Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
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Loss Minimization in a Multihoming Vehicular Network

Minimização de Perdas em Redes Veiculares com Multihoming

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor André Zúquete, Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Doutor Miguel Luís, Investigador Auxiliar do Instituto de Telecomunicações de Aveiro.

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agradecimentos

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Resumo

O interesse crescente em Redes Veiculares está a encorajar a sua implementação em novos ambientes, permitindo o desenvolvimento de aplicações de segurança e de entretenimento. Os veículos podem-se ligar a outros veículos ou à infraestrutura, tendo assim uma ligação à Internet. O equipamento de comunicação colocado nos veículos poderá ter múltiplas interfaces de rede de tecnologias diferentes, como por exemplo, IEEE 802.11p/WAVE, IEEE 802.11a/g/n (Wi-Fi) e celular. Esta diversidade permite a exploração e utilização de mecanismos de Multihoming e de Network Coding, os quais podem ser usados para oferecer maior largura de banda e maior fiabilidade a este tipo de aplicações, reduzindo as perdas de pacotes na presença de um sinal sem fios de fraca qualidade, melhorando assim a qualidade de serviço.

Esta dissertação tem como objetivo melhorar a qualidade de comunicação de uma rede veicular que suporta Multihoming, assim como melhorar os seus mecanismos de Network Coding e do protocolo de mobilidade. Mais especificamente, foram feitas alterações a nível do processo de handover entre redes, para ajudar a infraestrutura a reagir mais rapidamente às condições de comunicação de um nó móvel na rede. Numa perspetiva diferente, foi desenvolvido um mecanismo que permite a aplicação de Network Coding através de diferentes tecnologias em Multihoming, o qual faz uso das diferentes tecnologias simultaneamente para codificar e recuperar os pacotes.

Ambos os mecanismos foram avaliados em cenários de laboratório com sistemas reais. Os resultados obtidos relativos ao envio das mensagens de controlo mostram que esta nova abordagem é capaz de fornecer uma comunicação com maior fiabilidade, reduzindo as perdas de pacotes no caso de uma desconexão abrupta, e quando na presença de outras tecnologias e ligações. Quanto à proposta de muti-tecnologia para o Network Coding, os testes experimentais avaliaram o seu impacto na taxa de entrega de pacotes efetiva e no atraso de transmissão. Os resultados comparativos evidenciam que, apesar de ter um pequeno impacto no atraso dos pacotes em comparação com a abordagem que considera o Network Coding em cada tecnologia de forma independente, a abordagem de multi-tecnologia apresenta uma melhor taxa de entrega.

Abstract

The growing interest in Vehicular Ad-hoc NETworks (VANETs) is encouraging its deployment in new environments, allowing the development of safety and entertainment applications. Vehicles can connect to other vehicles or to the infrastructure, providing an Internet connection. The communication equipment placed inside the vehicles may have multiple network interfaces of diverse technologies, such as IEEE 802.11p/WAVE, IEEE 802.11a/g/n (Wi-Fi) and cellular. This diversity enables the exploration of Multihoming (MH) and Network Coding (NC) mechanisms which can be used to provide higher bandwidth and reliability to these services, reducing packet losses due to poor wireless signal quality, therefore improving the final Quality-of-Service (QoS).

This dissertation enhances the communication quality of a MH vehicular network by improving its mobility protocol and the NC mechanisms. Specifically, changes were performed to ensure the reliability of control mobility messages to help the infrastructure to react faster to the wireless communication conditions of a mobile node. On a different perspective, it has been provided a mechanism to enable NC through different technologies being used in MH, and making use of all technologies simultaneously to code and recover the packets.

Both approaches were evaluated with real systems in a laboratory scenario. The obtained results on the reliability of the control messages show that the new approach is able to provide higher communication reliability, reducing the packet losses presented in case of an abrupt disconnection, and when in presence of other connections. For the multi-technology architecture proposed for the NC, the experimental tests evaluated its impact on the effective delivery ratio and the delay. The comparative results show that the multi-technology approach integrated with MH has a better delivery ratio when compared to the single-technology, despite the small impact on the packet delay.

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Acronyms

AU	Application Unit
BCE	Binding Cache Entry
CN	Correspondent Node
CCN	Content-Centric Network
CRN	Cognitive Radio Networks
FCE	Flow Cache Entry
GPS	Global Position System
HA	Home Agent
HIP	Host Identity Protocol
HMAC	Homomorphic Message Authentication Code
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
LMA	Local Mobility Anchor
LNC	Linear Network Coding
MAC	Media Access Control
MAG	Mobile Access Gateway
mMAG	mobile MAG
MIPv6	Mobile Internet Protocol version 6
MH	Multihoming
MN	Mobile Node
NAT	Network Address Translation

NAP	NAPNetwork Architectures and Protocols
NC	Network Coding
NEMO	NEtwork MObility
N-PMIPv6	Network-Proxy Mobile Internet Protocol version 6
OBU	On-Board Unit
PBA	Proxy Binding Acknowledgement
PBU	Proxy Binding Update
PMIPv6	Proxy Mobile Internet Protocol version 6
PoA	Point-of-Attachment
PoAs	Points-of-Attachment
PNC	Physical-layer Network Coding
RA	Router Advertisement
RS	Router Solicitation
RSSI	Radio Signal Strength Intensity
RSU	Road Side Unit
RNC	Random Network Coding
RLNC	Random Linear Network Coding
SCTP	Stream Control Transmission
SNC	Sistematic Network Coding
SHIM6	Site Multihoming by IPv6 Intermediation
SSDNC	Source Selection Dynamically Network Coding
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UCE	User Cache Entry
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc NETwork
VANETs	Vehicular Ad-hoc NETworks
WAVE	Wireless Access in Vehicular Environments - IEEE 802.11 p
Wi-Fi	IEEE 802.11 a/g/n

Chapter 1

Introduction

Nowadays, being connected all the time is one of the main goals of many research areas. This is also true when considering vehicles, namely for safety services, assisted and autonomous driving, and also to provide Internet access to users inside those vehicles. VANETs provide the possibility to connect cars, people, traffic signs, road sensors and many others, to create smart environments. One of the main challenges in these services is to provide them with a good Quality-of-Service (QoS). Having in mind that, day after day, more and more wireless connections are available in open spaces, and they will have a direct influence in the QoS provided to the deployed services. Thus, there is a need to have a reliable network that can handle these problems and provide the best possible user experience within the network.

The VANET in our group equips the vehicles with OBUs supporting multi-technology communications. The infrastructure is formed by RSUs connected to a centralized or distributed entity that manages the network mobility. The base approach already provides MH with a load balancing mechanism to take advantage of the throughput offered simultaneously by connections with different technologies. However, due to the high mobility of the vehicles inside the VANET, it is important to create mechanisms to deal with link interference and with abrupt changes in the connections. To do so, diverse mechanisms can be used to get over these aspects, and they are an essential component of the overall VANET increasing its robustness, reliability, and can also improve security and safety issues. Moreover, these environments will have inherent losses due to the unreliability of technologies and networks, and again, the high mobility. The possibility to use several technologies simultaneously, mix and code the packets in this multi-technology environment, can be a good approach to improve the overall losses in the network.

The objective and main motivation of this dissertation is to improve the reliability of the vehicular connections, therefore increasing the effective delivery ratio inside the network. To do so, the work developed in this dissertation improves the mobility protocol, to reduce communication outages, and improves the NC mechanism to benefit from multiple technologies in the MH. The first step of this work is to improve the current disconnect phase of the mobility protocol, where this mechanism should deal with a late decision from the mobility controller in the case of quality loss related to a connection with a specific OBU. The next step is to design and implement a new NC approach capable of making use of the MH feature and so provide a better delivery ratio in the network. In the single-technology approach, the encoding is performed at the RSUs, bringing the encoding and decoding processes independent of the technology; however, the data to be sent could avoid the loss of already received encoded

packets at the OBUs, because of an interrupted connection to an RSU where the NC is applied.

1.1 Objectives

The main objective of this dissertation is to improve our VANET with the focus on loss reduction. The proposed improvements arise with the need to overcome some of the main problems that are present in the VANET, as mentioned before, high mobility can have as negative aspect sudden link quality losses, and the infrastructure should be able to react as fast as possible to this situation. Another aspect is the optimization of the use of NC: it has a vast field of application in VANETs but its integration should increase the reliability and delivery ratio, not affecting negatively other network characteristics such as the available throughput and the delay. As such, the objectives for this dissertation are to:

- Improve the current disconnect process in the handover, where the OBU makes use of the MH feature to inform the local mobility controller about the connectivity loss.
- Develop a new NC strategy, capable of MH to make use of different connections and technologies simultaneously to reach the OBU.
- Design and implement a NC integration to improve the available throughput.
- Evaluate the proposed approaches by performing tests in a laboratory scenario.

1.2 Contributions

The work performed in this dissertation contributed in the following points:

- Creation of a more reliable VANET, with a better behaviour on the handover process, where the OBU uses the best possible connection for its control mobility messages during handover.
- Possibility to deploy this vehicular network in other platforms such as, for example, a Raspberry Pi.
- Integration of a NC approach directly with the mobility protocol at the LMA, resulting in a better throughput available for the VANET and also the possibility of making use of MH with NC in a multi-technology scenario.

With respect to the recognition of the work developed throughout this thesis, part of it was presented on the 24th RTCM Seminar held on February 2nd, in Covilhã, under the name "Multi-technology vs Single-technology Architecture for Network Coding in VANETs". Under the same name, a paper was presented at the 23rd IEEE Symposium on Computers and Communications, in June 2018.

1.3 Document Structure

This document is organized as follows:

Chapter 2 - State-of-the-Art : This chapter focuses on MH, mobility, and NC, and describes its fundamental concepts for a better understanding of the remaining document. It also provides an overview of the state of the art on MH applications in vehicular networks and general NC applications.

Chapter 3 - Base Work : Describes the base work developed by the NAP (NAP) research group that supports the work done in this dissertation.

Chapter 4 - N-PMIPv6 Improvements : Explains the improvements done on the mobility protocol.

Chapter 5 - Network Coding Improvements : Explains all the challenges found and the integration of a multi-technology approach for the NC, and also its integration with the mobility protocol.

Chapter 6 - Evaluation : Describes the evaluation scenarios and presents the results obtained with the solutions derived throughout this thesis.

Chapter 7 - Conclusions and Future Work : Presents the conclusions of this dissertation and proposes additional improvements for future work.

Chapter 2

State-of-the-Art

2.1 Introduction

This chapter introduces the fundamental concepts about MH, mobility, and NC in VANETs, and provides a better comprehension of the remaining document to the reader. It also present some related work for this dissertation. This chapter is organized as follows:

- Section 2.2 describes the main features and concepts of VANETs. It also presents the overall architecture, applications and services, and some of the main challenges.
- Section 2.3 describes some of the access technologies commonly used in VANETs, with a special emphasis on the WAVE technology, and how multiple wireless access technologies operate simultaneously.
- Section 2.4 describes some of the mobility protocols related to VANETs, their features and requirements to present a viable use for implementations in this area. It also describes some of the main aspects related to MH.
- Section 2.5 introduces the concept of NC, and enumerates its advantages and disadvantages when applied to VANETs.
- Section 2.6 provides some related work on MH applications in VANETs and also some different NC applications in wireless networks.
- Section 2.7 overviews the main ideas tackled in this chapter.

2.2 Vehicular Ad-Hoc Networks (VANETs)

Figure 2.1 illustrates the concept of a VANET application in real life. A VANET is an ad hoc network formed by moving vehicles and fixed stations allowing, for example, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. The equipments inside the vehicles are denominated by OBUs; they allow an end-user to connect to them creating an Intra-Vehicle network. The Road station equipments are denominated by RSUs which are responsible for establishing the V2I communication.

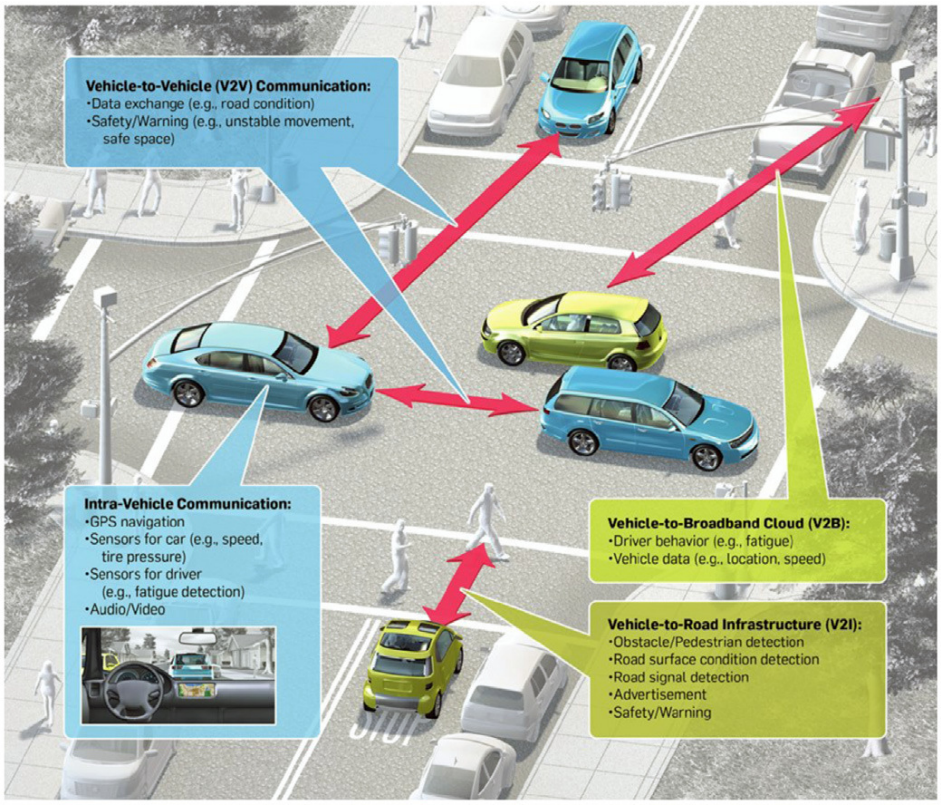


Figure 2.1: VANET applications (from [1]).

2.2.1 Architecture

A VANET presents three main entities:

RSU: A fixed equipment that is positioned in strategic places in order to establish communications with the OBUs. The main responsibility of this equipment is to serve as an access point for the OBU and establish communication between the OBUs and the Internet or a central processing unit. It can be equipped with different technologies such as WAVE and Wi-Fi.

OBU: A mobile entity in the VANET architecture installed in the vehicles. This equipment is responsible for creating an intra-vehicle network and is also capable of V2V communication using WAVE technology. It also connects to the RSUs through WAVE or other technologies such as Wi-Fi and cellular.

Application Unit (AU): It is connected to the OBU inside the vehicle and serves as a dedicated device to run safety applications, or as a personal device to run normally an Internet connection.

As shown in Figure 2.2, besides these three entities there are also three domains in which a VANET is divided. They are:

Infrastructure domain: Represents the possibility to provide Internet access to the OBUs through the connection by the RSUs, or also using cellular communications.

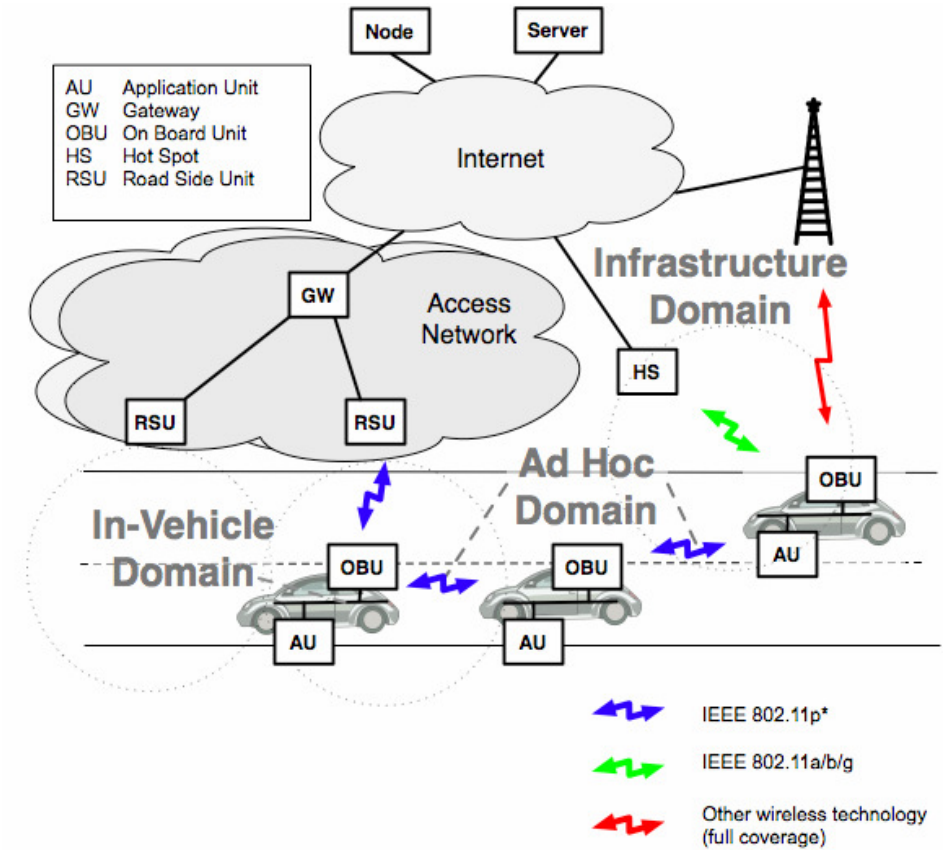


Figure 2.2: VANET architecture (from [2]).

Ad hoc domain: It is the network formed by the vehicles that contain an OBU and the RSUs allowing V2V and V2I communications.

In-Vehicle domain: It is formed by the OBU and existent AUs; the connection between them can be wired or also wireless.

2.2.2 Features

Based on [1] and [11], it is possible to identify some of the main features of VANETs:

Sufficient energy capacity and a significant processing power: The vehicles can support the energy consumption required by an OBU, and also support other entities connected inside the car to the OBU with more processing power with a higher energy consumption.

Dynamic network topology: This means that the network topology can be very dynamic and change several times in a reduced amount of time, due to the high mobility from the OBUs.

Predicted mobility: Cars can be equipped with Global Position System (GPS), and because the behaviour and movement of a vehicle is constrained to roads and a set number of

traffic rules, it is possible to predict and anticipate some of the car movements inside the VANET.

2.2.3 Applications and Services

Some of the main applications that VANETs can provide are:

Safety applications: The support of V2V and V2I communications allows the creation of road safety applications, e.g. the dissemination of emergency messages.

Traffic optimization: Real-time traffic monitoring gives a VANET information about all the cars connected to it. So, it is possible to inform other cars about accidents and certain roads that have high traffic congestion, allowing the drivers to avoid them and choose other routes.

More connectivity: The possibility to provide end-users connected to an OBU with Internet; this can be used for many purposes such as entertainment or publicity when connected to certain OBUs in public transports.

2.2.4 Challenges

The integration of VANETs in a public environment also present major concerns and challenges, which can be enumerated as follows:

Security and privacy: One of the major concerns about VANETs is the ability to provide security and privacy to its end-users. However, the broadcast nature of WAVE connections can turn out to be a negative point related to security aspects.

Network fragmentation: As mentioned before, the dynamic network topology that is characteristic of a VANET implies constant changes in established connections, which is not ideal for a normal network operation.

Signal degradation: Because a VANET is mostly implemented in urban areas, it leads to a natural signal degradation, due the fact that the signal encounters many obstacles like buildings and other vehicles, decreasing the connection quality.

2.3 Network Access Technologies

A VANET is capable of communicating through different network access technologies simultaneously, creating multi-technology environments. Taking into account all network access technologies currently available (we expect to use 5G in vehicular environments), the most important one and more suitable for a VANET is WAVE.

2.3.1 Wave protocol (IEEE 802.11p)

The WAVE protocol has been developed with the main purpose of providing dynamic connections in vehicular environments. This protocol does not require any association process and is able to establish connections in the order of 10-20ms, allowing faster communications

and taking advantage of short opportunities of data transmission; it also provides a communication range up to 1000m in line-of-sight. A WAVE protocol stack, as shown in Figure 2.3, was developed by Institute of Electrical and Electronics Engineers (IEEE) to address some of the mandatory characteristics of VANETs.

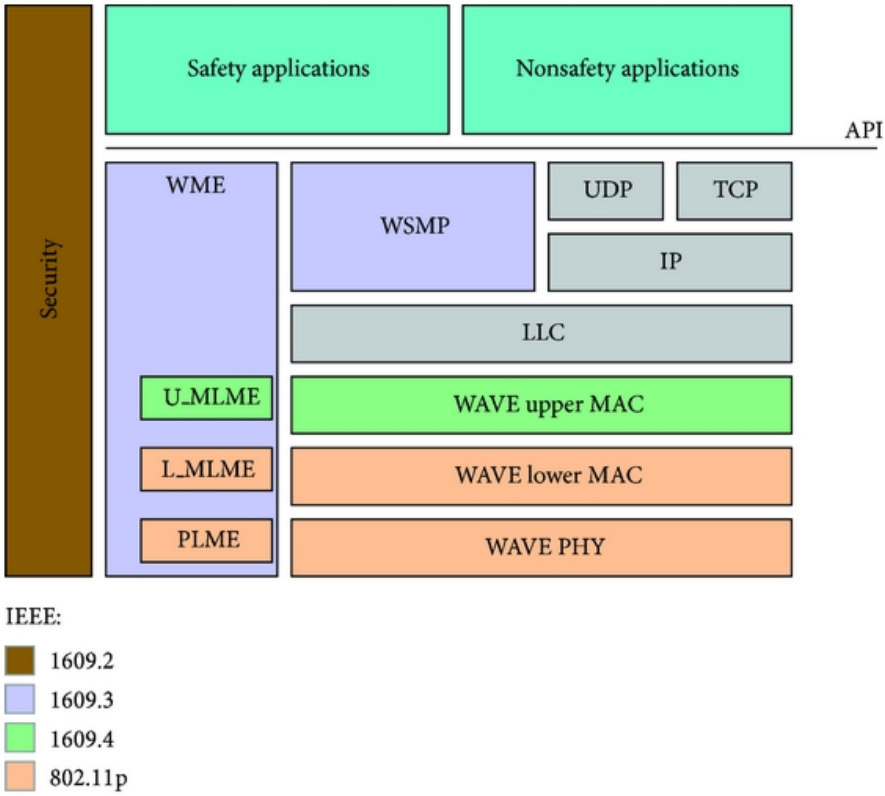


Figure 2.3: WAVE protocol stack (from [3]).

WAVE standard protocol provides a multichannel operation that is based on seven different channels, six of them are denominated as service channels and one is the control channel, shown in Figure 2.4

2.3.2 Multi-Technology implementations

As mentioned before, VANETs are able to communicate through different technologies simultaneously, creating this way multi-technology environments. For example, a VANET can use WAVE, Wi-Fi and cellular technologies to establish connections between the RSUs and the OBUs. Taking into account these three technologies, it is possible to create a hierarchy of priority for the established connections. It is clear that the best solution for vehicular environments is the WAVE technology, which was especially designed for this purpose; the others are considered secondary choices. For example, Wi-Fi presents a small communication range compared to WAVE, and its association process time is also a negative point. Cellular technology has a significant concern related to high costs for the end-users and its high latency.

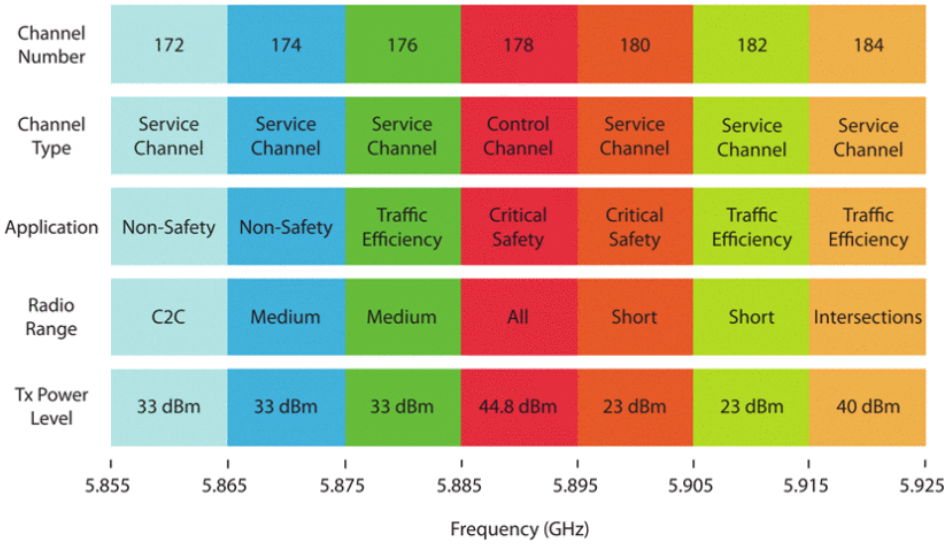


Figure 2.4: WAVE protocol frequency spectrum (from [3]).

2.4 Mobility Protocols and Multihoming

2.4.1 Mobility Protocols

For a VANET deployment to be fulfilled, it is essential to have mobility protocols that support the dynamic network topology and constant changes of connections. The mobility protocol supports the movement of entities inside the network, maintaining its session and all of its connected active devices. It is also responsible for tracking and updating the mobile nodes location and managing the essential handoff operations. Some of the main aspects that these protocols have to take into consideration are, for example, efficient handover performance, Internet Protocol version 6 (IPv6) support, multi-hop and MH support, scalability and efficiency.

These protocols can be: centralized, presenting a central node responsible for the routing operations; distributed, where the mobility functions are spread through multiple networks; or hybrid, which are a combination of the previous two. Focusing on the centralized protocols, some of them, which also served as base for the implemented VANET in our research group, are described in the following subsections.

2.4.1.1 Mobile Internet Protocol version 6 (MIPv6)

MIPv6 provides terminal mobility. This protocol is not ideal for a VANET implementation, since it does not handle network mobility, and it presents high values of latency for handovers, introduces signal overhead and high packet losses [12], which are some requirements that have to be taken in consideration for VANET applications. Figure 2.5 illustrates an overview of the MIPv6 protocol.

2.4.1.2 Proxy Mobile IPv6 (PMIPv6)

The PMIPv6 protocol was developed with the main objective to overcome some of the key aspects that the MIPv6 protocol could not fulfill. PMIPv6 eliminates the need for the

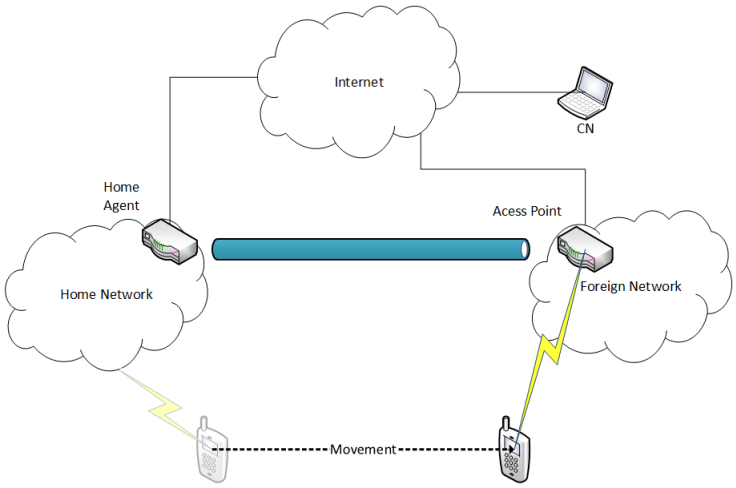


Figure 2.5: MIPv6 protocol overview (from [4]).

interaction of the Mobile Node (MN)s in the signaling process. Nevertheless, one major requirement for VANETs based on [13] is to be able to provide mobility for an entire network from a specific MN; in this protocol it just provides mobility for the MN itself. Figure 2.6 illustrates an overview of the PMIPv6 protocol.

This protocol also introduces some new entities such as, for example, the LMA and the MAG. The LMA is an entity that serves as an anchor point for the MN prefix and is responsible for the routing process and for managing the MNs binding states. The MAG is an entity that acts as a RSU which is an access router for the MN, and informs the LMA about mobility-related aspects.

2.4.1.3 Network Mobility (NEMO)

In order to improve the last two protocols and provide network mobility, the NEtwork MObility (NEMO) protocol was created. This protocol brought some improvements, such as the fact that it fulfills most of the VANET mobility requirements, though based on [5] and [14] this protocol still has a high handover latency, and it presents some limitations in high dynamic scenarios. Figure 2.7 represents an overview of the NEMO protocol.

2.4.1.4 Network-PMIPv6 (N-PMIPv6)

This protocol is based on the PMIPv6 and the NEMO approaches, and a global overview is illustrated in Figure 2.8. This protocol was the selected one to be implemented in our research group. It provides some major improvements in comparison with the other ones: it is able to perform mobility of an entire network with reduced handover latency, and it allows the end-users to connect directly to an OBU, which in the case of a handover, it will be the only entity that the MAG takes into consideration to inform the LMA about its movement, turning the end-users in a transparent entity in the process.

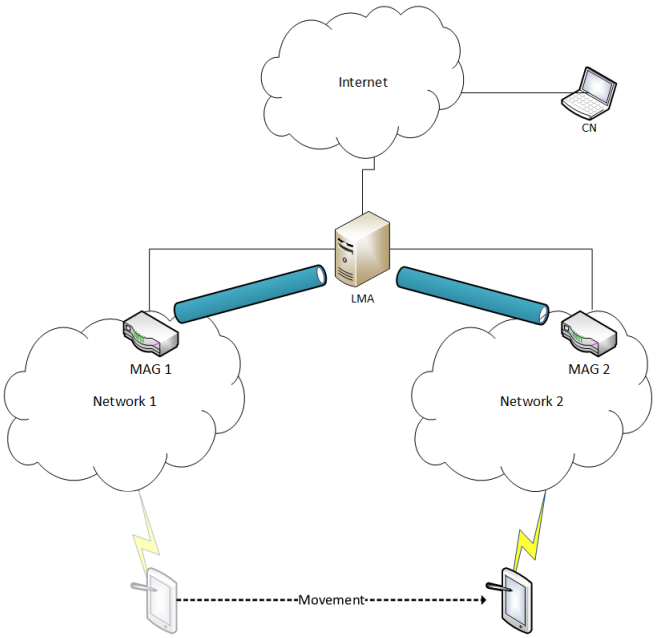


Figure 2.6: PMIPv6 protocol overview (from [4]).

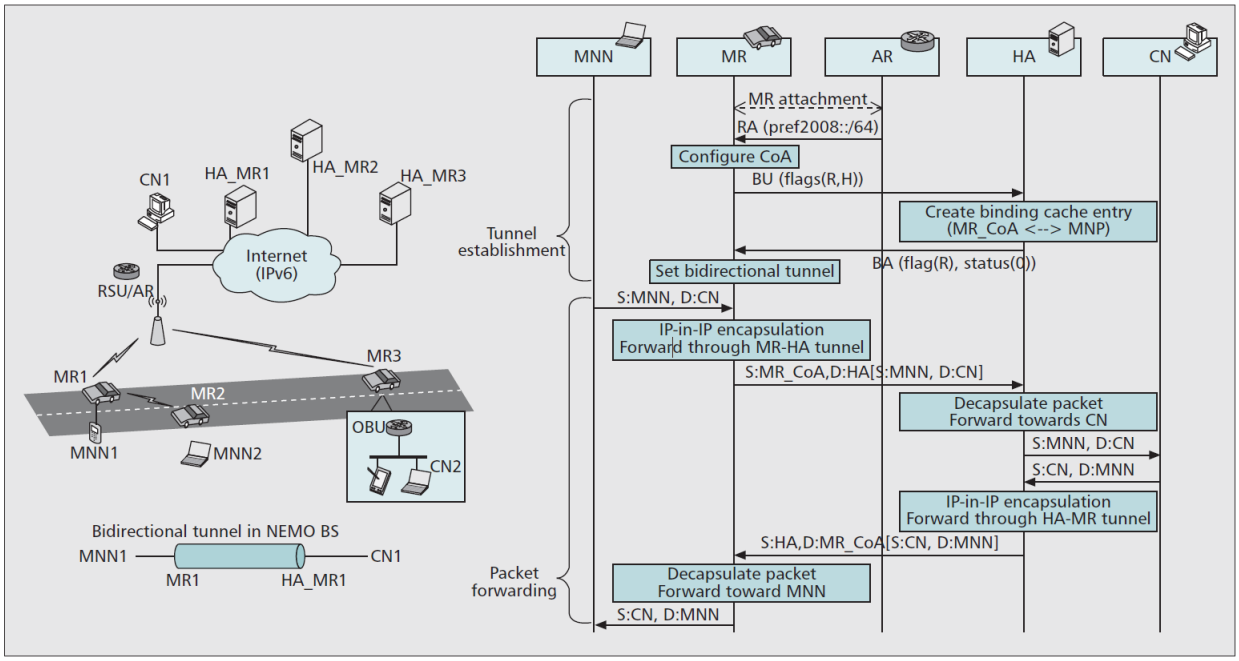


Figure 2.7: NEMO overview and association process (from [5]).

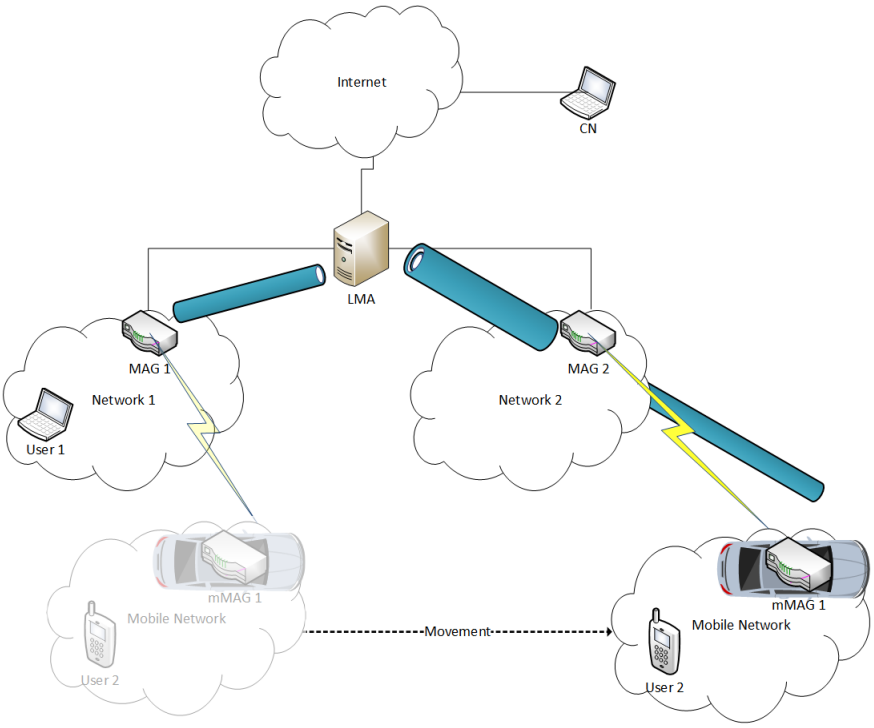


Figure 2.8: N-PMIPv6 protocol overview (from [4]).

2.4.2 Multihoming

The introduction of the MH feature in a VANET aims to optimize the network quality by the fact that it takes advantage of the multiple available access points, to provide inside the network load balancing through multiple connections simultaneously, and so, increasing reliability and presenting a better management of the available resources. Some of the protocols that are used to provide these features in VANETs are presented in the following subsections.

2.4.2.1 Multihoming Protocols

Stream Control Transmission (SCTP)

The SCTP protocol is a session-oriented protocol that is based on [15] and presents some features like MH support, data partitioning through multiple connections, and, for example, reliable transmissions with detection of duplicated, reordered, discarded and corrupted data. However, this protocol presents some negative aspects in order to be implemented in our VANET: its retransmission behaviour like in Transmission Control Protocol (TCP), and the fact that the MH in this protocol is just used for redundancy support.

Site Multihoming by IPv6 Intermediation (SHIM6)

The SHIM6 protocol is a network layer protocol; it enables IPv6 MH without compromising the scalability of the global routing system as shown in [16]. However, this protocol does not fulfill the requirements for being used in our VANET because it does not allow to decide which type of traffic flows through each available network interface. It then misses the possibility to provide differentiated load balancing.

2.4.2.2 Proxy multihoming as an extension in PMIPv6

To implement MH in a VANET, the work developed in [8] and [17] proposed a MH extension, based on a proxy-server placed in the network. In order to achieve MH, a single terminal, such as an OBU, can have multiple paths using Internet Protocol (IP) replications. This extension allows load balancing through the available Point-of-Attachment (PoA)s, while the mobility is assured by the PMIPv6 protocol, so there is no need to implement modifications on the MH user, the OBU, since all the added modifications are performed at the LMA and the RSUs.

2.5 Network coding

2.5.1 Concept

The concept of NC aims to optimize traffic transmission inside a network by combining two or more messages. It was first introduced by [18] as an alternative to routing. Instead of a normal behaviour from a traditional packet-switching network, where the information is simply store-and-forwarded through the intermediate nodes, in a NC network the packets are combined and sent along with coded packets, as shown in Figure 2.9. This process is called encoding process and it demands the existence of a decoding process on the receiver. The decoding process is also illustrated in a simple way in Figure 2.9, where there is the possibility to recover the lost information with the help of the coded packets that were created at the encoder. There are several NC approaches and applications that will be explained with more detail in the next subsections and in the next chapter of related work.

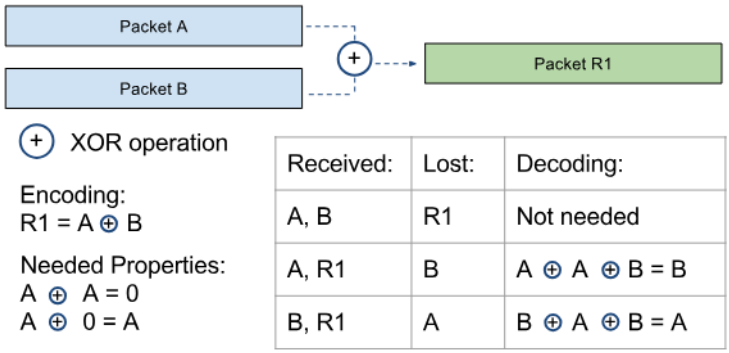


Figure 2.9: NC basic encoding and decoding process.

2.5.2 Advantages and disadvantages

The implementation of NC in a VANET presents some advantages, but also some disadvantages, as described below:

Advantages:

- Improves the delivery ratio, due to the fact that the endpoint can decode lost data through the redundant packets that reach the destination.

- Security, since due to the encoding process, it can be useful against simple attacks.
- Data compression which leads into an optimized bandwidth usage.

Disadvantages:

- Increased complexity in the coding and decoding processes.
- Synchronization plays a major role, especially in real-time applications.
- If there is a major security requirement on the network, the NC implementation during the packet manipulations has to assure that it does not affect the security mechanisms from the network.
- Introduces overhead to the network.

2.5.3 Linear and Random Linear Network Coding

Some possible approaches of NC are Linear Network Coding (LNC) [19] or Random Linear Network Coding (RLNC) [20]. On a LNC approach, the encoding process is done based on linear combinations, for example the linear combination of the incoming data packets. On the other side, the decoding process to recover all the information just needs to receive a sufficient number of linearly independent combination of packets. When compared with the general NC, this approach does not require a high complexity of implementation.

The RLNC approach, as shown in Figure 2.10, is more complex, and the encoding process can generate a diversity of coded packets based on random linear combinations, where the encoding coefficients are chosen randomly from a Galois field. In this approach, all the sent packets are encoded, so at the decoder there is the need to receive N packets from the ones that are sent.

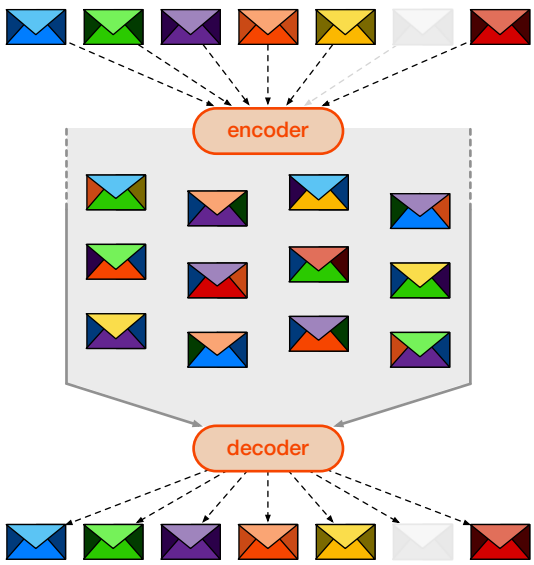


Figure 2.10: Random Linear Network Coding exemplification.

2.5.4 Systematic and Non Systematic Network Coding

Figure 2.11 illustrates two other NC approaches, the Systematic and Non Systematic NC. The major difference between them is that, inside each generation, the systematic NC has N original packets and M redundant coded ones; on the non systematic NC, each generation is established by N + M redundant coded packets. The decoding process to recover all the sent data has the same major requirement, that is, to receive at least N from the N + M packets from the generation.

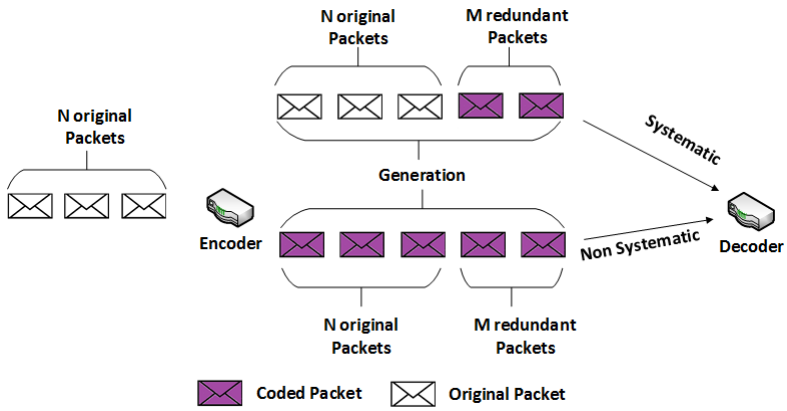


Figure 2.11: SNC and Non SNC.

2.6 Related work

VANETs are nowadays one main instrument that leads to the development and improvement of many network related aspects, since they provide an example of challenging communications. One of the network aspects that absorbs many research efforts is the creation of multihomed communications within VANETs. In [21] the authors proposed a Multipath TCP communication architecture, which should improve the QoS of a VANET taking advantage of multihomed devices using complementary access network technologies, to maintain the connectivity. Multipath TCP for data transfer in VANETs was also the main research point of the work presented in [22]. The MH mechanism in VANETs can be implemented using different protocols, each of them has its operation mode and fulfills different requirements. One of those is the Host Identity Protocol (HIP) protocol: in [23] the authors present a novel HIP based secure vehicular femtocell scenario, where some evaluations were made about the handover latency, packet loss, and throughput to compare multihomed and singlehomed communications.

To deal with challenges like mobility in VANETs, some aspects need to be considered such as the disconnect and reconnect process from entities with mobility capabilities. In [24] the authors presented a solution where each vehicle would share its trajectory information with its neighboring vehicles to mitigate disconnected links within the network. With the aim to also provide loss reduction and network optimization, some research has been made into the efficient RSU placement. The authors from [25] studied the performance of message dissemination in VANET environments and proposed a Safety-Based Disconnected RSU Placement algorithm (S-BRP), that reduces the dissemination delay in some areas and the amount of traffic flow.

To improve data reliability in wireless networks, one possible approach is the use of NC[26]. In [27] the authors proposed a Bearing Opportunistic Network (BON) coding procedure that operates in wireless multihop networks over multiple unicast sessions introducing a low overhead to the network increasing its performance, presenting a higher throughput and a smaller delay. Instead of using NC to recover data in lossy environments, they proposed the usage of NC to predict data that should arrive later to the destination, reducing this way the overall delay. This implementation presents some impressive results, but it also relies on that the network is static and the network topology is well known, turning this implementation impossible to deploy in dynamic VANETs. In [28] the authors studied and evaluated the problem of network coding-based multicast in multihop Cognitive Radio Networks (CRN) while considering the uncertain spectrum availability. Some research has been made on the implementation of fountain codes which are especially suitable for lossy environments, as they provide redundancy while reducing coordination overheads between the sender and the receiver.

In [29] the authors investigated how to minimize the duplicate transmissions in a multi-source environment. The work presented in [30] shows how NC can be used for very distinct applications. The authors proposed to increase the energy efficiency of wireless networks based on the IEEE 802.11 Standard. The proposed mechanism allows nodes to duty cycle by switching to a low-power state when they overhear coded packet transmissions that will not provide any new information for them. The presented results were promising with a considerable value of gains related to the energy efficiency. In [31] the authors use NC as a critical enabler to improve throughput and energy performance in a converged networks scenario. They proposed an optimization framework and a set of allocation policies to provide efficient, channel-aware load allocation for multihomed devices.

The decoding delay introduced in a network by RLNC is heavily evaluated in [32]. The authors performed tests with systematic and non-systematic NC implementations where they used the proposed framework to fine-tune the system parameters to optimize the value of packets that are sent over the broadcast channel. Still related with RLNC, more research efforts have been dedicated to improve decoding related aspects [33][34][35]. In [34] the authors propose an approach that paces the transmission of coded redundant packets with the aim of reducing the decoding delay. In [33] and [35] two different mechanism of sliding window scheme were presented. About the encoding process also related with RLNC, the work presented in [36] analyzes the impact from the different arguments, such as generation and symbol size at the introduced encoding delay. To avoid pollution attacks, where a small number of polluted messages will propagate in a network and corrupt bunches of legitimate messages, the work developed in [37] presents an improved scheme based on Homomorphic Message Authentication Code (HMAC) for RLNC-enabled wireless networks. At last, the performance of a RLNC approach in a multi-hop scenario was investigated in [38]. The authors discussed the issue of throughput-delay, and compared the obtained simulation results with the theoretical ones.

SNC and Random Network Coding (RNC) decoding probabilities in lossy wireless environments are analyzed in [39], and the study reveals that SNC presents better results in broadband wireless access networks. In [40] the authors proposed a novel architecture solution based on SNC on the link layer to improve the goodput of the communication on interfered links. The proposed approach estimates the packet erase rate in real time to adjust the encoding window. A closer look at the decoding performance of SNC in single-hop and multi-hop wireless networks is given by [41], where the authors derive closed-form expressions for the decoding probability.

NC is also a key aspect for data reliability in vehicular networks, and it is still an open

research issue. Research efforts have been dedicated to provide data reliability in VANETs, merging NC with concurrent multipath transfers [42]. To mitigate buffer blocking, in [42] the authors proposed a solution which avoids data reordering. Through computational simulations, they show that this framework improves QoS and decreases the number of retransmissions when compared with similar state-of-the-art solutions.

Some works present interesting aspects related to data dissemination in VANETs [43][44][45]. In [44] the authors analyze data dissemination with NC in Vehicle-to-Vehicle (V2V) communication. Although their case study was made for cars driving in opposite directions, it can be helpful in a multi-hop scenario. In [46] the authors used rateless codes to deliver multimedia content from roadside infostations of a centralized architecture. Instead of adopting a distributed paradigm, their work departed from architectures requiring centralized coordination and global network state knowledge. Moreover, they explored vehicles as mobile storage devices to achieve ubiquitous, reliable dissemination. Finally, they investigated several trade-offs concerning, for example, the buffer size or maximum capacity in order to maintain reliable paths between vehicles in V2V communications.

The authors in [47] aimed to improve transmission performance in VANETs using Content-centric information dissemination. They proposed a novel Source Selection Dynamically Network Coding (SSDNC)-based Information Centric Network protocol, which introduces Content-Centric Network (CCN) architecture in VANET. The main idea was to use and take advantage of NC to achieve higher performance by eliminating network redundancy and solving the packet disorder problem.

VANETs are not just present in urban scenarios, but they can also play a significant role in highway scenarios, some research efforts have been dedicated to this specific scenario such as in [48] and [49]. To solve the problem of short contact time between fast-moving vehicles, in [49] a detection method for Physical-layer Network Coding (PNC) is proposed, to mitigate the Doppler effect caused by fast-moving vehicles. Also related with PNC, in [50] the authors suggested a solution for basic safety messaging integrating PNC with RLNC. An interesting approach is proposed in [51], where the authors use a pseudo random NC for content distribution in a VANET. This implementation relies on sending a larger amount of different linear combinations and the vehicles only need to receive a defined number of independent linear combinations to decode the data. The work developed in [51] aims to implement such a scenario using for example IEEE 802.11p as communication technology.

In [52] the authors designed an architecture that aims to increase the reliability of emergency messages in a vehicular network with the help of periodically generated messages. They rebroadcast coded packets using a RLNC approach. The results showed that rebroadcasting coded data increases the data reliability and outperforms other repetition-based algorithms. In [53], the authors overview NC in VANETs and discuss its importance to improve QoS in such dynamic networks.

Considering the previous approaches in the literature, to the best of our knowledge, there are no works that are able to make use of NC in different technologies in a real VANET environment.

2.7 Summary

This chapter presented the overview of the fundamental concepts of this dissertation, starting with a brief explanation of the main features, challenges, and applications of a VANET.

Then, an overview of MH and mobility protocols was introduced along with the concept and characteristics of NC. From the presented mobility protocols, the most suitable for the proposed VANET is the N-PMIPv6. For the MH scenario, besides all the existent protocols, a proxy MH as an extension in the PMIPv6 protocol was used to fulfill the requirements that were established for the MH integration.

At last, related work in the literature was presented and discussed with some insights on the main research areas of this topic.

Chapter 3

Base Work

3.1 Introduction

This dissertation has as base work a VANET architecture with mobility, MH and NC features. As mentioned before, one of the objectives of this work is to improve some of the features currently available in the N-PMIPv6 mobility protocol, such as the handover mechanism. The other main objective focuses on the way that the NC is currently implemented: in a previous approach a single-technology approach was assumed, supporting multiple individual communication technologies. The primary goal here is to provide NC as a multi-technology approach. The remaining chapter has the following structure:

- Section 3.2 describes the mobility protocol used as base work for this dissertation: it describes its architecture, framework and some of its features.
- Section 3.3 describes the rationale and characteristics of the current connection manager.
- Section 3.4 describes the base approach of the NC in our VANET.
- Section 3.5 overviews the main ideas of this chapter.

3.2 Mobility Protocol - N-PMIPv6 implementation

The work done by [6] started the development of the mobility approach that is currently deployed in the VANET, which uses as base the PMIPv6 mobility protocol based on the NEMO-enabled Proxy Mobile IPv6 (N-PMIPv6) [54]. Some of the added features are, for example, the creation of a connection manager, the implementation of a mobility mechanism based on N-PMIPv6, and the possibility to provide Internet access via Internet Protocol version 4 (IPv4) to an end-user connected to the OBU.

All the entities involved in the operation of the aforementioned protocol are described and explained as follows:

- LMA: It is the Home Agent (HA) of this architecture. It manages the binding states off all mobile nodes, it is responsible for the routing process, and it also stores information about the overall network status to optimize the traffic distribution. In other words, this entity is the core element of our architecture;

- MAG: The MAG is responsible for tracking and notifying the LMA about the mobility-related aspects. The MAGs are RSUs where the end-devices can connect and serve as access links to the LMA. They behave like Points-of-Attachment (PoAs) to OBUs;
- mMAG: It acts as a mobile router, being responsible for providing IPv4 Internet access to the users connected to it. The mMAG is an OBU that creates an access link between the end-user and the mobility network;
- Correspondent Node (CN): The CN is a peer node with which a MN wants to communicate. It represents an entity connected to a global network (such as the Internet), where an LMA bridges its specific traffic to the mobile network.

LMA flowchart

In Figure 3.1 and Figure 3.2 we can observe the operation diagram of the LMA. Figure 3.1 presents the basic implementation and Figure 3.2 presents its operation diagram including MH logic for traffic distribution. The addition of MH has brought to the LMA operation mode two major entities, the User Cache Entry (UCE) and the Flow Cache Entry (FCE), that will be explained in more detail in section 3.2.1.

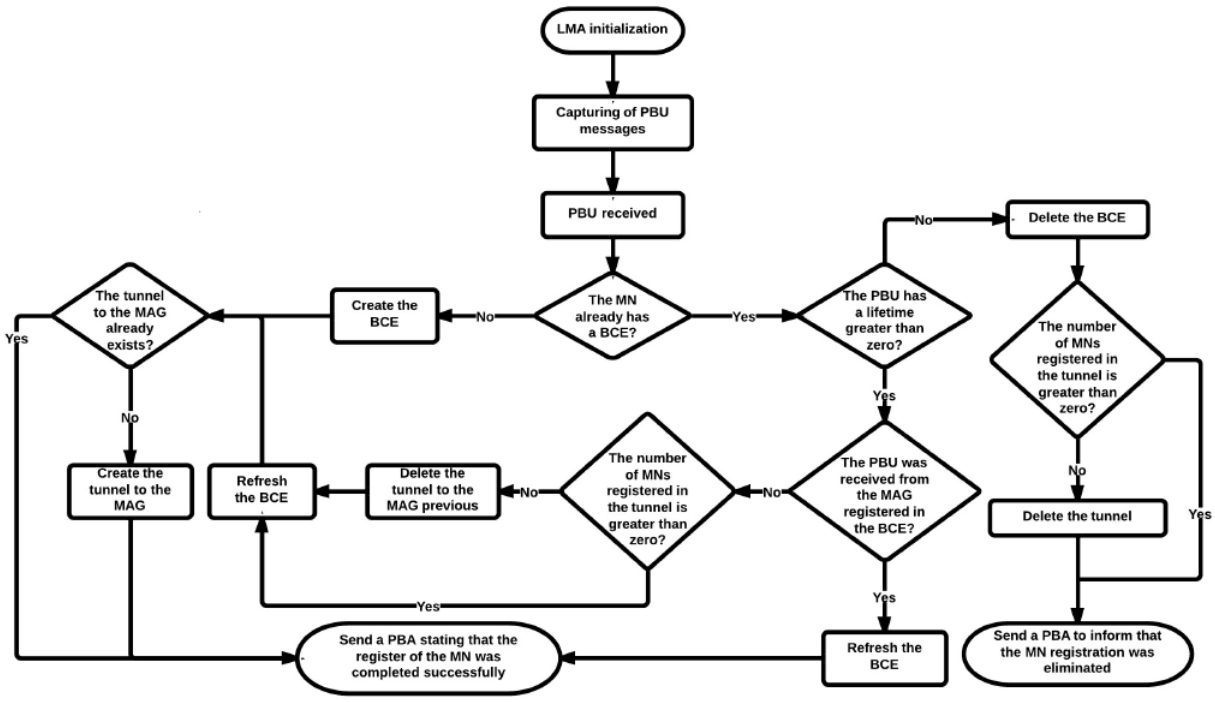


Figure 3.1: LMA flowchart based on [6].

A MN sends a PBU message to the LMA. When the LMA receives the Proxy Binding Update (PBU), two different outcomes can happen depending if the MN is already registered in the LMA, and has already an entry in the Binding Cache Entry (BCE), or if it is a new node that is trying to connect to the VANET. If the LMA is in presence of a new MN, the first step is the creation of a BCE, and after that, it verifies if the MAG that makes the connection between the LMA and the MN has already an IPv6 tunnel between itself and the LMA; if

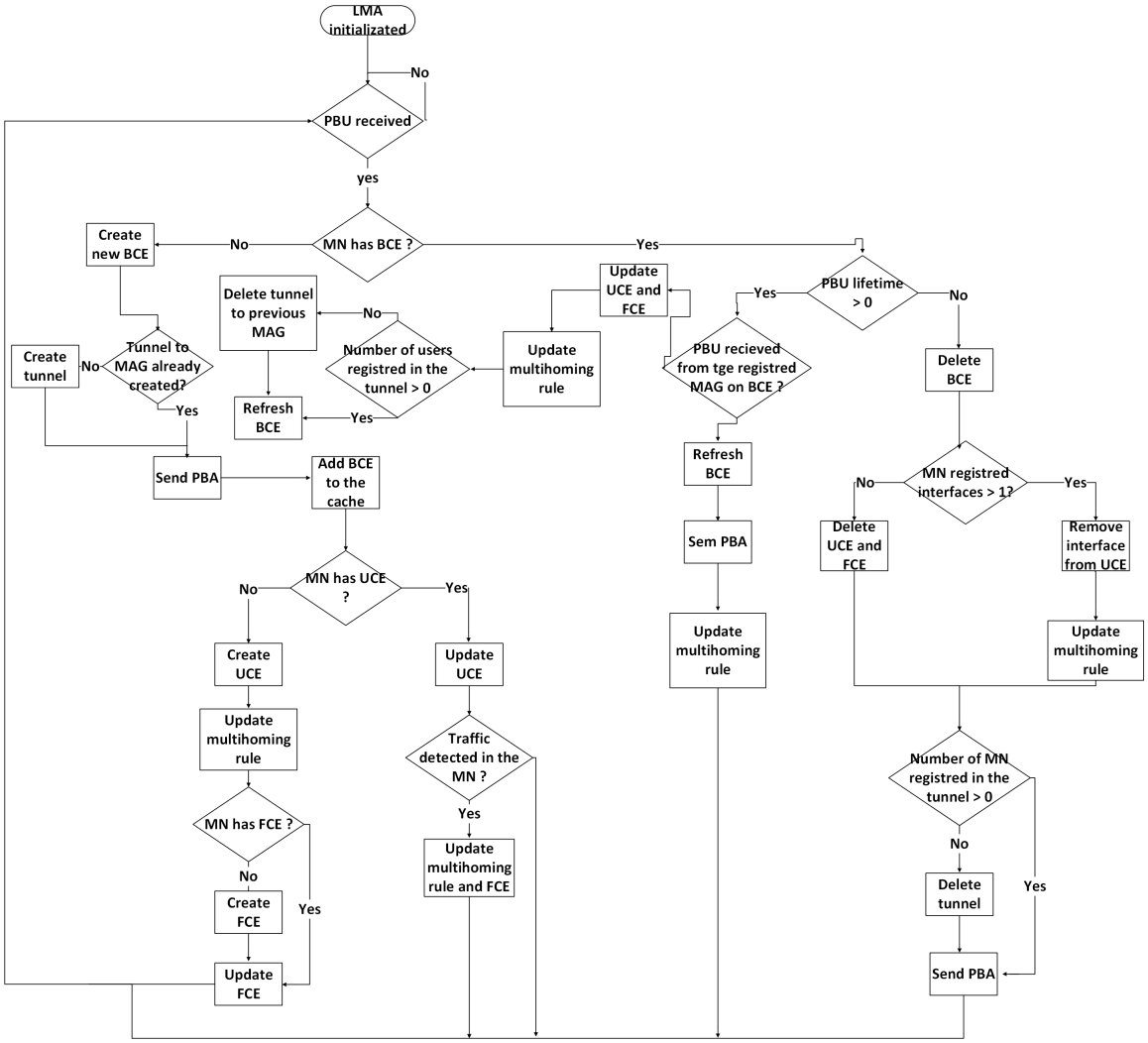


Figure 3.2: LMA flowchart for multihoming support based on [7].

not, a new IPv6 tunnel is created. After this procedure, the LMA sends a Proxy Binding Acknowledgement (PBA) signaling the completion of the registration process. Contrarily, if the MN is already registered, it will check the lifetime of the PBU. If it has already expired, the BCE is deleted as well as the IPv6 tunnel; if not, the PBU received at the LMA can have two different meanings: or it can be a regular PBU from an already registered MN, and the action the LMA should take is to refresh the BCE, or it can be a PBU signaling a handover, which means that the MN is already registered in the BCE but not to the MAG that sent the PBU. In this case the BCE is refreshed, and if there is the need to create a new IPv6 tunnel for the new serving MAG, it will be created. Finally, a PBA is sent signaling the completion of all the registration or maintenance operations.

MAG and mMAG flowchart

Figure 3.3 presents the operation diagram of a MAG and a mMAG. If the N-PMIPv6 configuration file predefines an egress address, which represents the address for the incoming traffic, for the MAG it will behave as a MAG or also called RSU; if not, it will behave as a mMAG also called as OBU. In both behaviours the entities will react the same way when they receive a Router Solicitation (RS) message that happens when another MN is trying to connect to the network. Due to the broadcast characteristic, it is mandatory to check if the RS was captured in the WAVE interface. It is considered that a new MN is detected when the message was not captured in a WAVE interface, or if the RS was captured in the WAVE interface and the entity itself is the actual RS destination. Another important aspect, just for the mMAG behavior: if the mMAG receives a Router Advertisement (RA) message, it will proceed to configure the network interface address because it joined the network successfully.

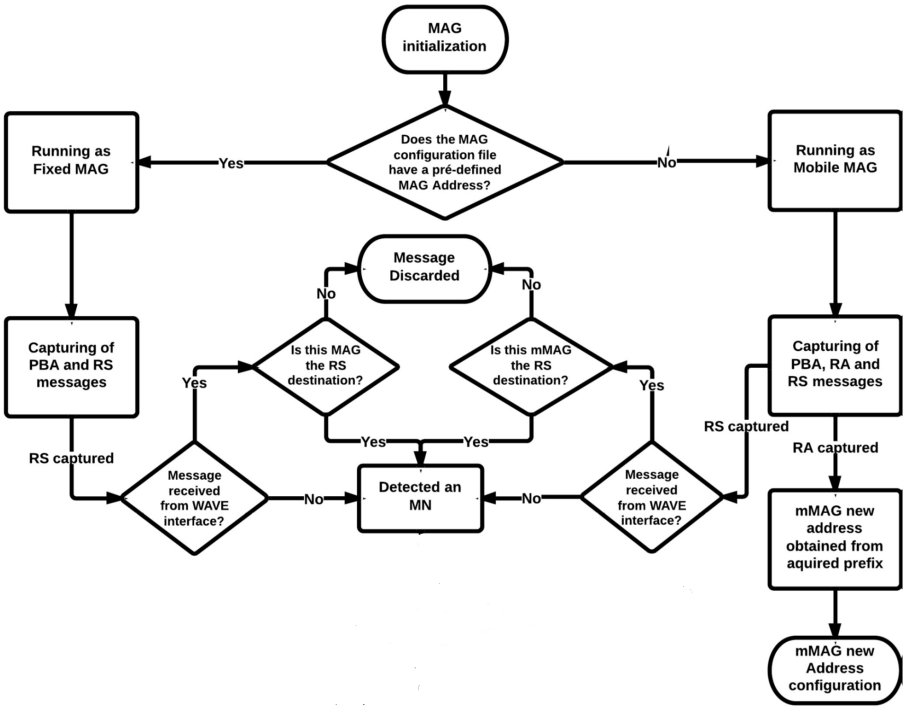


Figure 3.3: MAG and mMAG flowchart based on [6].

When a MN is detected, it means that it is already in the network or it is a new one, and its registration is required, as illustrated in Figure 3.4. If the MN has already a BCE, two different scenarios may be considered: the BCE is definitive and the RS was sent to maintain the session with the refreshment of the BCE, or the BCE was temporary and it will become definitive followed by the creation of an IPv6 tunnel to the LMA. If the MN does not have already a BCE, a temporary BCE is created allowing the LMA to send a PBA with the intent of starting the final process of the registration and the creation of the definitive BCE.

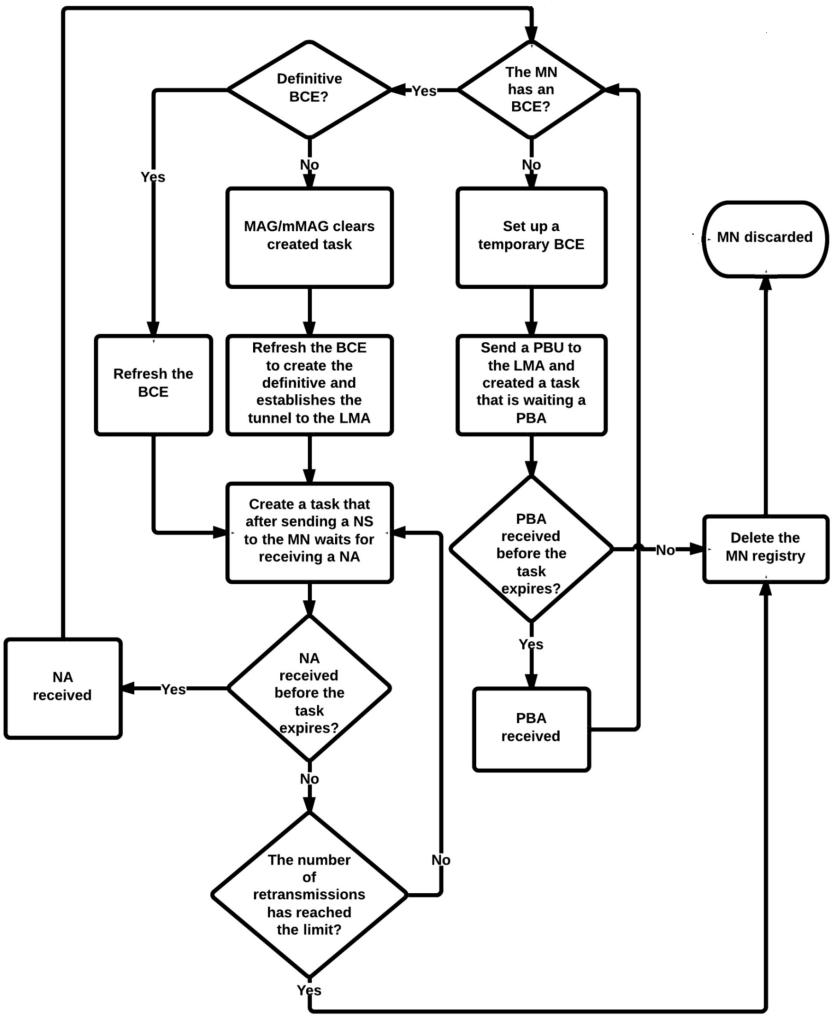


Figure 3.4: MAG and mMAG registration flowchart based on [6].

Before introducing the current state of the actual framework that served as starting-point for the work developed in this dissertation, it is important to explain the capability of abstraction of the N-PMIPv6 that allows a multi-hop scenario. As shown in Figure 3.5, with this abstraction, when the N-PMIPv6 is running in all entities, the mMAG1 will act like a normal MAG in the view of mMAG2, with the creation of a tunnel between the LMA and the mMAG1, and the mMAG2 will act normally as a mMAG.

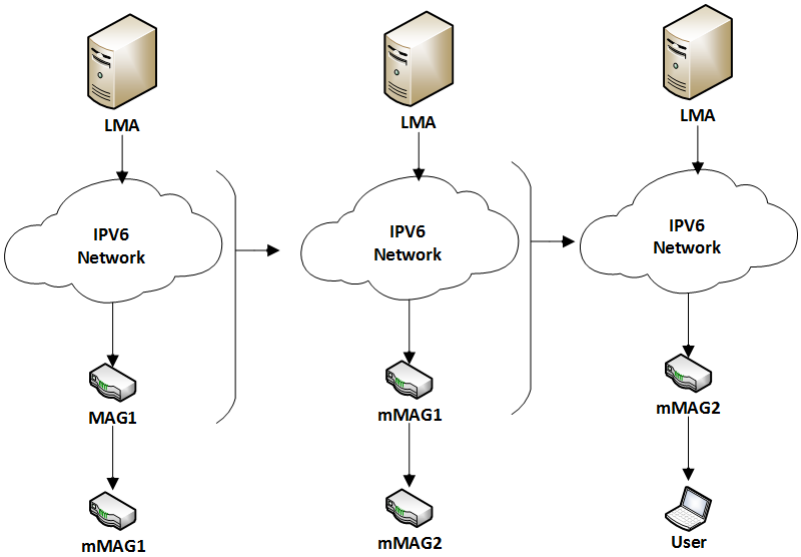


Figure 3.5: Network abstraction based on [6].

3.2.1 Multihoming architecture and framework

Figure 3.6 presents the overall architecture proposed in [8] for the MH approach in a VANET. This architecture takes into consideration an optimized load balancing mechanism for the traffic division between all available PoAs. This architecture is presented in Figure 3.7: it presents the work developed in [8] to assure MH in the VANET, where the LMA represents the Operator Core Network, the MAG represents the Mobile Access Networks Operator and the MH user represents the End-Users Mobile/Fixed Terminals. Each entity has a set of sub-entities that operate the VANET:

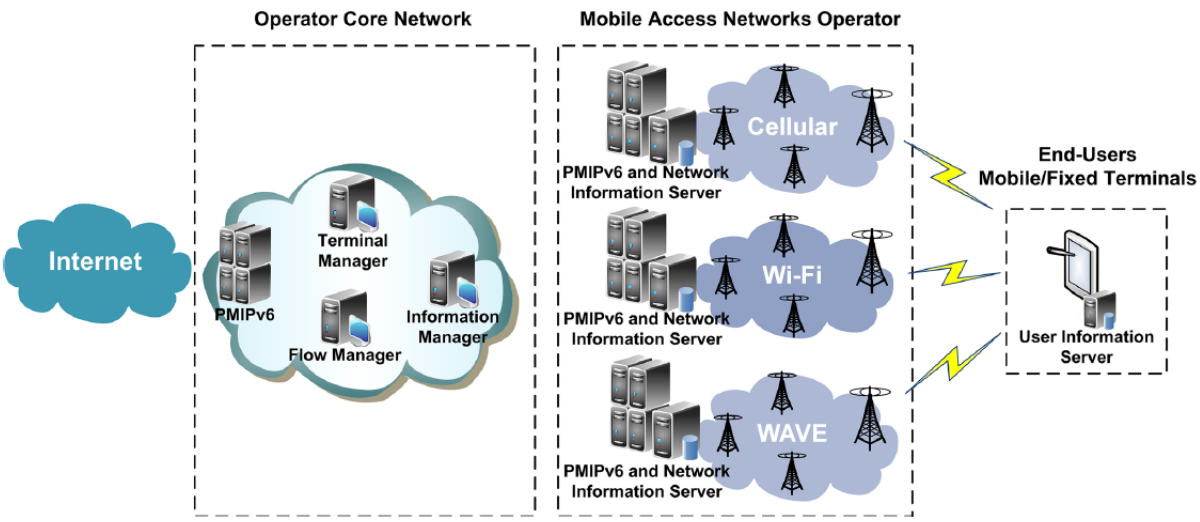


Figure 3.6: MH architecture based on [8].

- **PMIPv6** represents the mobility protocol running in the different entities.

- **Terminal Manager** is responsible for managing the user interfaces. One of the challenges was the development of a mechanism where, in a MH scenario, a user would have one identifier, correspondent of the Media Access Control (MAC) address of each connected interface from the same user. Therefore, [8] proposed the creation of a Terminal Manager that, supported by an UCE, contains information about each connected interface, being possible to associate different connections to the same end-user.

- **Information Manager and Flow Manager** Their primary responsibility is to assure the correct and best MH scenario. To do so, they take into consideration all information from the connections and from the traffic itself, e.g. preferred PoAs, available throughput for the best load balancing mechanism. At the Flow Manager, the FCE was introduced that contains the information between a specific flow and the end-user.

- **Network information server** is responsible for providing to the Information Manager the required information about the state of the access network.

- **Cellular/Wi-Fi/WAVE** Access networks where the user can connect to join the VANET.

- **User Information Server** also known as Connection Manager, will be explained in more detail in section 3.3. It is responsible for providing the Network Information Server with the needed information about the end-users terminal such as the Radio Signal Strength Intensity (RSSI) and achieved throughput. It is also responsible for storing and providing useful data about the users terminal.

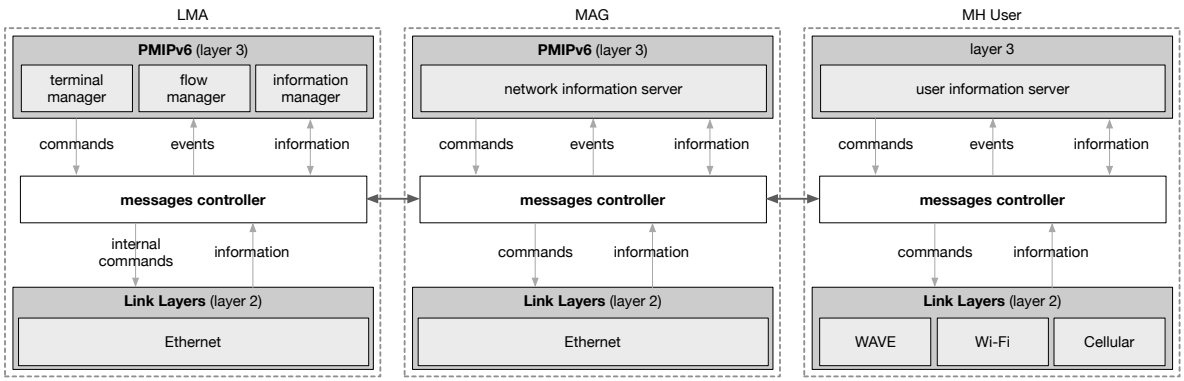


Figure 3.7: MH framework based on [8].

3.2.2 Internet support (IPv4 over IPv6)

One of the main challenges faced in [8] was the possibility of providing IPv4 Internet access to an end-user connected to an OBU, due to the fact that the implementation based on the N-PMIPv6 protocol only provides IPv6 support. To overcome this situation, [8] proposed an IPv4-in-IPv6 tunneling system connecting the LMA directly to the OBUs, as illustrated in Figure 3.8. With the configuration of a Network Address Translation (NAT) server at the LMA, it is possible to create, in point-of-view of the Internet, a unique user that in reality represents all VANET networks, so the LMA is responsible for forwarding the Internet packets in case of downlink and to process the request from the end-user in case of uplink.

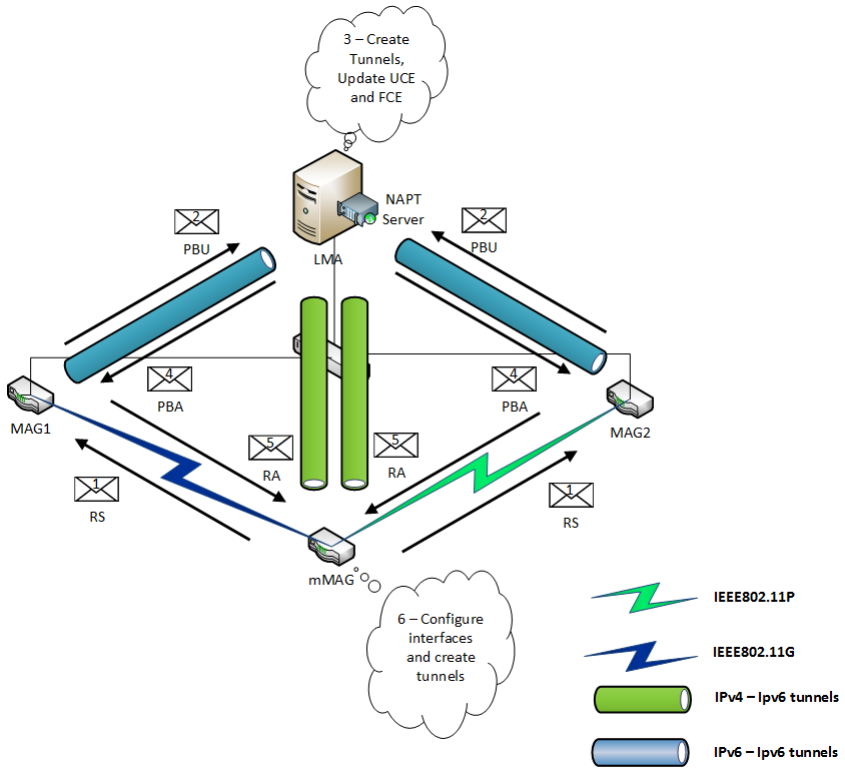


Figure 3.8: IPv4 over IPv6 tunnel creation

3.2.3 Uplink and disconnect messages

Some work developed in [4] was the inclusion of an uplink operation mode and disconnect messages.

Uplink management

At this point, in an uplink scenario, there was no MH available in our VANET. The main work from [4] was to implement an uplink manager, as shown in Figure 3.9, capable of supporting MH in an uplink scenario. The improvements performed in [4] at the already adapted N-PMIPv6 protocol come along with some features like traffic differentiation, multi-hop support, disconnect and reconnect messages following the main principles already applied in a downlink scenario. A simple overview of the uplink manager thread is illustrated in Figure 3.10.

Disconnect implementation

The current disconnect implementation would regularly check the quality signal of each connection from the OBU and, when the signal quality exceeds an established threshold, the next RS message sent to the RSU would start the disconnect process. As shown in Figure 3.11, the RS disconnect signaling message is transmitted through the own connection that will be shut down, not making use of other links in case of MH scenarios. This is one of the problems to be solved in this thesis.

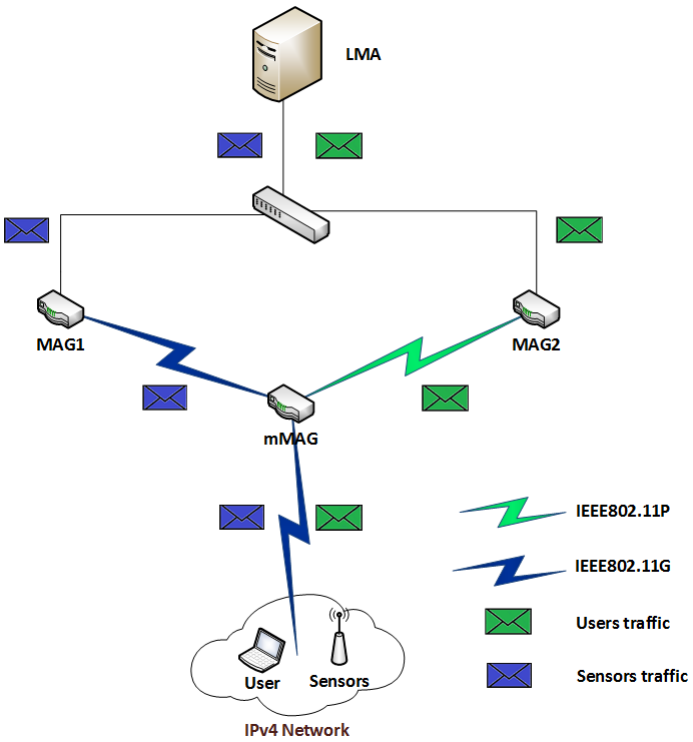


Figure 3.9: Uplink Management in [4].

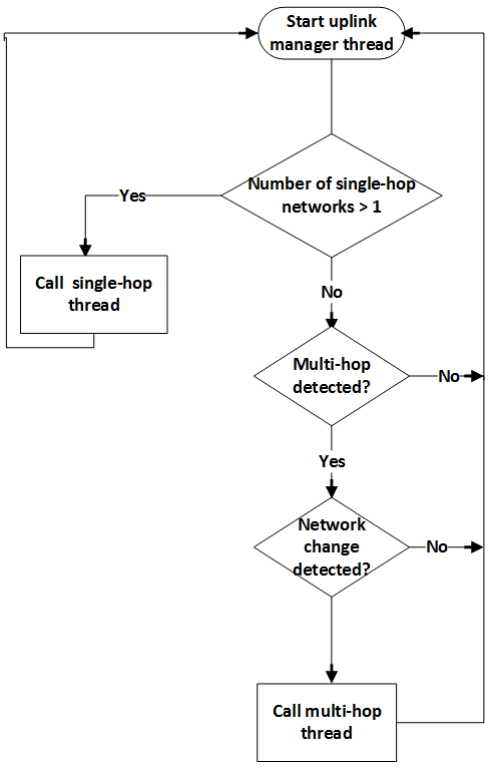


Figure 3.10: Uplink Management thread based on [4].

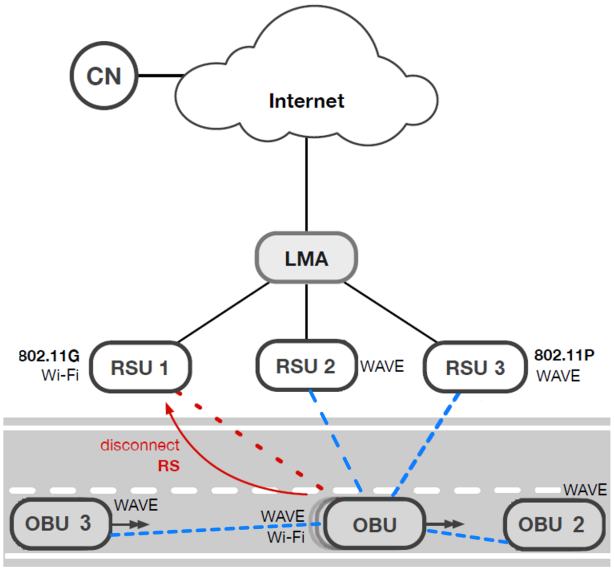


Figure 3.11: Disconnect operation based on [4].

3.3 Connection Manager with multi-technology support

The connection manager is responsible for selecting the best connection to communicate, and it is also responsible for sending the disconnect messages to the LMA. Figure 3.12 presents the work-flow of the currently deployed connection manager [4][7][8][9]. A closer look will be taken for each task except for the cellular operation, as it will not be used in the work developed in this dissertation.

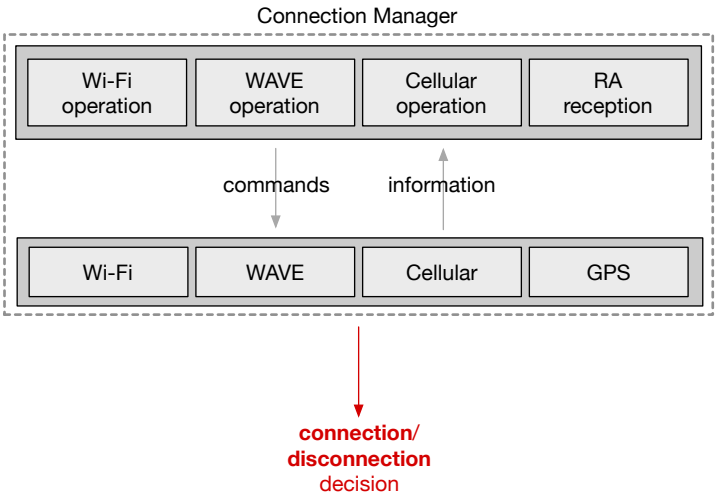


Figure 3.12: Connection manager framework based on [8].

Some of the features of the Connection Manager are the ability to connect to different technologies at the same time, which includes multiple WAVE connections and at least one Wi-Fi connection. It is responsible for the interface configuration, as shown in Figure 3.3, and it manages the routes for uplink and downlink.

3.3.1 WAVE operation

As we already know, the WAVE connection is designed to operate in VANETs, and due to its broadcast behavior, there is no need to exchange control messages or perform any handshake process, allowing the OBUs to connect to different connections of this technology simultaneously. This feature is used by the connection manager enabling the application with MH in the VANET, connecting an OBU to multiple RSUs. As shown in Figure 3.13, a periodic scan is performed in the connection manager to identify all the available WAVE connections in the surroundings. After that, it checks if the PoA under verification has already a connection established with the OBU. If not, it analyzes the signal quality. If it is suitable to create a connection, a RS message is sent to finalize this registration process. If the PoA has already a connection to the WAVE interface from the OBU, it can update the RSSI and send an RS message to maintain or disconnect the established connection, or it can also change the default route to the WAVE connection with the best signal quality at that moment.

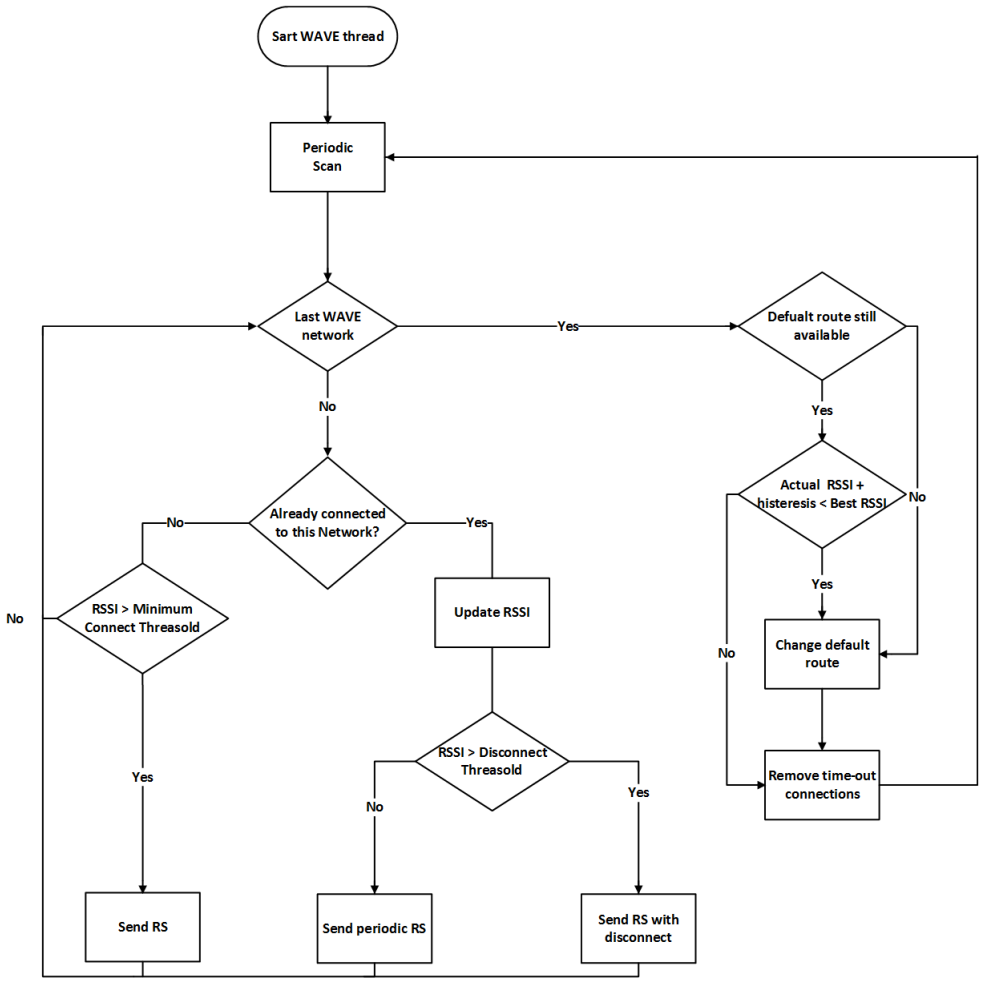


Figure 3.13: WAVE thread flowchart based on [9].

3.3.2 Wi-Fi operation

As shown in Figure 3.14, a periodic scan is performed to find all the available Wi-Fi networks in the surroundings. If some available connection is found, it is essential to verify the velocity of the vehicle, a mandatory process due to the time wasted in the association and authentication process, that makes this technology not the best one for a VANET. However, if the speed is lower than a predefined value, it is suitable to use this technology for the MH scenario. At this point, the next step is to verify if the mMAG is already connected through a Wi-Fi connection, and this can have two different outcomes. If it is already connected through Wi-Fi, it is necessary to check the connection quality: if the connection is good, i.e. higher than a specific threshold, a RS message is sent, signaling that the network should use this Wi-Fi connection as the default route; or if it is in the presence of a WAVE connection simultaneously, it should instead use this one as the default route. On the other hand, if the connection quality is lower than the predefined threshold, there is the need to perform another scan to detect a better connection. Finally, if the mMAG is not yet connected through a Wi-Fi connection, the connection manager checks all the available PoAs of this type and selects the best one to establish a connection through a RS message.

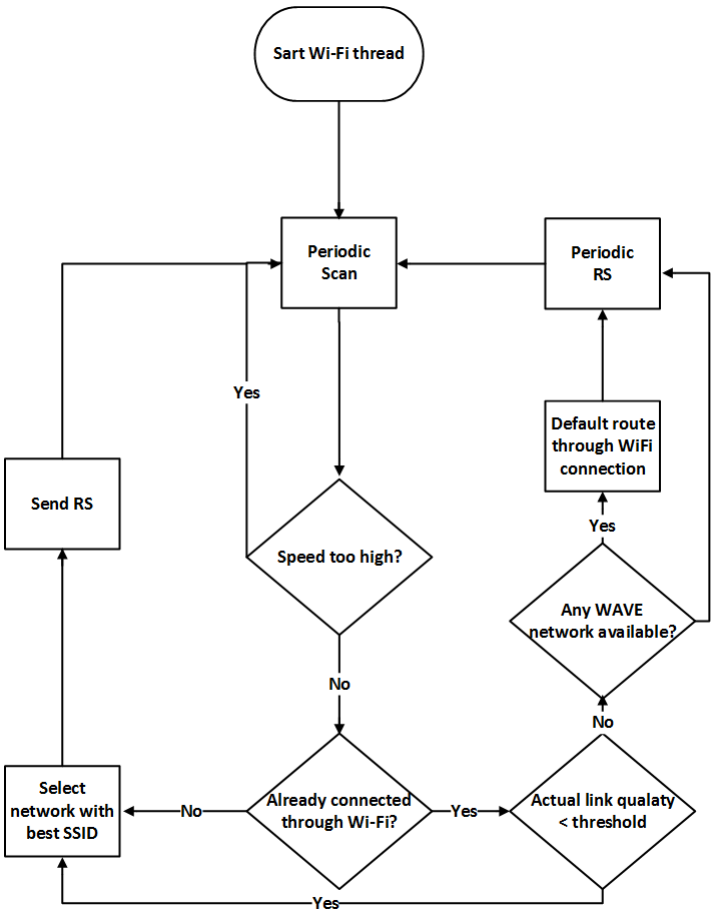


Figure 3.14: Wi-Fi thread flowchart based on [9].

3.3.3 RA reception

As shown in the previous subsections, the Wi-Fi and WAVE operation modes use RS messages to signal and communicate the desired information to the PoAs. However, there is also the need to capture and process the RA messages sent in the opposite direction of this connection as shown in Figure 3.15. The connection manager handles these messages by verifying if they were destined to itself: if so, the IPv6 address in the respective interface will be configured. This thread is also responsible for the validation and maintenance of the different connections, behaving differently in case the RA message was captured in a WAVE or a Wi-Fi interface.

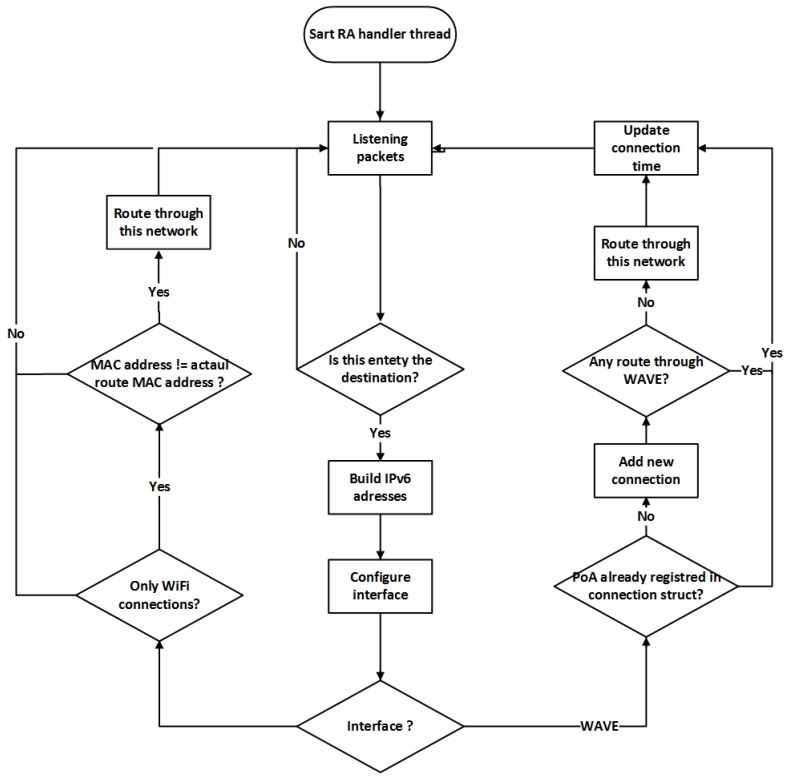


Figure 3.15: RA handler thread flowchart based on [9].

3.4 Network Coding

This section introduces the base encoding and decoding processes developed in [4], which includes a single-technology approach for the NC implementation.

The main goal of using NC is to reduce the losses in wireless connections. The NC process addressed in this thesis follows an SNC approach, where the traffic is split into generations with a pre-established amount of packets, defined by the encoder configurations. A generation in the SNC approach has N+M packets, N original packets plus M redundant coded packets, as shown in Figure 3.16. To recover from packet losses, this approach only needs to receive N from the N+M packets. The results presented in [55] justified the rationale for using this approach in our framework.

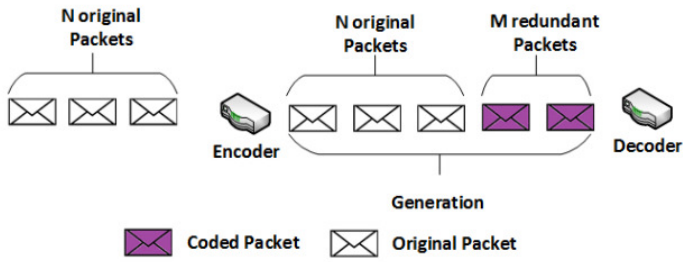


Figure 3.16: SNC approach.

3.4.1 Encoding

For a better understanding on how the encoding process is done, the Algorithm 1 describes its workflow. At the start, the packets are pushed to the encoder, where all packets will receive an ID which identifies them inside a generation. While the ID is lower than the total number of original packets inside the generation (N), the encoder saves a copy of the packet and sends it to the decoder. At the encoder, when it reaches the total number of original packets from a generation, it is time to generate the redundant packets and then send them also to the decoder.

Algorithm 1 Encoder behavior

```
procedure BEGIN
    if PacketId < N then
        Copy packet
        Send packet
    else
        if PacketId < N + M then
            Generate redundant packet
        else Send packets
```

This operation is called by an encoder thread that is running in the RSUs, and it behaves as shown in Algorithm 2.

Algorithm 2 Encoder thread

```
procedure BEGIN
    Create TAP interface
    Calculate coder parameters
    while 1 do
        Read TAP interface
        if Traffic detected and specific port then
            if Coder is not configured then
                configure coder
            Push packet to encoder
            if Multi-hop flag == 0 then
                if Encoder WAVE thread then
                    Read shared memory region
                    Send packets through WAVE
                if Destination Port == X then
                    Read shared memory region
                    Send packets through Wi-Fi
            if Destination Port == Y then
                Read shared memory region
                Send all packets through WAVE
```

The creation of the redundant packets is done using a PseudoRandom Number Generator (PRNG) algorithm, along with the copy of the original packets. The PRNG will generate pseudo-random values, called coding coefficients, which are multiplied with the copy of the original packets saved in the encoder. The results of this multiplications are logically added (XOR operation), thus obtaining the encoded data of the redundant packets, as shown in Figure 3.17. For a correct decoding process, we need to add an extra header between Layer 2 and 3, which has information about the packets sent, including the generation size (N+M), the number of redundant packets (M), the packet ID inside each generation and the seed used for generating the pseudo-random values.

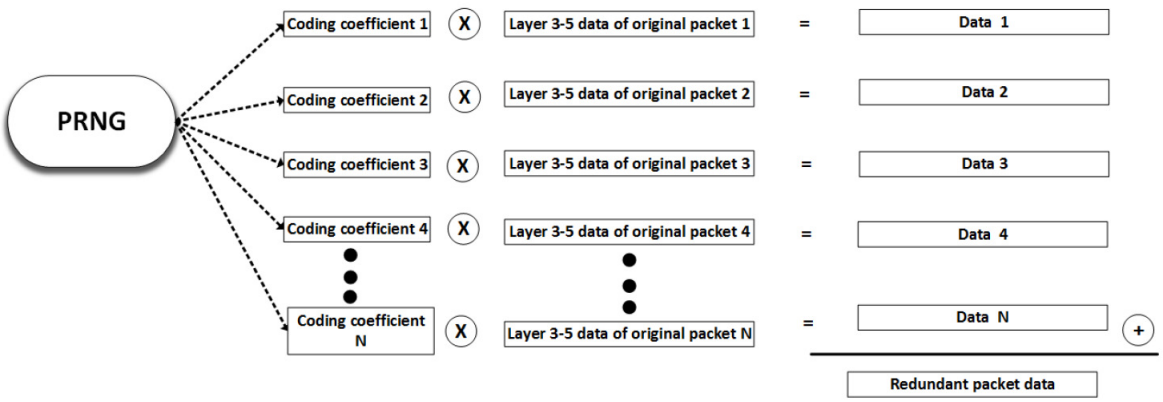


Figure 3.17: Redundant packets generation process.

3.4.2 Decoding

The Algorithm 3 describes how the decoding process is performed. If the packet that arrives at the decoder is an original one, it is copied, and the matrix is updated. If not, this packet is considered as redundant, and we need to verify if it is from the current generation and check if we have all the information needed to start the decoding process. If this applies, the matrix is updated; otherwise, we can proceed to the decoding process, calculating the inverse matrix and send the packets to an upper layer application, where they are handled. This matrix contains information about which packets were received, and if they are original or redundant.

Algorithm 3 Decoder behavior

```
procedure BEGIN
    if Redundant_packet = false then
        Copy packet
        Update Matrix
    else
        if From_current_generation = false then
            Decode
            Calculate inverse Matrix
            Send packets
        else Update Matrix
```

This decoder operation is called by a decoder thread executed in the OBUs, and it behaves as shown in Algorithm 4.

Algorithm 4 Decoder thread

```
procedure BEGIN
    Bind to input interface
    while 1 do
        Read input interface
        if Coded traffic detected then
            if Coder is not configured then
                configure decoder
            if Multi-hop flag == 0 then
                Push packet to decoder
                Read shared memory region
                Send traffic LMA
            if Multi-hop flag == 1 then
                if Destination Port == X then
                    Read shared memory region
                    Send packets through Wi-Fi
                if Destination Port == Y then
                    Read shared memory region
                    Send packets through WAVE
```

3.4.3 Single-technology Network Coding approach

The single-technology scenario is illustrated in Figure 3.18. It represents a distributed approach for NC process in a VANET context. In a downlink scenario, the encoding process is done at the RSUs and the decoding at the OBU. This approach has the potential to reduce the packet losses in the wireless connections, though it considers that an entire generation is sent using the same communication technology. Moreover, since the encoding process occurs at the RSUs, the MH load balancing mechanism is done before encoding and the creation of the generations. This way, all packets inside a generation will be received at the decoder from the same connection.

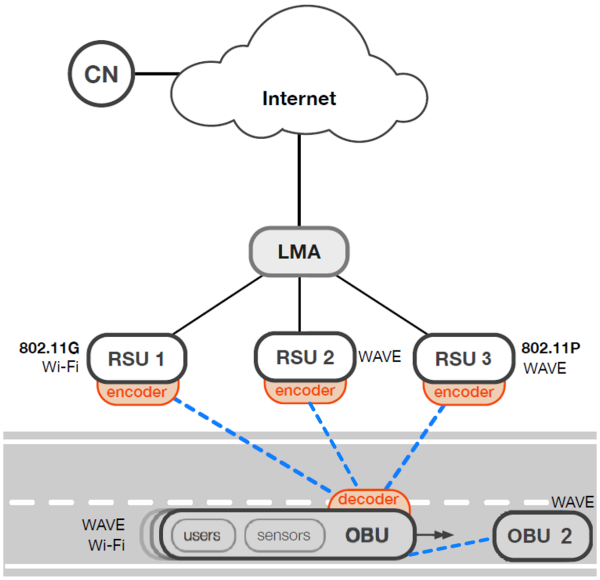


Figure 3.18: Single-technology scenario.

3.4.4 Network Coding configuration algorithms

For an optimized NC process, two different algorithms for the NC configuration were developed by [4]. They aim to optimize some of the critical aspects of the NC having in consideration an established trade-off of other significant elements, like total packet losses or overhead.

3.4.4.1 Algorithm for packet losses minimization

The Algorithm 5 represents an algorithm for packet losses minimization where the best configuration for the NC is established having in consideration a maximum value of overhead introduced in the VANET.

Algorithm 5 Network Coding Algorithm for packet losses minimization

```
procedure BEGIN
    for N = 2 to nLimit do
        for M = 1 to N < M do
            overhead = M/N
            if overhead < OverheadLimit then
                packetLosses = NetworkCoding_PacketLosses (M,N,Input_Packet_losses)
                if packetLosses < actualPacketLosses then
                    actual_Packet_losses = packetLosses
                    save_NC_Configurations()
                    if actualPacketLosses < 0.1 % then
                        save_NC_Configurations()
                        break
```

3.4.4.2 Algorithm for overhead minimization for specific packet losses

This second Algorithm 6 aims to establish a NC configuration with a minimized overhead for a pre-established maximum packet loss value, that is set before the launch of the NC operations. In this case, the main aspect to take into account is the target maximum packet loss, and the overhead is just the one required to achieve this target.

Algorithm 6 Algorithm for overhead minimization for specific packet losses

```
procedure BEGIN
    N = step
    while (M/N) < NetworkOverheadThreshold do
        packetLosses = NetworkCodingPacketLosses (M,N,InputPacketLosses)
        if packetLosses < packetLossesThreshold then
            break
        M++
    actualOverhead = (M/ N )
    N = 8
    for n = 1 to n = 4 do
        M = actualOverhead *N
        if M == 0 then M = 1;
        packetLosses = NetworkCodingPacketLosses(M, N, InputPacketLosses)
        if packetLosses < actualPacketLosses then
            actualPacketLosses = packetLosses
            saveNetworkCodingConfigurations()
        if N = 64 then
            break
        N = N * 2
```

3.5 Summary

This chapter presented some of the base work implemented in the actual VANET architecture. Regarding the mobility and MH approaches, we can see that the N-PMIPv6 protocol

with all the improved features which includes the MH proxy approach, is offering a stable behavior, still presenting a number of challenges that will be addressed in the following chapters. About the NC, a base integration was presented and will serve as a base for development and comparison for the new NC architecture that will be presented and evaluated in the final part of this thesis.

Chapter 4

N-PMIPv6 Improvements

4.1 Introduction

This chapter presents an evolution of the handover approach presented in [4] for the N-PMIPv6 mobility protocol. The previous mechanism did not make use of the different available connections to transmit the mobility control messages, which limited their reliability. The new approach takes advantage of all available connections to choose the best one to transmit mobility control messages, such as the ones to announce the disconnect occurrence.

This chapter is organized as follows:

- Section 4.2 introduces the proposed approach to send the disconnect occurrence through the best available network.
- Section 4.3 presents an overview and main ideas described in this chapter.

4.2 Disconnect Signaling through Multiple Interfaces

The current handover mechanism, illustrated in Figure 3.11, considers that the disconnect message is sent through the same link that has become unstable, and therefore presents a low transmission quality between the RSU and the specific OBU interface. Our goal is to avoid sending disconnect messages through the weak link and make use of the best current available links.

Our approach is illustrated in Figure 4.1: the connection manager sends the disconnect message through one of the stable links that the OBU has to communicate with the LMA through the RSUs.

The following requirements have been taken into account:

- **MH and multi-hop support:** this extension should not affect all the previously implemented features and should allow the correct workflow, like MH and multi-hop.
- **Avoiding overhead:** the proposed approach should try to avoid the introduction of more overhead on the communications inside the network, to avoid increased delays.

The first step to cope with this approach is to create a mechanism able to send the disconnect message. As it is possible to have multiple WAVE links, there is the possibility to

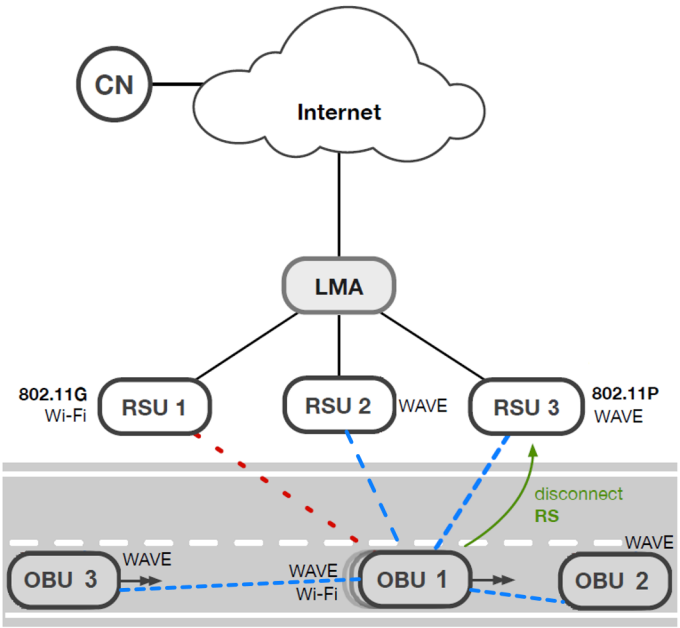


Figure 4.1: Proposed disconnect mechanism (weak link between the OBU and RSU1).

send this message through the best available link or using the broadcast characteristic from this technology, sending the disconnect message through all the WAVE PoAs to the LMA. In our work we decided to send it through the best connection available, since the other possibility would create redundancy as all the RSUs would send the same information to the LMA. Figure 4.2 presents the flowchart of the developed process to send disconnect messages.

Periodically, at the connection manager, the signal quality of each link between its PoA and the different OBU interfaces is evaluated and compared with an established disconnect threshold. If a disconnect needs to be performed, this function is triggered to send the disconnect message. Next, it has to be decided through which link should this disconnect message flow. First, the function checks if the disconnect needs to be performed for a WAVE or Wi-Fi link (notice that Wi-Fi is included here as one example of another technology, although it is not the one tailored for vehicular networks - this is to exemplify a multi-technology approach). If it needs to be performed in a Wi-Fi connection, this means that if the OBU has more available links to send the disconnect message, they are undoubtedly WAVE, since OBUs can only have one Wi-Fi connection to RSUs. So, in this case, the disconnect mechanism will check all available WAVE links and select the one with the best signal quality to send the disconnect message. If there are no available WAVE links, it has no other option than using the actual Wi-Fi connection.

If the disconnect needs to be performed on a WAVE link, the process is different. First, it will check all available WAVE links, since they are more reliable than Wi-Fi ones. If there are more WAVE links, the disconnect message is sent through the one with the best signal quality. The possibility of having other WAVE links that present a lower signal quality is discarded because, if the actual link is starting a disconnect process, another WAVE link with a lower quality signal would already be disconnected before. If there is no other WAVE link, it will check if there is a Wi-Fi one to perform the disconnect. If not, there is no other option than to send the disconnect message through the affected WAVE link.

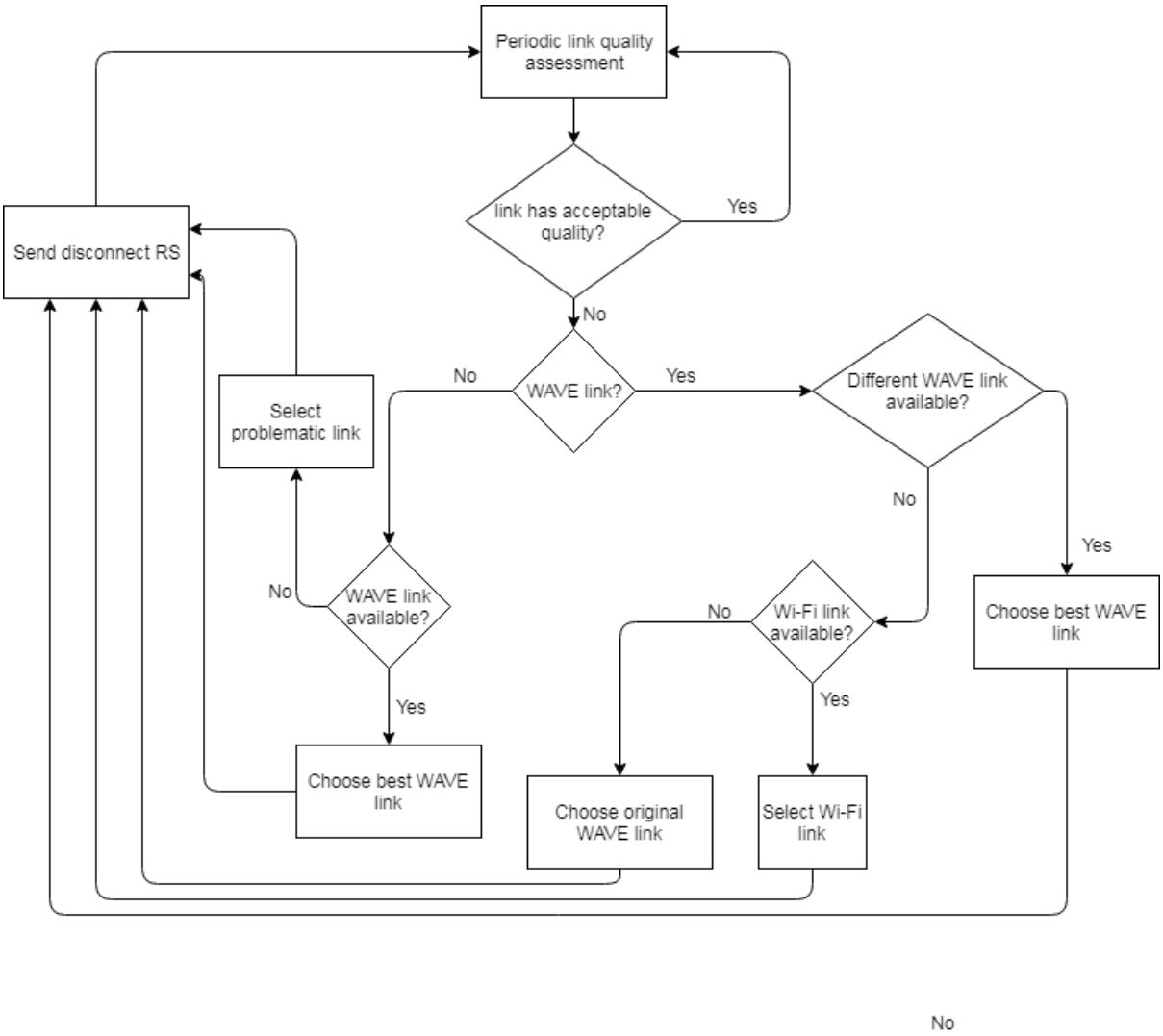


Figure 4.2: Flowchart to choose the technology to send the disconnect messages.

4.2.1 Disconnect threshold value configuration

In the current disconnect implementation, the disconnect threshold value was a pre-established, hardcoded value. This approach is not ideal because hardcoded values can sometimes create malfunctions when running applications in other scenarios, with different entities and different environment interferences. Therefore, a new mechanism was developed to autonomously establish the value of the disconnect threshold when the OBU connects to the network.

Once the connection is established, a value for the disconnect threshold needs to be set. This is accomplished through a predefined number of consecutive samples of the actual signal power; these samples are extracted to the connection manager, from automatic generated files in the OBUs, which stores the information about the interface link quality correspondent to the WAVE or the Wi-Fi connections.

For the calculation of the new threshold, two different equations are used, equation (4.1) for the Wi-Fi threshold, and (4.2) for the WAVE threshold. In these equations DTH means disconnect threshold, n represents the number of samples that were taken, SP represents the individual signal power from each sample, and K represents an empirical chosen value that multiplied with the mean value of the signal power provides the disconnect threshold limits.

$$DTH_{\text{Wi-Fi}} = \frac{\sum_{i=1}^{n} SP[i]}{n} * K_{\text{Wi-Fi}} \qquad [\max Lim_{\text{Wi-Fi}}] \tag{4.1}$$

$$DTH_{\text{WAVE}} = \frac{\sum_{i=1}^{n} SP[i]}{n} * K_{\text{WAVE}} \qquad [\min Lim_{\text{WAVE}}] \tag{4.2}$$

The signal quality for WAVE is presented in RSSI, and for Wi-Fi it is presented in dBm, as the value for the dBm is negative and the base N-PMIPv6 protocol uses its absolute value. The limits for the threshold value are created so that recently established connections that already present a low, but acceptable signal quality, do not set the disconnect threshold to values that will not assure the correct transmission of the disconnect message. These limit values that still represent an acceptable quality of the connection are represented by Lim, which are empirically chosen as a result of real experiments.

4.2.2 Disconnect message format and processing

To avoid introducing more control messages and to make this mechanism the most transparent possible for the normal workflow of the mobility protocol, the message for triggering the disconnect mechanism at the LMA is piggybacked in RS messages between the OBU and the RSU. When a disconnect has to be performed, the RS message will have some minor changes that allow communicating all the necessary information for the disconnect process to be performed. Figure 4.3 presents the RS message in case of a disconnection behaviour. The first 16 bits of the reserved field, represented by *field 1**, which in a normal RS message is used to send the RSSI value, for the disconnect message it is divided to send two different values. The first 7 bits are used to send the RSSI, and the other 9 to send the ID of the RSU that serves the link to shutdown. This addition is crucial because it allows the LMA to know which connection it should disconnect, regardless of the link used to send the message.

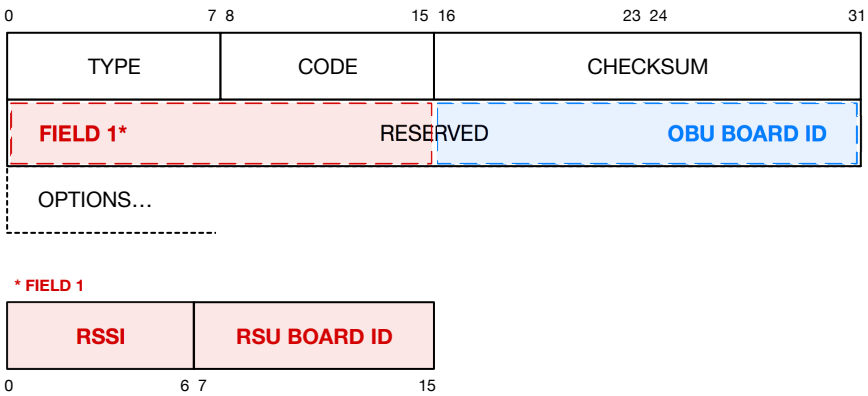


Figure 4.3: RS message format based on [10].

When the disconnect message arrives at the LMA, it will access the UCE and set the disconnect flag to 1. Finally, it can perform the disconnection, and so, update the load balancing rule to send traffic through the still available connections.

4.2.3 Disconnect message in Wi-Fi connections

One of the problems from the previous implementation, developed in [4], and referenced as possible future work, was that the scans to search for a new network in case of a disconnect from a Wi-Fi connection increased the delay momentarily and also affected the available throughput. This increase happened because, when the connection quality is weak, and a disconnect has to be performed, the number of Wi-Fi connections at the connection manager is automatically set to 0 before sending the RS disconnect message, starting to scan for new Wi-Fi links. To solve this situation, a new approach, represented in Figure 4.4, is developed, that changes the operation mode of the connection manager in this situation. This approach avoids that the connection manager tries to scan for new Wi-Fi networks before actually sending a RS message, to avoid loss of downlink packets while scanning for new Wi-Fi links.

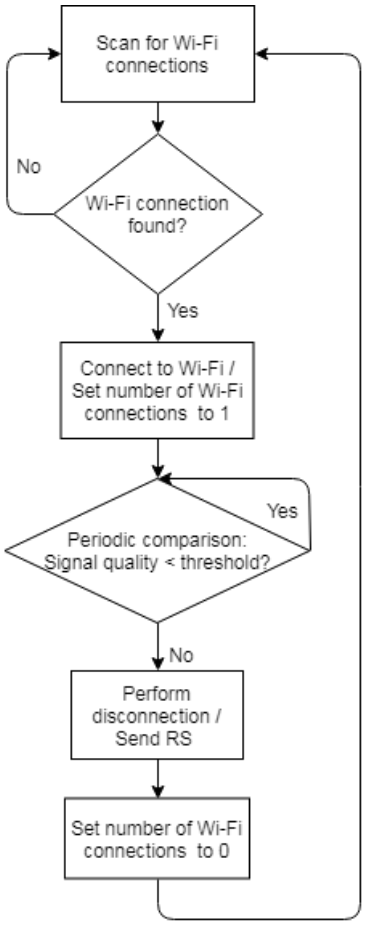


Figure 4.4: Flowchart from the Wi-Fi scan mechanism.

4.3 Summary

In this chapter, the primary objective was to improve the current N-PMIPv6 mobility protocol aiming at loss reduction. The significant step was made at the disconnect mechanism, where this newly developed mechanism takes advantage of all the available connections instead of just using the link to shutdown, increasing the guarantees of the correct reception of the message and its reliability. Several extensions have also been made to improve the Wi-Fi scan mechanism and the disconnect thresholds.

Chapter 5

Multi-Technology Network Coding

5.1 Introduction

One of the main objectives of this dissertation was to improve the current NC approach. This single-technology NC approach currently implemented in the VANET architecture brought some promising results; however, it presents some limitations as it does not consider the use of multiple technologies simultaneously, i.e. the packets from one generation must flow through the same connection, thus limiting the MH feature. Furthermore, the current implementation heavily bounds the available throughput, for two main reasons: first, the encoding is done at the RSUs, which have a limited computation power; and second, because the encoder is a user-level process, instead of a kernel module.

This chapter is organized as follows:

- Section 5.2 introduces the proposed architecture ideas and the challenges;
- Section 5.3 describes the first of two proposed multi-technology approaches;
- Section 5.4 describes the second proposed solution that will run as an integrated feature of the N-PMIPv6 and not as an external application to the mobility protocol;
- Section 5.5 describes how the proposed NC approach behaves in different mobility and MH scenarios, and in case of multi-hop;
- Section 5.6 overviews the main ideas described on this chapter.

5.2 Proposed Architecture and Challenges

The proposed architecture aims to enable a multi-technology approach. The encoding process is centralized in the LMA, in the downlink, instead of using RSUs. This way, the data of each generation can be divided and transmitted through different connections and technologies, which has two major advantages:

- The MH and load balancing mechanisms will be applied transparently to the NC.
- When the NC is applied with the single-technology approach, in case of a disconnection between the OBU and one of the RSUs, all the traffic already received from this connection but not yet decoded will be inevitably lost. With the proposed multi-technology

approach, as the packets flow from a generation through different connections, it is possible to receive from another connection the required information to decode all the packets needed to execute the disconnect process. In general, if one connection has low quality, it is still possible to recover all missing packets through the other connection.

Two different multi-technology NC approaches are developed and implemented, which will be explained in the following sections. Throughout the development of these new approaches, a number of challenges aroused, such as: how should the NC capture the incoming traffic for the encoding process, the need for further packet manipulation to ensure the delivery of the encoded data, how to deal with the MH and multi-hop process, and if it is possible to increase the available throughput limitation created by the single-technology NC application.

5.3 Multi-technology Approach

The first approach consisted only on bringing the encoding process up to the LMA, instead of being done at the RSUs as illustrated in Figure 5.1. In the downlink, the encoding process occurs at the LMA, creating the possibility to have MH dispatching within each generation. Therefore, multiple RSUs, with diverse technologies, can send traffic from the same generation.

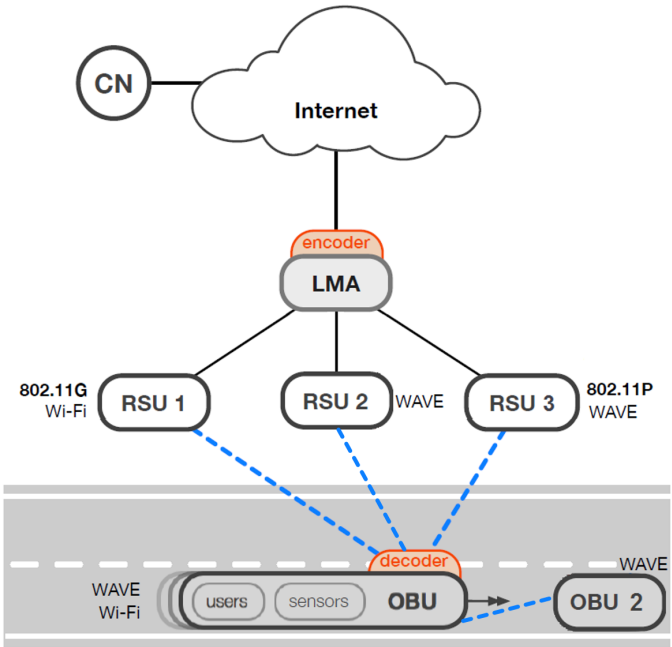


Figure 5.1: Multi-technology scenario.

The required steps for this new approach are presented as follows.

Traffic Capture for encoding

When the downlink traffic arrives at the LMA, it needs to be encoded. The first step is to avoid the kernel routing, allowing the encoding application to process the packets. To do so, a bridge interface is created that serves as master for the incoming traffic interface (e.g. physical Ethernet interface), and it is also associated to a TAP interface which is needed for

the encoding application, which just analyzes and processes the packets that flow through this interface. Figure 5.2 illustrates this process.

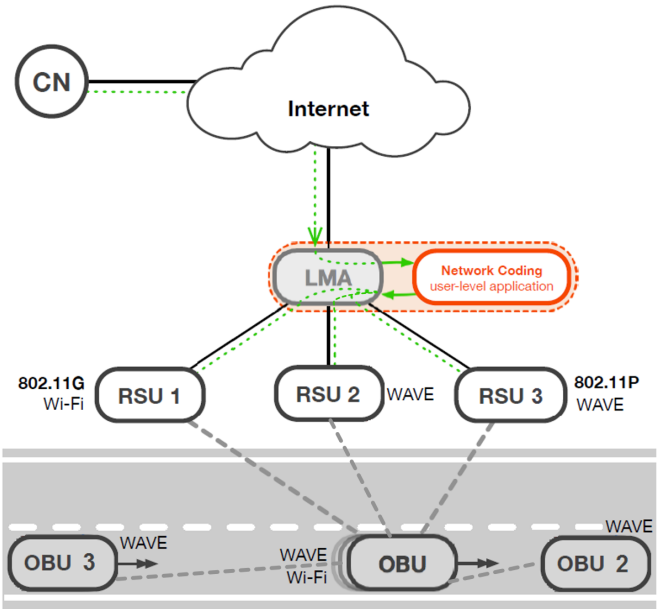


Figure 5.2: First multi-technology NC approach.

Route the encoded packets

The packets will be encoded and sent through the available connections, distributed to a specific PoA; this means that the NC application is responsible for the routing process. The mobility protocol returns the load balancing percentage value and some crucial information to the NC application, so it can route the packets accordingly to this distribution. Therefore, all packets from one generation, original and coded ones, can flow through different connections and technologies, to reach the destination node. The packets will reach the RSUs already with the encoded data, and they will be forwarded to the correspondent OBU.

Packet reassembling for decoding

When reaching the OBU, packets need to be decoded. Before the decoding takes place. This approach has to overcome two situations: reassemble the packets from the same generation arriving from different connections at different bit rates, and deal with out-of-order packets — a situation that will occur since the packets in the same generation are split between different connections.

To overcome both situations, a buffer is created with a dynamic size and capable of containing a specific amount of generations. Such buffer will save the incoming packets until it receives the needed amount of packets (N of the N+M) from one generation, to start the decoding process. At the same time, the incoming packets from each generation will be sorted to handle the out-of-order issue. The size of the buffer determines how long it is possible to wait for packets from one specific generation before discarding it and moving forward to allocate new generations.

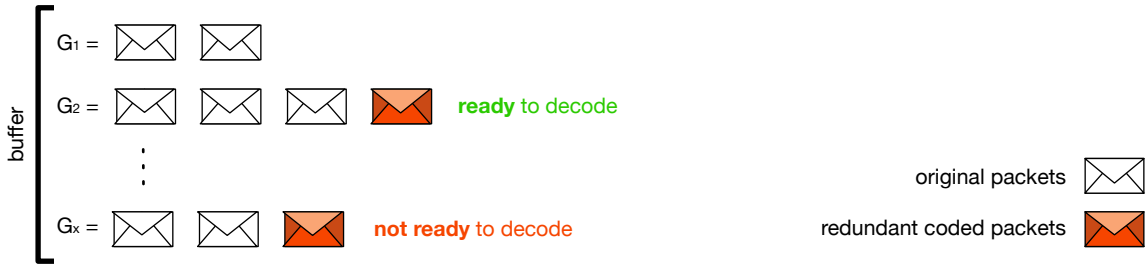


Figure 5.3: Buffer for capturing coded packets before the decoding process.

Figure 5.3 illustrates the decoding buffer where two different situations are illustrated. First, the generation 2 has already all the needed packets to decode by considering that one generation is established by four original packets (N) and two redundant coded ones (M). So this generation will be pushed to the decoder, and generation 1 is shifted to its place on the buffer, releasing space for new generations inside the buffer.

The other situation occurs with generation X. This generation holds the last available position of the buffer since the window size of the buffer is X, so if it has not already N from the N+M packet to be decoded, two situations can occur. First, if a packet from a newer generation arrives in the buffer and there are free slots to allocate this new generation, such as the open space created by generation 2, generation X will hold and wait for more packets from its generation to arrive. Second, if there are no free spaces for the new generation, the oldest one, in this case, generation X, is discarded and all the information belonging to this generation is lost.

To handle the out-of-order issue every packet has an ID indicating its order within the generation, so when they arrive at the buffer, they will be sorted correctly.

5.4 Network coding as an integrated N-PMIPv6 feature

This previous multi-technology approach takes into consideration the main requirements established at the start of the thesis. However, after some evaluation tests, that will be discussed later in Chapter 6, the available throughput was still considerably low. With this in mind, this second approach for a multi-technology implementation was developed, whose goal was to integrate the encoding in the N-PMIPv6 mobility protocol. The developed work to implement this second NC architecture will be explained in the following subsections.

5.4.1 Traffic Capture for Encoding

The idea behind this second multi-technology approach is to implement the NC encoding mechanism the most seamless possible within the mobility protocol. The first step is to identify the incoming traffic and try to process it without changing the routing mechanism in the mobility protocol. The N-PMIPv6 uses *nfqueue* for handling the incoming traffic and analyzing it at the mobility protocol. Then the packet is sent through a verdict function to its destination. By using this verdict function two interesting possibilities arise:

- The possibility to analyze and encode the packet when it is analyzed on the mobility protocol before setting its verdict and route the packet to its destination.

- The possibility to extract and encode only the payload, avoiding the encoding of the IP information.

Since the routing mechanism in this approach is performed within the mobility protocol, it becomes less intrusive on the original behavior from the VANET without the external NC application.

Figure 5.4 shows the base flowchart for capturing, encoding and routing the packets that arrive at the LMA in a downlink flow.

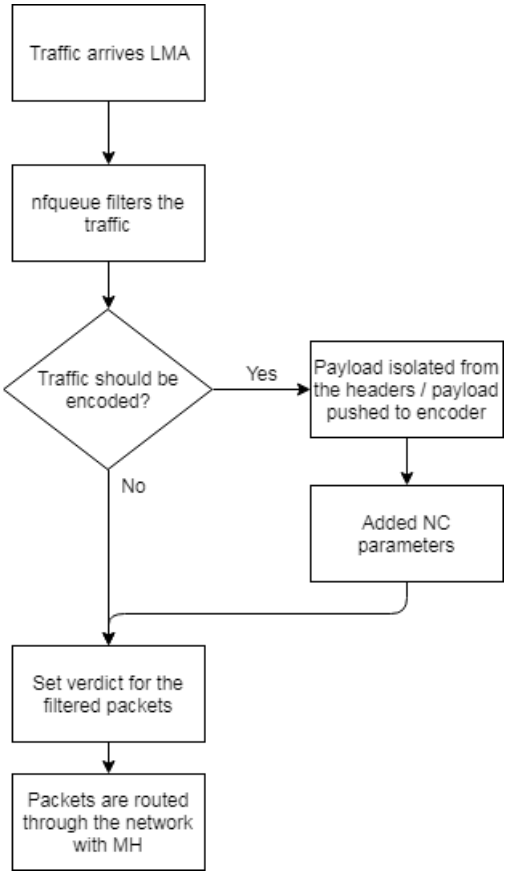


Figure 5.4: Flowchart of the mechanism to capture and encode incoming traffic.

5.4.2 Packet manipulation

After the first step, that allows the packet handling inside the mobility protocol, it is necessary to sort out the next steps. The first step is to separate the payload from the IPv6 headers. After the payload is isolated, it is possible to send it to the encoder process which will encode the data and make a copy of the original data to generate the redundant coded packets.

After the data is encoded, it will be attached to the headers to continue its travel to its destination. But before setting the verdict of this packet, some critical changes need to be made so that it is possible to decode the packet correctly and also to allow the changed packet to be routed through the network.

The first aspect to consider is the packet checksum in layer 4. Since the data is encoded and therefore changed, this packet will present a bad checksum when it is routed throughout the network. The approach to solve this issue is to set the checksum to 0x0000 which, in case of a User Datagram Protocol (UDP) packet in IPv6, results in the intermediate nodes ignoring this field. Another change that is made is the increment of the packet length that is originated by the extra coding information added to the packet, that allows the correct decoding process. The added information, also called coding parameters, is the following:

- nc_{type}: identifies the NC type (SNC, RLNC, etc.).
- nc_{seed}: seed used to generate the same coding/decoding coefficients.
- nc_n: number of original packets belonging to one generation.
- nc_m: number of redundant coded packets belonging to one generation.
- nc_{ger}: generation ID to which the packet belongs.
- nc_{id}: ID of the packet within the generation.

5.4.3 Handling from the redundant packets

Since the NC is running within the mobility protocol, the redundant coded packets that outcome from the combination of the original packets also need to be sent to its destination, allowing the correct decoding of the data in case some original packets are lost. The way used to send these packets is through the help of a dedicated socket. It has to be considered that these packets should also be able to be sorted by the load balancing mechanism from the mobility protocol to have the correct load distribution throughout the available connections. The advantage of using the $nfqueue$ in the mobility protocol is that the redundant coded packets sent by the socket can be intercepted by the $nfqueue$ filter and create the opportunity to process and route the redundant packets by the mobility protocol itself.

Figure 5.5 illustrates the flowchart of the encoding process integrated into the N-PMIPv6 mobility protocol, and also the way redundant coded packets are introduced in the load balancing mechanism.

5.4.4 Traffic Capture for Decoding

To perform the decoding, a program is created to capture and process all the incoming packets from the NC. This program creates dedicated threads to receive the incoming traffic from each available interface to the OBU. Concurrently, another thread is created that is responsible for processing the received packets, inserting them in the buffer and executing the decoding process.

The first threads that are created to receive the incoming traffic set up a dedicated socket to listen on a specific interface from the OBU. All the incoming packets received from the NC are handled with lists that act as sequenced containers. The incoming packets are inserted in the list allowing the packing processing thread to extract these packets from the list for further manipulation. The workflow of these packet capturing threads can be seen in Figure 5.6.

The post-processing thread, illustrated in Figure 5.7, extracts the packets from the list and deletes the entry from the container. Then, the extracted packet is inserted in the buffer

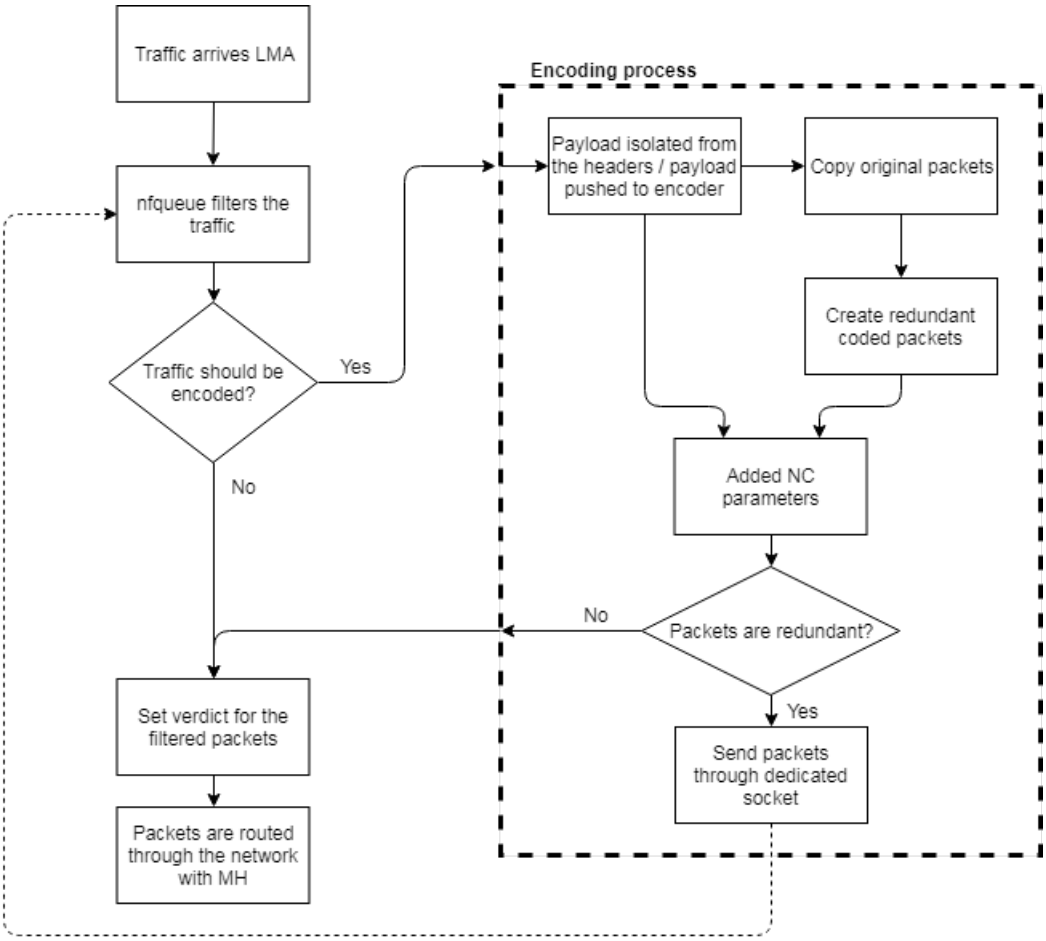


Figure 5.5: Flowchart of the network coding mechanism integrated in the mobility protocol.

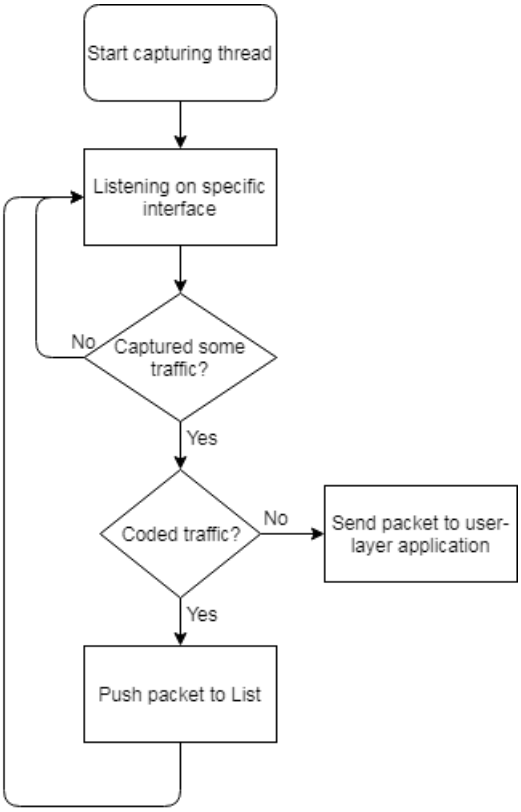


Figure 5.6: Flowchart of the traffic capture thread.

to regroup the different generations. After the decoding process is completed, the packets from each generation can be forwarded to another application or to end-users connected to the OBU.

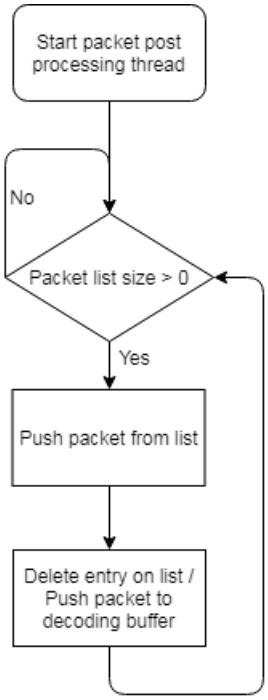


Figure 5.7: Flowchart of the packet post processing thread.

5.4.5 Out of order packet recovery mechanism

In this multi-technology approach, to overcome the two important situations of reassembling the packets from the same generation arriving from different connections at different bit rates, and to deal with out-of-order packets, a buffer is created, such as the one in Figure 5.3, to store the packets and be able to recover their original order.

5.4.6 Configuration file for network coding input parameters

In the single-technology approach, the input arguments for the NC application are input arguments that the user can define when starting the NC program at the encoder entities. In the new approach, since the NC runs as an integrated feature of the N-PMIPv6 protocol, a configuration file is created that is parsed by the running protocol. This allows fast changes on the desired NC behavior without the need to compile the mobility executable every time some changes regarding the NC parameters are made. This configuration file has the following parameters that can be edited:

- nc_{Active}: NC can be activated or not.
- $nc_{InputInterface}$: interface from the incoming traffic that should be encoded.
- nc_{Type}: NC type such as SNC or RLNC.

- $nc_{Algorithm}$: NC configuration algorithm (0 for packet loss minimization, 1 for overhead minimization)
- $nc_{Percentage}$: percentage value that is used by the configuration algorithms correspond to the percentage of the maximum overhead or the maximum packet loss value allowed.

For the decoding program, the parameters are inserted as common input arguments to the program.

5.5 Network Coding in Mobility and Multihoming scenarios

One of the major concerns when designing this new architecture is that the NC application should be transparent to the mobility protocol, the MH, and the multi-hop mechanisms. The fact that the encoding process occurs as an integrated feature of the N-PMIPv6 protocol allowed to achieve interest added capabilities. First of all, the encoding process is set to the actual payload, leaving all the layer 3 and the layer 4 headers unencoded, therefore simplifying the routing process where all the intermediate nodes are able to route the traffic; this is very important also for the multi-hop scenario. At last, it is worth to mention that the main purpose of this second implementation aims to improve the connection throughput that is available when applying NC to our VANET. The fact that the encoding and routing process occurs within the N-PMIPv6 protocol results in a less intrusive possible and more transparent implementation for the NC.

5.6 Summary

The work developed in this chapter created a multi-technology NC approach, able to fulfill its requirements and improve the existent single-technology approach. The first step was to bring the encoder to an upper level, in the case of downlink, allowing the data to be encoded at the LMA instead of the RSUs. Allowing to create multihomed generations, which means that packets belonging to the same generation can flow through all the available connections to reach the desired destination, resulted in a more reliable solution in case of specific disconnection from some RSUs with the OBUs.

After successfully designing and implementing a multi-technology approach, a next step was to integrate it with the mobility approach and increase the available throughput. The second multi-technology approach was applied as an integrated feature of the N-PMIPv6 mobility protocol, which allows to use NC seamlessly in our VANET architecture.

Chapter 6

Evaluation

6.1 Introduction

This chapter presents the real experiments that assess the proposed approaches. It presents the scenarios, tests and the obtained results. The chapter is organized in the following way:

- Section 6.2 describes the equipment used to perform the experiments.
- Section 6.3 describes and discusses the tests related with the N-PMIPv6 extensions.
- Section 6.4 describes and discusses the tests of the NC approach in static scenarios.
- Section 6.5 describes and discusses the tests the NC approach in mobile scenarios.
- Section 6.6 presents the final considerations about this chapter.

6.2 Equipment

The equipment used as LMA is a computer, whereas RSUs, OBUs and CN are implemented in NetRiders - single board computers containing IEEE 802.11p, 802.11b/g/n, GPS, and cellular interfaces, which are presented in Figure 6.1.

Table 6.1 illustrates the equipment characteristics.

Table 6.1: Equipment Characteristics.

Equipment	**CPU [MHz]**	**OS**	**Linux Kernel**
NetRiders	500	VeniamOS 19.2	3.7.4
LMA	1400 (2 cores)	Ubuntu Server 16.04.3	4.14.3
CN	500	VeniamOS 19.2	3.7.4
User	1700 (4 cores)	Ubuntu 12.04	3.13.1

6.3 N-PMIPv6 extensions

To evaluate the performance of the N-PMIPv6 extensions, each component of the testbed runs specific modules from the VANET framework: the LMA runs the N-PMIPv6 mobility

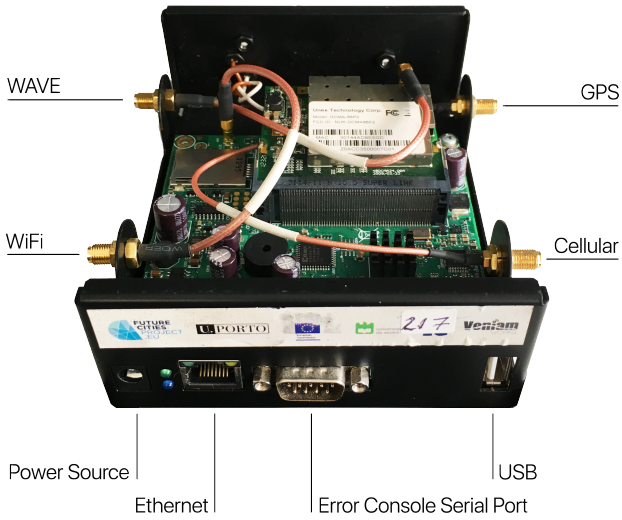


Figure 6.1: NetRider v2.

protocol, the MAGs run the N-PMIPv6, and the mMAGs run the N-PMIPv6 and the connection manager. The traffic is generated in the CN and the OBU is its destination, using the D-ITG tool [56].

The evaluation scenario is presented in Figure 6.2. The experiments will evaluate the N-PMIPv6 behavior in the case of a disconnect link (when considering MH) by comparing the previous approach in [4] with the one proposed in this dissertation. Each test is performed at least 3 times and the variance showed to be very small.

The value for the disconnect threshold is established with the equations (4.1) and (4.2) presented in chapter 4. The number of signal quality samples needed to define the threshold was set 5, while the remaining parameters are presented in Table 6.2. These values have been chosen empirically through a large set of tests in the real network.

Table 6.2: Empirical chosen values for the disconnect equations.

Variable	**Empirical chosen value**
K_Wi-Fi	1.5
K_WAVE	0.4
Lim_Wi-Fi	95 (dBm)
Lim_WAVE	15 (RSSI)

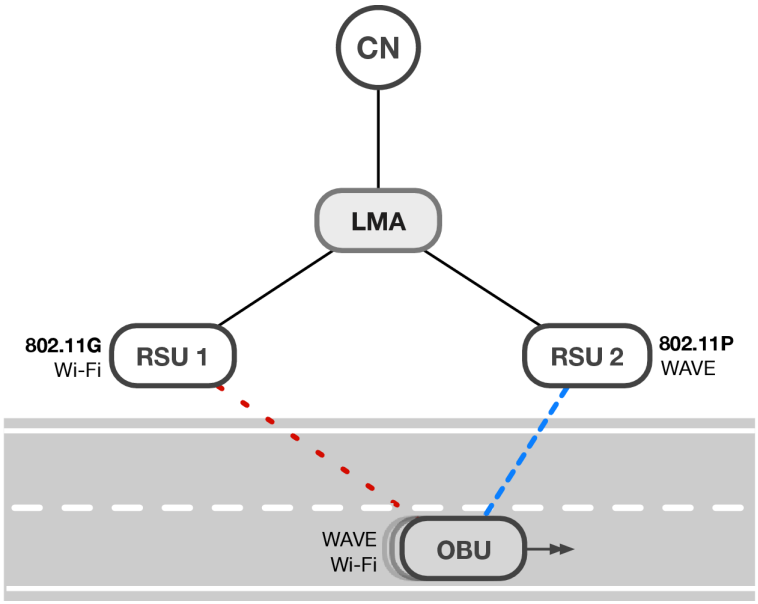
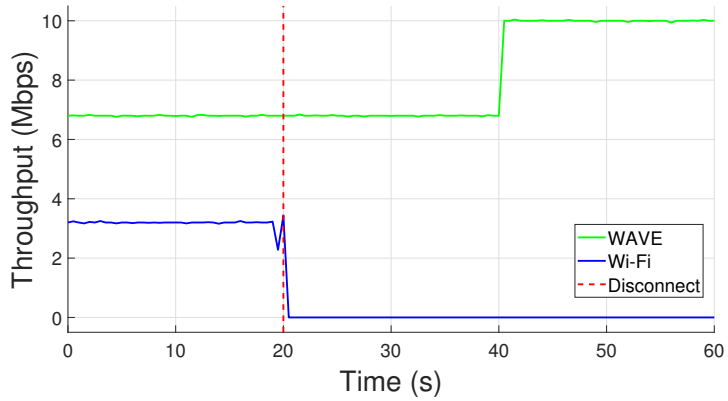


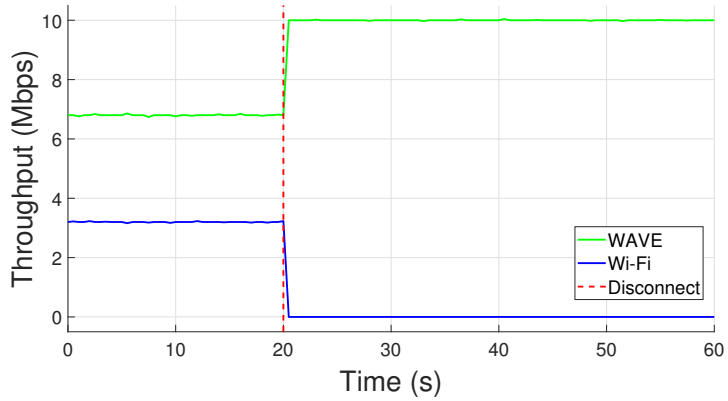
Figure 6.2: Evaluation testbed.

Test 1 : This first test compares the behaviour of the overall network in case of a disconnect occurrence. The CN sends 10Mbps of UDP traffic to the OBU during 60 seconds, and a complete loss of Wi-Fi connection between the OBU and the Wi-Fi RSU occurs at instant t=20 seconds.

Figure 6.3a shows how the previous approach reacts to an abrupt disconnection process, where there is no possibility to send the disconnect message to the LMA - because it was using the connection in use that has been broken. Then, the LMA has no information about the disconnection process, and just after 20 seconds, which is the time needed for the IPv6 tunnel to expire, the LMA recalculates the load balancing rule, therefore recovering the maximum available throughput. In the meantime, the traffic sent to the OBU through the disconnected link is lost. The drop and the small pike slightly before the disconnect will be better explained in Test 3. By observing the behavior of the new disconnect mechanism, illustrated in Figure 6.3b, the disconnect message arrives almost instantly at the LMA because it is sent through the stable connection, allowing the LMA to redirect the traffic to the available connections without having to wait for the IPv6 tunnel time-out.



(a) Previous disconnect mechanism.



(b) Improved disconnect mechanism.

Figure 6.3: Disconnect impact on throughput.

Test 2 : The second test evaluates the delivery ratio throughout the time, and analyzes its impact when a disconnection process takes place. 10Mbps are generated at the CN during 60 seconds, and a complete link loss is forced at t=20 seconds.

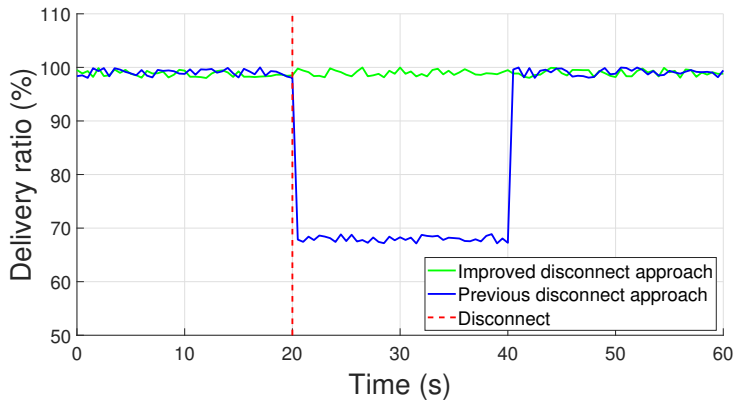
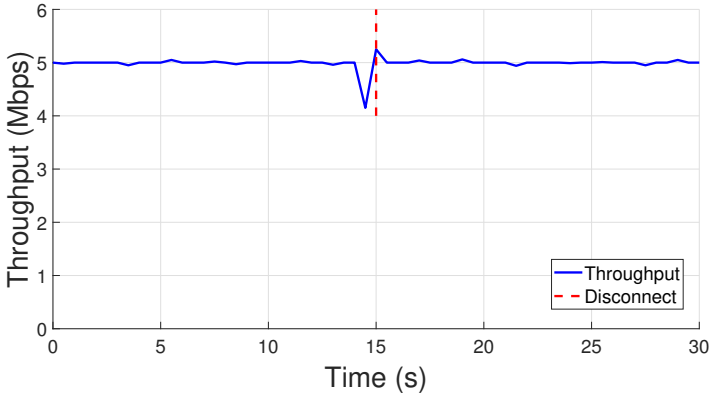


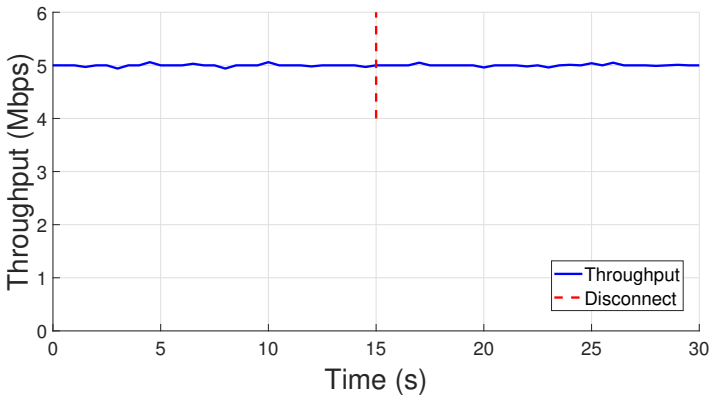
Figure 6.4: Disconnect impact on delivery ratio.

Figure 6.4 shows that, after the beginning of the disconnection process, the previous approach results in a drop in the delivery ratio. This occurs because the traffic flowing through the Wi-Fi connection is not capable of reaching the OBU. The new approach does not represent any loss in the delivery ratio, because the architecture reacts instantaneously to the disconnect mechanism. On the other hand, besides having a significant drop on the delivery ratio, the previous approach also takes an additional time to recover from this situation, due to the time needed to know about the link loss and to execute the load balancing rule, which is directly related with the predefined time-out period.

Test 3 : This third test analyzes the scenario where the link loss is performed at the Wi-Fi interface, but in this test the disconnection will not be so abrupt, also allowing the previous implementation to send the disconnect message, at the right time, to the LMA. This test is performed for 30 seconds, and the link loss occurs at t=15 seconds. The total value of generated traffic is 5Mbps divided through WAVE and Wi-Fi connection using MH.



(a) Previous disconnect mechanism.



(b) Improved disconnect mechanism.

Figure 6.5: Wi-Fi disconnect impact on throughput.

Figure 6.5a illustrates the impact of a link loss in the Wi-Fi interface with the previous approach, resulting in a throughput reduction. This happens because a Wi-Fi scan is performed before the disconnect message is sent. This drop is followed by a small

pike that can be justified by the fact that the Wi-Fi scan mechanism also increases momentarily the delay of some packets that arrived at the LMA, and have not been sent to the RSUs. Before the actual disconnection of the link, when these packets are finally released into the network, it presents this small increase in the throughput. Figure 6.5b presents the results achieved with the new disconnect mechanism. In this case, the Wi-Fi scan is not performed before the disconnect message is sent, and there is no loss in the throughput.

6.4 Network Coding

To evaluate the NC approach, each component runs specific modules of the VANET framework: the LMA runs the N-PMIPv6 and the NC, assuming an encoder role; the MAGs execute the N-PMIPv6, and the mMAG executes the N-PMIPv6, the connection manager, and the NC assuming a decoder role. The traffic is generated in the CN and the OBU is its destination, making use of the D-ITG tool [56], which allows further analysis of the connection, such as delays and packet losses.

The evaluation testbed is presented in Figure 6.6, where the OBU and RSUs are positioned near to each other, approximately 10cm to 20cm, where they stayed stationary throughout the experiments. It is relevant to state that this assessment scenario already presents a packet loss between 7% and 12%, due to environmental factors. This means that the packet loss rates, detailed in the following results, correspond to losses manually introduced at the RSU level, which are added to the base packet loss. Moreover, this testbed features downlink single-hop with MH, using both WAVE and Wi-Fi. Each test is performed 5 times, each for 2 minutes, with 300Kbps of sent traffic rate. The results in the graphics have a 95% confidence interval. With the help of the *netem* command that allows the emulation of network functionalities, it is possible to simulate the manual losses. These manual losses are executed at the RSUs with the following command:

- tc qdisc change dev <interface> root netem loss <lossValue>%

In this command <interface> represents the interface where the losses should be applied, and <lossValue> represents the loss threshold value, in percentage, that should be applied on the selected interface.

Test 1 : The first test evaluates the impact of the overhead (M/N) on the delivery ratio. The encoder configuration (generation size) is computed automatically by an algorithm which returns the best combination of original and redundant packets, resulting in the best packet loss recovery rate for the established limited overhead. The buffer size used at the decoder is 5 generations. The following results expose the effective delivery ratio, taking into consideration different amounts of losses in each connection (IEEE 802.11p and IEEE 802.11g).

From the analysis of Tables 6.3 and 6.4, we observe that a higher overhead yields a better delivery ratio. We can also observe that, by introducing 0% packet losses in the IEEE 802.11g connection link, and 35% losses in the IEEE 802.11p technology, a lower delivery ratio is achieved, rather than introducing 0% of losses in the IEEE 802.11p, and 35% in the IEEE 802.11g. This result is explained by the load balancing feature introduced with MH. In this test, the load balancing uses the following criterion: around 70% of the

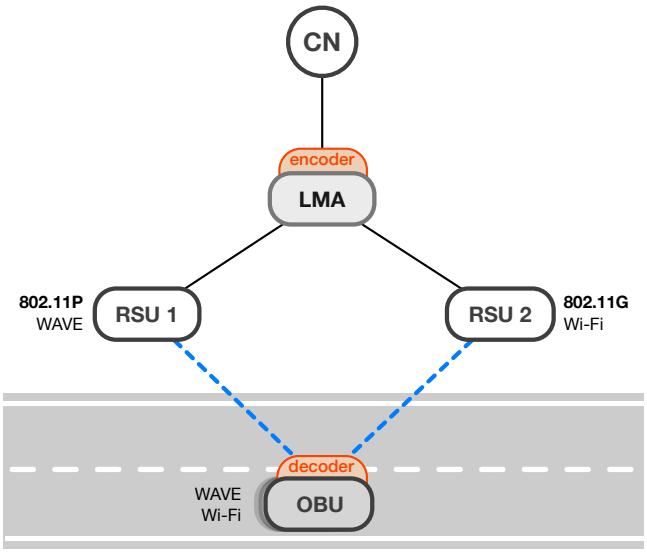


Figure 6.6: NC testbed.

Table 6.3: Delivery ratio with an overhead of 25% and Dynamic generation size.

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	99,99%	99,59%	98,81%	96,42%	94,65%	92,61%	90,39%	88,45%
5	98,70%	97,21%	94,49%	90,96%	90,79%	88,46%	86,53%	85,02%
10	94,82%	91,82%	88,79%	88,82%	86,46%	84,55%	83,04%	80,94%
15	88,07%	86,11%	86,48%	84,38%	82,39%	80,90%	78,59%	76,56%
20	84,14%	83,27%	82,03%	79,96%	78,78%	76,30%	74,17%	72,17%
25	79,48%	78,64%	77,07%	76,11%	73,62%	71,53%	69,23%	67,21%
30	74,73%	74,06%	73,13%	70,03%	69,29%	67,07%	64,39%	62,04%
35	70,96%	69,19%	67,36%	65,57%	63,64%	61,61%	58,73%	55,98%

Table 6.4: Delivery ratio with an overhead of 50% and Dynamic generation size.

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	100,00%	100,00%	100,00%	99,91%	99,44%	97,36%	93,60%	91,48%
5	100,00%	100,00%	99,86%	98,92%	96,12%	92,27%	89,80%	88,24%
10	99,94%	99,78%	98,17%	94,66%	90,77%	87,91%	86,35%	84,88%
15	99,62%	97,43%	92,94%	88,98%	85,94%	84,57%	82,94%	81,04%
20	95,73%	90,99%	87,18%	83,75%	82,64%	80,96%	78,87%	77,05%
25	87,82%	84,82%	81,49%	80,26%	78,82%	76,63%	74,72%	72,93%
30	81,73%	79,02%	77,84%	75,87%	73,91%	72,26%	70,22%	68,75%
35	75,28%	74,11%	72,85%	71,16%	69,40%	67,58%	65,73%	62,42%

traffic flows through the IEEE 802.11p connection, while 30% flows through the IEEE 802.11g connection. Load balancing calculations are performed with a genetic algorithm developed in [57]. Thus, the impact of losing 35% of the packets in the IEEE 802.11p connection is bigger than when the same 35% are lost in a IEEE 802.11g connection.

Test 2 : The second test evaluates the impact of the generation size on the effective delivery ratio. The encoder configurations are selected manually: Table 6.5 contains results of the delivery ratio for a small generation size (12 total packets, 8 original and 4 redundant, equivalent to a 50% overhead); and Table 6.6 contains the results of a big generation size (96 total packets, 64 original and 32 redundant ones, equivalent to a 50% overhead). These results can be compared with those from Table 6.4, which represents the best-case scenario of dynamic generation sizes.

Table 6.5: Delivery ratio with a generation size of 12 (8 normal + 4 redundant packets).

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	99,92%	99,90%	99,56%	98,81%	97,21%	95,37%	93,09%	90,81%
5	99,48%	99,05%	98,14%	96,23%	94,21%	91,97%	89,14%	85,57%
10	98,38%	97,22%	95,15%	92,95%	90,79%	87,36%	84,23%	84,08%
15	96,16%	93,63%	91,67%	89,40%	85,38%	82,55%	82,34%	80,24%
20	91,86%	89,86%	87,56%	83,35%	80,77%	80,76%	78,46%	76,36%
25	87,39%	85,68%	81,20%	78,95%	78,76%	76,62%	74,77%	72,45%
30	81,82%	78,93%	76,99%	76,62%	74,60%	72,43%	70,53%	67,63%
35	75,87%	74,75%	73,57%	71,89%	70,07%	68,32%	66,26%	62,38%

Table 6.6: Delivery ratio with a generation size of 96 (64 normal + 32 redundant packets).

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	100,00%	100,00%	100,00%	99,98%	99,45%	96,19%	91,95%	88,21%
5	100,00%	100,00%	99,91%	98,81%	94,96%	89,93%	86,37%	84,46%
10	99,99%	99,79%	97,97%	93,53%	87,86%	84,40%	82,15%	80,54%
15	99,62%	97,02%	92,01%	85,52%	82,43%	80,10%	78,42%	76,04%
20	95,77%	90,25%	83,37%	79,62%	77,46%	76,05%	73,63%	71,24%
25	87,97%	80,66%	76,88%	74,98%	73,57%	70,82%	68,78%	66,39%
30	77,03%	74,46%	72,16%	70,58%	67,84%	66,04%	63,97%	61,05%
35	70,16%	68,39%	66,53%	64,51%	62,42%	60,35%	58,08%	55,21%

These results show that a small generation size performs similarly to the best-case scenario for high packet losses but, with lower values, the ideal case outperforms the small generation size approach. Comparing the ideal case with the test with a big generation size, we observe that they perform similarly for low packet losses, but the ideal case outperforms for higher values of the applied amount of packet losses. This can be explained by the existence of the buffer at the decoder level. Big generations, with high amount of losses, have a higher probability of not receiving the needed amount of packets to successfully decode all the information inside the operation window (buffer size), decreasing the actual delivery ratio.

Test 3 : The next test evaluates the impact of the buffer size on the delivery ratio. The

encoder is configured with dynamic generation sizes and an overhead of 50%. The results from Table 6.7 correspond to a test with a buffer size of 2, and the results from Table 6.8 correspond to a buffer size of 8. They can be compared with the results from Table 6.4 that has a buffer size of 5.

Table 6.7: Delivery ratio with a buffer size of 2.

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	100,00%	100,00%	99,26%	98,71%	98,03%	96,42%	91,94%	86,78%
5	100,00%	98,79%	98,20%	97,71%	94,46%	90,38%	83,35%	83,82%
10	98,65%	98,03%	96,49%	92,31%	87,78%	81,21%	82,05%	80,85%
15	97,09%	95,16%	89,97%	85,38%	78,97%	79,45%	78,31%	76,48%
20	93,59%	87,46%	82,66%	76,89%	76,94%	75,43%	73,72%	72,04%
25	84,62%	79,68%	74,56%	74,00%	72,59%	70,45%	68,31%	64,28%
30	76,53%	72,01%	71,36%	69,52%	66,24%	64,19%	62,32%	58,07%
35	69,14%	68,21%	66,45%	65,74%	62,88%	59,97%	55,48%	51,69%

Table 6.8: Delivery ratio with a buffer size of 8.

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	100,00%	100,00%	100,00%	100,00%	99,67%	99,28%	95,17%	92,31%
5	100,00%	100,00%	100,00%	99,18%	97,62%	92,71%	90,53%	90,87%
10	100,00%	100,00%	98,26%	95,27%	91,36%	88,67%	88,26%	87,79%
15	99,89%	97,84%	93,74%	88,94%	86,41%	84,96%	85,63%	82,55%
20	96,64%	91,99%	87,72%	84,97%	83,14%	83,08%	81,03%	80,61%
25	90,86%	84,93%	82,73%	81,07%	79,51%	78,84%	77,38%	76,27%
30	83,14%	80,19%	78,74%	77,25%	76,32%	74,49%	73,29%	73,12%
35	77,51%	76,88%	75,32%	74,02%	72,95%	71,47%	69,18%	67,23%

From the results on Table 6.7 and Table 6.8, and by comparing them with Table 6.4, we observe some interesting facts. The impact of increasing the buffer size from 5 to 8 results in a better delivery ratio, but this is only noticeable in tests with high packet losses. If we split Table 6.8 diagonally, resulting in an upper-left zone and an under-right zone, the first one does not show noticeable improvements and the second zone shows an improvement, between 2% and 4%. Table 6.7, on the other hand, allows us to observe that reducing the buffer size from 5 to 2 has a bigger impact on the delivery ratio. If we split Table 6.7 diagonally, it is possible to observe that the upper-left zone has a decrease of about 1% to 3% in most cases, and the lower-right zone has a decrease between 5% and 10%.

Test 4 : All tests performed up to now used the multi-technology approach, that uses the external NC application, thus still limiting the available throughput in the network. The following test evaluates the performance of the integration from the NC within the N-PMIPv6 mobility protocol. The results will be compared with the best-case scenario from the previous test, illustrated in Table 6.4. The test will be performed under the following conditions: buffer size is established to 5; maximum overhead of 50%; and a dynamic generation size. Table 6.9 corresponds to a flow of 300Kbps and Table 6.10

corresponds to a flow of 5Mbps.

Table 6.9: Integrated multi-technology NC delivery ratio with 300Kbps.

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	100,00%	100,00%	99,99%	99,92%	99,48%	97,37%	93,64%	91,46%
5	100,00%	100,00%	99,84%	98,90%	96,14%	92,25%	89,92%	88,25%
10	99,94%	99,80%	98,20%	94,65%	90,76%	87,93%	86,31%	84,87%
15	99,65%	97,46%	92,93%	88,99%	85,89%	84,57%	82,91%	81,01%
20	95,69%	91,02%	87,23%	83,78%	82,69%	81,02%	78,89%	77,11%
25	87,85%	84,76%	81,42%	80,24%	78,84%	76,65%	74,67%	72,91%
30	81,79%	79,08%	77,83%	75,87%	73,87%	72,32%	70,28%	68,78%
35	75,27%	74,12%	72,86%	71,19%	69,48%	67,63%	65,70%	62,51%

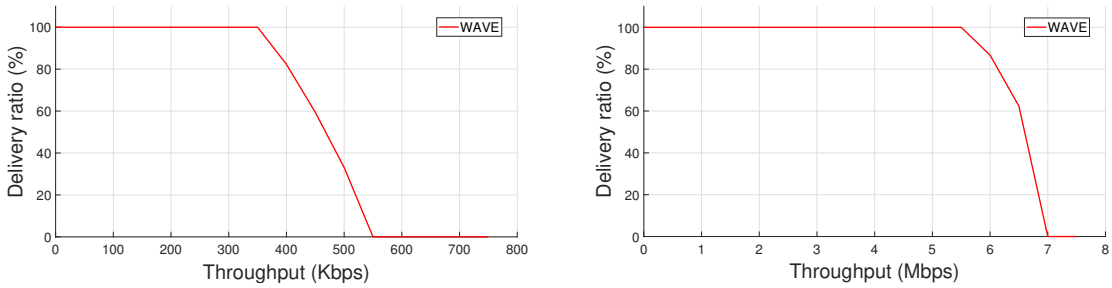
Table 6.10: Integrated multi-technology NC delivery ratio with 5Mbps.

Losses in 802.11p (%) \ Losses in 802.11b/g/n (%)	0	5	10	15	20	25	30	35
0	100,00%	100,00%	100,00%	99,93%	99,51%	97,42%	93,54%	91,52%
5	100,00%	100,00%	99,85%	98,86%	96,08%	92,33%	89,78%	88,16%
10	99,98%	99,74%	98,23%	94,62%	90,83%	87,88%	86,44%	85,02%
15	99,66%	97,48%	92,97%	88,93%	85,95%	84,48%	83,11%	79,95%
20	95,72%	91,03%	87,21%	83,79%	82,71%	80,88%	78,99%	77,17%
25	87,85%	84,79%	81,47%	80,41%	78,83%	76,49%	74,90%	73,06%
30	81,68%	79,07%	77,78%	75,96%	73,81%	72,08%	70,13%	68,59%
35	75,36%	74,04%	72,74%	71,30%	69,57%	67,62%	65,81%	62,27%

Comparing Table 6.9 with Table 6.4, it is possible to observe that they show a very similar behavior related to the effective delivery ratio, which means that the integration of the NC within the N-PMIPv6 protocol does not affect the promising results of the first multi-technology approach negatively. The results from Table 6.10, which test was performed in the same conditions of the results from Table 6.4 but with an increased value of traffic, also show that the delivery ratio remains similar, representing a strong improvement on the amount of traffic that can be sent through a connection with NC.

Test 5 : The next test evaluates the impact of the traffic rate on the delivery ratio, using the two different multi-technology approaches: the one that uses an external NC application and the one that has the NC integrated in the N-PMIPv6 mobility protocol. The test is performed under the following conditions: buffer size is established to 5 generations; manually introduced packet losses of 5%; maximum overhead of 50%; and a dynamic generation size.

Comparing Figure 6.7a and Figure 6.7b, it is clearly observed a major improvement on the available throughput with the integrated NC approach. The external NC approach, shown in Figure 6.7a, starts to have a drop on the delivery ratio at values close to 350 Kbps. However, a similar drop in the delivery ratio with the integrated NC approach occurs at approximately 5.5Mbps, as illustrated in Figure 6.7b. This increase occurs because the packets are processed faster at the LMA, without the need of having an external application that is also responsible for routing the packets.



(a) External NC approach.

(b) Integrated NC approach.

Figure 6.7: Throughput impact on delivery ratio.

Test 6 : The following test evaluates the performance of both multi-technology NC architectures by comparing them with the single-technology approach. This test compares the delay introduced by the NC in the normal workflow of the current mobility/multihoming framework. The traffic is sent similarly as in the previous tests, with different generation sizes and different buffer sizes represented by `BS`. the overhead is set to 50%, and the introduced packet losses are 10% in each connection. `st` represents the single-technology, `mt1` represents the first approach of multi-technology, and `mt2` represents the integrated approach of multi-technology NC.

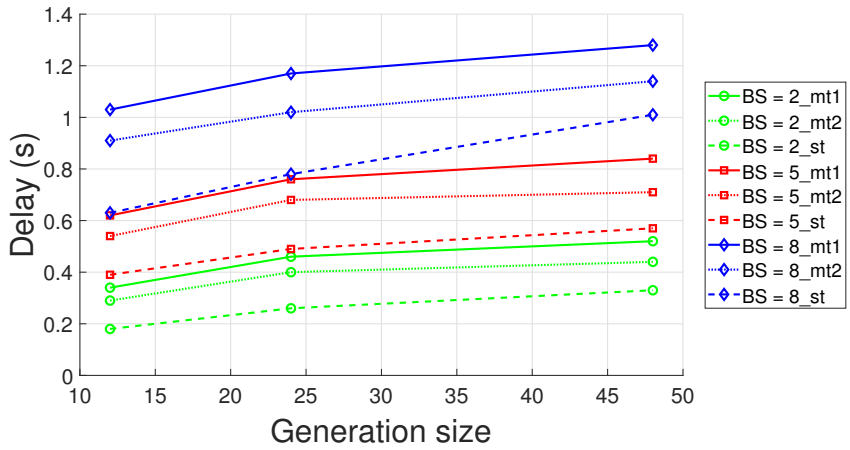


Figure 6.8: Generation and Buffer Size (BS) impact on delay using single-technology and multi-technology approaches.

From the analysis of Figure 6.8, we observe that the multi-technology approaches, in equivalent test conditions, present a higher delay when compared to the single-technology approach. This can be justified by the existence of the buffer in the multi-technology approach, needed to receive information related to the same generation from different technologies and connections, which also features an out-of-order recovery mechanism. In the single-technology approach, the decoder receives the packets from one generation always by the same technology and the same connection. Between both multi-technology implementations, `mt1` and `mt2`, there are also some differences: the integrated NC ap-

proach in the N-PMIPv6 protocol presents a small decrease of the delay, which is justified by the fact that at the encoder the packet does not need to be pushed to an external user-level application to be encoded and routed, which increases the delay.

In all three situations, the increase of the generation size results in an increase in the delay, since the decoder needs to receive more packets to go on with the decoding process. At last, it is also possible to observe that the increase on the buffer size also increases the delay, which is justified by the fact that a bigger buffer size allows the generation to stay longer at the buffer to receive all the needed packets, in order to start the decoding process.

Test 7 : The last test compares the effective delivery ratio between both architectures. The traffic rate is set to 300Kbps to allow a fair comparison between both architectures, where it is used a dynamic generation size, an overhead of 50%, and a buffer size of 5. In each test the value of manual losses in both technologies is the same, i.e. results with 15% of packet losses represent 15% of losses in the IEEE 802.11p and 15% of losses in the IEEE 802.11g connection.

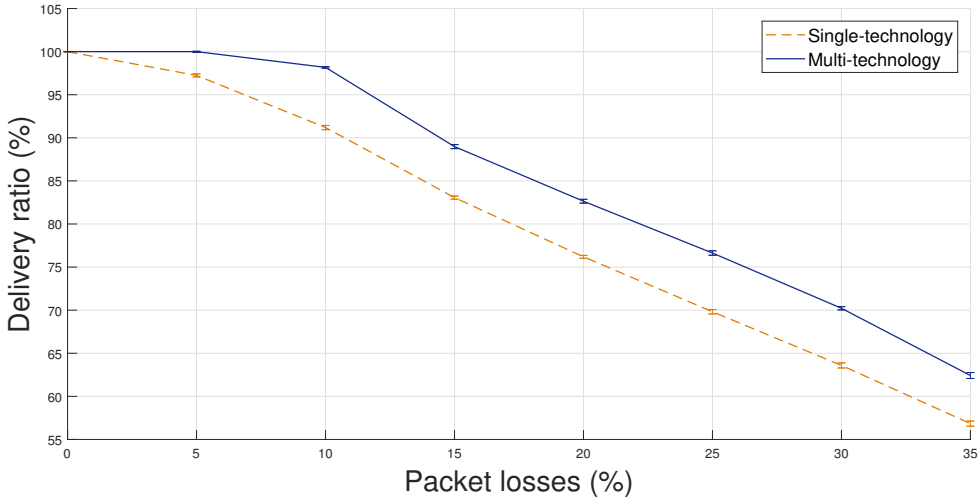


Figure 6.9: Multi-technology vs Single-technology approach impact on delivery ratio.

Figure 6.9 compares the improved delivery ratio between the multi-technology and the single-technology approaches. After a small introduction of packet losses, the multi-technology approach has a better delivery ratio, due to the fact that, in this approach, the generations flow through all possible connections, allowing the decoder to collect information, also from all connections to decode the incoming traffic.

6.5 Network Coding in mobile scenarios

This section evaluates the performance of the multi-technology NC architecture in mobile scenarios, comparing it with the single-technology approach. The following test compares the behavior in case of a disconnection when the OBU is moving inside the VANET, losing one of the available connections to the RSUs. The testbed is presented in Figure 6.10.

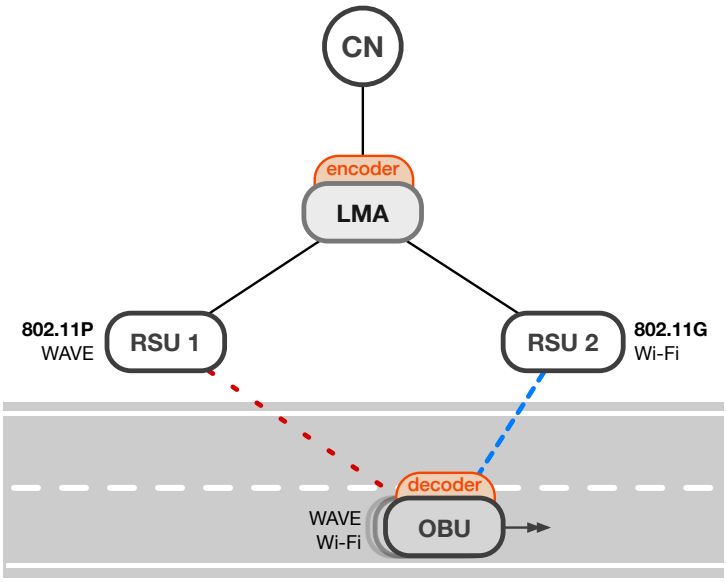


Figure 6.10: NC testbed in a mobility scenario.

This test will compare the delivery ratio when the OBU disconnects from one of the available RSUs. The traffic is sent for 60 seconds, and the link loss is performed at t=20 seconds. The NC has a dynamic overhead determined to comply with the target packet losses, a buffer size of 5, an overhead limited to 50% and a manually added packet loss value of 5% allowing a 100% value for loss recovery. Besides the opportunity to send more traffic with the multi-technology approach, as shown in the previous section, to compare the results in fair conditions the generated traffic will be 300Kbps.

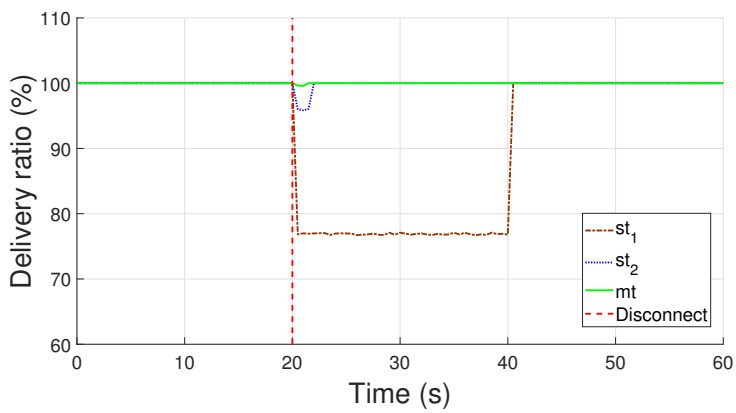


Figure 6.11: Delivery ratio with Multi-technology and Single-technology NC approaches.

Figure 6.11 shows an improvement in the delivery ratio in case of a link loss. Here two different aspects change the outcome: first, as seen before, in the single-technology approach the disconnect message may not arrive at time at the LMA to inform it from the disconnection, represented by **st1**. If the disconnect message arrives at the LMA, the single-technology approach does not make use of MH, which means that all the information arrived earlier from this specific connection is lost, and the delivery ratio is established when the next data

is received through the stable connection, as shown in `st2`. At last, observing the multi-technology approach, `mt`, it is possible to see that almost all the information is recovered because, besides the fact that a connection link was lost, the redundant coding was transmitted through other connections, creating multihomed generations.

In this previous test, the average delay was calculated to recover each generation for the multi-technology approach. Figure 6.12 shows an increase on the delay for the generations that follow the disconnection process. This happens because the generation will stay longer at the buffer for reassembling the needed amount of redundant data to decode the generation.

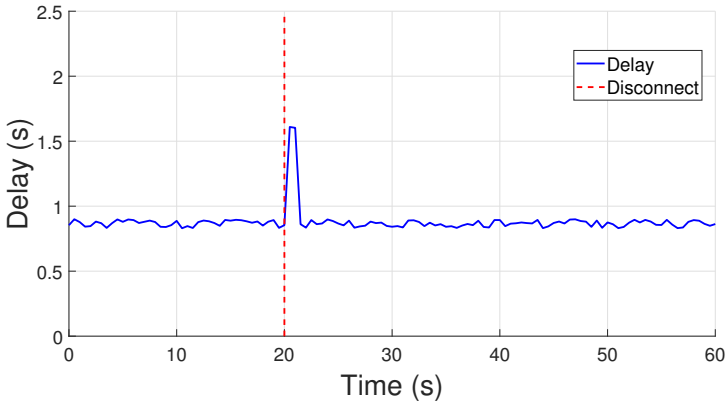


Figure 6.12: Mobility impact on delay with Multi-technology approach.

6.6 Summary

This chapter presented the experiments performed to evaluate the work developed in this dissertation.

The first tests validated the improvements on the N-PMIPv6 protocol, with the main emphasis on the disconnect mechanism. The comparative results showed that the improved disconnect mechanism is more reliable, assuring the reliable establishment of the disconnection process, resulting in a better delivery ratio in the overall performance. It also showed that the throughput remains unaffected when a Wi-Fi disconnect occurs, maintaining the desired throughput value during the disconnect process.

The evaluation tests on the proposed NC approach presented the impact of having different coding related aspects, such as the buffer size, overhead, introduced losses, on the effective delivery ratio. Then, a best use case scenario was established. The tests with the integrated NC approach showed that the delivery ratio was identical to the first multi-technology approach, but presented a significant improvement regarding the achievable throughput. The results also showed an improvement on the delivery ratio when the normal and coded packets make use of multiple technologies when compared to the single-technology approach, despite the increased delay.

The last tests showed how the new multi-technology approach of NC with the N-PMIPv6 extensions behave in comparison with both previous approaches, where it is clear to see an improvement on the delivery ratio, showing the improved reliability of the network when the NC makes use of the MH mechanism within each generation.

Chapter 7

Conclusion and Future Work

This chapter presents the overall conclusions of this dissertation, and addresses the major aspects that should be improved in future work.

7.1 Conclusion

The main goal of this dissertation was to develop and improve the handover process and the NC mechanism in a VANET capable of reducing the networks losses: namely concerning the N-PMIPv6 mobility protocol and the NC integration in a multihomed VANET.

The major contributions of this work can be summarized as follows:

Mobility protocol improvements : extensions were made to N-PMIPv6 mobility protocol where the first step was to develop a new disconnect mechanism to reduce losses in a VANET successfully. This new approach makes use of the MH feature to send, with more reliability, the disconnect message, allowing the LMA to react in a shorter time, routing the incoming traffic through the remaining available connections, therefore reducing the losses in the overall network. This approach was successfully validated by the means of different tests, where its behavior was compared compared with the previously developed approach.

Multi-technology Network Coding : The work developed on the NC had a strong impact on the loss reduction. The first focus was on bringing the encoder to an upper entity, creating so NC multihomed generations which resulted in a better delivery ratio as shown. This approach keeps the mobility-related aspects unaffected, as it was proposed an approach where the NC is integrated within the N-PMIPv6 mobility protocol. This approach increased the available throughput, and experimental results showed that its performance was kept for different NC configurations and scenarios.

7.2 Future Work

This section presents some future work that can be integrated or improved in the current state of the developed work.

Mobility protocol and Connection Manager:

- Disconnect threshold value configuration: In this dissertation, the first approach for an autonomous disconnect value configuration was developed, but it still can be optimized by turning this configuration dynamic during the time the OBU is connected to the VANET.
- Experiments in real mobile environments, with a large scale network.
- Experiments with differentiated traffic, considering both video and other real and non-real-time traffic.

Network Coding:

- Differentiated NC: currently when NC is configured, all the data that needs to be encoded will follow this configuration. It would be interesting to implement a mechanism where traffic differentiation at the LMA could also be submitted to a different NC mechanism, i.e., encoding video with one type of NC and other types of data with another NC configuration simultaneously.
- Encoding and Decoding operations: besides the introduced delay by the buffer that is created to reassemble the packets from the NC, the encoding and decoding process could be optimized to reduce the overall delay.
- Study other possible NC applications: as presented in the related work, many research efforts have been dedicated to NC, some interesting points that could be considered are for example increasing the throughput or improving the current buffer mechanism with sliding window mechanisms.
- Experiments in real mobile environments with both new MH and NC approaches.

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