Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
2019

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QoE de Streaming de Vídeo 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 de Computadores e Telemática, realizada sob a orientação científica do Doutor André Ventura da Cruz Marnoto Zúquete, Professor Auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Doutor Nuno Miguel Abreu Luís, Investigador Auxiliar no Instituto de Telecomunicações de Aveiro.

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agradecimentos / acknowledgements

Chega ao fim este grande capítulo da minha vida. Quero agradecer primeiramente e especialmente aos meus pais, por me darem esta oportunidade, por sempre me terem incentivado e apoiado. À restante família que me motivou neste percurso. Agradecer também à Samantha Oliveira por todo o apoio ao longo deste anos, por ter estado sempre ao meu lado e me ter aturado. Juntamente, ao Filipe Rocha e às demais viagens para a Universidade; aos pequenos-almoços em conjunto que davam a energia necessária logo pela manhã. Quero agradecer também ao Diogo Cunha pelos bons momentos e estadias passadas em Aveiro. Agradeço ao professor orientador André Zuquete, coorientador Miguel Luís e professora Susana Sargento pela orientação, ajuda prestada e oportunidade de fazer parte do NAP. Um agradecimento também aos colegas do NAP, obrigado por toda a ajuda. Um obrigado aos restantes amigos pelo apoio no meu percurso académico, e a tantos outros que também fizeram parte dele.

Palavras Chave

QoE, Video Streaming, Multihoming, Vehicular Ad-Hoc Networks, Mobility, IEEE 802.11p, Wi-Fi, N-PMIPv6

Resumo

Com o aumento contínuo do interesse e disponibilidade de redes veiculares, é importante agora estudar a Qualidade de Experiência fornecida por estas redes, que fundamentalmente determina a opinião e a percepção do público geral sobre um dado serviço. O vasto acesso à Internet, a evolução dos equipamentos, como os telemóveis atuais, tablets e computadores pessoais, e o aparecimento de serviços como o YouTube e o Netflix, está a fazer com que o conteúdo mais consumido seja cada vez mais em forma de streaming de vídeo. Quer seja motivado por aplicações de segurança ou comerciais, o streaming de vídeo em ambientes altamente móveis levanta vários desafios.

Esta dissertação avalia a Qualidade de Experiência de técnicas de multihoming, permitindo o uso de diferentes tecnologias de comunicação, como o WAVE e o Wi-Fi, para aumentar a fiabilidade e desempenho de streams de vídeo nestes ambientes. Para além disso, investiga também como é que diferentes mecanismos de rede, como o balanceamento, multihoming e o buffering, e métricas como a taxa de transferência e latência, afetam a QoE observada. Os resultados obtidos levaram à proposta de uma política de divisão de tráfego para aplicações de vídeo baseada em tecnologias de acesso para situações de multihoming, visando uma melhoria da QoE do utilizador. Utilizando o método proposto, os resultados mostram que a experiência do utilizador tem uma melhoria de 7,5%.

Keywords

QoE, Video Streaming, Multihoming, Vehicular Ad-Hoc Networks, Mobility, IEEE 802.11p, Wi-Fi, N-PMIPv6

Abstract

With the ever-increasing interest and availability of vehicular networks, it is important to study the Quality-of-Experience provided by these networks, which ultimately determines the general public perception and thus the overall user adoption. The broad Internet access, the evolution of user equipment, such as smartphones, tablets and personal computers, and the appearance of services like Youtube and Netflix, is leading the user content consumption to be more and more in the form of video streaming. Either motivated by safety or commercial applications, video streaming in such highly mobile environments offers multiple challenges.

This dissertation evaluates the QoE of a multihoming communication strategy, supported simultaneously by WAVE and Wi-Fi, for increasing the reliability and performance of video streams in these environments. Furthermore, it also investigates how distinct network functionalities, such as multihoming load balance, buffering, and network metrics such as throughput and latency affect the overall QoE observed. The results obtained led to the proposal of a multihoming load balance policy for video applications based on access technologies, aiming to improve QoE. The overall results show that QoE improves by 7.5% using the proposed approach.

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Acronyms

AR Access Router
BA Binding Acknowledgement
BC Binding Cache
BCE Binding Cache Entry
BU Binding Update
CoA Care of Adress
CN Correspondent Node
DASH Dynamic Adaptive Streaming over HTTP
DASH-IF DASH-Industry Forum
DSRC Dedicated Short-Range Communication
FCC Federal Communications Commission
FN Foreign Network
FPS Frames Per Second
GPS Global Positioning System
HA Home Agent
HDS HTTP Dynamic Streaming
HLS HTTP Live Streaming
HN Home Network
HTML5 Hypertext Markup Language version 5
HTTP Hypertext Transfer Protocol
IEEE Institute of Electrical and Electronics Engineers
IP Internet Protocol
IPv4 Internet Protocol version 4
IPv6 Internet Protocol version 6
ISO International Organization for Standardization
ISP Internet Service Provider
LMA Local Mobility Anchor
MAC Media Access Control
MAG Mobile Access Gateway
mMAG mobile MAG
MANET Mobile ad hoc Network
MIP Mobile Internet Protocol
MIPv6 Mobile Internet Protocol version 6
MN Mobile Node
MNN Mobile Network Node
MNP Mobile Network Prefix
MOS Mean Opinion Score
MPD Media Presentation Description
MPEG Moving Picture Experts Group
MR Mobile Router
MSE Media Source Extensions
NEMO Network Mobility
N-PMIPv6 Network-Proxy Mobile Internet Protocol version 6
OBU On-Board Unit
OSI Open Systems Interconnection
PBA Proxy Binding Acknowledgement
PBU Proxy Binding Update
PoA Point-of-Attachment
PMIPv6 Proxy Mobile Internet Protocol version 6
PSNR Peak Signal-to-Noise Ratio
QoE Quality-of-Experience
QoS Quality-of-Service
RA Router Advertisement
RS Router Solicitation
RSU Road Side Unit
RTP Real-time Transport Protocol
RTSP Real Time Streaming Protocol
SBC Single-Board Computer
URL Uniform Resource Locator
VoD Video-on-Demand
V2I Vehicle-to-Infrastructure
V2V Vehicle-to-Vehicle
UDP User Datagram Protocol
VANET Vehicular ad hoc Network
WAVE Wireless Access for Vehicular Environments
Wi-Fi Wireless Fidelity
XML Extensible Markup Language

CHAPTER 1

Introduction

1.1 Motivation

With the ever-increasing necessity by people to be and stay connected to the Internet, VANETs have more and more influence and play a more prominent role in society, making this goal more accessible. It is expected that every vehicle takes part in these networks, allowing their passengers to have access to the Internet at all times. Taking into account the content that users consume, the amount of video content is higher than ever, in quantity as well as in quality. According to [10], by 2022, Internet Protocol (IP) video traffic will account for more than 80 percent of all IP traffic. As such, it is essential to guarantee the delivery of this type of content with the best possible Quality-of-Experience (QoE).

However, in a VANET, the QoS requirements needed to achieve high QoE levels are sometimes hard to reach and keep, due to the volatility of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) connections, affecting bandwidth, latency, jitter and packet loss. To handle node mobility, a mobility protocol is required to maintain the required user connectivity, and to take advantage of the multiple access technologies simultaneously, such as WAVE and Wi-Fi, with the use of multihoming.

One of the most important metrics that influence the QoE is the amount and duration of buffering stalls that may occur during video playing. Adaptive streaming became one of the most used video transmission methods for avoiding buffer stalls. As the name suggests, the video quality adapts to accommodate network transmission fluctuations affecting the streaming. As the ability to adapt to the always changing environment is a desirable behavior in a VANET, adaptive video streaming might be a suitable method for video delivery. Therefore, questions regarding this objective arise:

- How does each wireless access technology impacts the video streaming QoE?

- What is the impact of mobility and multihoming simultaneously in the video streaming QoE?

1.2 Objectives and Contributions

The primary goal of this dissertation is to study and evaluate the impact of traffic balancing policies in a multihomed VANET relatively to the QoE of an adaptive video streaming process. As a second goal to look for is to improve that QoE by changing those policies.

In order to achieve these main objectives and answer the previous questions, it was first necessary to study and understand multiple subjects from diverse areas, from the different mobility protocols used in VANETs, to adaptive bitrate streaming techniques, or how the QoE score is given.

Thus, there were multiple objectives to tackle in this dissertation:

- Study the current architecture and implementation of the mobility protocol and multihoming process;
- Study and understand DASH adaptive bitrate streaming technique;
- Considering the underlying multihomed mobility network and the wireless access technologies available, evaluate the performance of adaptive streaming inside this environment, taking into account the different QoS metrics and their influence in the users' QoE;
- Propose traffic load balancing policies for improving the QoE of adaptive streaming;
- Evaluate the proposed improvements, with laboratory and real-world experiments.

1.3 Document Organization

This dissertation is divided into the following chapters:

- **Chapter 1 - Introduction:** presents a motivation for this dissertation and gives some context.
- **Chapter 2 - State of the art:** describes the current state of the art for VANETs, mobility protocols, multihoming and adaptive bitrate streaming in VANETs. It also presents the base architecture that supports this dissertation.
- **Chapter 3 - QoE Assessment:** depicts multiple steps to achieve a VANET scenario, while evaluating the performance impact that each step has on the QoE, in order to define a baseline.
- **Chapter 4 - QoE in Multihomed Environments:** discusses a policy for multihoming load balancing in order to achieve better adaptive streaming, describing the improvements made and presenting and discussing the obtained results.
- **Chapter 5 - Conclusions and Future Work:** provides the conclusions for the work done and suggests possible improvements for future work.

CHAPTER 2

State of the Art

2.1 Introduction

In order to understand the work done in this dissertation, it is essential first to understand the current state of the technologies involved and the work already done. As this dissertation joints various research areas, this chapter will cover topics ranging from VANETs to QoE and will be organized as described below:

- **Section 2.2 - Vehicular Networks:** this section gives insight to VANET networks and its characteristics.
- **Section 2.3 - Network Access Technologies:** the relevant access technologies used in VANETs for this work are described.
- **Section 2.4 - Mobility:** the main mobility protocols described, including their relation and aplications.
- **Section 2.5 - Multihoming:** some multihoming architectures are explained.
- **Section 2.6 - Adaptive Video Streaming:** an overview of the different adaptive video streaming solutions is presented.
- **Section 2.7 - QoE:** in this section the QoE is described.
- **Section 2.8 - Related Work:** contextualizes the work already done in the same field as this dissertation.
- **Section 2.9 - Summary:** this final section analyses the addressed subjects and summarizes their contribution.

2.2 Vehicular Networks

A Vehicular ad hoc Network (VANET) is a specific case of a Mobile ad hoc Network (MANET), where the network is created and maintained between moving vehicles and fixed stations. For a vehicle to be a node on the network, it has to be equipped with an On-Board Units (OBUs), which is responsible for the network connectivity, as well as giving passengers Internet access.

Road Side Units (RSUs) are also deployed alongside the road and are connected to the core network, providing Internet access to OBUs. As such, there are two possible types of communications: V2V communications, where the OBUs communicate between them, and V2I communications, where OBUs communicates directly with RSUs, the infrastructure. These communications are done through the technologies avaialable to both OBUs and RSUs, such as Wi-Fi, WAVE, and cellular.

2.2.1 Characteristics

VANETs have a specific set of characteristics that derive from their intrinsic nature. Some of these are [22], [40], [47]:

- **Global Positioning System (GPS) Availability:** OBUs are equipped with GPS, which can be used to track and monitor the vehicle position and velocity.
- **Nearly no power or computation constraints:** As OBUs are powered by the vehicles' battery, power accessibility is not an issue, and equipping OBUs with better components can allow for better communication or added features.
- **Dynamic Topology:** Since the network nodes are vehicles, which move freely and have variable speed, the network environment has a wide range of scenarios, from very low-density highways to high-density rush hour cities. Thus, there will be more or fewer disconnections depending on the situation, and the network has to cope with these challenges.
- **Large Scale:** This kind of network can easily extend and cover wide areas as more and more vehicles carry an OBU.
- **Predictable Mobility:** Vehicular nodes have, to a certain extent, predictable mobility, as they follow roads or paths. So, with the use of GPS tracking it is possible to infer their possible future positions.
- **Signal Degradation:** In a city environment, due to the possibility of obstacles surrounding vehicles, such as city building and other neighboring vehicles, the transmission signal may be deteriorated and may not even reach its destination.
- **Network fragmentation:** Network fragmentation may occur due to the high mobility of the network nodes and the constant changes in the network topology.

2.2.2 Applications

The following items describe the possible main VANET applications [22][28]:

- **Safety:** With the availability of V2V and V2I communications, messages can be sent to nearby vehicles in the case of accidents or emergency, assisting drivers and reducing the probability of accidents.
- **Traffic management:** traffic-related applications can help with general traffic flow. Knowing the surrounding environment can help in: avoiding traffic congestion, providing ideal itinerary choices, or even help in the garbage collection routine.
- **Entertainment and user services:** These kinds of applications and services are typically used with access to the infrastructure and Internet through the RSUs and

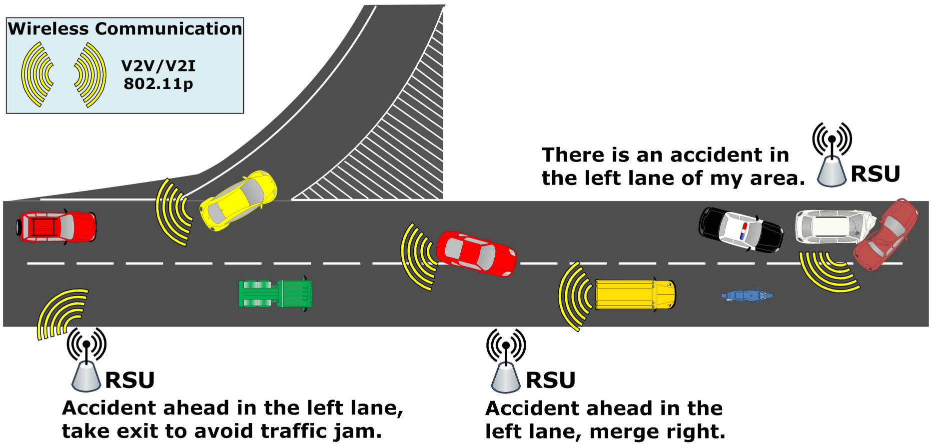


Figure 2.1: VANET accident scenario [2].

are intended to provide the vehicle occupants access to the Internet, increasing their commodity and comfort. Tourism information, online games, video streaming, or even location related advertisement, are some of the possibilities in this whole new world of entertainment. These applications are the least critical ones.

2.2.3 Architecture

In this work a VANET architecture with mobility and multihoming support was used, as illustrated in Figure 2.2, whose main elements are:

- On-Board Unit (OBU), the network element attached to every vehicle. It has communication and processing capabilities, and provides Internet access to its occupants (from hereafter denoted as users).
- Road Side Unit (RSU), a non-mobile element that connects OBUs to the infrastructure. For the particular case of this dissertation, the VANET is composed by two RSUs, one providing access through Institute of Electrical and Electronics Engineers (IEEE) 802.11p (WAVE), and another one through IEEE 802.11g (Wi-Fi).
- Local Mobility Anchor (LMA), responsible for the management of each OBU's binding state. It is responsible for keeping OBUs' location on the VANET map, and for forwarding packets from and to OBUs. This element is also responsible for calculating the traffic division when multihoming is explored.
- User, the end-user inside the vehicle that connects to the OBU communicating with the Internet, e.g. requesting video streams. This is also where the QoE probe is located.

2.3 Network Access Technologies

For wireless technologies in a vehicular environment, WAVE stands out with clear advantages [40], but other access technologies can also be used when accounting specific scenarios. In the following subsections, some of the possible VANET access technologies will be addressed, explaining its characteristics.

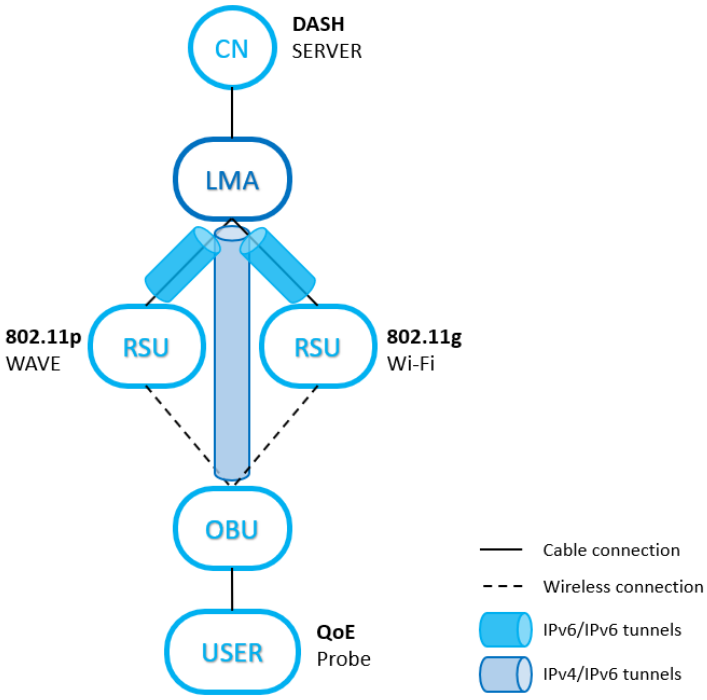


Figure 2.2: VANET architecture used in the experimental scenarios.

2.3.1 WAVE

IEEE 802.11p [21], also know as Wireless Access for Vehicular Environments (WAVE), is a standard specifically designed to accommodate wireless access in Dedicated Short-Range Communication (DSRC). DSRC is a short to medium range communication service allocated in the licensed 75 MHz spectrum band at 5.9 GHz (5.850-5.925 GHz) by the US Federal Communications Commission (FCC) in 1999. Its purpose [33] was to work as an enabler for safety applications and improvements in traffic flow in both V2V and V2I environments. WAVE integrates IEEE 802.11a (with transmission rates from 3 to 27 Mb/s, half the bandwidth assigned in IEEE 802.11a) and IEEE 802.11e (to enhance QoS), making it robust for scenarios with dynamic geographic topology, variable vehicle density and a high number of link failures. Moreover, it does not use any association process, which enables to benefit from very short opportunities of communication.

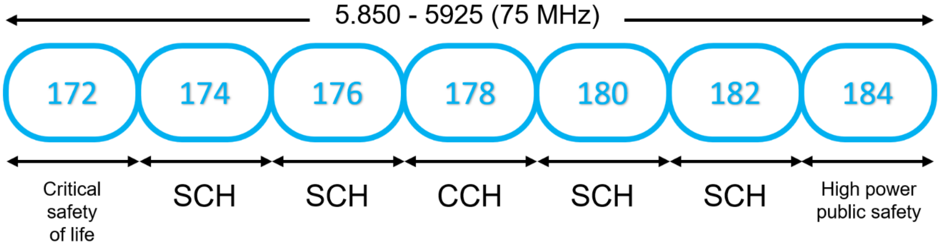


Figure 2.3: DSRC band based on [33].

2.3.2 Wi-Fi

Although WAVE is an obvious choice for VANETs, its still reduced deployment, and consequently small coverage, imposes a limiting factor. Therefore, making use of more widely deployed technologies, such as Wi-Fi, is a good way of making the deployment of such vehicular networks faster and more tightly integrated with the current environment [40]. The IEEE 802.11 b, g, and n standards are included in nearly every electronic device and free hot-spots are available and scattered throughout some cities. These allow a wider coverage for VANETs and allow for high data rates.

However, Wi-Fi presents numerous disadvantages. First, its range is lower than WAVE, meaning that it can be challenging to maintain connections when the coverage is not ideal or there's a low node density. Second, Wi-Fi performs poorly when used at high speeds or in highly mobile nodes, since the handshake process required for a data exchange requires multiple message exchanges, making it unreliable in the real world when connections between nodes last only a few seconds.

2.4 Mobility

The high mobility and velocity of VANET nodes require that the mobility protocol responsible for handling the communication fulfills a list of criteria and requirements, presented next:

- **Ubiquity:** The network should handle vehicle movement through different locations while maintaining connectivity and service continuity.
- **Internet Protocol version 6 (IPv6) support:** Due to the possibility of a large number of nodes, IPv6's large pool of possible addresses is advantageous, adding both better security and QoS on top of that, making it a better option over Internet Protocol version 4 (IPv4).
- **Fast handover:** With the amount of handovers a single OBU performs, due to the constant changes in location, it is of high importance that the handovers are fast and efficient, maximizing the amount of useful data exchanged between nodes and meeting the delay requirements of sensitive services and applications.
- **Multi-hop:** In order to extend the access range of existing RSUs, nodes connected to RSUs should be able to provide Internet access to nodes in their range but not in the range of an RSU.
- **Multihoming support:** To improve network performance, multihoming support should be provided, making the most of the available wireless access technologies, possibly simultaneously
- **Transparent to end-users:** End-users connected to the network through OBUs should not have to worry about setting up mobility protocols in their devices, nor should their QoE degraded by it.

2.4.1 MIPv6

MIPv6 [15] is an improvement to Mobile Internet Protocol (MIP) [30], making use of IPv6 instead of IPv4, thus taking advantage of IPv6 mobility features. Furthermore, with the use of IPv6, some network problems that can not be handled by IPv4 are also solved, such as triangular routing, and shortage of addresses. This protocol meets some of the mobility criteria presented previously but not all of them, namely multihoming support.

Terminology

- **Mobile Node (MN):** The entity that can move through multiple networks, for example, a phone or laptop.
- **Correspondent Node (CN):** The entity that communicates with the MN.
- **Home Network (HN):** The network where the MN resides and the Home Agent (HA) exists.
- **Foreign Network (FN):** The network that the MN connects to after moving away from the HN.
- **Home Agent (HA):** An entity in the MN's HN that knows the MN's current location. When in an FN, the HA captures the packets sent to the MN and tunnels them to the MN's actual location.
- **Care of Adress (CoA):** New address that the MN acquires when in an FN.

Method of Operation

The MIPv6 protocol has the following stages:

- **Discovery:** the IPv6 neighbor discovery protocol is used to detect the mobility of a node from the HN to a different one, acquiring a new address (CoA) through IPv6 auto-configuration.
- **Registration:** the MN sends a Binding Update (BU) to its HA with the new CoA, for it to be registered, creating a binding between the HA and the CoA. The HA stores this in the Binding Cache (BC) and sends back a Binding Acknowledgement (BA).
- **Tunneling:** after registration, a tunnel is created between the HA address and the MN's CoA, so that packets received at the HA are forwarded to the MN's current location through this tunnel.
- **CN registration:** to optimize the routing mechanism, the MN registers its current binding at the CN, allowing the direct communication between CN and the MN while using the new CoA. If the CN does not support mobility, the existing HA tunnel will be used instead.

2.4.2 NEMO

Network Mobility (NEMO) [42] support is an extension of MIPv6 that enables the mobility of an entire network and the users connected to it, this way an entire network can move to a new one as a whole unit. This extension creates a network mobility management protocol with multihop capabilities, but creates scalability problems due to increased tunneling overhead and still fails to deliver multihoming support.

Terminology

- **Mobile Router (MR):** Router able to change its point of attachment to the Internet along with the devices attached, serving as gateway between these devices and the Internet.

- **Mobile Network Node (MNN):** A device connected to the mobile network.
- **Mobile Network Prefix (MNP):** Prefix on every IP address that identifies the whole mobile network.
- **Access Router (AR):** router that serves a MR and provides Internet access.

Method of Operation

In NEMO's method of operation, the MR is now responsible for managing the mobility process instead of the MN. The Mobile Nodes connected to the MR can move along with it and MRs send a BU to the HA when a movement is done, informing it of the network's prefix, so that a binding is made with the MR's CoA and all the traffic sent to the HA with that network prefix is then sent to the MR.

- **Movement:** Using the MIPv6 mechanisms, the MR detects movements and acquires a CoA from the AR.
- **CoA Register:** After having a CoA, the MR sends a BU to the HA in order to register the CoA. For instance, the HA creates a Binding Cache Entry (BCE), with the Mobile Network Prefix of that MR, so that the traffic destined to an MNN of that MN is redirected through the respective CoA.
- **Tunneling:** A BA is sent back to the MR, and a bi-directional tunnel is created between the HA and the MR, to be used by the MNN whenever it wants to communicate with a CN.
- **Communication:** When the MNN communicates with a CN, the traffic is encapsulated and forwarded through the MR-HA tunnel. In the HA, the packets are encapsulated and forward to the CN. The response is made similarly.

2.4.3 PMIPv6

Another approach made to solve the IP mobility challenge is PMIPv6 [9], that improves on the bases of MIPv6. These improvements remove the need to have mobility management functionalities in the users' device, decreasing network overhead. Although, it fails to fulfil the multihop mobility protocol requirement mentioned previously as well as the multihoming support. In this subsection, it will be given an overview of the PMIPv6 protocol and described the terminology used.

Terminology

- **Local Mobility Anchor (LMA):** This entity plays the role of the HA that exists in MIPv6 and improves it, providing the MN prefixes, binding them and forwarding its traffic.
- **Mobile Access Gateway (MAG):** The entity that is responsible for providing access to the MN and for signaling the respective LMA about the mobility of such MN.
- **Binding Cache Entry (BCE):** Cache that keeps the information about every connected MN. Each entry corresponds to one MN.

Protocol Messages:

- **Proxy Binding Update (PBU):** message sent by the MAG to the LMA, giving information about the MN's binding intentions.
- **Proxy Binding Acknowledgement (PBA):** message sent back as response to the PBU, giving information about the prefix given to the MN.

Method of Operation

The PMIPv6 protocol has the following stages:

- **Movement:** When the MN moves to a new location it sends a Router Solicitation (RS) to the new MAG at the new location so that it can make a connection.
- **Tunneling:** After receiving the RS, the MAG sends a PBU to the LMA. If accepted by the LMA, it then creates a BCE, assigning to the MN a prefix, and sends back a PBA, creating a bi-directional tunnel to the MAG. In case there is no longer a MN in the previous location, the previous tunnel to that location is also removed.
- **Connectivity:** After the MAG receives the PBA from the LMA, the MAG configures its part of the bi-directional tunnel to the LMA and makes the necessary configurations to give the MN connectivity, sending to the MN a Router Advertisement (RA) with the necessary prefix for the interface;

2.4.4 N-PMIPv6

Network-Proxy Mobile Internet Protocol version 6 (N-PMIPv6) is a protocol that merges the NEMO and PMIPv6 protocols, creating a protocol similar to PMIPv6 but with support for network mobility. A new entity is introduced, the mMAG entity and similar terminologies are used.

Terminology

A new entity is added:

- **mobile MAG (mMAG):** a combination of the MR in NEMO and the MAG in PMIPv6, it provides access to the MN and manages its mobility; the mMAG can also change its point of attachment.

Method of Operation

N-PMIPv6's method of operation is as described next:

- **Movement:** Similar to a MN in PMIPv6, when the mMAG moves and wants to connect to a new network, it sends a RS to the MAG or mMAG serving that network to initiate the connection proccess;
- **Registration:** the MAG or mMAG sends a PBU to the LMA, informing about the new mMAG-ID and if there is not one already assigned, the LMA creates a new BCE, giving a Home Network Prefix (HNP) for that mMAG and checking if the flag 'M' from the PBU is set to '0' or '1', which indicates if it was sent from a MAG or mMAG, respectively;
- **Tunneling:** After the BCE, the LMA creates an IPv6 tunnel to the MAG or mMAG that is serving the new mMAG and sends a PBA informing about the new mMAG's

HNP. A RA is sent to the final destination (mMAG) with the HNP and the mMAG IPv6 address is configured with that prefix. In case there is no longer a MN in the previous location, the previous tunnel to that location is also removed;

- **New Mobile Node:** When a new user wants to join the network by connecting to a mMAG, e.g. a vehicle, the process explained above is performed, with the small difference that the PBU and PBA exchanged between the mMAG serving this user and the LMA have it's 'M' flag set to 1, indicating that it is a node in a mobile network;

This protocol shows interesting features, allowing the mobility of entire networks through other existing networks, only requiring the end-user to connect to the network provided by his vehicle (mMAG) for Internet access, without the necessity of installing any additional software or added configurations in their devices. Additionally, since the mMAGs are the ones responsible for handling the mobility of its connected users, the handover mechanism is assured to be efficient and the number of handovers is reduced from the N number of users connected to only 1, the mMAG.

For these reasons, N-PMIPv6 [16] was the mobility protocol used in this work, continuously upgraded with additional features over the last years [24] [17] [6] [7]. Some of these features include: a connection manager that selects and connects to the best radio interfaces; it allows the users inside the vehicle to access the Internet via IPv4; and integrates a multihoming framework in the mobility protocol to grant support for either single or multi-hop connectivity, and simultaneous access to WAVE, Wi-Fi, and cellular.

As mentioned previously, N-PMIPv6 has three main entities, LMA, Mobile Access Gateways (MAGs) and mobile MAGs (mMAGs), denoted by RSUs and OBUs in the VANET architecture, and establishes IPv6 tunnels between the LMA and the existing RSUs, with endpoints to route the traffic to the multiple OBUs that may be connected to each RSU. Furthermore, in order to provide Internet access over IPv4 to the users inside the car, and because the mobility protocol is based in IPv6, an IPv4 over IPv6 tunnel is created between the LMA and the OBU, through which the user is connected. The proccess logic and the communication exchange is explained as follows:

LMA

When the LMA receives a PBU sent from a MN that is trying to join the VANET, it checks if that MN is already registered or not. If it is not registered it creates a new entry for that MN, and if the IPv6 tunnel that connects the LMA and the MAG does not exist, it is then created. In the case of that MN already having a BCE, the PBU lifetime is checked. Depending on this value, it can be indicating to: delete the BCE of that MAG and the correspondent tunnel, if it has no more users associated; if the PBU received is from a different MAG, then refresh the BCE and delete previous MAG tunnels if they have no users; or simply refresh the BCE if the condition mentioned previously is not met. A PBA is then sent informing about the process. The LMA operation can be observed in Figure 2.4.

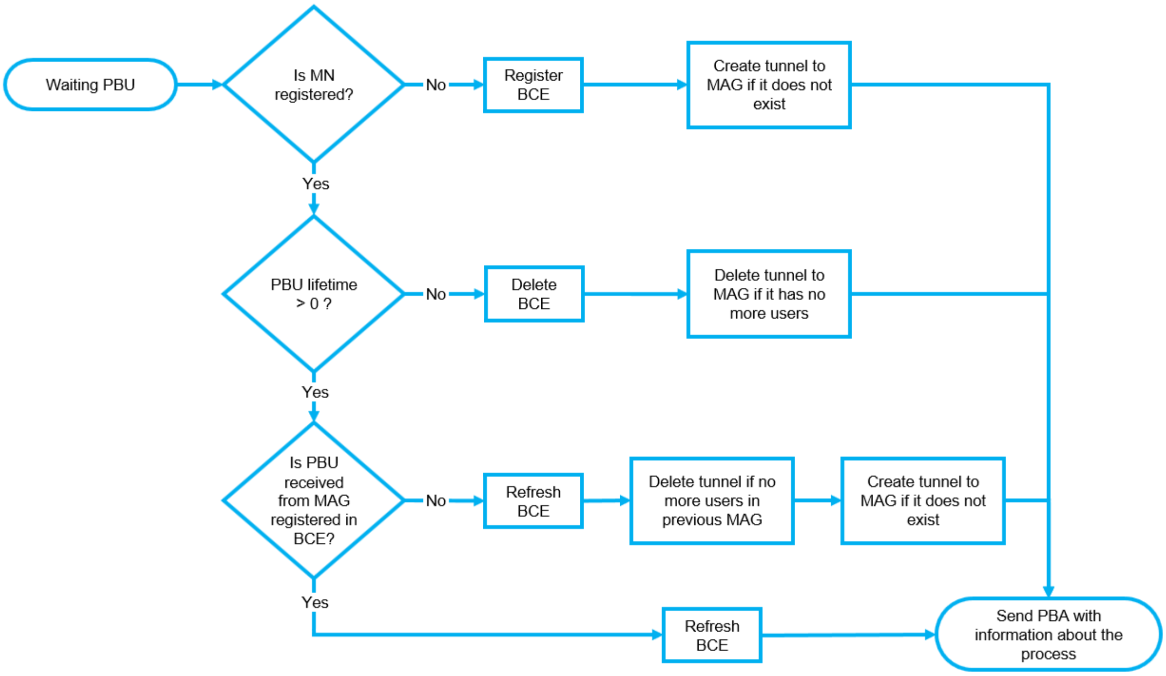


Figure 2.4: LMA N-PMIPv6 operation

MAG/mMAG

A MAG can both work as a MAG or mMAG, and that depends if it has a pre-configured MAG Address, in case it does, it runs as a MAG, otherwise as a mMAG. A mMAG will capture RSs and RAs. If it receives a RA, that means that it joined a network successfully, and with that RA it can configure its interface address, with the respective network prefix. If a RS is received, the MAG checks the destination, and if the RS destination matches his own address, it processes the detected MN, otherwise discards the message. When processing a detected MN, it is first checked if that MN is allowed in the network. If it is and the MN already has a definitive BCE, the goal of the RS is to maintain the session and thus only refreshing the BCE. If the MN does not have a BCE, a temporary BCE is created, awaiting a response by the LMA, confirming that the MN is suitable to join. After a predefined timeout of no response, the node is discarded. The MAG behavior is similar; the only difference is that it does not process RAs, only RSs and PBAs, since MAGs are designed to work as RSU. This operation is illustrated in Figure 2.5.

2.5 Multihoming

With the availability of multiple wireless access technologies in the network nodes, using only one access technology is a waste of resources and potential benefits. In a VANET scenario, the benefits that multihoming can provide are significant, as it can help reduce VANETs' weaknesses. Multihoming [23][19] is the possibility to explore connections through the various access technologies that are available in a single device, possibly simultaneously. It can be classified as Host Multihoming when a device can have more than one Point-of-

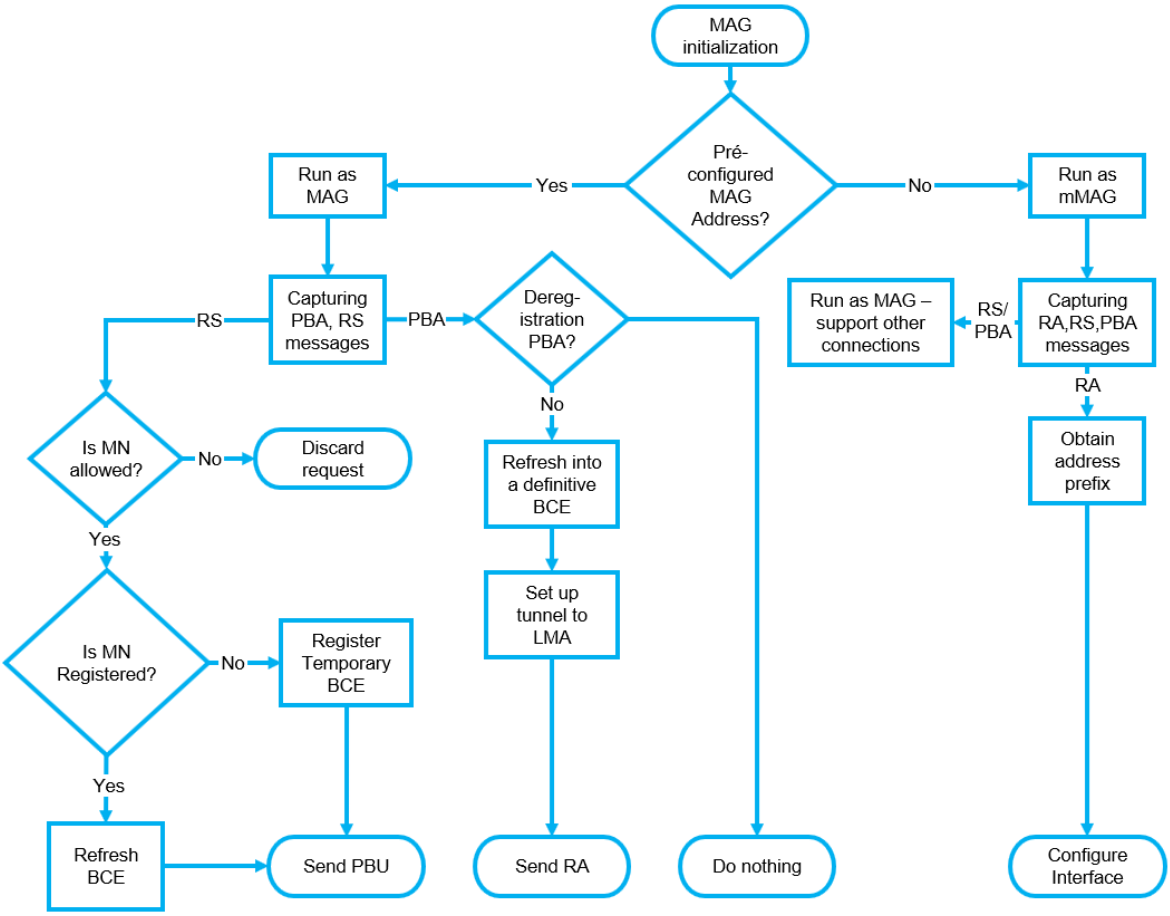


Figure 2.5: MAG/mMAG N-PMIPv6 operation

Attachment (PoA), and Site Multihoming, when a site, e.g., university campus, is connected to multiple Internet Service Providers (ISPs).

This practice brings several advantages that can be explored in a VANET, such as [34]:

- **Reliability:** With the existence of multiple paths for network connection, even when one of them disconnects and is lost, the connection is maintained through the other ones, thus increasing network reliability. Packet duplication through different paths can also be used, leading to a decrease in data errors at the destination.
- **Load Sharing:** A higher throughput can be achieved by aggregating the throughput achieved by each individual access technology, splitting and simultaneously transmitting traffic over the various access technologies. This can minimize the end-to-end delay as a direct effect of a higher bandwidth capacity and leading to improvements to real-time data transmission and therefore better QoE for the end-user.
- **Load balancing:** It allows the distribution of traffic to take the load of each path into account so that it can it divide the flows through the various paths and even the network load.

However several challenges arise and must be taken into account [13][34], such as packet reordering, network support, interface and application characteristics' estimation, identification of flows and sessions and increased power consumption. These led to the development of multiple multihoming solutions. These are commonly classified according to the Open Systems Interconnection (OSI) layer that the solution is implemented, which can be: Media Access Control (MAC), network, transport and application layer.

2.5.1 Proxy multihoming as a PMIPv6 extension

The multihoming solution chosen to be used in this work was developed in [4] [5], extending and providing multihoming support to the PMIPv6 mobility protocol, a protocol that N-PMIPv6 extends on as well. This solution implements a proxy entity together with PMIPv6's LMA, which manages the multihoming processing and conceals from the server the use of several paths. It supports dynamic connection and disconnection and uses IP replication at the user to enable multiple paths for a particular flow. Additionally, packets are scheduled with multiple parameters in mind, such as packet loss, throughput, or capacity variation. Furthermore, it uses the IPv6 prefix as an identifier of the node and the last 8bytes as the locator. This extension was then integrated with the N-PMIPv6 protocol [24], with further improvements in [6], optimizing the traffic load balance through the available technologies and increasing the overall network performance.

As such, and given the results achieved, this will be the multihoming solution that will be used in this dissertation.

The multihoming architecture is running in the three major entities: LMA, MAG and mMAG. The multihoming framework is depicted in Figure 2.6.

The LMA contains the following entities:

- **Terminal Manager**: Entity responsible for managing the users' interfaces.
- **Information Manager**: Entity that collects all the necessary and useful information for the multihoming process.
- **Flow Manager**: Entity that manages the traffic flows with the terminals, the traffic distribution, the rule calculation and its application .

The MAG contains the following entities:

- **Network Information Server**: Entity that is responsible for providing and storing the information about the state of the various access networks available.

Finally, the mMAG contains the following entity:

- **User Information Server**: Entity that stores the useful data about the users terminals, such as the interface name, the RSSI, interface quality level, noise level, packets losses, achieved throughput and the PoA load, and provides it to the Network Information Server.

In a multihoming scenario there is a need to select the amount of information that will flow from each wireless technology. The LMA calculates the traffic division through each path by using a Genetic Algorithm, that takes into account the information about the MAGs retrieved earlier, such as interface capacity, mean packet size, mean packets per second, available bandwidth, achieved throughput, and packet loss. This algorithm is described in [5], and was used to extract the optimal traffic division values through the minimization of the mean packets delay for multihoming user, independently of the number of interfaces.

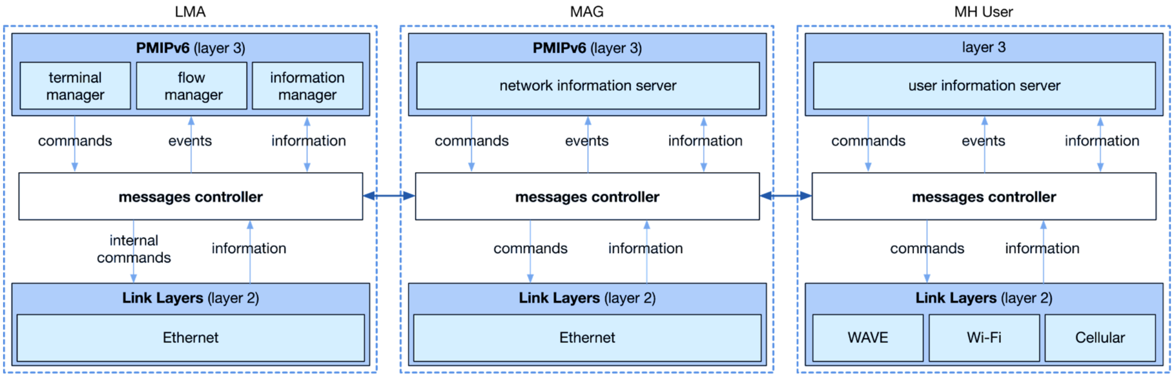


Figure 2.6: Multihoming framework based on [3]

The network performance metrics between the MAGs and mMAGs are obtained through the WBest [18] framework, a wireless bandwidth estimation tool designed for fast, non-intrusive, accurate estimation of available bandwidth in IEEE 802.11 networks. WBest is a two-stage algorithm, where first a packet pair technique estimates the effective capacity over a flow path containing a wireless LAN (WLAN), and second a packet train technique estimates the achievable throughput to infer the available bandwidth. WBest parameters are optimized given the tradeoffs of accuracy, intrusiveness and convergence time. The WBest analysis runs on all the available access networks, between MAGs and mMAGs. In this work only WAVE and Wi-Fi communication interfaces are considered.

2.6 Adaptive Video Streaming

With the improvements made in video compression standards, expansion of ubiquitous and efficient transmission systems and the growth of numerous consumer video entertainment services, such as YouTube and Netflix, video traffic is more and more prevalent [10], and consequently, it is also of higher importance to meet certain quality expectations when delivering this type of traffic to the end user [8].

IEEE 802.11p makes small improvements on top of the IEEE 802.11 standard with VANET's characteristics in mind. However, the characteristics of these environments difficults the deployment of video services, due to the high mobility of the nodes and the nature of city buildings, causing instability in the wireless channels and consequent variations in bandwidth, latency, jitter and packet loss during communications. Besides, network traffic congestion and delays may lead to additional packet loss, and since a single video frame is decomposed into smaller packets that are then sent to the network, if the packets that are lost exceeds a certain threshold for error correction, the receiver can not play this frame.

With these variations in mind, content must also adapt to the network conditions to improve the observed user QoE, and, as such, adaptive streaming emerged. One of the advantages is supporting adaptation, where through the feedback of QoS metrics, it is possible to adapt. In order to achieve an easy and scalable delivery process, HTTP protocol is used, since it is at its base a file transfer, but instead of one big progressive download, it relies on tiny progressive downloads (small chunks of video). The player is then responsible for merging all those chunks and make them appear to the user as a continuous stream. These chunks are usually 2 to 10 seconds long, and the original content is encoded with different qualities to allow quality (bitrate requested) switching, thus achieving bandwidth efficiency. As such, a big continuous stream is made at the client side with improved overall quality through that request process.

The popularity growth of adaptive HTTP streaming technologies lead significant industry players to develop their solutions:

- Smooth Streaming by Microsoft;
- HTTP Dynamic Streaming (HDS) by Adobe;
- HTTP Live Streaming (HLS) by Apple;
- DASH ISO by MPEG;

2.6.1 Dynamic Adaptive Streaming over HTTP

The MPEG Dynamic Adaptive Streaming over HTTP (DASH), also known as MPEG-DASH, standard comes as an adaptive video streaming delivery technology standard that uses HTTP streaming [39], with participating companies such as Microsoft, Adobe, Samsung, and others, after realizing that the market was too fragmented, and convergence was necessary for market growth, benefiting everyone. The DASH-Industry Forum (DASH-IF) was established shortly after the first standard approval [12] with the main focus being interoperability to avoid ecosystem fragmentation. This strategy succeeded, and DASH became fastly adopted, resulting in the integration of DASH on Hypertext Markup Language version 5 (HTML5) Media Source Extensions (MSE).

MPEG-DASH is codec-agnostic: it can send video in H.265, H-264 or any other codec, it does not change how the video is encoded, what it does is split the video source file into pieces, that it then duplicates and encodes at different bitrates, in order to try and give a coherent, variable bit-rate video, with the best experience possible given the resources available at the destination.

The adaptive HTTP streaming architecture is depicted in Fig. 2.7. The media preparation module provides tools for media adaptation, packetization, encapsulation, etc. so that the media is efficiently delivered to the client.

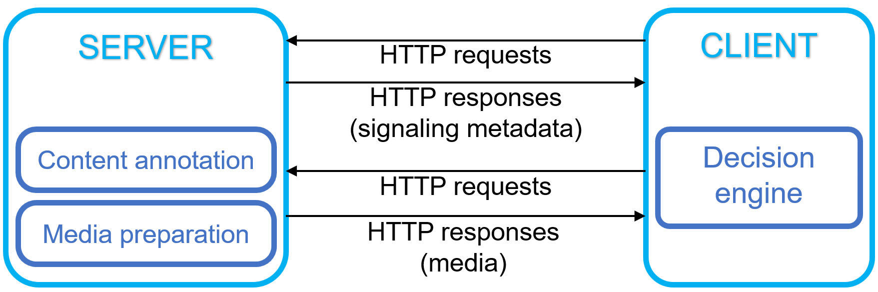


Figure 2.7: HTTP Video Streaming with MPEG-DASH based on [41].

MPEG DASH specifies the metadata, Media Presentation Description (MPD), an Extensible Markup Language (XML) file that comprises the various qualities of video and audio content, pointing to the right HTTP Uniform Resource Locator (URL), and media format exchanged between clients and servers. In conventional streaming, the media and signaling metadata are usually delivered by different protocols, like Real-time Transport Protocol (RTP) and Real Time Streaming Protocol (RTSP) [11]. However, with HTTP streaming, both signaling metadata and media are delivered by the HTTP protocol. The only requirement that Dash.js from DASH-IF has is that the web browser must support HTML5 MSE, which is already widely supported by most browsers.

2.7 QoE

QoS typically covers network performance analysis. However, given the increase of highly user-centered content, QoE is becoming a valuable parameter to take into account when measuring network performance. Ordinary users watching a video stream care about the experience and quality of the video that is being delivered to them, they do not care if some behind the scene innovative technology is being employed or if some QoS metric is marginally better if that does not translate into something meaningful to them. That is why QoE plays such a prominent role in determining the success or failure of technologies or products, and that is also why it is an important parameter to evaluate in a system.

QoE measurement can be objective or subjective, depending on how it is performed. Multiple QoS metrics evaluate the quality of video playback objectively, and while different from QoE, they are closely related and can be used to make inferences on QoE [27][26], such as:

- **Delay:** It corresponds to the time that it takes for a packet to get from the source to its destination. Long delay times mean poor video quality.
- **Signal Degradation:** Signal degradation during transmission can result in transmission errors, increasing the need for error prevention and recovery, thus delay.
- **Jitter:** Jitter is the variation in the delay, it measures how consistent the delay is: if all the packets have a similar delay (low jitter) or if some packets are fast and some others slow (high jitter). Video streaming requires low jitter; otherwise, the quality gets choppy.
- **Throughput:** Corresponds to the number of packets successfully delivered per amount of time. Issues with throughput are caused by connectivity issues, outages, or congestion, which are known to increase user drop-off.
- **Loss:** Packet loss must be minimized, as it can result in portions of the video content failing to reach the client-side player and requiring a retransmission request, which can delay playback;

However, these objective metrics miss one of the most important points in video transmission: human perception, subjective quality assessment. Subjective QoE assessments are performed through several studies that involve surveys, of the user experience in different scenarios under a controlled environment, in order to create a subjective evaluation. The metric to do so is called Mean Opinion Score (MOS), where a user rates the experience on a scale of 5, where 5 is the best experience. After that, objective metrics are added, such as video bitrate, video resolution, and buffer stalls, to connect to the user experience. Through multiple subjective surveys and studies, and by training objective assessment algorithms with this data, QoE models emerged. With these models, QoE estimations can be made on-the-fly for a given service or video stream. As mentioned previously, the objective metrics show correlation with QoE scores and how each QoS parameter impacted the final QoE [26][36].

Additional studies [20][32] shown that humans are time sensitive, which means that buffer stalls have a higher negative impact on QoE than video resolution variation.

2.7.1 Probing QoE in Adaptive Video Transmissions

In order to assess and improve the clients' QoE, a real-time QoE probe must be used. This analysis will be on the client side, clearly the best place to perform the QoE assessment. A QoE probe implementation was done in [36], writen in C#, with Microsoft Smooth Streaming in mind. For MPEG-DASH , the probe was then adapted in [25] to support the Dash.JS player, a multi-platform and license free option for DASH written in AngularJS. As such, it was refactored to the AngularJS environment and improved with the help of this environment to be more accurate. The probe was built using both objective and subjective experiments, simulating the human video scoring behavior, and gives a final score based on MOS heuristics every 2 seconds of video play. The QoE might increase or decrease due to the following metrics:

- Bitrate: is an indicator of the video quality playing in the user side, for a given codec, the higher the bitrate, the higher the quality.
- Frames Per Second (FPS): lack of processing power or network constraints can sometimes cause skipped frames, that affect video playback.
- Buffer Stalls: when the video player runs out of buffered chunks, the video playback stops. As such, this is one of the most important metrics that heavily impact the user's QoE negatively.
- Screen Ratio: the user's device resolution is taken into account to calculate a ratio between it and the video resolution. If the user has a FullHD screen but is watching a video in SD, it is bad for the user.

Different weights are given to each of these attributes since they influence the viewer in different ways. Additionally, a human memory filter technique is applied, taking into account past events and experiences in the current QoE evaluation. For example, having two consecutive buffer stalls is worse than having only one buffer stall happening; as such, the first experience has a more negative impact. When there is a buffer stall, the calculation halts and the event is registered, so the duration of the stall is also considered and affects the QoE calculation. The occurrence of buffer stalls is closely related with QoS metrics such as throughput and response latency, which ultimately influence the user's QoE, as detailed in Section 2.7. QoS metrics directly determine the possible DASH adaptive video quality for a continuous stream of video. Connections that provide higher throughputs and faster responses allow for higher video qualities to be delivered, consequently increasing the QoE. On the other hand, QoS metrics can also restrain video delivery by providing low maximum throughput or high latencies, which will require DASH to lower the video quality to maintain video playback, with the possible occurrence of buffer stalls, causing a decrease in QoE.

Given the close MOS estimation to the model above, it will be used to evaluate the QoE with adaptive video streaming and multihoming in a VANET.

2.8 Related Work

2.8.1 Video Transmission in VANETs

During the past few years, many authors investigated solutions for video transmission in VANETs and purposed different solutions for this kind of network environment.

According to Emna *et al.* [38], acceptable video quality can be achieved at velocities up to 40 Km/h. Higher velocities the level of losses reaches 70%, causing the video quality to degrade. It can be concluded that, the higher the velocity, the lower the video quality, and therefore a worse QoE. That imposes a challenge for real time video transmission in a VANET environment, where nodes are highly mobile. For video streaming dissemination from an RSU to vehicles other factors will influence the video transmission, such as RSU coverage and handover between RSUs.

Xie *et al.* [45] conducted a study that evaluates the performance and suitability of some techniques to unicast video streaming over VANETs. One conclusion is that receiver-based approaches outperform sender-based solutions, as they handle better the constant changes of topology. It was also analyzed the impact that different buffer sizes in the intermediary nodes have in the delivery ratio, since they are required to hold packets until a valid route to the destination is found, and concluded that to achieve high delivery ratios, large buffers are required. Two different policies for packet drop were also studied, early deadline first (EDF) and drop tail (DT), and it was observed that if the video frame level information is taken into consideration, a better quality video can be achieved.

The first approach capable of simulating and representing real-time video transmission in VANETs was proposed by Piñol *et al.* [31] where, by means of a simulation platform, they obtained Peak Signal-to-Noise Ratio (PSNR) results following the guidelines of [37] for the evaluation of video performance based on H.264 video coding standards. Furthermore, Torres *et al.* [43] evaluated the performance, in various traffic conditions, of different real time video flooding schemes in terms of PSNR when using the video coding standard H.265, and based on that evaluation proposed an Automatic Counter Distance Based (ACDB) Flooding Scheme that outperforms the majority of flooding schemes, achieving a high percentage of delivered packets within low delay bounds.

In [1], Mahdi *et al.* introduced a cross-layer approach approach where the routing decisions are made taking into consideration the application layer. Additionally, the queueing based mobility model, spatial traffic distribution and probability of connectivity for sparse and dense VANETs are taken into consideration for developing the cross-layer routing protocol. The

PSNR simulation results achieved show that the path selection scheme can achieve results close to the upper analytical bound.

Xu *et al.* [46] introduced a QoE-driven user-centric solution for Video-on-Demand (VoD) services in vehicular network environments that uniformly distributes video segments along a P2P overlay on top of a cellular network and also proposed a speculation-based prefetching strategy for smoothening the video playback. Zaidi *et al.* [48] proposed a new protocol called Enhanced User Datagram Protocol (EUDP) for video streaming in VANETs, which shows significant improvements when compared to User Datagram Protocol (UDP) with respect to error recovery rate, PSNR, and MOS of the transmitted video.

In [35], Ramaboli *et al.* proposed a multipath MPEG video streaming solution that can prevent the loss of video frames, ensuring that frames can be delivered meeting the playback requirements. Through their trace-driven simulation, they showed that the proposed solution can achieve better PSNR and Structural Similarity Index (SSIM), and visual quality. Vinel *et al.* [44] proposed a real-time scalable video codec for the video information, and performed real-world measurements using the off-the-shelf Componentality FlexRoad WAVE equipment.

The work in [14] built a video streaming framework over a cloud-based VANET architecture, where the video streaming content can be accessed and requested by vehicles. Control information about vehicles' mobility is exchanged using a background process in order to achieve uninterrupted streaming sessions. The vehicles include a QoE-monitor to measure and report the end-user video quality. In [29], a real-time V2V video transmission system for driving assistance was tested using WAVE, with real-world urban and highway conditions. Metrics such as delay and throughput were measured, and the video stream was delivered over HTTP. The results showed that streaming of video quality of up to 720p is possible with the available technologies, meeting the time and quality requirements, although only a maximum of two simultaneous transmissions is allowed with this quality, due to bandwidth restrictions. Truong *et al.* [41] studied the use of DASH for streaming audiovisual content and showed that it can provide the best possible quality to the users and still maintain a stable buffer when drastic changes of bandwidth occur. Even though this study did not consider VANETs, these same drastic changes of bandwidth are frequent in VANET environments.

All the aforementioned studies, with the exception of [44] and [29], were based on simulated results, instead of real experiments performed in real world, and are under the assumption of a wide availability of roadside units. Thus the problems that arise from wireless communications are mostly put aside. Furthermore, no studies were made exploring the multihoming possibility of WAVE and Wi-Fi technologies, and its impact on QoE with adaptive video streaming.

2.9 Summary

This chapter described several essential concepts related to VANETs, by giving some context on the subject and presenting some of the network access technologies used in this environment. The VANET architecture used in this work is also described.

The mobility protocol used was presented, the N-PMIPv6, and its logic and communication exchange between each mobility entity explained. N-PMIPv6 provides this work the necessary support for mobility, however, it may have an impact on QoE, which will be studied in the next chapter.

This chapter also gave an insight into the multihoming architecture and framework, and how the determination of the traffic division is done. Handling adaptive video streaming and load balancing between the existing access technologies, in order to take advantage of their strengths and to potentiate QoE, might not be as trivial as applying the default rules.

Then, adaptive video streaming and QoE are detailed. The QoE probe was described, relating its implementation and functionalities, tool that enables the correlation between QoS and QoE in this dissertation.

Lastly, the related work is presented.

CHAPTER 3

QoE Assessment

3.1 Introduction

This chapter evaluates the QoE of an adaptive video stream over a vehicular network. The analysis starts with a simple wired network, without mobility, and consequently without mobility support, and finishes with a network composed by all the elements that exist in a VANET, with wireless communication, and with support for mobility. This way, potential bottlenecks that might exist in the VANET network for real-time content delivery, such as video transmission, might become more apparent. Section 3.2 describes the testbed used for the experiments. Section 3.3 describes the methodology. The evaluation of QoE is done in Section 3.4, followed by the discussion of the results in Section 3.5.

3.2 Testbed

For the experiments, that will be presented and discussed in Section 3.4 and Section 3.5, respectively, the equipment used to act as LMA, OBUs, RSUs, and Users, creating the VANET architecture illustrated in Figure 2.2, are detailed as follows.

The LMA is located in an HP Pavilion DM1-4200SP laptop with the following specifications:

- CPU: AMD E1-1200 APU @ 1.40GHz
- Memory: 4GB DDR3 1066 MHz
- Disk: 320GB HDD
- OS: Ubuntu 18.04.1 LTS 64-bit

RSUs and OBUs are Single-Board Computers (SBCs) with the following specifications:

- CPU: AMD Geode LX800 @ 500 MHz
- Memory: 59 MB
- OS: VeniamOS
- WAVE interface: mini-PCI 802.11p-compliant wireless interface with the Atheros AR5414 chipset, controlled by an ath5k driver
- Wi-Fi interface: Wi-Fi Module compliant with IEEE 802.11a/b/g

Finally, the user equipment, hosting the QoE probe and requesting the video contents, is an Asus N552VX laptop with the following specifications:

- CPU: Intel Core i7-6700HQ @ 2.60GHz
- Memory: 16GB DDR4 2133 MHz
- Disk: 256GB SSD
- OS: Ubuntu 18.04.2 LTS 64-bit
- Screen Resolution: 1920x1080 FullHD
- Browser: Firefox version 67.0 (64-bit)

Additionally, in order to provide a controlled and consistent adaptive video to our user, a DASH server was set up. In this server the original video is encoded with multiple video qualities, allowing the video stream to adapt to the network or device conditions. To that end, a Correspondent Node (CN) hosting the DASH server was added to the network setup, receiving and processing the user's video requests.

The DASH server configured in the CN provides ten encoded video qualities as displayed in Figure 3.1.

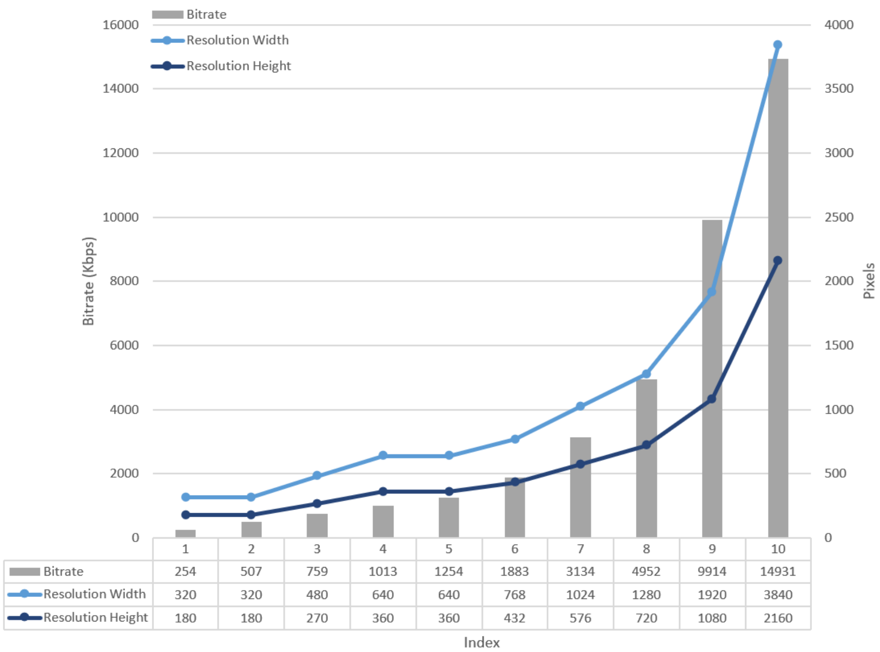


Figure 3.1: Encoded DASH video quality indexes.

3.3 Methodology

The methodology used in the experiments consisted in transmitting in downlink an adaptive video from a DASH server (CN). In the server, the video is encoded with different qualities, and upon request from the user, the requested video chunks are sent to the user. Reaching the user, the video is played, and the probe registers the QoS and QoE metrics, calculating the respective QoE MOS values. These values allow us to correlate the QoS metrics, such as throughput and latency, and QoE metrics, such as video bitrate and buffer length, given by the QoE probe.

The performance results for each scenario are supported by ten runs, where in each run a 3-minute DASH video was transmitted. Ten different quality indexes were available, being index 1 the lowest quality and index 10 the highest quality. Depending on the real-time characteristics of the network, the most appropriate quality index is chosen by DASH, followed by a request for a video chunk. The QoE MOS value ranges from 0 to 5, the higher, the better, and every 2 seconds a new QoE value is calculated. Additionally, network and video metrics were also logged. The results are presented with a 95% confidence interval.

3.4 Evaluation

Every scenario is composed by elements that establish a VANET. The starting point was a simple scenario, adding complexity in each step, making each scenario more and more similar to a full VANET. The first scenario consists of a wired network built with the essential elements that will take part in every experiment, evolving scenario upon scenario until, reaching scenarios that allow performance comparisons between VANETs that use WAVE as access technology and VANETs that use Wi-Fi.

For the QoS measurements, as these experiments were done in a controlled indoor environment laboratory, the measurements of jitter and packet loss were very low or even negligible across all scenarios. As such, the effect of these metrics will not be considered as a variable in the results obtained.

3.4.1 Scenario 1

An initial setup was created, illustrated in Figure 3.2a, where every node was directly connected by cable. In this scenario, only the essential elements are present: the CN (DASH server), the LMA, and the User, where the QoE probe is also located, allowing for an assessment without wireless connections.

Figure 3.2b presents the evolution of the QoE MOS value, throughput and latency observed for the setup of scenario 1. The achieved QoE MOS value was 4.9, close to the highest possible value. Such score is justified by the video quality index being transmitted, which was the one with the highest index, 10, and no buffer stalls occurred. The reason why the QoE MOS value was not the highest (5) was due to the screen ratio metric. The video being transmitted was at 4K resolution, but the User's device screen resolution was only FullHD. Figure 3.2c is relative to the video bitrate obtained in this scenario and Figure 3.2d to the buffer length. As observed, the video bitrate quickly reaches the highest value for the provided qualities by the DASH server (index 10), a bitrate of 14931 kbps (Figure 3.1). The buffer length also rapidly increases until a maximum value of 60s, and after reaching it, maintains that value throughout the rest of the transmission.

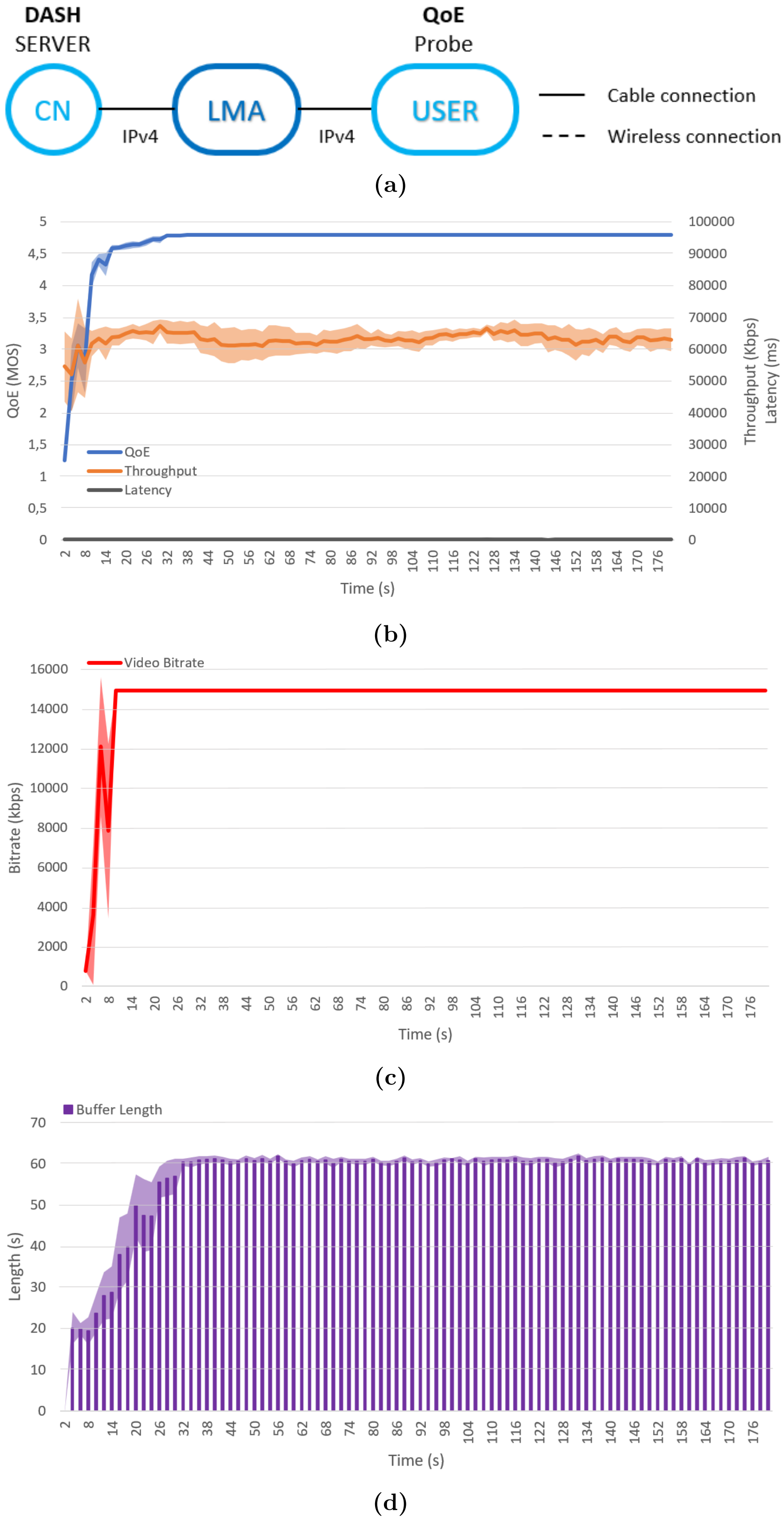


Figure 3.2: Scenario 1 architecture (a), QoE and QoS (throughput and latency) (b), video bitrate (c) and buffer length metrics over time (d).

3.4.2 Scenario 2

In a second scenario, two additional elements were added to the previous one, namely one OBU and one RSU connected through WAVE. Static routes were used to forward the traffic to and from the user. All the connections were made through IPv4 and the maximum allowed WAVE bandwidth was set to 12 Mbps. The second scenario is depicted in Figure 3.3a.

Figure 3.3b illustrates the QoE MOS value, throughput and latency over time observed for scenario 2. The results show a decrease in the QoE value, from 4.9 obtained in scenario 1 to 4.5, as a consequence of the WAVE wireless link connecting OBU and RSU. There was a substantial decrease in the throughput, closing in 6500 kbps, resulting in a decrease in the video quality that streamed from the DASH server to the User, as shown in Figure 3.3c, stabilizing at a video bitrate of 5000 kbps. Buffer length also decreased, but maintained levels fluctuating between 15 and 20 seconds (Figure 3.3d). The fluctuations now observed are caused by the use of a wireless communication channel, which is subject to the occurrence of contention and interferences, instead of the cable network connection in scenario 1.

3.4.3 Scenario 3

In a fully functional VANET with mobility support, such as the one provided by the N-PMIPv6 protocol, Clients access to the Internet through IPv4 over IPv6 tunnels. Then, in this third scenario an IPv4 over IPv6 tunnel was created between the LMA and the WAVE RSU, as shown in Figure 3.4a. This new element will be used to analyse the impact of the encapsulation process in the QoE.

Figure 3.4b illustrates the QoE MOS value, throughput, and latency for scenario 3. The QoE MOS value obtained is about 4.5, with a mean throughput of 6.5 Mbps. Figure 3.4c shows the video bitrate, reaching 5000 kbps, and Figure 3.4d illustrates the buffer length, that fluctuates between 15 and 20 seconds.

As observed in Figure 3.4b, the results are almost identical to the ones obtained in the previous scenario (Figure 3.3b). Thus, it can be concluded that there is no impact in making use of IPv4 over IPv6 tunnels between the LMA and RSU for adaptive video transmissions.

3.4.4 Scenario 4

In a fourth scenario the IPv4 over IPv6 tunnel is extended. Instead of connecting the LMA to the RSU, in this new scenario the tunnel connects the LMA to the OBU. This way the architecture comes closer to a real world VANET network. Now, the IPv4 traffic coming from and to the user is encapsulated in IPv6 between the LMA and OBU, as shown in Figure 3.5a.

The results obtained regarding QoE MOS value, throughput, and latency, for this scenario are shown in the graph of Figure 3.5b. Figure 3.5c regards to video bitrate, and Figure 3.5d regards to buffer length. The QoE score achieved is of approximately 3.7, considerably lower than scenario 3 QoE score of 4.5. Throughput decreases to around 4.1 Mbps, from the 6.5 Mbps in scenario 3, with a latency of 250 ms. The video bitrate is also lower when compared to the previous scenario, scenario 3, with a value around 3000 kbps. The buffer length follows the trend, slightly decreasing, now fluctuating around the 15 seconds mark.

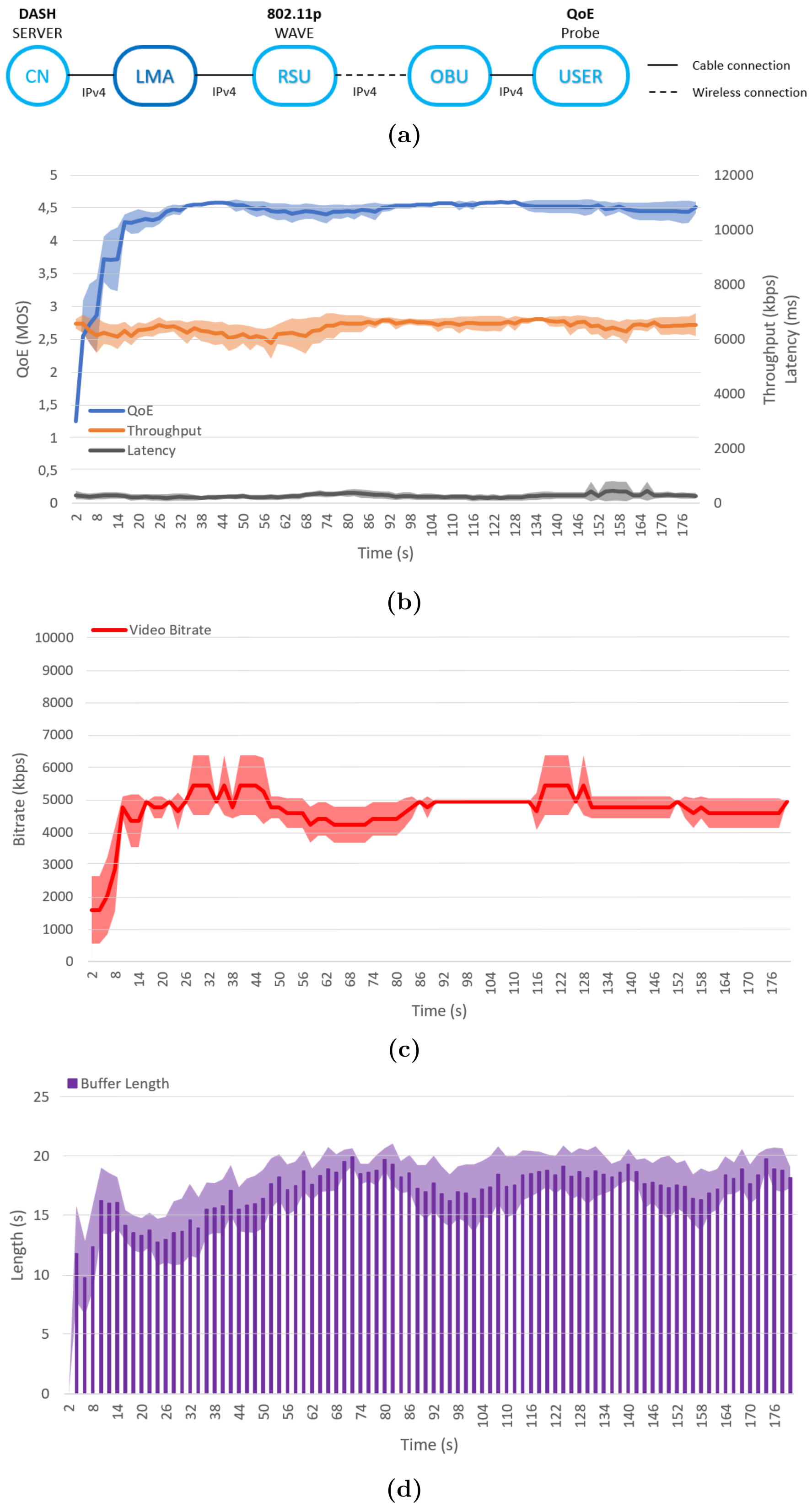


Figure 3.3: Scenario 2 architecture (a), QoE and QoS (throughput and latency) (b), video bitrate (c) and buffer length metrics over time (d).

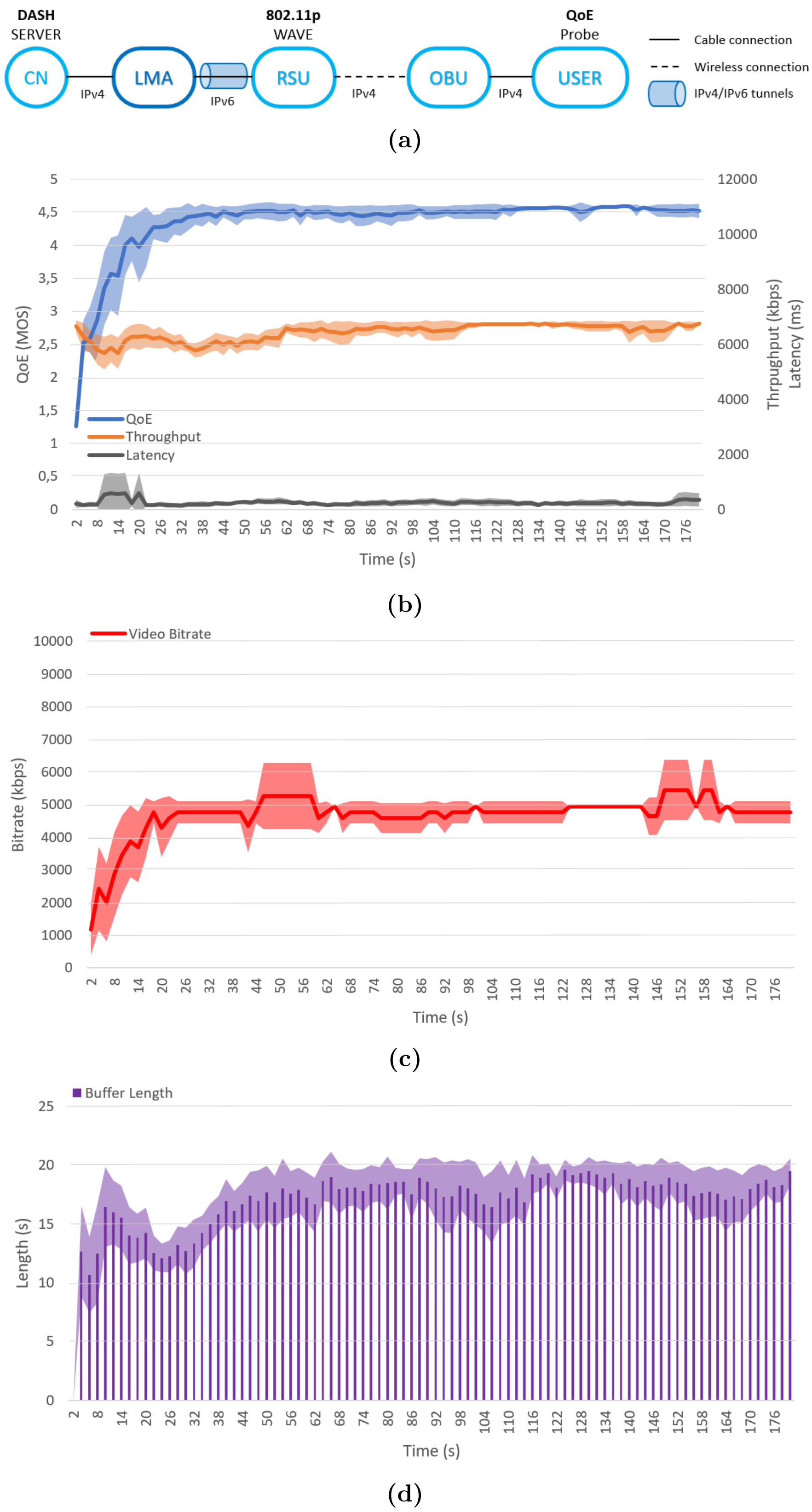
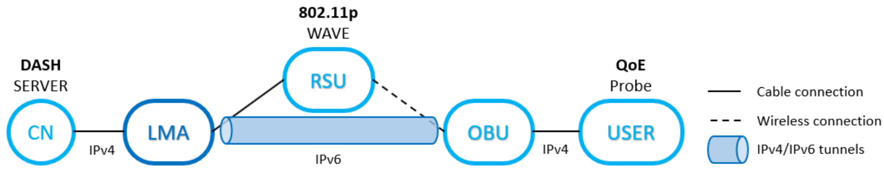
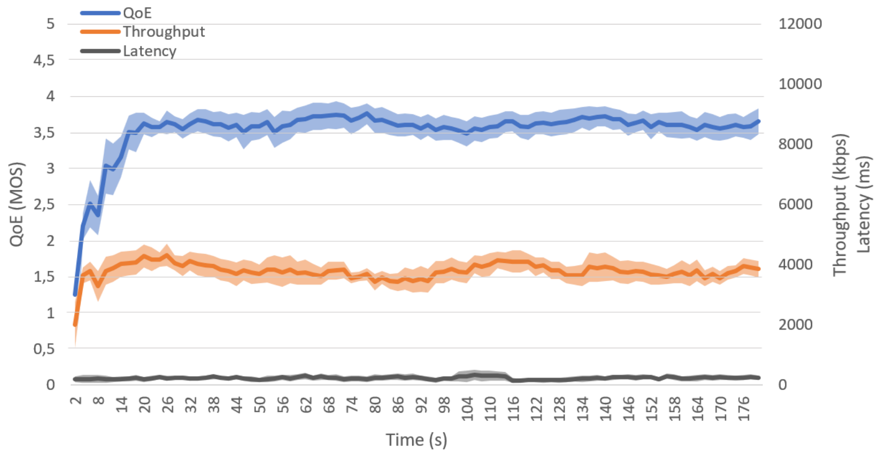


Figure 3.4: Scenario 3 architecture (a), QoE and QoS (throughput and latency) (b), video bitrate (c) and buffer length metrics over time (d).



(a)



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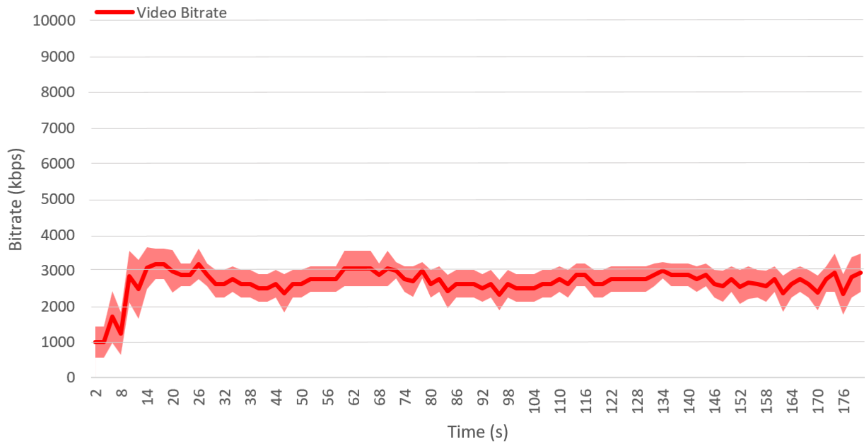

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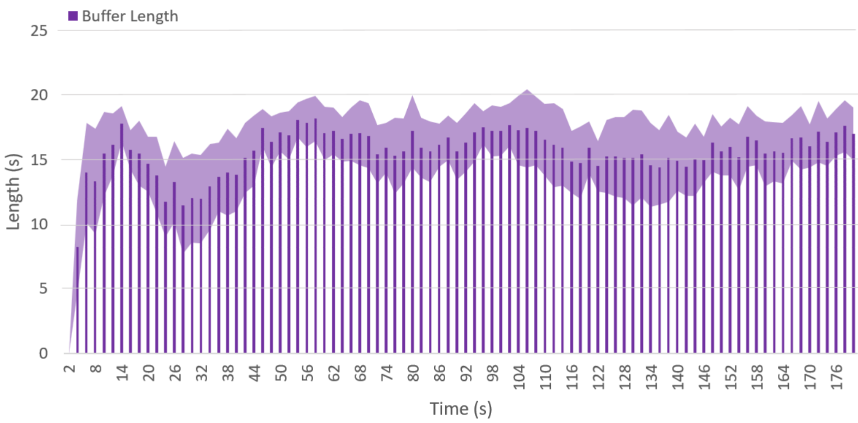


(d)

Figure 3.5: Scenario 4 architecture (a), QoE and QoS (throughput and latency) (b), video bitrate (c) and buffer length metrics over time (d).

By comparing both scenarios 3 and 4, the only difference is the end of the tunnel on the vehicular side and for that reason it was expected that the results would be similar. However, this was not the case. To understand the cause of such difference both scenarios were inspected, on each network element, with respect to the data transmission process. After some experiments with the iPerf tool and upon closer inspection with Wireshark, it was noted that in scenario 4, there was a shorter MTU in the wireless transmission segment, between the RSU and OBU, which was generating a lot more packet fragmentation when compared to scenario 3. This increased the number of necessary packet transmissions for the same video chunk, resulting in a less efficient process, and causing a decrease in throughput, as illustrated in Figure 3.5b.

With the scenario 4 full characterized, it is now appropriate to include the N-PMIPv6 mobility protocol into the remaining setup to see if it matches the actual performance or adds any additional overhead in the video transmission. It is also an opportunity to understand how to take advantage of the strengths provided by IEEE 802.11p (WAVE) and IEEE 802.11g (Wi-Fi), access technologies available in an OBU, and how these two technologies impact adaptive video streaming. First, it is assumed that the OBU is connected to the RSU exclusively through WAVE (IEEE 802.11p at 12 Mbps). Then, this technology is replaced by Wi-Fi (IEEE 802.11g at 54 Mbps).

3.4.5 Scenario 5

Scenario 5 uses the IEEE 802.11p (WAVE) access technology and the same architecture of scenario 4, but now with N-PMIPv6 mobility protocol taking responsibility of the management of the user connection to the Internet (to access our CN), replacing the static routes previously configured, illustrated in Figure 3.6a.

Figure 3.6b illustrates the QoE, throughput and latency of a VANET scenario using only the IEEE 802.11p technology. Additionally, Figure 3.6c shows the evolution of video bitrate, and Figure 3.6d is relative to the obtained buffer length. In this scenario, the QoE stabilizes around 3.5 MOS value throughout the entire video stream with small fluctuations regarding the throughput (around 4 Mbps) and latency (about 250 ms). Buffer length observed in this scenario is between 10 and 15 seconds.

When comparing the results of scenario 5 to scenario 4 (Figure 3.6b and Figure 3.5b), a small decrease in QoE score can be observed, justified by the small decrease in video bitrate (Figure 3.6c). The buffer length is also smaller. Therefore the addition of the N-PMIPv6 protocol added a small amount of overhead, which is reasonable to assume, as there are multiple protocol messages and packets exchanged while the video transmission is occurring.

3.4.6 Scenario 6

This scenario was elaborated with the architecture in scenario 5, but in this case the wireless connection between RSU and OBU uses IEEE 802.11g (Wi-Fi), as Figure 3.7a shows.

Figure 3.7b shows the QoE, throughput, and latency performance results for this scenario, Figure 3.7c illustrates the video bitrate evolution, and Figure 3.7d shows the buffer length. The obtained QoE score fluctuates around the 4.0 MOS value, as a consequence of a higher

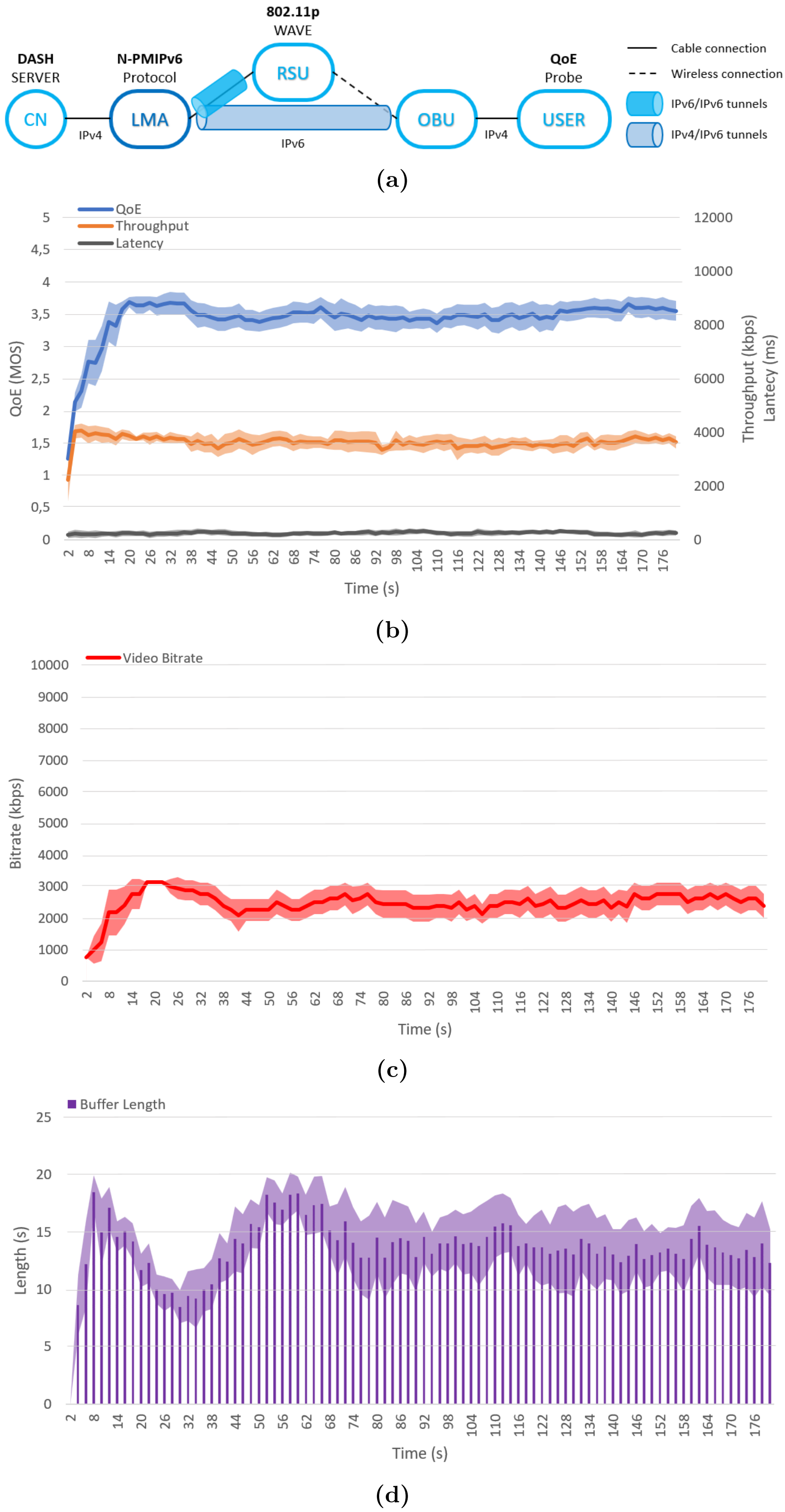
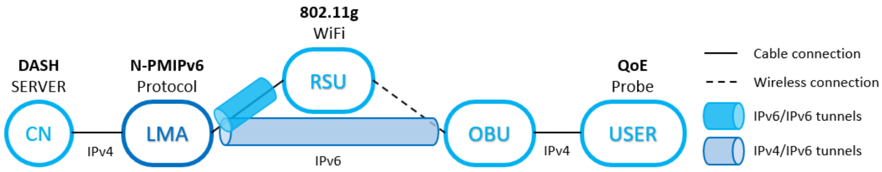
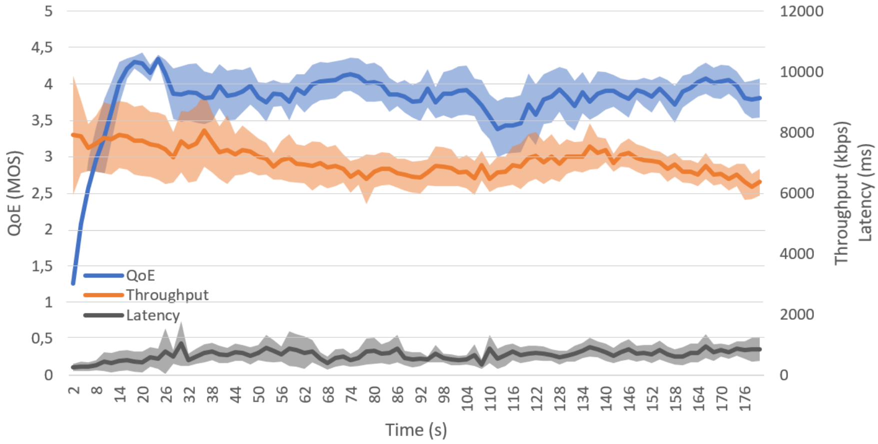


Figure 3.6: Scenario 5 architecture (a), QoE and QoS (throughput and latency) (b), video bitrate (c) and buffer length metrics over time (d).



(a)



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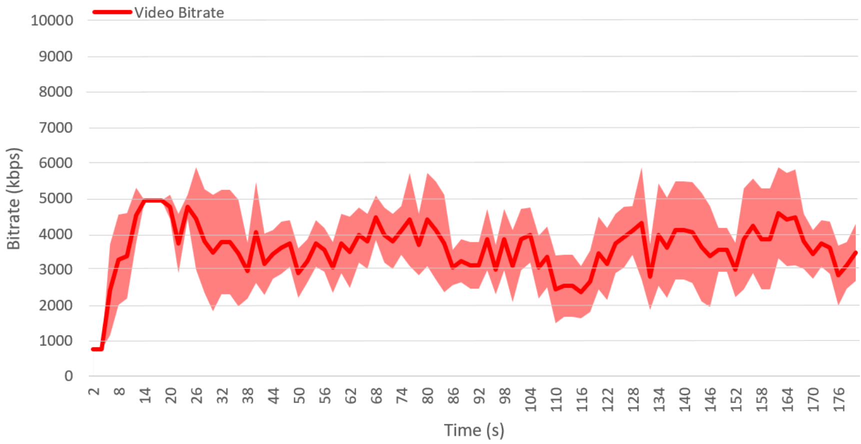

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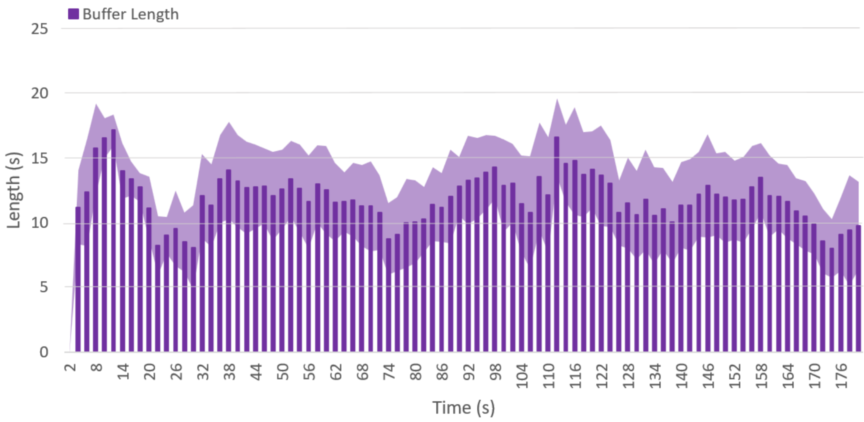


(d)

Figure 3.7: Scenario 6 architecture (a), QoE and QoS (throughput and latency) (b), video bitrate (c) and buffer length metrics over time (d).

variation in the achieved throughput, around the 7 Mbps mark, and latency, fluctuating near 500 ms, when compared to the previous scenario. However, and because the throughput offered by the Wi-Fi connection is higher than the IEEE 802.11p, the probe returns a higher value of QoE.

The results show an obvious increment in throughput and consequent increase in video bitrate, causing higher QoE scores to be achieved when using Wi-Fi compared to WAVE. However, in Figure 3.7d, it can be noted that the buffer length is more unstable and some dips are detected. This is justified by the higher occupation of the Wi-Fi medium, as this access technology is more utilized when compared to WAVE, being nowadays present in almost every user device, and therefore is more prone to the occurrence of interferences and contention.

3.5 Discussion

A first note to be made about the results obtained is that, in the first few seconds of the DASH adaptive video transmission, there is a higher fluctuation in the QoE metrics, namely video bitrate and buffer length. This behaviour is caused by the DASH adaptation process in finding the most appropriate video quality to deliver to the user, balancing video bitrate and buffer length, in order to achieve the best QoE, with the available network conditions.

Analysing all the results, the QoS metric that had the highest impact in adaptive video stream QoE was the throughput. From scenario 1 to scenario 2, a decrease in throughput was observed caused by the use of a WAVE connection between RSU and OBU that became a limiting factor, which was reflected in the reduction of QoE from 4.9, nearly the maximum score of 5 in MOS scale, to 4.5.

In the third scenario, an IPv4 over IPv6 tunnel was added between the LMA and RSU. According to the results, the maximum throughput slightly decreased when compared to the second scenario, and the mean QoE kept the same in a MOS value of 4.5. Therefore, the additional encapsulation process in the nodes does not interfere with the DASH video transmission process.

In scenario 4, the communication between LMA and OBU occurs using IPv6, such as in a VANET, with the use of an IPv4 over IPv6 tunnel. In this case, a drop in throughput is observed, as well as in the QoE score, achieving a mean score of 3.7. From further inspection, it was noted that a shorter MTU imposed by the wireless connection originated packet fragmentation, and consequently, a decrease in the network throughput.

Scenario 5 added the N-PMIPv6 protocol, resulting in a small decrease in the QoE MOS value from 3.7 to 3.5, justified by protocol overhead. This scenario serves as the baseline for adaptive video streaming QoE when using WAVE in a VANET.

With the premise that improving the throughput of the network may yield a positive effect on the user's QoE, scenario 6 has showed exactly that. With the use of Wi-Fi as the wireless technology between RSU and OBU, an increase in throughput was observed, followed by higher video bitrate, and higher QoE scores. This scenario serves as the baseline for adaptive video streaming QoE when using Wi-Fi in a VANET. This scenario, however, showed lower and more unstable buffer length, a detail that will be further discussed in the next chapter.

CHAPTER 4

QoE in Multihomed Environments

4.1 Introduction

Following the QoE results obtained in the previous chapter for the adaptive video streaming in a vehicular network, with IEEE 802.11p or IEEE 802.11g technologies, this chapter studies the multihoming performance when both technologies are used simultaneously, and understands how it affects the QoE. Following a preliminary evaluation, a QoE-aware policy for the multihoming load balancing policy is proposed. Finally, this chapter assesses the adaptive video streaming process in a real-world VANET scenario using real hardware and mobility.

4.2 WAVE versus Wi-Fi in Multihomed VANETs

Now, it is assessed the performance of using both WAVE and Wi-Fi simultaneously. The VANET architecture used for the multihoming experiments is illustrated in Figure 2.2. The maximum bandwidth allowed for access technologies was not changed from the previous experiments, with WAVE (IEEE 802.11p) at 12 Mbps and Wi-Fi (IEEE 802.11g) at 54 Mbps. The results were obtained using real hardware, in a laboratory environment, without mobility, in a multihoming scenario. The measurements were repeated 10 times and the results have a confidence interval of 95%.

Figure 4.1a illustrates the QoE, throughput and latency in a scenario where WAVE and Wi-Fi were used simultaneously, with a traffic division of 50% per technology. Comparing with the previous experiments with a single technology, this one exhibits more unstable throughput and latency results, with a mean QoE MOS value of 3.7. Figure 4.1b shows that the mean video bitrate increased up to about 3000 kbps, higher when compared to the baseline WAVE transmission (Figure 3.6c), but lower when compared to the baseline Wi-Fi transmission (Figure 3.7c). It terms of buffer length, depicted in Figure 4.1c, it is comparable to the Wi-Fi transmission (Figure 3.7d), showing unstable behaviour.

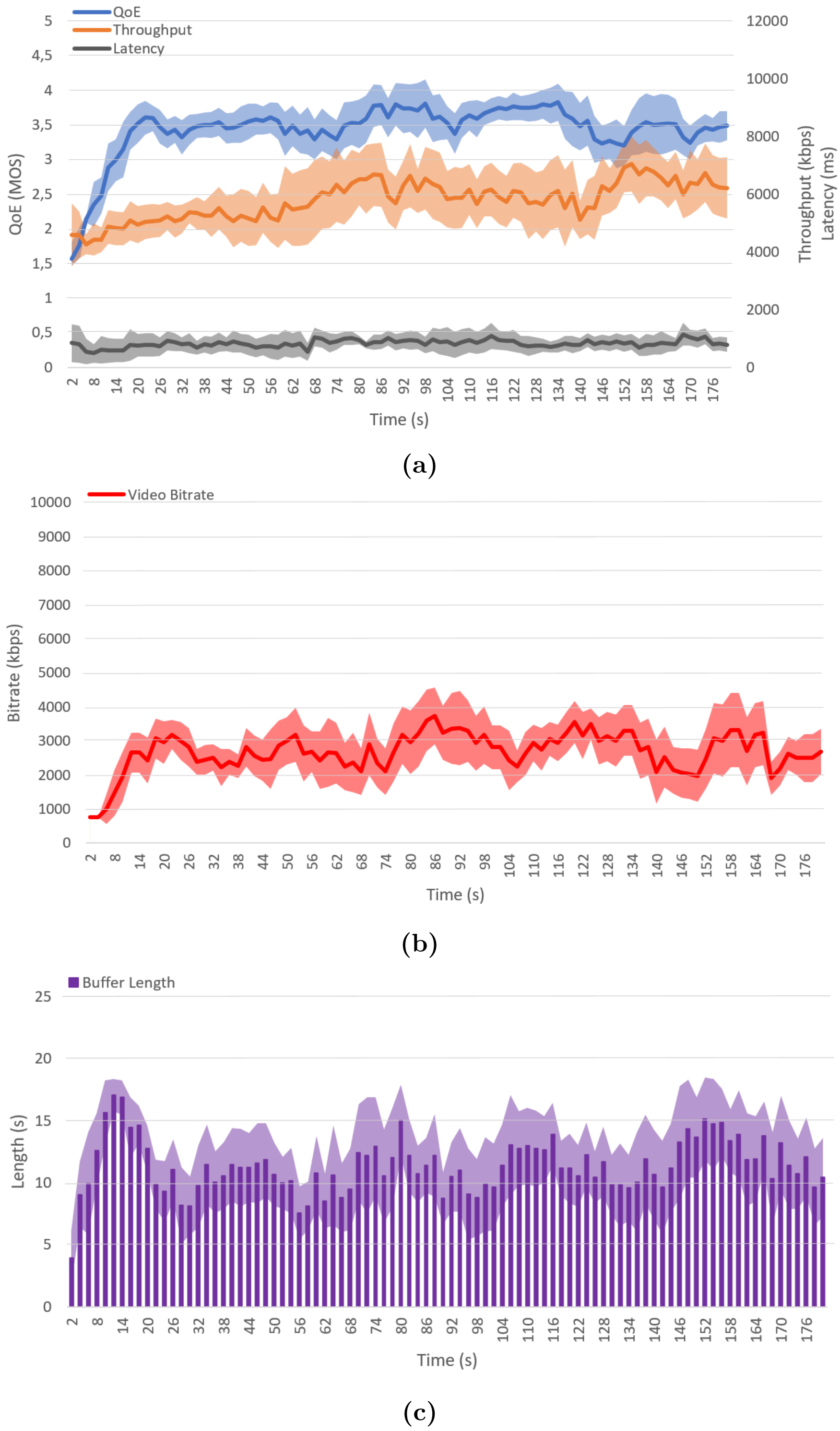


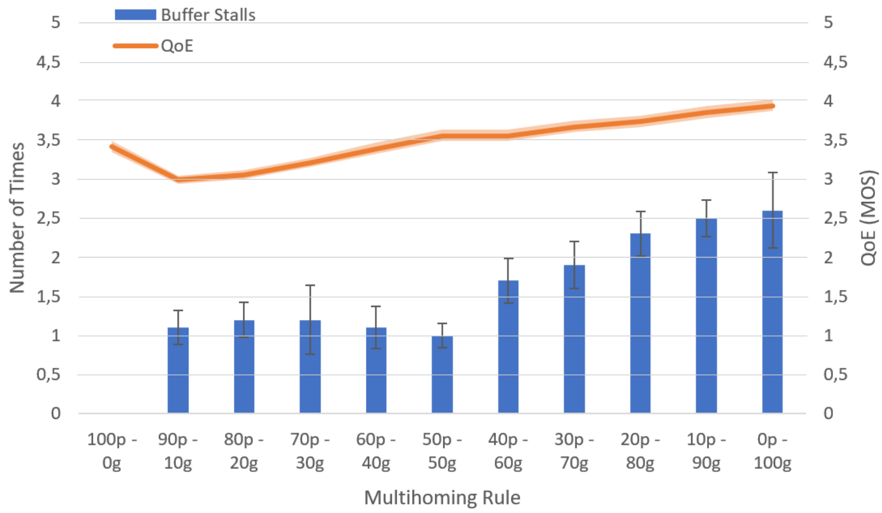
Figure 4.1: Multihoming Base Scenario - QoE and QoS metrics over time for 50% WAVE and 50% Wi-Fi.

As observed, a higher achievable throughput can be obtained when using Wi-Fi, causing the request of higher video qualities (mainly higher bitrates), which led to an increase in the QoE. However, the obtained QoE results were only marginally better.

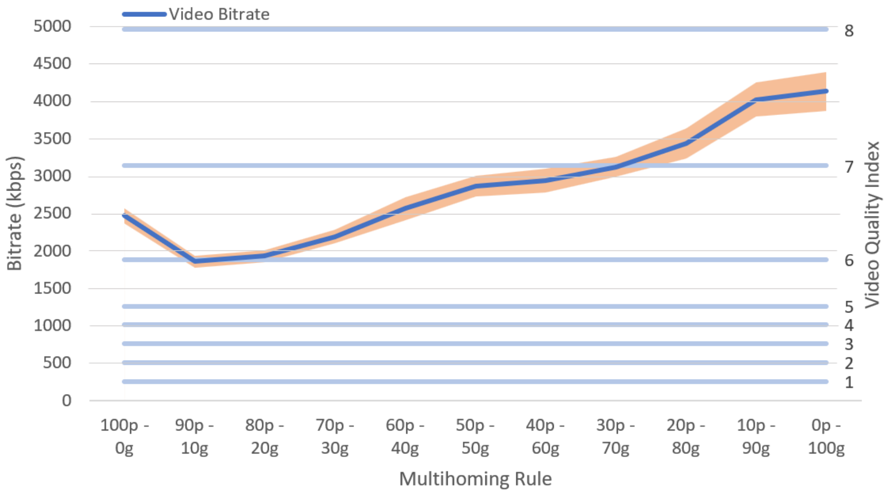
To better understand these results and the impact of each technology in the QoE, the analysis was extended for additional combinations of multihoming traffic division. The results are depicted in Figure 4.2a, and they represent the average QoE for the entire video stream, for 20 streams, and the average number of buffer stalls per stream. As the percentage of traffic routed through the Wi-Fi technology increases, so does the number of buffer stalls. Taking a more in-depth look at the metrics registered during the experiments, the video quality requested is higher when using Wi-Fi (Figure 4.2b), justified by the higher achievable throughput measured, and consequent request of higher video quality indexes. However, this situation creates a higher load in the vehicular network, also reflected in the latency. Consequently, this leads to an increase in buffer stalls, which have a huge negative impact in the user's QoE. So, even though the video quality increases, leading to an increase in QoE, the increase in buffer stalls leads to a decrease in the QoE. To summarize, the results have showed that by preferring the Wi-Fi technology a higher throughput is achieved. However, under this situation the network capacity cannot handle the increase in the multimedia quality, leading to buffer stalls that penalize the QoE, justifying why the QoE does not increase linearly with the achieved throughput.

4.3 A multihoming load balancing policy for video applications in VANETs

In a VANET scenario, characterized by high levels of mobility, the choice of the radio access technology is critical: by preferring the Wi-Fi, a higher QoE is obtained but shorter communication range, leading to a higher number of link failures and handovers. On the other hand, when using IEEE 802.11p less handovers are done, but also a lower level of QoE. Following the results in Figure 4.2a a multihoming load balance policy aiming to improve the user QoE is proposed. The rationale is as follows: in a periodic manner, the Genetic Algorithm returns the optimal traffic balance for the current network conditions. The output is accepted only if more than 70% of video stream is routed through Wi-Fi interface. If not, the load balancing is limited to route 70% of the video through Wi-Fi and 30% through IEEE 802.11p. This traffic division was selected with the objective of obtaining the highest levels of QoE. Observing the video bitrate results in Figure 4.2b, at the 30% WAVE and 70% Wi-Fi traffic division, a new level of video quality is reached (index 7), translating in a better mean video quality for the user, with higher bitrate and resolution. Although video bitrate keeps increasing with higher percentages of Wi-Fi, the 30% WAVE and 70% Wi-Fi division was selected to still take advantage of the WAVE technology, making use of a long range connectivity link to stream the video, anticipating future Wi-Fi handovers. Pseudocode regarding the implementation of this policy is presented in Algorithm 1.



(a)



(b)

Figure 4.2: Buffer stalls and QoE (a), and mean video bitrate for several multihoming traffic balance combinations (b). The xp-yg labels stand for x% of WAVE and y% of Wi-Fi.

Algorithm 1

while *multihoming with WAVE and Wi-Fi* **do**
  if *video streaming* **then**
    if *multihoming traffic balance for Wi-Fi < 70%* **then**
      set multihoming traffic balance for Wi-Fi to 70%
      set multihoming traffic balance for WAVE to 30%
    else
      set multihoming traffic balance as calculated
  apply multihoming traffic balance

4.4 Performance Evaluation

This section shows the adaptive video streaming performance in a real-world VANET scenario, using real hardware and mobility, with segments of multihoming with WAVE and Wi-Fi, and segments of transmission exclusively through WAVE. Furthermore, the QoE-aware multihoming policy proposed in the previous section is evaluated, comparing it to the default multihoming load balance. Two different mobility scenarios were tested. Additionally, a Wi-Fi connection would only be considered for multihoming if a signal level of at least -60 dBm was available; if the Wi-Fi signal strength was lower than that, the connection was not established. This ensures a minimum level of stability and reliability for a Wi-Fi connection, avoiding the bad usage of resources by not sending traffic through Wi-Fi connections that are too far away and do not meet the QoS requirements for video transmission. The testbed architecture used in the real-world experiments is the same as the one illustrated in Figure 2.2, and the hardware and software of the different components used is as described in Section 3.2.

4.4.1 Scenario 1

Scenario 1 consisted of requesting a 3-minute video stream considering a mobile situation with handovers and multihoming situations. The scenario is depicted in Figure 4.3. During the first minute, the moving vehicle is connected only through IEE 802.11p. For the next minute, the vehicle experiences a multihoming situation where IEEE 802.11p and Wi-Fi are used, which may represent a traffic light situation. Then, in the final minute the vehicle starts moving again, making use of a single communication technology, again IEEE 802.11p. The scenario was repeated 10 times, and the 95% confidence intervals are presented.

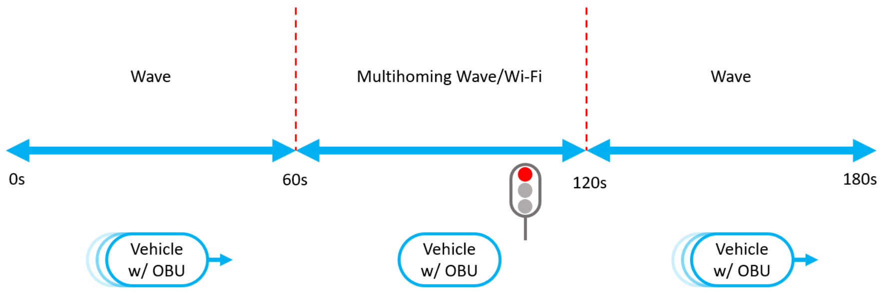


Figure 4.3: Real-world scenario 1 diagram.

Let us start by presenting the QoE results for scenario 1 when the multihoming load balance is given by the default rule, *i.e.* when the genetic algorithm is applied. Illustrated by Figure 4.4a, in the first minute, a mean value of QoE MOS around 3.5 is obtained, with a throughput measured of about 4 Mbps, and latency of about 250 ms. The video bitrate observed was between the 2000 and 3000 kbps, as shown in Figure 4.4b. Buffer length fluctuated between 5 and 15 seconds, illustrated in Figure 4.4c. During the second minute, a multihoming situation with both IEEE 802.11p and Wi-Fi occurs, increasing the overall throughput and the user's QoE, reaching the 4.0 MOS value. The appearance of Wi-Fi, allows for the use of multihoming in this segment, leading to higher available capacity, causing DASH to request higher quality video chunks, as observed in Figure 4.4b, reaching a mean video bitrate of 4000 kbps during this interval. Buffer length maintained the similar values. After the second minute, the vehicle moves out of range of Wi-Fi, and the QoE converges to similar values as observed during the first minute when only WAVE was present.

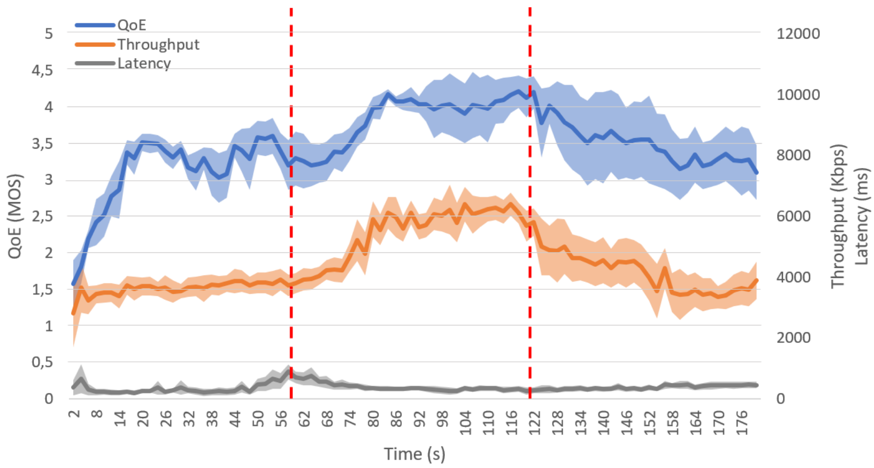
Figure 4.5a presents the QoE results for the same vehicular scenario using the QoE-awareness policy proposed in 4.3, *i.e.*, the traffic balance output is accepted if more than 70% of the video stream is routed through Wi-Fi, and if not, the load balancing the limited to route 70% of the video through Wi-Fi and 30% through WAVE. In the first minute, a QoE MOS of 3.5 is obtained, with throughput observed in the 4 Mbps mark. Latency is around 250 ms. Figure 4.5b shows that video bitrate in this interval stayed between 2000 and 3000 kbps, and Figure 4.5c shows a fluctuation in buffer length between 10 and 15 seconds. In the seconds minute, the multihoming segment for this scenario, an increase in QoE is observed, Figure 4.5a, reaching MOS values up to 4.3. Higher QoE results are justified by the higher achievable throughput that reaches the 9 Mbps mark, even if the observed latency is also slightly higher (around 500 ms). This comes as a consequence of the minimum utilization rate of Wi-Fi defined in the proposed traffic balancing policy. The video bitrate increased, with values of up to 5000 kbps (Figure 4.5b), and the video buffer length maintained values between 10 and 15 seconds (Figure 4.5c). In the third minute, QoE and other metrics converge to similar values as observed during the first minute when only WAVE was present, as the vehicle moves out of range of Wi-Fi.

In scenario 1, when the proposed traffic balancing policy was used, during the multihoming period, higher values of QoE can be seen when compared to the default results. Higher QoE results are justified by the higher achievable throughput, as a consequence of the minimum utilization rate of Wi-Fi defined in the proposed traffic balancing policy. This allows higher quality chunks to be requested, reaching a mean video bitrate of up to 5000 kbps (against 4000 kbps with the default load balance), leading to an increase in the QoE, of almost 4.3 MOS value (against 4.0 with the default load balance) even if more buffer stalls are experienced. It is also important to highlight that the proposed policy presents shorter QoE confidence intervals, granting a more stable behavior of the entire video stream system.

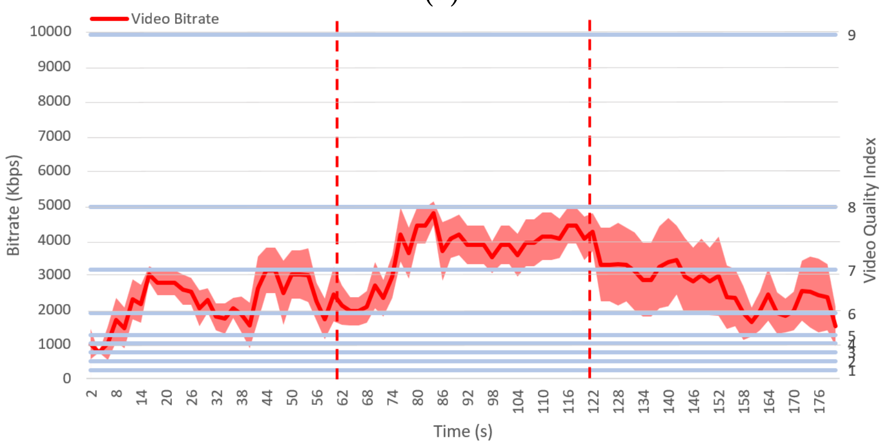
4.4.2 Scenario 2

Scenario 2 is depicted in Figure 4.6, and consisted of requesting the same 3-minute video stream as scenario 1, and considering a mobile situation with handovers and multihoming situations as well. Scenario 2, however, is the opposite of scenario 1: during the first minute, the moving vehicle is connected through WAVE and Wi-Fi, taking advantage of multihoming, which may represent a traffic light or traffic jam situation. In the second minute, the vehicle only has access to WAVE communication. Then, in the final minute, the vehicle enters again in the range of Wi-Fi and WAVE, allowing again for multihoming load balancing. The scenario was repeated 10 times, and the 95% confidence intervals are presented.

The evaluation of the video QoE under scenario 2 starts with the default policy of multihoming load balancing, *i.e.*, when the output of the genetic algorithm used in the traffic



(a)



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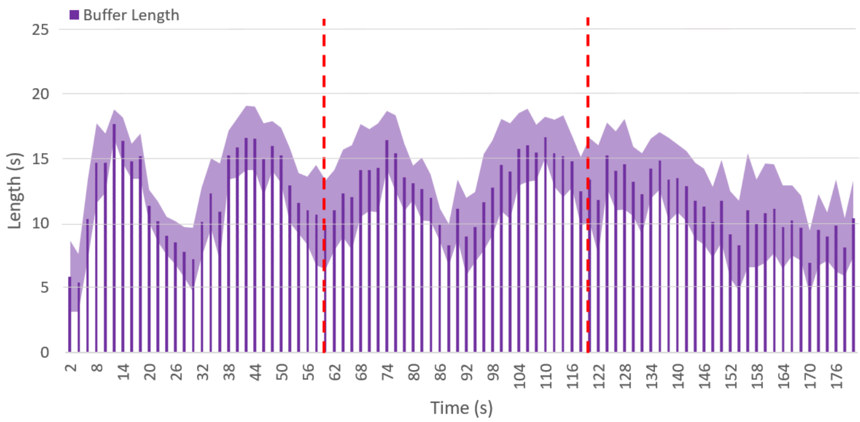
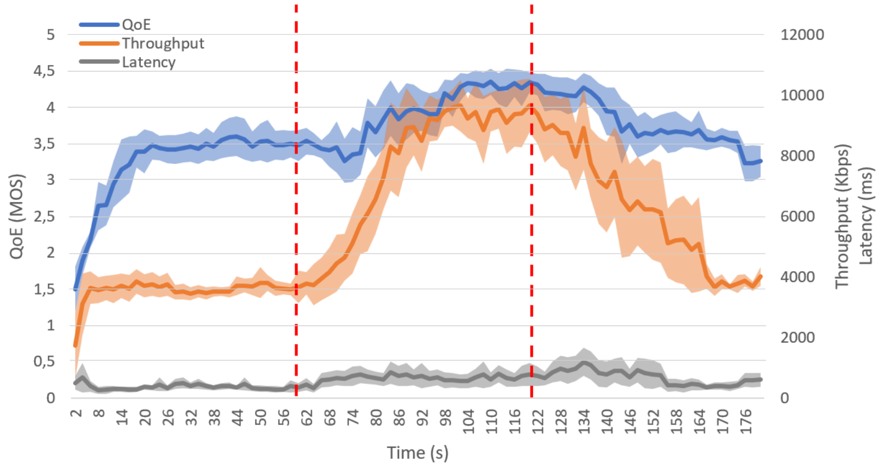
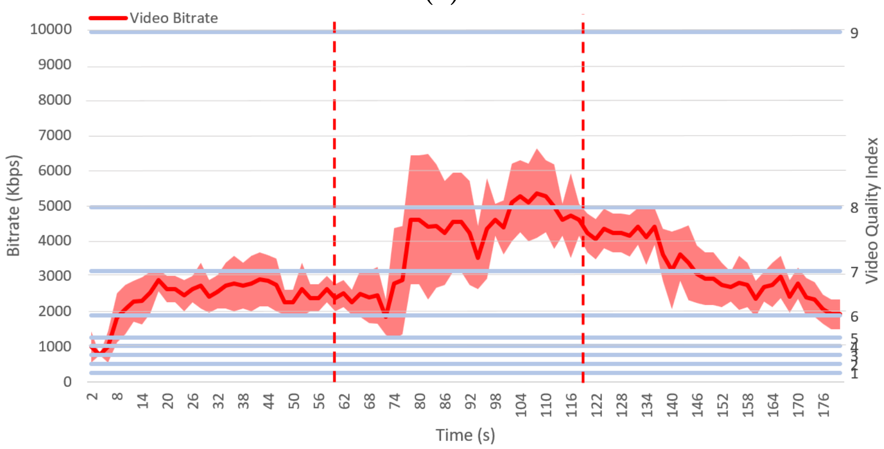


(c)

Figure 4.4: Real-world performance in scenario 1 with default multihoming traffic balance. QoE and QoS (throughput and latency) (a), video bitrate (b) and buffer length metrics over time (c).



(a)



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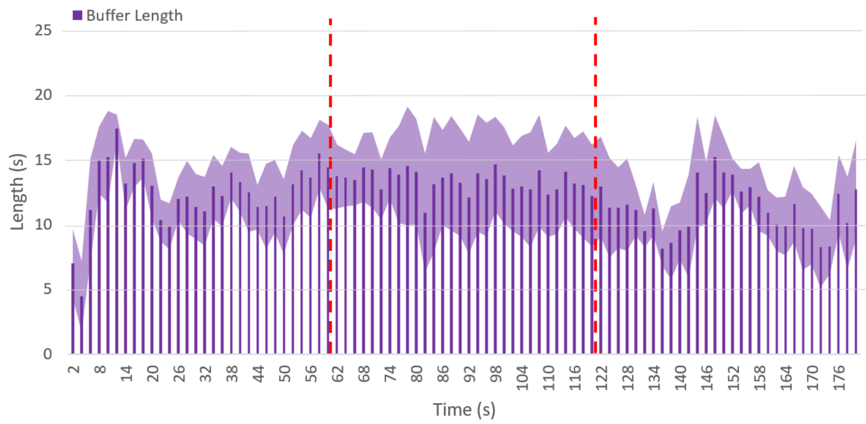


(c)

Figure 4.5: Real-world performance in scenario 1 with QoE-aware multihoming traffic balancing policy. QoE and QoS (throughput and latency) (a), video bitrate (b) and buffer length metrics over time (c).

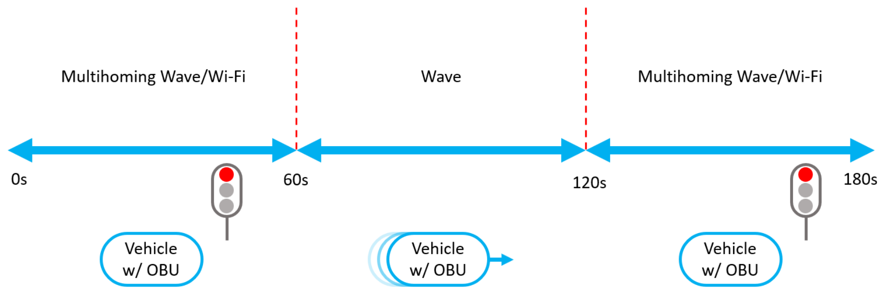
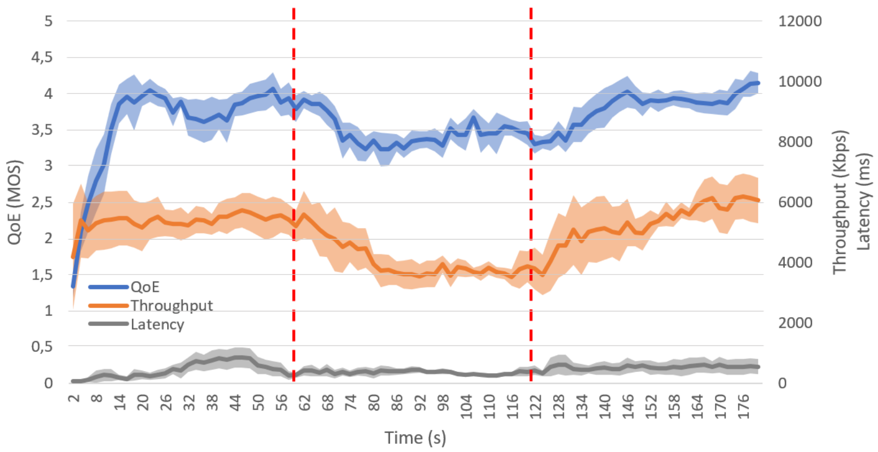


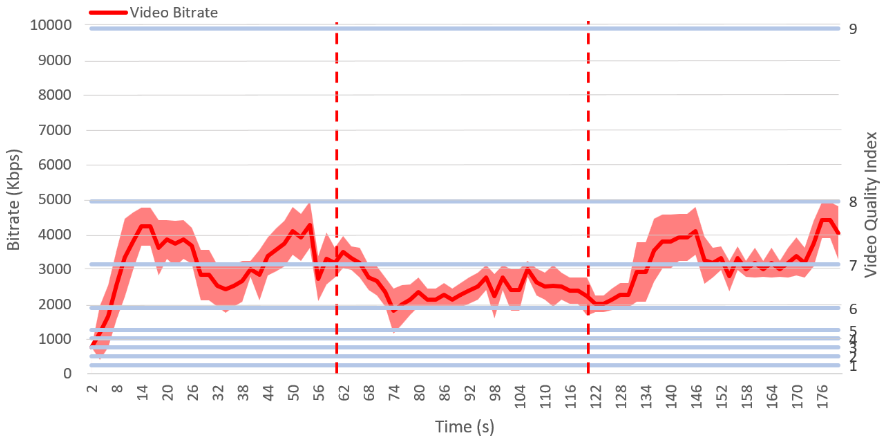
Figure 4.6: Real-world scenario 2 diagram.

division, explained in 2.5.1, is accepted without any modification. Illustrated by Figure 4.7a, during the first minute of streaming, an average QoE MOS value of about 4.0 was registered, with a measured throughput of approximately 6 Mbps, and latency reaching 500 ms. For video bitrate, depicted in Figure 4.7b, there is fluctuation between the 2500 and 4000 kbps values, which can be justified by the initial DASH adaptation process to the network conditions. Figure 4.7c shows the video buffer length, with fluctuation between 5 and 15 seconds. In the second minute, when the vehicle move out of range of Wi-Fi and the video stream is streamed exclusively through WAVE, the measured throughput decreased to 4 Mbps, which then caused DASH to adapt and decrease the streamed video quality, with video bitrates between 2000 and 3000 kbps, causing a subsequent drop in QoE MOS to 3.5. The buffer length observed fluctuated between 10 and 15 seconds. During the third minute, again with the occurrence of multihoming with WAVE and Wi-Fi, the metrics measured converge back to the values observed during the first minute: throughput observed was of 6 Mbps, QoE MOS value of 4.0, increase in video bitrate to values up to 4000 kbps, and similar buffer length behavior.

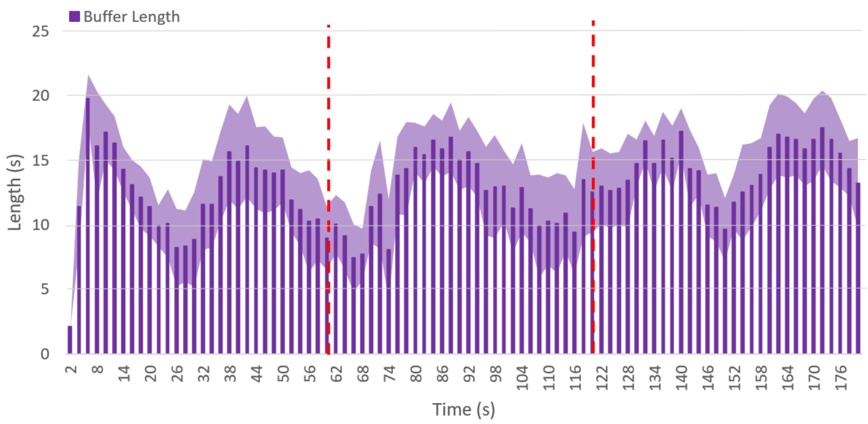
Now using the QoE-aware policy for multihoming load balancing, Figure 4.8a presents the QoE and QoS results for scenario 2. In the first minute, a multihoming situation, the obtained QoE MOS was 4.3, with a mean measured throughput of about 9 Mbps, and latency around 500 ms. Regarding video bitrate, illustrated in Figure 4.8b, a peak to values around 7000 kbps was observed, caused by the initial DASH adaptation to the network that, given the measured throughput, incorrectly requested higher quality video indexes. However, these qualities are not sustainable by the vehicular network, as shown in Figure 4.8c by the rapid decrease in buffer length, reaching 5 seconds and sometimes even caused buffer stalls, followed by DASH adaptation and decrease in video bitrate to values between 4000 and 5000 kbps (Figure 4.8b). The buffer length increases to values between 10 and 15 seconds. In the second minute, segment where multihoming is no longer possible and WAVE is used exclusively, QoE MOS decreased to around 3.5, throughput decreased to the 4 Mbps mark, and latency measured was between 250 and 300 ms. Video bitrate also decreased, fluctuating between 2000 and 3000 kbps, and buffer length stayed between 10 and 15 seconds. The decrease in QoE in this segment is justified by the observed decrease in throughput that caused DASH to request lower bitrate video chunks in order to maintain video playback. In the third minute, using again WAVE and Wi-Fi simultaneously with the QoE-aware policy for multihoming load balancing, the values obtained converge back to the values observed during the first



(a)



(b)



(c)

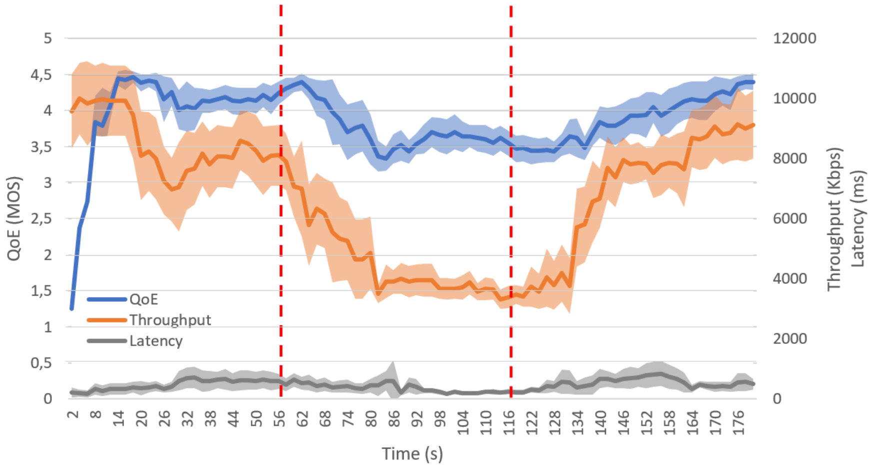
Figure 4.7: Real-world performance in scenario 2 with default multihoming traffic balance. QoE and QoS (throughput and latency) (a), video bitrate (b) and buffer length metrics over time (c).

minute: QoE MOS value increased to 4.3, throughput observed converged to 9 Mbps, video bitrate values up to 5000 kbps, and similar buffer length, that stayed between 10 and 15 seconds.

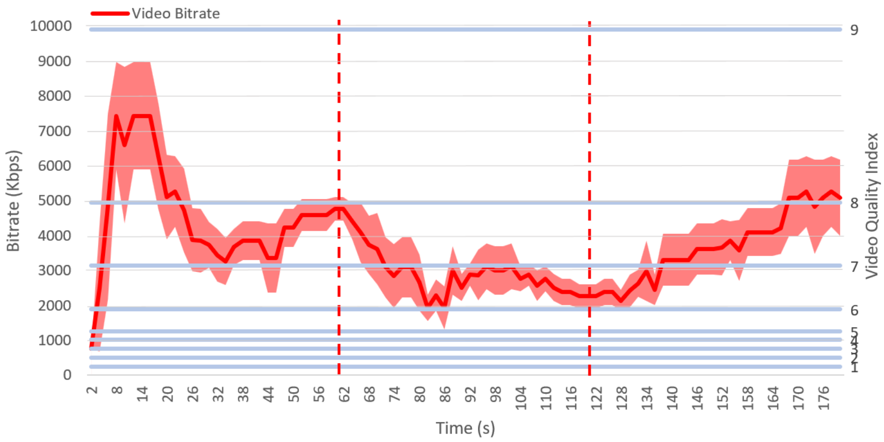
Comparing the obtained results for scenario 2, during the multihoming segments, the first and third minutes, higher values for QoE were obtained when using the proposed QoE-aware policy for multihoming load balancing. Compared to the default multihoming load balancing values obtained, QoE MOS increased from 4.0 (Figure 4.7a) to 4.3 (Figure 4.8a). These are justified by an observed increase in achievable throughput (from 6 Mbps to 9 Mbps), consequence of the minimum utilization rate of Wi-Fi defined in the proposed traffic balancing policy. This allowed the request of higher quality video chunks, resulting in an increase of video bitrate that ranged from values between 3000 and 4000 kbps (Figure 4.7b) to value between 4000 and 5000 kbps (Figure 4.8b). Regarding buffer length, the values obtained range from 10 to 15 seconds both when using the default multihoming load balancing (Figure 4.7c) and when using the proposed policy for multihoming load balancing (Figure 4.8c). However, the mean values obtained are slightly lower when using the proposed policy.

4.5 Summary

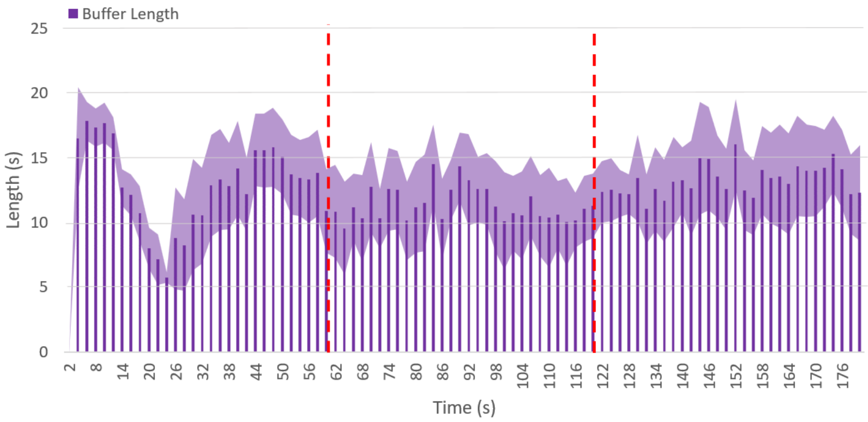
This chapter evaluated the QoE of an adaptive video stream over a vehicular network with multihoming support, where both IEEE 802.11p and IEEE 802.11g technologies were used simultaneously. The results showed the impact on the QoE of using both technologies simultaneously, showing that IEEE 802.11g offers better QoE due to higher bandwidth available, allowing for higher achievable throughputs during the video transmission. With that, a load balancing policy for multihoming scenarios, based on the available access technologies, was proposed to improve the user's QoE. The performance of the proposed policy was assessed in a real-world scenario, in a vehicular network with real hardware and real mobility. Two scenarios, with different multihoming connectivity patterns, were tested and allowed for load balancing situations between WAVE and Wi-Fi technologies. The scenarios displayed consistent behavior and results between them in each of the transmission segments. These scenarios also served the purpose of evaluating the proposed multihoming policy, showing that an increase in QoE is obtained by setting a minimum utilization rate for Wi-Fi in adaptive video streaming.



(a)



(b)



(c)

Figure 4.8: Real-world performance in scenario 2 with QoE-aware multihoming traffic balancing policy. QoE and QoS (throughput and latency) (a), video bitrate (b) and buffer length metrics over time (c).

CHAPTER 5

Conclusions and Future Work

This chapter presents the overall conclusions of this dissertation, and opens discussion for future work.

5.1 Conclusions

The main goal of this dissertation was to study and evaluate, in a multihomed VANET, the impact of traffic balancing policies on the QoE of an adaptive video streaming process. Additionally, the second goal was to improve that QoE by changing those policies. The major contributions of this work can be summarized as follows.

A study of QoE was done regarding an adaptive video transmission over a multihoming VANET. Using a VANET scenario without multihoming, the impact of IEEE 802.11p/WAVE and IEEE 802.11g/Wi-Fi communication technologies in a DASH-based video streaming QoE was analyzed, investigating how distinct network conditions affect the overall QoE. The study managed to successfully assess the QoE over various network conditions and quantify the impact of specific VANET elements in the adaptive video streaming process. It also clearly showed the impact in the QoE performance of each network access technologies by comparing both QoS and QoE metrics for each of the following technologies: WAVE and Wi-Fi. Wi-Fi provides a higher QoE, justified by the increase in achievable throughput when compared to WAVE.

Then, using several combinations of multihoming traffic division, with WAVE and Wi-Fi, it was analyzed how they impact the QoE. With this study, another metric analyzed was the occurence of buffer stalls that were negatively impacting the QoE score when sending higher percentages of traffic through Wi-Fi. However, this negative impact was outweighed by Wi-Fi's increase in throughput, that resulted in the stream of higher video qualities, and ultimately resulting in higher QoE values.

Then, following the QoE assessment results, a QoE-aware multihoming load balancing policy was proposed. This policy favors the Wi-Fi access technology to deliver adaptive video streams, as it showed to benefit QoE. However, and having in mind that vehicular networks are characterized by high volatile connections, a tradeoff between link stability and QoE should be guaranteed. Therefore, even if most of the traffic is sent through Wi-Fi, some is still delivered through WAVE. In real-world experiments, the proposed policy successfully improved the user's QoE when compared to the default use of multihoming, allowing for an increase in real-world performance from a QoE MOS value of 4.0 to 4.3.

With the QoE assessment and the real-world results, we can conclude that, although there is still room for improvement in the proposed solution, the user QoE is improved by applying load balancing policies based on the available access technologies to adaptive video streaming.

5.2 Future Work

This section presents some future work that can be done to improve the current state of the developed work.

QoE Assessment:

- Evaluate the QoE performance hit in adaptive video streaming for different levels of medium occupation, for both WAVE and Wi-Fi. Assess the performance of the implemented multihoming load balancing policy in such environments: creating multiple scenarios with different levels of Wi-Fi medium occupation, assess the impact in QoE performance with the implemented multihoming load balancing policy for adaptive video streaming and compare it with the default load balance. Can the preference for Wi-Fi perform worse than the default multihoming behavior for video streaming in environments with high levels of Wi-Fi noise?
- Study the best Wi-Fi connect and disconnect thresholds to best handle Wi-Fi multihoming and video streaming delivery. Configure OBUs with different connection and disconnection thresholds, so that the Connection Manager only establishes or ends Wi-Fi connection when meeting those threshold requirements. Assess QoE with these Wi-Fi signal thresholds with the load balancing policy proposed in this dissertation.
- Study the impact that vehicle velocity has on adaptive video streaming. In a real-world VANET scenario, experiment with scenarios of adaptive video streaming at several vehicle velocities, analyzing the impact of the vehicle's velocity on the QoE with both WAVE and Wi-Fi technologies, with and without the proposed load balancing policy.
- Study the use of additional access technologies, such as cellular: assess the users' QoE when using cellular to deliver adaptive video streaming. Additionally, experiments can be made with multihoming and different combinations of technologies involving WAVE, Wi-Fi, and cellular.

QoE Improvements:

- Modify the load balancing policy based on the obtained results for the aforementioned studies, to better suit the QoE behaviour and further improve user QoE.
- Minimize the impact of the mobility protocol and mechanisms. With the tunnel utilization to connect the LMA to OBUs, the overhead is highly increased, severely impacting user QoE. A lighter solution should be used.

- Explore technologies that allow higher throughput. By exploring technologies that might provide higher network capacities, as long as other QoS metrics, such as latency, do not get worse, the expected QoE behaviour for adaptive video streaming is to improve, by allowing streaming of higher video qualities, as shown in the QoE assessment of this dissertation.

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