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APPLICATIONS OF HAPTIC GLOVES TO REMOTELY CONTROL 5G-ENABLED AUTOMATED ROBOTS

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Resumen

Cada generación de telefonía móvil trae consigo mejoras técnicas que habilitan la aparición de nuevas aplicaciones. Una de las tecnologías potenciadas por 5G es el Internet de las Cosas (IoT), permitiendo la interconexión masiva de máquinas y su comunicación en tiempo real. La siguiente evolución de IoT es el llamado Internet Táctil, capaz de crear sensaciones inmersivas entre personas y máquinas mediante respuestas hápticas y visuales. El trabajo realizado se enmarca dentro del proyecto europeo H2020 iNGENIOUS (Next-GENeration IoT sOlutions for the Universal Supply chain), que tiene un caso de uso sobre conducción remota de robots conectados por 5G para el transporte de bienes en el puerto de Valencia. La telepresencia será soportada por dispositivos hápticos y gafas de realidad mixta, los cuales necesitan las capacidades de ultra-baja latencia de 5G para garantizar una experiencia inmersiva en tiempo real. El TFG consiste en la conexión de un prototipo de guante háptico con un robot autónomo (AGV) a través de 5G, y la posterior medida de parámetros de la red para evaluar la viabilidad del proyecto con la tecnología actual y futura.

Resum

Cada generació de telefonia mòbil porta amb si millores tècniques que habiliten l'aparició de noves aplicacions. Una de les tecnologies potenciades per 5G és l'Internet de les Coses (Iot), permetent la interconnexió massiva de màquines i la seva comunicació en temps real. La següent evolució de IoT és l'anomenat Internet Tàctil, capaç de crear sensacions immersives entre persones i màquines mitjançant respostes hápticas i visuals. El treball realitzat s'emmarca dins de el projecte europeu H2020 iNGENIOUS (Next-GENeration IoT sOlutions for the Universal Supply chain), que té un cas d'ús sobre conducció remota de robots connectats per 5G per al transport de béns en el port de València. La telepresència serà suportada per dispositius hàptics i ulleres de realitat mixta, els quals necessiten les capacitats d'ultra-baixa latència de 5G per garantir una experiència immersiva en temps real. El TFG consisteix en la connexió d'un prototip de guant hàptic amb un robot autònom (AGV) a través d'5G, i la posterior mesura de paràmetres de la xarxa per avaluar la viabilitat d'el projecte amb la tecnologia actual i futura.

Abstract

Each mobile phone generation brings technical enhancements that enable the emergence of new applications. One of the technologies boosted by 5G is the Internet of Things (IoT), which allows the massive connection of machines and their real-time communication. The next evolution of IoT is the so-called Tactile Internet, capable of creating immersive sensations between people and machines using haptic and visual feedback. This thesis takes place within the framework of the H2020 European project iNGENIOUS (Next-GENeration IoT sOlutions for the Universal Supply chain), which has a use case concerning the remote driving of robots for the transport of goods in the Valencia port. Telepresence will be supported by haptic devices and mixed reality glasses, which need the ultra-low latency capabilities of 5G to guarantee an immersive, real-time experience. This Thesis consists of the connection between a prototype of a haptic glove and an Automated Guided Vehicle (AGV) via 5G, and the subsequent measurement of the parameters of the network to evaluate the viability of the project with current and future technology.

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List of Acronyms

3GPP 3rd Generation Partnership Project.

5GC 5G Core network.

AGV Automated Guided Vehicle.

AI Artificial Intelligence.

AMF Access and mobility Management Function.

AMPS Advanced Mobile Phone System.

BLER Block Error Rate.

BW Bandwidth.

CA Carrier Aggregation.

DC Dual Connectivity.

DL Downlink.

DoF Degrees of Freedom.

E2E End to End.

eMBB enhanced Mobile Broadband.

ETSI European Telecommunications Standards Institute.

gNB next-generation NodeB.

GSM Global System for Mobile communications.

H2M Human to Machine.

HARQ Hybrid Automatic Repeat Request.

HMD Head-Mounted Display.

IEEE Institute of Electrical and Electronics Engineers.

IMU Inertial Measurement Unit.

IoT Internet of Things.

ITU International Telecommunication Union.

KPI Key Performance Indicator.

LPDC Low Density Parity Check.

LRA Linear Resonant Actuator.

LTE Long Term Evolution.

M2M Machine to Machine.

MAC Medium Access Control.

MEC Multi-access Edge Computing.

MIMO Multiple Input, Multiple Output.

ML Machine Learning.

mMTC massive Machine Type Communications.

mmW millimeter Wave.

MR Mixed Reality.

NAS Non Access Stratum.

NFV Network Function Virtualization.

NMT Nordisk Mobil Telefoni.

NR 5G New Radio.

NSA Non Stand Alone.

NTT Nippon Telegraph and Telephone.

OFDMA Orthogonal Frequency-Division Multiple Access.

PDCP Packet Data Convergence Protocol.

PDU Protocol Data Unit.

PHY Physical layer.

PoC Proof of Concept.

QoS Quality of Service.

RAN Radio Access Network.

RAT Radio Access Technology.

RLC Radio Link Control.

ROS Robot Operating System.

RRC Radio Resource Control.

SA Stand Alone.

SDAP Service Data Adaptation Protocol.

SDK Software Development Kit.

SDN Software Defined Networking.

SMF Session Management Function.

SNR Signal to Noise Ratio.

SoTA State of The Art.

TLS Transport Layer Security.

TSN Time Sensitive Networking.

UE User Equipment.

UL Uplink.

UMTS Universal Mobile Telecommunications System.

UPF User Plane Function.

URLLC Ultra-Reliable Low Latency Communications.

V2X Vehicle to Anything.

XR eXtended Reality.

Chapter 1

Introduction

5G has changed the telecommunications industry, allowing a new generation of devices and applications to be connected. These provide a more friendly and efficient environment to operators who are able to manage systems and devices with precision and reliability. One of the most exciting use cases of this new area is the remote driving of Automated Guided Vehicles (AGVs) using Head-Mounted Displays (HMDs) and haptic gloves, which are key enablers for improving operation of Internet of Things (IoT) systems in industrial and logistic environments.

The immersive teleoperation desired in this use case is clearly a Tactile Internet application, since it demands persevered real-time response. The ITU defines the Tactile Internet as “A network of networks for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes in perceived real time by humans or machines” [1]. Technically, this means the use of a 5G-driven architecture that supports bi-directional haptic control, satisfying simultaneously a few milliseconds of end-to-end (E2E) latency and ultra-high reliability in delivering the data. The term “haptics” alludes to both kinesthetic (awareness of the position and movement of the parts of the body) and tactile perception (any kind of information perceptible by touch, such as texture or friction). When ”tactile” is used in the term “Tactile Internet”, it is referring to the ultra-low latency capabilities needed in many 5G use cases including haptic communication [2].

Concepts and technologies around the IoT, 5G and the Tactile Internet overlap each other. In fact, the Tactile Internet is also known as Tactile IoT (referring it as the evolution of IoT), whereas 5G is the next-generation mobile network that enables both Tactile and non-Tactile IoT. The difference between them resides on the type of service that each targets. According to [3], IoT relies on machine-to-machine (M2M) communications involving low-power sensors and actuators, while Tactile Internet centers around human-to-machine (H2M) or even M2M communications with real-time demands.

As well as IoT existed (technically limited) long before 5G, the Tactile Internet may not release its full potential until the deployment of 6G and beyond. However, this thesis will take a rather 5G-approach with the aim of designig a functional telepresence solution. All these advancements will be corroborated, demonstrated and validated by experimentation within the Horizon 2020 European project iNGENIOUS. The reliability and precision of the remote operation of vehicles or infrastructures will be defined by the required KPIs provided by each device and network component involved in the different services.

1.1 Scope

The Fourth Industrial Revolution, so-called Industry 4.0, was defined in 2011 by the German manufacturing industry as the growing trend towards automation and digitalization in industrial environments [4]. The First Industrial Revolution introduced mechanization using water and steam power. The Second Industrial Revolution created mass production thanks to electricity and railroads. The Third Industrial Revolution used electronics to automate production. Now, even more disrupting technologies are emerging: Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), quantum computing, biotechnology, etc. The Industry 4.0 can be seen as the ultimate merge between information and communication technologies and industrial processes, which promises to be revolutionary in terms of sustainability, effectiveness, and economic impact. Four design principles can be identified in the literature [4]:

- Interconnection: massive connection of machines, devices, sensors, and people as a joint collaboration for reaching common goals.
- Information transparency: every participant of the network has access to real-time data from the rest of the participants, thus context-aware decisions can be made.
- Decentralized decisions: tasks are automated and self-monitored, and therefore decisions are taken at a higher level only in case of conflict.
- Technical assistance: human operators are assisted when they must perform difficult or unsafe tasks.

To fulfill the principles listed, advanced M2M and H2M interfaces must be implemented, supported inter alia by cyber-physical systems, blockchain, edge and cloud computing, and cybersecurity. Current systems often rely on wired connections between sensors and actuators, but next-generation use cases demand higher flexibility. Wireless networks, in particular 5G systems are the best approach to achieve the interconnection [5]. Thus, 5G IoT is the best candidate to satisfy M2M communications in non-critical industrial applications, while H2M communications have strict requirements that the 5G Tactile Internet is more suited to address. In fact, according to [3], the enhancement of H2M interaction is the main aim of Tactile Internet: ”By building on the areas where machines are strong and humans are weak, the machines are more likely to complement humans rather than substitute for them. The value of human inputs will grow, not shrink, as the power of machines increases”.

The H2M cooperation becomes undoubtedly stronger the more immersive the user experience is. When Gerhard P. Fettweis coined the term ”Tactile Internet” in 2014, he was thinking on a platform for controlling real and virtual objects through human tactile and visual feedback. This would not only be applied to industry, but also to many situations of the daily life, bringing more sophistication to societies [6]. Nevertheless, the idea of combining haptics and Mixed Reality (MR) was not introduced along with the Tactile Internet. Studies from IEEE in 2007 [7] already envisioned that the potential of haptic devices and applications is not only to simulate real touch, but also to engage the user via multimedia applications that utilize gesture recognition, tactile sensing, and force feedback. According to [8] “Haptics is a key area of technological development. Applied to MR (i.e. virtual and augmented reality), haptics allows users to ‘touch’ things in the virtual world and get instant feedback. It helps users ‘feel’ interactions, enhancing the virtual experience. Haptics has the potential to enhance user interfaces with intuitive gestural controls in workstations, which could lead to increased productivity or add an extra dimension to data visualization". Furthermore, this report states: "The gigabit per second speeds promised by 5G networks will almost certainly benefit MR through reduced latency, delivering a smoother, richer and more engrossing user experience. 5G will also mean headsets are no longer as reliant on built-in processing or storage, likely bringing down cost and enabling more user-friendly designs. That processing and storage will be pushed to the cloud instead". These statements envisage a perfect match between next generation communications and immersive equipment.

1.2 Motivation

Supply chains have become complex ecosystems where every process is critical and addresses a certain risk to individuals and/or resources. The way that products are made and delivered needs an evolution towards the Industry 4.0 principles, making the flow of goods and services as smart and monitored as possible. The decentralized approach of Industry 4.0 benefits the management of processes and H2M interaction within a supply chain, thus helping industries to improve efficiency and productivity.

In this context, the iNGENIOUS project aims at the digitalization and automation of the supply chain management, defining the Next-Generation IoT solution and creating new business models. It places a particular emphasis on 5G and the development of Edge and Cloud computing extensions for IoT, in addition to providing smart networking and data management solutions with AI/ML [9]. iNGENIOUS offers IoT and Tactile Internet solutions, using both 5G New Radio (NR) and 5G Core (5GC) for enabling the full potential of 5G capabilities, with special focus on six novel supply chain use cases (see Figure 1.1):

- Automated robots with heterogeneous networks (Factory use case): focuses on the connection of IoT sensors and multi-task robots via Smart IoT gateways, guaranteeing at the same time the interoperability with wired Time Sensitive Networking (TSN) systems.
- Transportation platforms health monitoring (Transport use case): targets rail health for cost-savings in logistics using low power sensors continuously connected to the edge.
- Situational understanding and predictive models in smart logistics scenarios (Port entrance use case): monitors the time that trucks spend loading/unloading the cargo using massive sensors and analytics, with the objective of optimising this process.
- Improved driver's safety with MR and haptic solutions (AGVs use case): enables teleoperation of AGVs through Tactile Internet and immersive enablers to guarantee the operator's safety in hazardous situations.
- Inter-modal asset tracking via IoT and satellite (Ship use case): tracks shipping containers when sailing through oceans via satellite backhaul from the IoT RAN to the control centre.
- Supply chain ecosystem integration (DLT use case): provides interoperability between the M2M platforms that form the supply chain, guaranteeing data privacy and security thanks to the use of Distributed Ledger Technologies (DLT).

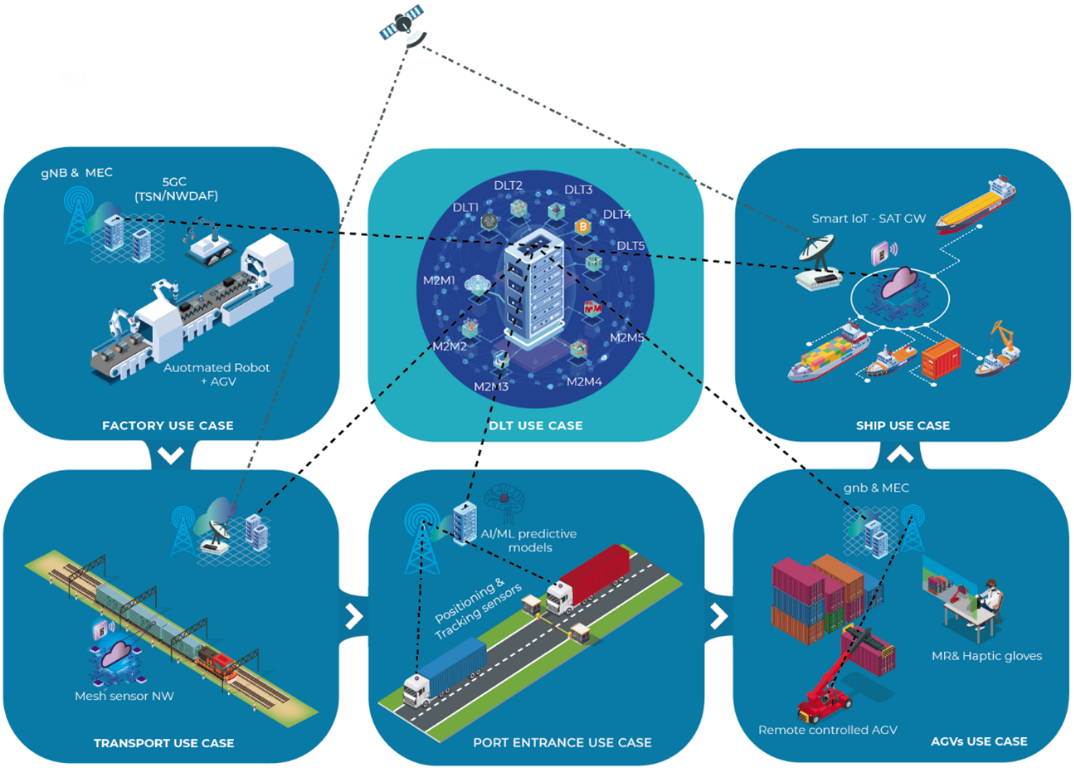

Figure 1.1: iNGENIOUS next generation supply chain use cases [10]

This thesis is based on the "Improved driver's safety" use case, which aims to explore the remote transportation of goods with AGVs thanks to Tactile Internet, Multi-access Edge Computing (MEC), and immersive enablers. The final scenario is a terminal of the Valencia port that will be reserved for this use case. The idea is that an operator located in an indoor, safe environment can take control of an AGV when necessary (i.e. when automated routes cannot be followed) using MR and haptic solutions, which will be integrated in the remote indoor cockpit. The operator's telepresence is provided by low-latency video cameras and proximity sensors installed in the AGV, wirelessly connected to the cockpit via 5G and a compatible MEC infrastructure.

The use of haptic gloves and haptic sensors will improve the perception, quality and safety of the remote operators managing AGVs, which is required to guarantee the operation even in very exceptional situations where the autonomous robots cannot operate [9]. Haptic gloves will produce haptic feedback allowing operators to create a tactile experience in the shape of psychophysical stimulations including precise texture discrimination, pressure, or the sensation of holding objects. Haptic reactions and vibrations will be used as alarms for the remote driving experience in case of any detected risks. In a future prototype of the haptic gloves, biometric sensors will be implemented to monitor blood pulse, respiration frequency and body posture. This information will be processed to estimate fatigue or stress levels, detecting risk for the operator and further avoiding accidents [10].

1.3 Objectives

The main aim of this thesis is to develop a Proof of Concept (PoC) to test the viability of the final iNGENIOUS use case. This PoC consists of a Unity3D application that integrates the haptic gloves and the MR headset into the immersive cockpit and communicates with the AGV via 5G. Secondary objectives corresponding with the intermediary steps include:

- Study the (SoTA) technologies regarding 5G Tactile Internet and immersive devices.
- Achieve the control of the AGV using gestures with the glove.
- Implement the reception of visual and haptic feedback from the AGV.
- Create an user friendly, immersive MR interface in Unity.
- Perform 4G and 5G measurements to justify the improvement in terms of connectivity.

1.4 Methodology

During my internship in the Institute of Telecommunications and Multimedia Applications (iTEAM), I have been part of the Mobile Communications Group (MCG) leaded by Dr David Gómez Barquero. This group is composed by researchers in the area of Telecommunications, who have shared with me their experience and knowledge.

I have worked in the ”Improved driver’s safety” use case of iNGENIOUS, developing a PoC regarding the remote control of AGVs using haptic gloves and MR glasses. For this purpose, I have assisted to regular meetings with many of the partners of this use case. In particular, I have worked closely to NeuroDigital (the haptic gloves manufacturers) and Fivecomm (start-up that provides the AGV and the 5G routers). I have also taken part in a visit to the Valencia port to check the facilities where the AGV is expected to work, although the testing of this experimental cockpit takes place in the Fivecomm laboratory. Finally, I have collaborated in a public demonstration along with Fivecomm in the V5G day event held in Valencia in June 7th.

The integration was performed in an additive way, starting from an empty script in Unity. The project timeline can be appreciated in Figure 1.2. The first step was to familiarize with the

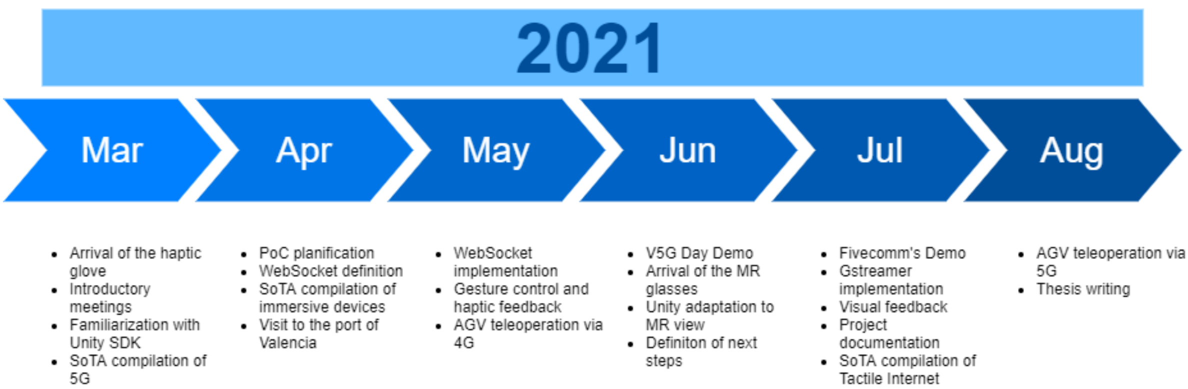

Figure 1.2: Project timeline

native SDK provided along with the glove, since specific functions must be used for registering gestures and setting vibrations. Once the AGV was ready, these functions were adapted to send instructions and receive real-time feedback. In a second phase, several plugins were needed to achieve the desired functionalities, including adaptation to the MR headset and live video rendering from the AGV camera. Most of the tasks, from setting up the glove to correctly receiving the video streaming were tedious processes and took several weeks to be completed. Several difficulties were faced, including the late arrival of the MR glasses or the unavailability of the 5G Orange network until August.

Second chapter of this thesis corresponds to a detailed description of the SoTA technologies regarding 5G and Tactile Internet. Third chapter shows the architecture and components of the solution, with special emphasis on the immersive devices. Fourth chapter focuses on the application itself, complementing the results obtained in the demos with several supporting network measurements. Finally, the fifth chapter summarise the present and the future of this solution.

Chapter 2

5G-enabled Tactile Internet

2.1 Internet of Senses

In the next decade, people will be able to virtually feel the world through the five senses. Technology is set to respond to our thoughts, and even create digital smell, taste, and touch experiences. Ericsson calls this future trend the ”Internet of Senses”, a full sensory immersion made possible by the low latency and high bandwidth capabilities of 5G and beyond [11]. This report explains that virtual experiences of any kind, including virtual odours and taste, are possible through brain stimulation. Several experiments have already been conducted on this area, such as Vocktail [12], a bottle capable to give a personalized taste to the water using electrical stimulation of the tongue.

The Internet of Senses may sound like science fiction, since today's screen-based world is focused on audiovisual interaction. However, the sense of touch is currently gaining relevance and plays an important role in the 5G era. Audiovisual experiences are expected to undergo a radical transformation too, as they shift towards holoportation and MR. One example is Microsoft Mesh, a cloud-based platform that can host massive live events where everyone equipped with a HoloLens MR headset shares the same holographic experience [13].

The Tactile Internet will enable all these Internet of Senses experiences, mainly due to its real-time response. The term ”real-time” does not describe instant communication, but communication with imperceptible delay for the user. An interaction with a technical system is felt as intuitive and natural only if the E2E latency of the system is below the human reaction time, which depends on the participating human senses (see figure 2.1). It also depends on the expectancy of the subject to the event. For instance, an unprepared muscular response to an unexpected stimulus can take up to 1 second, while if prepared the muscular response goes down to 100 ms [14].

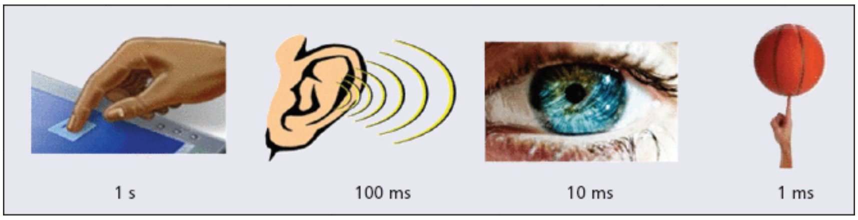

Figure 2.1: Order of magnitude of real-time constants [14]

The shorter real-time latency constants come from the combination of visual and tactile interaction. If the user is expecting speed, such as when manually controlling a highly dynamic visual scene, E2E latency for noticeable synchronization can be as strict as 1 millisecond. When this experience is also immersive (i.e. when using MR headsets) real-time feedback of a few milliseconds is crucial to avoid discomfort or even motion sickness [15]. Communication systems are designed to match these real-time constants, but the actual technology makes it unfeasible to obtain only 1 ms of E2E latency in most of the cases. In MR for instance, the time to capture, encode, transmit, decode and render the video vastly exceeds this number, so a more reasonable target would be 20 ms [16]. 5G Release 16 promises 1 ms of user plane latency, but E2E latency depends on the application by definition. Once these systems are optimized and new technologies emerge, novel use cases and sensory experiences will appear.

2.2 Application fields and KPIs

The 5G system is expected to provide support for a variety of tactile and non-tactile services, each of them characterized by different Key Performance Indicators (KPIs) combining reliability, latency, throughput, positioning, and availability [17]. The aim of 5G wireless access and core network architectures is to enable use cases that are currently not addressed by cellular network. Once cellular communications have connected the vast majority of people around the globe, the next logical step is to connect the machines and devices as well [6]. Potential 5G applications range from education, entertainment, and gaming, to industry, healthcare, and energy. Many of these potential applications need instantaneous reaction and therefore they are classified into the Tactile Internet family. Details of some discussed application fields and use case examples can be found below, though the Tactile Internet is sure to find unknown application domains in the future [15].

- Robotics and telepresence:

  In industry and manufacturing, autonomous robots enable customization and optimization of the production lines. The majority of existing industrial robotic cells are formed by isolated robots controlled by a local Programmable Logic Controller (PLC). Moving control to a cloud environment enhances coordination and saves costs, facilitating a higher density production [18]. In fields where autonomous driving is not an option, remote controlled robots are a promising alternative. They are necessary in dangerous scenarios such as nuclear waste management, offshore construction tasks, satellite maintenance, etc. Current advances in communication infrastructures allow a complete remote immersion achieved by the combination of audio, video and haptic information in real-time [2].

  When robots are used to transport goods, their control must happen fast enough for the robot and its object not to start mechanically resonating [6]. Taking this into account, scenarios in manufacturing are led to a extremely low target of 100 µs of communication latency and an E2E latency of 1 ms, the same target discussed for the Tactile Internet. However, the requirements actually depend on the control functions that are moved into a cloud execution. The more control functions moved into the cloud, the more flexibility for the solution, but also the more stringent requirements. An illustration of this can be seen in Figure 2.2.

  The 3GPP and the ITU provide various examples of latency KPIs to support robotics use cases in logistics [17]. For remote vehicle control without tactile interaction, an E2E latency

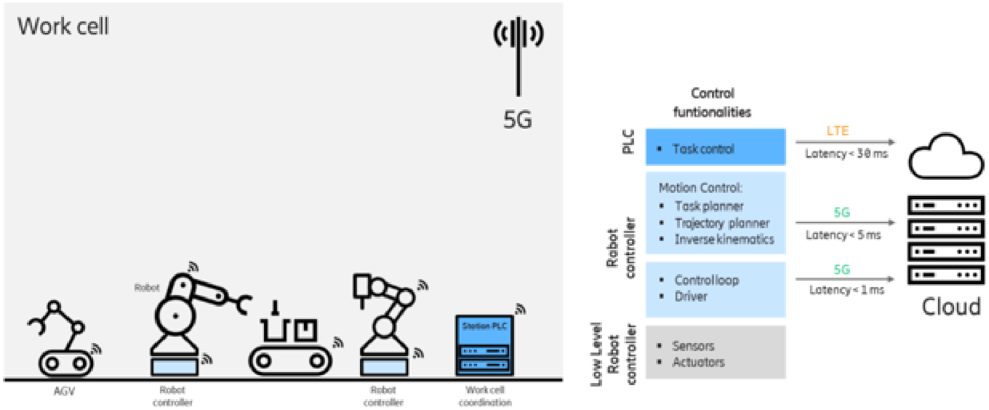

Figure 2.2: Cloud robotics and latency requirements [18]

of 10-30 ms would be enough, combined with 99.9999% of reliability and 99.9999% of availability. When tactile feedback is also needed, the latency requirement could go down to 1 ms E2E for the haptic channel.

- eXtended Reality:

  Broadcasting of 360º video is the next surrounding experience in live events, providing free election to the spectator to watch it in different angles and directions. The spectator will use MR headsets that reproduce the multiple 360º cameras installed at the event, acquiring for instance first person view of the pilots in a Formula E race [18]. In the industrial level, "Shared haptic virtual environments" will be enabled, allowing several users to interact with the same objects in a precise and sensitive way. Adding information into the user's field of view can also be useful for city guides, driver-assistance systems, healthcare, or education [15].

  Interaction is only possible if the round-trip communication latency is in the order of milliseconds, and even a wired connection may not be sufficient for distant users (every 300 km of separation between users, the speed of light adds 1 ms of latency). Another barrier is the computer power demanded in the goggles, which has impact in their size and mobility. Again, the proposed solution is to offload this power to the Edge Cloud. The cloud will in addition enable collaborative MR gaming, with applications in entertainment, education, training, simulation and health. As usual, the E2E latency is a key factor to perceive realism in the game mechanics. Similarly to other MR applications, 20 ms of E2E delay is the minimum requisite, although 1 ms is desirable for an optimal game experience [17]. Other important KPIs for eXtended Reality are 99.999% of reliability and considerably high throughputs up to 1 Gbps.

- Healthcare:

  Using advanced tele-medicine tools, remote physical examination and operation could be possible anywhere and anytime, improving success rates and cost-efficiency. For instance, envisioned tele-rehabilitation systems see patients wearing an exoskeleton commanded by the therapist to correctly do the necessary motions. Provided that cheap solutions arrive to the market, the use of medical exoskeletons could be extended to any force-demanding task, such as manufacturing and construction [6].

Accurate tele-medical treatment is a typical example of stringent real-time interaction with needed telepresence and haptic feedback. Some existing approaches work with packet loss and 100 ms of E2E latency, but the fidelity and accuracy is insufficient [15]. Less than 10 ms of E2E latency are needed to achieve the high fidelity required, together with ultra-high reliability and availability [1].

Another major example is training medical students. High-risk tasks could be experienced from a safe distance, preparing students to the real circumstances. For instance, students could haptically experience a surgery, allowing the teacher to perform instant corrective actions, without risking human lives [15].

- Automotive and traffic:

  Road accidents and fatalities could be totally avoided by vehicle communication and coordination. The capability of detecting safety-critical situations increases the more aware the driver is about the vehicle surroundings. Through V2X communications, a vehicle turns from an autonomous system into a component of a more efficient cooperative one, avoiding traffic congestion and collisions [1]. The time needed for collision avoidance is below 10 ms [17], but in case a bidirectional data exchange is needed, only 1 ms E2E would be recommended [15]. Apart from the vehicles, pedestrians could engage a personal bubble with their smartphone, ensuring that they are not hit by any car [6].

- Smart grid:

  The growing usage of renewable energies accentuates the need for a proper injection of the generated energy into the power grid, leading to distributed energy suppliers. The Tactile Internet enables dynamic activation and deactivation of generation and consumption, considering even the AC phase to minimize the generation of unusable reactive power [15]. According to [6], 1 ms of link latency between suppliers can ensure an 18º of phase coherence in 50 Hz power networks. Using smart grids intelligent monitors can optimize consumers' power supply and so reduce associated costs.

2.3 5G New Radio

The first generation (1G) of cellular mobile communications was born in the 1980s as an analog voice calling service, in a manner that several different standards originated all around the globe. The most notable examples of 1G technologies were the American AMPS, the Japanese NTT and the Nordic NMT [19]. A decade later, the commercial success of wireless telecommunications encouraged the European countries to abandon their national systems and define a common 2G standard, which resulted in the foundation of the ETSI and the creation of the GSM standard. The GSM was revolutionary due to the inclusion of digital communications and data services, and the energy efficiency of TDMA (Time-Division Multiple Access) made it suitable for still being used today in many low-power systems.

In order to avoid investing in a totally new system, in 2001 the ETSI proposed to create an international 3G standard based on the GSM evolution, and so they founded the 3GPP consortium that successfully defined the UMTS system. It relied on WCDMA (Wideband Code-Division Multiple Access) to support high densities of users, but the exponential growth of traffic induced the 3GPP to embrace OFDMA (Orthogonal Frequency-Division Multiple Access) in their 4G standard.

LTE was first introduced in 2008 by the 3GPP Release 8 as an evolution of GSM and UMTS; with the novelty of being an IP-based network, resulting in a simpler architecture and therefore lower costs. LTE Advanced, corresponding from Releases 10 to 12 provided up to 1 Gbps in downlink when carrier aggregation, 256QAM modulations and 4x4 MIMO are used.

It can be observed that every standard is built upon the basis of the previous one, mainly due to economical reasons, and this trend is accentuated in the transition between 4G and 5G. For instance, UMTS and LTE used different core networks, while 5G NR is initially deployed as a non-standalone (NSA) solution dependant of the LTE core network. The NR enhancements over LTE can be summarized in Table 2.1. Although being evolutionary in terms of technology, 5G is revolutionary in terms of connectivity. For the first time in a mobile system, the network adapts to the application instead of the opposite. Thus, the real potential of 5G resides in the new use cases that it enables. Through the support for big game changers such as massive IoT, critical services and cloud computation, 5G NR goes far beyond LTE and targets any kind of device and application.

	LTE	NR
Frequency of Operation	Up to 6 GHz	Up to 52 GHz
Carrier Bandwidth	Up to 20 MHz	Up to 1 GHz
Carrier Aggregation	Up to 32	Up to 16
Analog Beamforming	Not Supported	Supported
Digital Beamforming	Up to 8 Layers	Up to 12 Layers
Channel Coding	Turbo/Convolutional Coding	LDPC/Polar Coding
Subcarrier Spacing	15 kHz	15 kHz to 240kHz
Self-contained Subframe	Not Supported	Supported
Spectrum Occupancy	90% of Channel BW	Up to 98% of Channel BW

Table 2.1: Differences between LTE and NR [20]

2.3.1 5G Services

As can be seen in Figure 2.3, 5G encompasses three main use case families with distinct connectivity requirements: enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC) and Ultra-Reliable Low latency Communications (URLLC). On the one hand, eMBB satisfies human-centric use cases where multimedia delivery demands extremely high data rates. On the other hand, both mMTC and URLLC target machine-centric use cases. Nevertheless, whereas mMTC targets narrow-bandwidth devices, URLLC is designed for real-time human-machine collaboration that demands much more stringent requirements. In reality, many use cases can have hybrid requirements stemming one, two, or three categories. Those services of Tactile Internet that require high throughput as well as low latency are only feasible using both eMBB and URLLC, but in that case the reliability would be reduced since it is limited by the available bandwidth [21].

Although the first 5G NR specification was described in Release 15 (2018), the RAT beyond LTE had been studied in previous Releases since 2015. Despite that ongoing releases further describe the three use case families, the 3GPP had previously standardized many of the mMTC requirements given their connection with the cellular IoT standards (LTE-M and NB-IoT [22]),

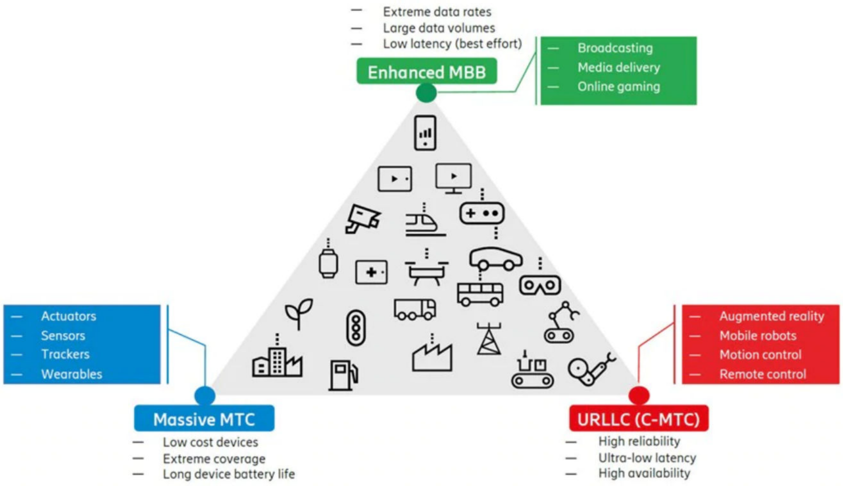

Figure 2.3: 5G use case families [22]

although a full 5G mMTC specification is not expected until Release 18. NB-IoT and LTE-M standards have indeed forward compatibility with 5G mMTC and are planned to be allocated into a 5G NR frequency band [23].

In eMBB, the main goal is to support the always increasing traffic demands in a sustainable way. The requirement on data rate is set as 20 Gbps for DL and 10 Gbps for UL. A bandwidth of 800 MHz [22], available aggregating two channels in the mmW band (28 GHz), would widely fulfil this rate. Regarding sustainability, spectral efficiency must surpass 30 bps/Hz for DL and 15 bps/Hz for UL, achievable using 256QAM modulations and up to 8x8 MIMO configurations. Although user plane latency is not as relevant as in URLLC, the requirement specifies a target of 4 ms, and therefore some techniques used by URLLC also apply to this category.

URLLC aims to support mission-critical applications and hence, is the closest approach to the 5G-enabled Tactile Internet. Since the time it takes for human perception or reaction is in order of tens of milliseconds, packet transmission time for mission-critical applications needs to be in order of hundreds of microseconds. The future of many of these applications depends on wireless connectivity with guaranteed E2E latencies of 1 ms and Block Error Rates (BLERs) as low as 10^{-9}. To achieve the 1-millisecond goal, it is necessary to optimize the total latency, which includes user plane latency (network latency) contributions and application processing times. Among the three use case families described, the design of URLLC is perhaps the most challenging. In order to improve reliability, more resources for signaling, re-transmission, redundancy, and parity are needed, resulting in an increase of the latency. Besides, similarly to eMBB, URLLC is expected to require large amounts of spectrum available only in mid-band (sub-6 GHz) and high-band (mmW) spectrum, depending on the application. Typical low-band spectrum (700 MHz) provides better coverage, but can not satisfy the high bitrates and low latencies needed. Thus, the efficient use of the 5G spectrum consists in the dynamic allocation of the mMTC, eMBB and URLLC services.

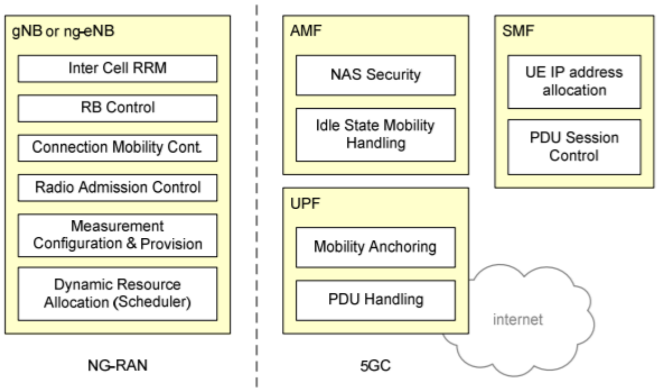

Figure 2.4: Functions corresponding to NG-RAN and 5GC [24]

2.3.2 5G System overview

The 5G-driven architecture, composed by the Radio Access Network (NG-RAN), the Core Network (5GC) and the User Equipments (UEs), is expected to meet the key requirements imposed by the Tactile Internet applications. The NG-RAN consists of a set of gNBs connected to the 5GC (in the case of a SA deployment) through the NG interfaces. Besides, the gNBs are interconnected through the Xn interfaces. The main features of the NG-RAN are Radio Resource Management (RRM), efficient and reliable packet delivery through the Physical layer (PHY), and optimal resolution of conflicts using Medium Access Control (MAC) techniques. On the other hand, the 5GC hosts functions for UE connectivity, such as Access and mobility Management Functions (AMF), User Plane Functions (UPF) and Session Management Functions (SMF). The 3GPP Release 15 provides a more detailed functional split, as can be seen in Figure 2.4.

One key element of the NG-RAN is the separation of the gNB Baseband Unit into a Central Unit (CU) and one or several Distributed Units (DUs), splitting protocol functionality of the gNBs (see Figure 2.5). The CU satisfies high layer protocol functions of SDAP and PDCP, whereas the DU covers lower layer protocols such as RLC, MAC and the high part of the PHY. Finally, the Radio Units (RUs), directly connected to the antennas, perform the RF functions and the low part of the PHY. This architecture provides flexibility by allowing the geographical separation of the components and the placement of these close to the edge [25]. Specifically, Multi-Access Edge Computing (MEC) is used to permit the software execution at the optimal place in the network. MEC is an evolution of cloud computing that moves the applications from a centralized cloud to the network edge near the users. This allows a faster response of the applications and the ability to adjust data during runtime [26].

Flexibility is indeed a key feature of 5G networks, since multiple types of 5G services need to coexist in very heterogeneous environments. Resources are dynamically reallocated depending on the Quality of Service (QoS) required for the application, which is done by network slicing. It consists in the multiplexing of logical E2E networks into the same physical infrastructure. Each slice is a piece of software that can be dynamically created and modified based on the user requirements. For the purpose, 5G networks are highly programmable, building on the Network Function Virtualization (NFV) and Software-Defined Networking (SDN) paradigms. NFV provides the separation of the network functionality from the hardware and therefore increases the scalability of the network. SDN allows for easier configuration of the network functions via open interfaces and

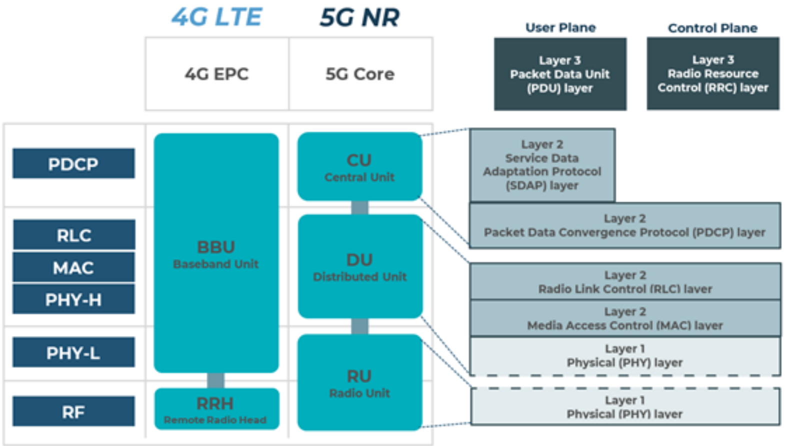

Figure 2.5: RAN architecture and layers [25]

abstractions. Combined, they provide means to customize network configurations in addition to a high degree of automation [27].

2.3.3 5G System capabilities for URLLC

3GPP divided the 5G NR standardization process into two phases: NR Phase 1 corresponding to Release 15 and NR Phase 2 corresponding to Release 16. According to the 3GPP workplan [28], URLLC specification ranges from Release 15 to Release 17. In Release 15 (2018), URLLC is only supported in the LTE core, whereas 5G URLLC is fully described in Release 16 (2020). It is expected that Release 17 (2022) introduces several key improvements for URLLC, such as combination with Industrial IoT. Most of the enhancements corresponding to Release 16 are described below. URLLC is defined as a toolbox, and therefore each application can choose what RAN and Core tools to use.

2.3.3.1 PHY/MAC layer design

Although the 5G NR requirement of 1-millisecond latency is established for the user plane (one-way packet transmission between PDCP layers), in Section 2.2 was explained that this requirement may become E2E (application level delay) for some use cases. Satisfying 1 ms of E2E latency is the major challenge of URLLC, since every sub-step of the data delivery must lie below this upper limit. From signaling exchange and processing to packet transmission, everything must happen in the order of hundreds of microseconds. An example of this is represented in Figure 2.6, where an one-way PHY layer transmission of 100 µs is required. Considering encoding and decoding at the transmitter and the receiver, each packet duration cannot exceed 33 µs [6]. However, standard OFDM sub-carrier spacing of 15 kHz provides a symbol duration of 66.67 µs and every slot is composed by 14 OFDM symbols. As showed in Table 2.2, mini-slot structures and numerologies with increased sub-carrier spacing can achieve transmission latencies as low as 18 µs. Higher frequency bands such as mmW fulfill the 120 kHz sub-carrier spacing and provide the high data rates demanded by some URLLC applications, although their range is limited by the delay spread introduced by the short cyclic prefix (CP) involved [27].

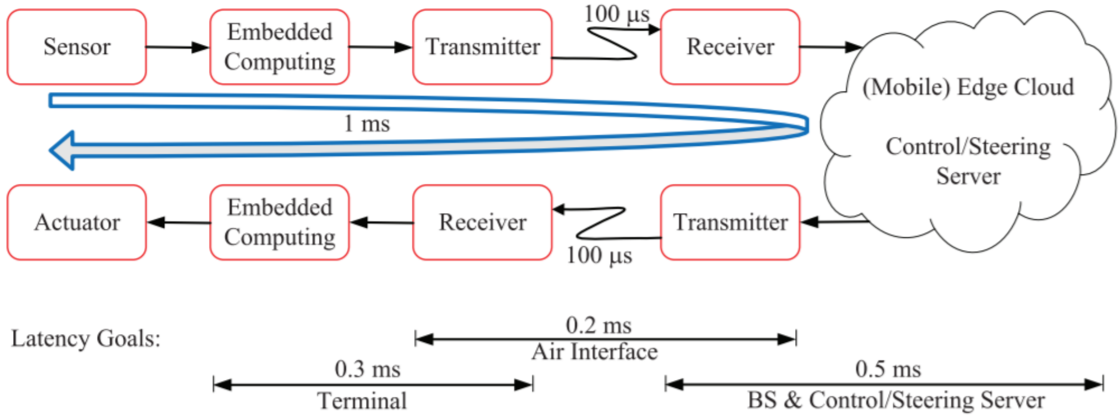

Figure 2.6: E2E example for 1 ms of latency [26]

	Δf	Symbol	CP	Slot (14 symb)	Mini-slot 7 symb	Mini-slot 4 symb	Mini-slot 2 symb
NR and LTE	15 kHz	66.67 µs	4.76 µs	1000 µs	500 µs	286 µs	143 µs
NR	30 kHz	33.33 µs	2.38 µs	500 µs	250 µs	143 µs	71 µs
NR	60 kHz	16.67 µs	1.19 µs	250 µs	125 µs	71 µs	36 µs
NR	120 kHz	8.33 µs	0.59 µs	125 µs	63 µs	36 µs	18 µs

Table 2.2: Transmission latency for different OFDM numerologies [27]

In scheduling based systems, an extra benefit of reducing packet transmission duration is the increased frequency of transmission opportunities, which reduces the waiting time for delivering the information. The DL control channel carries the scheduling information for both DL and UL, and therefore the UE needs to monitor the DL control channel as frequently as one OFDM symbol. In UL, when a URLLC packet is generated, the UE sends a scheduling request to the gNB in demand of resources, involving an additional latency. Nevertheless, the gNB can reserve periodic URLLC resources from eMBB packets to avoid this scheduling request, which is called as grant-free based UL. According to [27], UL latencies become similar to DL latencies using grant-free UL. The drawback of this technique is that reserved resources will be wasted when there is no URLLC transmission in the scheduled period, in addition to a degraded performance of eMBB services [29].

The coexistence of URLLC with other type of services is an important issue in the PHY/MAC design. The flexible packet structure mitigates this problem, but several other techniques are considered by 3GPP NR:

- Preemption indicator transmission:

  When resources are not reserved to URLLC and they are already in use by other traffic such as eMBB, preemption allows the gNB to temporary pause the transmission or reception of the eMBB traffic and quickly schedule the URLLC traffic. To inform the eMBB users about the reason for packet errors, the gNB broadcasts a preemption indicator.

- Code-block-group (CBG)-based retransmission:

  Fast retransmissions are supported using Hybrid Automatic Repeat Request (HARQ) feed-

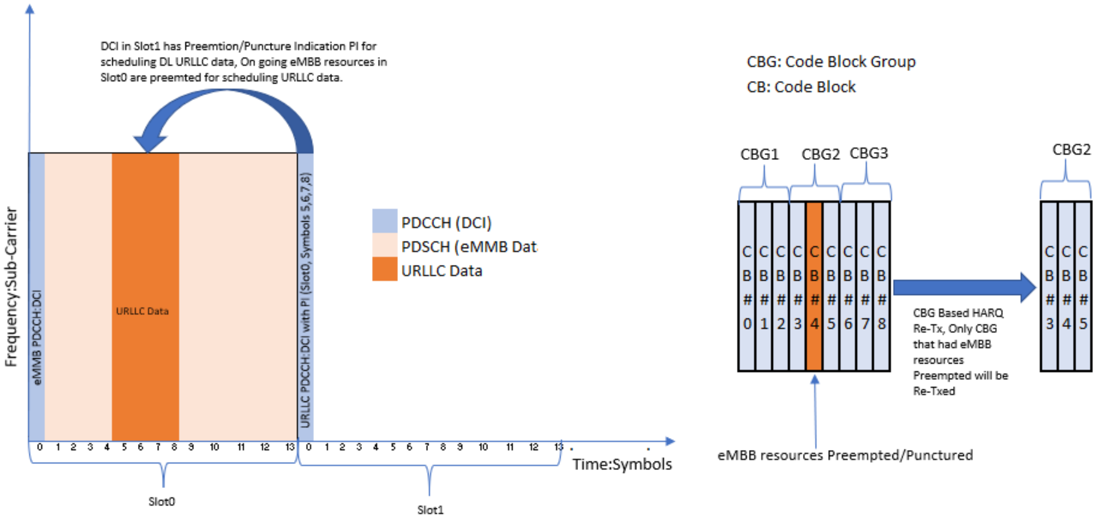

Figure 2.7: Preemption and CBG-based HARQ [32]

back that guarantees both low latency and high reliability [30]. After a preemption, part of the affected eMBB block is retransmitted. Using CBG-based HARQ (see Figure 2.7), only the code block groups in error are retransmitted, so that the receiver can perform soft symbol combining between the transmitted and the retransmitted data. If the HARQ retransmissions occur frequently for any reason, the reliability of the retransmitted service will be reduced. Hence, reliability of URLLC services must be provided beyond the HARQ retransmissions.

- Robustness improvement:

  Robustness provided by polar codes and LPDC codes is key to guarantee a target BLER of 10^{-5} [27]. Low BLERs are achieved by selecting lower spectral efficiency entries in the Modulation Coding Scheme (MCS) table (e.g. QPSK modulation and low code rates). For a fixed BLER, the required SNR is higher the higher the MCS (a comparison of required SNR for URLLC and eMBB transmissions can be found in [31]).

Diversity in frequency and space is also key to provide high reliability levels. In the frequency domain, diversity is achieved by distributed frequency hopping and carrier aggregation (CA). Diversity in the spatial domain is provided by multi-antenna configurations, i.e. MIMO, and Dual-connectivity (DC). The main advantage of DC with packet duplication is that utilizes less HARQ retransmissions and therefore improves both latency and reliability [27]. It also enables interruption-free handovers by maintaining at least one gNB connected to the UE during the mobility. CA and DC are often combined to connect one UE to two different gNBs through multiple carriers. The difference between them can be observed in Figure 2.8.

2.3.3.2 Upper layer design and architecture

3GPP provides several system and core network enhancements to support URLLC requirements in upper layers, including the following.

- QoS monitoring:

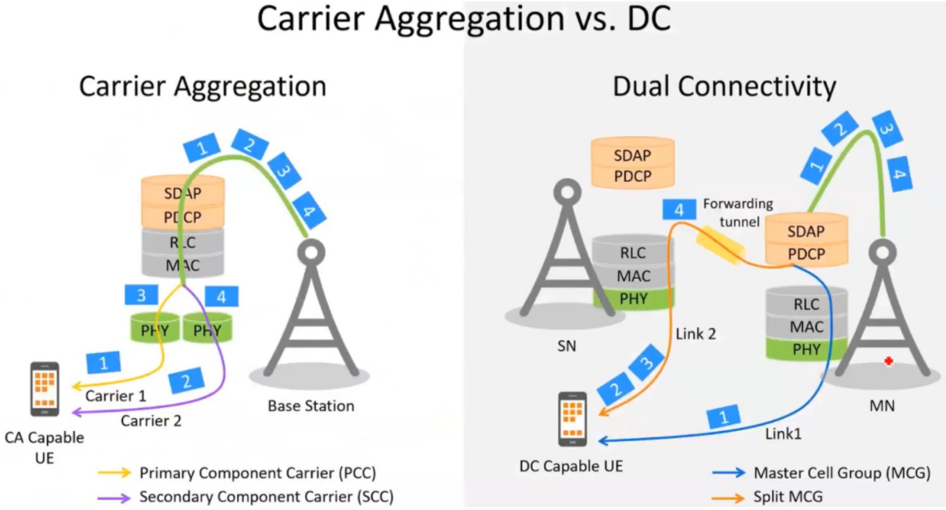

Figure 2.8: CA vs DC (source: The 3G4G Blog)

The QoS differentiation within a Protocol Data Unit (PDU) session is defined by the QoS Flow, which is identified by a QoS Flow ID (QFI). Traffic associated with the same QFI receives the same QoS forwarding treatment. A new aspect in 5G is the RAN flexibility to bind QoS flows onto Digital Radio Broadcastings (DRBs). The UE determines the UL data to be QoS-bound based on explicit QoS signaling.

- MEC and servers:

  MEC enables the operator and third-party services to be hosted close to the UE access point, resulting in low latency and efficient utilization of radio and network resources. MEC uses a virtualization platform which may be shared with other applications, allowing a third party to manage trusted third-party applications to improve the user's experience. There are several MEC enablers [30]:

  - Flexible placement of User Plane Function (UPF) to route the user traffic to the local data network.
  - Multiple data paths with redundant transmission in the user plane to ensure reliable delivery of application data.
  - Session and Service Continuity (SSC) provided by DC to enable UE and application mobility.
  - Application function influence on UPF selection and traffic routing.
  - Network capability exposure with 5G core network and application function providing information to each other.

  From a hardware perspective, the best enabler for MEC is the combination of servers into the same box that gNBs. The solution of this is the highly adaptive and energy-efficient computing (HAEC) box, which promises 104 times the performance of today's servers [26].

- Always-on PDU sessions:

  It is used when plane resources are activated during every transition from idle mode to connected mode. An always-on session is requested by the UE and network-controlled. The

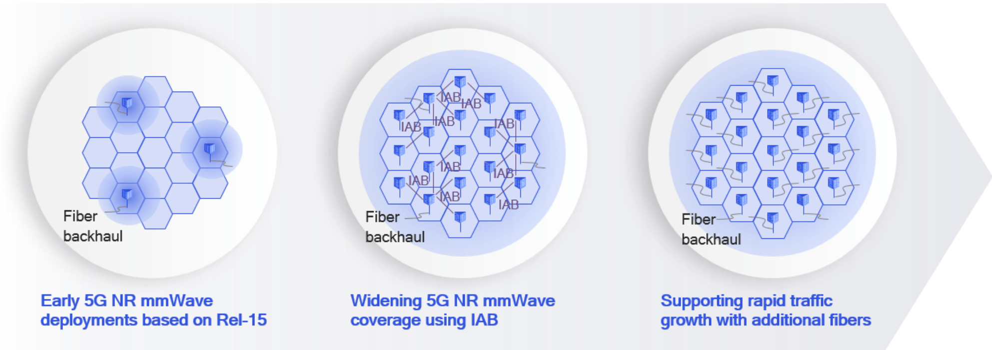

Figure 2.9: IAB for mmW [33]

activation of resources during the transition to connected mode enables the UE to conduct user data transmission with low latency and jitter.

- RRC inactive state:

  NR defines a third UE state for inactive UEs in addition to the idle and connected states. In the RRC Inactive state, Radio Resource Control (RRC) connection is kept while the UE is sleeping to conserve battery. This allows the UE to skip the request for a RRC connection setup and also wake up to transmit and receive data much faster as compared to moving from the idle to the active state.

- Integrated Access and Backhaul (IAB):

  In order to expand 5G mmW network coverage, it is necessary to deploy additional base stations, which usually requires new fiber optics backhaul installations. To make mmW densification more cost effective, Release 16 allows a base station to provide both wireless access for devices and wireless backhaul connectivity, allowing operators to quickly add new base stations dynamically (see Figure 2.9).

- Non-public networks (NPN):

  Release 16 added support for private networks, which can be crucial for industrial IoT use cases. NPNs utilize dedicated resources, providing security and privacy, and ensuring URLLC requirements.

- Time sensitive networking (TSN):

  Industrial IoT use cases are also supported by TSN integration, that can ensure time-deterministic delivery of data packets. It includes precise synchronizing, mapping of TSN configuration into 5G QoS framework, and efficient transport of Ethernet frames [33].

While advances in hardware, protocols and architecture are crucial to reduce E2E delays, the limit is actually set by the speed of light. Movement prediction based on AI/ML allows a wider separation between the tactile ends [26]. In addition, AI/ML is integrated with 5GC to efficiently manage network slices, estimating the available resources and routing them through the best way [25].

2.3.3.3 Security

URLLC devices may be deployed in unattended environments, which makes them susceptible to malicious attacks. To overcome such attacks, devices need to be security hardened. They should support the capability to verify the integrity of the applications, as well as the data provenance and its authenticity. 5G NR offers state-of-the-art (SoTA) security functions such as support for secure protocols (e.g. TLS and IPsec), advanced logging and analytic tools, and policy verification [25].

The 5G systems aims at high reliability and low latency over the radio link even in presence of attacks against availability, especially radio jamming attacks. Non-selective jamming, especially against the Physical Uplink Control Channel (PUCCH), impacts all the UEs connected to a base station. The gNB can identify the attacks and trigger a reactive measure, such as spreading PUCCH to a wider bandwidth, or multiplexing the data and control channels to randomize the jamming. In the 5G system, the AMF holds the capacity to terminate the NAS Security and protect the system from bid-down attacks. Besides, PDCP layer provides ciphering and deciphering functions, and RRC layer provides key management functions. Ciphering and integrity protection are activated based on security policy sent by the SMF.

Chapter 3

Architecture of the solution

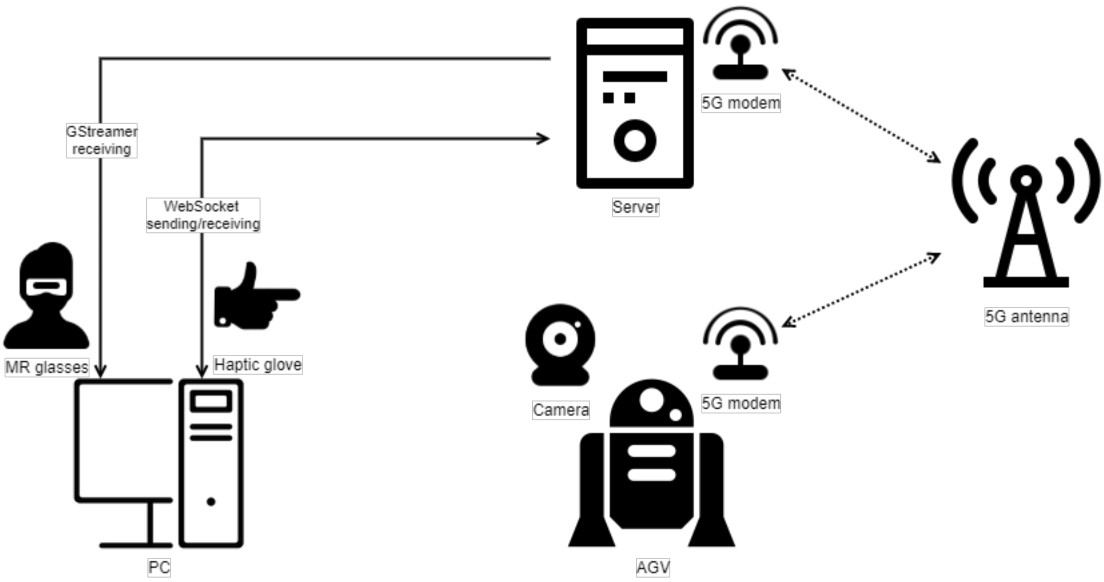

Figure 3.1: Architecture and components

As showed in Figure 3.1, the user is equipped with a pair of Varjo XR-3 glasses and one Sensorial XR haptic glove. Through a wired connection, these are attached to a Windows computer that belongs to the same network that the Linux server. The aim of using two computers is that the second acts as the MEC in the near future, reducing the required computational power both in the user and in the AGV. This server is in charge of the communication with the AGV, using Robot Operating System (ROS) over the 5G network. A state machine programmed in the server defines the behaviour of the robot, whereas the MR glasses and haptic glove are controlled by Unity3D code. While the MR glasses are programmed with the functionality of displaying live video from the AGV, the haptic glove is capable to send commands and receive haptic feedback. In UL, the PC communicates with the server through WebSocket commands, whereas in DL the server communicates with the PC through either GStreamer (for video streaming) or WebSocket (for haptic feedback) commands. More details are provided in the following sections.

3.1 Immersive devices

The immersive cockpit enables telepresence and remote control of the AGV from an indoor environment. The devices used for the purpose consist in a pair of cutting-edge MR glasses provided by the manufacturer Varjo, and a haptic glove capable of recognize gestures and simulate realistic touch provided by the manufacturer NeuroDigital. Before detailing their operation, a study on the SoTA technologies involving both devices and their competitors must be realized.

3.1.1 Haptic gloves

Haptic gloves usually have three main capabilities: i) hand and finger tracking, ii) kinesthetic feedback, and iii) tactile feedback. The first capability is measured according to the degrees of freedom (DoF) allowed, which refers to the basic movements of the human hand that the glove can be modeled with. Natural movements define a total of 23 DoF (see Figure 3.2 and Figure 3.3): four in each finger (3x flexion/extension and 1x abduction/adduction) and three in the wrist (1x flexion/extension, 1x abduction/adduction and 1x pronation/supination) [34]. On the other hand, kinesthetic and tactile information possess different characteristics. As commented in the Introduction, kinesthetic refers to ”awareness of the position and movement of the parts of the body”, and tactile to ”any kind of information perceptible by touch, such as texture or friction”. While kinesthetic communication is closed-loop and extremely sensitive to latency, tactile communication is open-loop and slightly more tolerant to latency [35].

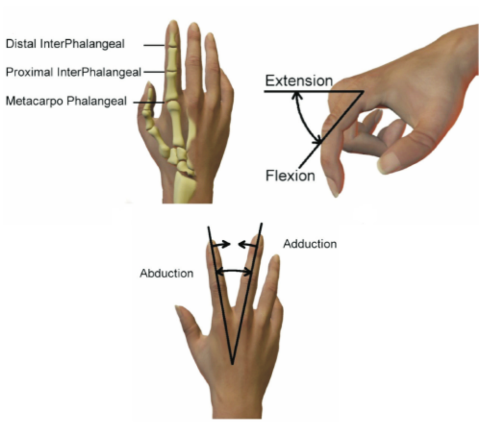

Figure 3.2: Finger’s two DoF [36]

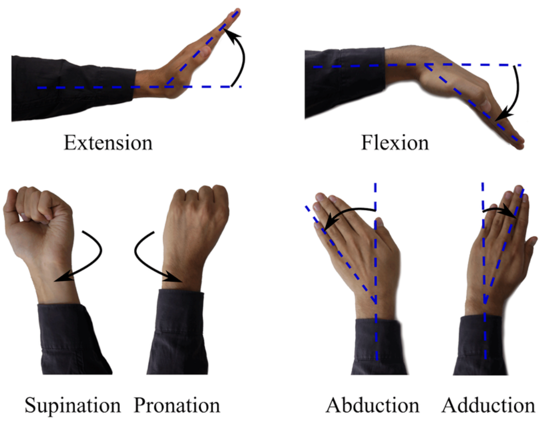

Figure 3.3: Wirst’s three DoF [37]

Current haptic feedback technologies can simulate complex sensations, but are far from replicating the natural sense of touch. According to [38], ”they lack the capacity to stimulate the synergistic behavior that takes place when various mechanoreceptors in the skin and muscles simultaneously become activated in real touch”. In other words, haptic experiences are in their early stages, and hence current haptic gloves are very primitive. Furthermore, the manufacturers have to face several design challenges [39]:

- The sensors and actuators should be small enough to be placed close to the fingers.
- The whole device should be flexible and sustain deformations without damage in order to not restrict the user’s movements.

- A battery of several hours of use should be provided, keeping the device small, light, and comfortable.
- The device should be sufficiently affordable to be commercially successful.

Haptic gloves are often referred as "data gloves", "sensory gloves", "smart gloves", or "VR gloves". These names highlight the capability of capture motion data over the haptic feedback, but the latter is the truly revolutionary feature. Based on [34], [39] and an exhaustive search on the Internet, a compilation of the commercially available haptic gloves is provided in Table 3.1. Those gloves that do not allow tactile feedback have been discarded. Figure 3.4 shows that the gloves that include force-feedback (kinesthetic feedback) are designed as heavy, expensive exoskeletons; while the more handy devices are built in fabric.

Device	Glove Type	KF	TF	HT	Weight	Battery	Price
Dexmo	Exoskeleton	Yes	6 LRA	10 DoF	300 gr	6 h	$12000
Forte Data Glove	Strips	No	6 actuators	13 DoF	103 gr	6-8 h	$3000
HaptX DK2	Exoskeleton	Yes	133 points	23 DoF	500 gr	wired	unknown
Hi5 VR	Fabric	No	1 rumbler	8 DoF	105 gr	3 h	$999
Manus Prime X	Fabric	No	5 LRA	14 DoF	60 gr	6 h	$2499
SenseGlove Nova	Exoskeleton	Yes	2 LRA	8 DoF	315 gr	4 h	$4499
Senso DK3	Fabric	No	6 LRA	9 DoF	300 gr	4 h	$999
Sensorial XR	Fabric	No	10 LRA	9 DoF	140 gr	5-8 h	$4350
VMG 35 Haptic	Fabric	No	5 actuators	23 DoF	unknown	5 h	unknown

Table 3.1: Haptic Gloves available at 2021 (KF = kinesthetic feedback, TF = tactile feedback, HT = hand tracking)

Figure 3.4: Haptic Gloves from the Table 3.1

Sensorial XR is the third product launched by Neurodigital, after Glove One and Avatar VR. It is a well balanced device despite its higher price. It feels comfortable thanks to the flexible fabric and intelligent placing of the 7 Inertial Measurement Units (IMUs) and 10 Linear Resonant

Figure 3.5: Sensorial XR in detail

Actuators (LRAs) that create immersive motion tracking and tactile sensations. It differentiates from its competitors in the conductive zones (palm, thumb, index and middle) that enable the user to trigger actions through gestures. Figure 3.5 represents the distribution of the different components within the glove. The current features of Sensorial XR include [10]:

- Dual core processor at a frequency of up to 64 MHz providing high performance and low power. The processor supports ARM instructions and embeds a radio compliant with Bluetooth 5.2 and with IEEE 802.15.4-2011.
- Ten customized vibrotactile Y-axis LRAs arranged on the fingertips and the palm of the hand. Actuators have a diameter of 10 mm, a resonant frequency of 205 Hz and vibration amplitude of 1.8 G (i.e. the gravitational constant). They can vibrate in 1024 different intensities with a latency of 10 ms. This means that very complex and rich touch sensations can be simulated.
- Seven 9-Axis IMUs for hand and finger tracking. Sample rate is > 200 Hz.
- Four conductive textile zones that detect fingers-hand interaction for gesture-programmable command triggering.
- Built-in 600 mA Li-Po battery. Under normal work conditions it ensures from 5 to 8 hours of use.
- One micro Universal Serial Bus (USB) port for battery charge and data communications.
- Compatible with commercial MR headsets.
- Software development kit (SDK) available for Unity and Unreal platforms.

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In the near future, Sensorial XR will be improved to include trackbands and biometric sensors to monitor Blood volume pulse (BVP), respiration frequency and amplitude of bleeding, and upper body posture [10]. This data will be used to estimate physical and psychological status of the operator, sending a warning in case of fatigue, drowsiness or stress.

3.1.2 Mixed Reality glasses

Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are emerging technologies in the field of human-machine interaction. They are categories of the umbrella term eXtended Reality (XR), which refers to any combination of real and virtual environments generated by computing technologies. These technologies slightly differentiate from each other, as it is explained below:

- VR:

  Provides interaction with virtual objects in a completely synthetic world, reaching a high level of immersion. Such virtual world can either replicate a real environment or be fictional, and physical laws don't need to be followed [40]. VR headsets are well-established in the gaming industry, and are also used to train workers in high-risk environments [41].

- AR:

  Consists in supplementing the real world with virtual objects that can't interact with the environment. It takes places exclusively in the real world, overlaying digital content onto it. Unlike VR and MR, HMDs are not mandatory, since AR can be also experienced in smartphones or tablets (a famous example is Pokemon Go) [42].

- MR:

  Combines VR and AR to produce hybrid real-virtual environments where physical and digital objects co-exist and interact in real time. In addition to virtual objects interacting with the real environment, real objects can modify the virtual ones. The main environment is usually the real world, but the virtual objects are merged instead of overlaid [43]. The mainstreaming of this technology is more slowly than was anticipated, and therefore companies are more focused on professional applications [41].

Similarly to haptic gloves, current HMDs are unattractive to the general public. They are usually expensive devices that require even more expensive computers to run the applications, but this is expected to change. Sooner or later, stand alone (SA) headsets will prevail, enabled by 5G networks and cloud computing. In fact, current VR/MR headsets equipped with Qualcomm chip XR2 have optional connectivity to both sub-6 GHz and mmW 5G spectrum [44], but none company has taken part of this possibility yet. Qualcomm utilizes the term Boundless XR to define the utilization of MEC for low latency, high performance computing in XR services, distributing the content processing through split rendering (see Figure 3.6). When this solution becomes commercially available, not only wires will be removed, but HMDs will be lighter and more affordable. Some approaches to Boundless XR are already available, such as ISAR SDK plugin for Unity [45], which can be integrated into any application. Once ISAR is installed, the rendering process shifts from the XR device to a remote server, guaranteeing latencies of 16 ms over 5G.

The most interesting VR/MR devices in 2021 are detailed in Table 3.2. AR glasses have been discarded since they don't allow the interaction with virtual objects, which is the aim of the integration with haptic gloves. It can be observed in Table 3.2 that the Varjo XR-3 is the most premium device of the market [47]. It is indeed designed for professional purposes that require human-eye resolution and virtual objects almost indistinguishable from the real ones. It is the first device to include light detection and ranging (LiDAR) for depth awareness and pixel occlusion. According to Varjo, the video pass-through based mixed reality feels more realistic than optical see-through

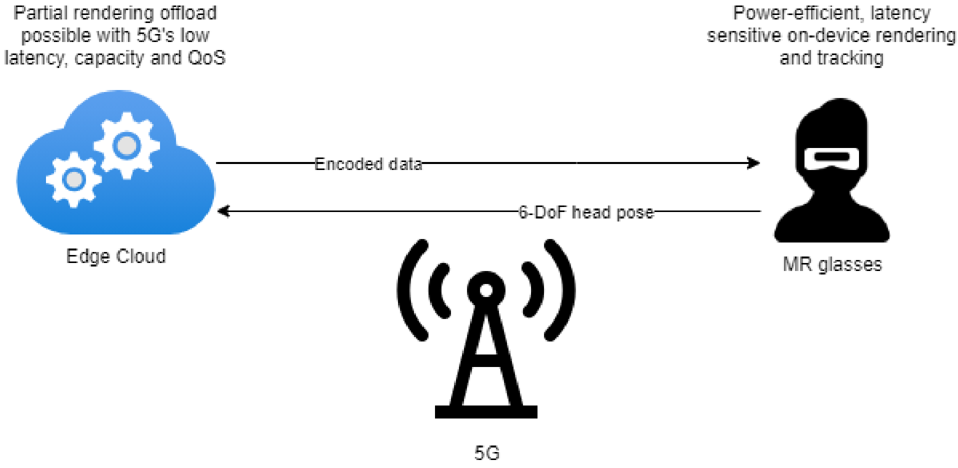


Figure 3.6: Augmented on-device processing for boundless photorealistic mobile XR [46]

Device	Type	Resolution	HT	ET	Weight	Connectivity	Price
HoloLens 2	MR	2048 x 1080	Yes	Yes	566 gr	SA or WiFi/wired NSA	$3500
HP Reverb G2	VR	2160 x 2160	No	No	550 gr	wired NSA	$600
Vive Focus 3	VR	2448 x 2448	No	No	785 gr	WiFi/wired NSA	$1300
Magic Leap 1	MR	1280 x 960	Yes	Yes	316 gr	SA or WiFi/wired NSA	$2300
Oculus Quest 2	VR	1832 x 1920	Yes	No	503 gr	SA or WiFi/wired NSA	$399
Varjo VR-3	VR	2880 x 2720	Yes	Yes	944 gr	wired NSA	$3990
Varjo XR-3	MR	2880 x 2720	Yes	Yes	980 gr	wired NSA	$6990
Valve Index	VR	1440 x 1600	Yes	No	809 gr	wired NSA	$799

Table 3.2: XR glasses available at 2021 (HT = hand tracking, ET = eye tracking)

devices (e.g. HoloLens2 and Magic Leap 1), since virtual object is rendered together with the real environment. The device is represented in Figure 3.7, and its main features include:

- Photorealistic, true-to-life mixed reality powered by low-latency, 12-megapixel video pass-through.
- The industry's highest resolution (over 70 ppd) and the widest field of view (115°).
- Depth awareness for pixel-perfect real-time occlusion and 3D world reconstruction.
- The widest-ever colour gamut matches 99% with the sRGB colour space for the most realistic scenes ever produced.
- Integrated Ultraleap's hand tracking and integrated 200 Hz eye tracking for natural interactions.
- Inside-out tracking, offering flexibility for deployments without the need for base stations.
- Total comfort with a 3-point precision fit headband, active cooling, and ultra-wide optical design to reduce eye strain and simulator sickness.

- Complete software compatibility. Any software is easily ported into Varjo via OpenXR 1.0 or Varjo native software development kit (SDK). Varjo also supports OpenVR content, Unity, and Unreal Engine.

Figure 3.7: Varjo XR-3

In addition, Varjo is developing a platform called Varjo Reality Cloud [48], which will allow photorealistic virtual teleportation, meaning that anybody will be able to capture their surroundings in 3D and then invite somebody else to join that same exact reality. This is technically possible using the Varjo's foveated transport algorithm, which can be used to stream the reality with a lower bit rate than streaming a movie from Netflix while still keeping the human-eye resolution quality. The use cases for Varjo Reality Cloud are endless, from personal connections to office life to factory work and beyond. This platform will be available in XR-3 later this year (2021), but in the future the power of the cloud will allow to add compatibility with any device, including laptops, phones, tablets, and wireless headsets. Using the company's API, developers will be able to create content for every industry vertical.

It is necessary to add that Varjo Reality Cloud has interesting competitors such as NVIDIA Omniverse [49], a similar platform for 3D production pipelines based on Pixar's Universal Scene Description and NVIDIA RTX. Contrary to Varjo's solution, NVIDIA Omniverse is based on open-standards and protocols, supporting different clients and applications. Their aim is to create a unified platform for engineering teams, contractors and suppliers to develop and build their products smartly and with minimal effort. Manufacturing processes can benefit not only from teleportation capabilities, but also from the integrated, cloud-native AI training. This platform is already on the market, and it is not constrained to VR/MR headsets at launch, but compatibility with wireless devices is still pending.

3.2 Automated Guided Vehicle

The robot employed is the model RB-1 Base manufactured by Robotnik. It is an AGV designed for autonomous logistics in indoors environments, but it is also used for testing or R&D applications due to its compact dimensions (515 mm of diameter and 303 mm of height). Up to 50 kg of cargo can be transported and a maximum speed of 1.5 m/s can be reached, supported by two motor wheels and three omni wheels. The motor wheels have a power of 250 W each, whereas the omni wheels are in charge of providing stability. The robot can detect obstacles from both a RGB-D

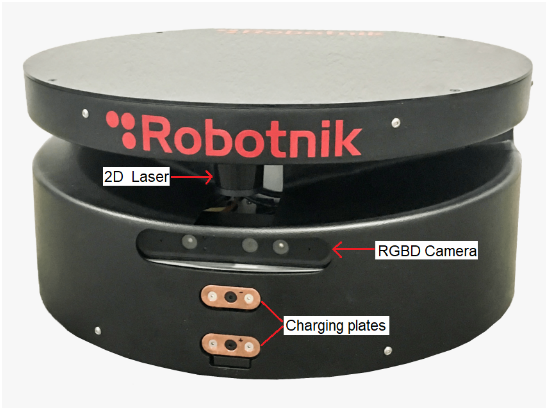


Figure 3.8: RB-1 Base Robot (Source: Robotnik)

Figure 3.9: RB-1 Base Robot with Fivecomm torso

sensor (depth sensing camera) and a laser sensor used for navigation and positioning (see Figure 3.8). The 2D laser gives a 270º vision range and detects obstacles located at a height of 195 mm from the ground. When an obstacle is at a distance of 1 m, the robot looks for an alternative route if possible or otherwise stops. For smooth H2M interaction, Fivecomm has equipped the AGV with a humanoid torso that contains a display and two more RGB-D cameras (see Figure 3.9). The display has not been used since it is not necessary for teleoperation, whereas the camera selected to be streamed has been the upper one due to a better placement, at a height similar to human head.

RB-1 Base is controlled by native ROS over an embedded Linux PC. ROS is a free and open-source framework that provides tools and libraries for the development of robot software. It allows to reuse code between different robots with the following features [50]:

- Message passing interface between processes
- Operating system–like features
- High-level programming language support and tools
- Availability of third-party libraries
- Off-the-shelf algorithms
- Ease in prototyping
- Ecosystem/community support
- Extensive tools and simulators

The iNGENIOUS project also contemplates the use of an AGV manufactured by ASTI, which will be indeed the AGV used in the Valencia port. The main difference between the two robots is that the ASTI AGV uses a proprietary communication system based on UDP frames instead of ROS. Nevertheless, this robot will not be available in the Fivecomm laboratory finally.

Figure 3.10: 3D map of the location of Fivecomm and the 5G antenna within the UPV campus

3.3 5G Network

The gNB used in the final demo is located at 370 m from the cockpit, as can be appreciated in Figure 3.10. It is a 5G antenna recently installed by Orange working in the sub-6 GHz band. There is line of sight between the gNB and the 5G modems, so the conditions should be optimal. However, it is a NSA deployment in experimental phase, and therefore the full 5G capabilities are not released. Indeed, it was not available until August, which delayed the 4G/5G network evaluation. In the near future, a mmW antenna is expected to be installed at the site, which will make also feasible the ultra-low latency provided by 3GPP Release 16 (URLLC).

The 5G modems used are the Huawei 5G CPE Pro 2, which specifications are the following:

- Communication standard: 3GPP Release 15 (eMBB)
- Network mode: 5G NSA/SA and 4G
- Transmission rate: Up to 3.6 Gbps in DL for 5G
- Supporting TDD/FDD and 11 5G frequency bands
- Supporting carrier aggregation
- Supporting network slicing

3.4 Cockpit

The glove and the glasses are integrated into the indoor cockpit through a wired connection (see Figure 3.11), since the firmware of Sensorial XR has to be updated to allow Bluetooth connectivity. The Windows PC includes a powerful NVIDIA RTX 3080 GPU to satisfy the computing demands of the Varjo XR-3 glasses. Besides, the remote execution using MEC is not possible yet due to software incompatibilities, and therefore the PC runs all the necessary client-side applications

Figure 3.11: (1) Varjo XR-3, (2) Sensorial XR, (3) Windows PC, (4) Linux Server, (5)(6) Modems

locally. As an intermediary step, the intention is that this PC acts as a gateway and the software runs in the server, but Neurodigital is still working in the migration of their SDK to Linux. Both the PC and the Server are connected to a 5G modem (number (5) in the figure) and the AGV is equipped with another modem (number (6) in the figure).

The Windows PC executes a Unity3D application that mixes a synthetic rendered scenario with real-time video captured from a camera which is streaming UDP H.264 video. The telemetry received from the AGV is handled by the same application for rendering visual information and creating haptic sensations. On the other hand, the Linux server functionalities have been programmed by Fivecomm and therefore they are confidential. The software needed on this PC is:

- Unity3D with Neurodigital SDK (confidential), Varjo XR SDK Plugin [51] and mray's GStreamer Plugin [52].
- Visual Studio Code or a similar code editor.
- .NET SDK 5.0
- GIT
- Varjo Base.

Chapter 4

Integration and demonstration

4.1 First demo: V5G Day

The V5G day event is an international 5G showcase held in Valencia. The agenda of the event is composed by round tables and demonstrations regarding 5G technologies, and one of these demonstrations was the remote control of AGVs using haptic gloves proposed in this thesis. Although the event was celebrated the 7th of June, the preparation started months before. The Sensorial XR glove arrived to the iTEAM laboratory in March, but the Robotnik AGV was unavailable until May. Those two months were spent in getting used to Neurodigital SDK and studying the SoTA technologies involving 5G and immersive devices.

It had been initially proposed that the glove was connected to the same Linux PC that controls the robot, and therefore this work would also consider the definition of automated routes using ROS. However, the final use case of the iNEGNIOUS project has discarded the use of ROS given the ASTI AGV possibility of working with simpler UDP frames. Furthermore, Neurodigital SDK only functions on Windows and Android, so the application was split into two separated PCs: the Windows PC commands the peripherals and the Linux PC commands the AGV. As commented before, the intention in the near future is that all the applications are migrated to the server and that it acts as the MEC. The first architecture proposed (Figure 4.1) considered the possibility

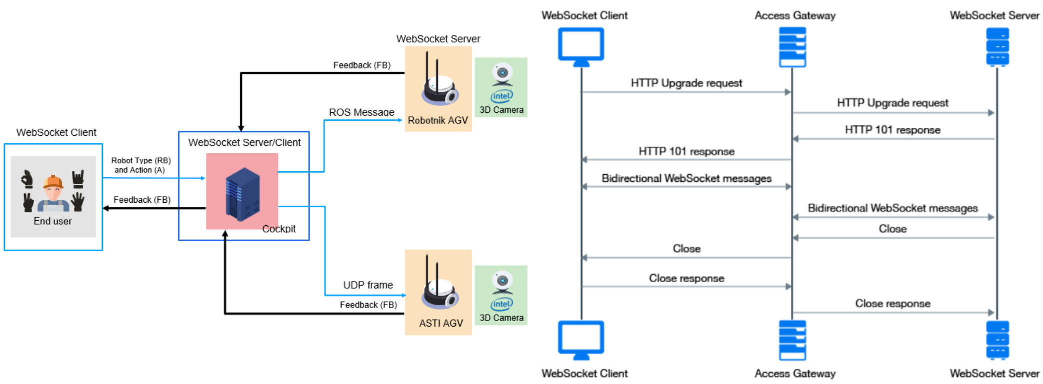
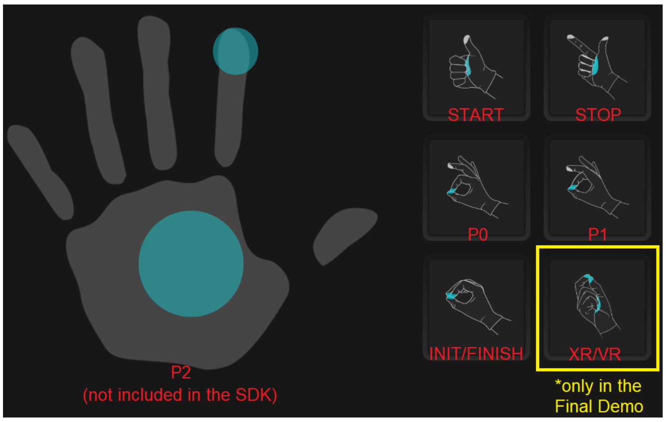


Figure 4.1: Communication protocols considering both Robotnik AGV and ASTI AGV

of communicating with the two AGVs simultaneously, but finally only the Robotnik robot has been used. The protocol deployed between the Windows PC and the Linux PC is WebSocket. It provides full-duplex channels over a TCP connection for real-time data transfer. One single TCP connection is used for traffic in both directions, with lower overhead than half-duplex alternatives such as HTTP polling. However, it is designed to support HTTP technologies and infrastructure [53]. The protocol is designed for web sessions, and consists of opening handshake, data transfer and closing handshake.

WebSocket is supported by .NET SDK added in C# language and therefore it can be easily programmed in Unity importing the package ”System.Net.WebSockets”. The script attached to the Unity hand object is programmed to establish a permanent bidirectional connection with the server, sending a command every time a gesture is made and receiving haptic feedback when the AGV detects an obstacle. The messages from the user to the server will be considered as uplink (UL) and the messages from the server to the user will be considered as downlink (DL).

The UL messages consist in the gesture type performed in the glove and detected by the Unity script. In order to clearly distinguish the recognized gestures, a brief delay was intentionally introduced between them (around 100 ms). This was motivated by several errors obtained in the first tests, specially in gestures that are very similar and only vary in one finger (for instance, performing the gesture START supposed a momentary detection of either the gesture STOP or the gesture P2). The gestures defined and the consequent AGV action can be found in Figure 4.2. Few gestures were provided by the SDK since Sensorial XR only has 4 conductive zones, so a new gesture was created (P2) and others were duplicated (INIT/FINISH and XR/VR). Finally, a short vibration is set in the zones involved in the recognized gesture, with the aim of notifying the user that the command has been sent.



- INIT: opens the communication with the server
- XR: enables the rendering of MR
- P0: goes to P0 if the AGV is in P1 or P2
- P1: goes to P1 if the AGV is in P0 or P2
- P2: goes to P2 if the AGV is in P0 or P1
- STOP: stops the AGV when it is in a route
- START: resumes the AGV route
- VR: disables the rendering of MR
- FINISH: closes the communication with the server

Figure 4.2: Gestures defined for the V5G Day and the Final Demo

The DL messages contain the minimum distance detected by the AGV laser. Depending on this value, an haptic vibration is activated in the glove, the more intense the more close is the obstacle to the AGV. The dependence between the intensity and the distance was selected to be the smoothest possible, and thus finally an exponential function was chosen (Figure 4.3).

All the commented functionalities were prepared and tested in the Fivecomm office before the demonstration in the V5G Day site. The user interface developed can be appreciated in Figure 4.4, whereas the routes defined for the event are displayed in Figure 4.5. That interface is also used in the final demo, and basically consists of three buttons that display the INIT/FINISH state, the route

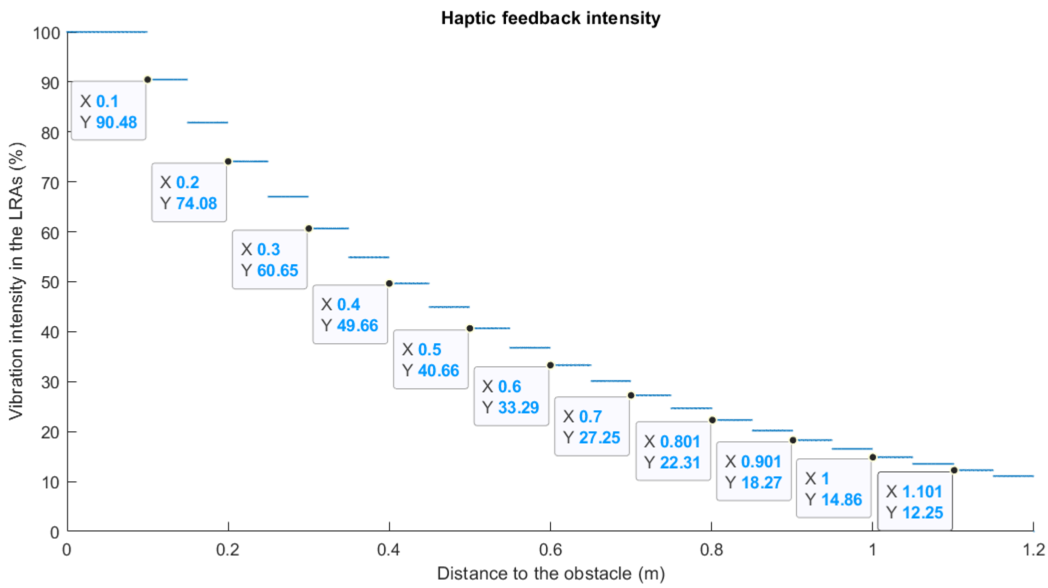


Figure 4.3: Haptic feedback intensity as a response to the obstacle closeness

selected, and the START/STOP state. The AGV was shared with two more demos, so in order to not restrict the AGV movement around the site, a new route could not be selected by the user until the previous one had finalized. However, the number of people walking near and interacting with the AGV screen supposed that the AGV continuously stopped and few people could actually test the remote control properly.

Figure 4.4: User interface developed for the V5G Day demo

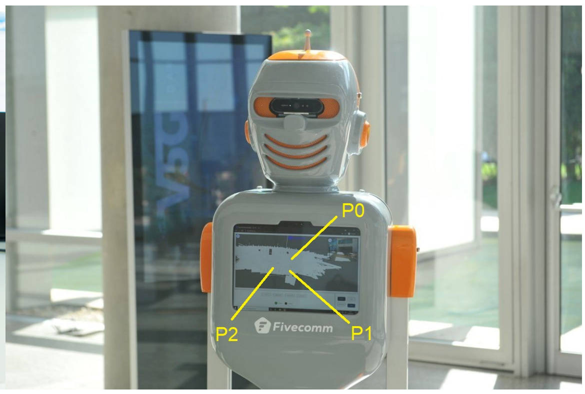


Figure 4.5: AGV displaying the site map with the routes defined

4.2 Final demo: Fivecomm office

The integration of the MR glasses supposed a big step forward for the immersive solution. They were available right after the V5G Day event, and therefore they have only been used in the Fivecomm office. To support the MR view, the whole Unity scene had to be migrated to a XR

Rig hierarchy [54], adding a Tracked Pose Driver to the Main Camera and installing the Varjo XR plug-in. Thus, the Main Camera follows the HMD position and rotation as long as the user is wearing the HMD. The rendering settings were left as default, since standard MR is desired. The gestures XR/VR control the rendering of the see-through image.

The next step was to add telepresence using the AGV camera. However, it was required a low latency, high frame rate video stream that WebSocket and TCP could not satisfy. After exploring several options, finally RTP streaming using GStreamer was chosen. GStreamer is an open source multimedia framework for media streaming and processing, where developers can add codecs and filters. The main features of GStreamer are [55]:

- Graph-based structure with multi-threaded pipeline construction
- QoS control, high performance and low latency
- Clocking to ensure global inter-stream synchronization
- Debugging system for both core and plug-ins
- All known types of sources, filters and sinks handled

One important setback for the integration was that the streaming didn't work because the Windows Firewall was blocking the connection, so the solution was to temporary disable it. The encoding format used for the streaming was H264, given its high image quality at low bit rates. The commands used in server and client can be found in Figure 4.6, whilst the video streaming within the Unity workspace is showed in Figure 4.7. All the parameters were selected to achieve the minimum latency.

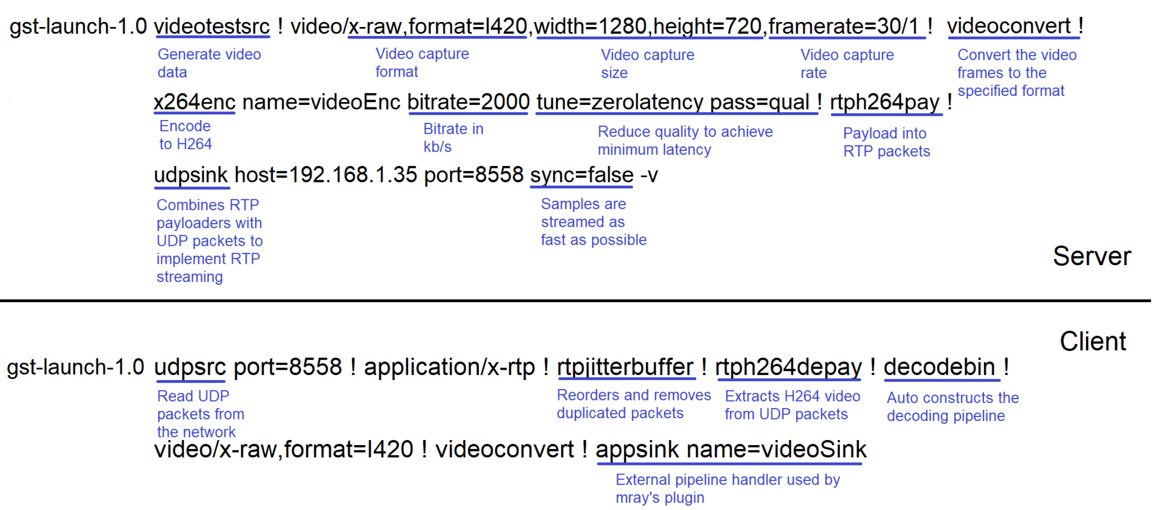


Figure 4.6: GStreamer pipelines used in server and client

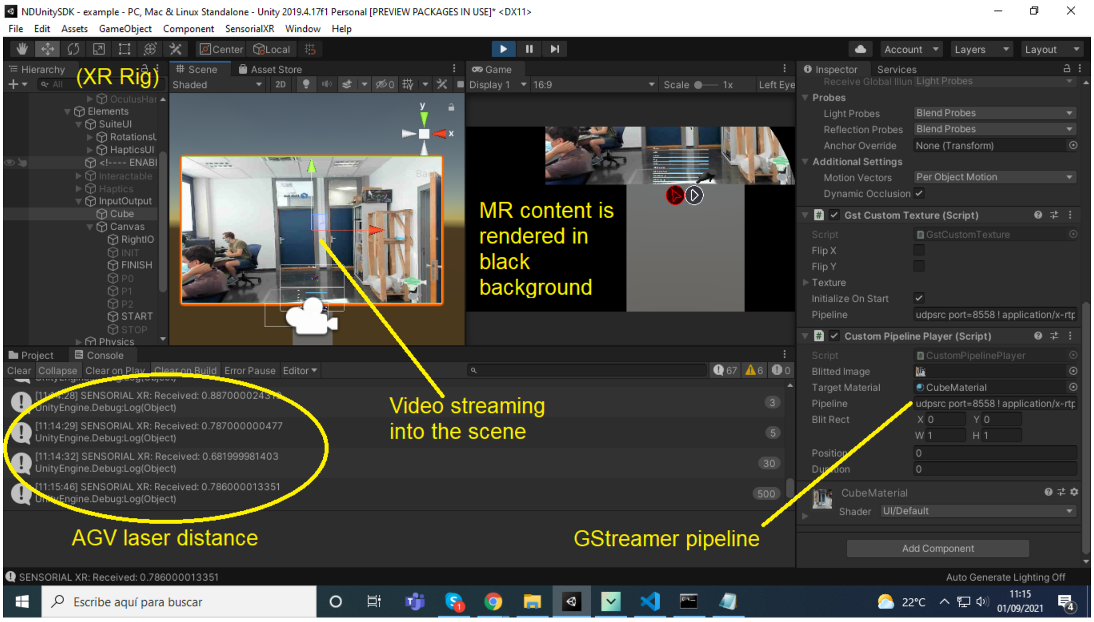


Figure 4.7: Unity workspace

4.3 4G/5G network evaluation

Finally, a comparison between the performance of 4G and 5G should be provided for this specific use case. In particular, network latency, E2E latency for video, E2E latency for gestures, and throughput were measured. The reliability was not measured because a lot of time and resources should be employed, since the methodology would be to continuously send pings until a packet got lost (actually no packets got lost during the measurements).

4.3.1 Network latency

```
C:\Users\Raul>ping 10.101.1.4

Haciendo ping a 10.101.1.4 con 32 bytes de datos:
Respuesta desde 10.101.1.4: bytes=32 tiempo<1m TTL=64
Respuesta desde 10.101.1.4: bytes=32 tiempo<1m TTL=64
Respuesta desde 10.101.1.4: bytes=32 tiempo<1m TTL=64
Respuesta desde 10.101.1.4: bytes=32 tiempo=2ms TTL=64

Estadísticas de ping para 10.101.1.4:
    Paquetes: enviados = 4, recibidos = 4, perdidos = 0
    (0% perdidos),
Tiempos aproximados de ida y vuelta en milisegundos:
    Mínimo = 0ms, Máximo = 2ms, Media = 0ms
```

Figure 4.8: Wired round trip network latency between the PC and the server

The average round trip network latency (ping) between the PC and the server is 0 ms (Figure 4.8), since they are both connected to the same modem. For that reason, the round trip network latency has been studied between the server and the AGV, with the results showed in Figure 4.9. In 5G the latency is significantly lower than in 4G (36.11 ms vs 63.61 ms respectively), besides of being a more stable network with a standard deviation also lower (10.11 ms vs 14.23 ms). The 5G network still operates with 3GPP Release 15 (eMBB) in experimental conditions, so it is far from offering the 1 ms promised by Release 16 (URLLC).

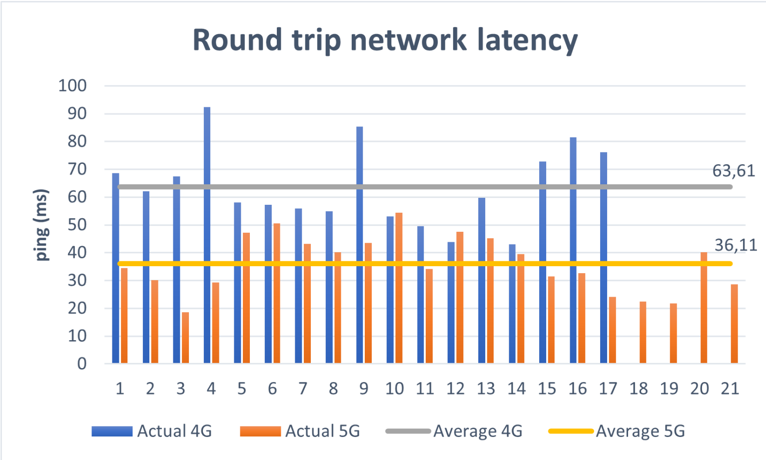


Figure 4.9: Round trip network latency for 4G vs 5G

4.3.2 E2E latency

The way of measuring the E2E video latency was pointing the AGV camera and the MR pass-through cameras at the same screen, where a millisecond-sensitive clock is displayed (Figure 4.10). In the screen, the view from the glasses is also displayed using Varjo Base, and this view includes the pass-through cameras view and the AGV camera view. The screen used has a refresh rate of 60 Hz, and therefore the error margin of the captures is 16.66 ms. The E2E latency (t_{E2E}) includes processing delays (t_{proc}) in the AGV, the server and the PC; round trip network latency (t_{RTT}) over 5G, corresponding to the communication between the two modems; the Unity application delay (t_{app}); and display latency in the goggles (t_{dis}).

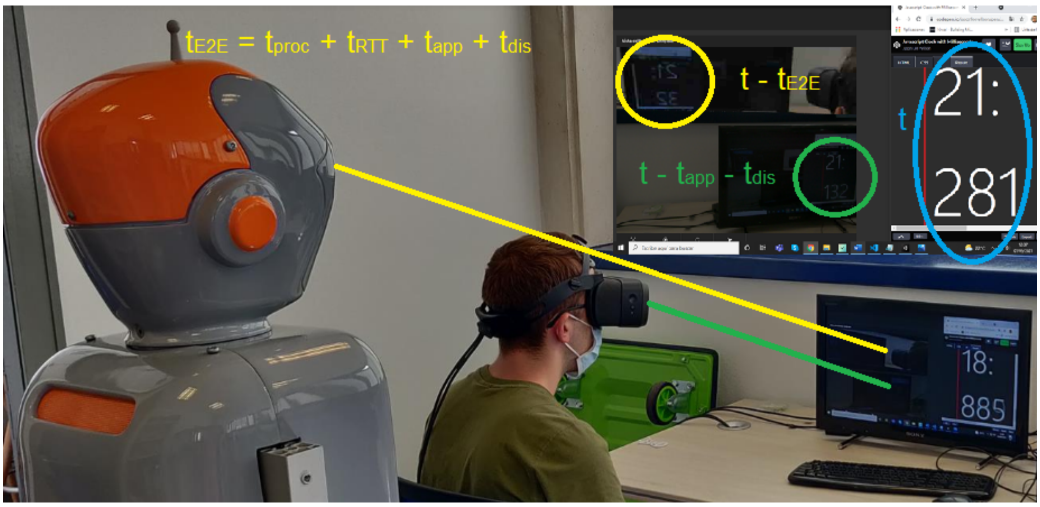


Figure 4.10: E2E video latency measurement

Only t_{proc} and t_{app} are unknown, but they can be estimated. According to Varjo, the XR-3 combines the real images and the virtual content using the integrated GPU, with a display latency of 20 ms. On the other hand, the round trip network latency has been estimated as 36.11 ms via 5G and 63.61 ms via 4G. Hence, it has been obtained from the measurements an average t_{app} of 126.32 ms and an average t_{proc} of 52.78 ms. Finally, the E2E latency measured is displayed in Figure 4.11. The difference between 5G and 4G in average E2E video latency (240,71 ms vs 257,21 ms respectively) is lower than in average network latency, which could be due to a change in the network conditions. It can be appreciated that the Unity application needs optimization, since its delay represents half the E2E delay.

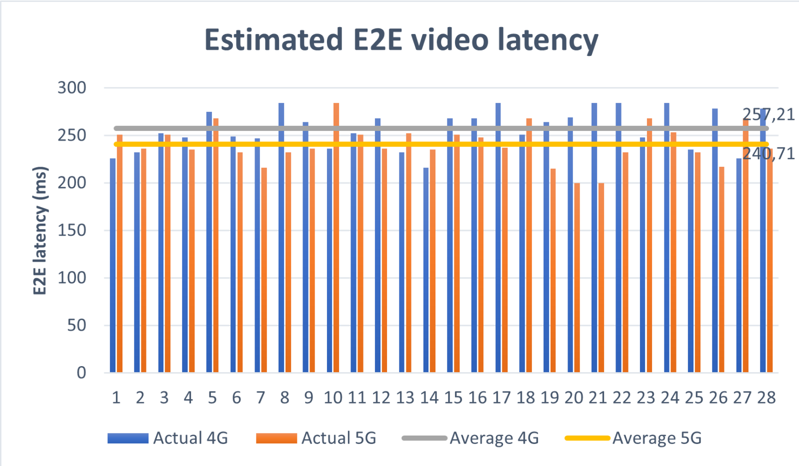


Figure 4.11: E2E video latency results

On the other hand, the E2E gesture latency was measured through a slow-motion video, analyzing the delay between the realization of the gesture (Figure 4.12) and the movement of the AGV (Figure 4.13). This procedure is far from accurate, and therefore only one type of measurements (5G) was completed. Six gestures, three of START and three of STOP were performed, with the results showed in Table 4.1. The E2E gesture latency is significantly higher than the E2E video latency due to the delay of the glove and moreover the delay of the AGV in accelerating/decelerating. The average value is indeed slightly lower in decelerating than in accelerating (877 ms vs 883.67 ms respectively), since the brakes act faster than the motors.

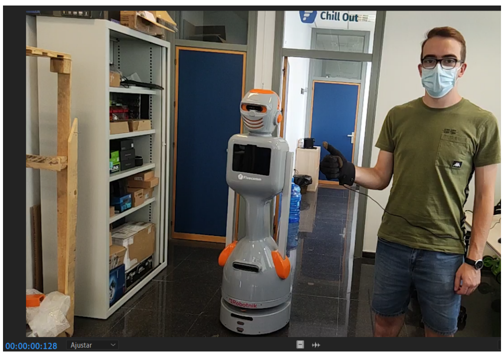


Figure 4.12: START gesture performed

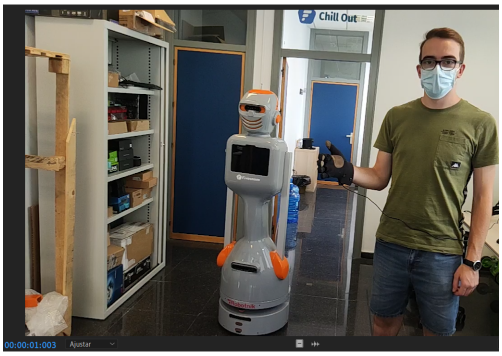


Figure 4.13: AGV begins to move

Gesture type	Gesture time	AGV action	E2E latency (ms)
START	0:128	1:003	875
STOP	3:186	4:041	855
START	5:151	6:047	896
STOP	7:155	8:035	880
START	9:166	10:046	880
STOP	11:128	12:024	896

Table 4.1: Estimated E2E gesture latency over 5G

4.3.3 Throughput

A simple speed test carried out on the browser was enough to know the magnitude order of the throughput. The web page selected was Ookla [56], which by the way offers measurements of the round trip network latency (ping). An example can be seen in Figure 4.14. Six measurements, three for 4G and three for 5G were performed, with the results showed in Table 4.2. Unlike the latency, the throughput does satisfy the requirements of the use case, reaching 5G downlink speeds around of 400 Mbps. The 5G network has proved to be unstable however, considering the UL throughput drop from 78.87 Mbps to 12.5 Mbps.

Figure 4.14: Ookla speed test example for 5G

Network	Ping latency	DL throughput	UL throughput
4G	41 ms	39,53 Mbps	37,95 Mbps
	47 ms	37,44 Mbps	34,84 Mbps
	40 ms	36,29 Mbps	36,23 Mbps
5G	30 ms	373,08 Mbps	78,87 Mbps
	31 ms	404,66 Mbps	70,1 Mbps
	34 ms	399,77 Mbps	12,5 Mbps

Table 4.2: Measured throughput and ping latency using Ookla speed test

Chapter 5

Conclusion and future steps

This thesis has presented the remote driving of AGVs via 5G using haptic gloves and MR glasses. Immersive devices are key enablers for improving operation of IoT systems in industrial and logistic environments, which is the aim of the H2020 iNGENIOUS (Next-GENeration IoT sOlutions for the Universal Supply chain) project that motivates this thesis. Among the Industry 4.0 principles, iNGENIOUS specially targets the automation and digitalization of the supply chain, with emphasis in 5G and MEC infrastructures. The particular use case that targets this thesis explores the remote transportation of goods in the Valencia port, in order to improve the operator's safety. Before the deployment in the final scenario, a PoC has been developed in the Fivecomm office to test the viability of this use case. In addition, a review of the SoTA enabling technologies has been provided.

Considering the strict latency requirements of this use case, it is classified into the Tactile Internet, a network for manipulating real or virtual objects in real time. The Tactile Internet scope is not limited to haptic communications; it targets any kind of H2M or M2M communications with real-time demands, and therefore it is considered as the evolution of IoT. A compilation of the expected Tactile Internet use cases has been provided in Section 2.2, but the majority of them will require E2E latencies of 1 ms that are unfeasible with today's technology. The closest approach to Tactile Internet is the 5G URLLC use case family, which promises 1 ms of network latency. URLLC is defined as a toolbox, and therefore each application can choose what tools to use. These tools include aspects of PHY/MAC layer design (mini-slot, grant-free UL, preemption, CBG-based HARQ, etc) or from upper layers and architecture (QoS monitoring, MEC, always-on PDU, RRC inactive, etc).

The immersive devices integrated in the indoor cockpit have been the Sensorial XR haptic glove and the Varjo XR-3 mixed reality glasses. They are both cutting-edge, premium devices despite being limited for a wired connection. The Sensorial XR unique feature is the four conductive zones that allow to carry out gestures, whereas the haptic capabilities are provided by ten vibrotactile actuators. On the other hand, the Varjo XR-3 include pass-through cameras that enable the combination of VR and AR to create immersive MR environments. Both the glove and the HMD are controlled by an Unity application that communicates with the robot through an intermediary server. The UL communication only involves the specified gesture, whereas in DL the cockpit receives haptic and visual feedback from the AGV peripherals. All the communications have been performed via 5G, but only eMBB in the sub-6 GHz band was available.

A series of 4G and 5G measurements have been performed to test the current viability of the iNGENIOUS use case. The average network latency obtained has been 36.11 ms via 5G and 63.61 ms via 4G, whereas the average DL throughput measured has been 392.5 Mbps via 5G and 37.75 Mbps via 4G. It has been demonstrated that current 5G eMBB networks improve the performance of 4G, but they do not get close to the strict latency requirements of Tactile Internet. It is expected that the installation of a mmW antenna compliant with URLLC will reduce network latency, but the target of 1 ms will be hard to met. Nevertheless, the network latency is negligible in comparison to the E2E latency. The average E2E latency via 5G has been measured for both video streaming and gesture control, obtaining 240.71 ms and 880 ms respectively. These results show that the developed application needs further optimization specially in the AGV control, since a delay of 880 ms makes unfeasible the deployment in the Valencia port, where a real-time response is needed. However, this is an innovative use case with a lot of work left, so future lines will focus on reducing latency and improving the functionalities, reaching higher levels of immersion. Although new ideas will emerge, the next steps expected for this project are the following:

- Reduce gesture delay: The intentionally added delay between gestures will be eliminated, and a more efficient alternative will be designed. It has been proposed that the gestures are defined by hand postures rather than by the union of conductive zones.
- Drive tests: More accurate network measurements will be performed using the professional network scanner ROMES. Instead of hotspot measurements like the described in this thesis, drive tests evaluate the network in a certain geographical area. This area will be the UPV campus and the Valencia port, since mmW antennas are programmed to be installed there in the next months.
- Cloud rendering: The XR application can be partially or completely rendered on a remote server using the ISAR SDK commented in Section 3.1.2. This would liberate the MR headset computing demands, and thus SA devices could be considered.
- Improve video streaming: Different codecs and bit rates will be tested to analyse the performance. High resolutions and qualities can be supported by the high throughput available, but it could have an impact on latency.
- Migration to MEC: Since the Linux server does not support the application so far, a possibility could be to create a Windows virtual machine in the server, which would eliminate the WebSocket and GStreamer communications and latency. When a MEC infrastructure is available and the application is compatible, a full migration will be carried out.
- 360 camera: The AGV will be equipped with either a 360º camera or 2x180º cameras to achieve higher immersion. The counterpart is that streaming the whole 360 video has a big impact on latency, and therefore the solution is to implement an algorithm that streams only a certain direction at the time.
- ASTI AGV: The ASTI robot, working with faster UDP frames, should provide a lower E2E gesture latency than ROS systems.
- Eye tracking: It could be used to analyse where the operator often looks at, thus he would be advised if he is not supervising relevant zones of the port. In addition, augmented reality could be used to display information about the elements in sight.

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