POLITECNICO DI TORINO

Master's Degree in ICT for Smart Societies

Master's Degree Thesis

Communication networks for connected vehicle: simulating, validating, and testing techniques

Supervisors

Prof. CARLA FABIANA CHIASSERINI

Prof. CLAUDIO CASETTI

Company Mentor ALESSANDRO ROCCASALVA

Candidate

Andrea Corino

MONTH YEAR

Acknowledgements

I would like to express my deep gratitude to a multitude of individuals who have made the completion of this work possible. First and foremost, I want to thank my beloved family: my father, my mother and my brother and my incredible girlfriend for their unwavering love, constant support, and for inspiring me during moments of doubt. My friends and university colleagues have been an invaluable source of motivation and encouragement, and for this, I can never thank them enough. I also want to convey my heartfelt appreciation to my advisor, Professor Carla Fabiana Chiasserini, and my internship supervisor, Alessandro Roccasalva, for their expert guidance, invaluable advice, and the trust they placed in me. I would 'd like also to express my gratitude to my colleagues Praven Zalaya, Miguel Vasquez and Maria Giordanino, all of whom have contributed significantly to this project and provided consistent support. Without the contributions of these remarkable people, this thesis would never have become a reality. I am deeply grateful to each and every one of you for your unconditional support and belief in me. Your presence in my life has been the driving force behind my academic achievement. Every one of you deserves a sincere thank you.

Table of Contents

List of Tables

List of Figures

Acronyms

3GPP
: 3rd Generation Partnership Project

AI
: artificial intelligence

API
: Application Programming Interface

CA
: Carrier Aggregation

CV2X
: Cellular Vehicle to Everything

ETSI
: European Telecommunications Standards Institute

GUI
: Graphical User Interface

IoT
: Internet of Things

ITS
: Intelligent Transport System

MEC
: Multi-access Edge Computing

MIMO

Multiple Input Multiple Output

ML

Machine Learning

NFV

Network Functions Virtualization

NR

New Radio

NSA

Non-Standalone

OSM

OpenStreetMap

SA

Standalone

SUMO

Simulation of Urban MObility

TraCI

Traffic Control Inteface

V2I

Vehicle to Infrastructure

V2N

Vehicle to Network

V2V

Vehicle to Vehicle

V2X

Vehicle to Everything

Chapter 1

Introduction

Autonomous driving represents one of the most significant challenges in the automotive industry as it promises to revolutionize how people travel and interact with vehicles. The 5G technology offers advanced connectivity that can support and enhance autonomous driving systems, enabling fast and reliable communication between vehicles, road infrastructures, and external devices. 5G and C-V2X are Key harnessing pillar's of AI capabilities with cloud computing in autonomous and connected driving. The V2X in it's all version (V2V, V2I, V2N..etc) could be seen as the third eye of the vehicle, which give access to the information of other vehicles and their surroundings that are not possible otherwise.
This thesis work is part of an EU project called AI@EDGE, from which one of the test cases is being considered for developing this thesis work. The report first discusses the key technological enabler's of AI@EDGE platform based on AI exploitation for various connected vehicle services and functions.

In order to assess its functionality in a virtual setting, a traffic simulator called SUMO is being utilized, specifically in the construction of a simulated scenario. The simulation data is subscribed and communicated to the edge server through the utilization of SUMO's TraCI library. To facilitate the transmission and reception of CAM/DENM messages, an AMQP client has been integrated into the TraCI-based program. In order to deploy the program, along with the AMQP client, into a TBM (on-board device), communication-specific testing is conducted on a 5G emulation bench. Various test cases pertaining to cellular networks LTE/5G, such as cell handover, dual-connectivity, carrier aggregation, and MIMO, are performed in a network-based emulation HIL environment. Additionally, network throughput testing is carried out on the Device Under Test, which is equipped with a C-V2X wave stack. Ultimately, the feasibility of a virtual validation platform for vehicular perception is assessed based on the developed capabilities and results obtained from the HIL testing.

Chapter 2

Overview

2.1 Context

The automotive sector is one of the most competitive sectors in the industry. Vehicles' manufacturers are constantly advancing and developing new features that can provide an added value for the society. Right now, one of the main challenges that the industry is facing is the Autonomous Driving. The final goal is to achieve a full autonomous driving vehicle that can perform under any situation without the need of a human intervention. This main goal has been divided into smaller pieces and objectives, to make it easier to face and handle. These intermediate milestones are defined in the SAE levels of driving automation as show in Figure 2.1.[1]

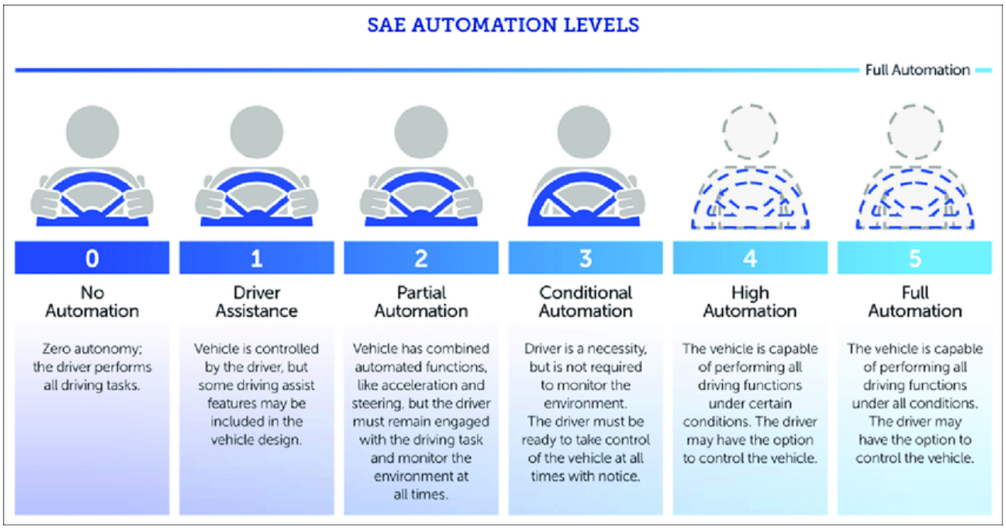

Figure 2.1: SAE Automation levels

This poses not only a technological hurdle but also requires the implementation of new laws and widespread social acceptance. While original equipment manufacturers (OEMs) may already be at SAE level 3 or even SAE level 4 in terms of technological advancement, regular road vehicles still operate at SAE level 2. The main challenge in this context is the legal responsibility in the event of an accident. In the first three levels (SAE 0 to SAE 2), humans are in control of the vehicle and are responsible for any incidents, even if the vehicle has some assistance features. However, in the last three levels, the driver is not responsible for the vehicle's actions, making it difficult to determine fault in case of an accident. Did the software fail? Was it the actuators or perception devices? Perhaps improper vehicle maintenance? Answering this question is not straightforward and requires societal consensus.

However, focusing only on the technical aspect, there are still many milestones to achieve before reaching a dependable SAE level 4. Automated driving vehicles rely on various sensors such as radars, lidars, and cameras to perceive the environment as show in Figure 2.2.

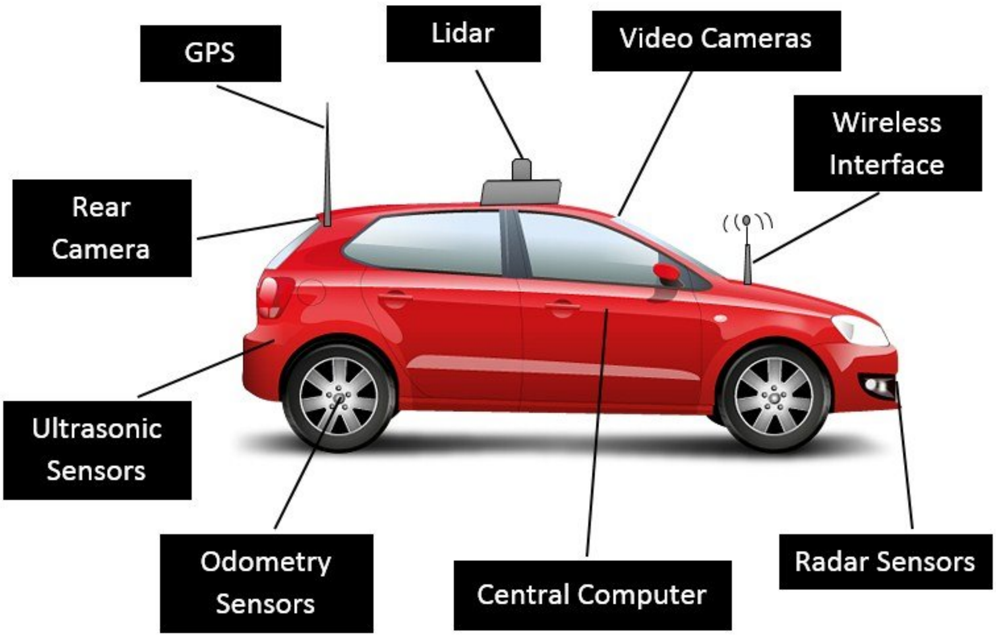

Figure 2.2: Autonomous vehicle components

These sensors can be likened to the driver's senses, particularly the eyes that observe the surroundings. At the moment, the sensors surpass human perception capabilities, so this is not the primary challenge at the moment (although significant improvements can still be made in terms of cost and product optimization).

After receiving and processing all the gathered information, the automated vehicle can respond accordingly. This is where the divergence between human drivers and automated vehicles becomes apparent, as humans possess the ability to understand and make decisions based on intuition, even with incomplete information about the surroundings. The autonomous driving sector faces significant challenges starting from simple situations. For instance, imagine a group of people conversing near a crosswalk. A human driver can easily identify the situation and understand that the pedestrians do not intend to cross the road. However, an automated vehicle merely sees individuals near a crosswalk and instinctively applies the brakes. This scenario is a simplified example of an issue that can potentially be resolved through a specific algorithm or AI. Nonetheless, there are numerous situations in which intuition plays a crucial role, and attempting to solve all of them through complex computing programs may demand computational capacities that are currently unavailable for onboard units.

Nowadays, vehicles necessitate a more deterministic approach to analyze situations that human drivers typically handle based on experience and intuition. Thus, although certain sensors can enhance perception capabilities, they alone are insufficient. Consequently, autonomous vehicles are incorporating multiple perception systems and attempting to acquire environment information from diverse sources.

Vehicle communication systems are likely to play an important role in the advancement of autonomous driving, as they can provide additional information that other sensors cannot perceive. These communication systems can function as supplementary sensors and aid in resolving complex situations.

This emerging paradigm, known as autonomous and connected driving, join autonomous driving with vehicle communication systems. Moreover, vehicle communication systems offer benefits beyond automated driving applications, such as:

- Traffic management: Real-time information about vehicles in a particular area facilitates the development of algorithms for optimizing traffic flow.

- Travel comfort: When vehicles can communicate with each other, they can synchronize traveling speeds, routes, and turns, promoting smoother driving experiences.

- Enhanced safety: The ability to communicate and anticipate hazardous situations contributes to accident prevention.

- Infotainment: Seamless internet connectivity enables the development of entertainment applications.

This project will focus on the field of vehicle communication systems and aims to provide a testing environment for those possible applications.

2.2 State of the art

2.2.1 Vehicle Communication Technologies

Vehicular communication systems are a new communication network in which vehicles and other traffic agents exchange information regarding safety warnings, traffic information, infotainment services, etc. When talking about vehicle communication systems, different approaches can be found depending on the functionalities of the communication, or the nodes that take part in the exchange of information. Focusing on the nodes communicating, there are different terminology to classify it:

- Vehicle to Vehicle (V2V): It enables vehicles to exchange information with each other, improving safety and efficiency on the road. It is usually done by using direct communication technologies like Dedicated Short-Range Communication (DSRC) or Cellular Vehicle-to-Everything (C-V2X), vehicles can share data such as position, speed, and heading, allowing for collision avoidance, intersection management, and cooperative driving.

- Vehicle to Infrastructure (V2I): It involves the exchange of information between vehicles and the surrounding infrastructure, such as traffic lights and road signs. This communication enables vehicles to receive real-time traffic updates, optimize routing, and interact with traffic management systems to improve traffic flow and reduce congestion.

- Vehicle to Pedestrian (V2P): It aims to improve safety by allowing vehicles to detect and communicate with pedestrians or vulnerable road users. This can be achieved through various means such as smartphone apps, wearable devices, or sensors that transmit data to vehicles, alerting drivers to the presence of pedestrians and improving their awareness.

- Vehicle to Network (V2N): V2N communication focuses on the exchange of information between vehicles and the nearest network infrastructure. It involves the communication between vehicles and various network elements, such as cellular networks, cloud services, and centralized data centers.

- Vehicle to Everything (V2X): V2X is a term used to put together all the previously mentioned cases. It refers to the general exchange of information and data between vehicles and various elements of the transportation ecosystem.

From the functionality point of view, these communication systems can be used with very different purposes. For example, starting with the V2N communication, cloud connectivity enables vehicles to leverage cloud-based services for various purposes. This includes real-time traffic and navigation updates, remote vehicle

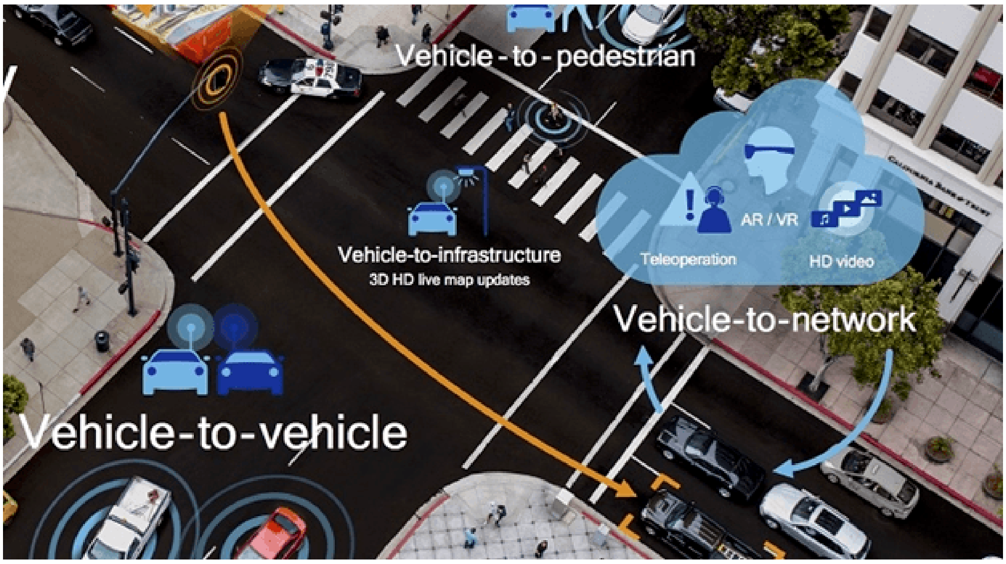

Figure 2.3: Different communication of vehicle

monitoring and control, and personalized settings and profiles. In addition, Over-the-Air (OTA) Updates can be performed with this type of communication. This enables vehicles to receive software updates remotely, similar to how smartphones or computers are updated. This technology allows automakers to deliver bug fixes, performance improvements, and new features to vehicles without requiring owners to visit a dealership and keeping vehicles up to date with the latest software. On the other hand, V2X communication also leverages autonomous driving since autonomous vehicles can rely on communication systems for coordination and decision making. Data exchange between different traffic nodes can help make informed decisions in real-time, contributing to safe and efficient autonomous driving.

2.2.2 Standard Messages

In order to ensure interoperability among different ITS systems and enable V2X communications, several message types have been standardized. These standards do not specify the communication technology to transmit the messages, but only their information and structure. Various organizations have developed similar ITS standards, being the ETSI standard the one followed and analyzed in this document.[2]

CAM: Cooperative Awareness Message

CAMs are the basic message type for C-ITS. They contain essential information about a vehicle's status, such as its position, speed, heading, acceleration, and vehicle identification. These messages are broadcasted periodically by equipped vehicles to nearby vehicles and infrastructure units. By exchanging CAM messages, vehicles can obtain real-time situational awareness of nearby vehicles and make informed decisions based on this information. CAMs follow standardized message formats, such as the one defined in the European Telecommunications Standards Institute (ETSI EN 302 637-2) standard for C-ITS communication and shown in Figure 2.4.[3]

The main information of a CAM message typically includes the following elements:

- Basic Information: This includes vehicle identification and basic safety- related data, such as the vehicle's speed, heading, and acceleration.
- Position Information: CAM messages provide precise location information, including latitude, longitude, and altitude, to enable accurate positioning of the vehicle.
- Time Synchronization: CAM messages include a timestamp to ensure synchronization between different vehicles and infrastructure units.
- Vehicle Dynamics: Information related to the vehicle's dynamics, such as the rate of change of speed and heading, may be included to provide additional context about the vehicle's movement.
- Vehicle Safety Attributes: CAM messages may contain safety-related attributes, such as the presence of hazard lights, indicating the vehicle's status and potential risks.

DENM: Decentralized Environmental Notification Message

DENM messages are used to alert about hazardous situations, road conditions, incidents, and other environmental factors that may affect traffic and road safety. Differently from CAMs, these are not cyclic messages, but they are only broadcasted when an event occurs. The information coded in the DENMs helps vehicles and drivers make informed decisions, adapt their driving behavior, and enhance overall road safety. DENM are standardized by ETSI EN 302 637-3.[3] The DENMs are very flexible messages that can be adapted to share different information. Typically, they include the following elements:

- Event Type: DENMs specify the type of environmental event or situation being reported. For each specific event type, a unique code is defined in the standard composed by two designations: CauseCode and SubCauseCode. The

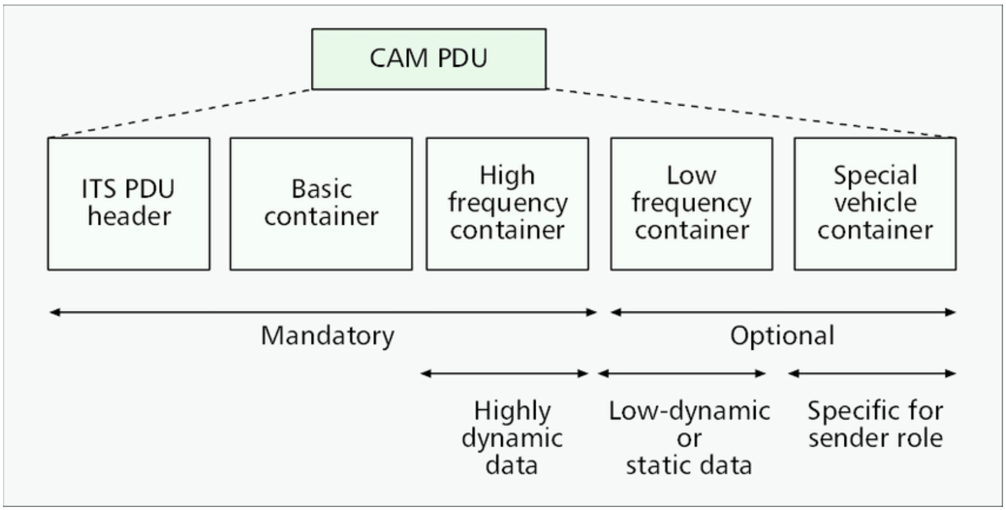

Figure 2.4: Structure of a CAM message

CauseCode is the direct cause code that provides a high-level description of the detected event type, instas the SubCauseCode it is used to provide more detailed information of the event.

- Location: DENMs provide precise location information about the event or situation. This includes latitude, longitude, and altitude coordinates to identify the geographic area affected by the event. The location details help recipients understand the specific area impacted and plan their routes accordingly.
- Severity Level: DENMs may indicate the severity level or impact of the environmental event. This can range from minor disruptions to severe incidents.
- Duration: DENMs specify the expected duration of the event or situation.
- Event Dynamics: If applicable, DENMs may provide information about the dynamics or evolving nature of the event. For example, in the case of changing weather conditions, the DENM might include details about the rate of change or anticipated developments.
- Relevance and Validity: DENMs may contain information regarding the relevance and validity of the notification. This includes details about the originating source of the notification, the time of generation, and the expiration time indicating until when the information is considered valid.

CPM: Collective Perception Message

The Collective Perception Messages aim to transmit data about locally detected

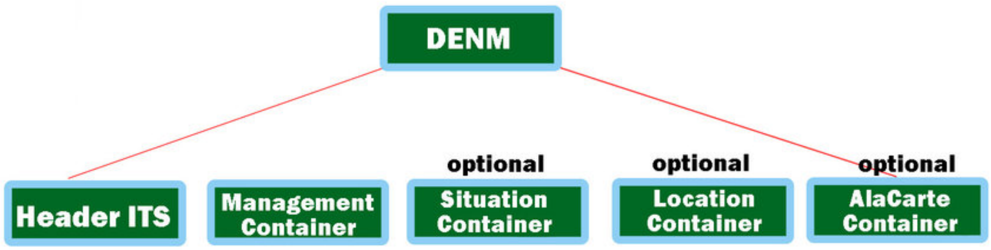

Figure 2.5: Structure of a DENM message

objects (i.e. non-cooperative traffic participants, obstacles and alike) to improve situational awareness. Unlike DENM, which only send an alert of a hazardous situation, CPM are more complex messages that share the information to identify and precisely locate the detected object. This message type will be specially interesting for autonomous driving vehicles, since they will be able to overcome these obstacles in a safer and faster way.

2.3 Communication Technologies

Ensuring a reliable and stable communication channels between moving vehicles, carries some difficulties that had not been considered before in static communications or even in mobile phones communications. This are some of the main requirements that are needed:

- The communication system must be able to support nodes moving at high speeds. And even more taking into consideration relative speed when two vehicles are going in opposite directions.
- Latency must be very low and with high reliability for safety functionalities
- The system must have a very high capacity since there would be a very large number of vehicles exchanging information in the same area.
- To cover all the previously mentioned situations (V2X), both direct communication systems and network systems are needed.

Having these requirements in mind, several standards have been developed to ensure interoperability and harmonization of ITS systems and components. Some of the most known ones can be the IEEE 802.11p, the ETSI ITS-G5, the SAE J2735, or some ISO standards (ISO 15628, ISO 21217, ISO 14813). However, most of these standards only provide guidance for a small portion of the V2X spectrum. For example, the IEEE 802.11p, the ITS-G5, and the SAE J2735, only define protocols for direct communication systems which could be used for V2V, V2I or V2P communications, but do not support V2N communications.

3GPP Cellular-V2X

The Cellular-V2X (C-V2X) communication standard, introduced by 3GPP, is a highly comprehensive standard used also in this project. It utilizes cellular networks to facilitate both direct and network communications.

3GPP,is a global organization responsible for developing cellular communication standards such as 2G, 3G, 4G LTE, and 5G, and has also formulated specifications for C-V2X communication within LTE and 5G cellular networks. This organization plays a crucial role in the context of Intelligent Transportation Systems (ITS).[4]

Compared to other standards, C-V2X offers several advantages, including wider coverage, longer communication range, and seamless integration with existing cellular infrastructure.

The C-V2X standards defined by 3GPP establish communication protocols, message formats, and system architecture for V2X communication. These standards ensure interoperability and compatibility among various C-V2X implementations from different manufacturers, enabling smooth communication and collaboration within the ITS ecosystem.

Wireless communication standards are continuously evolving and undergoing adjustments and modifications as shown in Figure 2.6[5]. 3GPP employs a system of parallel "Releases" to periodically update the standards. This approach provides developers with a stable platform for implementing features at a specific point and allows for the addition of new functionalities in subsequent Releases.

3GPP releases have been instrumental in standardizing communication technologies since 1992, with the significance of vehicle communication systems growing notably in Release 14 and Release 15. Release 14 established the foundational standard for C-V2X communications using the 4G LTE network, while Release 15 introduced 5G and adapted the C-V2X standard to the new generation.[6][7]

The C-V2X standard encompasses two communication links: Vehicle to Network (V2N) that relies on the existing cellular network (Uu), and direct communication for other V2X services through the PC5 link.

PC5 Interface

The C-V2X PC5 interface is based on the Sidelink adaptation of the cellular network, which allows direct communication between two devices without going through a base station.[] In Release 12, 3GPP introduced the concept of Sidelink as a standard for Public Safety communications. Up to that moment,, public safety communications relied on diverse standards across different geographical

3GPP RELEASES

3GPP RELEASE	RELEASE DATE	DETAILS
Phase 1	1992	Basic GSM
Phase 2	1995	GSM features including EFR Codec
Release 96	Q1 1997	GSM Updates, 14.4 kbps user data
Release 97	Q1 1998	GSM additional features, GPRS
Release 98	Q1 1999	GSM additional features, GPRS for PCS 1900, AMR, EDGE
Release 99	Q1 2000	3G UMTS incorporating WCDMA radio access
Release 4	Q2 2001	UMTS all-IP Core Network
Release 5	Q1 2002	IMS and HSDPA
Release 6	Q4 2004	HSUPA, MBMS, IMS enhancements, Push to Talk over Cellular, operation with WLAN
Release 7	Q4 2007	Improvements in QoS & latency, VoIP, HSPA+, NFC integration, EDGE Evolution
Release 8	Q4 2008	Introduction of LTE, SAE, OFDMA, MIMO, Dual Cell HSDPA
Release 9	Q4 2009	WiMAX / LTE / UMTS interoperability, Dual Cell HSDPA with MIMO, Dual Cell HSUPA, LTE HeNB
Release 10	Q1 2011	LTE-Advanced, Backwards compatibility with Release 8 (LTE), Multi-Cell HSDPA
Release 11	Q3 2012	Heterogeneous networks (HetNet), Coordinated Multipoint (CoMP), In device Coexistence (IDC), Advanced IP interconnection of Services,
Release 12	March 2015	Enhanced Small Cells operation, Carrier Aggregation (2 uplink carriers, 3 downlink carriers, FDD/TDD carrier aggregation), MIMO (3D channel modelling, elevation beamforming, massive MIMO), MTC - UE Cat 0 introduced, D2D communication, eMBMS enhancements.
Release 13	Q1 2016	LTE-U / LTE-LAA, LTE-M, Elevation beamforming / Full Dimension MIMO, Indoor positioning, LTE-M Cat 1.4MHz & Cat 200kHz introduced
Release 14	Mid 2017	Elements on road to 5G
Release 15	End 2018	5G Phase 1 specification
Release 16	2020	5G Phase 2 specification
Release 17	~Sept 2021	

Figure 2.6: 3GPP Releases

regions, and even within a single country. This fragmentation made it challenging for different public safety groups to collaborate effectively. The introduction of Sidelink aimed to address this issue by providing a solution.

Usually, when establishing a connection with a network base station, two types of communication occur: uplink and downlink as shown in Figure 2.7. Sidelink, an adaptation of the core network standard initially used in the LTE network, enables direct communication between two devices without the need to go through a base station. This facilitates direct device-to-device communication, improving the efficiency and effectiveness of public safety communications. In Release 14, the Sidelink standard was modified to accommodate C-V2X communications, enabling direct wireless communication between vehicles, infrastructure, and pedestrians. PC5 communications utilize the dedicated Intelligent Transportation Systems (ITS) 5.9 GHz spectrum, which operates independently of cellular networks. When comparing PC5 to other direct communication system standards such as Dedicated Short-Range Communication (DSRC) or 802.11p, PC5 offers several advantages.

These include an extended communication range, improved performance in non-line-of-sight (NLOS) scenarios, enhanced reliability, and cost efficiency.[8]

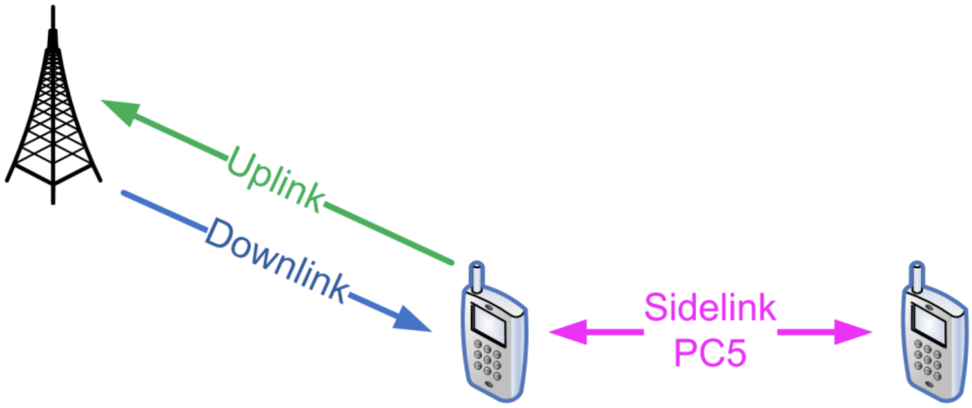

Figure 2.7: Sidelink

Uu Interface

The CV2X Uu interface is a communication interface that is defined within the architecture of the LTE and/or 5G cellular network. Specifically, the Uu interface regards the air interface between the Base Stations and the devices that enable vehicle communication.

By utilizing the Uu interface, CV2X-enabled devices can access and make use of the capabilities offered by the cellular network. This allows them to take advantage of the reliability, coverage, and low-latency communication features provided by LTE/5G technology. Through this interface, efficient and secure transmission of data between vehicles and the network is made possible. It supports a range of applications and services related to traffic safety, efficiency, and connected mobility.

It is worth noting that the CV2X Uu interface operates within the existing infrastructure of the cellular network and uses its standard protocols and communication mechanisms. However, there may be specific modifications or enhancements made to accommodate the unique requirements of CV2X communication. These adaptations can include prioritizing safety-critical messages, managing low-latency communication, and facilitating reliable V2X communication within the context of the cellular network.

Chapter 3

AI@EDGE Project

In the future, autonomous and connected vehicles will strongly depend on Artificial Intelligence, which is a key component of Industry 4.0. This trend has been recognized by various authorities and policymakers, who emphasize the need for intelligent, reliable, secure, and high-performance networks to support the development and advancement of the Next Generation Internet (NGI) capable of offering multiple services. Over the past few years, AI-driven systems, based on high performance to operate effectively and safely, have made a big step forward. Furthermore, the seamless integration of these systems with various applications and the provision of high-quality services necessitate autonomous decision-making capabilities.

In the AI@EDGE project, European industries, academics, and innovative small and medium-sized enterprises (SMEs) have come together with the idea of making a significant impact on the AI-for-networks and networks-for-AI paradigms in beyond 5G systems. The focus is on key areas such as cooperative perception for vehicular networks, secure multi-stakeholder AI for IoT, aerial infrastructure inspections, and in-flight entertainment, with the goal of maximizing commercial, societal, and environmental benefits.

To achieve this objective, AI@EDGE aims to make significant breakthroughs in two main areas. Firstly, by developing general-purpose frameworks for closed-loop network automation that can support flexible and programmable pipelines for creating, utilizing, and adapting secure, reusable, and trustworthy AI/ML models. Secondly, by creating a connect-compute platform that can manage resilient, elastic, and secure end-to-end slices, capable of supporting different range of AI-enabled network applications.

The AI@EDGE project will focus on six main areas of innovation as shown in Figure 3.1 [9]:

1. AI/ML for closed loop automation, enabling efficient and intelligent network

management

2. Privacy preserving, ML for multi-stakeholder environments

3. Distributed and decentralized connect-compute platform, providing robust and scalable infrastructure for AI-enabled networks

4. Provisioning of AI-enabled applications

5. Hardware-accelerated serverless platform for AI/ML, enhancing the performance and efficiency of AI computations at the network edge

6. Cross-layer, multi-connectivity, and disaggregated radio access, enabling seamless and efficient connectivity across heterogeneous networks

The AI@EDGE platform will be validated through the implementation of four carefully selected use cases, each having specific requirements that cannot be met by the current 5G networks based on the 3GPP Rel15 and 3GPP R16 standards. These use cases particularly demand support for latency-sensitive and highly dynamic AI-enabled applications. By addressing these challenges and achieving the breakthroughs, AI@EDGE aims to bring about significant advancements in the field of AI-enabled networks, benefiting a wide range of industries, academia, and society as a whole.

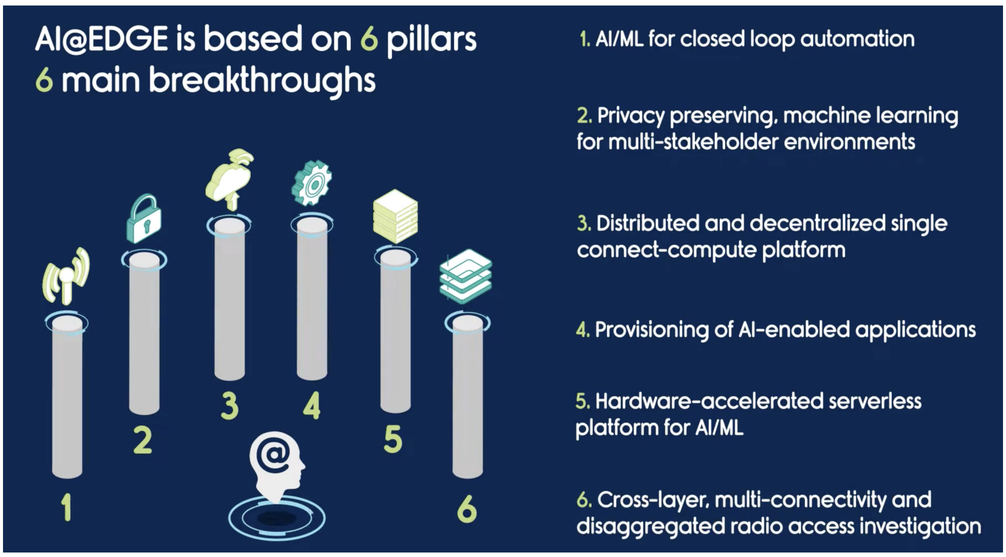

Figure 3.1: Six technological pillars

3.1 Overview

The work under this project will touch different critical areas, such as e-health, smart homes and cities, self driving vehicles and drones. One of the main application of the AI@EDGE project is on Autonomous Vehicles where the most important things to consider are Virtual and Augmented reality (VR/AR), real-time computer vision with the help of cloud and edge computing in various connectivity dependent services or function especially in ADAS. These capabilities, in the Next Generation Internet Applications, will strongly rely on intensive AI/ML based compute platform, and the overall performance and reliability of connectivity in the mobility.
Therefore, the main goal of AI@EDGE is the efficient and optimal management of Multi-access Edge Computing (MEC) resources. While 4G systems already offer effective connectivity and capacity, the introduction of 5G brings edge resources and end-to-end slicing capabilities. However, to achieve large-scale implementation of AI/ML requires several challenges. Firs of all, existing intercommunication methods are designed for fixed and homogeneous cloud environments, in which the targeted applications involve millions of distributed IoT devices with different characteristics. Second, in dynamic mobile environments, factors such as system heterogeneity, connectivity issues (e.g., variable channel conditions, handovers, and churn), introduce uncertainties regarding resource availability and accessibility for distributed processing tasks.And finally, it is crucial to maintain data privacy and ensure the integrity of learned models while sharing resources and deploying them by guaranteeing end-to-end security throughout the entire resource deployment process.

3.2 Objective and scopes

AI@EDGE will focus on the development of platform and essential tools to securely, reliably, and autonomously deploy extensive cloud and edge computing resources, along with their corresponding infrastructures. In a serverless computing paradigm, the network, storage, and compute infrastructures—which are the heterogeneous MEC resources are essentially never touched. To achieve this, AI@EDGE integrates cross-layer, multi-connectivity radio access and incorporates native hardware acceleration, such as GPU and FPGA capabilities.
The AI@EDGE platform will try to achieve three main objectives:

1. **Scalability**: achieved by combining a serverless co-fabric (compute- control) with a distributed messaging architecture and dynamically deploying data-driven AI functionalities

2. **Adaptability**: realized through the use of adaptive management functions

based on data-driven methodologies and learning models, implementing security models and intelligent countermeasures, infrastructure resilience, and efficient resource usage

3. **Automation**: discussed in terms of identifying efficient processes, utilizing developed systems concepts and methods, and putting into practice scalable and adaptable management functions

In order to check and confirm the results of the AI@EDGE platform will be studied four different use cases inside the following domains: Industrial Internet of Things, Unmanned Aerial Vehicle for Industrial Operations, Connected and Automated Mobility and In-Flight Entertainment.
Those use cases will face various critical challenges, such as achieving ultra-low latency, ensuring secure communication, establishing faster connections, ensuring resilience, and maintaining service continuity in mobile scenarios. At the end of the project, there is a strong expectation that the AI@EDGE platform and the concepts developed will have a substantial impact on the 5G ecosystem.

3.3 AI@EDGE Concept and methodology

The main scope of the AI@EDGE platform is to facilitate the automatic deployment of a secure and adaptive compute layer. This platform will incorporate crucial APIs that enable the implementation of expansive compute virtual overlays, consisting of interconnected virtual machines, containers, and serverless instances. These overlays can be deployed across different and interconnected infrastructures, supporting various upcoming key applications as shown in Figure 3.2 . AI@EDGE project

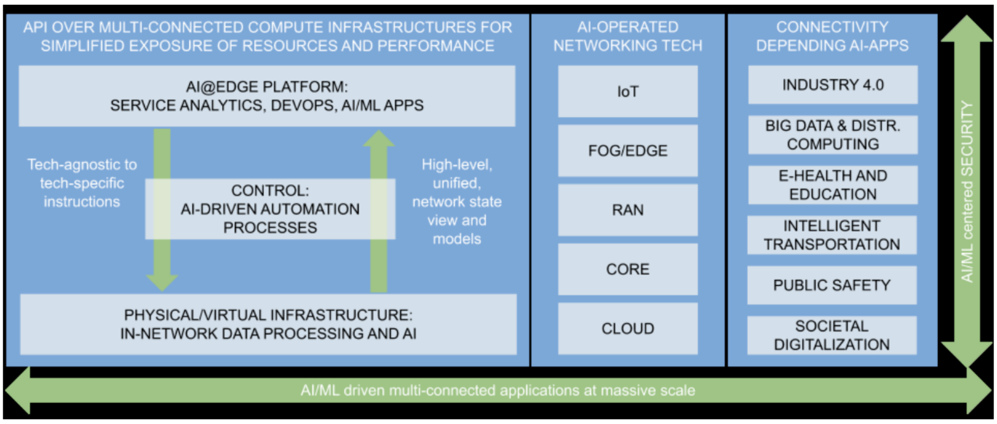

Figure 3.2: Functional overview of the platform and project scope

try to create a connect-compute infrastructure that can effectively handle flexible and secure end-to-end slices of data. These slices will be capable of supporting various AI applications. To ensure the privacy of stakeholders while using the platform, techniques such as privacy-preserving machine learning and trustworthy networking will be employed. A visual representation of the AI@EDGE AI-enabled connect compute platform can be found in Figure 3.3, and further information about it will be provided in subsequent sections[10]. As shown before in Figure

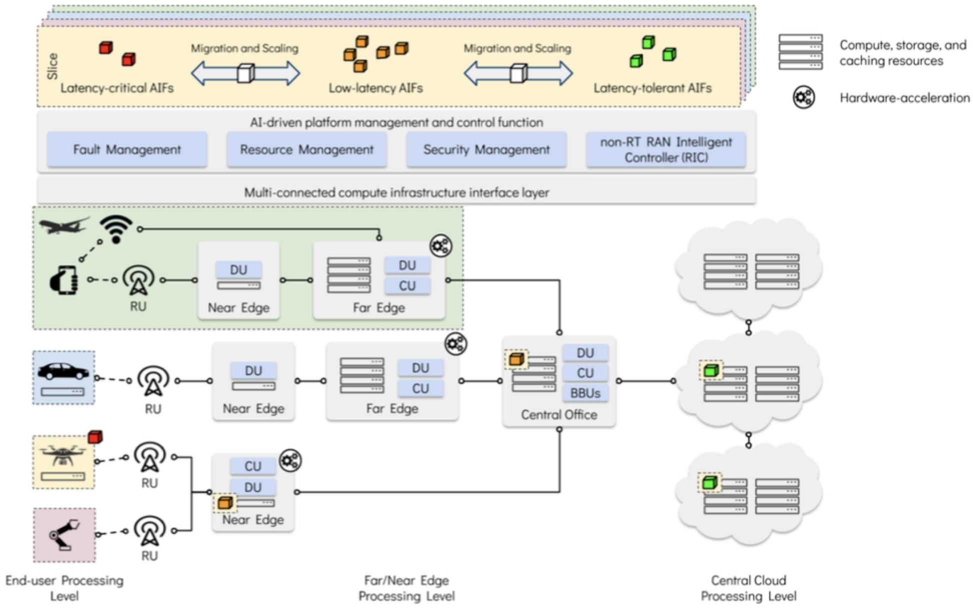

Figure 3.3: Connect compute platform for AI-enable

3.1, the core objectives of the AI@EDGE framework consists of six significant advancements. The subsequent subsections provide a comprehensive explanation of these innovations and their relevance to the four designated use cases. These six breakthroughs can be divided into two main categories. The first one is about the incorporation of AI/ML solutions into 5G networks, specifically referring to breakthroughs 1 and 2. The second category, referring to breakthroughs 3 to 6, will focus on the development of distributed, hardware-accelerated connect-compute platforms.

3.3.1 Artificial Intelligence and Machine Learning for closed loop automation

One of the main critical requirement in the development of networking application is to have a low latency. In order to meet this demand, Mobile Edge Computing (MEC) technology plays a crucial role, even though it is still in its early stages.

When creating AI-driven applications on a large scale, it is not practical to put the majority of computing operations to the cloud. Therefore, as Internet technology, applications and businesses are advancing, shifting these compute tasks to the edge becomes a viable approach to accommodate the immense scale of the domain, acknowledging the interdependence between AI-based apps, AI-driven network operations, and service management Because of that, the scale and speed at which computing resources need to be allocated and scaled require a level of comprehensive automation that have never been tested before. It is expected that at least 99% of service management and network operations can be automated without any human interaction, in only exceptional cases such as failures that cannot be resolved automatically. This emphasizes the need for a high degree of automation to handle the vast majority of tasks in order to achieve efficient and seamless operation with a high level of reliability.
The concept behind AI@EDGE is to develop a platform that automates the deployment of AI/ML compute infrastructure across MEC nodes. This platform requires three essential components:

1. It needs information-efficient and high-fidelity local models that accurately represent the performance and available resources of each local node, taking into account factors like proximity in terms of latency.
2. It needs efficient data processing pipelines and strategies for data dissemination, minimizing the overhead associated with data transmission
3. It needs to include AI/ML-based functions for automated infrastructure control.

These three components are crucial to address the key challenges and enable distributed and federated learning at a large scale.
Deploying distributed processes is a challenging task due to the instability of mobile edge resources, which include both fixed edge nodes and mobile User Equipment (UEs) with computing capabilities. These resources often experience fluctuations in network performance and resource availability. The monitoring methods that are used now, are insufficient to accurately predict the performance and availability of networking and computing resources under such a wide range of circumstances. The cost and inefficiency of monitoring billions of devices with the required level of accuracy for efficient resource utilization are prohibitive.

To overcome these challenges, the AI@EDGE objective is to develop advanced strategies such as federated learning and local modeling. These approaches facilitate the exchange of information about network performance and resource availability. By using these methods, high-fidelity models can be created, enabling automated decision-making processes with significantly improved prediction performance. This will lead to enhanced resource utilization, energy efficiency, and the ability to meet stricter Service Level Objectives (SLOs). Moreover, these strategies reduce the amount of data required for monitoring and information exchange, further improving efficiency and effectiveness in resource management.

Efficient data processing and dissemination of partial outcomes in distributed and federated learning is an extensively studied area in cloud infrastructures. The most common approach involves a server coordinating the output among a group of workers, with significant research efforts dedicated to reducing the overhead, associated with model parameter updates between the parameter server and workers. The dissemination approach plays a crucial role in addressing data transaction overhead, durability, and convergence rate for the specific learning algorithm.

However, the existing paradigm targets fixed cloud computing infrastructures. In the context of MEC infrastructures characterized by resource volatility and heterogeneity in performance and capacity, novel dissemination strategies become necessary. This is particularly important in scenarios where millions of algorithms with different dimensions need to be executed at scale across volatile resources. To address this challenge, AI@EDGE aims to advance the current research on efficient and scalable AI/ML virtual learning infrastructures. The focus will be on developing efficient information exchange methods specifically designed for MEC environments, taking into account the unique characteristics and requirements of such infrastructures.

In order for current and emerging networking technologies like MEC, 5G, and future advancements to realize their full potential, automated and zero-touch network operation and service management are vital. While network automation and controls have been studied for many years, the current landscape is different due to notable advancements in machine learning, increased computational power, infrastructure processing capabilities, enhanced link bandwidth, and innovations in distributed computing. These developments create opportunities for practical AI functions. However, existing machine learning techniques primarily focus on offline, centralized processing and are not specifically designed for the unique requirements of network operation and service management. In the context of AI@EDGE, the scope is to create machine learning concepts that are well-suited for the operation of distributed systems and resilient service management, particularly in terms of fault and resource management. The main focus will be on developing rapid, scalable, and adaptable machine learning-based methods.

These methods will incorporate a combination of deep learning techniques such as Generative Adversarial Networks (GAN), Long Short-Term Memory (LSTM), Gated Recurrent Units (GRU), Deep Reinforcement Learning (DRL), and Graph Neural Networks (GNN). Additionally, AI@EDGE will explore representation learning, attention mechanisms, pointer networks, and other relevant aspects to design machine learning methods that are specifically applicable to the unique circumstances of 5G MEC. Overall, the project's objective is to accumulate significant knowledge on machine learning design patterns that are practically useful for the zero-touch management of distributed systems and networking infrastructures. This will be supported by the relevant research.

3.3.2 Secure, reusable, and resilient machine learning for multi stakeholder environments

The AI@EDGE architecture is built on the concept of security through design. It will develop frameworks for intrusion detection algorithms, implement them, and evaluate their effectiveness. Our proposed machine learning methodology follows a distributed approach, emphasizing cooperation and privacy considerations in environments involving multiple stakeholders. The research will address three primary questions:

- Detection speed and resistance to intrusions
- Model propagation and computational efficiency
- Privacy of exchanged parameters

Firstly, the advantages of involving a variety of edge devices in terms of their identification capabilities, recognition speed (stay time), and interruption flexibility (e.g., in the event of compromised edge devices) are examined. Additionally, the proposed architecture not only has the ability to withstand compromises of edge devices and associated attack scenarios like malicious machine learning and poisoning attacks within the detection sensor network but also to promptly and reliably detect such attacks. Adversarial machine learning refers to a technique where malicious data is crafted to deceive AI algorithms. In order to make the AI model strong against malicious machine learning assaults, there will be created countermeasure and all the weaknesses in the model will be recognized.

When something bad compromises a specific edge node and introduces manipulated data to retrain an AI model, it can lead to harmful attacks. A preliminary approach to mitigate this risk involves using exception recognition based filtering, which has been described in writing. However, additional measures for mitigation will be outlined. Ongoing research indicates that blockchain and distributed ledger technologies can be exploited to establish secure audit trails as a protective mechanism in malicious AI environments. These findings will be used to have a better resilience of the proposed system against intrusions. Early detection also facilitates the automated generation of countermeasures in addition to identification. While developing countermeasures from scratch is computationally intensive (such as resource outsourcing or traffic rerouting based on optimization algorithms), creating a database of known attack patterns will increase the defense against such attacks.

Secondly, the capabilities of zero-day detection, propagation of detection models, and computational efficiency of federated learning in the network of edge devices are examined. The proposed architecture will have the ability to efficiently update and distribute learning detection models within the sensor network, adapting to previously unknown attack types, long-term attacks and distributed attacks (where security events are observed across multiple edge devices). Considering the increasing reliability on smartphones and IoT devices for edge applications, a specific focus is given to the search for mobile device-level botnet attacks, which will be investigated using publicly available traces. Federated learning allows the creation of a shared machine learning model by combining local models obtained from edge devices, ensuring privacy constraints and data confidentiality. Initially, a first model is trained on the edge devices using relevant local data, and improved models are then aggregated into a global model. While federated learning shows promise, there are several challenges that need to be addressed. AI@EDGE will explore techniques for adjusting parameters and hyperparameters and for combining heterogeneous datasets despite local biases or temporal differences.

Thirdly, the privacy considerations of federated learning architectures are assessed in terms of the information gained for the local threat model versus the parameters exchanged among edge devices, which may be under the control of different entities. As no stakeholder will have the ability to extract business-relevant information from the exchanged detection model parameters, it will be feasible to conduct extensive parameter exchanges, thereby enhancing the detection capabilities[10][11][12].

3.3.3 Distributed and decentralized serverless connecting platform

AI@EDGE will combine established cloud-native paradigms to create a unified connect-compute platform for developers. This platform will integrate Function-as-a-Service (FaaS)/serverless computing, hardware acceleration (such as GPU, FPGA, and CPU), and a dis-aggregated Radio Access Network (RAN) with multi-connectivity capabilities at the cross-layer level. The serverless and FaaS computing paradigms, which are gaining popularity, provide a cloud computing execution model that relieves developers and service providers from the weight of resource management. Instead, they can focus mainly on their core activities, such as managing their code and services. In this model, the infrastructure provider takes responsibility for managing the underlying infrastructure and dynamically allocating sufficient resources to automatically scale applications and services based on demand.

Serverless computing offers several advantages over traditional computing and is well-suited for various use cases, including stream data processing, chatbots, and stateless HTTP applications. These advantages include the ability to scale down to zero, eliminating charges for idle time, as well as simplified server management and automated scaling.
AI@EDGE aims to empower telecommunication operators in transitioning their networks to a hybrid multi-cloud-native paradigm by integrating the principles of serverless computing and FaaS as integral components within the 5G ecosystem. This integration will not only enhance developer productivity but also offer solutions for the deployment of applications that can effectively leverage advanced 5G functionalities. Furthermore, AI@EDGE will establish a set of open APIs, enabling the neutral host model and facilitating interaction between mobile network operators (including virtual operators), vertical industries, service providers, and end users with the network.

As part of the AI@EDGE project, it will be enhance the existing ETSI MEC/NFV architectures by incorporating application and application-intent models that can effectively capture the different nature of application development. Additionally, we will introduce serverless technologies to the Cloud Native Application Bundling (CNAB) initiative within AI@EDGE. Currently, CNAB only supports virtual machines and containers, but our aim is to extend its capabilities.
Furthermore, AI@EDGE will implement intelligent control and management of applications and services deployed on the serverless, decentralized, and distributed AI@EDGE platform. This will be achieved by using the context and the metadata obtained from the application and application-intent modeling studies.[11][12]

3.3.4 Artificial Intelligence applications

The use of AI@EDGE will revolutionize the way AI-enabled applications are delivered over a distributed computing platform. It involves transforming the complete range of computation, storage, and network capabilities needed for provisioning these applications. To achieve this advancement, AI@EDGE focuses on two key areas:

- Reference model for Artificial Intelligent Functions (AIFs). AI@EDGE will develop a understanding reference model for AIFs that effectively captures and represents their diversity across different levels of the technology stack. This reference model will be constructed using advanced ontology engineering techniques and will consist of interconnected modular ontologies. Standard knowledge representation languages like OWL will be employed for its implementation. The focus will go beyond describing the functionality of AIFs, which can be found in other catalogs, by also incorporating the necessary constraints for their dynamic orchestration and additional capabilities such as computation, communication, storage, and hardware acceleration. Furthermore, the reference model will include strategies for facilitating the provisioning of AI-enabled applications. As part of this task, a catalog of AIFs will be created, containing AIFs sourced from AI@EDGE as well as other available resources.

- End-to-end orchestration of AIFs. For the deployment of AI-enabled applications, it is necessary to allocate resources across different administrative and technological domains. To achieve this, AI@EDGE will divide applications consisting of multiple AIFs into separate domains based on each AIF's requirements. Initially, well-established orchestration standards like Docker and Kubernetes will be used, along with their emerging variants like FaaS, to cater to diverse provisioning scenarios involving software and hardware resources. AI@EDGE will explore innovative approaches to orchestrate end-to-end AI-enabled applications, taking into account the complexity and heterogeneity of edge computing platforms. Specifically, this project focuses on extensive edge computing platforms. The AI@EDGE network automation platform will be utilized to design and develop monitoring solutions tailored to optimized hardware, edge devices, communication infrastructures, and cloud services. These solutions aim to ensure the successful orchestration of multiple AIFs within complex AI-enabled applications.The monitoring subsystem will collect Quality of Service (QoS) indicators that provide insights into the proper functioning of orchestrated and interconnected AIFs. These indicators will encompass traditional IT system metrics such as performance, as well as specific criteria to validate that AIFs operate according to their intended design. Finally, the collected quality indicators and metrics will enable effective management of orchestrated AIFs, incorporating AI-based capabilities for detecting abnorm situations and facilitating predictive maintenance.

3.3.5 Cross-layer, multi-connectivity, and disaggregated radio access

Enabling use cases beyond the capabilities of 5G networks will require the adoption of fundamentally different communication approaches. One example of such an approach is dual connectivity, which was initially introduced in Release 15 of 3GPP radio access technologies to enable Ultra-Reliable Low Latency Communications (URLLC). This introduction aimed to enhance support for Industrial Internet of Things (IIoT) applications. In the current version of the dual connectivity paradigm, data duplication is employed at the PDCP layer to improve reliability in terms of packet delivery ratio, without significantly increasing latency. However, its major drawback it is in its suboptimal utilization of radio resources, as data is replicated even when unnecessary. To address these limitations, significant enhancements were made to dual connectivity in 3GPP Release 16. Further improvements and advancements will be introduced in 3GPP Release 17 to build upon the enhancements made in the previous release. AI@EDGE will explore the transition from current dual-connectivity solutions to future multi-node connectivity approaches by leveraging heterogeneous radio access technologies such as 3GPP (5G and beyond) and non-3GPP technologies like Wi-Fi. The investigation will focus on different user-plane data replication strategies across various protocol stack layers. The main focus will be on the user-plane traffic duplication at layers 3 and 4, particularly using Multi-Path TCP (MP-TCP), to enable link bonding with non-3GPP interfaces. This approach ensures that mobile devices receive the same information over multiple wireless links. The primary goal is to optimize the utilization of radio resources while simultaneously improving throughput and reliability without compromising latency. In order to achieve this, we will develop a multi-path AIF (AI Inference Framework) that serves as a multi-path Conversion Point (MCP) on the path to the application servers. This AIF will integrate the different traffic flows received from the terminal across multiple paths. Throughout the project, we will investigate techniques such as traffic load balancing and determine the most effective placement and scaling of the MCP to achieve optimal performance[13][14].

3.4 Use Cases

The AI@EDGE project will be addressing four distinct use cases. These use cases encompass a range of applications where AI technologies will be deployed at the edge, showcasing the potential impact of AI@EDGE in various domains cases as shown also in Figure 3.4:

1. Use Case 1: Virtual Validation of Vehicle Cooperative Perception. Real-time trajectory exchange among vehicles enables them to utilize artificial intelligence models to comprehend the surrounding environment and anticipate potential danger situations

2. Use Case 2: Secure and Resilient Orchestration of Large Industrial IoT Networks. The communication and computing infrastructures in smart factories are designed to be both secure and resilient, accommodating a diverse range of industrial actuators, sensors, specialized application servers, and network

fabric. These measures ensure protection against faults, attacks, bugs, and fluctuations in workload, thus maintaining the overall stability and reliability of the system.

3. Use Case 3: Edge AI Assisted Monitoring of Linear Infrastructures in Beyond Visual Line of Sight Operations. To identify anomalies, monitoring drones collaborate with ground computing facilities by exchanging data. They employ techniques such as 3D environment reconstruction and data fusion to guide drone mobility and operations over extensive distances. This collaborative approach enhances the effectiveness of detecting irregularities and enables efficient monitoring activities.

4. Use Case 4: Smart Content and Data Creation for In-Flight Entertainment Services. Passengers are provided with high-definition multimedia content by dynamically computing the content based on their preferences. To achieve high throughput and reliability, a combination of 3GPP and non-3GPP network technologies is utilized, allowing for efficient aggregation of resources. This ensures that passengers can enjoy a seamless and reliable multimedia experience during their journey.

In this thesis project, the main focus will be on the Use Case 1 and into its motivation, goals, and overall framework. The discussion will focus on categorizing the Use Case 1 into different parts, with particular emphasis placed on the aspects that have been accomplished during the time period of this thesis project. Furthermore, we will explore the potential objectives associated with those completed parts.

Technological Enabler	UC1	UC2	UC3	UC4
Distributed and decentralized serverless connect-compute platform	Y	Y	Y	Y
AI-enabled application provisioning	Y	Y	Y	Y
Cross-layer, multi-connectivity radio access				Y
Hardware accelerated serverless platform for AI/ML			Y	Y
Network and service automation platform	Y	Y	Y	
Secure, reusable, and resilient machine learning for multi-stakeholder environments		Y		

Figure 3.4: Table of the technologies studied in the different use cases

3.4.1 Use case architecture

The main application of the AI@EDGE in cooperative perception is the implementation of a virtual validation testing platform that spans multiple geographic locations. This platform aims to support cooperative vehicle operations, enabling efficient and collaborative testing and validation processes.

To implement this geographically distributed use case, multiple components need to be organized and managed by different teams. The architecture of this use case is shown in Fig 3.5 and its main components include:

- **Simulation Environments**: This assures the virtual roundabout simulation environment and the simulation environment for outgoing and incoming surrounding traffic.
- **AI Traffic Controller**: This component is responsible for managing traffic using AI algorithms.
- **Digital Twin**: It represents a virtual representation of the roundabout and its surroundings. It is created by collecting information from various resources, including static data from digital maps, semi-static data such as road signs and landmarks, semi-dynamic data for temporary changes like weather and traffic jams, and dynamic data such as real-time vehicle information including GPS position, speed, and heading.
- **5G Network Emulation Infrastructure**: This infrastructure emulates a 5G network environment to facilitate communication between different components.
- **Telemetic Box**: It is an onboard unit that provides connectivity for vehicles. It includes radio interfaces such as Uu and PC5, GPS for positioning, and messaging protocols like MQTT/AMQP and C-V2X.

These components need to be categorized and managed by various teams to ensure the successful implementation of the geographically distributed use case.

Since the Use Case 1 involves two different locations connected through a 5G network and is geographically distributed, computational resources are shared between these locations. Figure 3.6 shows the geographically dispersed testbed between Milan and Turin. The components at each site are as follows:

Turin site:

- On-board Telemetic box setup emulation with Uu and PC5 interfaces, TBM with CAN Bus, and Head unit with an HMI.
- PC5 channel emulator.
- V2X simulation environment for vehicles and road-side units.
- 5G RAN emulation.

Milan site:

- Driving Simulator.
- Traffic simulation environment.
- Sensor for detecting drivers' psychological workload.

Also, the 5G network components include a 5G core network as a Mobile Edge Computing (MEC) based solution, enabling local traffic break out and a MEC and Cloud server.
The Digital Twin and AI traffic controllers are managed by the AI@EDGE Platform on the 5G network. Due to the project's complexity and limited time available, implementing all the components at the Turin site is beyond the scope of this thesis. So the primary focus of this thesis project under is on the following categories: On-board Telemetic box setup emulation. LTE/5G Network Virtualization, including running test cases involving RF network signals in the Hardware-in-the-Loop (HIL) using a TBM box. Traffic simulation, including sending and receiving vehicle information. Further detailed discussions regarding these components will be presented in dedicated chapters.

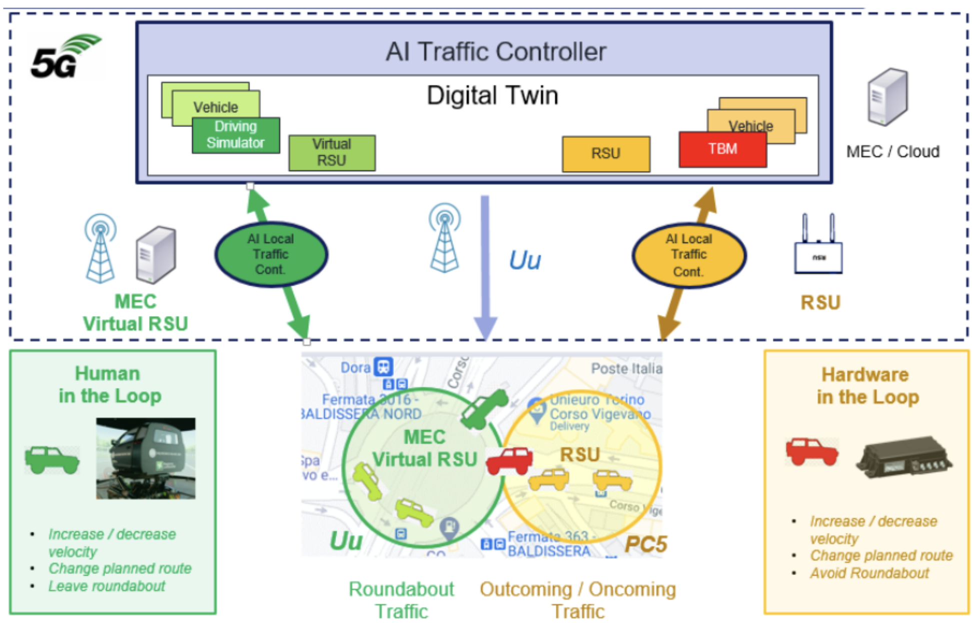

Figure 3.5: Cooperative Perception of the Use Cases Architecture

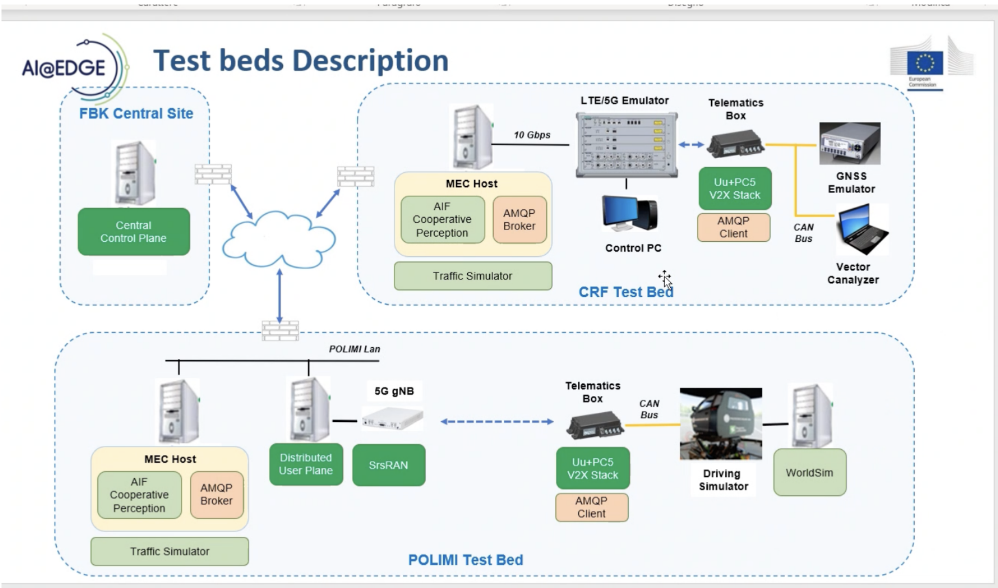

Figure 3.6: Testbed environment for Use Case 1

3.4.2 Use case : Virtual Validation of Vehicle Cooperative Perception

As said before, the main focus of this thesis project will be on the Use Case 1. Cooperative perception involves a group of vehicles within a specific area of a traffic situation. These vehicles collaborate with each other by sharing information about their current and future intended paths. The shared data is collected in a decentralized manner at the network's edge. Then all the data are processed to create a map of the surrounding scenarios. This map is then utilized by Artificial Intelligence Functions (AIFs) to anticipate potential dangerous situations like collisions, road damage, and possible accidents. Developing the entire closed loop system is a highly intricate and challenging task, which also have substantial costs for the development of the Use Case platform. Therefore, Use Case 1 employs an environment-based emulation technique that can handle such complexity and conduct comprehensive tests that can be replicated.
In the case of AI@EDGE, the combined framework of 5G and AI-based connect-compute plays an important role in equipping the traffic system with the necessary capabilities to enhance traffic flow and improve road safety. Among the challenging and potentially hazardous scenarios, the roundabout situation is one of the most significant difficulties in maintaining both safety and smooth traffic movement. To address this challenge, Use Case 1 is considering conducting tests specifically focused on roundabouts, which include a mix of automated, manual, and semi-automated

vehicles. Validating the cooperative perception of vehicles becomes particularly challenging due to the large number of vehicles involved in the roundabout scenario. This validation process requires:

- Real-time detection of scenarios
- Transmission and reception of sensed data between vehicles and the cloud
- Dissemination of trajectory to other vehicles while ensouring privacy and safety

The complexity increases when mixed traffic scenarios involve both automated and human-driven vehicles. In such cases, simulation environments alone are insufficient to replicate these complex scenarios. Therefore, the proposed strategy in this use case involves linking a traffic simulator like SUMO with a dynamic driving simulator controlled by a human driver in the loop. At the level of information sharing, a digital twinning framework is utilized to combine real and simulated vehicles. As shown in Figure 3.7 the objective is to establish a network-level data exchange that facilitates cooperative perception between virtual and emulated scenarios, as well as the human in the loop.[14]
In the Figure 3.4 we can identify the two primary technological foundations that AI-enabled digital twinning leverages, which are AI-enabled application provisioning features and the distributed and decentralized serverless connect-compute platform. Furthermore, the AI@EDGE network and service automation functions also play a crucial role in the dynamic radio network environment during the digital twinning process. The network automation platform enables testing on a 5G emulation network, allowing for a bigger range of connectivity-related test scenarios, including connection failure, mobility, and the handover process on both LTE and 5G radio frequencies (RFs), which will be discussed further in the subsequent chapter on 5G emulation. One of the significant advantages of digital twinning in this mixed environment of virtual and real world, is its ability to anticipate the actions taken by a human driver in the driving simulator, which is twinned with the virtual traffic simulator. This capability holds particular value in a driving simulator, where the simulation-emulation environment plays a central role in predicting and exchanging information about traffic and vehicle situations. It can be perceived as an automated car controlled remotely by a human driver. By examining the outcomes of remote operations, the viability of 5G and the extent to which the introduction of NR (New Radio) can enable the safe remote guidance of vehicles can be evaluated. The measurement of 5G key performance indicators (KPIs) will precisely determine the required node density, communication latency, and overall quality of service (QoS) necessary for this use case. These KPIs will also inform the implementation of the cooperative perception paradigm for connected vehicles. The two most critical key performance indicators (KPIs) for this use case, as

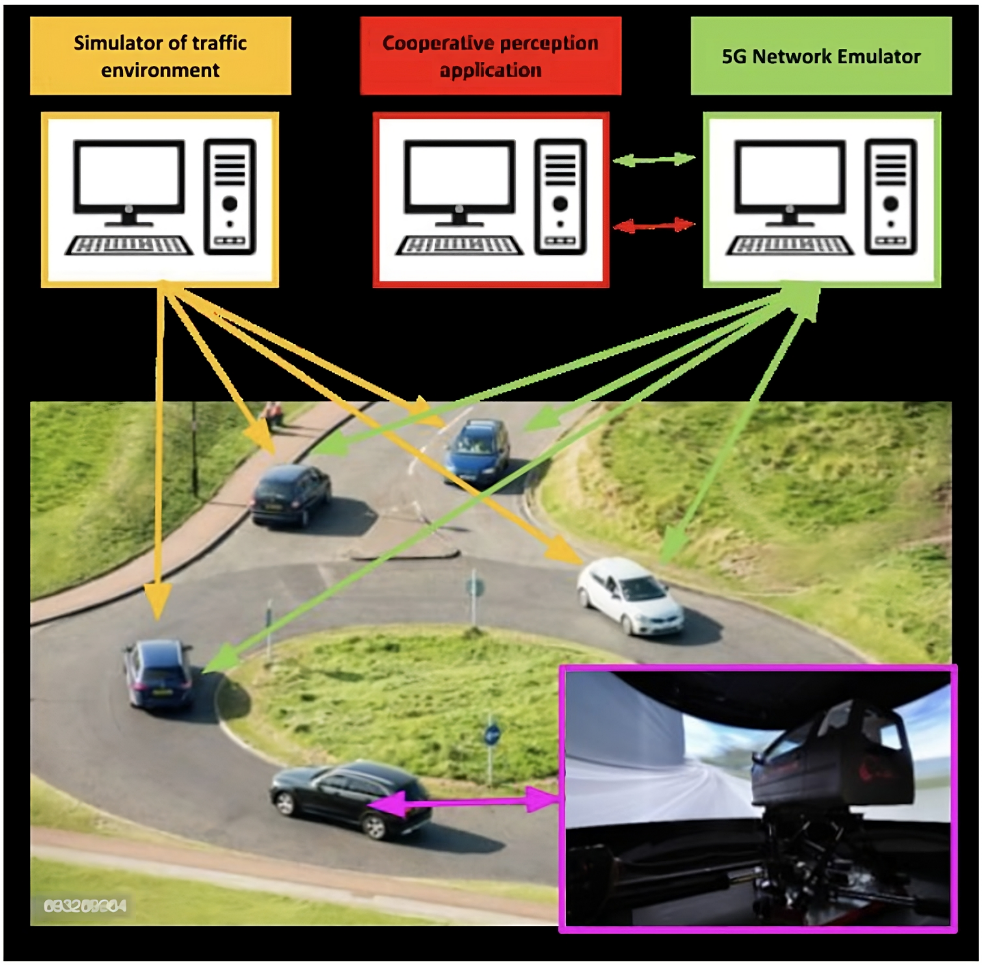

Figure 3.7: Virtual Validation of vehicles cooperative perception

highlighted in Figure 3.8 are latency and reliability. The primary concern is whether the current mobile network, as defined by the 3rd Generation Partnership Project (3GPP) in Release 15 and Release 16, satisfies these requirements. However, the anticipated performance levels for this use case pose a fundamental challenge that surpasses the existing design framework of the 5G network. Cooperative perception necessitates real-time data exchange with performance levels and measurement time resolutions below 10 milliseconds for practical implementation. Furthermore, the density of vehicles significantly influences the capabilities of cooperative perception. Another significant challenge is the testing of the speed at which the motion control systems of surrounding vehicles can collect, update, process, distribute cooperative perception data to other vehicles, and fuse it with sensed data. The current architectures of mobile networks face considerable obstacles at each of these steps, contributing to the overall communication latency.

KPI	Goal
Vehicle Density	1200 vehicles/km2 at 20km/h
Sensor fusion latency	Total from sensor detection to vehicle including sensor fusion on edge less than 10 ms
Communication reliability	from 99.9% to 99.9999%
Range	Up yo 500m

Figure 3.8: KPIs for this Use Case

Conducting complex data-sharing experiments in real-world settings presents several challenges within the framework of cooperative perception. To ensure widespread adoption of cooperative perception devices, regular and extensive testing is required, accompanied by strict safety regulations. However, leveraging the dynamic driving simulator enables the completion of a large number of complex and repetitive tests at a relatively low cost and in a shorter timeframe.

The implementation of AI@EDGE represents a significant advancement in deploying technological facilitators for automated and connected vehicles, particularly in validating the vehicle's cooperative perception. Through dynamic resource allocation and autonomous connect-compute container deployment, AI@EDGE enables efficient management of numerous vehicles in urban traffic situations for various cooperative perception services. This is achieved by:

- Utilizing knowledge of network systems to implement localized learning models
- Adapting the network to accommodate service requirements
- Employing data-driven service management strategies based on Multi-Access Edge Computing and Network Function Virtualization for Artificial Intelligence Functions
- Allocating resources and deploying distributed AI/ML services while ensuring privacy and security.

Furthermore, the overall impact of this study extends to the success of connected and autonomous vehicles, as cooperative perception serves as a fundamental enabler for numerous safety-related driving services. These services comprehend aspects such as vision transparency, forward collision warning, collision detection at intersections, and automated systems for avoiding hidden obstacles.

Chapter 4

General Overview: Simulating and Validating Networks

The objective of the use case studied in this thesis is to establish a geographically distributed testbed for virtual validation, as elaborated in the AI@EDGE chapter. This testbed aims to support cooperative vehicle operations and show the capabilities of safety-critical connected services and functions. In this context, the role of a network system becomes particularly significant. Therefore, for testing and validating these cooperative applications, the Cellular Vehicle-to-Everything system (C-V2X) heavily relies on network emulation.

To male easier the operations related to this use case, the virtual validation platform would be connected to a 5G network using the 3GPP system with Uu and PC5 interfaces. This network emulation enables the testing and validation of cooperative applications within the use case.

Before going into the details of the emulation and testing aspects, it is essential to discuss the evolution of various communication systems for V2X (Vehicle-to-Everything) applications. Understanding this progression helps trace the overall technological advancements these systems have undergone over the years.

4.1 Vehicle Communication

Recalling what has been said in the Chapter 2.2.1, improving safety-related systems is a key focus in automotive industry research. Over the years, numerous advancements have been made in safety systems, ranging from basic features like hydraulic brakes and seat belts to more advanced technologies such as ABS systems and airbags. The primary objective behind these developments is to ensure the safety of both drivers and passengers. In recent times, there has been a significant emphasis on the maturation of Intelligent Transportation Systems (ITS) within the automotive industry. These systems go beyond safety and also focus on improving traffic efficiency, enhancing user experience, and offering different mobility options, all with the overarching goal of enhancing safety. As a result, the entire transportation ecosystem is working together to establish standardized ITS systems. Among the various components of ITS, vehicle communication networks have witnessed substantial advancements. A crucial enabler for these advancements is the implementation of vehicle-specific communication and network systems. These systems facilitate faster, more direct, and reliable information exchange. By utilizing technologies such as Dedicated Short Range Communication (DSRC), Wireless Access in Vehicular Environments (WAVE), and Cellular Networks (C-V2X), vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P) information exchanges can occur with minimal latency. These communication technologies play a vital role in enabling effective and efficient communication within the ITS framework.

4.1.1 ITS Architecture

An Intelligent Transportation System (ITS) joins the primary communication domains that encompass nearly all components of a traffic system, specifically the communication between V2X. The in-vehicle domain, which can be considered as an internal communication system within the vehicle, collects data from the vehicle's sensors regarding its surroundings. This data includes information about the vehicle itself and the traffic conditions. The onboard communication device, acting as an agent, facilitates the exchange of this information with other vehicles and edge servers. However, network-related testing, specifically for LTE/5G services, is conducted in a Hardware-in-the-Loop (HIL) environment. In preparation for this testing, the Telematic Box Module (TBM) or Tele-communication Unit (TCU) is being prepared and used. The V2X domain, primarily focus on communication and equipment involving third parties. So, referring to it as inter-vehicle/infrastructure communication is not inaccurate. Due to the involvement of multiple parties and organizations, standardization becomes crucial in this context. While we won't go deeply into the infrastructure aspect, it is valuable to understand the different communication standards for V2X applications. There are two competing standardized communication technologies, as defined by the 3rd Generation Partnership Project (3GPP) and the Institute of Electrical and Electronics Engineers (IEEE), respectively. The first is C-V2X, defined by 3GPP, and the second is Dedicated Short Range Communication (DSRC), also known as WAVE in the United States and ITS-G5 in the European Union. However, the challenge it is in the allocation of frequency bands in ITS systems and the significance of these technologies within that spectrum. Many experts envision a future for V2X that involves the coexistence of DSRC and C-V2X networking systems. A possible solution it's to ensure that safety-critical ITS services/functions in both types of technologies can operate without interference from co-channel signals. We will focus on the revision of these technologies, specifically DSRC and C-V2X, for V2X deployment. By critically examining and highlighting their key limitations, we need to develop a comprehensive understanding. Furthermore, we will explore the potential for coexistence among these technologies in the vehicle networking system, along with the opportunities presented by each. Before the standardization of IEEE 802.11p, IP-based fixed networks and long-range radio communication systems such as Cellular 2G, 3G, and 5G were available. However, there was a notable absence of Short Range Radio Communication (SRC). ITS necessitate the presence of an SRC system. The primary requirements of ITS is contradicted by the possibility of unavailability, overload, or extreme slowness of cellular networks (up to 3G and sometimes 4G). These requirements are crucial for fast mobility scenarios aimed at improving road safety. For a general usage in ITS, a network should fulfill specific functional requirements, including operation within an allocated 5 GHz band, a high data rate of 10 Mbps for fast data transfers, and affordability. Although IEEE 802.11a technology could meet most of these functional requirements, it falls short in terms of providing a fast connection, which is a critical element. Without a reliable connection between vehicles and Roadside Units (RSUs), meeting this functional requirements becomes irrelevant. So, in order to address the requirements of Road Transport Telematics (RTT) applications, IEEE 802.11p was developed as a solution. This standard repurposes much of the technology from IEEE 802.11a and adapts the MAC (Media Access Control) protocol for V2V and V2I communication. Improvements were implemented to address the issue of slow association that was present in the earlier version.

As an additional protocol within the IEEE 802.11 family, IEEE 802.11p retains compatibility with the common features shared by all 802.11 protocols. The primary objective of IEEE 802.11p is to define the essential specifications required to ensure interoperability between infrastructure or ad-hoc IEEE 802.11 networks and wireless devices in rapidly changing communication environments. It also addresses to situations where transactions must be completed within significantly shorter timeframes than the minimum achievable (10ms - 100ms). But the IEEE 802.11p standard alone is inadequate for implementing V2V and V2I systems. There are two main reasons for this limitation. The firs one is that the standard only addresses the two lowest layers of the network architecture, and the second one is that V2V and V2I communication applications heavily rely on these layers. Therefore, additional network layers are essential to support these applications effectively. Consequently, two additional protocol stacks, namely ITS-G5 (in the European Union) and WAVE (in the USA), have been defined. These protocol stacks are almost identical and have been introduced to complement IEEE 802.11p and fulfill the requirements of V2V and V2R communication systems.

The IEEE WAVE (Wireless Access in Vehicular Environments) protocols are a collection of standards. These protocols utilize the IEEE 802.2 standard at the logical link control (LLC) layer and the IEEE 802.11p standard at the MAC and physical layers. The WAVE system is a radio communication system specifically designed to provide seamless and interoperable transportation services. Several services recognized by the U.S. National Intelligent Transportation Systems Architecture, as well as those under consideration by the automotive and transportation infrastructure industries, are part of the WAVE system. Examples of these services include vehicle-to-roadside and vehicle-to-vehicle communications between On-Board Units and Roadside Units. The objective of this standard is to specify the functions and services of the MAC sub-layer, enabling multi-channel wireless connectivity among IEEE 802.11 WAVE devices. The IEEE 802.11p defines the operation of WAVE-based applications in this environment, building upon the management activities described in IEEE P1609.1, the security protocols specified in IEEE P1609.2, and the network-layer protocol defined in IEEE P1609.3. Additionally, the IEEE 1609.4 protocol, situated above 802.11p, facilitates multi-channel operation and channel coordination between WAVE devices without relying on physical channel access parameters. The WAVE protocol stack includes a data plane for higher-level information and a management plane for information transfers between the layers.

The ITS-G5 standard for vehicular communication was established by ETSI, building upon the WAVE architecture. It defines the ITS-G5 protocol stack, which covers a broader range of specifications from MAC to applications. Compared to WAVE, the ITS-G5 protocol stack offers more extensive and complex capabilities. Moreover, one of its remarkable features is the ability to support a wide range of Access Methods . In the next chapter, the implications of this standard's other functionalities, such as Cooperative Awareness (CA) and Decentralized Environmental Notification (DEN), on a traffic simulator are explored and discussed.

4.1.2 CV2X

When 3GPP successfully standardized C-V2X technology in Release 14 [6], it has create a significant interest towards cellular-based technologies for vehicular communication. Based on the earlier discussion, it becomes clear that IEEE 802.11p fell short in meeting the demanding requirements for V2X applications

in several aspects. Despite nearly a decade passing between the introduction of these two technologies, 3GPP's solutions incorporate state-of-the-art features such as expanded radio coverage, reduced reliance on additional infrastructure, and a higher penetration rate due to the widespread deployment of smartphones.
The C-V2X, known as LTE-V2X, and the flexible definition of V2V communications, relying on D2D (Device-to-Device) communication, started with the 3GPP Release 14. Prior to this, in 3GPP's Rel12 and Rel13, D2D communications were already established as part of ProSe (Proximity Service) services. The introduction of a novel physical layer channel named sidelink enabled V2V communication to become feasible. This sidelink was specifically designed to cater to vehicular use cases, accommodating a high node density even at high speeds. The 3GPP has defined two modes of operation to enable V2X communications. One is the PC5 Interface Communication. In this mode (Mode 3 and Mode 4), the PC5 interface facilitates direct communication between User Equipment around the transmitter. The other one is the LTE-Uu Interface Communication, which connects the UEs to the eNB (E-UTRAN NodeB), which serves as the base station in LTE networks. V2X messages can be received through unicast or broadcast over a downlink, while sending V2X messages occurs over an uplink. This type of communication is supported only when the UE is part of the network. Release 14 of 3GPP also aims to deliver data transport services to facilities using basic service messaging like CAM and DENM, similar to what IEEE 802.11p does.
LTE-V2X has some limitations in meeting specific use case requirements such as latency, reliability, throughput, and node density. As a result, 5G V2X was introduced to complement these needs, rather than replacing its predecessor. While some 5G NR V2X use cases demand timely delivery of non-periodic messages, most do not require regular transmission of traffic data. Not all use cases operate through broadcasting messages, some like vehicle platooning only send messages to a predetermined number of vehicles or UEs. Moreover, the improvements of 5G-V2X's PC5 interface include a 64-QAM modulation and coding method, frequencies above 6 GHz, the use of MIMO antennas, and other features, with results of testing these capabilities discussed in the following sections.

4.2 Device Under Test

The Device Under Test (DUT) employed in this project is a prototype TCU developed by Stellantis as shown in Fugure 4.1. To be compatible with the test bench, the DUT must possess the following key capabilities:

- Hardware requirements:
  - GNSS reception through the RF connector.

- Exchange of CV2X messages via the RF connector.

- Software requirements:
  - GNSS signal reception stack.
  - CV2X standard messages generation stack.
  - CV2X direct communication capabilities.

Moving on to the discussion about communication technologies for V2X applications, the DUT modem equipped with the ITS network system and C-V2X capabilities is a Quectecl AG55xQ series (5G NR + C-V2X/DSDA Module). This DUT serves as the foundation, capable of operating in both the NSA and SA modes of 5G NR. While it offers fundamental networking-related tests like device registration, mobility from LTE to NR and back in both modes, carrier aggregation, and MIMO antenna-based connection, it features a basic version of the aforementioned functionalities. Additionally, the DUT supports C-V2X PC5 direct communications, but the currently used modem (Sample-1) lacks this capability. Nonetheless, it opens avenues for future project developments. From a compatibility perspective, this module is integrated into various systems, including traffic systems' On-Board Units (OBU), telematics boxes (TBM), telematic control units (TCU), ADS systems, and C-V2X systems.

Figure 4.1: Stellantis's TCU

4.3 5G Emulator Bench

As said in the chapters before, AI@EDGE's technological foundation includes the seamless integration of the network automation platform with the 5G network emulator, enabling comprehensive testing encompassing network configuration and complex scenario assessments. Traditionally, the automotive industry preferred direct module testing on vehicles within real network environments. However, the advent of hardware-in-the-loop (HIL) testing equipment for network testing and the growing demands of V2X have made virtual environment-based testing increasingly favorable. Including a virtual validation platform accelerates the overall development cycle while reducing associated costs. The emulation, within the wider context of cooperative perception, aims to evaluate essential key performance indicators (KPIs) such as node density, end-to-end latency, and overall quality of service. This process also includes radio communication tests, where LTE and 5G-based communication registration testing, Carrier Aggregation (CA), EN-DC mode, and MIMO, among other aspects, serve as the primary test cases. Addressing RF and application testing for 5G SA/NSA devices, the Anritsu MT8000A single box platform emerges as the go-to test solution, as shown in Figure 4.2.

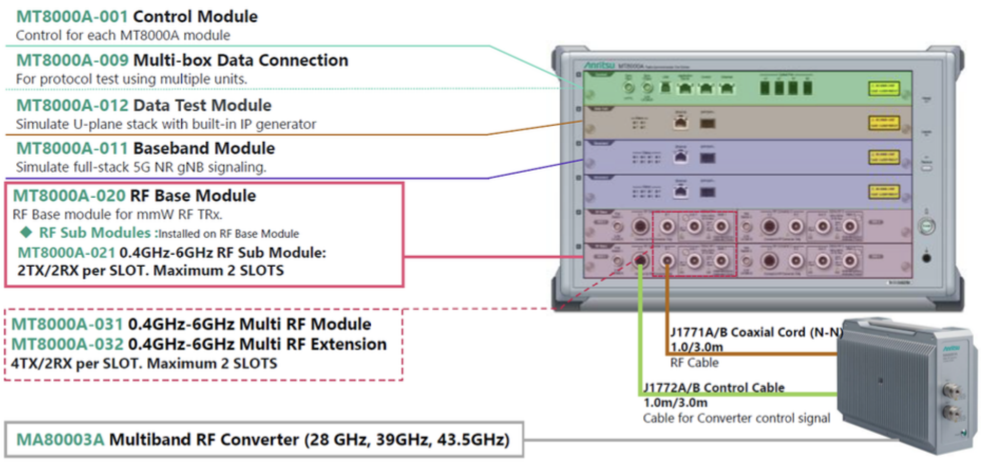

Figure 4.2: Radio Communication Test Station Anritsu MT8000A

Facilitating a quick and easy setup of the 5G connection test environment through its MT8000A base station simulating function, it supports 3GPP-compliant RF tests alongside various application tests like IP layer data transfer and throughput assessments. This platform effectively resolves issues related to 5G device verification, guaranteeing reliable connectivity and smooth communication[15]. Figure 4.3 illustrates the basic layout of this 5G emulator bench.

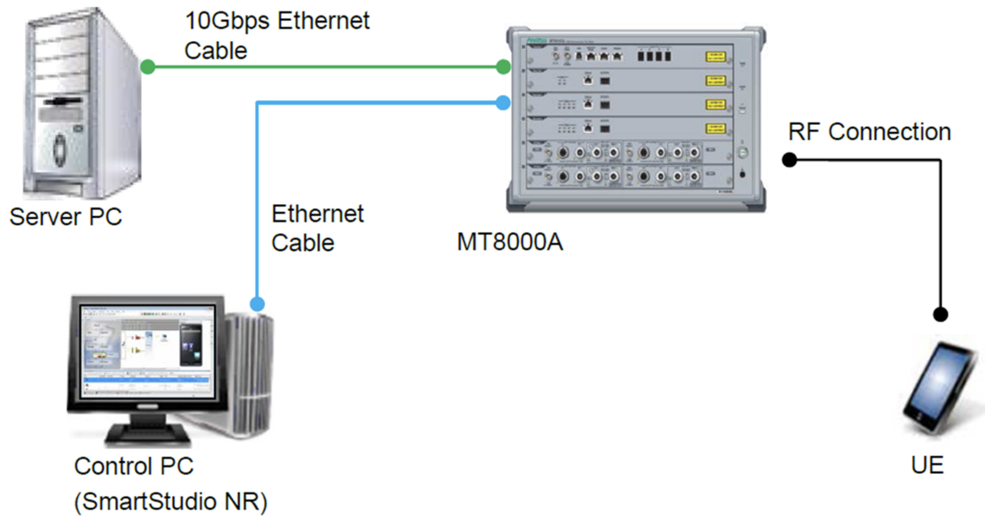

Figure 4.3: 5g Emulator Bench layout

As shown in Figure 4.3 the platform is equipped with SmartStudio NR (SSNR) control software for the MT8000A test station. SSNR replicates the network conditions and communication between the mobile terminal and the 5G network, enabling efficient functional tests, application tests, and software regression tests without necessitating users to possess specialized knowledge of the intricate scripting and communication protocols between the base station and mobile terminal. For functional and application testing, SSNR employs a Graphical User Interface (GUI) based on state machines. The platform further facilitates NSA/SA environment simulation with extensive interaction for scenarios like measurements, dual connectivity, handovers, and carrier aggregation-based connectivity. During device registration or communication, SSNR grants the capability to reject or ignore signaling messages. Among other supported features and functions are IMS, SMS/PWS service, EPS Fallback, VoLTE, VoNR, DSS, network slicing, and more. However, this work's scope does not focus on covering all these aspects in detail.

4.4 Example of Network Testing

This section will focus on the network testing aspect, along with a comprehensive analysis of the results. Leveraging the V2X requirements, a careful selection and execution of diverse test cases for the 5G network's array of features and functions have been carried out on this virtual validation platform. For easy reference, the Figure 4.4 shows a list of test cases along with concise procedures for each one.

Test cases	Description
LTE to NR HO SA (In opposite direction also)	LTE1 and NR1 (SA) cell is available. Network performs cell handover to NR1 cell.
LN1 to LN2 HO NSA	LTE1, NR1 (NSA) and NR2 (NSA) cells are available. Network adds NR1 cell in EN-DC. Network triggers NR cell change procedure where NR1 cell is removed and NR2 cell is added in EN-DC.
LTE to LTE HO + NR add - NSA	LTE1, LTE2 and NR1 (NSA) cells are available. Network triggers handover from LTE1 to LTE2 cell and adds NR1 cell to END-DC.
LTE to LTE HO + NR Release - NSA	LTE1, LTE2 and NR1 (NSA) cells are available. Network triggers Handover from LTE1 to LTE2 and releases NR1 cell from EN-DC.
LTE to LTE HO + NR change - NSA	LTE1, LTE2, NR1 (NSA) and NR2 (NSA) cells are available. Network triggers handover from LTE1 to LTE2 and changes EN-DC cells from NR1 to NR2.
LTE to LTE HO + NR no change - NSA	LTE1, LTE2 and NR1 (NSA) cells are available. Network triggers Handover from LTE1 to LTE2 and keeps NR1 cell in EN-DC.
Carrier Aggregation - SA/NSA	LTE1, LTE2 cells are available. DUT registers to LTE.
2x2 and 4x4 MIMO - SA/NSA	LTE1 and NR1 (SA/NSA) cell is available. This connection is done according to MIMO type, if 2x2 then 2DL antennas and 4DL antennas if 4x4 MIMO simulated.

Figure 4.4: Test cases done with the Network Emulation Platform

4.4.1 Handover

In the context of cellular networks, ensuring seamless communication for mobile users is one of the most important focus. The Handover procedure, also known as handoff, plays an important role in delivering uninterrupted calls during active

conversations and efficient mobile user localization while idle. Its fundamental purpose lies in enabling cellular networks to supply uninterrupted telephone services to mobile users, regardless of their movements. This mechanism exemplifies the network's ability to seamlessly transfer an ongoing call or data session from one cell to another, guaranteeing consistent connectivity and an enhanced user experience on the move. As the mobile terminal moves at a very high speed, the process of handover enables the seamless transfer of an active call from the current cell to a nearby cell. This transfer could occur between an LTE cell and a 5G cell or vice versa, particularly in the NSA mode of 5G with dual connectivity. Handover is a complex operation involving numerous network entities, demanding fast and reliable communication protocols, and necessitating a high level of security. Given the exceptionally brief time frame allowed for call transfer between cells, handover can only take place within the network's boundaries. The handover test case is carried out after the mobile device registers with an LTE cell in this mode. During the power rampage, as mobility occurs from the LTE to NR cell, the LTE cell power decreases while the NR cell power rises until reaching a threshold before connecting to the mobile device. This process ensures a seamless transition between the two cells and maintains uninterrupted communication for the User Equipment (UE).
In each test case, the initiating cell responsible for paging and sending the Radio Resource Control (RRC) connection request must possess specific cell parameters that match the capabilities of the User Equipment (UE), such as the supported channel, cell type, and band combination, among others. Ensuring these parameters align is crucial for a successful handover and optimal performance.
To initiate the network emulation, the target network simulation configuration is set up after selecting the target cell parameters. The physical connection with the device under test is established according to the target network emulation, ensuring accurate representation of real-world conditions during the testing process.
Figure 4.5 shows a possible connection diagram for this handover scenario, where SA mode, LTE, and NR cells are simulated. The RF modules connected to the MT8000A include MT8000A-030/031 RF Sub-module, 0.4GHz-6 GHz:2TX/2RX per SLOT, up to a maximum of 2 SLOTS. These modules facilitate the simulation of the LTE and NR cells and provide the necessary connectivity for the testing environment. The connection diagram reveals two RF antennas, one for the NR cell and one for LTE, while the external server hub and control PC with SSNR are also connected to maintain smooth data flow.

Once the simulation configuration and target cell parameters are set up, device registration is initiated, and a connection is established with an LTE cell, as depicted in Figure 4.6. This step is vital as it forms the basis for the subsequent test cases and the actual handover process.

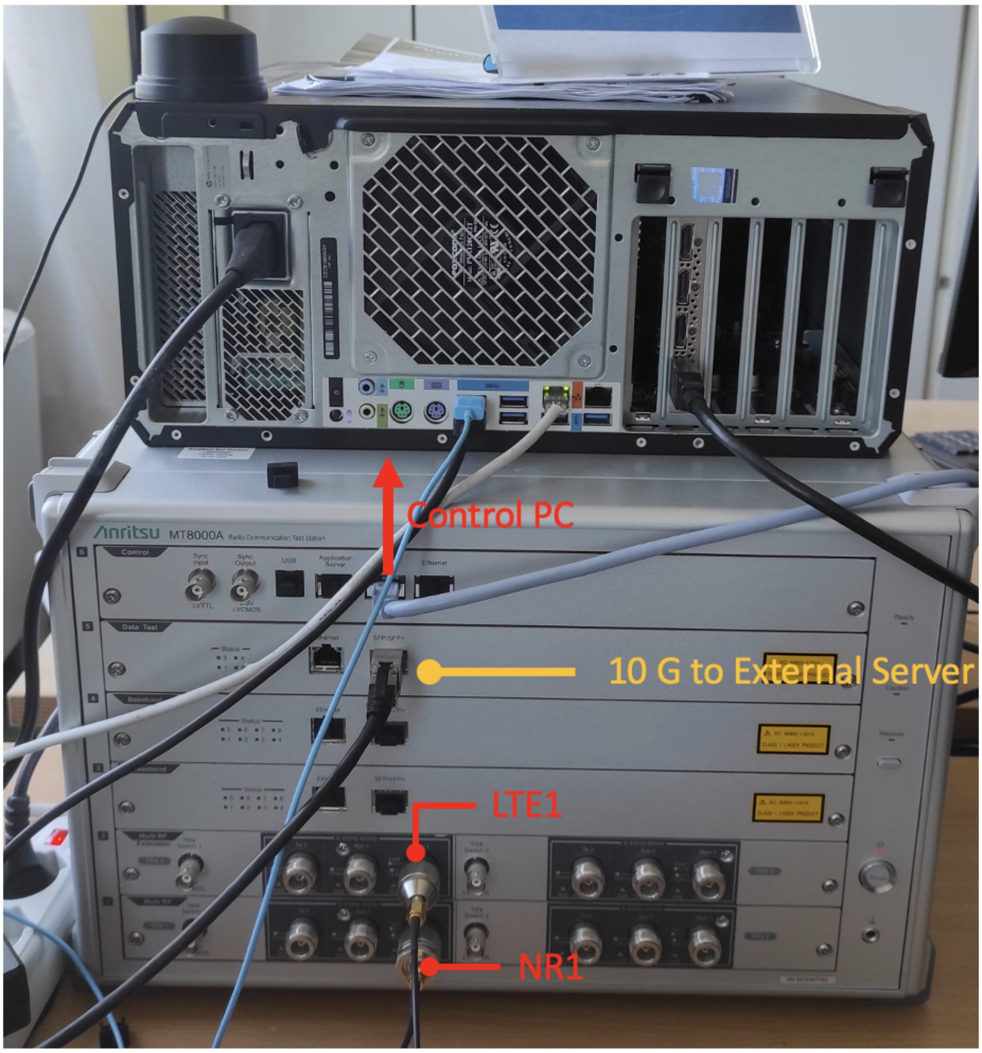

Figure 4.5: MT8000A connection for LTE and NR

The setup is now prepared to execute the test cases for this scenario once the simulation is started and the connection is established. To ensure accurate emulation of real-world conditions, it is crucial to obtain the UE capability once the connection is established. This information can be located in the simulation's sequence log as a UE capability file. The DUT's capability, including various bandwidths for single connection, multi-cell connection, EN-DC mode, and carrier aggregation, can be observed in Figure 4.7. This information is necessary when configuring additional test cases that require these values to be taken into account.

Once the connection is established, and the fundamental UE information has been

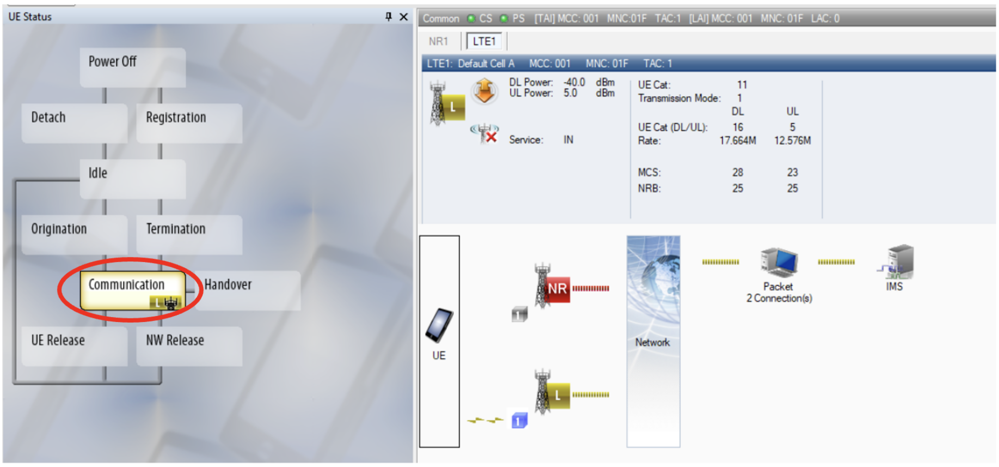

Figure 4.6: Device registration and connection with LTE cell

UE Capability Information
NR
Supported Band = n2, n5, n25, n41, n48, n66, n71, n77, n78
CA Band Combinations:
n48A, n41A, n71A, n66A, n78A, n25A, n2A, n77A, n5A
LTE
Supported Band = 2, 4, 5, 7, 12, 13, 14, 17, 25, 26, 28, 29, 30, 41, 48, 66, 71
CA Band Combinations:
2A-66B, 2A-5A-66A, 2C-5A, 4A-13A, 5A-25A, 5A-66A, 4A-7A, 2A-30A, 4A, 12A, 66B, 29A, 2A-7A-66A, 2A-13A-66A, 4A-17A, 13A-66A
14A-66A, 12A-66A, 2A-17A, 41A, 14A-30A, 4A-71A, 66A-66A, 4A-12A, 12A-30A, 5A-7A, 5A-7A, 2A-13A, 2A-17A, 2A-66A-66A, 2A-66A-66A
2A-4A-71A, 25A-25A, 25A-26A, 25A-26A, 5B, 5A-5A, 7B, 2A-12A, 2A-29A, 25A, 2A, 4A-4A, 4A-13A, 66C, 29A-66A, 4A-5A, 7C, 2A-4A, 13A
4A-71A, 66A-71A, 12B, 7A-66A, 2A-71A, 14A, 13A-66A, 14A-66A, 4A-12A, 12A-12A, 12A-66A, 7A-12A, 26A, 2A-2A-66A, 2A-5A-66A
2A-7A-66A, 2A-5B, 4A-17A, 5A-30A, 7A-12A, 2A-7A, 2A-66B, 2A-66C, 2A-13A-66A, 4A-30A, 30A-66A, 66A-71A, 2A-12A, 2A-66A, 2A-66A
48A, 71A, 2A-2A-71A, 2A-4A-71A, 28A, 2C-29A, 2A-7C, 2A-7A-7A, 2A-7A-7A, 4A-7A, 2A-5A, 2A-7A, 66A, 5A, 2A-2A-29A, 12A-25A, 5A-25
2A-5A, 2A-66C, 2A-2A-66A, ...
EN-DC Band Combinations:
2A-n41A, 2A-n48A, 7A-n71A, 7A-n77A, 7A-n78A, 12A-n2A, 13A-n2A, 71A-n2A, 12A-n25A, 5A-n66A, 12A-n66A, 66A-n41A, 66A-n77A
12A-n78A, 5A-n2A, 13A-n66A, 66A-n71A, 2A-n5A, 25A-n41A, 66A-n48A, 12A-n77A, 66A-n25A, 66A-n2A, 66A-n5A, 5A-n41A, 5A-n48A
2A-n71A, 2A-n77A, 2A-n78A, 71A-n66A, 5A-n77A, 5A-n78A, 66A-n78A, 2A-n66A

Figure 4.7: UE capability

traced, the Handover scenario can be planned and executed. There are options for setting up this test case, including the power rampage and its values, which determine the behavior of the cells during the handover process. Additionally, the direction of handover (LTE to NR in this case) is defined, influencing the sequence of events during the handover process. Figure 4.9 displays the handover direction diagram generated by the MT8000A once the setup is ready, giving a visual representation of how the handover process will occur.
During the execution of this mobility scenario, the UE status changes to handover mode, and the cell switches from LTE to NR, as shown in Figure 4.8. This mode switch ensures that the UE maintains a connection with the network while moving between cells, guaranteeing uninterrupted data transmission and call continuity. Notably, the downlink (DL) throughput significantly increases from 17.64 Mbps

to 333.3 Mbps after the handover, as observed in Figure 4.6 and Figure 4.8. This substantial improvement in throughput highlights the efficiency of the handover process and the seamless transition between the LTE and NR cells.

In conclusion, the handover scenario between LTE and NR cells is a critical aspect of testing and evaluating the performance of mobile devices. The test setup, including the configuration of cell parameters, network emulation, and UE capabilities, plays a crucial role in ensuring accurate representation of real-world scenarios. The success of the handover is evident in the increased throughput observed after the handover process. The ability to maintain high data transfer rates during mobility scenarios is essential for providing a smooth user experience in modern mobile communication networks.

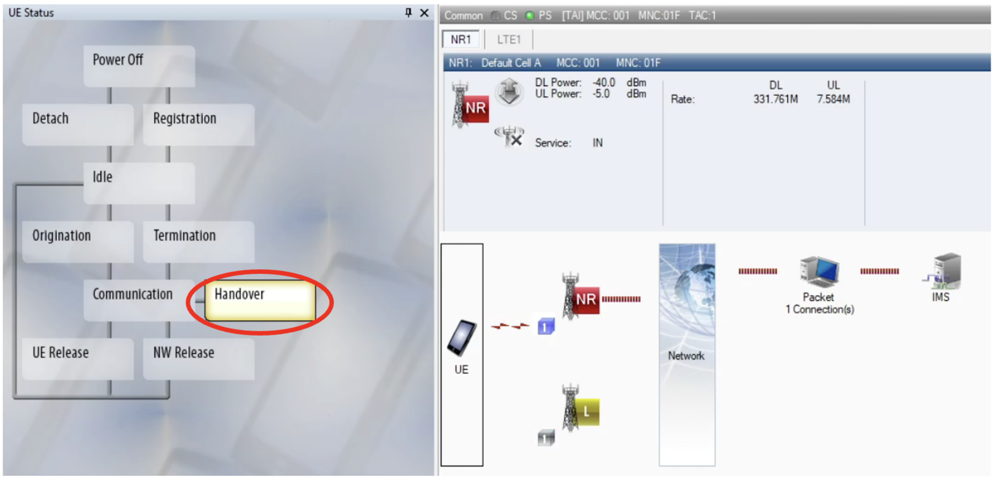

Figure 4.8: Handover and connection with the NR cell

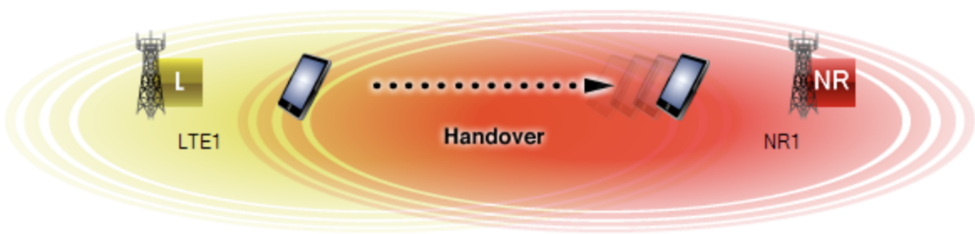

Figure 4.9: Handover and connection with the NR cell

4.4.2 Dual Connectivity Handover

The technology that enables simultaneous connections with both 4G and 5G cells is known as dual connectivity or EN-DC (E-UTRAN New Radio – Dual Connectivity). ENDC allows data connections from LTE and 5G to coexist, boosting overall bandwidth and reducing service interruptions. This innovative approach ensures a seamless user experience by leveraging the strengths of both 4G and 5G networks. The LTE-based network acts as an anchor band complemented by NR through multi-cell dual connectivity. The concept of multi-cell dual connectivity involves the coordination of two LTE cells and two NR cells to efficiently manage data transmission. Depending on traffic requirements and network conditions, data transmission may occur via LTE or be routed to a 5G stream when connected to a 5G modem. This dynamic switching mechanism optimizes data flow and improves network efficiency. Establishing the connection with LTE remains similar to before, except now there are four cells involved in the process: two LTE cells and two NR cells. While LTE cell parameters remain unchanged, the NR band selection depends on the supported bands depicted in the UE capability, as also reported in Figure 4.7. This flexibility allows for seamless integration of the two networks, ensuring compatibility and smooth handover procedures.
Among the supported LTE bands, any of the NR bands (n41, n71, n77, or n78) can be chosen based on the UE's capability. Additionally, the supported band list allows for the selection of either 5A-77A or 5A-78A for other LTE-NR cell combinations. This adaptability ensures that the most suitable combination is chosen for the specific scenario, maximizing data throughput and network performance. As the connection diagram for MT8000A remains the same, the implementation of dual connectivity requires the use of two additional antennas, one for each NR cell, to facilitate the simultaneous connections effectively. Upon selecting the cell and simulation parameters, the network emulation can be initiated, and the network connection before enabling EN-DC mode is shown in Figure 4.10. This step ensures that the setup is accurate and reflects the real-world conditions for testing and evaluation. Once the connection is established, the setup for multi-cell connection parameters can be configured. In this setup, NR serves as the secondary node, while LTE always acts as the master node. This hierarchical arrangement ensures a robust and efficient network architecture, where the master node (LTE) coordinates the activities of the secondary node (NR) to provide a seamless user experience.

Achieving dual connectivity requires aligning the UE capabilities with the emulated network's band combination. This synchronization is essential to ensure smooth handovers and efficient data transmission between LTE and NR cells. The network

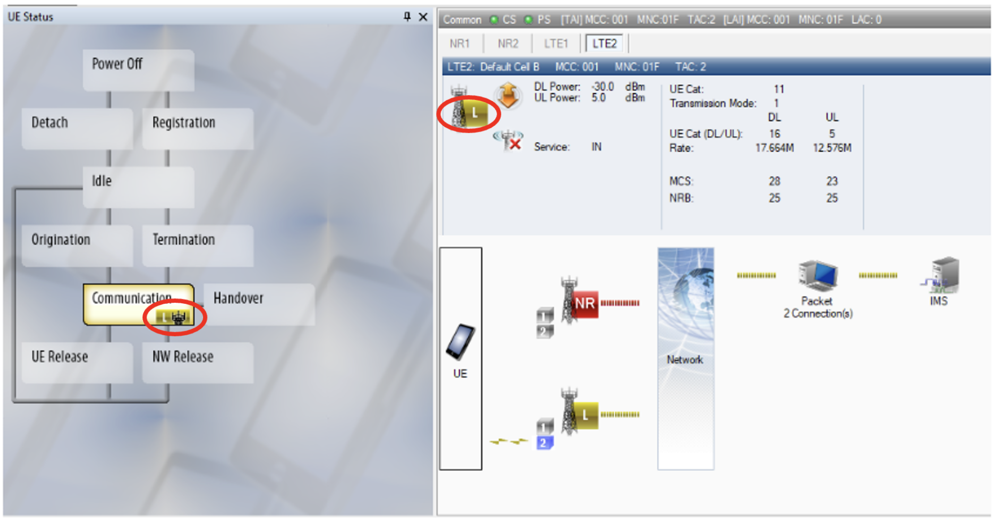

Figure 4.10: Multi-cell network connection before enabling EN-DC mode

connection in ENDC multi-cell mode is shown in Figure 4.11 after executing the multi-cell connection, depicting the successful integration and coordination of both LTE and NR cells.

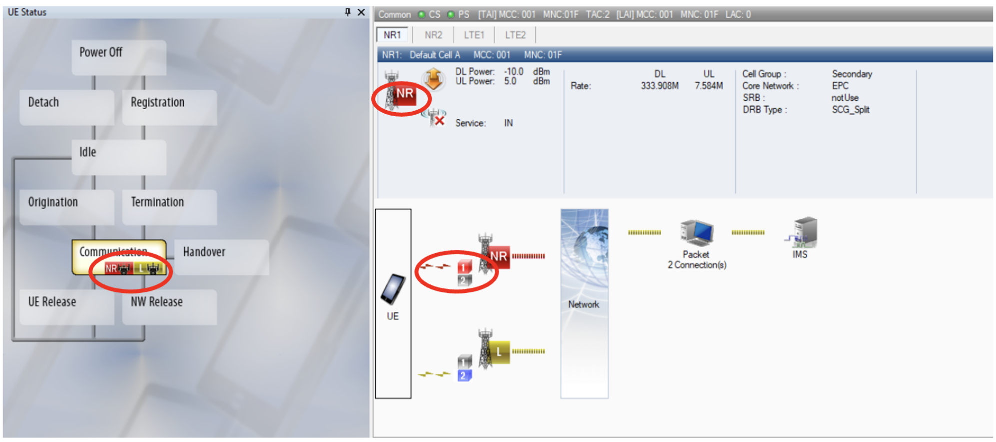

Figure 4.11: Multi-cell network connection after enabling EN-DC mode

Similar to the SA handover case, the handover test setup parameters can also be configured here. The handover direction may involve LTE1 to LTE2 or vice versa, depending on the specific test scenario being evaluated. In this instance, the handover of an LTE cell to another results in four possible outcomes: NR-added, NR-change, NR no-change, and NR-Release. These outcomes are meticulously

tested to ensure comprehensive evaluation and to provide valuable insights into the network's performance during handover scenarios.
Following the handover, the Figure 4.12 shows the connection in EN-DC multi-cell mode, illustrating how the network smoothly transitions from one LTE cell to another while maintaining a seamless connection with the NR cell. This successful handover demonstrates the robustness of the dual connectivity approach and its ability to optimize data transfer rates and overall network performance. In conclusion, dual connectivity or EN-DC is a cutting-edge technology that combines the capabilities of both 4G and 5G networks to provide enhanced data transmission, reduced service interruptions, and a seamless user experience. Through careful configuration and synchronization of cell parameters and UE capabilities, the network effectively manages data flow and handover scenarios, resulting in optimal performance and high-quality connectivity for mobile users. The successful integration of LTE and NR cells in multi-cell dual connectivity mode highlights the advancements in modern mobile communication networks and open the way for a more connected and efficient future.

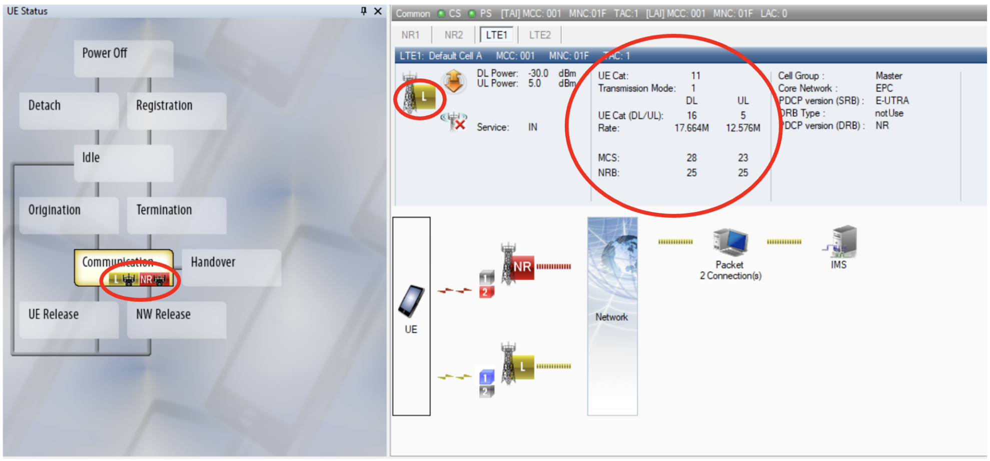

Figure 4.12: Multi-cell network connection after handover in EN-DC mode

4.4.3 Carrier Aggregation

LTE-Advanced employs a powerful technique known as carrier aggregation (CA) to enhance bit-rate and overall bandwidth, functioning in both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes. This feature allows the same user to be assigned multiple frequency blocks, known as component carriers.

In the case of LTE-Advanced, it can combine up to five component carriers, each with up to 20 MHz of bandwidth, leading to transmissions of up to 100 MHz. This capability has a significant impact on data rates, enabling LTE-Advanced to meet the International Mobile Telecommunications-Advanced (IMT-Advanced) requirements for peak data rates.
It is worth noting that while 5G CA is also possible, the MT8000A system being utilized for testing is currently limited to LTE only, preventing the evaluation of this option. However, within the scope of LTE carrier aggregation, the test aims to aggregate the bandwidth and evaluate the total bit rate for a more comprehensive understanding of the system's performance. With carrier aggregation, the test scenario involves assigning multiple frequency blocks to the same user, allowing the MT8000A system to assess how efficiently it can utilize the aggregated bandwidth. However, due to the allowed bandwidth of 5 MHz, the aggregation is currently limited to the downlink component only. Despite this limitation, the test still provides valuable insights into the system's capabilities and potential improvements in throughput. To conduct the carrier aggregation test case, the simulation setup remains unchanged, requiring two LTE cells and an additional NR cell to test additional capabilities. For this specific test case, band 2 and band 5 have been chosen for the aggregated bands, each utilizing 5 MHz of downlink frequency as shown in Figure 4.13.

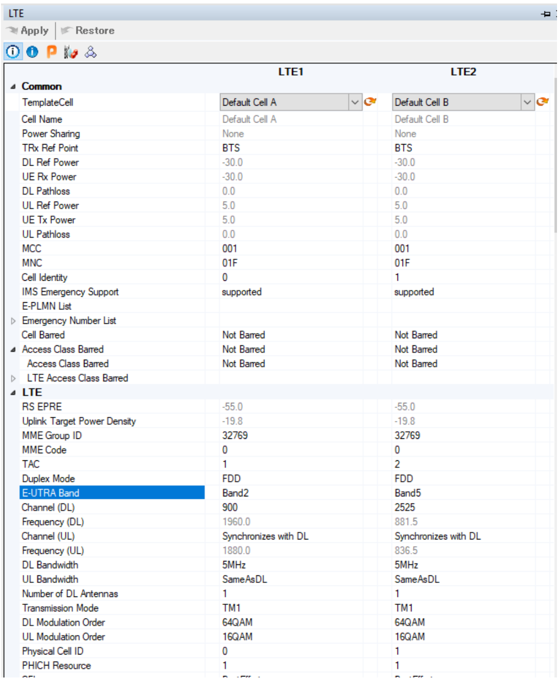

Figure 4.13: Cell Parameters

Following the setup of parameters for the carrier aggregation test case, an LTE cell is added to the simulation, followed by the addition of another LTE cell, similar to the multi-cell test case. It is essential to note that since aggregation is currently limited to the downlink, the additional LTE cells with uplink will share the same band while the downlink band is aggregated. This utilization of available resources results in nearly a two-fold increase in throughput, as the Figure 4.14 shows the amplified bit rate achieved through carrier aggregation.

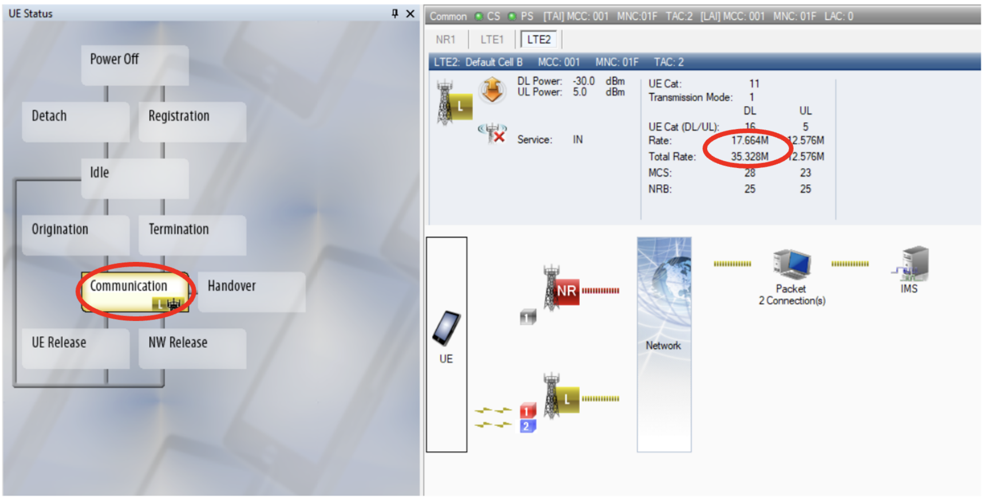

Figure 4.14: Carrier Aggregation

To gain a more comprehensive understanding of the system's performance, a throughput graph with time is presented in Figure 4.15. This graph effectively highlights the increased throughput observed for the downlink after implementing carrier aggregation, while the uplink throughput remains unchanged. The resulting curve demonstrates the potential benefits of utilizing carrier aggregation to enhance data rates and improve overall network performance.

To conclude, carrier aggregation is a groundbreaking feature of LTE-Advanced that significantly enhances bit-rate and overall bandwidth, meeting the stringent IMT-Advanced requirements for peak data rates. While the MT8000A system used for testing is currently limited to LTE only, the carrier aggregation test case still provides valuable insights into the system's performance and potential improvements in throughput. Through intelligent allocation and combination of frequency blocks, carrier aggregation unlocks the true potential of LTE-Advanced, enabling it to deliver seamless, high-speed connectivity and meet the increasing demands of modern mobile communication networks.

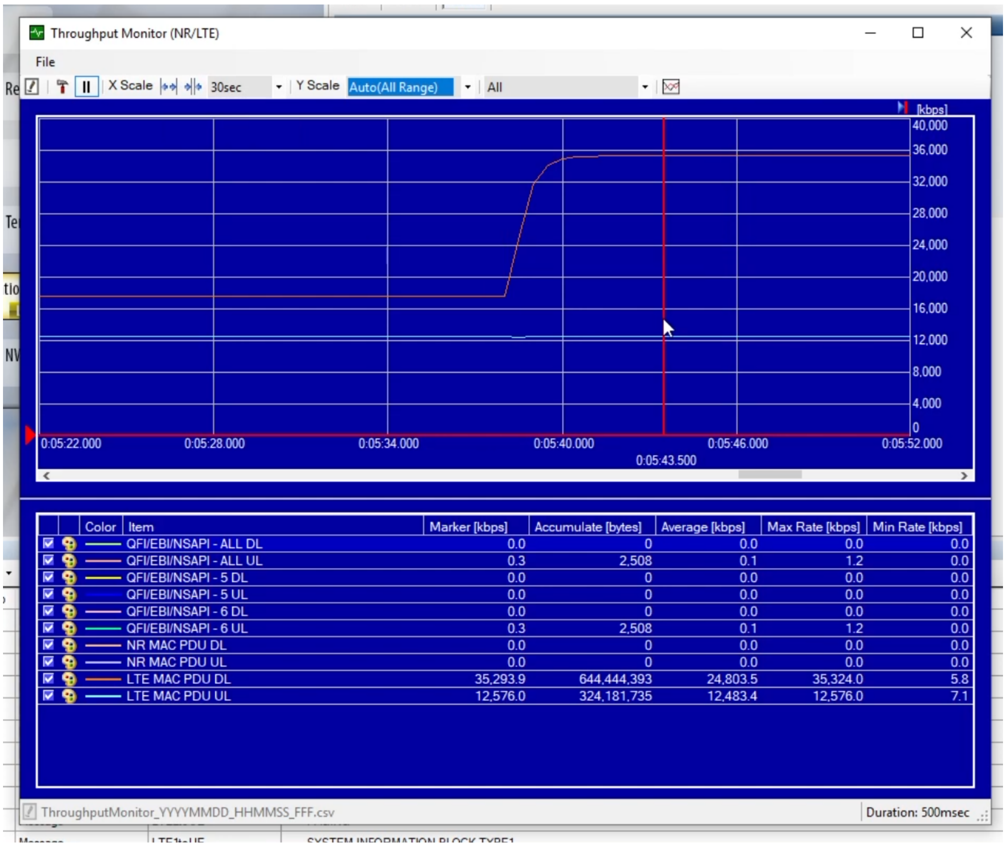

Figure 4.15: Throughput measurements in Carrier Aggregation

4.4.4 Multiple-Input and Multiple-Output

In wireless communications, a groundbreaking technology called multiple-input/multiple-output (MIMO) enables simultaneous data transmission and reception over the same radio channels, significantly enhancing network performance. MIMO systems are employed in various wireless networks, including Wi-Fi, 3G, and 4G LTE, as they leverage multiple antennas and sophisticated algorithms to improve connectivity, data speed, and overall user experiences. The integration of multiple antennas in both mobile devices and network infrastructure has become commonplace, reflecting the industry's commitment to providing seamless and efficient communication services.

In this particular test case, the primary focus is on basic testing with multiple antennas to explore the benefits of MIMO technology further. The test begins with a 2x2 MIMO setup, where two antennas are utilized for both data transmission

(Tx) and reception (Rx). This configuration effectively enhances overall throughput and network efficiency. Subsequently, a more advanced 4x4 MIMO test case is performed, further optimizing data rates and improving user experiences. To ensure a comprehensive evaluation, the simulation setup and cell parameters are designed similarly to the preceding cases, utilizing two simulated cells—one for LTE and another for NR as shown in both Figure 4.16 and 4.17.

When configuring the simulation, the MIMO option must be set to the intended type (two-by-two or four-by-four), and the corresponding cell is selected accordingly. Figure 4.18 shows the physical connection diagram after configuring the simulation for the MIMO test cases.

Notably, in the 2x2 MIMO setup, two antennas are employed for downlink (DL) data transmission, while one antenna is used for reception (Rx). The diagram illustrates how LTE antenna 2 functions solely as a Tx antenna, while LTE antenna 1, occupying the primary sub-slot, serves both Tx and Rx purposes. This intelligent allocation of antennas ensures efficient data flow and optimal network performance. Similar principles apply when simulating NR 2x2 MIMO on the NR slots. To emulate a MIMO-based network, the number of antennas must be selected based on the specific MIMO mode as shown in Figure 4.19.

For downlink (DL) data transmission, the LTE cell should have two antennas for 2x2 MIMO, significantly improving data throughput. However, in the current setup, uplink (UL) MIMO for LTE is not supported. By adjusting the number of antennas in both DL and UL for the NR cell, while keeping other parameters unchanged, a comprehensive MIMO-based simulation is established. This setup allows for the exploration of the benefits of MIMO technology and its impact on network efficiency. After configuring the simulation and cell parameters, including the adjustment of the number of antennas, the simulation is initiated, and the mobile device is registered. Figures 4.20 and 4.21 present the device connection with one DL antenna and then with two DL antennas, respectively. Both figures indicate that the first case achieves a throughput of 333.9 Mbps, while the second case achieves a substantially improved throughput of 727.34 Mbps with 2x2 MIMO. These results validate the significant enhancements in data rates and overall network performance enabled by MIMO technology.

So, the MIMO technology is a game-changer in the field of wireless communications, allowing for simultaneous data transmission and reception over the same radio channels. The integration of multiple antennas and sophisticated algorithms has paved the way for enhanced network efficiency, improved connectivity, and faster

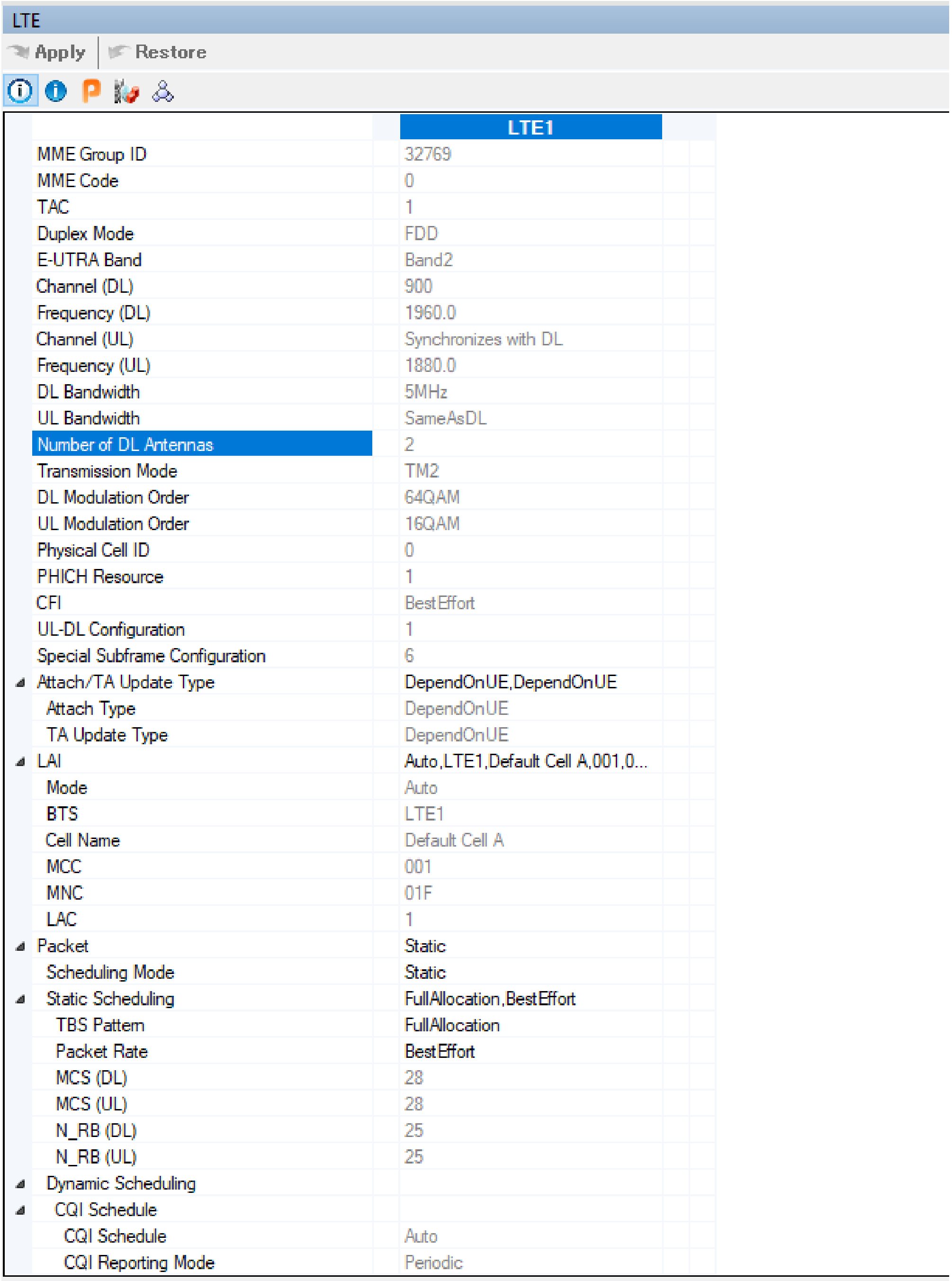

Figure 4.16: Cell parameter LTE

data speeds. The implementation of MIMO in both LTE and NR cells holds the potential to revolutionize the way we experience mobile communication, providing

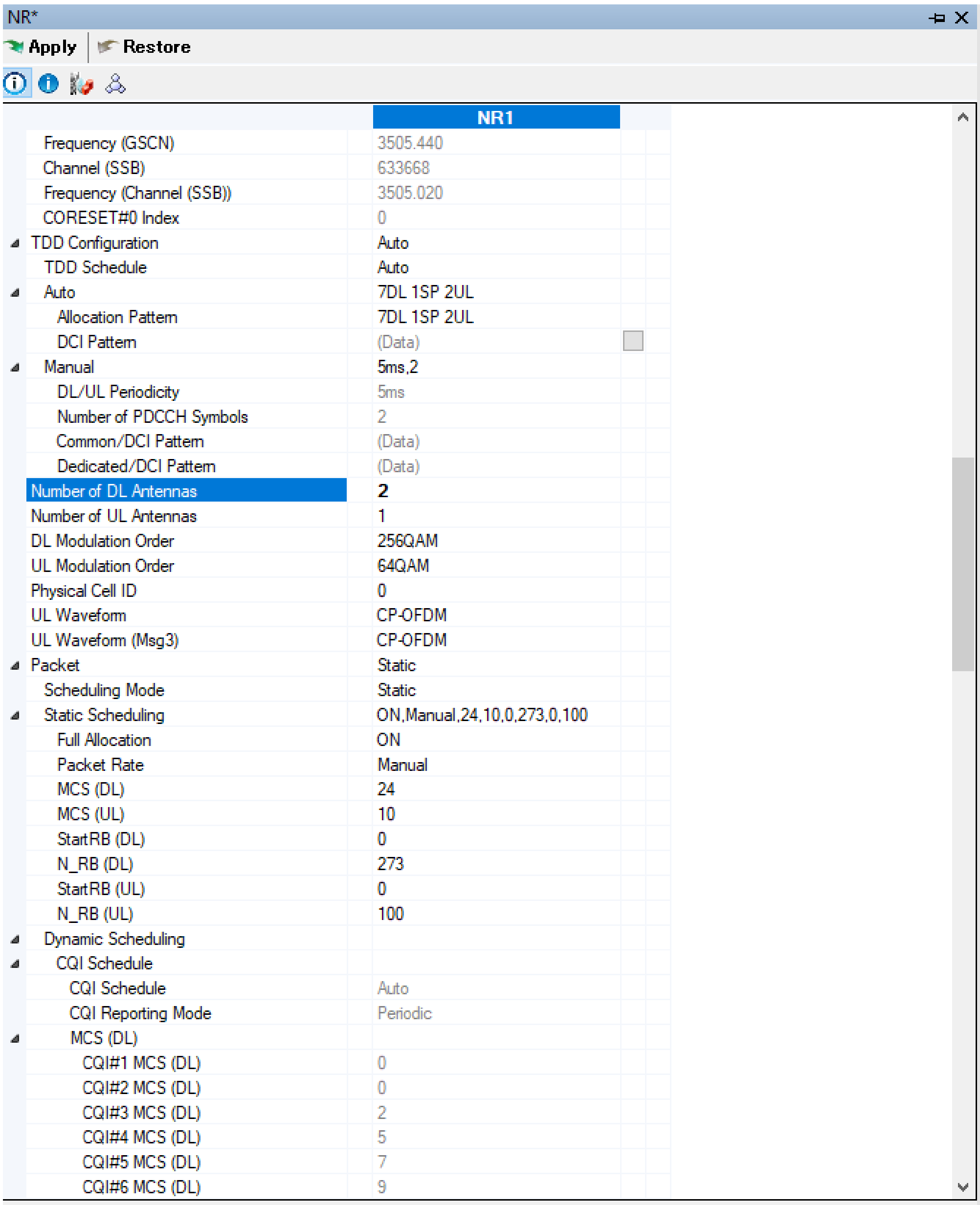

Figure 4.17: Cell parameter NR

users with seamless, high-speed connectivity and paving the way for a more connected and efficient future.

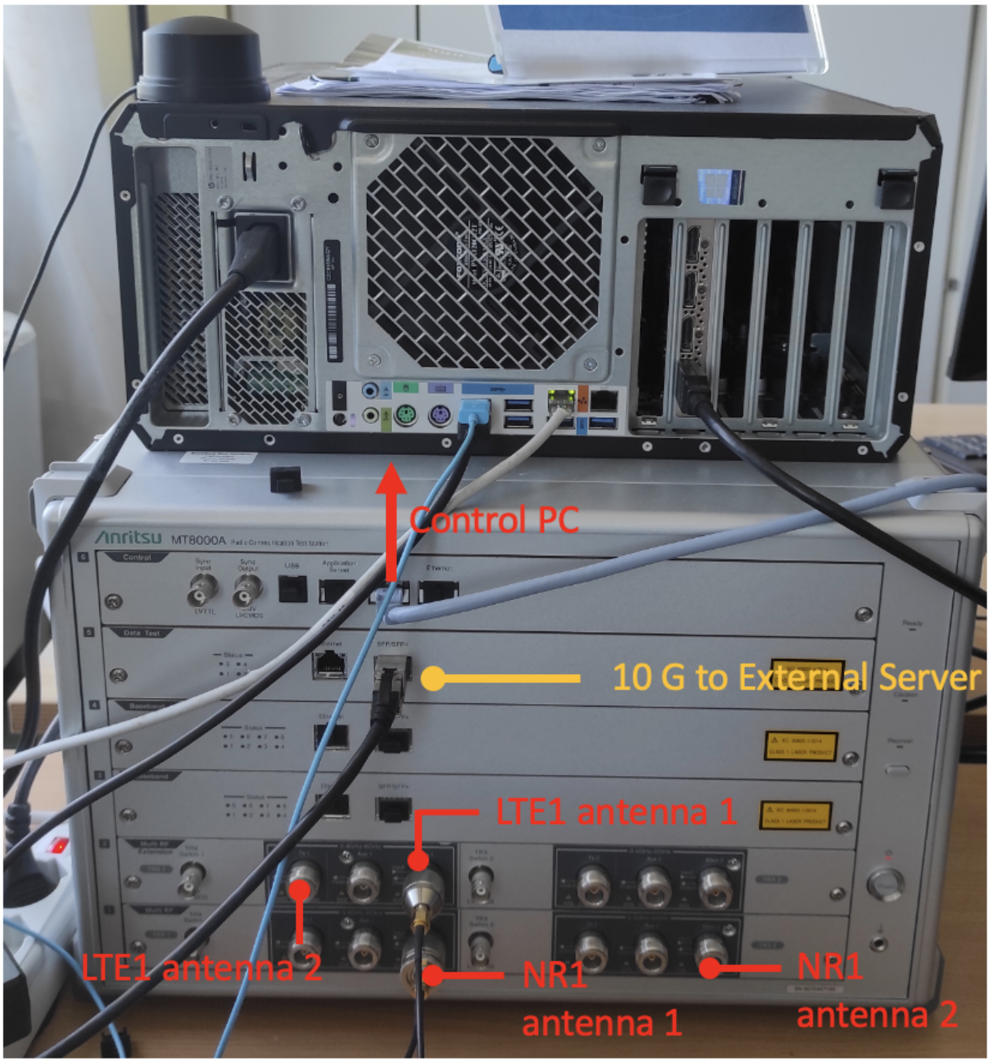

Figure 4.18: MT8000A connection for MIMO 2x2

4.4.5 4x4 Multiple-Input and Multiple-Output

The final test case involves the application of NR cells to conduct a 4x4 MIMO configuration, leveraging the power of four antennas for downlink data transmission, while retaining a single antenna for uplink communication. As anticipated, this strategic setup results in a remarkable increase in throughput, reaching a high value of 1335.45 Mbps. This significant improvement in data rates demonstrates the efficiency of 4x4 MIMO technology. To assess the device connection and throughput status effectively, Figure 4.22 provides a comprehensive illustration of the setup, clearly presenting the achieved data rates and the efficiency of the

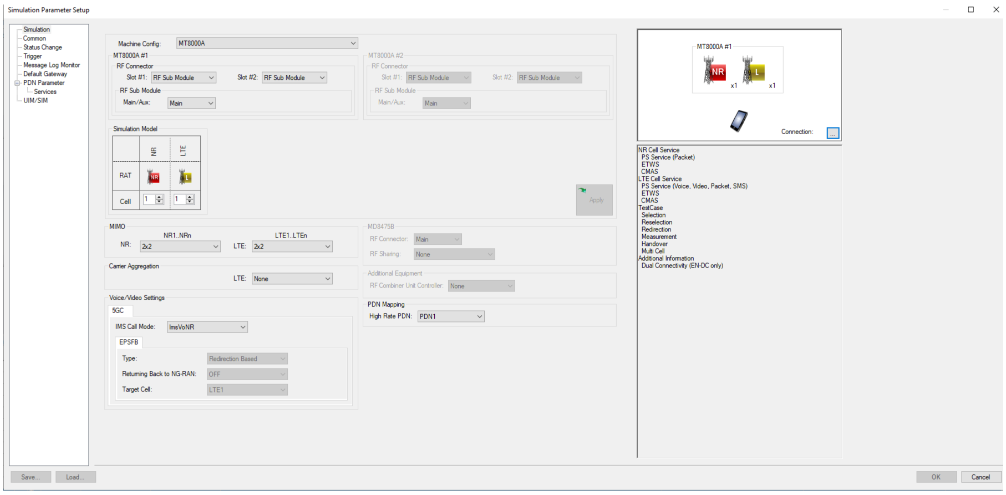

Figure 4.19: Simulation parameter for MIMO 2x2

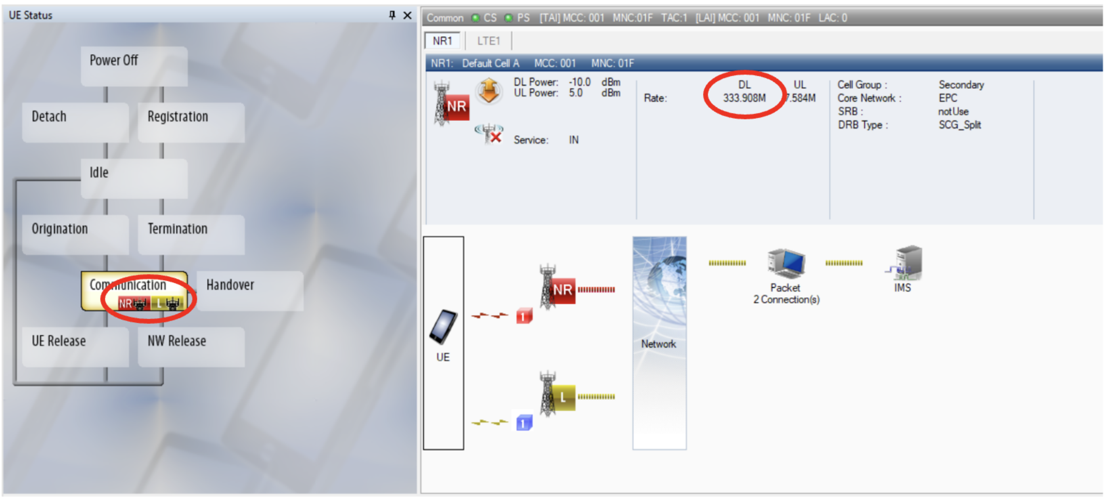

Figure 4.20: Connection without MIMO

4x4 MIMO configuration. These visual representations offer valuable insights into the performance of the network and the benefits of employing MIMO technology, particularly in a 4x4 configuration. Since the device under test is equipped with only two ports, one for LTE and one for NR, it becomes necessary to employ a multiplexer, also known as a combiner. This intelligent device acts as a bridge, enabling seamless connection and evaluation of advanced features that require more than two antennas, such as MIMO, multi-cell, and carrier aggregation. By utilizing the multiplexer, the testing environment becomes versatile and unrestricted, allowing for comprehensive assessments of various network configurations without

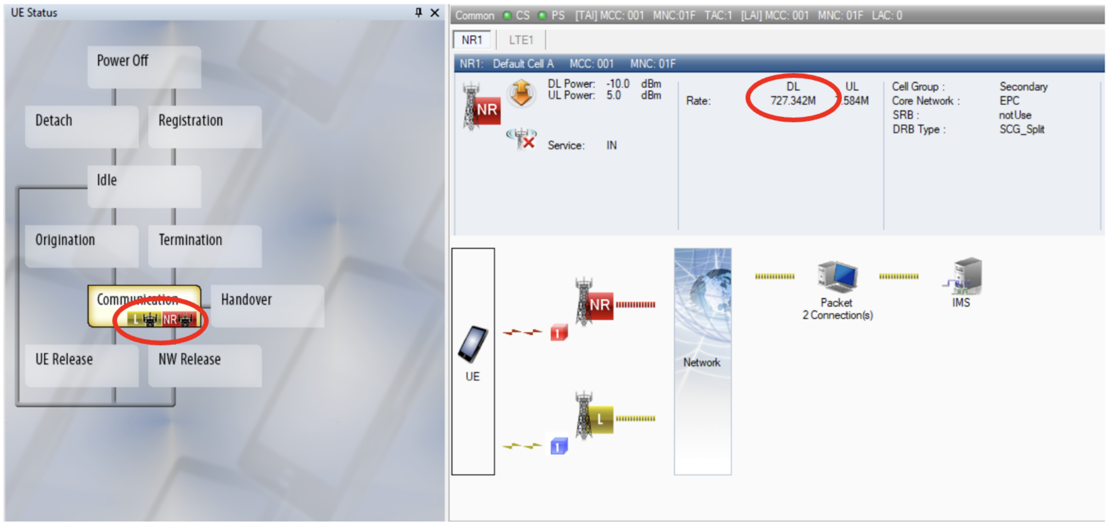

Figure 4.21: Connection with MIMO 2x2

being obstructed by the number of available ports. This approach enables efficient testing of MIMO technology, multi-cell setups, and CA scenarios, providing a more comprehensive evaluation of the network's capabilities and performance. Moreover, the implementation of the multiplexer ensures that the testing setup closely mimics real-world conditions, where a diverse range of antennas and configurations are commonly deployed. As a result, the testing results become more representative and reliable, facilitating informed decision-making and optimization of network configurations. The final test case explores the remarkable potential of 4x4 MIMO technology, leveraging four antennas for downlink data transmission and one antenna for uplink communication. This strategic allocation of antennas results in a substantial increase in throughput, demonstrating the effectiveness of MIMO in enhancing network efficiency and data rates. The accompanying connection diagrams and throughput status representations provide valuable visual insights into the performance of the 4x4 MIMO setup. Additionally, the integration of a multiplexer in the testing environment overcomes limitations posed by the number of available ports on the device, ensuring seamless evaluation of advanced features without constraints.

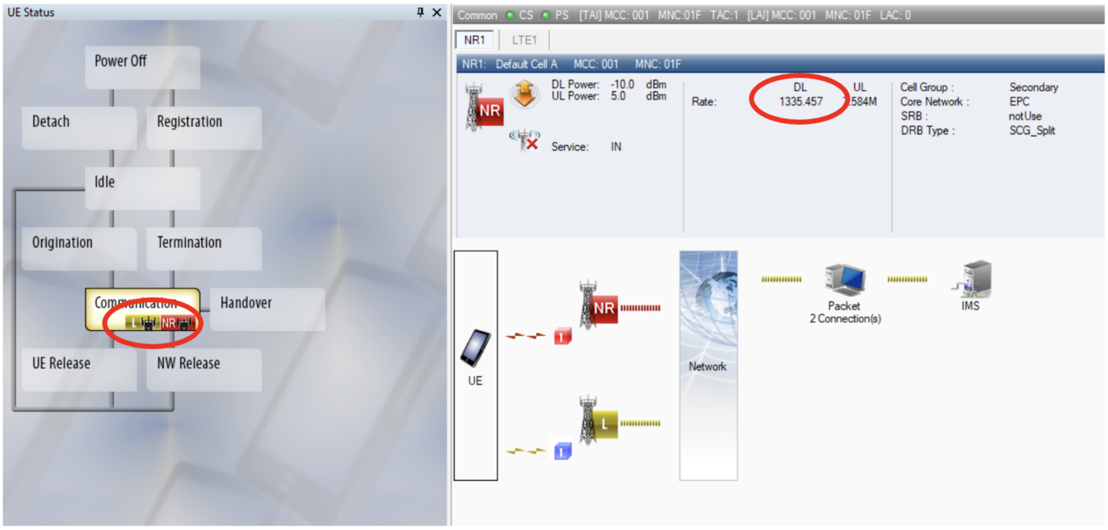

Figure 4.22: Connection with MIMO 4x4

Chapter 5

Traffic scenario simulation: vehicle's communication

5.1 Simulation of Urban MObility (SUMO)

The Simulation of Urban Mobility (SUMO) is a sophisticated and versatile open-source software platform dedicated to the simulation and analysis of urban transportation systems. Developed by the Institute of Transportation Systems at the German Aerospace Center (DLR), SUMO plays a big role in addressing the complex challenges posed by modern urban mobility. Its primary function is to emulate the intricate interplay of vehicles, pedestrians, cyclists, and public transport within urban landscapes, providing a comprehensive and accurate virtual environment for studying transportation dynamics. SUMO is an useful tool for a diverse range of professionals, including researchers, urban planners, traffic engineers, and policy-makers. By utilizing SUMO's advanced simulation capabilities, these stakeholders can gain valuable insights into traffic patterns, congestion hotspots, travel times, and the overall performance of transportation networks. The software allows for the evaluation and optimization of various mobility scenarios, such as the integration of new infrastructure, the implementation of traffic management strategies, and the assessment of sustainable transportation initiatives.
Through its user-friendly interface and extensive set of features, SUMO facilitates the modeling of complex urban scenarios, taking into account real-world factors like traffic signals, road geometries, and vehicle characteristics. It enables users to experiment with different configurations, test hypotheses, and observe how changes to the transportation system impact overall efficiency and sustainability.
SUMO also contributes to the advancement of urban mobility research by providing a platform for the development and testing of innovative algorithms and intelligent transportation systems. This creates a collaborative environment where

experts from various disciplines can collaborate to address the evolving challenges of urbanization, traffic congestion, environmental impact, and safety[16].

5.2 Generating Vehicle Data through Simulations

5.2.1 Usage of SUMO for connected vehicles

For what concern the connected vehicles, SUMO emerges as a very useful tool, offering a variety of applications that contribute to the realization of intelligent and efficient transportation systems. SUMO plays a crucial role in simulating and analyzing the interactions between connected vehicles, infrastructure, and other road users in dynamic urban environments. It enables researchers and engineers to explore a multitude of scenarios, such as testing the performance of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication protocols, evaluating the impact of connected vehicle technologies on traffic flow, and assessing the potential benefits of cooperative adaptive cruise control and platooning.
SUMO's intricate modeling capabilities facilitate the examination of traffic management strategies enhanced by connected vehicle data. It allows for the assessment of real-time traffic information dissemination, predictive traffic control, and the optimization of traffic signal timings through communication with connected vehicles. Furthermore, SUMO empowers researchers to go deeper into the challenges and opportunities posed by connected and autonomous vehicles (CAVs), including the study of mixed traffic scenarios where traditional and connected vehicles coexist. The software's ability to simulate varying levels of connectivity and automation helps in understanding how these factors influence traffic efficiency, safety, and overall system performance. By replicating diverse connectivity scenarios, SUMO enables the analysis of scenarios like platooning benefits on highways, intersection negotiation strategies for connected vehicles, and the development of novel algorithms for cooperative traffic management.
One of SUMO's significant advantages it is its capacity to evaluate the potential societal impacts of connected vehicles, such as reductions in congestion, fuel consumption, and emissions. Researchers can explore the implications of different penetration rates of connected vehicles on these metrics, thereby informing policy decisions and infrastructure investments. SUMO also facilitates the investigation of human factors associated with connected vehicle technologies, helping in the design of user-friendly interfaces and assessing driver behavior within the context of emerging connected environments.

5.2.2 TraCi

The effective exchange of data between vehicles and a cloud server is a crucial role in the virtual validation of cooperative vehicle perception, demanding an interface that simplifies access to ongoing traffic simulations. TraCI, short for "Traffic Control Interface," emerges as a crucial tool, providing users with access to active SUMO instances through a sequence of commands.
This interface establishes a connection with operational SUMO, orchestrating a TCP-based client/server architecture, with SUMO functioning as the server. TraCI efficiently categorizes these commands into fourteen distinct domains, spanning GUI, points of interest, simulation dynamics, lanes, edges, routes, traffic lights, junctions, induction loops, multi-entry exits, polygons, individuals, vehicles, and vehicle types. Among TraCI's expansive capabilities, the Python library holds significance in this context.
TraCI offers three primary command categories:

1. **Control-oriented commands**: These orchestrate simulation steps, initiate/terminate connections, and reload simulations.

2. **Value retrieval**: This category enables extraction of real-time simulation data, encompassing vehicle attributes, route specifics, Charging Station information, and edge parameters.

3. **State manipulation**: TraCI empowers users to alter object states, exemplified by changing vehicle attributes, adjusting individual conditions, modifying vehicle type attributes, and revising route statuses.

During the development of TraCI-associated applications, certain limitations must be taken into account, particularly the potential for simulation slowdown. This deceleration is influenced by factors such as the frequency of TraCI function invocations during simulation steps, the resource-intensive nature of specific TraCI functions, internal computations within the TraCI script, the supplementary communication channel introduced by AMQP broker-based TraCI function calls, and the chosen client language.
The Traffic Control Interface (TraCI) serves as a fundamental component enhancing the capabilities of the Simulation of Urban Mobility (SUMO) software. By facilitating dynamic and real-time interaction between external software tools and simulated traffic environments, TraCI offers a powerful bi-directional communication interface. This functionality provides a wide array of possibilities for researchers, developers, and practitioners to implement and test advanced traffic management strategies, control algorithms, and intelligent transportation systems.
Through TraCI, users can access real-time information from SUMO simulations, including vehicle positions, speeds, and traffic signal states. This data is invaluable

for developing and validating algorithms for connected and autonomous vehicles, as well as for designing and assessing real-time traffic control strategies. TraCI also enables users to actively influence simulations by sending commands to SUMO, such as adjusting traffic light timings, adding or removing vehicles, and introducing disruptions to traffic flow. This capability is essential for testing the responsiveness of different control systems under various conditions.
Beyond individual vehicle control, TraCI's versatility extends to the implementation of cooperative strategies among vehicles and infrastructure elements. This enables the study of platooning, intersection management, and congestion mitigation in connected vehicle environments. Researchers can use TraCI to explore scenarios like cooperative adaptive cruise control, traffic information sharing, and decentralized decision-making among connected vehicles, all of which are critical for realizing the potential of intelligent and interconnected transportation systems.
In Figure 5.1 is represented how TraCI is establishing a connection to SUMO [17].

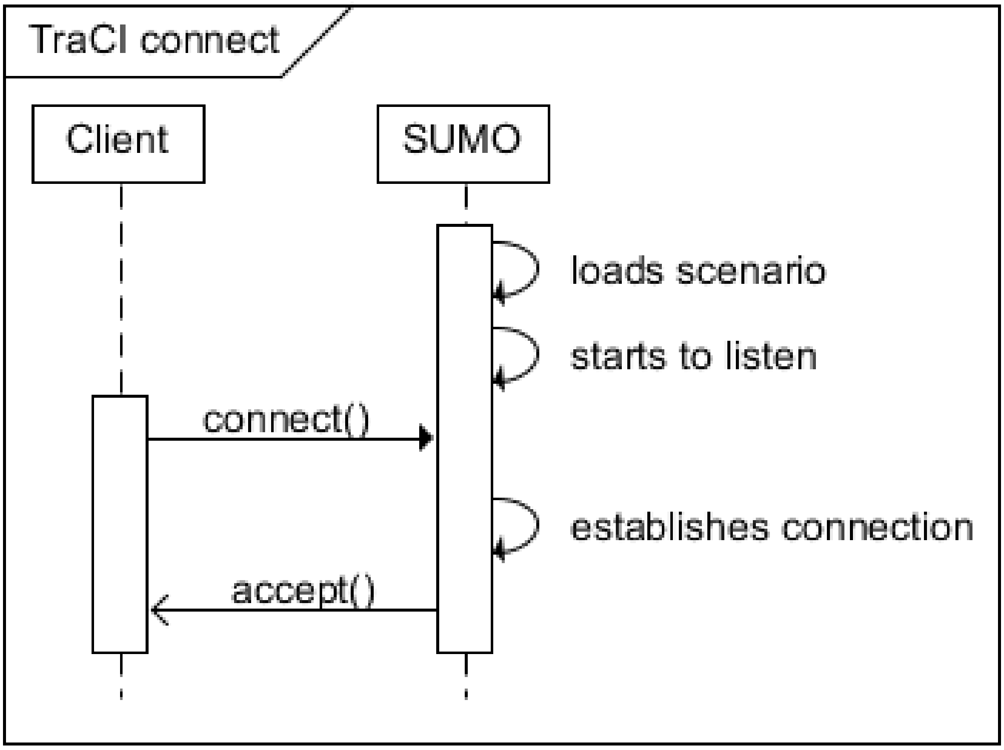

Figure 5.1: TraCI: establishing a connection to SUMO

5.2.3 Data generation

The utilization of TraCI functions is essential for accessing simulation variables and asserting authority over them. Referred to as the SUMO client application, this software serves a multifaceted purpose which comprises simulation, message transmission, and vehicle data generation. Complementary submodules, including the Subscriber, message binder, AMQP client, and others, are enclosed within this context.
Once the simulation begins, free from network-related impediments such as unconnected roads or poorly positioned vehicles, invoking the SUMO client via the TraCI API becomes feasible. The entirety of the SUMO client process can be encapsulated within the subsequent steps, with a high-level architectural:

1. Introducing diverse traffic entities through TraCI, including vehicles, traffic lights, and simulation timing steps. These enumerable entities are distinctly designated by specific ID numbers.

2. Utilizing the assigned vehicle IDs to retrieve other traffic-related parameters particular to each vehicle. These include vehicle position (then translated into longitude and latitude), temporal and date data, vehicle velocity, road edge and lane, vehicle turning angle, and the subsequent traffic light signal the vehicle is approaching.

3. Exploring lane-specific traffic light-related information, including the ongoing signal state, duration of the traffic light phase, and the next signal transition.

4. Incorporating functions for governing and updating vehicle and traffic-linked variables, acquired from the edge/server during the preceding simulation step and decoded utilizing the V2X coder application.

5. Compiling all the data for potential use in CAM/DENM formation and enabling exportation in formats such as csv/xls files.

6. Arranging all requisite information into the CAM/DENM format in adherence to ETSI standards.

7. Concluding the process by encoding messages through the V2X coder application and transmitting them to the edge server via the AMQP client.

In Figure 5.2, a high-level design is also shown.
The next chapter will provide a more thorough explanation of some of the topics stated above with an example of a scenario created usong SUMO.

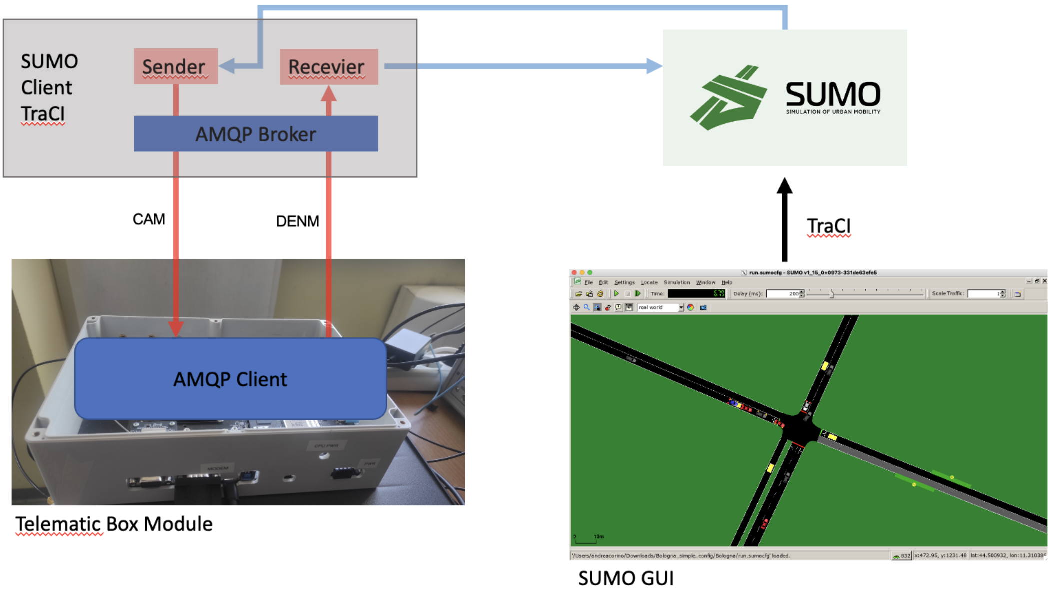

Figure 5.2: High level SUMO Client architecture

Chapter 6

Simulated Use Cases

6.1 Roundabout generated using SUMO

In traffic simulation, the art of shaping scenarios or ensuring the availability of accurate maps stands as a very complex effort. It is in this case that the significance of SUMO truly comes to help. SUMO, is a versatile tool employed to faithfully replicate specific scenarios or situations. Whether it's simulating the dynamics of a roundabout or distilling the essence of a small-scale junction, SUMO's skill are very useful. The process of refining maps, too, doesn't represent a challenge when crafting these compact scenarios. The generation of synthetic traffic within the confines of the desired study scope is a straightforward task.
However, the complexity becomes even more big when the research scope demands the creation of expansive scenarios. A multitude of studies and research projects have gone into details on the intricacies of constructing elaborate scenarios, underscoring the criticality of this endeavor. The ability to accurately replicate real-world traffic conditions holds the key to producing meaningful simulations. To this end, the majority of efforts dedicated to generating sizable scenarios have been directed towards amassing a trove of input data. This includes an intricate interplay of data points that span the realm of traffic dynamics and map intricacies.
The scenario we're currently dissecting is a very particular one and unique, as noted earlier. Its uniqueness lies in its complexity and the challenges it poses, especially when transposed into the dynamic environment of urban and intercity traffic. The scenario at hand revolves around the enigmatic roundabout – a peculiar form of intersection where the flow of traffic is elegantly orchestrated in a circular manner around a central island. The shape and design of a roundabout are one of the main objective in dictating the behavior of vehicles. It's not just about navigating turns; it's about creating an environment that encourages controlled speeds and fluid movements, minimizing stops while maximizing safety and efficiency[18].

The implementation of roundabout traffic management could have a big impact in a new era of traffic safety and operational efficiency. The interplay of geometry and design necessitates a thoughtful approach, ensuring that vehicles enter and traverse the roundabout at an optimal pace. This involves considerations like entry speeds, the number of lanes, the flow of pedestrian and cyclist traffic, and the overall layout – all working together to orchestrate a symphony of movement.
However, within the scope of this study, the focus isn't on designing scenarios themselves but rather on exploring the impact of different vehicle types within a roundabout setting. This includes a panoramic view of manually driven vehicles, semi-automated counterparts, and the cutting-edge realm of autonomous systems. The main focus lies in understand and deciphering how these vehicles interact with both the infrastructure and each other, culminating in an improved level of operational awareness. This novel dimension brings forth the concept of a virtual testing environment, where data streams from vehicles intertwine with insights from a driving simulator, courtesy of the Telecommunication Box Unit.
Such a harmonious convergence gives rise to an intriguing prospect: the birth of a cooperative perception mechanism. With the assistance of AI frameworks strategically placed at traffic stations, this mechanism could have a big role in the future of road safety. Imagine a scenario where traffic flow is directed with precision around roundabouts, real-time warnings are issued to drivers or autonomous systems about impending dangers, and a higher level of situational awareness prevails.
While the traffic simulator used for this project has been referenced previously, the exploration of alternate tools for simulating roundabouts bears merit. Take, for example, the work of Trueblood Dale (2003) [19], who employed VISSIM to simulate the intricacies of roundabout traffic. Their study underscored four main components that lay the foundation for VISSIM's realistic portrayal of roundabouts. These encompassed geometric coding, routing decisions, meticulous gap acceptance modeling, and a nuanced simulation control for the vehicle's final speed. Moreover, the TRACSIM program by Krogscheepers Roebuck (1999), which goes deeper into driver behavior and gap acceptance at roundabouts, has also been harnessed to enrich the roundabout simulation experience.
In the world of research, the LuST (Luxembourg SUMO Traffic) project serves as a poignant example. This endeavor leverages the prowess of SUMO to craft expansive scenarios, including a 24-hour simulation in the bustling urban landscape of Luxembourg City. The proficiency and advantages conferred by SUMO, the chosen traffic simulator for this study, streamline the process of generating roundabout scenarios, significantly reducing the associated complexities[20].
Now that we have gone deeper into the world of simulators and their crucial role, it's prudent to step further into the art of crafting scenarios within the SUMO framework. This includes unveiling the intricacies of scenario construction and unearthing any ancillary steps that illuminate the path forward.

6.1.1 Creating the Network's process

In the world of traffic simulation there are a lot of complexities, where the art of crafting scenarios and ensuring accurate map availability assumes a significant importance. Within this landscape, SUMO emerges as a versatile beacon, offering three primary avenues to construct networks: netconvert, netgenerate, and netedit. Although they represent distinct tools, they share a common thread of process.
Zooming out, the construction of networks and the orchestration of simulations is composed of a four-step choreography. At the heart of this orchestration lies the SUMO network, a digital representation housing a wealth of information. Each street metamorphoses into a collection of lanes, traffic light coordination dances into the mix, junctions become the crossroads of urban choreography, and the seamless interplay of lanes at junctions assumes the role of a traffic symphony conductor.
This choreography is open to enhancement through intricate district layouts and the fine-tuning of roundabout dynamics. User inputs also contribute to this symphony, shaping the processing options that ultimately define the digital urban landscape. But our endeavor transcends the mere imitation of traffic dynamics. It evolves into an exploration of uncharted territories – a world where a communication platform thrives, and where the capabilities of six cutting-edge AI@EDGE enablers are tested. In this context, crafting an elaborate network isn't just about scale; it's about striking a balance that avoids overwhelming the simulation with an abundance of traffic entities.
Beyond SUMO's shores, alternate digital networks hold potential. The compatibility of other frameworks with SUMO enables novel avenues for network creation. One such example is OpenStreetMap (OSM), an expansive repository of geographical data. By configuring network-related parameters, OSM's data can be harnessed to breathe life into SUMO's digital streets. The intricate nuances of roundabouts, synonymous with intricate traffic scenarios, come to life with tools like Neconvert and Netgenerate. These converters and importers facilitate the translation of tailored descriptions into tangible digital networks.
In Figure 6.1 is shown an example of the usage of OSM for the city of Turin.

The network can be obtained by different sources, be it the open expanse of OpenStreetMap or the meticulous simulations of tools like VISUM, VISSIM, and SUMO's own XML descriptions. Figure 6.2 shows the journey of the network creation of SUMO. The methodology employed to forge the enigmatic roundabout, for instance, stands spotlighted on the canvas, showcasing the marriage of the NETCONVERT command-line application with custom descriptions of nodes, edges, and connections.

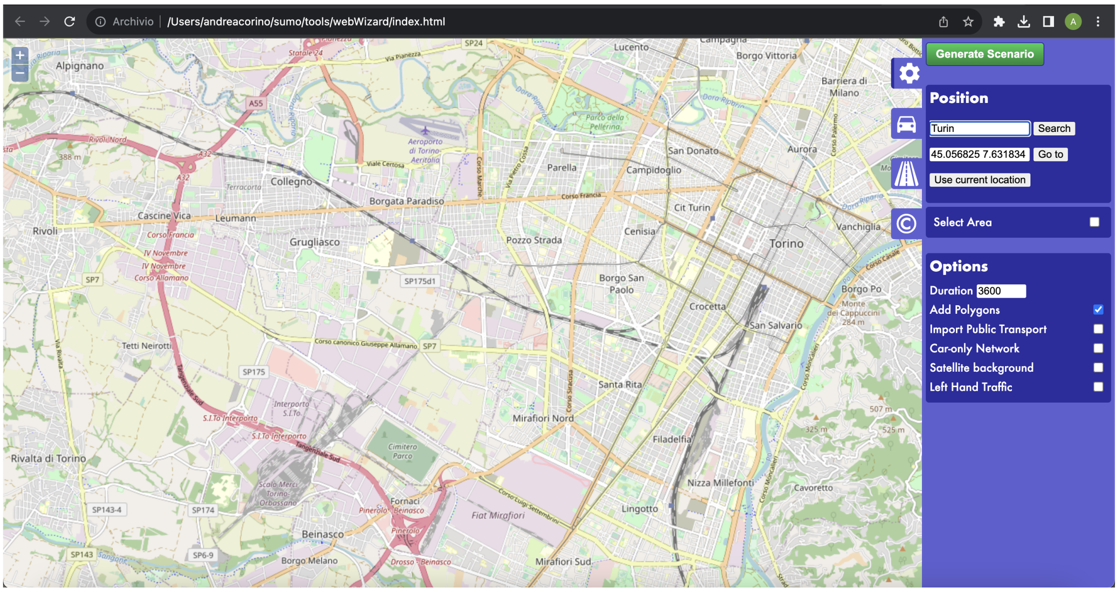

Figure 6.1: Geographical area of Turin shown using OpenStreetMap

After laying the groundwork, the next stage is to give the network the fluctuation of traffic that the real world experiences. This integration is achieved through the deft manipulation of routes files, which deal with the movement of vehicles. The canvas of the routes file is adorned with traffic-related variables – the number of vehicles traversing the digital lanes, the different vehicle types, the intricate routes each vehicle navigates, and the different properties of each vehicle. A big amount of data comes together, culminating in a coherent narrative of traffic dynamics.
This approach is very useful when dealing with a modest number of routes and traffic entities. However, the difficulty is higher as the complexity of the vehicles and routes increases. Each vehicle type brings its unique signature to the composition, encapsulating attributes such as acceleration, deceleration, length, color, and maximum speed. The description file not only imparts these traits but also confers each vehicle with a distinct identity in the digital landscape.
Yet, even within this amount of information, constraints are fundamentals. Routes must intertwine, forming seamless connections across a network. Each route, must encompass at least two edges to ensure continuity and coherence. This rich composition also accommodates the vehicle's startup dynamics: a vehicle's journey can start from specific locations before moving to designated edges, all synchronized with its unique and recognizable path.
As shown in Figure 6.1 there is a multitude of avenues through which randomized networks can be spawned using OpenStreetMap. OSM stands as a dynamic canvas, a global map open to anyone's input, allowing the creation and contribution of

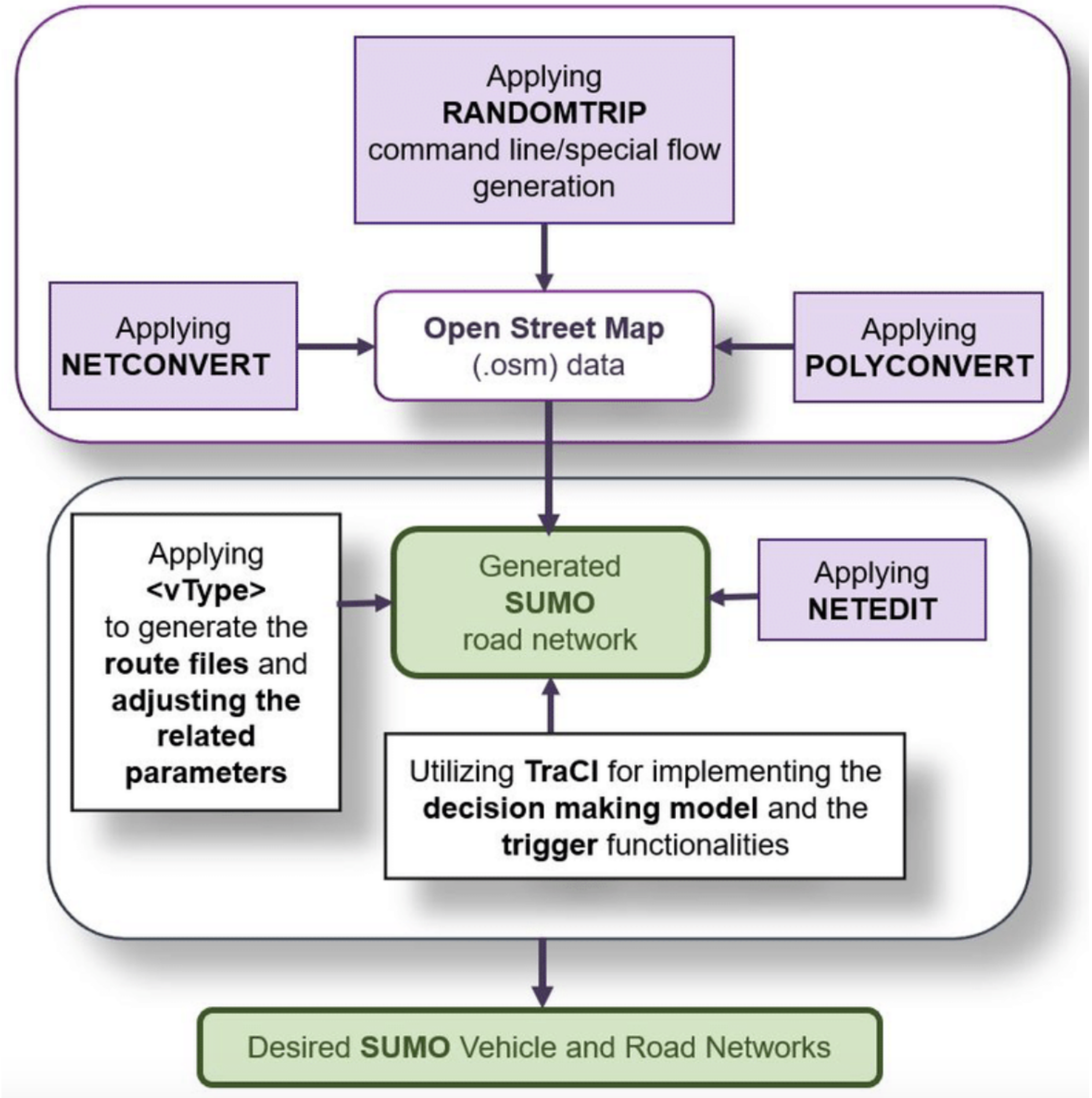

Figure 6.2: SUMO network building procedure

data for virtually any locale. The data contains street maps and may ultimately be converted into an SUMO network file using NETCONVERT. The usage of osmWebWizard.py script, an incantation of simplicity, is invoked to solve very specific and complete scenarios. This approach simplifies the creation of complete scenarios. Diverse maps can be employed to import the network, providing flexibility in generating different traffic patterns with a range of traffic elements. However, the method's cost-free nature is accompanied by technical and legal constraints, limiting users from fully unleashing their creative and productive potential with

the data.
The creation of the roundabout scenario adhering to the process detailed in Figure 6.2, which utilizes the description files such as Nodes, Edges, and Connections along with other essential traffic parameters. For the sake of simplicity, the network will make use of only 10 vehicles. The SUMO GUI comes to life in the instantiation of the simulation setup, as can be seen in Figure 6.3 The resulting network is unveiled, showing the roundabout's intricate design.

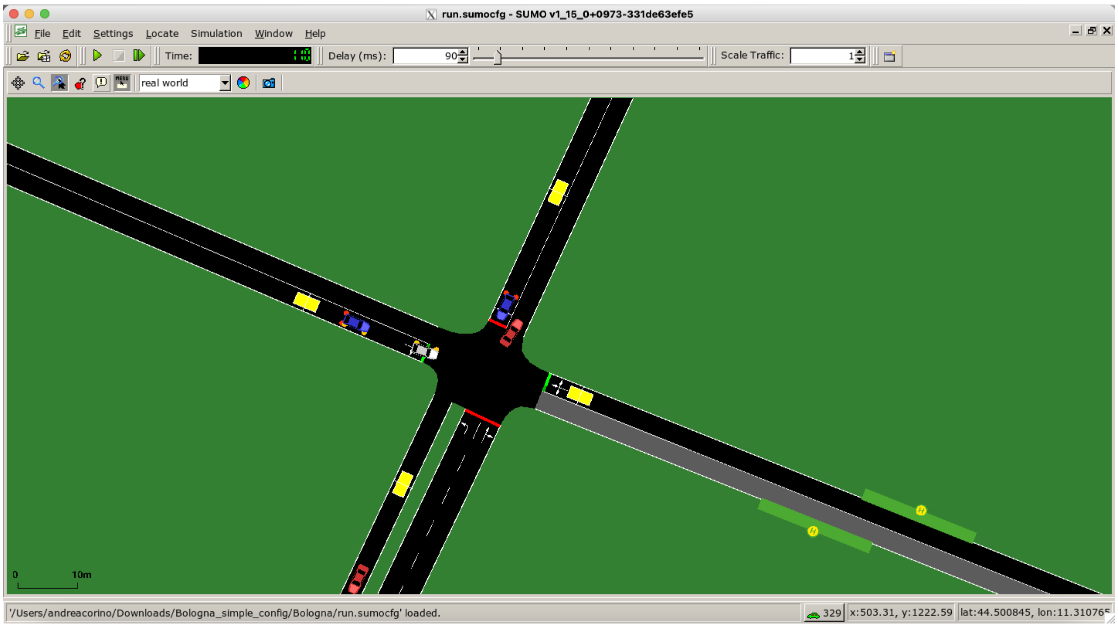

Figure 6.3: Representation of the roundabout using SUMO-GUI

That's why simulation comes in extremely handy. The SUMO GUI provides an important environment for this network to be studied and analyzed. Alternatively, the use of TraCI API applications and command-line invocations provide a step for simulation without using a graphical interface. In this case, the TraCI Python library takes center stage, extending an invitation to tread this path with or without the GUI's embrace. With defined start and end times, the simulation is prepared for execution, yielding the foundational model of the desired network. This model can subsequently be applied to other simulation scenarios involving vehicle dynamics, extending its utility beyond the current context. In the next sections we will go over simulation and car data subscription from running sumo instances.

6.2 V2X

Having a standardized message format for communication between vehicles and edge servers, as well as among vehicles themselves, plays an important role within the domain of vehicle messaging. Consequently, an overarching framework is employed to establish a set of fundamental functionalities within the realm of the Intelligent Transport System (ITS). Of utmost importance are the Cooperative Awareness (CA) and Road Hazard Warnings (RHW) services, which form the main focus of this framework. CA, operating as a collaborative entity, engages in cooperative perception among a fleet of vehicles, facilitated by edge services. This collaboration takes shape through the exchange of messages across the ITS network, elevating awareness among fellow vehicles and road users. Meanwhile, exploiting the V2V and V2I networks, RHW aims to enhance traffic efficiency and elevate road safety standards. The Cooperative Awareness Messaging underpins CA, while the RHW relies on the Decentralized Environmental Notification application, a variant of emergency service.
The services that have just been described, resides within the V2X coder module of the SUMO client application. Within this module, the ETSI-prescribed format is harnessed to encode and decode vehicle-specific information in the simulated traffic environment.

6.2.1 CAM: Cooperative awareness Messaging

The operational implementation of the services that have just been described is facilitated through the utilization of ETSI-prescribed standard structures, commonly referred to as Cooperative awareness Messaging (CAM) and Decentralized Enviromental Notification Messaging (DENM). Acting as the linchpin, cooperative awareness services oversee the transmission and reception of CAMs. A noteworthy aspect lies in the varying transmission frequency of CAMs among distinct ITS stations. To harness the data gleaned from CAMs effectively, the CA services interface at the facility layer harmonizes with the application layer[21].
The encoding and decoding functions are imperative for the seamless exchange of CAMs. While transmission and reception management sub-functions are requisites, the focal tasks center around encoding and decoding ports, given their consistent operation within the ambit of the V2X coder. In the study of virtual traffic simulation, the dissemination of CAMs is less of a challenge, operating largely at the programmatic level. Nonetheless, devising an efficacious dissemination strategy holds paramount importance for comprehensive coverage of a given region with CA messages. Typically, CAMs are disseminated in a singular hop to all proximate ITS stations set within range. The dynamic operation of ITS-S within this range

leads to the activation and deactivation of a vehicle's data stream. The extent of channel congestion has an influence over the frequency of message dissemination, although the message generation process accommodates a time span ranging from 100 to 1000 milliseconds. Divergence might occur across different network systems, such as LTE-V2X, where channel congestion management rests within the purview of the access layer, consequently influencing generation timing.
A very important component within the CAM framework is the ITS PDU (Protocol Data Unit) header. This header contains vital information encompassing protocol version, message type, and the unique ITS-S ID from which the message originated. Within this context, the ITS-S identity may pertain to a vehicle, RSU (Roadside Unit), or a pedestrian.
The architecture of a CAM comprehends three primary container types:

1. The Basic Container encapsulates foundational details pertaining to the originating ITS-Station.

2. The High Frequency Container comprises dynamic, highly mutable information concerning the ITS-Station (typically vehicles in our context).

3. The Low Frequency Container embraces static or gradual-changing information.

4. The Special Vehicle Container caters to specialized vehicle categories, housing information tailored to specific types of vehicles (e.g., Public Transport, Special Transport, etc.).

Illustrated in Figure 6.4 is the CAM container structure.

6.2.2 DENM: Decentralized Environmental Notification Messaging

The DEN (Decentralized Environmental Notification) services, as their name implies, exhibit a distinctive application compared to CA services. DEN services are geared towards specific event detection, notifying users in a decentralized manner upon event occurrence[21]. The ITS employs a specialized process for leveraging DEN services:

1. DENM broadcasts itself across ITS stations within a designated region known as the 'Zone of Relevance' when an alert is triggered.

2. Transmission persists until the detected hazardous event has subsided.

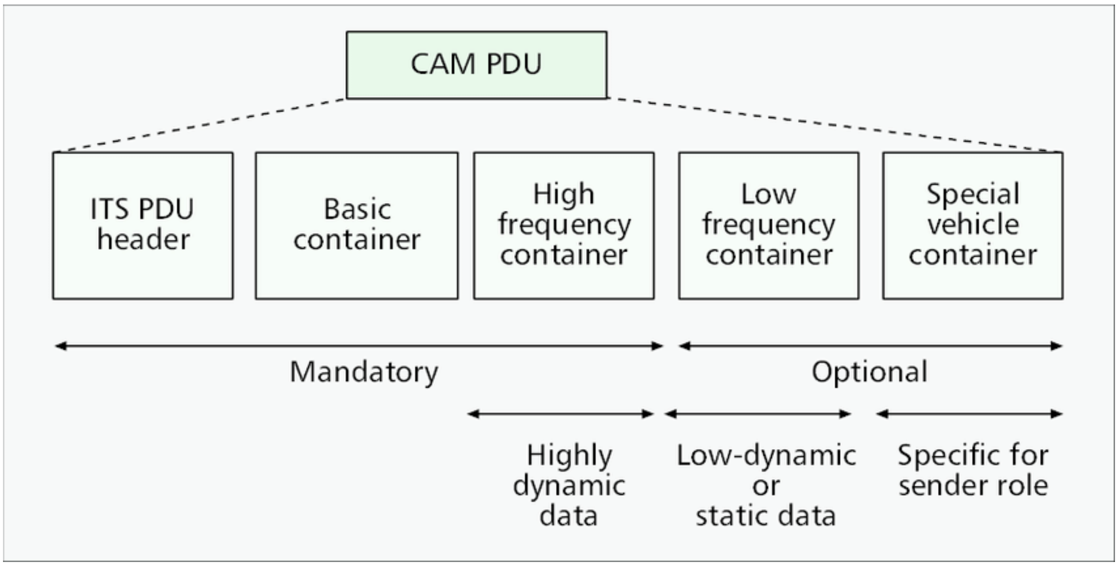

Figure 6.4: Structure of a CAM message

3. Messages can be relayed between ITS-S stations.
4. While optional, Human-Machine Interface (HMI) can also be utilized to apprise users of information contained in DENMs.

Paralleling the DENM architecture, the CA service architecture interfaces with the application layer for DENM transmission and reception. Upon message reception, the Local Dynamic Map (LDP) within the facility layer undergoes updates. Despite the architectural similarities between CA and DEN services, a distinctive feature lies in the identification of the message-generating station. When alert events at the application layer trigger DEN services, an unused actionID is generated, enabling the source station's differentiation from others.
An eminent attribute of DENMs is their relevance area, delineating an exposed region where vehicles could be imperiled. The generating station consistently incorporates this zone, alongside two additional parameters: the relevanceDistance parameter, signifying the distance within which other vehicles will receive messages, and the relevanceTrafficDirection parameter, dictating the direction in which vehicles should encounter the alert.
The DENM Container is analogous to CAMs, DENMs encompass an ITS-PDU header with identical functionality. Illustrated in Figure 6.5 is the DENM container structure, comprising five distinct containers.

The situation container encapsulates core event information destined for communication to other ITS stations. The management container holds details concerning

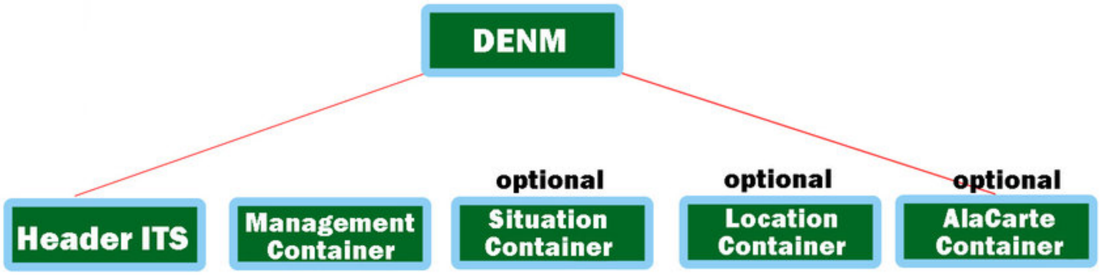

Figure 6.5: Structure of a DENM message

actionID, detectionTime, referenceTime, etc. Essential information such as event speed, position heading, traces, and road type specifics are stored within the location container. Lastly, the à la carte container, although optional, serves as a repository for additional information that may prove indispensable in exceptional circumstances, information that other containers cannot accommodate, such as externalTemperature.

6.2.3 IP end-to-end

Now, let's focus on the case of IP end-to-end communication within the context of CAMs and DENMs, exploring how this communication paradigm underpins the seamless exchange of critical information for enhanced road safety and cooperative awareness. At the heart of modern Intelligent Transport Systems (ITS), the effective dissemination of crucial information holds paramount importance. CAMs and DENMs serve as the informational bedrock, relaying real-time data about road conditions, vehicular states, and potential hazards. IP end-to-end communication emerges as the cornerstone of this data flow, orchestrating the intricate process of message generation, transmission, and reception[22].
IP end-to-end communication encompasses a holistic approach to data exchange, spanning the entire network from the point of origin to the intended recipients. The underlying IP-based architecture ensures that the content and context of CAMs and DENMs remain intact throughout their journey. By encapsulating these messages within IP packets, complete with appropriate headers and routing information, the system maintains data integrity and accuracy. Through the application of the end-to-end principle inherent in the IP protocol, the system guards against data corruption, loss, and misinterpretation. This principle dictates that intelligence and decision-making should reside at the endpoints, allowing for robust and reliable communication even in the presence of intermediate nodes or potential network disruptions. As a result, the information carried by CAMs and DENMs traverses diverse communication links, seamlessly navigating through both Vehicle-to-Vehicle

(V2V) and Vehicle-to-Infrastructure (V2I) networks.
IP addresses play a crucial role in directing packets to their designated destinations, ensuring that messages reach the appropriate vehicles and ITS stations with precision. This addressing mechanism aligns with the broader goal of cooperative awareness and road safety by facilitating targeted and efficient communication.
IP end-to-end communication fosters bidirectional interaction between vehicles and infrastructure. As vehicles receive CAMs and DENMs, they also generate acknowledgment messages, affirming successful reception. This two-way communication forms a vital feedback loop, assuring the sending vehicle that its message has been effectively transmitted and received, thus contributing to the overall reliability of the cooperative awareness ecosystem.

6.3 AMQP Client

The deployment of CA and DEN services within the SUMO client involves the integration of CAM and DENM message exchange with the server, subsequent to a concise exploration of their architectural frameworks and message structures. To conform to specific formatting requirements, the aggregation of vehicular and traffic-related data is imperative. This fusion is orchestrated by sub-functions embedded within the SUMO client, orchestrating the transformation of data into JSON format before encoding it into binary representations for onward transmission to the server. On the contrary, upon receipt of the message, the decoding process follows.
Local encoding and decoding responsibilities is done by the SUMO client, while the orchestration of message transmission and reception is managed by an AMQP client. These functionalities encompass an array of tasks, ranging from CAM to BIN, CAM to HEX, DENM to HEX conversions, and beyond. This dynamic suite of applications, exhibiting different operational methodologies, finds its utilization within the ambit of the SUMO client.
Functionality invocation centers around the Encoder/Decoder application, which can be seamlessly invoked, instigating a sequence of requisite operations within the SUMO simulation timeline, subsequent to the culmination of CAM aggregation and binding. This approach amalgamates both message transformation and data exchange, culminating in a cohesive communication framework within the case of SUMO simulation steps.
A few requirements outlined by ETSI and listed in Appendix A must be met in order to deliver a CAM message. Therefore, before the message generating process could begin, these requirements must be satisfied.

6.3.1 Sender

In the context of a simulation step, the Sender undertakes the responsibility of transmitting vital information to the server, a process that necessitates the establishment of a robust connection. This fundamental transmission task finds its roots in the construction of application logic within a meticulously crafted specialized class, explicitly designed to handle different types of events. It is worth pointing out that the procedural framework that drives the dispatch mechanism is closely intertwined with the core tenets of this aforementioned class.
The application container, one of the main component of this system, seamlessly integrates several distinct classes, each meticulously tailored to define and manage specific events. The orchestration of these events is handled by the Proton event handler, ensuring the system's responsiveness and efficiency.
These include:

1. on_start: This event is meticulously triggered during the initialization phase of the event loop. It serves as the beacon signaling the commencement of the process.

2. on_sendable: The activation of this event is a crucial juncture that signifies the link's readiness to accommodate the flow of messages. It hinges on the availability of adequate credit, ensuring a smooth message exchange.

3. on_accepted: This particular event comes into play when the remote peer extends acknowledgment for a message that emanated from the sender's end. The recognition of successful transmission is encapsulated within this event.

4. on_disconnected: This event, distinct in its nature, is exclusively invoked when the connection socket is deliberately closed. Its invocation symbolizes the conclusion of the communication process.

All these events that have just been described, converge within the Reactor class container, purposefully imported to fulfill this exact role. This ingenious approach significantly streamlines the task of crafting an event loop that remains primed to react and adapt as events dynamically unfold. It is imperative to underscore that with each instantiation of the container, the provision of the broker's address becomes indispensable. The broker's address takes the following form: "admin:...@13.38.15.28:5001/amqpclient://"
It is worth nothing that the composite structure of the broker's address inherently includes both the address and the port, with the default port for AMQP transmissions being predefined as 5001. Following this, the spotlight is directed towards the delineation of the subject matter.
In a carefully orchestrated sequence, the encoded CAM/DENM messages find

seamless integration within the very core of the event loop's initialization process, inserted comfortably within the container. This integration is further accentuated by the meticulous specification of the destination address that the messages are destined for. As an important preparatory step before the actual transmission, the command "event.sender.message" assumes center stage, bearing the crucial role of uniquely labeling the message with an identification code that imparts a distinct identity.

6.3.2 Receiver

The Receiver, much like its counterpart Sender, also assumes its functional role within a dedicated container that serves as the hub for managing an array of events. This orchestration process mirrors the procedure established for the Sender, fostering a parallel and coherent approach.
The unfolding sequence of subsequent events seamlessly falls within the jurisdiction of the Receiver's operation:

1. on_start: Within this initial event stage, the main process of variable initialization takes center stage. It is during this phase that the foundational groundwork for subsequent operations is meticulously laid.

2. on_message: This important juncture in the Receiver's operation is where a series of intricate operations unfolds. These operations comprehend the critical tasks of message decoding and the subsequent extrapolation of Geo-networking information embedded within the received messages. The Receiver's capacity to adeptly handle these tasks marks a significant milestone in its operational efficacy.

Drawing a parallel to the approach undertaken by the Sender, the Receiver aligns itself with a predefined topic, shaping its behavior in response to specific criteria. This predefined topic, encapsulated within the address:
"admin:...@13.38.15.28:5001/amqpclient://" becomes the focal point of the Receiver's attention. Messages that traverse this particular address, harmonizing with the thematic contours of the designated topic, seamlessly flow into the case of the Receiver.
Employing the rich capabilities of TraCI, the Receiver harnesses its adeptness to interact with the simulator in a profound manner. The information gleaned from the ingested messages becomes a potent resource in trying to have a better effort. The Receiver, acting as a conduit between the message content and the simulator, meticulously extracts the relevant data through TraCI functions. This data, once successfully retrieved, is primed for dispatch to the simulator, where it assumes an important role in influencing the trajectory of the simulation. This

well-choreographed process, initiated by the consummation of the received messages, forms an integral part of the Receiver's multifaceted operation, contributing significantly to the overall system's efficiency and efficacy.

Chapter 7

Conclusions

A virtual validation-oriented approach has been investigated for the cooperative perception of vehicles within the larger framework known as AI@EDGE. Chapter 3 of the report begins by going into details on the six key technological drivers behind the AI@EDGE platform, which harnesses artificial intelligence for diverse connected vehicle services and functionalities. Among the primary focal points of discussion are cooperative perception for vehicular networks, secure multi-stakeholder AI for the Internet of Things (IoT), aerial infrastructure inspections, and in-flight entertainment.
The thesis project centers on a specific use case and within this context, the response of the AI@EDGE architecture to the challenges and resolutions of the use case is elaborated upon in subsequent sections of the discussion chapter. To address the intricacy and cost of supporting a large number of vehicles in a real-world scenario, the use case relies on virtual traffic simulation environments and 5G emulation.
Aligned with this use case, a challenging traffic situation, the roundabout, crucial for safety and smooth traffic flow, is emulated using a traffic simulator named SUMO. The Python-based TraCI library is employed to streamline the retrieval of real-time data from the traffic simulator. Facilitating the data subscription process, an AMQP client built using Qpid Proton's standard Python API acts as the SUMO client, facilitating the exchange of this data with the edge server and other vehicles. In accordance with ITS standards, traffic and vehicle-related information are compatible with the format defined by ETSI as CAM and DENM message services before being transmitted to the server. Communication-specific testing is conducted within a 5G emulation environment, as the ultimate goal is to implement the previously developed functionalities on an onboard Telematic Box Module device.
Various test scenarios involving cell handover, dual-connectivity, carrier aggregation, MIMO, and more are executed within a network-based emulation Hardware-in-the-Loop (HIL) setup in relation to the LTE/5G cellular network. By manipulating different network-related parameters such as frequency, modulation technique, and

band parameters, the Device Under Test, equipped with C-V2X wave stack, is examined to assess network throughput. The testing reveals that carrier aggregation and techniques like MIMO enhance throughput in the downlink mode and that seamless handover can be achieved through power ramp-up.
Drawing from the capabilities developed and the results of HIL testing, an assessment of a virtual validation platform for vehicular perception is ongoing.

Appendix A

Algorithm for generating the Cooperative Awareness Message

The dynamic non-deterministic generation of the CAM leads to a very efficient use of the spectrum and can help to avoid congestion in the wireless channel maintaining the required information deliverable to the surrounding vehicles and devices[23].

Algorithm 1: CAM message generation algorithm

Input: A new position read p, if any; a record of previous positions pHist; the last CAM message sent lastCam

Output: A new CAM message is sent and lastCam is updated, if applicable; pHist is updated with p, if applicable

```
while true do
    time = System.getTime()
    heading = calcHeading(pHist, p)
    lastPos = lastPosition(pHist)
    lastHist = pHist \ lastPos
    lastHead = calcHeading(lastHist, lastPos)
    speed = calcSpeed(pHist, p)
    if p ≠ null then
        lastSpeed = calcSpeed(lastHist, lastPos)
        if distance(p, lastCam.pos) ≥ D_THRESHOLD or
        heading - lastCam.heading| ≥ H_THRESHOLD or
        speed - lastCam.speed| ≥ S_THRESHOLD then
            cam = newCam(time, p, heading, speed)
            sendCam(cam)
            lastCam = cam
            pHist = pHist ∪ p
    else
        p = lastPos
        heading = lastHead
    if time - lastCam.time ≥ T_THRESHOLD then
        cam = newCam(time, p, heading, speed)
        sendCam(cam)
        lastCam = cam
    System.wait(CHECK_PERIOD)
```

With the following triggering conditions:

D_THRESHOLD = 4 m
H_THRESHOLD = +/- 4◦,
S_THRESHOLD = 0,5m/sec, and
T_THRESHOLD = 1 sec
CHECK_PERIOD = 0.1 sec

Figure A.1: Cooperative Awareness Message generation algorithm descibed by ETSI

Bibliography

[1] Ryan J. Harrington, Carmine Senatore, John M. Scanlon, and Ryan M. Yee. «The Role of Infrastructure in an Automated Vehicle Future». In: (). URL: https://www.researchgate.net/publication/326656172_The_Role_of_Infrastructure_in_an_Automated_Vehicle_Future (cit. on p. 2).

[2] European Commission. «Definition of V2X message sets». In: (). URL: https://www.etsi.org/deliver/etsi_en/302600_302699/30263703/01.02.01_30/en_30263703v010201v.pdf (cit. on p. 6).

[3] E. Standard. «Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service.» In: (). URL: https://www.etsi.org/deliver/etsi_en/302600_302699/30263702/01.03.01_30/en_30263702v010301v.pdf (cit. on p. 7).

[4] Wikipedia. «Cellular V2X.» In: (). URL: https://en.wikipedia.org/wiki/Cellular_V2X (cit. on p. 10).

[5] . «3GPP 3GPP Specification Release Numbers.» In: (). URL: https://www.electronics-notes.com/articles/connectivity/3gpp/standards-releases.php (cit. on p. 10).

[6] 3GPP. «Release 14». In: (). URL: https://www.3gpp.org/specifications-technologies/releases/release-14 (cit. on pp. 10, 35).

[7] 3GPP. «Release 15». In: (). URL: https://www.3gpp.org/specifications-technologies/releases/release-15 (cit. on p. 10).

[8] «What is LTE-V2X (PC5)? - everything RF». In: (). URL: https://www.everythingrf.com/community/what-is-lte-v2x-pc5 (cit. on p. 12).

[9] AI@EDGE. «A Secure and Reusable Artificial Intelligence Platform for Edge Computing in Beyond 5G Networks». In: (). URL: https://aiatedge.eu/publications/ (cit. on p. 13).

[10] Dr. Roberto Riggio AI@EDGE (FBK). «A Secure and Reusable Artificial Intelligence Platform for Edge Computing in Beyond 5G Networks». In: (June 2020). URL: https://aiatedge.eu/publications/ (cit. on pp. 17, 21).

[11] Roberto Riggio, Estefanía Coronado, Neiva Linder, Adzic Jovanka, Gianpiero Mastinu, Leonardo Goratti, Miguel Rosa, Hans Schotten, and Marco Pistore. «AI@EDGE: A Secure and Reusable Artificial Intelligence Platform for Edge Computing». In: (June 2021). URL: https://doi.org/10.1109/EuCNC/6GSummit51104.2021.9482440 (cit. on pp. 21, 22).

[12] AI@EDGE. «Initial report of systems and methods for AI@EDGE platform automation.» In: (2022). URL: https://aiatedge.eu/wp-content/uploads/2022/03/AI@EDGE_D3.1_Initial-report-of-systems-and-methods-for-AI@EDGE-platform-automation.pdf (cit. on pp. 21, 22).

[13] AI@EDGE. «D5.1 Testing and Validation Methodology, Planning and Preparation.» In: (3/2022). URL: https://aiatedge.eu/wp-content/uploads/2022/03/AI@EDGE_D5.1_Testing-and-Validation-Methodology-Planning-and-Preparation_v2.0.pdf (cit. on p. 24).

[14] AI@EDGE. «D2.1 Use cases, requirements, and preliminary system architecture.» In: (9/2021). URL: https://aiatedge.eu/wp-content/uploads/2021/09/AI@EDGE_D2.1_Use-cases-requirements-and-preliminary-system-architecture_v1.0-1.pdf (cit. on pp. 24, 29).

[15] Radio Communication Test Station MT8000A Brochure. «Single Box Solution for RF and Application Testing of 5G SA/NSA Devices.» In: (). URL: https://usermanual.wiki/m/d4e59599d59c27c2d794164556a8f3b329c72b6537b7c6bbce4a289d558a3c08#iframe (cit. on p. 38).

[16] Institute of Transportation Systems. «SUMO – Simulation of Urban Mobility». In: (). URL: https://www.intelligentcitieschallenge.eu/good-practices/sumo-simulation-urban-mobility (cit. on p. 59).

[17] Protocol- SUMO Documentation. In: (). URL: https://sumo.dlr.de/docs/TraCI/Protocol.html (cit. on p. 61).

[18] Bernardo Leite, Pedro Azevedo, Rui Leixo and Rosaldo J. F. Rossetti. «Simulating a Three-Lane Roundabout Using SUMO». In: (). URL: https://eudl.eu/pdf/10.1007/978-3-030-38822-5_2 (cit. on p. 64).

[19] Yali Yang, Hao Chen, and Lihua Chen. «Evaluation of public transportation system in Shanghai, China». In: (). URL: https://ieeexplore.ieee.org/document/5543156 (cit. on p. 65).

[20] Lara Codeca, Raphael Frank, Thomas Engel. «Luxembourg SUMO Traffic (LuST) Scenario: 24 hours of mobility for vehicular networking research». In: (). URL: https://www.scinapse.io/papers/2221980827 (cit. on p. 65).

[21] José Santa,Fernando Pereniguez-Garcia,Antonio Moragón,Antonio Skarmeta. «Experimental evaluation of CAM and DENM messaging services in vehicular communications». In: (9/2014). URL: https://www.researchgate.net/publication/263050012_Experimental_evaluation_of_CAM_and_DENM_messaging_services_in_vehicular_communications (cit. on pp. 70, 71).

[22] TechTarget Contributor. «End-to-end principle». In: (). URL: https://www.techtarget.com/whatis/definition/end-to-end-principle#:~:text=The%20end%2Dto%2Dend%20principle,intermediate%20nodes%20pass%20data%20randomly. (cit. on p. 73).

[23] «CAR 2 CAR Communication Consortium». In: (). URL: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_TR_2052_Survey_on_CAM_statistics.pdf (cit. on p. 80).