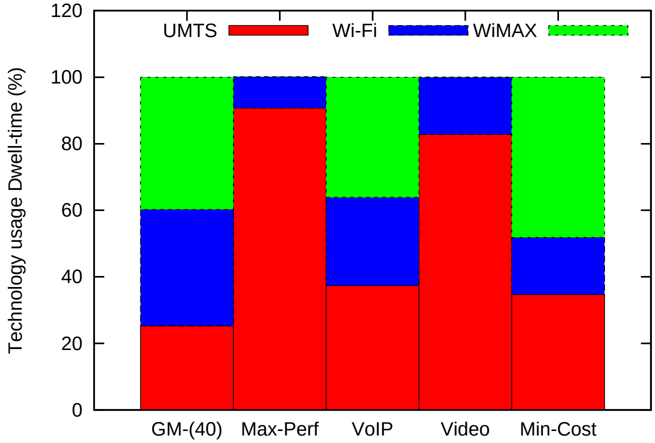


Figure 5.40: Dwell-time comparison.

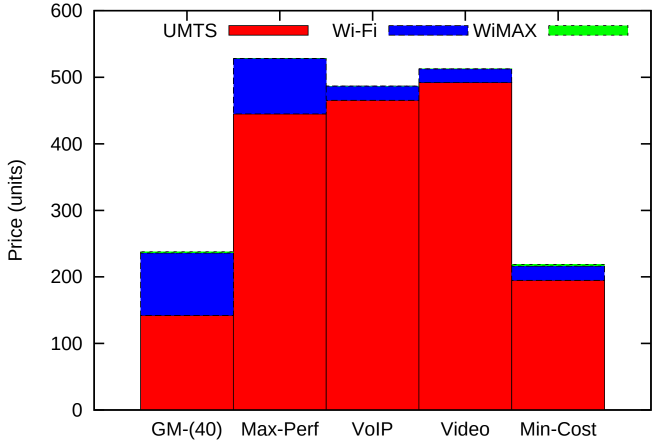


Figure 5.41: Price comparison.

5.7 Summary

VANETs offer seamless delivery of safety and infotainment messages to the vehicles and its passengers. In fact, they are becoming an important element to reinforce the passengers' safety by allowing vehicles to exchange warnings among themselves. Moreover, contents can be delivered to the vehicles through VANETs regardless of the density of RSUs conforming the infrastructure.

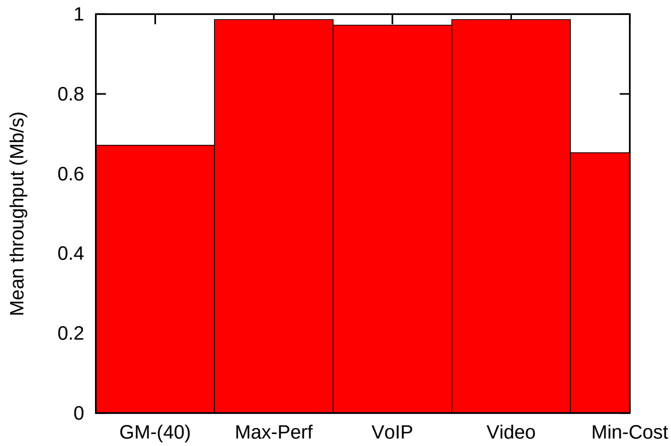


Figure 5.42: Throughput comparison.

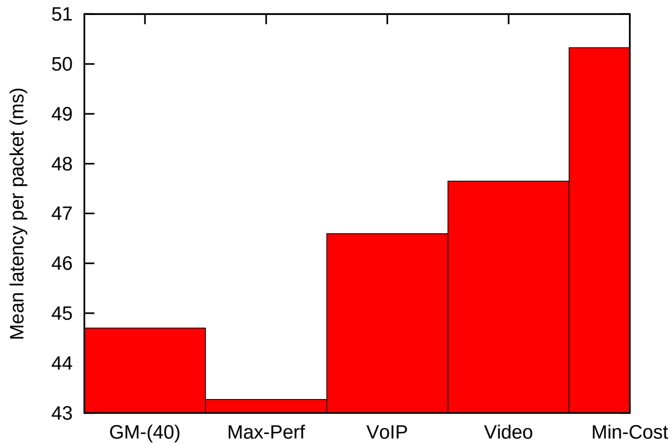


Figure 5.43: Latency comparison.

With the aim of evaluating the effectiveness of an infotainment content delivery scheme over multi-hop vehicular networks, we have set a simulation framework using the ns-2 simulator. Contents are delivered through the HTTP Protocol, while the AODV protocol is used to handle routing tasks. Concerning the PHY/MAC layers, these follow the IEEE 802.11p standard.

We evaluate the user perceived latency to measure the degree of satisfaction, and the packet loss to analyze the performance of the network. Experiments reveal that, when increasing the vehicular density, the user perceived latency is reduced, as well

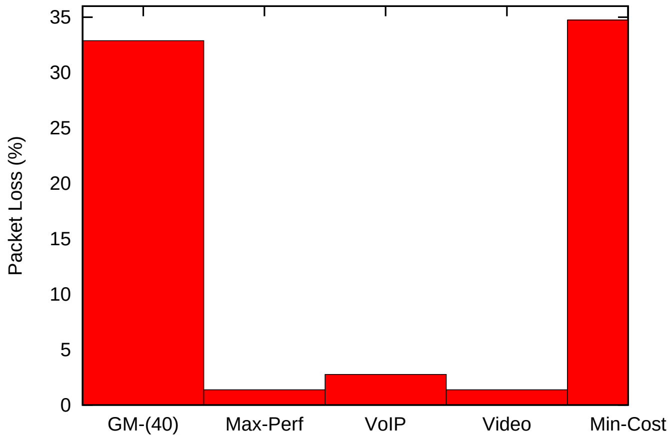


Figure 5.44: Packet loss comparison.

as the packet loss ratio. We also find that performance is improved when the speed of vehicles is moderate/high. Finally, we observed that, by increasing the workload beyond 3 Mbps, the overall performance is affected, showing an exponential growth for latency.

In order to evaluate the performance limits of the most widely used wireless technologies for mobile devices (Wi-Fi, WiMAX, UMTS), we setup a simulation framework using the Network Simulator (ns-2), as well as other extensions such as *EURANE* and *NIST secure and mobility*. We determine the achievable throughput under high load conditions for the different wireless technologies.

Experiments reveal that, depending on the parameter configuration of each wireless network, the available capacity can vary significantly. However, VHO strategies must take into account not only the channel capacity of the different wireless networks, but also other parameters such as available bandwidth, coverage area and mobility patterns.

Concerning Vertical Handover Decision Algorithms (VHDAs), in order to evaluate our proposed algorithms, we have used the ns-2 powered by the NIST add-on, which offers an implementation of the MICS and the MIES services of the IEEE 802.21 standard. We have developed a GPS module to manage geolocation, map information, and route calculation within the ns-2, and we have also extended the NIST add-on in order to be able to use the MIIS of the IEEE 802.21, thereby taking context into account for making the best VHO decisions.

We have performed several experiments in order to evaluate a technology-aware VHDA which considers availability and capacity for the decision-making process.

Experiments showed that VHO processes reach higher latencies when dealing with newly discovered candidate networks due to the processes triggered in order to perform a seamless VHO. Concerning packet loss, VHO processes drop packets due to bandwidth availability restrictions whenever downgrading from a network to another. Results were optimistic due to the “best-case” conditions offered by the different wireless technologies, since no other traffic was decreasing the performance of the different networks. Experiments also reveal that considering only the highest capacity technology is not enough to evaluate the candidate networks to switch to. In fact, our results clearly demonstrate that making the decision considering only the technology with higher theoretical data rate may not only fail to fulfill our requirements, but might also decrease our connectivity dramatically.

Through simulation we have demonstrated that, when considering only this criteria and avoiding 802.21 context information, the VHO process is prone to pick a network with a lower performance, thus decreasing the QoS experienced by applications running at the UE.

We have also presented the MACHU VHDA, which combines different data sources at the OBUs used in vehicular environments. Our algorithm takes advantage of GPS information, maps, surrounding context information and routes, with the multiple connectivity features of the Wi-Fi, WiMAX and UMTS interfaces of the OBU. Moreover, our algorithm takes advantage of the IEEE 802.21 standard, the latest standard for performing handovers among heterogeneous networks.

Through a set of experiments, we have validated the correctness of our algorithm, and we compared it against a Technology-aware algorithm. Results showed that our algorithm avoids performing worthless VHO processes, thus reducing their adverse effects such as the increase of packet loss.

Moreover, the Geo-MACHU VHDA, powered by the IEEE 802.21 Standard for Vehicular Networks, takes into account network context, geolocation and navigation information to guarantee the QoS of the chosen candidate network by considering realistic propagation models for the underlying wireless networks, such as Wi-Fi, WiMAX and UMTS, thus improving the flow transition process from one PoA to another.

Results clearly demonstrate that the proposed VHDA, which considers geolocation with respect to the PoAs, guarantees data flow switches to a similar or better network than the current one, thus boosting performance in comparison previously proposed solutions.

Finally, we find that the MCDM-MACHU VHDA increases the accuracy of the proposed VHDAs by considering multiple criteria, taking into account not only network and geolocation information, but also user preferences and application requirements.

Results demonstrate that, depending on the user profile selected, different trade-offs between performance and cost can be obtained, thus allowing users to tune the algorithm's behaviour according to their preferences. Moreover, through simulations we have demonstrate that β_i sets calculated for each profile are able to fulfill the application requirements within the bounds defined for the different profiles considered.

Part IV

Conclusions

Chapter 6

Conclusions, Publications and Future work

6.1 Conclusions

Wireless communications are continuously being improved, mainly due to factors such as user demand trends, more sophisticated mobile devices in terms of both capabilities and physical/design issues, market trends, and specially by the broad deployment of different access technologies. The automobile industry is also being constantly improved, taking advantage of wireless communication enhancements, and offering improvements in different areas such as safety, entertainment, and comfort. Vehicular Networks (VNs) have to deal with the multiple issues such as connectivity loss, handover delay, and Quality of Service (QoS) fluctuations, caused by the high mobility associated with cars when moving from one place to another, thus driving through the coverage areas of different technologies. In order to maintain a continuous connectivity and to avoid those adverse effects, Vertical Handover (VHO) techniques must be adopted.

In this thesis we have not only developed different Vertical Handover Decision Algorithms (VHDAs), but we have also studied several factors to improve the VHDA performance in order to guarantee the QoS required by the users' demand. Moreover, we have developed and extended different simulation tools to improve the simulation/emulation processes, and we have adopted the IEEE 802.21 protocol to boost the VHO process among heterogeneous networks.

Below we briefly summarize the most relevant contributions of this thesis:

- A **survey of the most significant proposals** found in the literature concerning VHO techniques, including both particular proposals and standards. In addition, we emphasized on the VHO process from a VN perspective, highlighting those techniques and algorithms that better fit to this type of networks. This survey can be useful to the research community by providing a broad overview of the techniques, tools and algorithms used at the different VHO stages.

- **Development of a simulation framework** able to simulate and evaluate different authors' proposals, as well as our own contributions. Moreover, we extended the Network Simulator (ns-2) [KK09a] and applied third-party add-ons such as the *NIST mobility package for the ns-2* [Adv], in conjunction with the Enhanced UMTS Radio Access Network Extensions (EURANE) [ET] to be able to simulate VN contexts, Wireless Fidelity (Wi-Fi), Worldwide interoperability for Microwave Access (WiMAX) and Universal Mobile Telecommunications System (UMTS) underlying wireless technologies, along with Global Positioning System (GPS) geolocation and geonavigation, thus performing seamless VHO powered by the IEEE 802.21 standard and its services.

- A multi-layer performance evaluation of a **content delivery framework over multi-hop vehicular networks** that focused not only on the application layer, but also on the transport and routing layers. In this framework, contents from remote servers are accessed through the HiperText Transfer Protocol (HTTP). To evaluate the performance of the proposed framework we performed experiments varying different parameters affecting Vehicular *Ad-hoc* Network (VANET) performance, such as vehicle speed, density of vehicles, the user request rate, and the pattern of these requests.

- A **performance evaluation of the main wireless technologies** currently in use by mobile devices: **Wi-Fi, WiMAX and UMTS** was done by testing various schemes with different parameters for each technology, including modulation and channel bandwidth, under different network congestion conditions. Results showed that each technology offers different data rates, depending on the selected parameters.

- Concerning VHO among heterogeneous wireless networks within the VN context, we presented the evaluation of an **IEEE 802.21-based Tech-aware VHDA** in order to demonstrate its interoperability among Wi-Fi, WiMAX and UMTS technologies, and to demonstrate the need of considering different parameters when making VHO decisions in a video streaming transmission scenario under different network conditions.

- Proposal of a novel VHDA, called **Multi-ACcess network Handover algorithm for vehicUlar environments (MACHU)**, which combines GPS-based geolocation, map information, surround context information and route calculation, with the functionality of the IEEE 802.21 standard. For the decision-making process, MACHU takes advantage of both current and future geolocation of the vehicle (within the route and map layout), along with the networking information provided by the different services of the IEEE 802.21 standard. The purpose was to choose the most suitable access network along the route when following the pathway from one location to another.

- The **Geolocation-based Multi-ACcess network Handover algorithm for vehicUlar environments (Geo-MACHU) VHDA**. In this proposal we extended the features of the MACHU algorithm by combining GPS information (both geolocation and navigation), underlying network information (realistic propagation models), as well as network architecture information, in order to optimize the network selection process, a critical element of the VHO process.

- A **Multiple Criteria Decision-Making based Multi-ACcess network Handover algorithm for vehicUlar environments (MCDM-MACHU) VHDA**, based on Geo-MACHU, takes into account not only geolocation and network context information, but also considers the application requirements and the user profiles. This VHDA represents a step forward in the decision-making process by applying Multiple Criteria Decision-Making (MCDM) techniques. Moreover, we have defined and optimized different user profiles (Maximum performance, Guaranteed VoIP, Guaranteed Video, and Minimum Cost) in order to improve the VHDA and the overall VHO performance.

6.2 Publications related to the thesis

Book chapters

- Pedro J. Fernández, Cristian A. Nieto, José Santa, Antonio F. Gómez-Skarmeta, Johann Márquez-Barja, Pietro Manzoni. *Experience Developing a Vehicular Network Based on Heterogeneous Communication Technologies.* In Wireless Technologies in Vehicular Ad Hoc Networks: Present and Future Challenges.

Information Science Reference (an imprint of IGI Global). pp 298-317. ISBN 978-1-4666-0209-0. January, 2012. [FNS+12].

This chapter describes the experiences and findings when deploying a vehicular network architecture supporting different communication technologies. This approach has been developed taking into account key issues regarding mobility and security. These two aspects have been provided by means of the NEMO and IKEv2 protocols, respectively. In addition, thanks to the EAP protocol, transported by IKEv2, an extensible authentication method can be used to implement an access control mechanism. This work also focuses on how the terminal is aware of the surrounding environment in order to boost the hand-off processes among heterogeneous networks using the IEEE 802.21 protocol. Besides the description of the on-board system architecture, a WiMAX/Wi-Fi infrastructure was deployed to validate the development of the mobility and security environment designed for vehicular networks.

Journals

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. An overview of vertical handover techniques: Algorithms, protocols and tools. Computer Communications, 34(8):985-997, June 2011. [MBCCM11a]

  In this paper we present an overview of VHO techniques, along with the main algorithms, protocols and tools proposed in the literature. In addition, we suggest the most appropriate VHO techniques to efficiently communicate in vehicular network environments considering the particular characteristics of this type of networks.

  This paper has been awarded for being in list of the most demanded articles in 2011 (Top 25 Hottest Articles) by the Computer Communications Journal and the Elsevier Editorial.

- Jorge Hortelano, Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. RuralMaya: Internet de bajo coste para paises en vias de desarrollo. Dialogos transdisciplinarios en la sociedad de la informacion - Era Digital, i/2010:130-135, ISBN 2220-7120. May 2010. [HMBC+10]

  In this paper, we have evaluated the viability of deploying a mesh wireless network in order to offer connectivity to geographically isolated areas in developing countries. Moreover, a real study case is presented, demonstrating that this type of wireless networks could solve connectivity issues wherever traditional access solutions could not be applied.

International conferences

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. A Geolocation-based Vertical Handover Decision Algorithm for Vehicular Networks. In IEEE 37th Conference on Local Computer Networks (LCN 12), Clearwater, Florida, USA. October 2012.

  This paper presents the Geo-MACHU algorithm, which takes advantage of the current devices deployed in the vehicle's on-board unit by considering geolocation, car navigation and realistic propagation model of different underlying networks such as Wi-Fi, WiMAX, and UMTS. By combining the gathered information, the algorithm is able to provide a QoS borderline at the coverage areas to improve not only the decision-making process but also the overall VHO process.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Vertical Handover: When the Context Matters. In 7-th ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks (PM2HW2N 2012), Paphos, Cyprus Island. October 2012.

  In this paper, we have demonstrate that not taking into consideration the surrounding context when applying decision-making processes could lead to decrease the connectivity performance, thus not fulfilling the user and application requirements.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. MACHU: A novel vertical handover algorithm for vehicular environments. In IEEE XI Annual Wireless Telecommunications Symposium (WTS 2012), pages 1-7. London, United Kingdom. April 2012. [MBCCM12b]

  In this paper we present the MACHU algorithm designed for dynamic environments. The decision making process is optimized by combining networking information, obtained by the services of the IEEE 802.21 standard, with geolocation, map information, surround context information and route calculation, thereby improving the handovers' performance

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Performance trade-offs of an IEEE 802.21-based vertical handover decision algorithm under different network conditions. In 10th IEEE International Symposium on Network Computing and Applications (NCA 11), pages 294-297, Cambridge, USA. August 2011.[MBCCM11d]

  In this paper we demonstrate the viability of performing VHO processes based on the IEEE 802.21 protocol. To do so, we have evaluated a VHO strategy which considers network availability and maximum data rate in order to choose the best network candidate among Wi-Fi, WiMAX, and UMTS. Moreover, throughout a set of experiments, we have also evaluated the maximum performance of the available networks.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Evaluation of a technology-aware vertical handover algorithm based on the IEEE 802.21 standard. In IEEE Wireless Communications and Networking Conference (WCNC 11), pages 617-622, Cancun, Mexico. March 2011. [MBCCM11b]

  In this work, we present a set of experiments to evaluate the vertical handover performance when relying on the IEEE 802.21 standard in scenarios where Wi-Fi, WiMAX and UMTS technologies are available. The decision making process is based on the Tech-aware VHDA. Experimental results show that a technology-aware vertical handover mechanism is able to achieve an adequate performance when traffic congestion is low.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Evaluating the performance boundaries of Wi-Fi, WiMAX and UMTS using the Network Simulator ns-2. In 5-th ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks (PM2HW2N 2010), pages 25-30, Bodrum, Turkey. October 2010. [MBCCM10b]

  In this paper we present a performance evaluation of Wi-Fi, WiMAX and UMTS. We evaluated the performance of each network technology under different network congestion conditions. Results showed that each technology offers different data rates and performance depending on the selected parameters. Moreover, we found that assessing the bandwidth availability status becomes of utmost importance to guarantee a successful vertical handover.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Multi-Layer Performance Evaluation of a Content Delivery Framework for Urban Vehicular Networks. In ICC10 Workshop on Vehicular Networking & Applications (IEEE Vehi-Mobi 2010). pages 1-5. Cape Town, South Africa. May, 2010. [MCCM10]

  In this paper we provide a performance evaluation to assess the viability of a content delivery framework for VANETs. In our experiments we vary several parameters, such as vehicular density, vehicular speed, and content demand rate under different environmental conditions. We evaluate, from a multi-layer perspective, the impact they have on metrics such as delivery latency, throughput, and packet loss; in particular, we evaluate user satisfaction through the latency perceived at the application layer, and the network performance via the packet loss. Results show that the overall performance is improved when speed and vehicular density are relatively high compared to typical urban traffic patterns.

National conferences

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. An enhanced vertical handover decision algorithm designed for vehicular networks. In XXIII Jornadas de Paralelismo, Elche (Alicante), Spain. September 2012. [MBCCM12a]

  In this paper we present a Vertical Handover Decision Algorithm designed for vehicular environments. To improve the performance of the handover we combine networking information with geolocation, map information, surround context information and route calculation to select the most appropriate candidate network.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Performance analysis of an IEEE 802.21 based Vertical Handover protocol using ns-2. In XXII Jornadas de Paralelismo, pages 427-446, Tenerife, Spain. September 2011. [MBCCM11c]

  In this paper we evaluate a set of experiments to analyze the performance of a VHDA empowered by the IEEE 802.21. Experiments reveal that the VHDA under study offers good performance when traffic conditions are adequate.

- Johann Marquez, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Determining the performance limits of Wi-Fi, WiMAX and UMTS using the Network Simulator (ns-2). In XXI Jornadas de Paralelismo, pages 829-836, Valencia, Spain. September 2010.[MBCCM10a]

  A set of experiments were performed in this work to evaluate the performance of the most widely used wireless technologies, *i.e.*, Wi-Fi, WiMAX and UMTS. Results demonstrate, that depending on modulation and channel bandwidth, different data rates can be achieved.

- Johann Marquez-Barja, Carlos T. Calafate, Juan-Carlos Cano, and Pietro Manzoni. Cross-Layer Evaluation of a VANET-based Content Delivery Framework. In XX Jornadas de Paralelismo, pages 529-534, La Coruña, Spain. September 2009. [MCCM09]

  In this paper we evaluate the viability of content delivery over VANETs. To do so, metrics such as delivery latency, routing overhead, throughput, and packet loss were evaluated based on different parameters (*e.g.*, vehicular density, speed, and content demand rate). Results show that, for typical ranges of values, performance is improved when speed and vehicular density increase.

6.3 Other publications obtained during the PhD research period

International conferences

- Johann Marquez, Josep Domenech, Jose Gil, and Ana Pont. An intelligent Controlling the Cost of Web Prefetch at the Server Side. In IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology, pages 669-675, Sidney, Australia, December 2008. [MDGP08b]

  In this paper we propose an intelligent prefetching mechanism that dynamically adjusts the aggressiveness of the prefetching algorithm at the server side. To this end, we also propose a traffic estimation model that allows accurately calculating, at the server side, the extra load and traffic generated by the prefetching mechanism.

- Johann Marquez, Josep Domenech, Jose Gil, and Ana Pont. Exploring the Benefits of Caching and Prefetching in the Mobile Web. In 2nd IFIP International Symposium on Wireless Communications and Information Technology in Developing Countries, Pretoria, South Africa, October 2008. [MDGP08c]

  In this paper we present an initial approach to study the benefits that techniques like caching and prefetching can achieve for the mobile web users.

- Jose Gil, Johann Marquez, and Ana Pont. Claves para un correcto modelado y evaluacion de arquitecturas web con prebusqueda. In XXXIV Conferencia Latinoamericana de Informatica, pages 1199-1208, Buenos Aires, Argentina. September 2008. [GMP08]

  In this paper we present a detailed overview of the prefetching technique, as well as the most relevant aspects to take into account when evaluating the performance of such technique.

- Johann Marquez, Josep Domenech, Jose Gil, and Ana Pont. A Web Caching and Prefetching Simulator. In 16th IEEE International Conference on Software, Telecommunications and Computer Networks, SoftCOM, pages 346-350, Split, Croacia, 2008.[MDGP08a]

  In this paper we present a novel global framework for performance evaluation in scenarios where different parts of the web architecture interact. Unlike existing proposals, our approach is a fast and flexible tool that allows to faithfully represent the behaviour of each element of the architecture in order to study, reproduce, evaluate and design web strategies that decrease the user's perceived latency when surfing the web.

- Josep Domenech, Jose A. Gil, Julio Sahuquillo, Johann Marquez, and Ana Pont. La Heterogeneidad de los indices de Prestaciones de la Prebusqueda Web. In

XXXII Conferencia Latinoamericana de Informatica (CLEI 2006), Santiago de Chile, Chile. Agosto 2006.[DGS+06]

This paper classifies the most used indexes in the open literature, when studying the performance of web prefetching techniques. For this purpose, we propose a three categories based taxonomy which identifies analogies and differences among the indexes. To evaluate the performance in an appropriate manner it is extremely important to choose suitable indexes.

6.4 Future work

This thesis has provided different contributions within the VNs and the VHDAs areas. However, there are still some issues that can be improved in order to enhance the VHO processes. Moreover, during the research process of this thesis, several issues have been identified. We now proceed to briefly describe the most relevant ones:

- A simulation/emulation tool must be developed or extended to embrace many VHO study cases. Also, the tool must implement different VHDAs in order to compare the performance of new proposals against the implemented VHDAs.
- A taxonomy must be developed in order to organize the different evaluation/performance metrics when evaluating VHDAs. That way, authors could fairly compare the performance of different VHDAs.
- Concerning the IEEE 802.21 protocol, a security framework should be developed that takes into account privacy and authentication issues when performing VHO processes.
- Improving the accuracy of the decision making process by relaying on Genetic Algorithms to adjust the most adequate weighting parameters used in MCDM algorithms.
- Applying Game Theory methods for the decision making process may also be helpful in order to choose, in a fairly manner, the most adequate candidate network.
- In order to improve the Quality of Experience (QoE) when using heterogeneous wireless networks, Cognitive Radio mechanisms may be applied at physical/link layers.

Part V

Appendices and References

Acronyms

3GPP	Third Generation Partnership Project	16
AAA	Authentication, Authorization, and Accounting	13
ACK	acknowledgement	11
AHP	Analysis Hierarchy Process	40
AHS	Advanced Highway Systems	20
ANP	Analytic Network Process	52
AODV	*Ad-hoc* On-demand Distance Vector	80
AP	Access Point	103
API	Application Programming Interface	34
ASN	Access Service Network	13
ASN-GW	Access Service Network Gateway	13
ASV	Advanced Safety Vehicle	20
ATM	Asynchronous Transfer Mode	15

BA Binding Acknowledgement . . . 62
BC Binding Cache . . . 62
BE Best Effort . . . 15
BER Bit Error Ratio . . . 32
BPSK Binary Phase Shift Keying . . . 14
BPSK Binary Phase Shift Keying . . . 14
BS Base Station . . . 103
BSS Basic Service Set . . . 9
BT Bluetooth . . . 23
BU Binding Update . . . 61
CALM Communication Access for Land Mobiles . . . 53
CALM M5 Continuous Air Interface for Long and Medium Range . . . 52
CBR Constant Bit Rate . . . 89
CCK Complementary Code Keying . . . 9
CDMA Code Division Multiple Access . . . 94
CIR Carrier to Interference Ratio . . . 32
CIR Committed Information Rate . . . 32
CN Core Network . . . 61
CN Correspondent Node . . . 61
CoA Care-Of-Address . . . 61
CS Circuit Switching . . . 16
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance . . . 94
CSN Connectivity Service Network . . . 13
DS Distribution System . . . 10
DSL Digital Subscriber Line . . . 12
DSSS Direct Sequence Spread Spectrum . . . 9
DVB Digital Video Broadcasting . . . 23
EAP Extensible Authentication Protocol . . . 29
ELECTRE ELimination Et Choix Traduisant la REalité (french)[Elimination and Choice Translating Priority] . . . 41
ERT-VR Extended Real-Time Variable Rate . . . 15
ESS Extended Service Set . . . 10
EURANE Enhanced UMTS Radio Access Network Extensions . . . 126

FDD	Frequency Division Duplex	14
FHSS	Frequency Hopping Spread Spectrum	10
FHSS	Frequency Hopping Spread Spectrum	10
FPMIP	Fast Proxy Mobile IP	43
Geo-MACHU	Geolocation-based Multi-ACcess network Handover algorithm for vehicUlar environments	127
GGSN	Gateway GPRS Support Node	90
GGSN	Gateway GPRS Support Node	90
GPRS	General Packet Radio System	90
GPS	Global Positioning System	126
GRA	Grey Relational Analysis	39
HAD	Home Agent Discovery	61
HA	Home Agent	61
HIP	Host Identity Protocol	42
HTTP	HiperText Transfer Protocol	126
IBSS	Independent Basis Service Set	10
IETF	Internet Engineering Task Force	61
IETF	Internet Engineering Task Force	61
IP	Internet Protocol	63
IR	InfraRed	10
ISM	Industrial, Scientific, and Medical	10
ISM	Industry, Scientific and Medical	10
ISO	International Organization for Standardization	20
IVHS	Intelligent Vehicle Highway Systems	20
LAN	Local Area Network	10
LDPC	Low Density Parity Check	14
LEO	Low Earth Orbit	23
LTE	Long Term Evolution	23
MACHU	Multi-ACcess network Handover algorithm for vehicUlar environments	127
MAC	Medium Access Control	11
MADM	Multiple Attribute Decision-Making	39
MBMS	Multimedia Broadcast/Multicast Service	23

MCDM-MACHU	Multiple Criteria Decision-Making based Multi-ACcess network Handover algorithm for vehicUlar environments	127
MCDM	Multiple Criteria Decision-Making	127
MDP	Markov Decision Process	38
MICS	Media Independent Command Service	106
MIES	Media Independent Event Service	106
MIHF	Media Independent Handover Function	60
MIH	Media Independent Handover	25
MIHU	Media Independent Handover User	25
MIIS	Media Independent Information Service	106
MIMO	Multiple-Input Multiple-Output	11
MIMO	Multiple Input-Multiple Output	11
MIP	Mobility for IP	66
MIPv4	Mobility support for Internet Protocol v.4	42
MIPv6	Mobility support for Internet Protocol v.6	103
MIP	Mobile IP	63
MN	Mobile Node	61
MODM	Multiple Objective Decision-Making	39
MSC	Mobile Switching Center	16
mSCTP	Mobile Stream Control Transmission Protocol	43
MS	Mobile Station	13
MWE	Multiplicative Weighting Exponent	40
NEMO	Network Mobility Basic Support Protocol	42
NIST	National Institute of Standards and Technology	88
nrtPS	Non-Real-Time Polling Service	15
ns-2	Network Simulator	126
ns-3	Network Simulator	50
NSR	Noise Signal Ratio	32
OBU	On-Board Unit	80
OFDMA	Orthogonal Frequency-Division Multiple Access	94
OFDM	Orthogonal Frequency Division Multiplexing	9
OFDM	Orthogonal Frequency Division Multiplexing	9
PDA	Personal Digital Assistant	17

PHY	Physical	10
PKM	Privacy Key Management	15
PMIP	Proxy Mobile IP	43
PoA	Point of Attachment	99
PS	Packet Switching	16
QAM	Quadrature Amplitude Modulation	14
QoE	Quality of Experience	133
QoS	Quality of Service	125
QPSK	Quadrature Phase Shift Keying	14
QPSK	Quadrature Phase Shift Keying	14
RA	Router Advertisement	65
RFID	Radio Frequency Identification	23
RIWCoS	Reconfigurable Interoperability of Wireless Communications System	51
RNC	Radio Network Control	90
RNC	Radio Network Controller	90
RS-Code	Reed–Solomon Code	14
RS	Router Solicitation	65
RSS	Received Signal Strength	60
RSU	RoadSide Unit	80
rtPS	Real-Time Polling Service	15
SAP	Service Access Point	25
SAW	Simple Additive Weighting	72
SCTP	Stream Control Transmission Protocol	43
SGSN	Serving GPRS Support Node	90
SGSN	Serving GPRS Support Node	90
SIM	Subscriber Identity Module	17
SIP	Session Initiated Protocol	42
SIR	Signal to Interference Ratio	32
SLA	Service Level Agreement	29
SS	Subscriber Station	13
TCP	Transmission Control Protocol	86
TDD	ime Division Duplex	14

TDD	Time Division Duplex	14
TDMA	Time Division Multiple Access	16
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution	38
UE	User Equipment	90
UGS	Unsolicited Grant Service	15
UMTS	Universal Mobile Telecommunications System	126
UTRAN	UMTS Terrestrial Radio Access Network	17
V2V	Vehicle-to-Infrastructure	53
V2V	Vehicle-to-Vehicle	53
VANET	Vehicular *Ad-hoc* Network	126
VHDA	Vertical Handover Decision Algorithm	126
VHO	Vertical Handover	126
VII	Vehicular Infrastructure Integration	20
VIKOR	Vlsekriterijumska optimizacija I KOmpromisno Resenje (serbian) [multi-criteria optimization and compromise solution]	41
VLR	Visitor Locator Register	16
VN	Vehicular Network	125
VSC	Vehicle Safety Consortium	20
WAVE	Wireless Access in Vehicular Environments	20
WCDMA	Wide-band Code Division Multiple Access	17
WiBro	Wireless Broadband	23
Wi-Fi	Wireless Fidelity	126
WiMAX	Worldwide interoperability for Microwave Access	126
WLAN	Wireless Local Area Network	9
WMC	Weighted Markov Chain	38
ZigBee	ZigBee	4

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