FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Empirical evaluation of 5G and 802.11p for supporting Cooperative Perception Services

João Nuno Barbosa Neves

Mestrado Integrado em Engenharia Eletrotécnica e de Computadores

Supervisor: Ana Aguiar

Co-Supervisor: Pedro d'Orey

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Abstract

With the recent appearance of 5G technology, different use cases that would have been impossible to execute until now are starting to be implemented. From high precision remote surgery, industrial automation, augmented and virtual reality, communication between vehicles, pedestrians, and infrastructures are examples of these use cases. With this last example, V2X communication, we chose to make an empirical evaluation of both 5G technology and the standard used so far for this area, Wifi 802.11p. It is essential that the evolution in this area continues, as it can bring more excellent safety to road users is always very relevant. With this goal, we created a collaborative perception platform in which messages are sent between members of the public road so that everyone has a better sense of the environment around them. Thus, we used a reduced visibility scenario for a vehicle approaching a pedestrian crossing, a common situation on public roads that causes accidents every day. We placed an element with a view of the crossing (RSU) that sends standardised messages called Cooperative Perception Messages (CPMs), which warns nearby elements (OBUs) of the existence of a pedestrian crossing the street. In this way, the vehicle can be aware of the existence of the pedestrian before it sees him and thus, avoid an accident. We created two configurations, one in the vehicle approaching the pedestrian and another in the infrastructure with visibility towards the zebra crossing. Different tests were carried out with a similar configuration on both sides and in which only the communication technology used is different. We used GNSS modules with GPS antennas and clock synchronisation software to have high accuracy in the two configurations, essential for comparing latencies and packet losses. We also used ZED 2 stereoscopic cameras to have good resolution and object detection capability through software libraries developed for this purpose. In 802.11p communication, we used modules that send the data in broadcast using antennas for that purpose. On the 5G's side, we used mobile phones that communicate with each other in unicast through the existing infrastructure in the college. After several attempts, resolution of errors, and existing problems in the configuration, we obtained results that allow a performance evaluation of both communication technologies. From these we extracted data and generated graphs that facilitate the discussion and obtain conclusions. We chose latency, data loss in communication, the amount of data transmitted between the parties and the time gain of the message received versus the local detection of the OBU to be the primary metrics. We got results for all the pipeline latencies where we found differences between both setups. Joining the results from communication latencies with both technologies we could evaluate the performance of the setups created. We also got values for the time gain the VRU Protection System can offer in both communication technologies used with different dissemination rules configurations. In the end we concluded that the system provides higher safety to both vehicle passengers and pedestrians by warning the presence of the latter on the crosswalk. We also concluded that the 5G installation offers latencies higher than expected, which may reduce the time gain of the warnings.

Keywords: V2X, 5G, 802.11p

Resumo

Com o recente aparecimento da tecnologia 5G, diferentes casos de uso que teriam sido impossíveis de executar, até agora, começam a poder ser implementados. Desde a cirurgia remota de alta precisão, automação industrial, realidade aumentada e/ou virtual, comunicação entre veículos, peões e infraestruturas, são alguns exemplos destes casos de uso. Foi com este último exemplo, a comunicação V2X, que escolhemos fazer uma avaliação empírica da tecnologia 5G e da norma utilizada até agora para esta área, o Wifi 802.11p. É importante que a evolução nesta área continue, uma vez que trazer maior segurança aos utilizadores da estrada é sempre relevante. Foi com este objetivo que decidimos criar uma plataforma de perceção colaborativa em que são enviadas mensagens entre membros da via pública para que todos tenham melhor noção do ambiente à sua volta. Assim, usámos um cenário de visibilidade reduzida para um veículo que se aproxima de uma passagem de peões, uma situação comum na via pública que origina acidentes todos os dias, e situámos um elemento com visão para a passadeira (RSU) que envia mensagens estandardizadas e denominadas por Cooperative Perception Messages (CPMs), que avisa elementos por perto (OBUs) da existência de um peão a atravessar a rua. Desta forma é possível que o veículo saiba da existência do peão previamente à visualização do mesmo e assim evitar um acidente. Foram criadas duas configurações, uma no veículo que se aproxima do peão e outra na infraestrutura com visibilidade para a passadeira, e foram feitos diferentes testes com setup comum nos dois lados e em que apenas a tecnologia de comunicação usada era diferente. Utilizámos módulos GNSS com antenas GPS e software de sincronização para ter alta precisão nos tempos das duas configurações, essencial para a comparação de latências e perda de pacotes. Usámos também câmaras estereoscópicas ZED 2 para ter boa resolução e capacidade de deteção de objetos através de bibliotecas de software desenvolvidas para o efeito. No caso da comunicação 802.11p foram utilizados módulos que enviam os dados em broadcast utilizando antenas para esse fim. No lado 5G foram utilizados telemóveis que comunicam um com o outro em unicast através da infraestrutura 5G/LTE existente na faculdade. Após várias tentativas, resolução de erros e problemas existentes na configuração, acabámos por obter resultados que permitem avaliar a eficiência de ambas as tecnologias de comunicação. A partir destes dados foram extraídos e gerados gráficos que facilitam a discussão e a obtenção de conclusões. Escolhemos como métricas principais a latência, a perda de dados na comunicação, a quantidade de dados transmitidos entre as partes e o ganho de tempo existente entre a receção de CPMs relativas ao peão e a deteção local pelo veículo. Obtivemos resultados para todas as latências de processamento onde encontrámos diferenças entre ambas as configurações. Juntando os resultados das latências de comunicação com ambas as tecnologias, pudemos avaliar o desempenho das configurações criadas. Também obtivemos valores para o ganho de tempo que o Sistema de Protecção VRU pode oferecer em ambas as tecnologias de comunicação utilizadas com diferentes configurações de regras de disseminação. No final, concluímos que o sistema proporciona maior segurança tanto aos passageiros dos veículos como aos peões, avisando sobre a presença dos últimos na faixa de pedestres. Também concluímos que a instalação 5G oferece

latências superiores ao esperado, o que poderá reduzir o ganho de tempo dos avisos.

Keywords: V2X, 5G, 802.11p

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João Neves

"If you can't explain it to a six year old,
You don't understand it yourself."

Albert Einstein

Contents

List of Figures

List of Tables

Abbreviations

ADAS	Advanced Driver-assistance systems
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CPM	Cooperative Perception Message
DENM	Decentralized Environmental Notification Message
ETSI	European Telecommunications Standards Institute
FEUP	Faculdade de Engenharia da Universidade do Porto
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPSd	Global Positioning System Daemon
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITS	Intelligent Transportation Systems
LTE	Long Term Evolution
mMIMO	massive Multiple Input Multiple Output
MAC	Medium Access Control
NR	New Radio
OBU	On-board Unit
PHY	Physical
ROS	Robotic Operative System
RSU	Road-Side Unit
SSH	Secure Shell Protocol
SSID	Service Set Identifier
URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User

Chapter 1

Introduction

Recent advances in mobile network technology have made everyday life easier for everyone, and their influence on the industry has led to the development of the next generation of wireless networks. Since the inception of mobile communications, the focus has been on improving the speed and efficiency of networks, but there are still many areas where wireless networks must improve: The healthcare industry, industrial automation, or virtual and augmented reality services are some of the examples of applications that can directly benefit from the quality of services offered by new wireless technologies [22][37].

The work we made focuses on V2X communications, by empirically evaluating the performance of the IEEE WiFi amendment 802.11p [23] versus the 3GPP 5G-NR technology [15]. We took advantage of a previously developed Cooperative Perception System that used 802.11p for inter-vehicular communication, and we improved the platform by making possible the utilization of 5G. We then developed a set of experiments in scenarios where we could evaluate the capabilities of both technologies by using the results as input for software-made plots.

As of today there are already many ADAS use cases implemented that offer higher security to pedestrians and passengers. In [39] we can see some of these use cases like Low Speed Follow + Adaptative Cruise Control, Lane Departure Warning and Lane Keeping or Emergency Break Assistant. Regarding V2X, it is possible with new technology to increase the ability of vehicles, infrastructures, and pedestrians to communicate with each other to increase the safety and efficiency of transport. This brings the possibility of implementing other ADAS use cases which offer even higher safety. In [27] the authors enumerate some interesting warnings that the infrastructures can give to vehicles like alert the on Pedestrian dangers, as we do on this thesis, road congestion and traffic flow analysis, hazard driver behaviour detection, weather condition analysis, traffic signs control and message boards.

The Cooperative Perception System makes possible the communication between the various nodes of the network through messages already standardized by ETSI and called Cooperative

Perception Messages (CPMs) [16], an evolution of what was initially proposed and called Co-operative Awareness Messages (CAMs) where only awareness warnings would be sent and not specific messages with data obtained by the various sensors on the road. By having all nodes sharing information it is possible to ensure several improvements to the perception of the surrounding environment of the road users, bringing higher safety to who is inside the vehicles and to the Vulnerable Road Users (VRUs).

It is estimated that 5G could bring added value in these areas due to the low latency, high speed and robustness, spectral efficiency, and low power consumption that it is associated with [31][38]. Furthermore, according to a report published by Nokia Communication [11], between 2020 and 2030, there will be an increase of 10000 times more traffic between mobile networks, which can only be supported by a 5G network with an architecture capable of establishing connections at high frequencies, low power consumption, and low latency so the traffic density should be something to take into account when evaluating the both technologies

1.1 Motivation

Every year about 1.35 million people die on the roads, a statistic that may be changed for the better with the implementation of these road safety and prevention systems. Being a relatively new technological area there is still plenty of room for evolution, not only regarding 5G but also the integration of the technology in already existing infrastructures that despite not having the ideal characteristics can have their performance improved to maximize the reach of the use cases[24].

1.2 Objectives

Our aim is to make an empirical evaluation, comparing the performance of the 5G technology using the recent infrastructure installed in FEUP with the current standard for Intelligent Transport Systems (ITS), 802.11p. The comparison should be made to conclude the advantages and disadvantages of each technology in the scenario we used. To this end, a scenario was set up in which there is a Road Side Unit (RSU) detecting people on a pedestrian crossing and sending CPMs with this information to the On Board Unit (OBU) which is approaching the crossing. The objective is then to calculate the time gain which is equal to the time when the message is received and processed by the vehicle versus the time when the vehicle detects the pedestrians crossing the street. This gain will depend on the performance of the data transport network since the one with lower latency and higher reliability will bring better results. We follow the existing standard about sending CPMs to maximise the relationship with a real scenario. From here we evaluate both technologies using logs made in the experiments as input for plots that specify latency, processing chain timelines, local detection versus received information, among others.

1.3 Document Structure

The present document is structured as follows. In chapter 2 we present a literature review to define the state of the art; In chapter 3 we define a generic cooperative perception system describing each of its building blocks; In chapter 4 we describe the problem we face and the ways we chose to reach a reasoned solution. Then, in chapter 5 we evaluate results and discuss the metrics considered relevant to assess cooperative perception systems and test methodologies; Finally, in chapter 6 we make the end conclusions and suggest future works.

Chapter 2

State of the art

In this Chapter we will resume the studies developed on the state of the art regarding the topics approached in this thesis. We will start on the 5G technology on Section 2.1, focusing on the advantages it may bring on mobility scenarios and specifying the Release we take into account for this project, in Section 2.1.1 Since we used the 5G infrastructure at FEUP we only focus on the capabilities it has and not what will have. We then demonstrate the current state on Vehicular to Anything (V2X) communication using 802.11p, in Section 2.2, since it is the standard technology used to approach mobility scenarios. We will also mention the standard V2X message construction and dissemination that we used as mean of transport of data between the Road Units in Section 2.3. Finally there will also be mentioned works made that we took into account due to the similarity of the projects in Section 2.4 and some final notes regarding this chapter in Section 2.5.

2.1 5G in mobility scenarios

5G provides a highly scalable network technology for V2X scenarios where vehicles, pedestrians, infrastructures and the network are connected. In our case it still uses LTE for connection control but the data sent and received is through 5G hardware, providing a resilient core system with end-to-end support. It requires that all connections travel to the main core, a fact that will directly impact this thesis's results and it is on developing by our service provider to be made independently in the future for each physical infrastructure.

2.1.1 Release 14 and 15

Releases 14/15 introduced the LTE-V2X (Vehicle-to-everything) communication service, side link design specifically addressed for high speed and high-density scenarios [19]. This is the starting point for the evolution of applications that have so far not been supported by mobile communications technologies [18]. From this point on, the first use cases of communication appear for basic safety messages (BSMs), cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENMs). Some examples of these use cases can be seen on Figure 2.1.

Figure 2.1: Release 14 Use Cases - From [19]

V2X use-case description	Min End to end Latency (msec)	Max Reliability (%)	Minimum communication range (meters)
Platooning: Cooperative driving with information exchange between platoon leader and group of vehicles	10	99.99	0-350
Advanced Driving: Vehicle shares its driving intention with vehicles in proximity such as cooperative maneuvers and Emergency trajectory alignment between vehicles	3	99.999	60-700
Extended Sensor: Exchange of raw or processed data gathered through local sensors or live video images among vehicles	3	99.999	0-1000
Remote Driving: Remote driver or a V2X application to operate a remote vehicle for those passengers who cannot drive by themselves or remote vehicles located in dangerous environments	5	99.999	N.A.

In Release 15, New Radio (NR) is started simultaneously to the development of LTE. While mobile communications remain the main focus, critical machine-type communications including V2X services are also starting to be of great importance[12]. Here, the basis for Ultra-Reliable Low Latency Communications (URLLC) in 5G is developed, especially concerning low latency communications. For massive machine type communications (mMTC), the NR is complemented by communications technologies known as LTE-M and Narrow Band IoT (NB-IoT) developed by 3GPP in Release 13 which provides low-power wide-area performance covering a wide range of data rates and deployment scenarios. It should be noted that progress is made taking into account the compatibility between technologies, which enables the phased implementation of systems in the real world. Thus, the second phase of 5G is standardized in Release 16 [21].

2.2 802.11p in V2X communication

The WAVE protocol stack is composed of several components, most notably the IEEE 802.11p which is essentially an IEEE 802.11-based standard adapted for the vehicular networking environment. The noteworthy characteristic of the PHY layer is the reduction to 10 MHz bandwidth from

IEEE 80.11a 20 MHz, which halves the data rate to 3 to 27 Mbps from 6 to 54 Mbps. The IEEE 802.11p MAC is 802.11e Enhanced Distributed Channel Access (EDCA) with quality of service (QoS) support.The PHY layer and the MAC layer together allow *adhoc* communication among OBUs as well as between OBUs and the RSUs. The absence of infrastructure-assisted channel access mechanism and wireless communication among high-speed vehicles over the varying channel condition possesses significant challenges in terms of overall network performances[13]. In [28] the author shows the performance of 802.11p latency times in a scenario with the distance increasing from 5 to 100 meters.

2.3 Cooperative Perception

The existence of autonomous vehicles requires the installation of sensors in cars that can detect the environment and understand it in a short time. However, the presence of obstacles and adverse weather conditions can prevent the sensors from performing the perception successfully. This perception of the environment can be improved by using wireless communications to exchange data between nearby vehicles so that everyone has a better sense of the space around them. This data exchange is known as cooperative perception[35]. It started with Cooperative Awareness Messages, explored in the next section, and it evolved into Cooperative Perception Messages, which we use on this dissertation for communication between V2X nodes.

2.3.1 Cooperative Awareness Messages

The ETSI ITS G5 standard [17] defines these data exchanges as Cooperative Awareness Messages (CAMs). With these, the vehicles have the ability to maintain awareness of each other and improve the efficiency of the journeys they make. These messages are periodic and include vehicle status information such as time, position, direction, active systems, among others. But they also include information on attributes such as dimensions, type of vehicle, and role on the road, which can be personal vehicles, public transport, goods, etc. The vehicles that receive these messages become aware of the presence of the transmitting vehicle, thus being able to warn the driver about possible collisions and improve the route in the short term, for example by changing lanes on the motorway, or in the long term by changing the route to the destination when they know of a collision that happened nearby. In [14], the authors make an empirical evaluation of CAMs in vehicular communication and demonstrate that cooperative awareness is strongly dependent on the transmitter-receiver separation and the propagation conditions, with neighbour interference being a high importance factor too. This analysis could also be made on our project but it wasn't our focus.

2.3.2 Cooperative Perception Messages

This technology has evolved into Cooperative Perception Messages where more information is sent because the vehicles have sensors capturing the environment around them. In a CPM there is an ITS PDU header and 4 types of containers: Management Container, Station Data Container, Sensor Information Container (SICs) and Perceived Object Containers (POCs). The header includes Data Elements as the protocol version, the message ID, and the station ID. The Management Container is mandatory and provides basic information regarding the transmitting vehicle, such as its position, used by the receivers as a reference to know the location of the objects. The Station Data Container is optional and includes additional information about the transmitting vehicle such as its speed, direction, and acceleration. Besides, the CPM can include up to 10 SICs to describe the capabilities of the sensors in the vehicle. Finally, POCs contain information about the detected objects such as the distance between the object and the transmitting vehicle, its speed if any, the dimensions, and the time at which the object was detected. Each CPM can include up to 255 POCs[16].

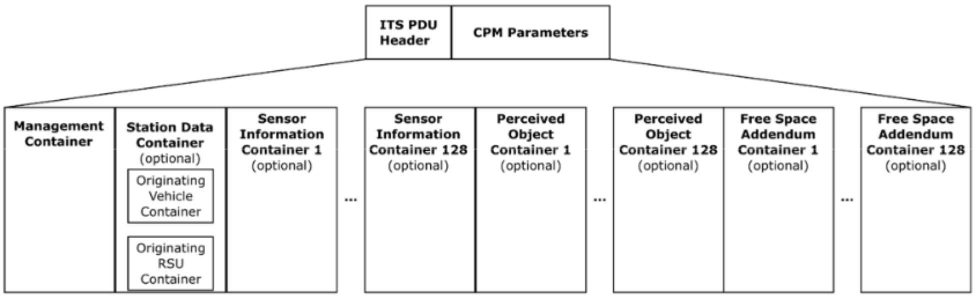


Figure 2.2: CPM Packet (From ETSI TR 103 562)

The standard also defines the rules for the generation and dissemination of CPMs. The vehicle has to check at each T_GenCpm whether a new CPM should be generated and transmitted. By default, T_GenCpm is equal to 100ms but can be changed to any multiple of 100ms between 100ms and 1000ms. At each T_GenCpm, a vehicle must a CPM if it detects a new object, or if any of the following conditions are met for any of the previously detected objects:

- **1** – Its absolute position has changed more than 4m since it was last included in a CPM;
- **2** – Its speed has changed by more than 0.5m/s since it was last included in a CPM;
- **3** – The last time you were added to a CPM was 1 or more seconds ago.

In [32] the authors demonstrate how by using CPMs it's possible that a connected vehicle (CV) can "see" a pedestrian around the corners. They also demonstrate how connected and automated vehicles can autonomously and safely interact with walking and running pedestrians, relying only on the CP information from the intelligent RSU through vehicle-to-infrastructure (V2I) communication. In [20] the authors make a simulation study about both the provided service quality for receiving Intelligent Transport System stations and the generated network load on the employed radio channel, and provide a set of generation rules for the Collective Perception Service that provides a trade-off between these two factors. They show that depending on specific radio channel and Decentralized Congestion Control settings, the simulations reveal co-existence challenges with other services and messages disseminated on the same channel, e.g., the legacy Cooperative Awareness Messages. In [36] the authors also focus on generation rules and the content of the messages. They show that generating a high number of messages results in an inefficient use of the communication channel that reduces the effectiveness of collective perception. They propose a different algorithm where they compute for each detected object the difference in absolute position, speed and time elapsed since the last time the detected object was included in a CPM. This proposal ended up being adopted as the current standard aforementioned.

In the results they demonstrate that the proposed solution improves the reliability of V2X communication and the perception of CAVs.

2.4 Related Work

In this section we mention some works made around this topic that bring interesting conclusions and help us identify the evaluation metrics relevant to be tested and others we may not be able to test but should take into account regarding the final conclusions. In [13] the authors make a performance evaluation between LTE and 802.11p, much like what we do in this project but replacing LTE with 5G. They define vehicle density, vehicle speed and beacon transmission frequency as parameter settings for the experiments. Beacon transmission being the CAMs that were the standard in the time of making of the paper. It is concluded that IEEE 802.11p offers acceptable performance for sparse network topologies with limited mobility support. On the other hand, LTE meets most of the application requirements in terms of reliability, scalability, and mobility support; however, it is challenging to obtain stringent delay requirements in the presence of higher cellular network traffic load.

2.5 Final Notes

It is also important to report that the Collaborative Perception platform oriented to the protection of vulnerable road users that we developed was started in a previous project where it was already possible to send CPMs between setups using 802.11p technology. Our contribution to this platform was the implementation of the protection use case by using 5G and the classification of detected objects. Subsequently, the time gain is calculated between the local detection that is made of the vehicle approaching the zebra crossing, with the moment when the warning reaches it. We have also implemented 5G communication technology as an alternative to 802.11p independently of the rest of the setup. We also developed software for creating graphics that allowed us to empirically evaluate both technologies.

Chapter 3

Cooperative Perception System

Cooperative perception consists of sharing information in real-time between different elements of the network in situations that can improve the sense of the environment that surrounds them. Depending on the quality of service offered by the network, raw data from the sensors and cameras available to each of these elements can be shared, or processed and sent according to a common standard that facilitates the fusion of the information received.

Autonomous vehicles and Advanced Driver-assistance systems (ADAS) take advantage of this type of system because it improves the quality of driving due to a better perception of the space around them[26]. In a situation of reduced visibility, this information complements the awareness that the vehicle lacks, something that happens many times on the road. Taking into account the high mobility of vehicles and pedestrians in the system, the requirement regarding the delay with which this information is sent is very high. Hence the need for a robust system that not only reduces the delay but also has a low error percentage.

Therefore, the standardisation of this type of system has become increasingly mature as technology evolves, and in this chapter, we will describe its architecture and how we can ensure it meets the requirements.

3.1 Building Blocks

Figure 3.1 shows the architecture of the system regarding the blocks that constitute it. Initially, images are acquired by the ZED 2 cameras, where elements of interest will be detected and processed. This information is sent to the respective board (TX2 or Xavier) which is running a Publish-Subscribe pattern[34] using the Robot Operating System (ROS), an open-source robotics middleware suite. After that, the information received is encapsulated in messages to be sent by the communications part, which will be 802.11p or 5G, being this the part of the system that we want to evaluate. Taking advantage of this pattern we can publish logs while the tests are happening with information about the Cooperative Perception Messages (CPMs) sent that help us build plots for further evaluation and comparison of technologies. In this way, we could easily discuss the results and improve the platform regarding its performance and evaluation methods.

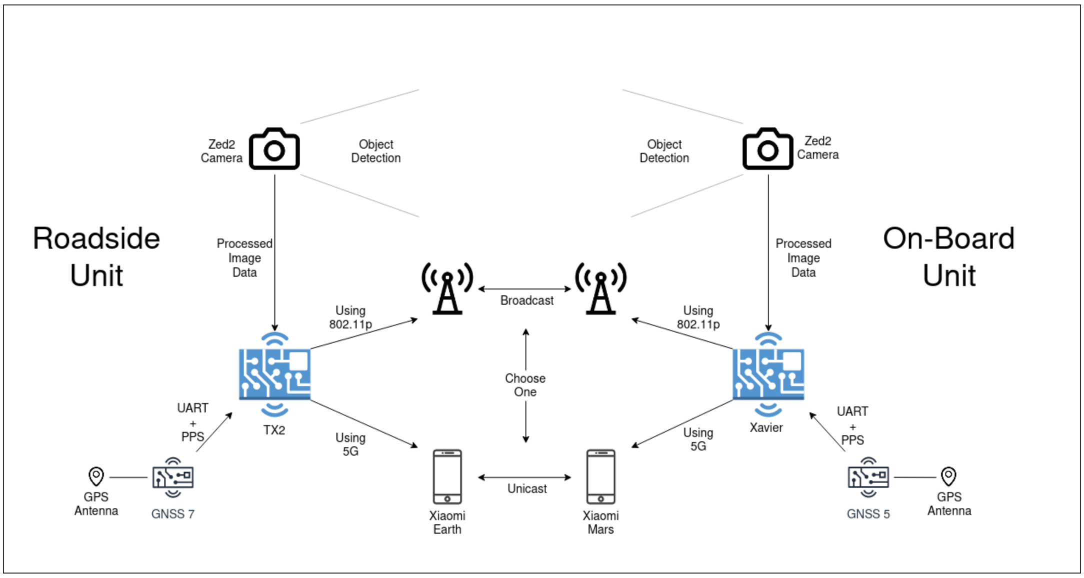


Figure 3.1: Building Blocks

3.1.1 Image Acquisition and Sensor Data Processing

The image acquisition is made by ZED 2 cameras that combine 3D sensing with artificial intelligence to create high-quality spatial awareness and thus provide data regarding the detection of objects of interest for the system, in this case, pedestrians and other vehicles[3]. The processing of these images is done in ROS using libraries made for the cameras that display the detected objects in real-time including their bounding boxes, position, speed, among others. This way it is possible to use this data to build the messages to be sent without considerable delays.

As previously mentioned, the video capturing hardware used was the ZED 2 AI Stereo Cameras from Stereolabs 3.2 equipped with Wide-angle all-glass dual lens with optically corrected distortion providing 110°(H) x 70°(V) field of view and 0.2 - 20 meters depth range. They have object detection and can classify objects between persons or vehicles.

They also can track the objects and output the speed, location and bounding boxes in 2D or 3D. It is also possible to configure the video output in the following ways:

Table 3.1: ZED 2 Video Output Options

Video mode	Frames per second	Output Resolution (side by side)
2.2K	15	4416x1242
1080p	30 / 15	3840x1080
720p	60 / 30 / 15	2560x720
WVGA	100 / 60 / 30 / 15	1344x376

Figure 3.2: ZED 2

Since we need good resolution for optimal object detection we chose 1080p Video mode at 15 frames per second as the way to go. As we will explain in Chapter 5, the setup's performance had impact on this decision. The two lenses present in the camera work at the same frame rate as the one configured as video output. The data is first created in raw format and encoded using Bayer Encoding for further processing. By using a radial and tangential distortion model called plumb bob it is possible to have the distortion correction created by the use of two lenses. After these correction tasks, it is possible to determine the depth data and 2/3D bounding boxes for the objects detected at each frame. In the end, the information captured by the camera is published in the image topics.

As for the software part, the images are published in different topics to which it is possible to subscribe. From here, we can receive the images in different formats (raw or any combination of colour/monochrome and distorted/rectified) where we are able to conclude if it is working as expected comparing with the configuration made.

3.1.2 Boards and Robot Operating System

From here is described how the setup used organises the data published by the camera and sends it using CPMs. Starting with the hardware we used a Jetson TX2 board and a Jetson Xavier from Nvidia, which can be seen in Figure 3.3.

Table 3.2: Specifications of the boards used [2]

	Xavier	**TX2**
Compute Performance	6 TFLOPS (FP16)	1.3 TFLOPS (FP16)
GPU	NVIDIA Volta architecture with 384 NVIDIA CUDA® cores and 48 Tensor cores	256-core NVIDIA Pascal™ GPU architecture with 256 NVIDIA CUDA cores
CPU	6-core NVIDIA Carmel ARM®v8.2 64-bit CPU 6 MB L2 + 4 MB L3	Dual-Core NVIDIA Denver 2 64-Bit CPU Quad-Core ARM® Cortex®-A57 MPCore
Memory	8 GB 128-bit LPDDR4x	8GB 128-bit LPDDR4

(a) Jetson Xavier NX

(b) Jetson TX2 Developer Kit

Figure 3.3: Nvidia boards used

In Table 3.2 we present some technical specifications of both boards. It is noticeable from the hardware difference that the Xavier board is better and therefore should have better performance. The difference between the number of floating point operations and the difference in the GPU's specifications are the most notable. Jetson Xavier NX is packed with the newer Volta Architecture[8] equipped with Tensor cores which are properly designed to handle machine learning libraries like Tensorflow[5], that it's used on the object detection algorithms. This will have an impact on how we decide which one takes which place in the experiments and will also influence the results.

The reason for choosing this hardware is due to the already established interconnection between the operating system used, Linux Tegra, the ROS middleware and the SDK from Stereolabs for the ZED 2 camera. Coupling this with the zed-ros-wrapper library we have a platform formed between the components that allow the reception of data sent by the camera from already defined topic subscriptions. This project was made using ZED SDK 3.2.2[7] for the cameras and Nvidia Jetpack 4.4[8] Deep Learning libraries empowered by TensorRT[9], a high performance deep learning inference runtime for image classification, segmentation, and object detection neural networks. We also use the 3.1 version of the zed-ros-wrapper library[6].

It is also possible to create new topics and post to them and thus get relevant information after the experiments. In the figure 3.4 there is a graphic example of the existing nodes in our setup and the respective subscription/publishing of messages by them. Note that nodes are represented by ellipsoid areas while topics are the rectangular areas. Some critical things to understand about this graph are:

- The **/zed2** box represents the default nodes and topics available with the zed-ros-wrapper library while the other ones were created by us.

- The **/cp_udp_receiver** node takes care of the CPM received and publishes the information to two topics, one for system awareness and the other for log files.

- The **/gpsd** node publishes in the **/fix** topic the current position of the setup which is subscribed by the main node **/cp_service** to join with the other information.

- The **/cp_service** node is the main node for sending information through publish on the **/cpm_raw_out** topic and further subscription by the **/cp_udp_sender** node.

- The **/rosbag_real** is the main log generation node from where we take the input data for the plots after the experiments end.

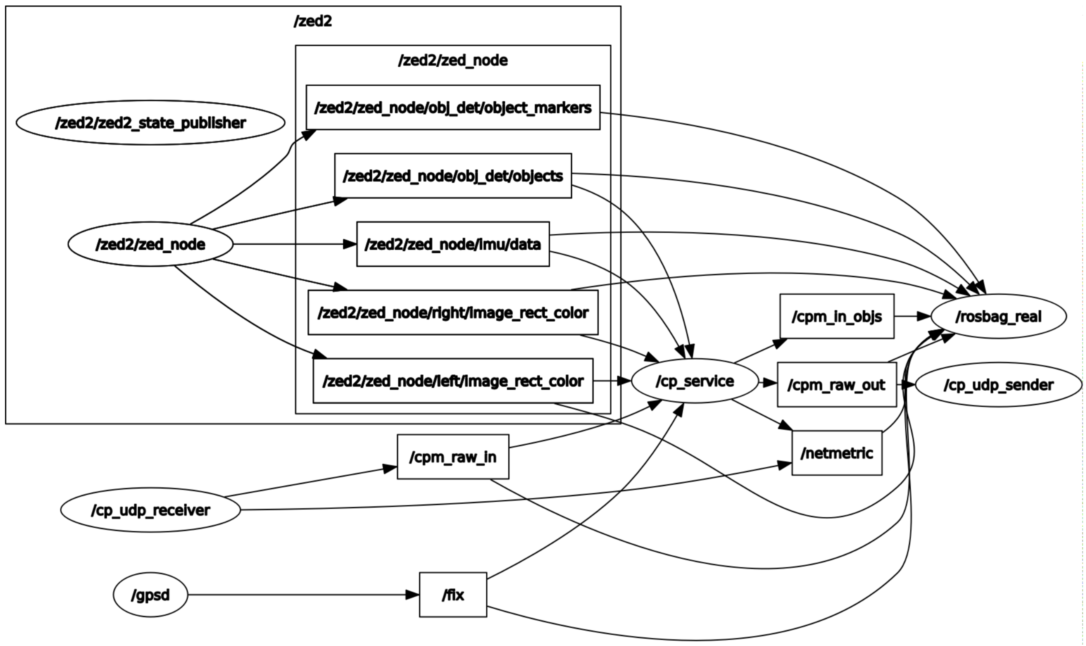


Figure 3.4: ROS Operations

In the figure 3.5 it is possible to see an example of a message published by the node defined by the left lens that contains a frame before any compression.

```
# This message contains an uncompressed image
# (0, 0) is at top-left corner of image
#

Header header        # Header timestamp should be acquisition time of image
                     # Header frame_id should be optical frame of camera
                     # origin of frame should be optical center of camera
                     # +x should point to the right in the image
                     # +y should point down in the image
                     # +z should point into to plane of the image
                     # If the frame_id here and the frame_id of the CameraInfo
                     # message associated with the image conflict
                     # the behavior is undefined

uint32 height         # image height, that is, number of rows
uint32 width          # image width, that is, number of columns

# The legal values for encoding are in file src/image_encodings.cpp
# If you want to standardize a new string format, join
# ros-users@lists.sourceforge.net and send an email proposing a new encoding.

string encoding       # Encoding of pixels -- channel meaning, ordering, size
                      # taken from the list of strings in include/sensor_msgs/image_encodings.h

uint8 is_bigendian    # is this data bigendian?
uint32 step           # Full row length in bytes
uint8[] data          # actual matrix data, size is (step * rows)
```

Figure 3.5: Image Message Published by the Camera

3.1.3 Cooperative Perception Messages

After receiving the data from the cameras the software organizes it following what is stated in the standard for Cooperative Perception Messages[16]. In this specification, a focus is made on reducing network load by defining strategies to reduce message size. For example, raw data cannot be sent over the network, rather object detection information should be in the form of bounding boxes. However, these objects can be the result of mixed information from multiple sensors or from prediction algorithms when new object data is not available, according to the standard. Using object tracking and only one ZED 2 camera per car as sensor, the following algorithm will be used:

- At the start, all new objects will be stored in a list
- Then, when there are new objects the list will be appended. If an object with the same id was already present the older detection will be discarded.
- When dissemination rules are met, a CPM is generated with the objects from the list and the list is emptied.

Regarding the dissemination rules, Intelligent Transportation Systems (ITS) stations should generate a CPM when new objects with enough level of confidence are detected. When there are no objects detected, a CPM should be generated periodically to inform other stations of its ability to send messages. This rule aims to balance frequent updates of detected objects while minimizing network usage. Thus, minimum and maximum time intervals in which a CPM should be generated are defined, as was previously mentioned in Section 2.3.2. The detected objects included in a CPM should meet certain parameters to be selected for transmission, like its velocity, acceleration and heading. Besides that, data included in each CPM should be reduced by omitting information during specific time intervals. For instance, information about the sensor specifications, which include the sensor's field of view, is only generated if its timeout specification has not ended.

Moreover, an encoded CPM has a maximum length. If this length exceeds its maximum, messages should be segmented and objects should be sorted as the product of its confidence and speed in a descending fashion. To reduce network utilization by the duplicate dissemination of the same object by different ITS stations, duplicate redundancy mitigation techniques are enabled when a certain threshold of network load is reached. In the setup we created first dissemination rule regarding new detected objects is always respected but there's an option to activate and deactivate the periodicity of dissemination so we can see the impact that these have on the results. If it's activated a CPM is generated if:

- A new object is detected and 100 milliseconds have passed since the last one sent (standard's maximum rate)
- If 1 second has passed since the last dissemination, send CPM (standard's minimum rate)

This was done to contradict the tendency of the system to send more CPMs on the OBU's side, as it normally operates at a higher frame rate, filling the batch first and sending objects at a higher frequency than the RSU. In Chapter 5 we present the results with these rules activated and deactivated to show the impact of said directives.

3.2 Network and Dissemination

The network part of the system is where we try different configurations to evaluate the performance of each one in very similar scenarios. The first configuration uses a communication module that includes an IEEE 802.11p capable radio. It disseminates the messages by broadcasting them to nearby receptors which in this case was the other system. This brings the advantage of not using servers or access points which will cut out operations that happen in a scenario with servers.

The other configuration uses 5G for data transferring and LTE for control messages with the non-standalone system installed at FEUP. We make it work by using each 5G phone as modem to a Raspberry Pi working as an interface bridge between the boards and the phone and configuring the connection to be unicast between the phones, as seen in Figure 3.6. We used the Raspberry Pi because the board's architecture doesn't support the necessary kernel modules for USB tethering to work but the solution we found should not bring any additional delays to the communication.

3.3 Time Synchronisation

It is highly important to have good time synchronisation since the delays observed are sometimes units of a millisecond. To satisfy these demands we use GPS antennas connected to a Global Navigation Satellite System (GNSS) module that offers timestamps with error estimation from real-time around the unit of a microsecond as we can see on Figure 3.7. It is a screenshot of both boards while connected to the GNSS and using the Chrony application to receive the GPS signal and use it to synchronize the clock.

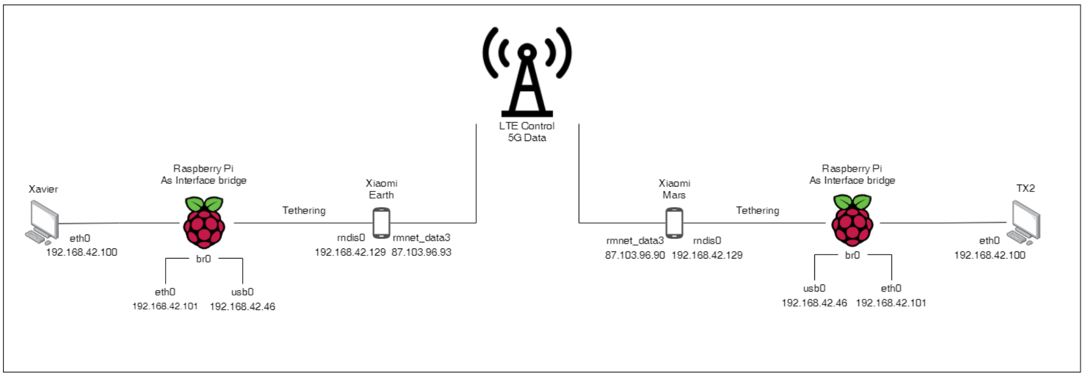


Figure 3.6: 5G Network Architecture

The ublox GNSS's sensor was configured with u-center, a manufacturer tool that can be used to visualize sensor data and perform configuration[10]. Some of the parameters equally configured in both setups where **Navigation Rate**, that specifies the rate at which the sensor outputs new location data; **GNSS systems**, that allows to choose GPS and Global Navigation Satellite System (GLONASS) as the constellations used since those have shown to result in a greater number of satellites detected; **Baud rate**, that defines the speed of the serial communication between the sensor and the host. Due to the increased navigation rate it was required to change baud rate to 115200.

In order to synchronise time, a clock source and a synchronisation algorithm is needed. For mobile nodes it is common to use either an internet time or GNSS sensor as a time source. For synchronisation algorithms Network Time Protocol Daemon (NTPd) and Chrony clients are the most commonly used. Soares et al. [33] have done experiments of several common synchronisation protocols and concluded that by using Chrony Network Time Protocol (NTP) client with GPSd and the GNSS sensor's PPS signal yielded the best results. Since our project already required a GNSS, the implementation effort was low so it was the chosen option.

At the end of the experiments, we use the logs to generate plots about the processing pipeline, packet reception, packet latency, among others, as functions of time. In the end, we compare the results so we can improve the platform and make conclusions about situations where one configuration out-performs the other.

3.4 Improvements to the Platform

Taking into account that the development of the collaborative perception platform started in a dissertation project before this one, changes and improvements were made to adapt the results obtained to the proposed objectives.

Firstly, object classification (person or vehicle) by changing the algorithm in the code that processes the information received when subscribing objects detected topic. With some development in the code, it was possible to have the differentiation of the object detected by the camera, relevant

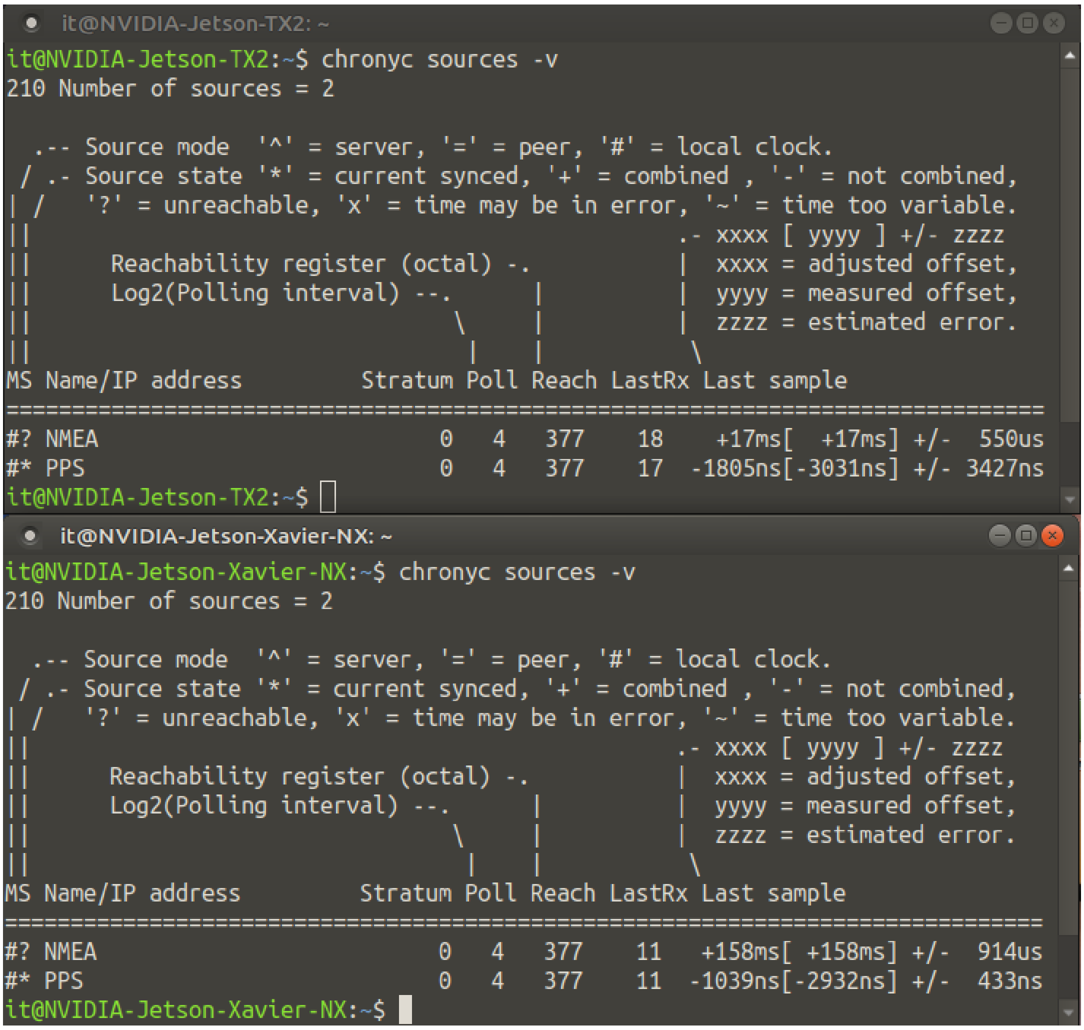


Figure 3.7: Time Synchronisation with Chrony

information that allows easier comparison of time gains in the local detection system versus the reception of the same object by the second system.

Secondly, the possibility of changing the technology used for communication between 802.11p and 5G. Being this the focus of the empirical evaluation of the thesis it was essential to add this option to the platform. With few changes in the hardware connections and small changes in the code regarding network configurations it is possible to change the way how the systems communicate, due to the independence between elements of the system.

Finally, the elaboration of data processing code to build graphs showing results that until now would not be relevant. We took advantage of the many logs created by the subscription of different topics and created plots that represent:

- Latency
- Packet Loss

- Object Detection vs Objects received from CPM as function of time and distance
- Time between operations such as
  - Frames
  - Object detection
  - CPM sent
  - CPM received

The automation in the generation of these graphs was also taken into account to reduce the time between tests and discussion of results.

Chapter 4

Vulnerable Road User Protection System

As previously mentioned in Section 1.2, the objective lies in finding out the performance of both technologies in a mobility scenario in order to bring higher security to the Vulnerable Road User (VRU), since these are the most unprotected in any accident scenario. In this chapter, we will explain the problem we face and how we decided to solve it. There will be a Challenge and Objectives section where the situation and solution are briefly specified. Secondly, the requirements that exist for the realization of the experiments. Then a scenario description with the reasons why we chose to make it this way, and also a section regarding evaluation metrics used to confidently evaluate and compare both technologies. Finally, there will be a section regarding some technical problems we faced in performing the tests, in developing the platform and how these were solved.

4.1 Challenge & Objectives

It is possible to simplify the challenge we set out as follows: How can we empirically evaluate the performance of two communication technologies associated with a V2X communication environment? The solution involves conferring the following objectives:

- We needed to create a platform where the setup is independent regarding the communication technology used so that the only part that changes between tests is the part we want to evaluate.
- It is also necessary that the experiments are carried out in a scenario where it is possible to use both technologies without one having performance setbacks concerning the other.

The goal is at the end of the experiments to have data that allows being inserted in the same code making graphs for a good performance evaluation of both setups.

4.2 Requirements

Firstly, a stable testing platform in a road environment is required. Through the setup created it is possible to perform the tests in the field using power inverters connected to a car. After simple calculations, it was verified that the necessary power for the elaboration of the tests in the maximum performance is 45W from the Jetson TX2 plus the 802.11p communication module and the power offered by the inverters is 75W.

The next requirement concerns the need for a scenario where it is possible to calculate the time gain when receiving messages about detections relevant to the vehicle path. We need to choose a place where there is poor visibility of vehicles in some situation where the information about objects detected in the road can bring a time gain for vehicles to stop. Regarding the time of the day, it's also required to make the experiments on a sunny day so that the cameras can detect every perceivable object without light being an obstacle. We also need to ensure that the experiments can be made safely and without constraining the traffic running at the moment.

Alongside this, the location must allow both technologies to offer the best quality of service. On the 802.11p's side, there are no problems in the chosen location as the communication is direct and does not depend on external servers or antennas. In the case of 5G, the antenna is fixed on building A of the college so the chosen location has to take that into account. Fortunately, a thesis is running at the same time which, among other things, analyzes the 5G's environment in the college area and according to Figure 4.1 the 5G's signal quality in the test area (between 150 and 300 meters) is sufficient for the technology endorsement.

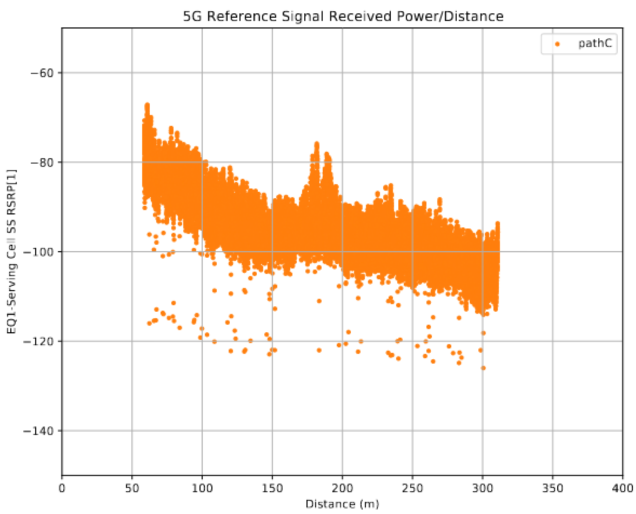


Figure 4.1: Reference Signal Received Power in the experiments area

Efforts have also been made to make sure that the independence of the communication technology and the rest of the setup is well marked. In this way, it is possible to test both technologies at once and thus obtain results with the closest possible proximity regarding the external factors previously specified. The platform should also provide the tools for log generation from the experiments in a way that is easy to deal with so the plots can be automatically created without major changes to the code.

As summary of this section we list all the hardware necessary for the experiments:

Table 4.1: List of hardware for experiments

Road Side Unit	On-Board Unit
Jetson TX2	Jetson Xavier NX
ZED 2 Stereo Camera	ZED 2 Stereo Camera
GNSS 7	GNSS 5
GPS antenna	GPS antenna
Veniam NetRider 802.11p + Antenna	Veniam NetRider 802.11p + Antenna
Car Lighter Power Inverter	Car Lighter Power Inverter
Xiaomi Mi 10 5G	Xiaomi Mi 10 5G
Raspberry Pi 1	Raspberry Pi 1
8GB SD Card	32GB USB Stick

Alongside this we also needed two conventional vehicles. In the RSU is not mandatory since the purpose is to simulate any road side unit but the car makes it easier for power supply. The vehicle being used on the OBU has 1.50 meters height and it also provides power to the setup.

4.3 Scenario description

Taking into account the requirements for the scenario we chose D. Frei Vicente da Soledade e Castro street in front of the college to be the place for the experiments. It's an urban scenario with vehicles parked on both sides where one of the existing zebra crossings offers poor visibility for eastbound-to-westbound vehicles when there are cars parked on the north side of the street, as seen in figure 4.2 taken from Google Maps. It is also worth mentioning the existence of trees between the site and the 5G installation that may have impact on signal propagation.

From [25], it was possible to approximate the distance a car goes through to stop. If the car is going at 50 Km/h it needs approximately 35 meters to stop the vehicle which is not enough to prevent an accident in this crossing zone since the vehicle only has line of sight to it from about 22 meters. Though with the RSU warning the presence of the pedestrian walking the crossing it gives a time gain for the car to stop.

The RSU is located in a vehicle parked in the first parking space on the pedestrian's right-hand side, in the figure, and provides unobstructed visibility for the pedestrian throughout the experiment. The pedestrian is still on the sidewalk, very close to the zebra crossing. For practical reasons this approach is made, which in a real situation would happen when the pedestrian is crossing at the exact moment the approaching vehicle has poor visibility. However, this causes the sending of detection by the RSU to be constant. That is, on the OBU's side the message is received at all times that the pedestrian is about to enter the zebra crossing and thus this information is

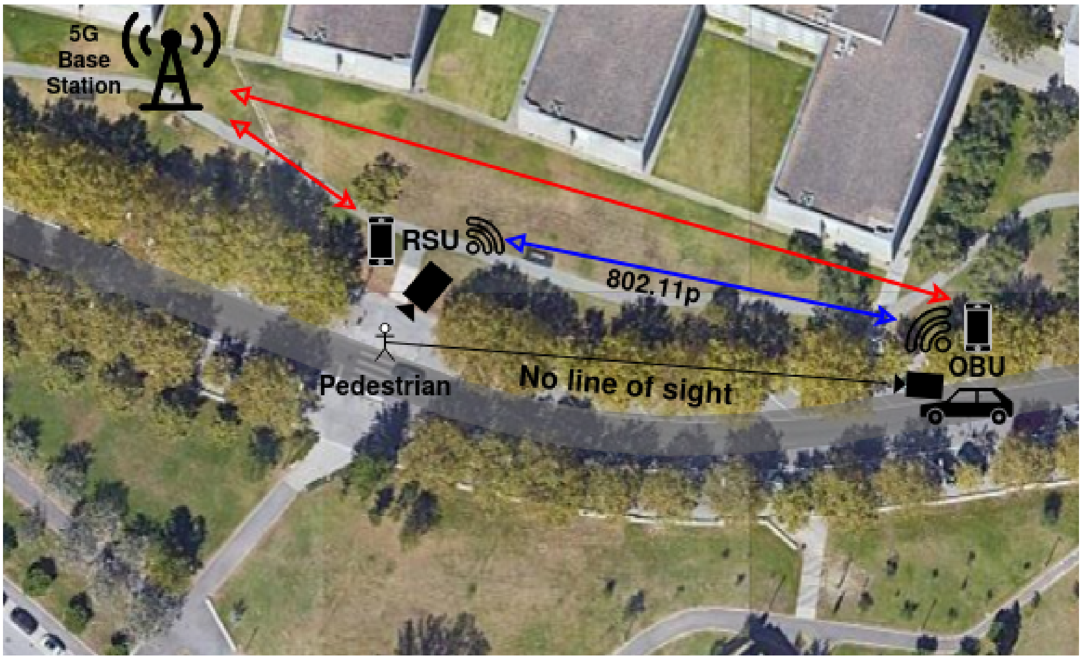


Figure 4.2: View of the Scenario

sometimes discarded for being repetitive. The gain is therefore calculated at the moment the message is received, when the vehicle approaches, i.e. the moment this information becomes relevant.

4.4 Setup Preparation

After making the necessary hardware connections as seen on 3.1 we also need to prepare software configurations to have everything working. In this section, we will briefly specify these connections dividing them into both technologies used.

5G: First we need to configure a hotspot on another phone that is not either of the 5G ones. We do it by using the same SSID and password of the lab network so that the connection by all the elements is automatic. After that, we open SSH connections to the boards and execute a script that mounts USB and SD drives to the directory used for log saving. The script also gives permissions to the GPSd user on the GNSS associated device for precise location purposes. We then make sure the GPS signal is being properly handled with the gpsmon application from the GPSd package[29] and if the time synchronisation is working as intended, using chronyc[1], a versatile implementation of the Network Time Protocol (NTP).

We then proceed to take care of network configurations. The phone automatically creates the tethering interface with IP 192.168.42.29 in the 192.168.42.0/24 network. Because of that, we configure the Ethernet device on the boards to be in the same network with a different IP. We also add the default gateway on the boards to be the IP of the phone. After this and having both board and phone connected to the Raspberry Pi we set up the interface bridge using the following bash commands:

```
ifconfig eth0 down && ifconfig eth0 192.168.42.101/24
brctl addbr br0 # creating the bridge
ifconfig br0 up # turning the bridge interface on
brctl addif br0 eth0 # adding both interfaces to the bridge
brctl addif br0 usb0
echo 1 > /proc/sys/net/ipv4/ip_forward
dhclient -d br0 # assign IP to br0 interface
```

Finally, we test pings from the boards to the phone and to the internet to make sure everything is set up properly. If it is we change the receiver and sender IP configuration in the Cooperative Perception Services software. We also change both receiving and destination ports to 35600. The last step of the configuration is to activate the Socat application on both phones with:

```
socat udp4-recvfrom:35600,fork udp4-sendto:192.168.42.100:35600
```

This was the solution found to be able to redirect packets received by the phone to the boards. The command is executed on an Android application called Termux that emulates a standard UNIX shell.

802.11p: Here the configuration is simpler cause there is no need for Raspberry Pi's being used as an interface bridge. The GNSS time and positional configurations are the same as in 5G. The IP of the board is set up to be in the same 192.168.109.0/24 network as the Veniam Netrider 802.11p module. The module is configured to send the packets in broadcast to a 172.16.6.0/24 which is received by the other party since the configuration is done similarly. After changing IP and port configurations on the software we test the setup and prepare to make the experiments.

4.5 Data logging and Evaluation Metrics

Logs are stored after the experiments that help not only to evaluate the performance of communication technologies but also the latencies associated with the processing pipeline inherent to the hardware used. We saved experiment data from the phone software TEMS Pocket [4] which gave us information about the 5G connection and all the signaling received and sent between the User Equipment and the eNodeB. This helped us clarify and better interpret the results obtained on the 5G experiments. We also took logs from ROS topic subscription, from where we made all the plots demonstrating the results obtained. There is the possibility to save logs about other information but for the metrics chosen the essential data is:

- Timestamp of each Frame
- Timestamp of each detection

- Timestamp of CPMs sent
- Timestamp of CPMs received
- Quantity of objects sent per CPM
- Quantity of CPMs sent per second
- Object classification (Person or Vehicle)
- Object position and distance between setups (Using Haversine formula [30])

In both experiments the same logs are stored and used in the same parsing algorithm that uses them as input to extract the desired metrics. We will consider several metrics to evaluate the performance of both setups. The choice of metrics was made taking into account their influence on what will be the main metric of the paper, which is:

- **Awareness Latency**: the time gain between the first reception of the "pedestrian" object detected on the crossing and the detection that the OBU itself makes of that same pedestrian. As already mentioned in 4.3, this time can determine the difference between an accident or not. We obtain the values by comparing the timestamp of the CPM received with a pedestrian detected and compare it to the local detection of the OBU. For this end we use the following formula:

  $$t_{Xmeters} = (Xmeters - Ymeters)/Car\_Speed$$

  where

  - $t_{Xmeters}$ is the time gain.
  - $Xmeters$ is the distance from the crosswalk at which the cpm is received.
  - $Ymeters$ is the distance from the crosswalk at which the vehicle detects the pedestrian.
  - Car_Speed is the vehicle's speed when the message is received.

  The following metrics were also taken into account:

- **End to End latency**: which is characterized by the time interval between image frame acquisition in source node (S) and provision of object representations in destination node (D), including the decomposition into:

  $$t_{E2E} = t^{S}_{IA} + t^{S}_{OD} + t^{S}_{CPM} + t_{PL} + t^{D}_{CPM}$$

  where

  - t_{IA} is the time for image acquisition.

  - t_{OD} is the time for object detection.
  - t_{CPM} is the time for CPMs processing (source and destination nodes).
  - t_{PL} is the time for packet latency.

  We calculate each part of this metric separately. Image acquisition, detection and CPM processing metrics are determined by the timestamps saved when it is published by ROS. The network latency is obtained by comparing the timestamp of sending a CPM and the reception of the same CPM in the other setup.

- **Message generation**: The frequency that the sender node is disseminating messages. It will impact the awareness latency of a given object. To obtain data about this metric we use the same method as in the network latency, the timestamp of each message is saved and we can extrapolate a plot of CPM sent per second.
- **Packet reception as a function of time**, which is a communication technology metric of high importance. It is determined by comparing CPMs sent and received. They don't have a sequential number but are easily compared by some of the fields present in the message. The results are obtained by making time divisions of 10 seconds and calculating the Packet Delivery Ratio for each of these intervals.
- **Number of objects sent as a function of time** so we can see when there were more objects sent and if that has an impact on the other metrics. Same method than in network latency is used here to obtain the values for this and the last metric.
- **Number of messages sent as a function of time** to also help understand latency and reception results by comparing them to the evolution of sent messages per second.

4.6 Problem Solving

We had some problems when trying to make everything work which is normal and expected in a project that requires field experiments. Most of the problems were solved and we found solutions to go around the ones we didn't. In the end, we got a fully working setup with the objectives determined in the beginning so we can mark it as a success. In a chronological order we state the problems faced:

- **Problem**:The first two phones we used to make the experiments were not prepared to receive the proper software which allowed us to use the TEMS Pocket software. We needed this software to lock the LTE/5G communication to the antenna at FEUP. There was a lot of time trying to make it work with the help of the engineers at Infovista, from where we bought the software, but the phones were not working as intended.

  Solution: We then asked our telecommunication service provider Porto directly and received two prepared Xiaomi Mi 10 5G phones that had the necessary configurations for TEMS Pocket to be correctly installed and after that the experiments were possible.

- **Problem**: The setup in the OBU has a higher performance than the one in RSU. Because of that, the number of CPMs sent on that side is higher than the other. Buying another Jetson Xavier NX was not a viable solution so we had to find another way. To graphically represent this difference we can see figure 5.3 in Chapter 5 obtained from about 10 different experiments where the delay in detection operations is almost 50 milliseconds faster in 80% of the time in the Xavier board.

  Solution: As a way to try to mitigate this problem we activate the rules specified in Section 3.1.3. In Chapter 5 we present the results with these rules activated and deactivated since this was always the way we made the experiments. It is important to try and make both setups work the same way. But since we have two different setups it is also interesting to characterize the performance of both boards in the system we use.

- **Problem**: Tethering connection between the phones and the boards does not work since they have not the necessary kernel modules to handle internet connection through USB. We tried to find and install said modules but it revealed to be a hard task because the architecture on the boards is ARM64 and there were not many available options to make it work using open-source software.

  Solution: We decided to use a Raspberry Pi as an interface bridge that connects to the board using Ethernet on one side and gets tethered to the phone through the other side. This solution should not include any additional delays to the communication since the data just travels through the Raspberry Pi's interfaces, which was exactly what we needed.

- **Problem**: After having the Raspberry Pi working we had to find a way to redirect packets received in the phone to the boards. The first was to use Port Forwarding with the Iptables package but we could not make it work.

  Solution: The first solution was to use Netcat package but the results were not consistent. We then tried to use Socat which yielded better results. This application can redirect the UDP packets received during the time of the experiments without failing.

Chapter 5

Results and Discussion

This chapter presents the results of the experiments and the respective conclusions. In the beginning, we will present results common to both setups, concerning the hardware used and unavoidable latencies inherent to the system. We will try to follow an order consistent with the metrics explained in Section 4.5 and in the end discuss results and variables that exist and influence them. Despite the adversities and the difficulty in having experiments performed successfully, in the end, it was possible to obtain results that allow a valid discussion.

5.1 Process pipeline latencies

In this section, we present the results related to processing pipeline latencies. From image acquisition to sending a CPM there are delays inherent to the hardware used that will have a direct impact on system performance. It is described in the 4.5 section under End to End Latency as the image acquisition time plus the object detection time plus the CPM's processing time. Graphs will be presented for both the time of these operations and the time between consecutive publications of the results of the operations. They will be taken into account as constant system delays and used to evaluate the performance of both setups.

The first subsection presents the latencies related to the cameras used and to the publication of the images by the ROS. Then, we present the latencies for object detection and for sending and receiving CPMs on both boards, which vary according to the setup as already mentioned in 3.1.2.

5.1.1 Frames and Image Publications

As already mentioned in 3.1.1 the video mode chosen was 1080p at 15 frames per second. This could be verified from the subscription of the topic regarding the publishing of images by the ZED 2 camera node on ROS. By obtaining the data for each board we were able to generate a graph regarding this metric for both setups. We used the *boxplot* function from python panda's library for this and other figures present in the results, which shows 25% and 75% of the values inside the box, 5% below the bottom line and 95% below the top line. The horizontal line in the middle of the box refers to the median.

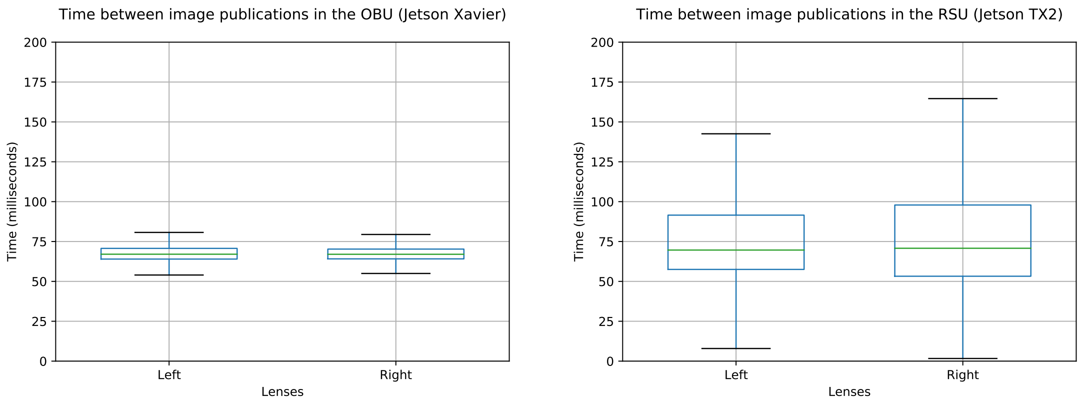


Figure 5.1: Time between image publications in both boards

In the figure 5.1 on the OBU - Xavier's side, the time between images publication is around 66 milliseconds, which is in accordance with the 15 frames per second configured. On the other hand, in the RSU - TX2's setup, this same time has a larger variance despite the median being in the same area. There are values close to zero that are due to the creation of a buffer of publications that at the time of subscription appear with 0 milliseconds of consecutive time, and due to the delay that creates this buffer they also appear about 25% of the values greater than 100 milliseconds. As for the operation time, relevant for the calculation of the End to End Latency, this is close to 0 for the image acquisition operation and will have a reduced impact on the final latency of the processing chain.

5.1.2 Detections

Regarding the detections, the data is generated in the same way, i.e., the ZED 2 camera node publishes the detection in the `/cp_service` topic, which is subsequently subscribed by the `/netmetric` node that stores the timestamps. From these, a graph is generated with the same structure as the previous one in which it is possible to see the time between object detections in each of the setups.

In Figure 5.2 on the OBU's side, we can see that the time between detections goes according to the image acquisition and that the latency included in this step will be of small dimension. In the RSU's however, once again we can see the difference in processing power. The image acquisition will have an influence on this delay but the increase is even more marked with about 25% of the values above 200 milliseconds of delay. In relation to the time of these operations, it is possible to see in Figure 5.3 that about 80% of the OBU's detection operations are 50 milliseconds faster than the RSU's side.

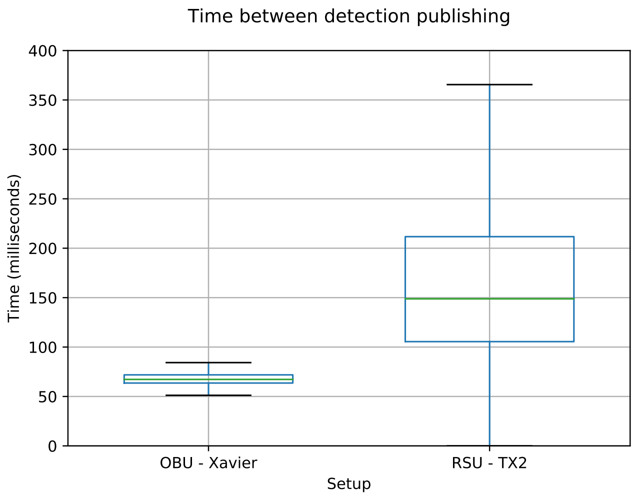


Figure 5.2: Time between consecutive detections

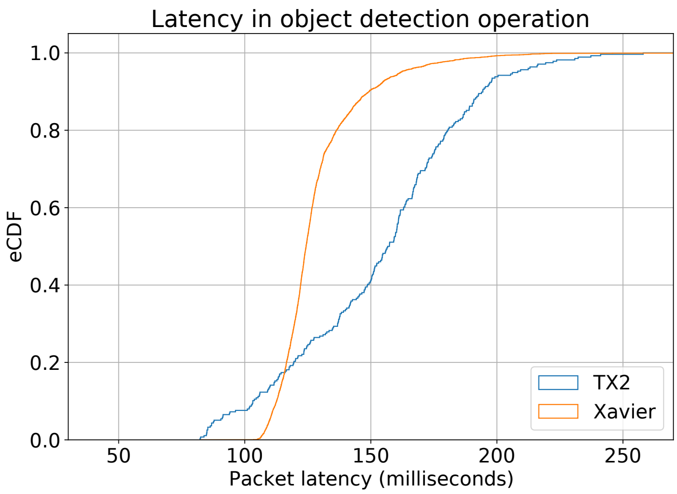


Figure 5.3: Comparison of detection operation times

5.1.3 CPM processing

Regarding the processing of CPMs, we can separate them in encoding when sending and decoding when receiving. In Figure 5.4 it is possible to see the encoding in both boards. This is related to the setup that does it and we can see that the delays already existing in previous plots are maintained. In the OBU we still have the same median and deviations that existed in image acquisition. In the RSU the median remains at 150 milliseconds, which is in accordance with the negligible time that the system takes to encode the messages.

The time of this operation is quite short as shown in Figure 5.5. Therefore it will not have much impact on the final End to End latency.

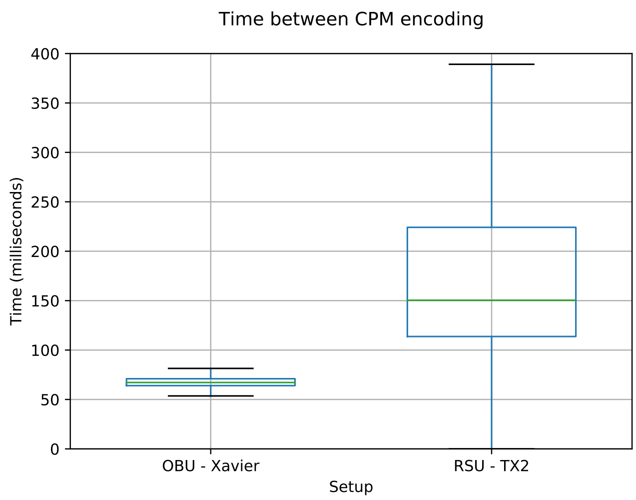


Figure 5.4: Time between consecutive CPM encoding

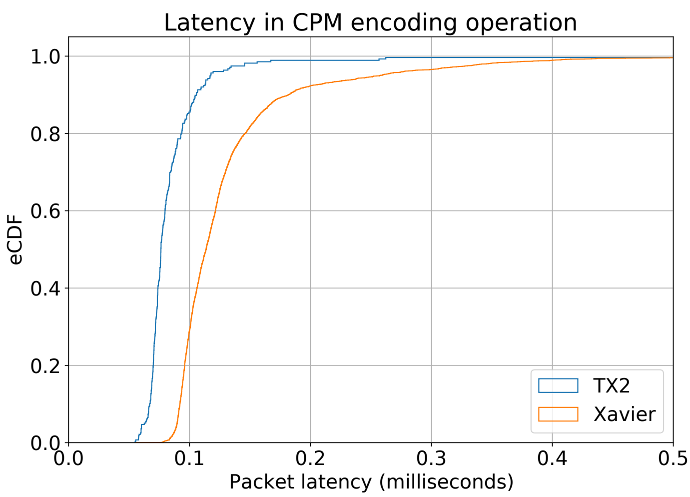


Figure 5.5: Comparison of CPM encoding operation times

As for the decoding part, this will depend on the sender and not on the receiver. As it is possible to see in the figure 5.6, the delay in the OBU is directly related to the delay in the encoding of the RSU in the previous graph. On the other hand, in the RSU we can observe the encoding results in the OBU. This also confirms that the decoding operation is extremely short and does not add delays in the processing chain.

In Figure 5.7 it is possible to see that the latency time of this operation time will be, as in the encoding, close to 0 milliseconds. Therefore, it has reduced impact on the final total latency.

With these 3 components specified so far is described part of the End to End Latency, missing only the communication latency described in sections ahead. From here the results will depend on the communication technology used and that's how we'll have them disposed. Inside each

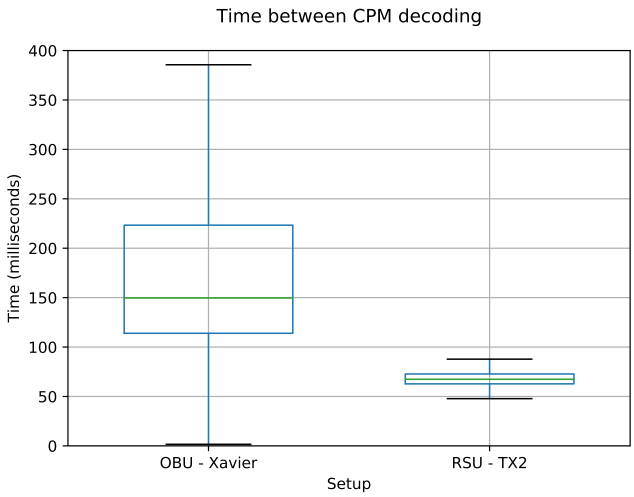


Figure 5.6: Time between consecutive CPM decoding

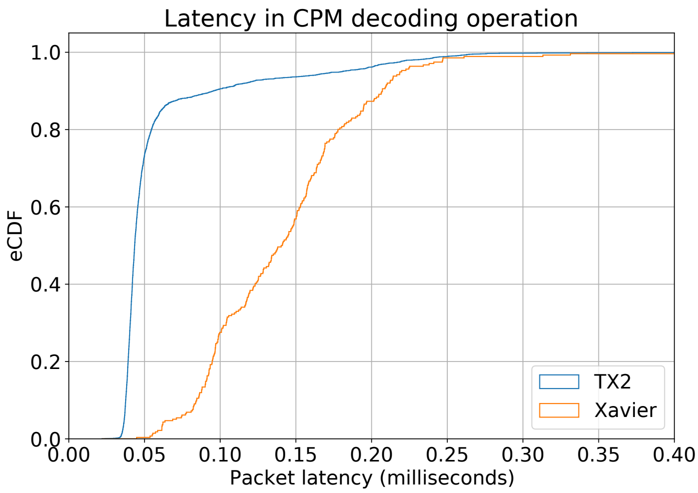


Figure 5.7: Comparison of CPM decoding operation times

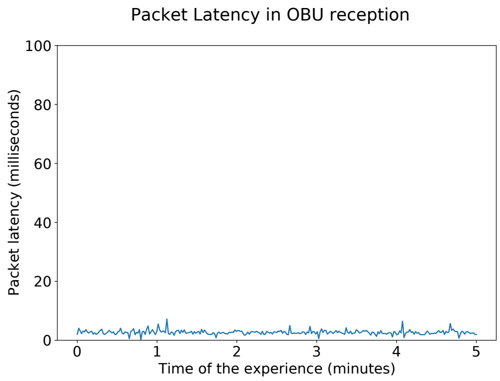
technology section, there will also be a division between experiments using the dissemination rules specified in 3.1.3 as active and deactivated.

5.2 802.11p

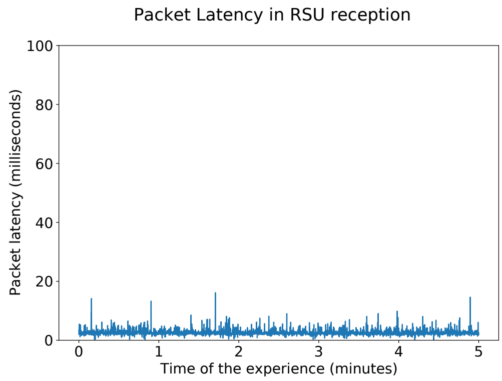
We will start the demonstration of results with 802.11p technology. As already mentioned, the division will be made between experiments with and without rules. At the beginning will be arranged the results of communication latency in order to complete the metric of End to End latency. Next will be the packet reception rate as a function of time, the rate of objects and messages sent as a function of time and at the end the metric referring to awareness latency that will be the most relevant to the capability that the platform will have to prevent traffic accidents.

5.2.1 Packet Latency

The calculation of the communication latency of each packet is done by subtracting from the packet receiving timestamp, the sending timestamp of the same packet. Having as reference the Figure 3.4, these timestamps are stored by the /netmetric topic in both setups at the moment of message arrival publication by the `/cp_udp_receiver` node in the `/cpm_raw_in` topic and at the moment of message sending publication by the `/cp_service` node in the `/cpm_raw_out` topic. Although there is no sequential number for each CPM sent/received, we can easily compare each message by the fields present in the logs. For this technology without the dissemination rules enabled the results were as shown in Figure 5.8.



(a) Jetson Xavier NX



(b) Jetson TX2 Developer Kit

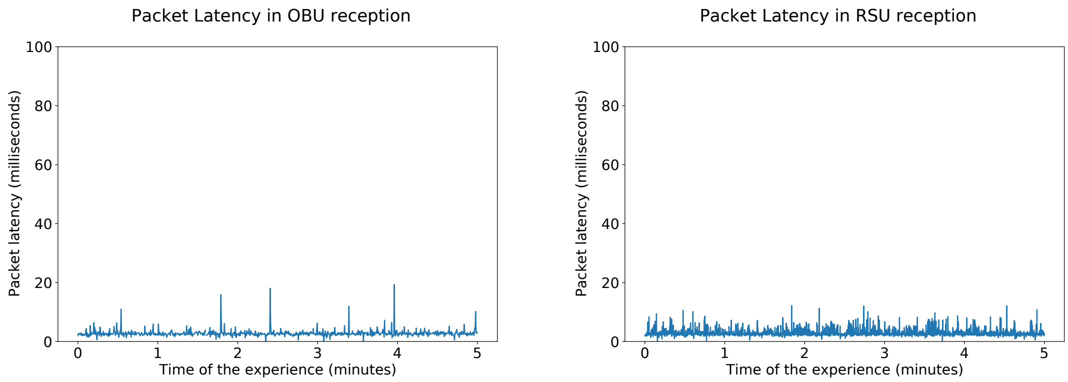
Figure 5.8: Communication Latency using 802.11p with No Rules

In the case of the experiments with the rules activated, we obtained the results presented in Figure 5.9, where it is possible to identify a higher flow of messages on the receiving side in the OBU, which confirms the higher sending of the TX2 board in the RSU when comparing with the experiments with the rules deactivated. Otherwise, latencies remain low with an average of 5 milliseconds.

From the graphs, it is possible to see that the latency in the path of the packets is extremely short. Since the communication happens directly between the antennas used with the 802.11p modem, it only depends on the distance between the setups. It is also possible to see the difference in the amount of data sent by the OBU in relation to the RSU, an aspect that will also be demonstrated later. Finished the calculations of the first metric in the end we have that the End to End Latency will be for both cases:

$$t_{E2E} = t_{IA}^{S} + t_{OD}^{S} + t_{CPM}^{S} + t_{net}^{S\&D} + t_{CPM}^{D}$$

where



(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.9: Communication Latency using 802.11p with Rules

$$t_{E2E\_OBU} = 0ms + 200ms + 0.4ms + 40ms + 0.3ms = 240.7ms$$

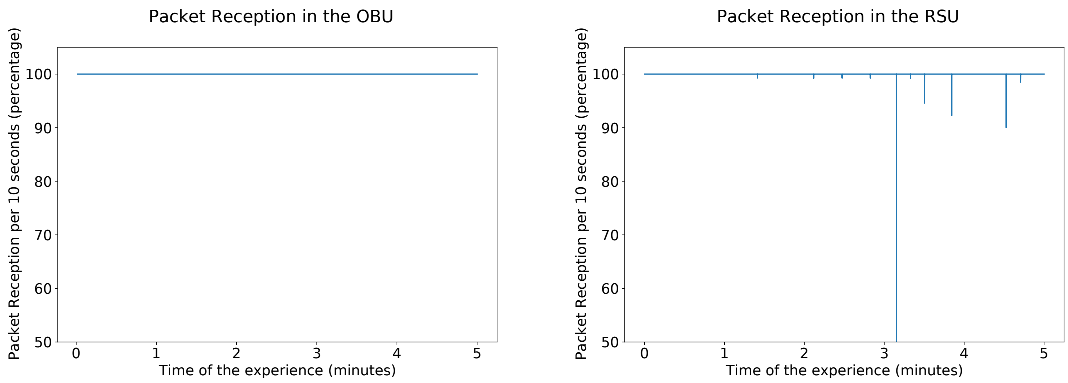
and

$$t_{E2E\_RSU} = 0ms + 250ms + 0.3ms + 40ms + 0.3ms = 290.6ms$$

Concluding the metric, the total processing chain time using 802.11p technology will be 205.7 milliseconds with the OBU and 255.6 milliseconds with the RSU, with object detection being the operation that implies the longest delay in the process.

5.2.2 Packet Reception

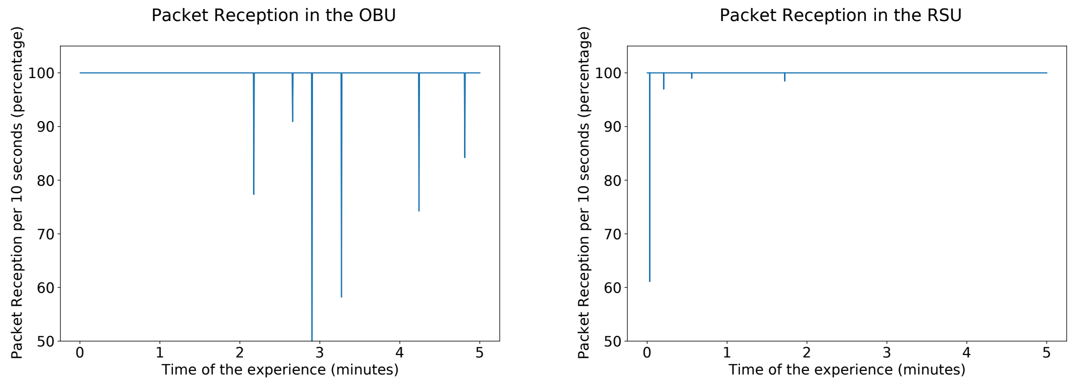
Moving on to packet reception rate, this was obtained by making a comparison between sent and received packets, as for latency. However here we considered the packets that are sent and not received instead of the time between them. We obtain the results as shown in Figure 5.10.



(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.10: Message reception rate using 802.11p with No Rules

As for the results of the experiments with rules, it is possible to see more occurrences of percentages in 10 seconds smaller than 100% but overall the communication is done with good reception on both sides.



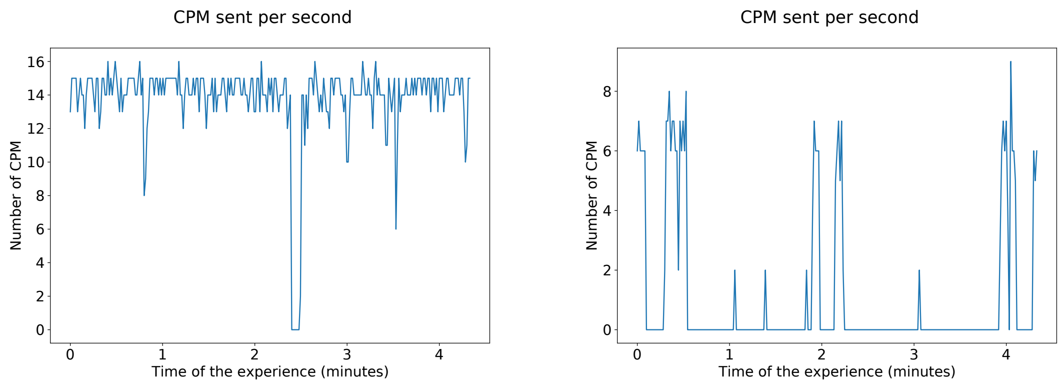
(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.11: Message reception rate using 802.11p with Rules

5.2.3 Messages Sent

This section shows the number of CPMs sent per second. This is a metric that perfectly portrays the performance difference between both setups and the difference between results when rules are enabled or not.

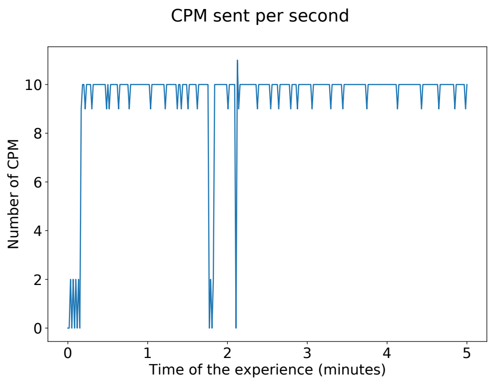
In Figure 5.12 we can see the CPMs sending results between setups in the experiments without rules. The average number of messages sent by the OBU's setup with the Xavier board is about 14 per second while in the RSU's setup with the TX2 board it is approximately 1.



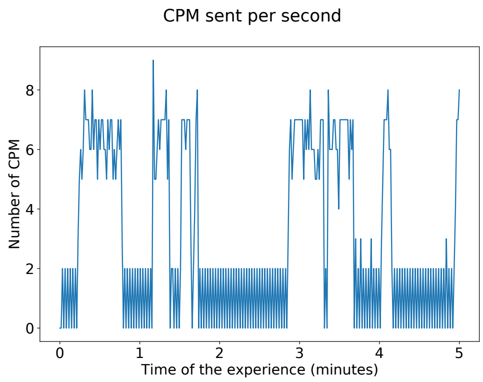
(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.12: Message dissemination rate using 802.11p with No Rules

With the rules enabled, we obtained results with greater similarity. In Figure 5.12 it can be seen that on the OBU's side approximately 10 CPMs are sent per second due to the rule sending every 100 milliseconds. On the other hand on the RSU's the average is now 4 messages per second due to the rule of sending at least every second.



(a) Jetson Xavier NX



(b) Jetson TX2 Developer Kit

Figure 5.13: Message dissemination rate using 802.11p with Rules

5.2.4 Objects Sent

Considering the number of messages sent per second, it is also interesting to know the number of objects sent, since the quantity of new objects determines the quantity of new information of the disseminated message. On the other hand, in the experiments we performed and due to the scenario, the RSU is continuously detecting the pedestrian on the zebra crossing but is not continuously sending it. It will be important to identify the moments of interest for this sending and respective receiving since on the OBU's side this information is only relevant when the pedestrian is approaching the crossing.

In the figure 5.14 it is possible to see the sending of messages from the RSU to the OBU and the reception of the same messages in the experiments without rules. We can already notice a relation with the graph presented in 5.12b when comparing different sending instants. Next, we can see that the reception coincides with what is sent, except in the final part of the experiment where there are messages whose objects had already been detected by the setup destination of the messages that discarded them.

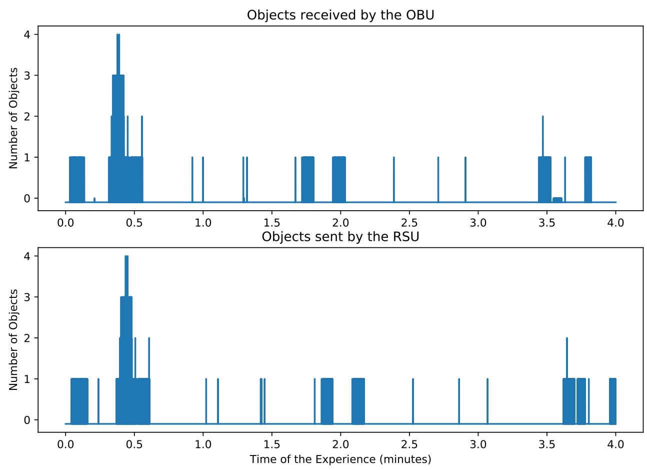


Figure 5.14: Objects sent and received with802.11p No Rules

Moving on to the experiments with rules we can see in Figure 5.15 a clear increase in the number of messages sent as already seen but many will be with 0 objects. The ones that are not 0, represent the detection of the pedestrian near the zebra crossing and sometimes other vehicles/-pedestrians passing nearby. We can see between the second and third minutes of the experiment a difference in the number of objects between the graphs. The reception is happening as already demonstrated but the received objects are being discarded as they are not considered new information.

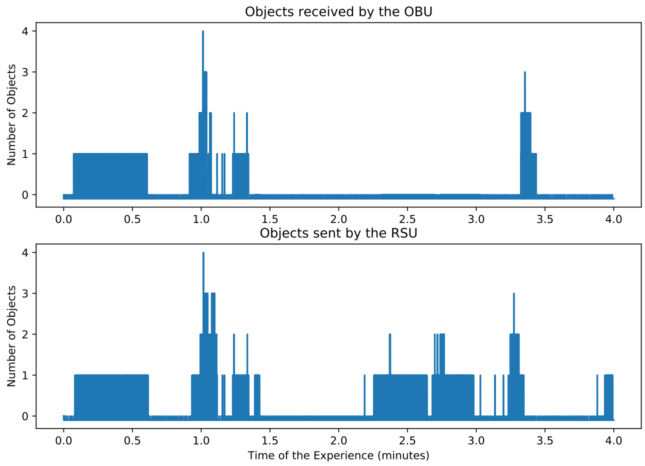


Figure 5.15: Objects sent and received with 802.11p Rules

5.2.5 Awareness Latency

To conclude the presentation of the results of the experiments with 802.11p technology we have the metric related to the time gain that the OBU has when receiving information about the detection of the pedestrian moments before it detects it. For the elaboration of the following graphics data from several logs were gathered to have the distance between vehicles, objects detected locally and received by CPMs and the time of the experiment.

Looking at Figure 5.16 we can see the information about local detections, CPM receptions and distance between setups. In blue in a triangular shape is the distance between setups. Considering that in each experiment 3 trips are made on the zebra crossing, we can see each of them in this graph. The smaller triangles will therefore be the moment of reversal.

Then, in green, we have the detections made by OBU and in red the detections received by CPMs. Space where there is an intersection of:

- Approaching the zebra crossing (large triangle decreasing)
- Less than 60 meters
- Higher than 35 meters

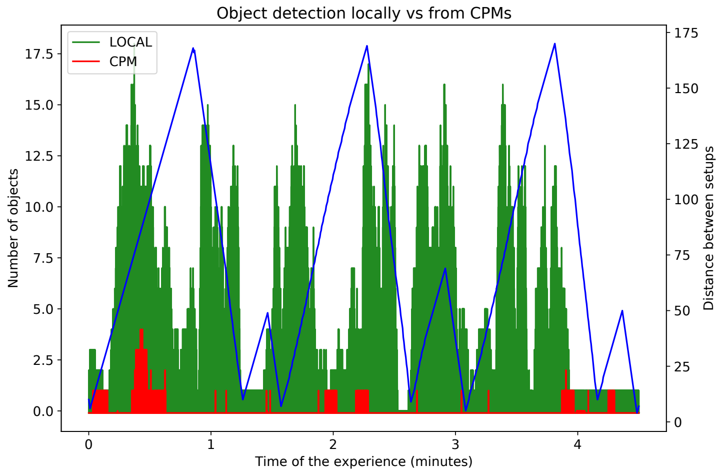


Figure 5.16: Local detections & Objects received with 802.11p No Rules

- CPM received (in red)

It will be where we ensure that there is a time gain for the OBU. It is possible in Figure 5.17 to observe in more detail the space defined as time gain at the first crossing through the zebra crossing. The two horizontal lines represent the space of time that we consider as relevant gain. The lower line is 22 meters from the zebra crossing which will be moments before the OBU itself makes the detection. The upper one is between 35 and 60 meters. It is not taken into account the time gain between 22 and 35 meters because according to the findings and discussions in Chapter 2 it takes at least 35 meters for the vehicle to stop and if the message is received between this time interval the accident will occur in the same way, with less severity. We chose the upper interval to be 60 because of the time it would take for the pedestrian to cross the zebra crossing. If the warning comes too early it becomes irrelevant.

Taking into account that the speed in the experiments was variable and that the OBU only has visibility to the walkway at about 22 metres the gain will be linear and following the following formula:

$$t_{X meters} = \frac{X - 22}{Car\_Speed}$$

So for this experiment, with a speed of 30.8 km/h the gain will be

$$t_{45.7 meters} = 2.7 seconds$$

.

Moving on to the experiments with rules we can see in Figure 5.18 that only on the first leg are messages received with the presence of objects on the crossing. The time gain there will be

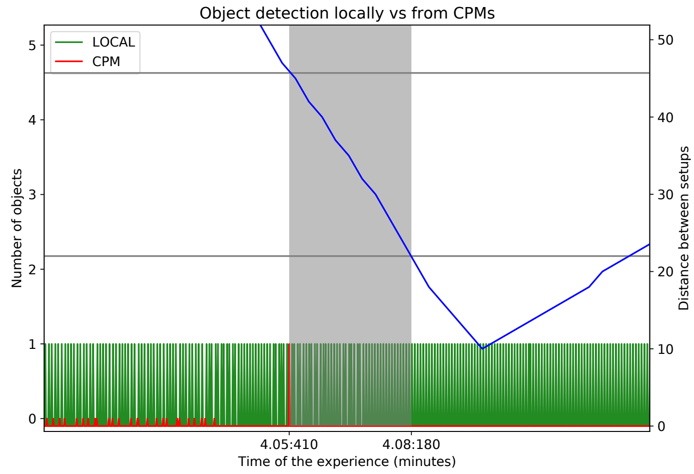


Figure 5.17: Time Gain with 802.11p No Rules

the equivalent for 60 meters at 30 km/h, that is,

$$t_{60meters} = 4.6 seconds$$

As can be seen in Figure 5.19. For the remaining routes, there is no information that represents any time gain for the OBU.

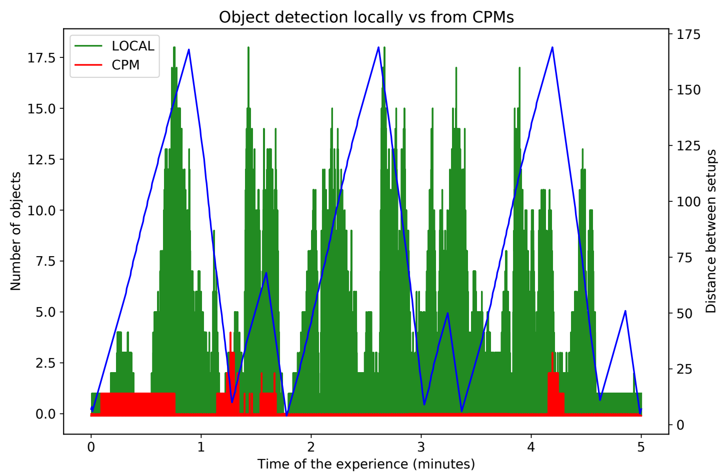


Figure 5.18: Local detections & Objects received with 802.11p Rules

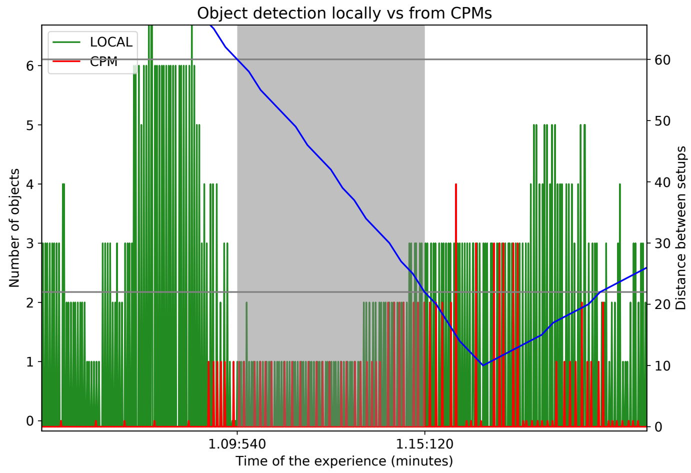


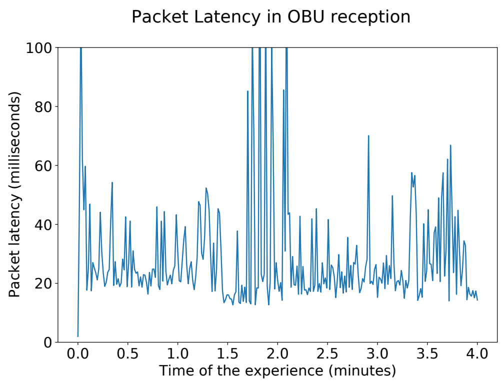
Figure 5.19: Time Gain with 802.11p - Rules

5.3 5G

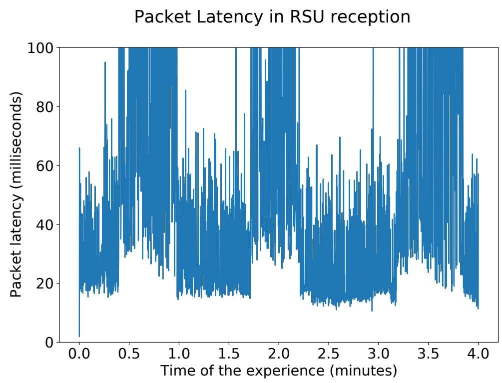
In this section, the results for 5G technology will be demonstrated. The latencies inherent to the hardware used remain relevant for this part. We will follow the same order as for 802.11p starting with latency to calculate the first metric, going through the rest and ending with the metric of time gain using this technology. In addition, the demonstration will be made in a more simplified way and the explanation of how to obtain these results was already done in the respective sections on 802.11p technology.

5.3.1 Packet Latency

Following the same calculation form used in 5.2.1, the results obtained for the experiments without rules were:



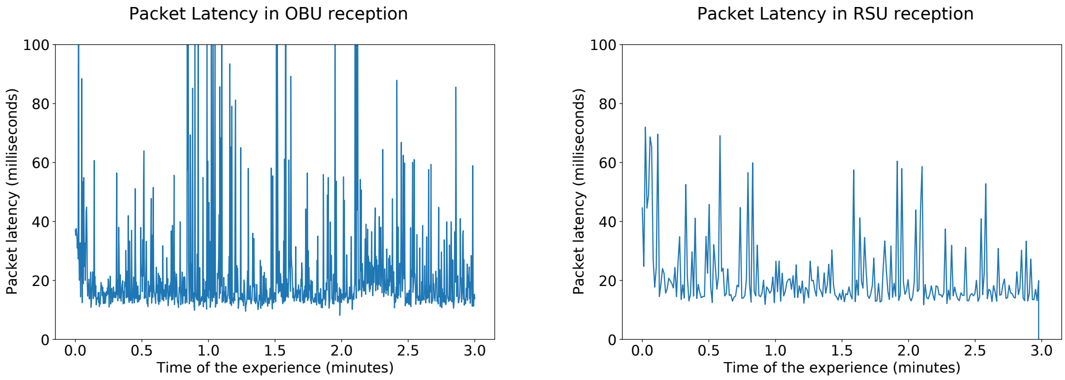
(a) Jetson Xavier NX



(b) Jetson TX2 Developer Kit

Figure 5.20: Communication Latency using 5G with No Rules

We can see a significant increase in latencies, which had in these experiments an average of 40 milliseconds, which would not be expected for 5G. In addition, we can also see successive increases in latency to values above 100 milliseconds. After some investigation, we found out that packets are being sent all the way to the central node of our mobile operator in the region and that this round trip time implies a constant irreversible delay. We tried to explore the possibility of having routing running on FEUP's eNodeB but it was not possible at the time of this thesis. As for the increases up to 100 ms, in Section 5.4 possibilities of explaining this phenomenon are explored.

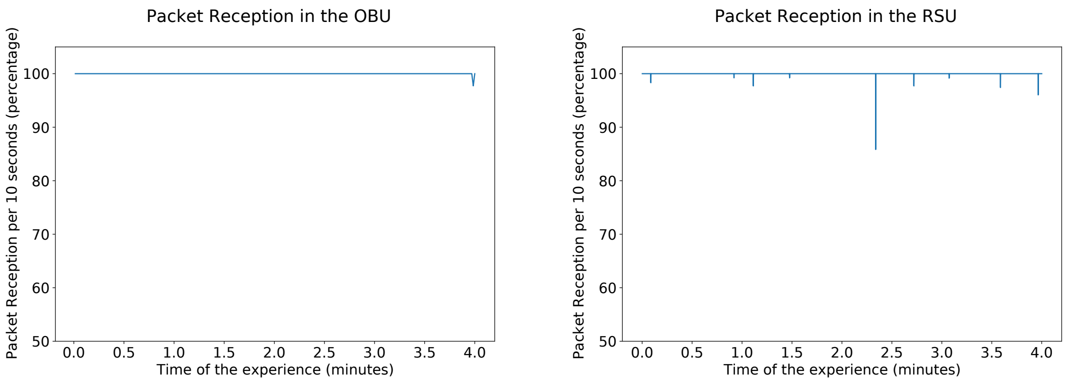


(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.21: Communication Latency using 5G with Rules

5.3.2 Packet Reception

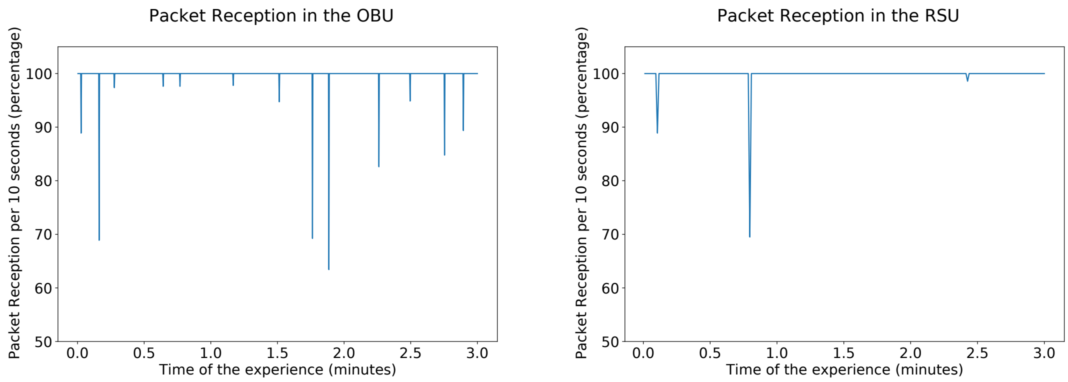
Moving on to the reception of packages the method used was the same and the results remained in a similar register. As you can see in Figure 5.22, in both setups there was little packet loss.



(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.22: Message Reception using 5G with No Rules

For the experiments with rules we obtained:

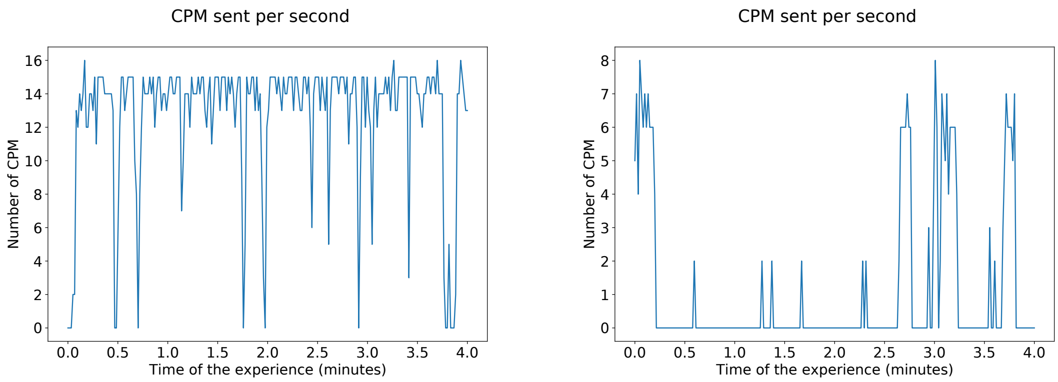


(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.23: Message Reception using 5G with Rules

5.3.3 Messages Sent

The number of messages sent in the experiments with 5G without rules is demonstrated in Figure 5.24. There is not much change from what was happening with 802.11p as the communication technology has no implications on this metric. However in the experiments with rules, in 5.25, it is possible to see a greater amount of objects sent. This factor depends on the moment of the experiment when there is more passage of pedestrians and vehicles unrelated to the experiments through the area where the RSU makes the detection. Besides, these plots help the interpretation of other metrics, as they make it possible to identify moments of higher or lower transmission of CPMs per second.

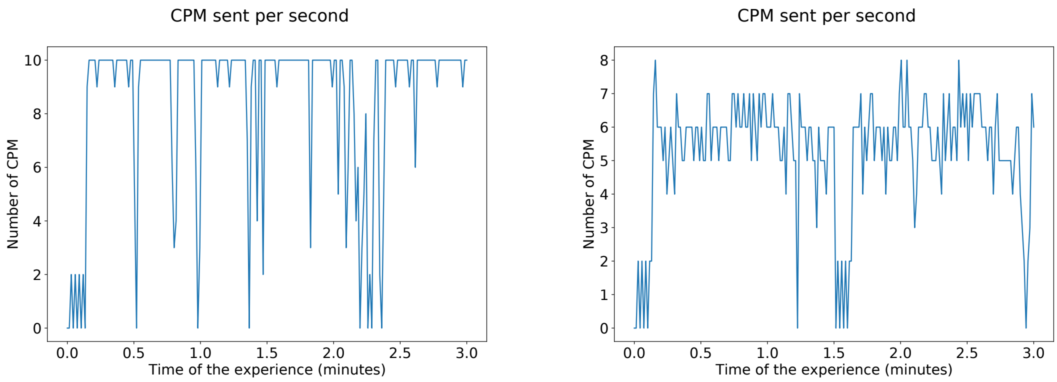


(a) Jetson Xavier NX (b) Jetson TX2 Developer Kit

Figure 5.24: Message dissemination rate using 5G with No Rules

5.3.4 Objects Sent

Turning to the number of objects sent we can see that in the experiments with rules the sending of at least one object will have been more constant than in those without rules. On the other hand, the number of objects also increased in the final instants of the experiment. Despite being a positive



(a) Jetson Xavier NX

(b) Jetson TX2 Developer Kit

Figure 5.25: Message dissemination rate using 5G with Rules

factor, the requirement for this setup is to send at least one object, which will be the pedestrian in front of the detection equipment. The amount of extra objects is due to different passersby randomly passing through the area where the experiments are performed.

In the figure 5.26 it is possible to see the sending of messages from the RSU to the OBU and the reception of the same messages in the experiments without rules. We can already notice a relation with the graph presented in 5.24a when comparing different sending instants. Next, we can see that the reception coincides with what is sent, except for a part of the beginning and the final part of the experiment where there are messages whose objects had already been detected by the setup in the OBU and therefore discarded. In Figure 5.27 we can see the same situation occurring. However, here we have more 1-object sending moments and a higher level of security regarding the time gain that will exist for the OBU when receiving this information.

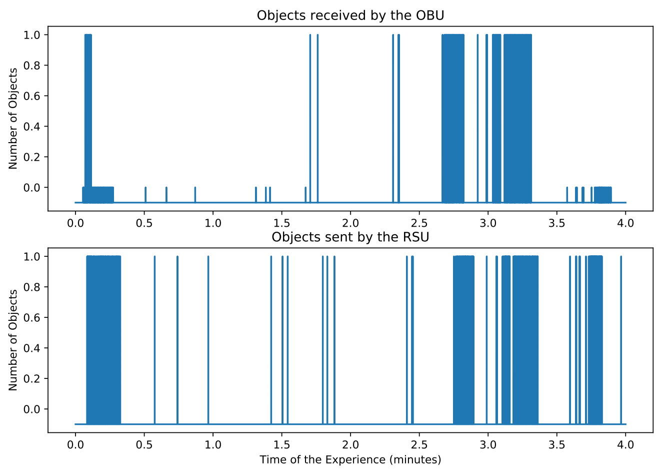


Figure 5.26: Objects sent and received with 5G No Rules

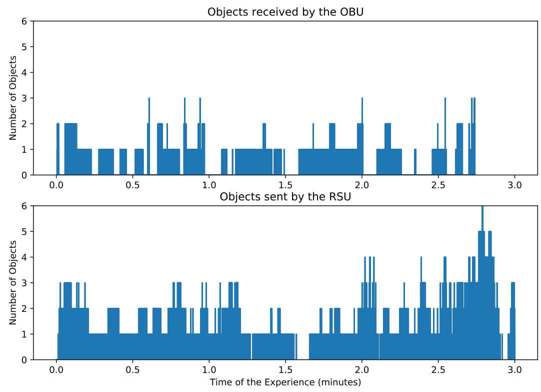


Figure 5.27: Objects sent and received with 5G Rules

5.3.5 Awareness Latency

Finishing with the metric that characterises the time gain offered by the system, we can see in Figure 5.28 that only in the second leg there is information received about the presence of the pedestrian on the crossing. On this occasion, the message is not received in the interval that we consider of most interest (between 35 and 60 metres away from the pedestrian crossing), however, we made the calculation of the existing time gain anyway assuming that the information could be relevant in a real situation. That said, and knowing that the speed at the time was 36.69 km/h, we obtained

$$t_{85.6meters} = 6.33 seconds$$

of time gain. You can see in detail in Figure 5.29 the time interval in which this happens.

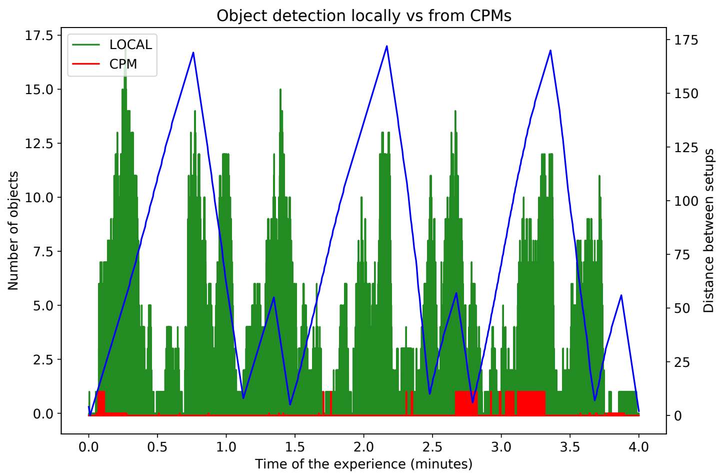


Figure 5.28: Local detections & Objects received with 5G No Rules

In the experiments with rules, as already demonstrated, the number of messages and objects received by the OBU was more consistent. This allowed obtaining the maximum gain determined

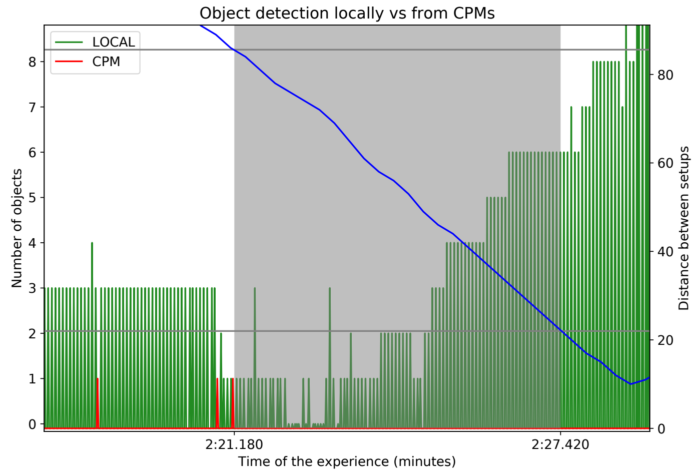


Figure 5.29: Time Gain with 5G No Rules

for the distance of approximately 60 meters to the zebra crossing. As can be seen in Figure 5.31 we obtained, at 20 km/h speed, a gain of

$$t_{58.4meters} = 6.55seconds$$

For all experiments, the speed was calculated from the graphs using the slope of the triangular function.

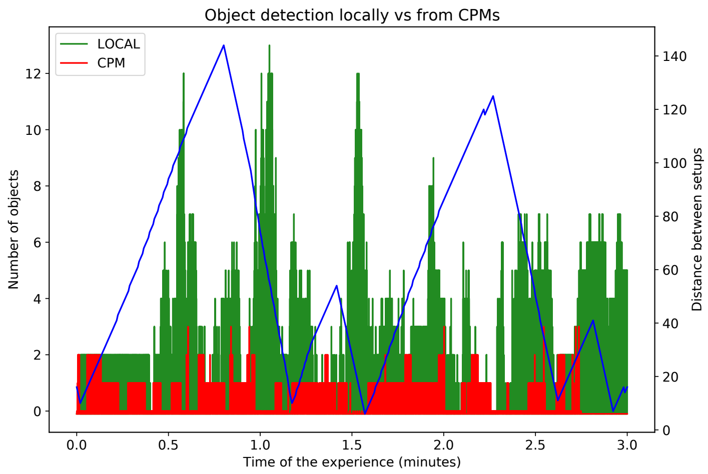


Figure 5.30: Local detections & Objects received with 5G Rules

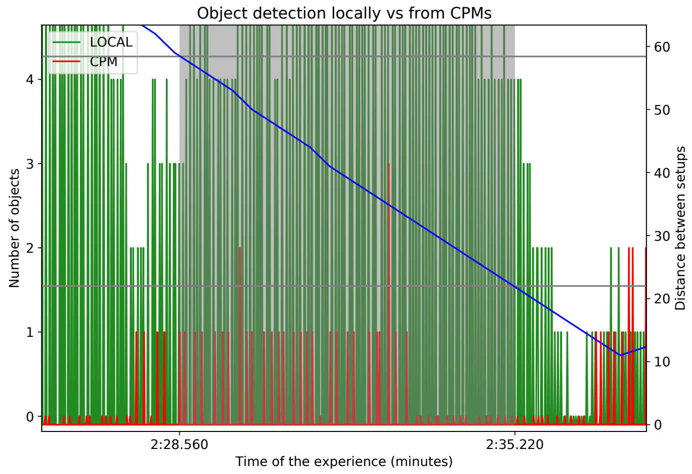


Figure 5.31: Time Gain with 5G - Rules

5.4 5G Latency causes

After observing the results obtained with the experiments on 5G we decided to try to investigate the reasons for the latency increases to higher values. We raised several hypotheses to explain the results and in this section, we will demonstrate the results and conclusions obtained in that regard.

Firstly, with the logs we saved from the TEMS Pocket software present on the phone we were able to obtain the data on different metrics and their variation during the experiments. From here we started by testing the variation of Signal to Interference plus Noise Ratio (SINR) as a function of latency. As can be seen in Figure 5.32 the results we obtained were non-linear and so we discarded this hypothesis.

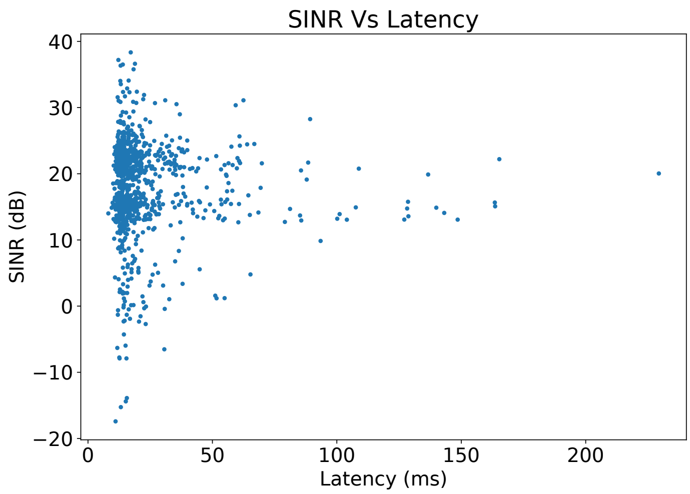


Figure 5.32: SINR Vs Latency in 5G Rules Experiment

We then ran the same test for Reference Signal Received Power (RSRP) and as can be seen in Figure 5.33 the relationship between increasing latency and decreasing RSRP does not hold.

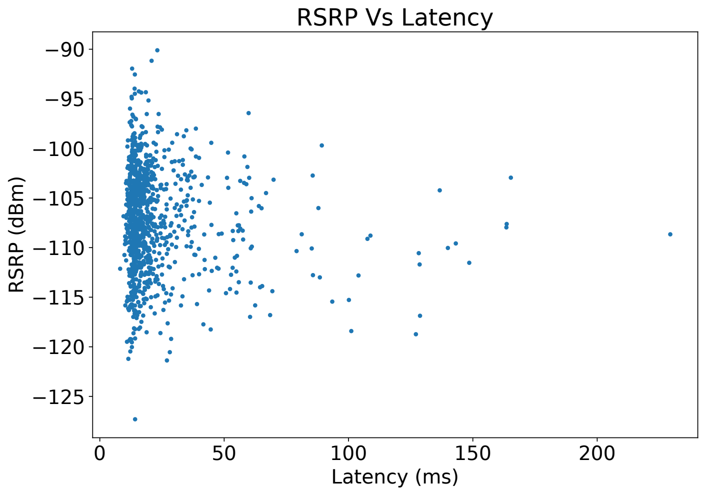


Figure 5.33: RSRP Vs Latency in 5G Rules Experiment

We also tested the relationship between the change in signal modulation, which varies between Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) in its 16 and 64 point variations. In Figure 5.34 it is possible to see the evolution of modulation and latency as a function of time and it is not possible to determine a direct relationship between both.

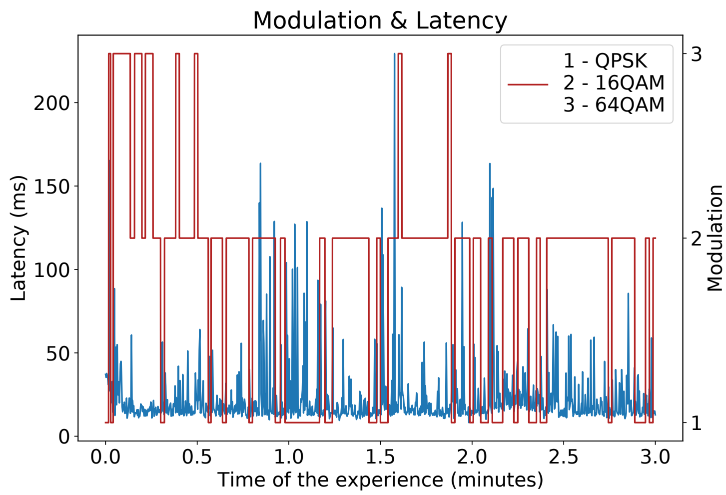


Figure 5.34: Signal Modulation in 5G Rules Experiment

The next possibility tested was Block Error Rate (BLER), where again, no relationship was found to be warranted. It is possible to see in Figure 5.35 the results of this hypothesis test.

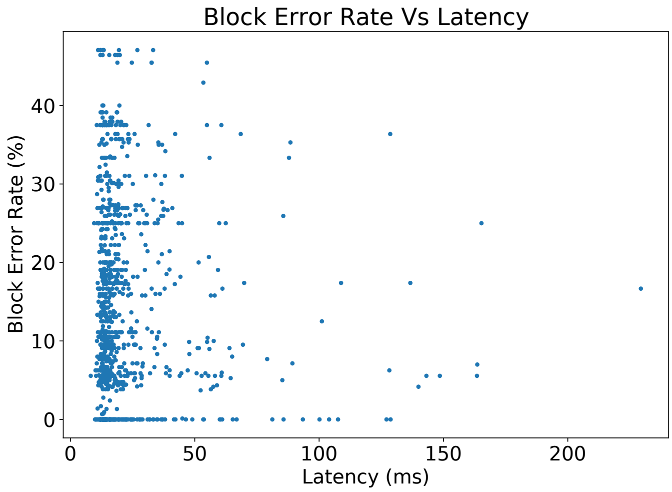


Figure 5.35: BLER Vs Latency in 5G Rules Experiment

Finally, we also decided to test the relationship that could exist between latency increases and other packets sent by the mobile phone unrelated to the experiments that could somehow delay communication. No relationship was found either, as it is possible to see in Figure 5.36.

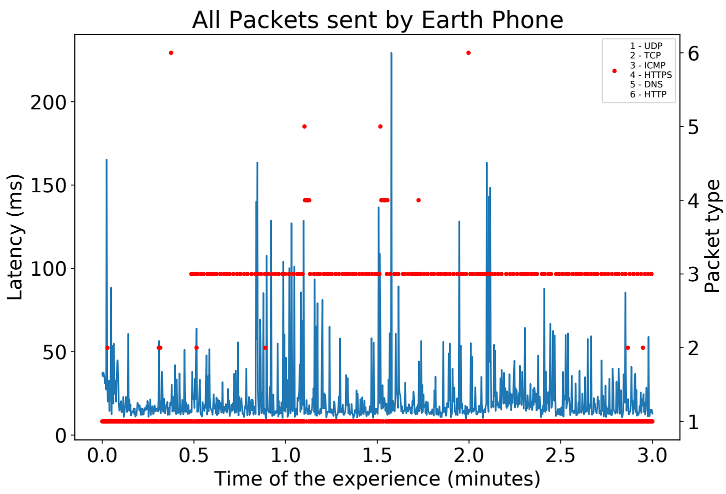


Figure 5.36: Packets sent in 5G Rules Experiment

From here on we have exhausted the most immediate hypotheses for explaining latencies and we have decided to propose as future work the investigation of the reasons and experimentation with varied situations that will allow us to understand the reason for the results we obtain.

5.5 Conclusions

Looking at the experiments done in a retrospective way we may say that having the whole setup working was a challenge but in the end, we obtained logical results that allow a performance evaluation of both technologies, which was the main goal of the dissertation. We also demonstrated that the Vulnerable Road User Protection System works and it offers valuable time to prevent accidents. The fact that one board is worse than another also includes a factor of inequalities between infrastructures that nevertheless end up showing good results. Next is the final chapter where there will be a more detailed conclusion, contributions and proposal for future work.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The aim defined at the beginning of the project was to be able to develop a collaborative Perception Services platform that would allow an empirical evaluation of different communication technologies. After overcoming all the difficulties that appeared in the end we were able to obtain results from experiments by using that same platform. Taking into account that the practical purpose of the platform is to provide greater road safety by sending CPMs to improve the perception of the environment, this was also completed.

Furthermore, the platform created supports different use cases beyond the one used in this thesis and could therefore serve as a basis for different projects. Taking advantage of the independence between the parts of the setups it is possible to apply the tools and methods used here for further empirical evaluations using camera detection or the ROS's publishing and subscription middleware or the part of the communication with 5G that did not exist until now.

The rest of the chapter will explore the contributions made to the investigation area in which we identify and propose future work using this setup or suggesting changes that enable different use cases not testable at the moment.

6.2 Contributions

Next, in no particular order, will be described the contributions made to the technological area:

- **CP system design on real hardware**: In this work, we have designed and deployed a system to real hardware that can be used as a foundation to evaluate cooperative perception services.

- **5G mobile phones as a modem for sending CPMs**: The use of tethering for public IP creation and the Socat terminal application for sending and receiving CPM messages between an RSU and an OBU.

- **Empirical evaluation of the 802.11p Veniam Netrider module**: The implementation of the 802.11p Veniam Netrider communication module in mobility scenarios for sending and receiving CPM messages between a RSU and an OBU.

6.3 Future Work

There will be some ways through which the evaluation that has been done can be expanded namely with different hardware, a larger number of units participating in the experiments or exploring future evolutions of 5G.

Hardware: As the difference between processing power was a factor to be taken into account in this thesis, the independence between elements enables easier implementation of different boards that allow the platform to produce different results.

Larger number of units: With more RSUs and OBUs participating the results can be more enlightening concerning what would be a real scenario in a more crowded lane. Given that mobile networks scale better when the number of users increases, compared to networks coming from WiFI, this is an unexplored factor but would show interesting results. In 2.4 we mentioned a paper that took into account this parameter and concluded that mobile communications bring higher scalability with the number of units participating but also that it is challenging to obtain stringent delay requirements in the presence of higher cellular network traffic load. However, this was tested in LTE in 2014 and the technological evolution can reduce this challenge.

5G: Being a relatively new technology, some changes will occur in the infrastructure that would improve the quality of service offered at the moment. As it was explained before, the current connection as it is today requires a trip to the telecommunication service provider center in Oporto. With new Releases, it will be possible to have smaller nodes such as the FEUP's node routing that allows shorter trips between cellular connections.

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