5G smarT mObility, media and e-health for toURists and citizenS

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Final Touristic City use case results

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List of Acronyms and Abbreviations

Acronym	Description
3D	3 Dimensional
3GPP	Third Generation Partnership Project
4K-HDR	4K High Dynamic Range
5G	5th Generation mobile Wireless Communication System
5G PPP	5G Public Private Partnership
5GC	5G Core
A/V	Audio-visual
AAC	Advanced Audio Codec
AMCL	Adaptive Monte Carlo Localization
AI	Artificial Intelligence
API	Application Programming Interface
APN	Access Point Name
AQI	Air Quality Index
AR	Augmented Reality
ATE	Augmented Tourism Experience
AWS	Amazon Web Services
BMSC	Broadcast Multicast Service Centre
BSCC	Broadcast Service & Control Centre
CDN	Content Delivery Network
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COAP	Constrained Application Protocol
CPU	Central Processor Unit
DASH	Dynamic Adaptive Streaming over HTTP
DC	Datacentre
EBU	European Broadcasting Union
eMBB	enhanced Mobile Broadband
eMBMS	evolved Multimedia Broadcast Multicast Service
eNB	Evolved Node B
ENM	Ericsson Network Manager
enTV	Enhancement for TV Service
EPC	Evolved Packet Core
EPG	Evolved Packet Gateway
FEC	Forward Error Correction
FeMBMS	Further evolved Multimedia Broadcast Multicast Service
FPS	Frame Per Second
FTP	File Transfer Protocol
GAM	Modern Art Galley
GDP	Gross Domestic Product
GPU	Graphics Processing Unit
gNB	5G Node B
GUI	Graphical User Interface
HDR	High Dynamic Range
HEVC	High Efficiency Video Coding
HLS	HTTP Live Streaming
HPA	High Power Amplifier
HPHT	High-Power High-Tower
HSS	Home Subscriber Server
HTTP	HyperText Transfer Protocol
ICT	Information and Communication Technology
IFB	Interference Free Band
iFN	Institut für Nachrichtentechnik - University of Braunschweig
IGMP	Internet Group Management Protocol
IIT	Istituto Italiano di Tecnologia
IoT	Internet of Things
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LED	Light Emitting Diodes
LIDAR	Light Detection and Ranging
LTE	Long Term Evolution
MANO	NFV management and network orchestration
MAO	Museum of Oriental Arts
MAUA	Museum of Augmented Urban Arts
MBMS	Multimedia Broadcast Multicast Service
MBMS-GW	MBMS Gateway
MCE	Mobile Cloud Engine
MCS	Modulation and Coding Scheme
MCU/SFU	Multipoint Conferencing Unit / Selective Forwarding Unit
MEC	Multi-Access Edge Computing
MME	Mobility Management Entity
mMTC	massive Machine Type Communications
MNO	Mobile Network Operator
MR	Mixed Reality
MQTT	Message Queue Telemetry Transport
NB-IoT	Narrow Band IoT
NO_2	Nitrogen Dioxide
NR	New Radio
NSA	Non Standalone
O_3	Ozone
open-WRT	OPEN Wireless RouTer
OSS/BSS	Operations support system and business support system
OTT	
P2P	Peer-to-Peer
PCF	Policy Control Function
QoE	Quality of Experience
QoS	Quality of Service
RAI	Radio Televisione Italiana
RAI-CRITS	RAI Centro Ricerche Innovazione Tecnologica e Sperimantazione
RAN	Radio Access Network
RGB	Red Green Blue
RTMP	Real-time Messaging Protocol
RTP	Real-time Transport Protocol
RTSP	Real-time Streaming Protocol

ROS	Robot Operating System
RTT	Round Trip Time
SDI	Serial Digital Interface
SBA	Service Based Architecture
SDR	Single Data Rate
SFN	Single-Frequency Network
SGI	LTE interface to the Packet Data Network (PDN)
SLA	Service-Level Agreement
SLAM	Simultaneous Localisation and Mapping
SO_2	Sulphur Dioxide
SRT	Secure Reliable Transport
STEAM	Science Technology Engineering Arts Mathematics
STUN / TURN	Session Traversal Utilities for NAT/ Traversal Using Relays around NAT
SVG	Scalable Vector Graphics
TCP	Transmission Control Protocol
TS	Transport Stream
TV	Television

UC	Use Case
UDP	User Datagram Protocol
UE	User Equipment
UHD	Ultra HD
UI	User Interface
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPF	User Plane Function
URL	Uniform Resource Locator
USB	Universal Serial Bus
UWB	Ultra Wide Band
VHF	Very high frequency
VLC	VideoLAN Client
VN	Virtual Machine
VNF	*Virtual Network Function*
VPN	Virtual Private Network
VR	Virtual Reality
WP	Work Package
XR	Extended Reality
YARP	Yet Another Robot Platform

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Executive Summary

This deliverable D4.4 is intended to be the final document representing the results collected after the deployment, implementation and trial phase of each use cases belonging to WP4 and related to the Touristic City (media production and distribution, safety and security in smart cities, museum and education, robotics).

This document follows the deliverables D4.1 (5G-TOURS, D4.1 Robotic, Media and Smart Cities solutions for Touristic Cities, October 2019) and D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) previously prepared by WP4.

The aim of the document is to show the progress done after the strong cooperation between technical partners and verticals and in terms of network deployment installation and coverage.

The five main use cases are detailed as next:

- UC 1 - Augmented tourism experience

  This use case is focused on the use of Augmented and Virtual Reality technology. It provides visitors of targeted museums with an improved and more engaging experience based on the use of an augmented reality inside and outside the Palazzo Madama Museum concerning virtual reality technology: its use has been gamified through a memory game provided thanks to Oculus Quest viewers connected to the 5G network, and the use of an interactive wall.

- UC 2 - Telepresence

  This use case provide the possibility for a robot located inside the museum to be controlled by a remote user by exploiting an underlying 5G network capable of meeting the stringent KPIs necessary for effective robot control and low latency high quality video stream. The use of telepresence robots in the tourism sector opens up various possibilities for extending the usability of museums over time and space. The most natural case is the remote visit of a museum which, thanks to the potential of the 5G network, can take place virtually from any place and can be carried out even during the closing periods of the museums.

- UC 3 - Robot-assisted Museum guide

  This use case leverages the use of robotic technology to provide an enhanced museum visit experience. This guided tour is performed autonomously by the robot following a predefined path. In this use case the humanoid robot R1 is used to carry out a guided tour. The 5G network is exploited for its higher bandwidth (in this UC especially in uploads) and for its low latency. The data collected by the robot is sent to a remote computer which processes them and sends movement commands to the robot.

- UC 4 - High-quality video services distribution

  This use case enables the distribution of enhanced high-quality video services for tourists to improve the user experience when visiting a city. The use case is based on the use of 5G broadcast delivery services using the broadcasting network and the development of a 5G core multicast component.

- UC 5 - Remote and distributed video production

  This use case explores the 5G-TOURS network features for remote television production, in a distributed TV video production context; the content has been produced by mixing local and remote audio and video contributions in the TV studio

All the aforementioned use cases imposed a careful design of the network, partly done by leveraging and integrating into the 5G-EVE infrastructure and partly obtained through the deployment of new hardware and software that extended and complemented the already available infrastructure.

The use cases have been developed in Palazzo Madama and GAM, two of Turin's main museums: Palazzo Madama is located in the heart of Turin and is a UNESCO heritage site and seat of the first Senate of the Kingdom of Italy. It sums up the entire history of the city: from a Roman gate it was transformed in the Middle Ages into a fortress and then into the castle of the princes of Acaja. Since 1934 the Palace has housed the collections of ancient art of the Civic Museum with over 70,000 works including paintings, sculptures,

illuminated manuscripts, majolica and porcelain, gold and silver, furnishings and fabrics that illustrate European art from the early Middle Ages to the Baroque; the GAM (Gallery of Modern and Contemporary Art of Turin), with its collection of over 50,000 works including paintings, sculptures, works on paper, installations, videos and photographs, offers the public a path that ranges from the 19th century to the contemporary with artists such as Pellizza by Volpedo, Medardo Rosso, Chagall, Andy Warhol. In addition to the collections, it hosts a rich program of temporary exhibition: from major exhibitions of Italian and international artists to contemporary research.

A considerable effort was dedicated to network coverage solutions within the two museums: Palazzo Madama and GAM. The case of Palazzo Madama was particularly challenging in terms of historical context and because of the physical characteristic of the building (structure characterized by medieval walls with considerable sections, towers, spaces that are difficult to reach). This had required ad hoc solutions to be integrated in such historical environment. One example is that of the radio technology that has been carefully studied with an architectural studio and has been integrated into the existing seats of the museum, flanked by information poles. The solutions provided had to follow a strict administrative process before obtaining the Superintendency validation and agreement.
The specific characteristics of the use cases, that requires very high bandwidth (for the AR and VR applications), low latency (for the Robotic UCs) or broadcast capabilities required specific features in the network components. Besides, WP4 use cases has been used for the evaluation of PoCs related to Artificial Intelligence, as discussed in D3.4 [7].

The results achieved for WP4 use cases are to be considered as a starting point for upcoming experiments and collaborations, as demonstrated by the feedbacks collected during the events organized on a local scale. The last event named “The Art meets 5G” took place at GAM on the 25th of May and foresaw the presentation of WP4 case studies together with a direct demonstration of some of them (UC1, UC2 and UC3).

The event was attended by local experts, Museums and political representatives of the Culture sector who were able to experience firsthand the work carried out during the last three years and evaluate possible connections and new collaborations.

1 Introduction

The Touristic City UCs enables a new ecosystem of applications and solutions that improve the quality of the visit of citizens and tourists in the city of Turin, under many points of view. First, to allow people to access and enjoy attractions in enhanced or novel ways, and second to enable new opportunities for the vertical sectors (Tourism and Media) to exploit the available assets.

The use cases tested within the project are part of a wider spectrum of innovative solutions in the cultural field, on which the city of Turin has worked and will work in the coming years.

In line with the "Europe 2020" strategy and with the financing trajectories defined in the 2024-2020 European Commission programming, the city started to develop and tested innovative vertical solutions in the following sectors: energy, environment, mobility, accessibility, social inclusion and cohesion and culture.

In continuity with this, it is mentioned among the others the ongoing project House of Emerging Technologies (CTE NEXT), co-funded by the Italian Ministry of Economic Development with a total budget of 13 million euro and aimed to transform the city into a widespread technology transfer center on 5G enabled emerging technologies (Iot, AI, Blockchain) in strategic sectors for the territory: intelligent mobility, industry 4.0 and innovative urban services, including Culture & Tourism.

Launched in March 2021, Turin “House” is now fully operational and is offering its 5G and Multi-edge computing infrastructure to business and R&D actors for co-developing and testing innovative urban solutions through a complete set of acceleration and transfer tech services as well as through dedicated “Call for proposals” targeted to start-ups and SMEs.

Due to the high interest already verified at local level, including the new born ICCi hub (“Italian cultural content industry hub”) with its headquarter in Turin and the NFT and metaverse R&D Business Initiative in OGR Tech Torino, as well as thanks to a strong strategy around 5 to 6G in the audiovisual sector carried out by the National Ministry of Economic Development, some upcoming activities of Turin House of Emerging Technology will focus “5G for Culture and Tourism” as a mainstream towards the business community.

In terms of public investments at the local level, the City of Turin has already launched or planned the following activities thanks to React pillar, within current ESI funds programming with a total budget of 103,7 million euros, dedicated to:

- Call for innovative widespread cultural activities for urban regeneration targeted to the third sector organization (ongoing – React);
- Renewal of historical parks and realization of the new central public library at Torino Esposizioni with a strong technological innovation focus.

Finally, among these 323,5 million euros dedicated to the urban regeneration of Turin Metropolitan City, a strong priority is on widespread interventions on schools and libraries which will include technology enhanced cultural and educational experiences, including enabling infrastructures.

More than this at national level, specific investments addressed to support the cultural sector have been included in the National Recovery and Resilience Plan (PNRR) approved in June 2021. The Mission 1 (digitisation, innovation, competitiveness, culture), Component 3 (tourism and culture) of PNRR is focused on tourism and culture and foresee 6,68 Mld of euros dedicated to these sectors. Among the general objectives of Mission 1 there is the willingness to increase the level of tourist and cultural attractiveness of the country modernizing the material and intangible infrastructure of the historical and artistic heritage; to renew and modernize the tourist offer also through the requalification of the receptive structures; and to enhance infrastructures and strategic tourist services supporting the digital and green transition in the tourism and culture sectors.

The use cases developed in WP4 explores the 5G technology to provide such innovative functionality in real-world scenarios in the Turin City centre, with trials involving external visitors belonging to different stakeholders and user groups that allow to assess both the performance of the network and the benefits of the proposed use case.

The touristic city use case ecosystem is composed by 5 innovative applications that improve the quality of experience of the tourists visiting different museums and attractions in the city.

This deliverable is intended to be a document covering the final description of the use cases for the Touristic City. For each of them the final stages of the UC development, testing and deployment are explained, as well as the collected results. A more thorough analysis of the obtained insights will be provided in a dedicated section related to WP4 use cases results that will be included in WP7 deliverable D7.4 [9].

While the whole descriptions of WP4 use cases are included in deliverable D4.1 (5G-TOURS, D4.1 Robotic, Media and Smart Cities solutions for Touristic Cities, October 2019), in this document we focus on their execution, and the document is structured as follows.

From Chapter 2 to Chapter 6, we discuss the main implementation activities of each use case together with the on-site trial phase and related results, according to the 5G-TOURS use cases.

Chapter 2 describes the use case UC 1 - Augmented tourism experience developed both in Palazzo Madama and GAM thanks to three different use cases: the experience includes the provision of contextual information (such as level of crowding or alarms) and multimedia contents (photos, videos, audio guides) on the rooms visited via sensors and beacons; the provision of key information on art pieces based on image recognition; the ability to interact with works of art (high resolution 3D models) and additional tourist information (bike / car sharing stalls, transport, weather, pollution) through smart city services; the use of virtual reality for the creation of a “memory game” virtually set in camera delle Guardie in Palazzo Madama and addressed to general visitors and for the creation of an interactive wall dedicated to children and students in GAM (Galleria d'Arte Moderna) that allow groups to paint on a virtual canvas and reproduce the compositions of the artist Nicola De Maria.

Chapter 3 describes the use case UC2 – Telepresence tested both in Palazzo Madama and GAM with three main sub use cases: exclusive visit to the basement of Palazzo Madama, remote visit of Palazzo Madama; and Treasure Hunt at the GAM in collaboration with Edu Lab in Turin (Learning solutions laboratory).

Chapter 4 describes the use case UC3 – Robot-assisted Museum Guide; In this UC the humanoid robot R1 is used to carry out a guided tour inside a museum both in Palazzo Madama and GAM. R1 was developed by IIT - the Italian Institute of Technology - as a service robot (able to perform useful activities for humans in the public environment) and as a research platform in the field of AI. It is an autonomous robot, not teleoperated. In this use case the 5G mobile network is used to extend the capabilities of the humanoid robot R1, giving it additional computing power.

Chapter 5 describes UC4 - High Quality video service. In the framework of the 5G-TOURS project, during the show “The Garden of Forking Paths” by composer A. Molino, RAI-CRITS tested the transmission of a high-quality video towards mobile devices in 5G Broadcast mode from the Torino Eremo RaiWay Transmitter. The use case demonstrates how with 5G broadcast, the smartphone becomes a real mobile TV on which to watch TV without consuming the data traffic of the SIM and without the risk of losing the signal if the mobile network is overloaded.

Chapter 6 describes the UC5 – Remote and distributed video production. The use case resulted in an event of great cultural appeal named “The Garden of Forking Path”, directed by Andrea Molino conductor and held in Palazzo Madama in November 2021.

We report for each use case to be deployed on the Turin node the UC implementation in terms of application components, terminal equipment components and interfaces. Furthermore, we report about integration and test in lab/on field and the final trialing in the network.

Chapter 7 includes a detailed description of the 5G-TOURS network implementation aspects for the Turin site, with a special focus on the additional network equipment that has been provided in the two UC trailing locations in Palazzo Madama and GAM, as well as the integration with the 5G EVE architecture. The section 7.3 highlight the innovation aspects related to Network and Applications.

Lastly, the Conclusion Chapter provides feedback and impressions from verticals (Fondazione Torino Musei and RAI) about the use cases’ implementation and trials, including an overview of the results achieved.

2 UC1 - Augmented tourism experience

2.1 UC1 definition

This use case aims to provide visitors of targeted museums with an improved and more engaging experience based on the use of an Application inside and outside the Palazzo Madama Museum and the use of an interactive wall dedicated to children and students in GAM (Galleria d'Arte Moderna) Museum. Users' experience is enhanced by augmented content such as interactive 3-Dimensional (3D) models, virtual scenarios, immersive videos, and interactive walls. The UC1 is divided into two sub-cases:

UC1.a. AR and VR: In the very heart of Turin

This sub-use case aims to create and test an integrated, immersive visit in the Museum and surrounding areas using a mobile App that integrates different technologies such as AR and beacon localization technology. Through the App, the visitor has access to additional information such as level of crowding in a museum room, map of the Museum, and related points of interest as well as has access to more content related to specific rooms and artworks. It is possible to interact with 3D objects or participate in a virtual scenario to improve the visitor knowledge by taking actions. Furthermore, at the end of the visit, the App help visitors to find further places of interest interacting with "smart city services" that also suggests a sustainable way to reach them. Finally, once at home, the city tourists can retrieve artworks descriptions and models previously stored during the tour. The application also integrates an early warning emergency notification system that notify users in case of fire or earthquake

UC1.b: GAM and Edulab – Gamification, let's play artist

The objective of this sub-use case is to allow users to enter the life of De Maria contemporary artist and to directly test the art creation process as well as learn about it through gamification. It's an educational Case Study addressed to students or families with children. The experience mixes XR (Extended Reality) with gamification and it allows children to work on an interactive wall reproducing the artist's canvas by choosing shape and colours contents.

2.2 UC1 Implementation

UC1.a AR: In the very heart of Turin

The app of augmented tourism provides the visitors of Palazzo Madama with an enriched experience. The app customizes its content depending on the current room and also allows visitors to scan artworks to retrieve extra media content about them.

After the visit ends, the app also suggests to visitors' other museums to go to and how to reach them (by car or bike sharing, on foot, etc.).

Furthermore, the app uses the sensors scattered inside the museum to launch, in case of emergency, a fire or earthquake warning, asking visitors to leave the museum premises and showing the closest emergency route.

The app development focused on the implementation of the aforementioned Warning screen (that will alert in case of emergency in the museum) and on the integration with Museum Services and Smart City services, APIs back-ends provided by TIM. These modules are described in section 2.2.1.

The actual UI has been refined according to FTM guidelines, which have been finalised after a turning process. This process of review and feedback ensures that the final application is in line with FTM expectation. The enhancements of the app implemented in its final version are the following:

- A new button that shows a map with the artwork disposition in the ceramic room.
- Some improvements were done to the description panel in order to be bigger, to be fixed to the screen, and to allow zooming the text. Also, the contrast has been increased in every text included in the app to improve accessibility.

- The last missing artworks were included in the app, adding up to a total of 22 ceramics, plus some models like statues, tables, etc.
- ATOS presented several options to FTM to change the style of the markers used to recognize the artworks. After choosing the new style, all the old markers were updated to fit the new style.
- A new functionality that allows showing different text descriptions was included, depending on the 3D artwork vision angle (top, bottom, front, back) that the users are viewing at that moment.
- A new screen was added to the app. It will automatically appear if the museum's sensors (provided by TIM) detect a fire or an earthquake. A text will alert the visitors and ask them to leave the museum using the closest emergency exits, indicated by the app.
- Smart City's functionality was added, integrating our app with the endpoints of TIM and showing augmented information of the city that is relevant to the visitors. The app now has 2 new screens to show this new information:
    - Weather and air quality
    - A map with interesting places close to the tourist's current location, like parking lots, bike stations, and other museums.
- The text descriptions of the different rooms were converted to audio using text to speech technology, and the app was modified to be able to listen to those audios freely while walking through the room.
- 3D artworks user experience were improved (resizing, calibrate position where they appear).
- A button to check if there are some 3D artworks on the actual room was added.
- Some useless buttons were removed.
- The Palazzo Madama emblem for the app icon was added.
- The app for the 5G-EVE network was adapted.
- Some 3D artwork textures were fixed.

In the app, a video of one artwork per room is available. These videos can be watched by the visitors anytime while they are in the current room.

Figure 1 shows the welcome screen that appears at the start of the visit and shows relevant information about the museum. Figure 2 shows a map with the crowding level of every room of the museum in real-time.

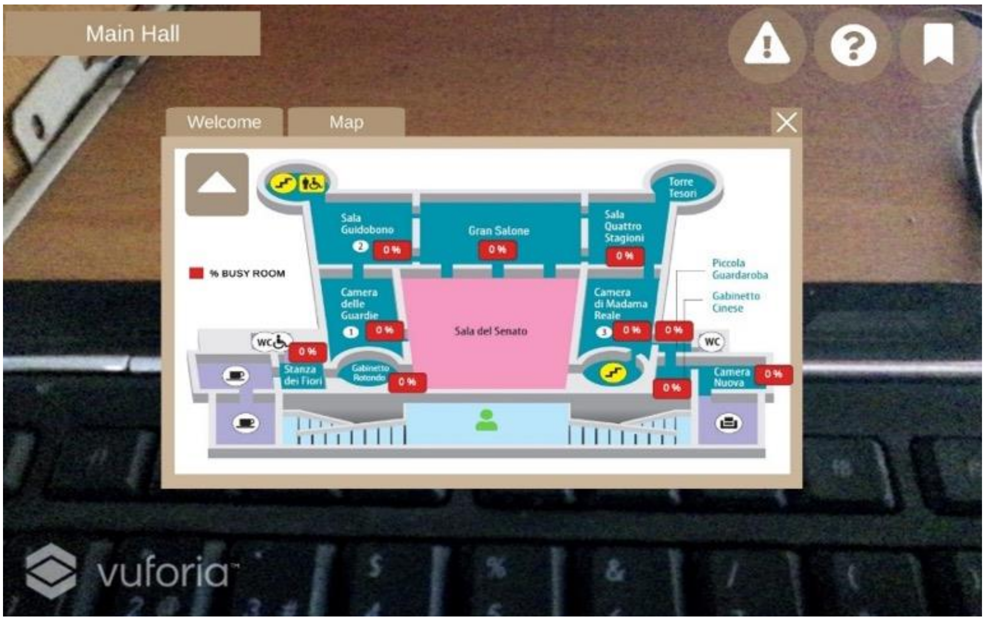


Figure 1. AR App - welcome screen.

Figure 2 shows how the 3D examination and manipulation works. The app allows zooming in and out to inspect the model of an object present in the room, revealing details that may be hard to notice in the real object, for example, at its bottom; Figure 3 shows the pictures gallery while Figure 4 shows how the video player is integrated. The app knows its location thanks to the Beacons system and has different videos available depending on the current room.

Figure 2. AR app - Video player.

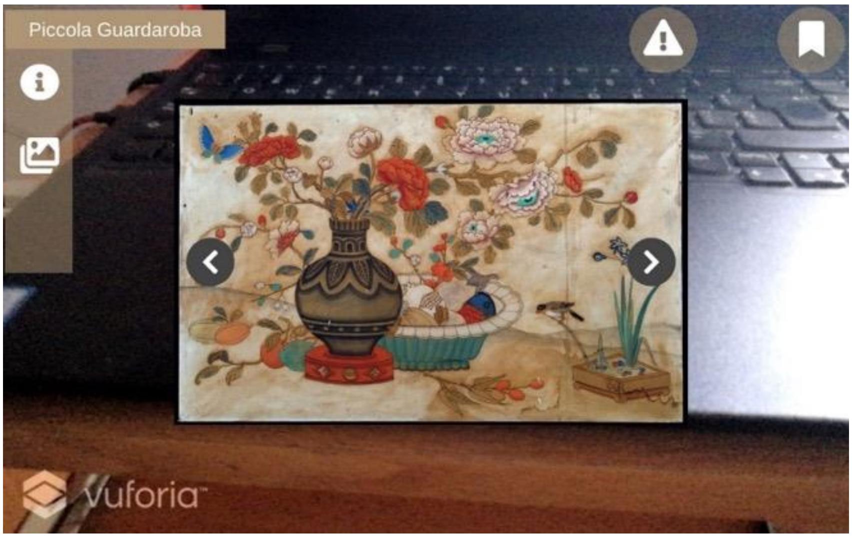


Figure 3. AR app - 3D model examination.

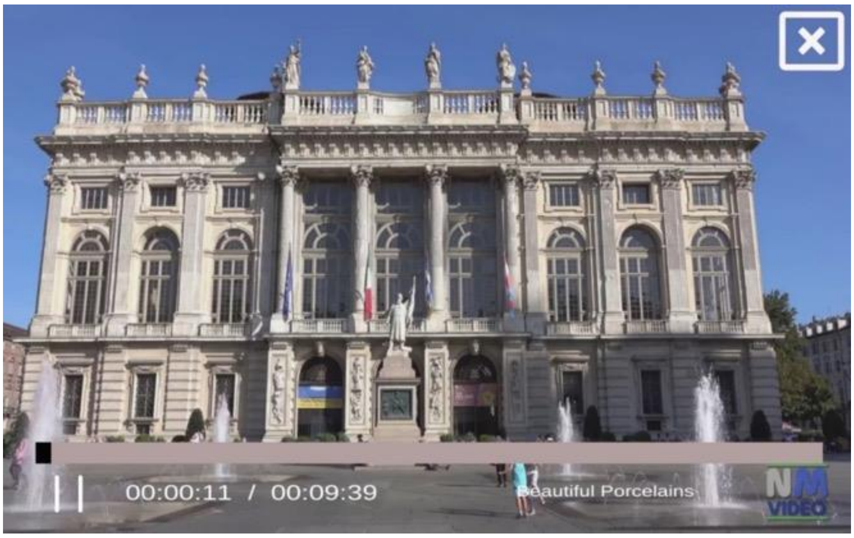


Figure 4. AR app - Video player.

Figure 5 shows the map for an emergency event (e.g., earthquake). The app makes a sound alarm and shows the evacuation map with the actual position of the user. If you close this window the app will exit.

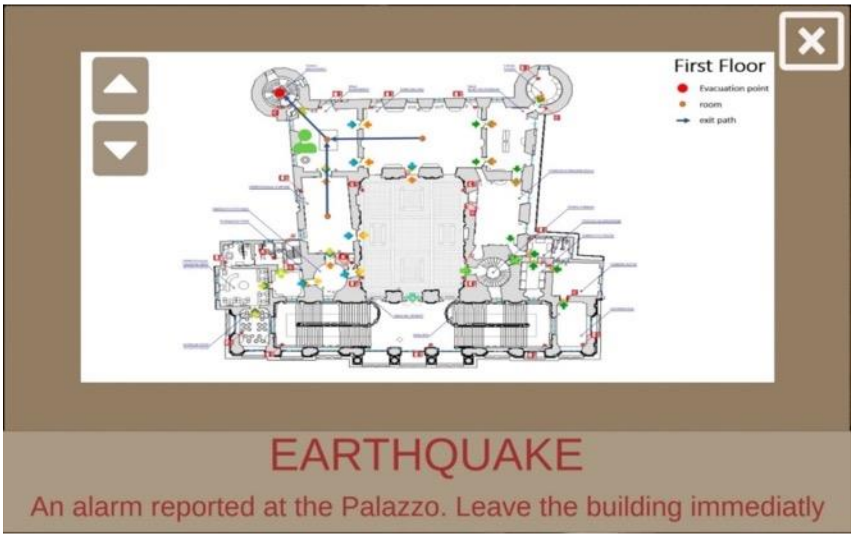


Figure 5. AR app – Warning screen.

Screenshots about Smart City Services, (Figure 6) show how the application aims to give the tourist additional information in terms of other touristic places to visit and how to reach them, suggesting sustainable mobility solutions.

Figure 6. Smart City Services.

The <u>first</u> screen shows current data such as weather and air quality, which could be taken into consideration by the visitors to select a mobility way (e.g., in case of rain or bad air quality conditions the visitor cloud avoid walking or biking around the city). By clicking into the building button, the screen action will move to the second view.

The <u>second</u> screen shows details of a selected place. By clicking on the Let’s Go! Button, the application will move to the third view.

The <u>third</u> screen displays the path for reaching the selected destination on a map, along with other points of interest that are close to the visitor at that moment. The suggested path is related to a walking itinerary, anyway the user can choose other mobility way by selecting the nearest car or bike sharing station.

<u>UC1.a. VR: In the very heart of Turin</u>

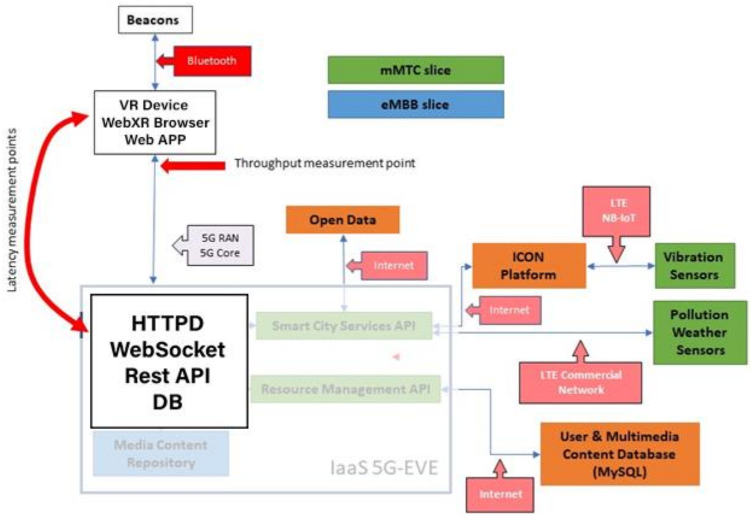


Figure 7. The VR application components.

The VR experience developed by Samsung Research UK (SRUK) uses WebXR API (WebXR Device API - Web APIs | MDN (mozilla.org)). All application components are based on Web technologies (Web technology for developers | MDN (mozilla.org)), enabling compatibility with multiple headsets and mobile devices. All interactions from-to the application (if needed) are enabled by services available through the web, although the experience itself is self-contained and accessible through the browser.

The entire storyline provided by FTM was implemented. Players can experience Palazzo Madama and the different paintings in the room of Camera Delle Guardie. There are three playing modes implemented: Free Play, Single, and Multiplayer (for real-time collaboration). SRUK reworked and improved the 3D models of the room to keep the experience close to real dimensions and lighting. The initial 3D scan was optimized in order to reduce the required data rate.

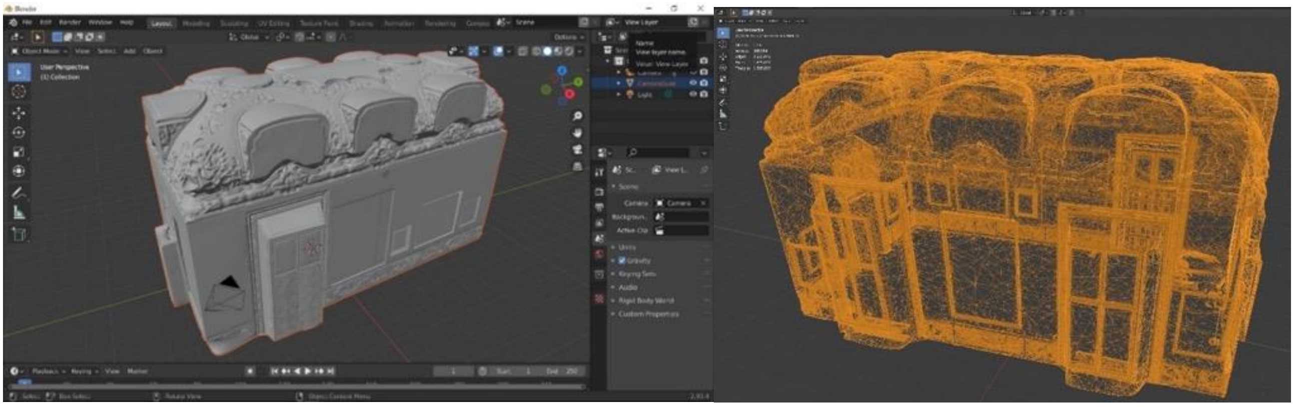


Figure 8. Optimization of 3D Scans in Blender.

Optimization (decimation of geometries and texture compression) produced a high volume of irregular artifacts which takes a lot of invisible data with no positive impact on visual quality. For the technical aspects of WebXR, they consumed too much memory and GPU power slowing down the virtual machine of the WebXR-enabled browsers (Samsung Internet Browser, Oculus Browser). Lastly, simplified models and projected textures from provided diversified assets were created: high-resolution photography, spherical panomas, and CAD models that can be found in Video1 and Video2.

Figure 9. Equirectangular photography used for textures projection.

Players can move in the room, admire the art pieces and see each other (if additional devices are connected). The journey starts in the VR headset lobby. User can open multiple instances (up to 3 tabs) of Oculus Browser. Oculus platform also provides other WebXR ready browser apps: Wolvic (formerly Firefox Reality). There are two entry options to choose: [OBSERVATION] mode and [ENTER VR]. The first one is just a direct entry to the VR realm from the Oculus lobby and the second one can be used by assisting person. [OBSERVATION] mode can be also accessed on non-VR devices via Chrome-based browsers. Assisting person can remotely see the positions of player(s) and their interactions depend on the game mode (taking off or placing paintings, putting random shapes to the bucket).

UC1.b: GAM and Edulab – Gamification, let’s play artist

Use Case 1.b takes place at ‘Galleria d'Arte Moderna’ (GAM) in Turin. It consists of an interactive wall were kids aged 6-12 can create compositions based on art by artist Nicola de Maria. The setup consists of three main points:

- Experience input: The experience is controlled with motion. It is important to highlight that among the requirements it is key to maintain users highly engaged with the experience; therefore, the input must be through a device that supports a way of capturing movement.
- Application: The application consists of a wall where kids can translate, scale, and rotate different shapes based on De Maria’s work. The shapes and colors provided by the Museum in RGB and vector format (like SVGs converted to PNG and highly compressed Basis format textures for WebGL). The application itself is based entirely in Web technology, making it cross-platform accessible through multiple devices with a Web Browser (Chrome, Samsung Internet, Firefox). It is embedded HTML5 canvas, so the WebGL renderer use of Javascript PixiJS library. Cloud based Webserver (NGINX) provides an URL and the assets data (images, videos, javascriptscript bundle and hypertext components – HTML5, CSS) are requested and sent securely via Internet Protocol, HTTPs and WebSocket WSs bilateral (full duplex – low latency mode) using available Networks.
- Display: The application is projected from the browser on PC (Windows, MacOS, Linux) onto a wall at GAM, where the intended way of interaction is to be in front of the wall, creating compositions with colors and shapes provided. The interaction is through movements enabled from the input hardware described below.

The type of compositions is based on the following De Maria’s art-works:

Figure 10. Paintings of Nicola De Maria were the source of digital assets (shapes and art direction) for the Interactive Wall.

2.2.1 Application Components

UC1.a: In the very heart of Turin

Figure 11 shows the architecture of the use case which includes both software and hardware components (beacons and IoT devices will be described in the next section). This paragraph only describes new or updated application components with respect to deliverable D4.2 [2].

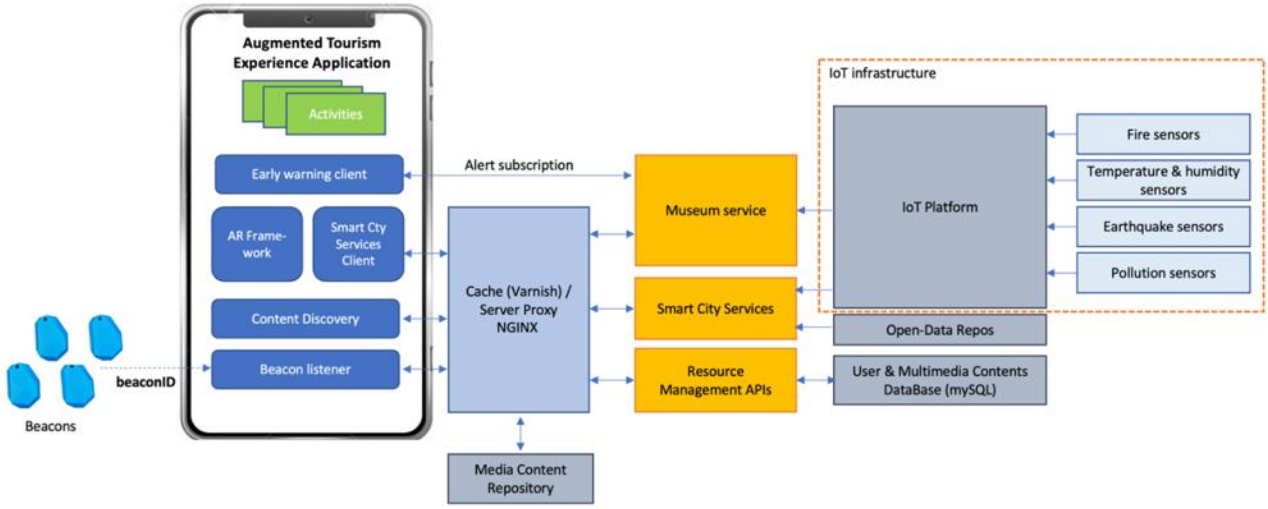


Figure 11. Augmented Tourism Experience application components.

Beacon Listener

The Beacon Listener is a background service from the client; its purpose is to scan continuously for beacons. When the nearest beacon ID changes, it means that the user moved to another room. This event triggers a call to the Museum Service APIs that allows communicating the position update of the user and retrieving the room name. Every time the room changes, it notifies other processes of the application so they can customize the content accordingly.

Content Discovery

This module downloads media content on the fly when it's needed. That includes when the user walks to another room and when they scan a marker of a specific artwork that they want to explore in detail. The content download may include 3D models, video, audio, pictures, and texts.

Smart City Services client

This module is a new section of the client, where visitors can explore new options to visit after their tour ends. It integrates Smart City Service APIs allowing retrieving other places to visit and other information regarding mobility and air quality.

IoT Infrastructure

The IoT infrastructure includes the IoT Platform, described in deliverable D4.2 [2], and the following sensor:

- Temperature, humidity, fire: that has been deployed on every room covered by this UC.
- Earthquake: deployed inside towers of the Museum, not accessible to visitors.
- Pollution: deployed on top of Torre Nord.

Section 2.2.2 provides a description and deployment information of each type of sensor.

Data provided by the IoT infrastructure are also used in by UC2.c.

Museum Services (back-end)

This back-end application has been developed to offer, by means of APIs, the following features inside the museum:

- Crowding service: it integrates the functionalities of the Beacon analytics backend described in deliverable D4.2 [2]. When a visitor moves to another room, this action is detected by the beacon listener that sends a location update. Every location update of a user is collected to create a historical dataset that can be used to create insight such as: time spent on a single room, duration of the tour, etc. Location updates are used to:
  - update the crowding map, which gives an indication of the crowding index of each room and is showed inside the mobile app.
  - provide the user with the name of the room he entered.
  - track the user's position inside the museum. This feature is exploited in UC2 to locate the robot.
- Data service: data collected from the IoT Infrastructure are exposed by means of API. This allows retrieving temperature and humidity of each room and historical time series.
- Notification system: when the service starts, a subscription for each digital twin of the IoT platform is created (only for fire and earthquake sensors). Values coming from subscriptions and crowding data are analyzed from the back-end that will generate a notification, using WebSocket, when one of the following conditions happen:
  1. Fire or earthquake
  2. Low battery level of a device
  3. A room is overcrowded

  There are two kinds of client: normal (the mobile app that will receive only the first kind of notification) and dashboard (used in UC2.c that receive all kind of notifications).

Crowding levels of each room are evaluated using information provided by FTM: space needed for each visitor (5 meter squared) and room surface, see the picture below:

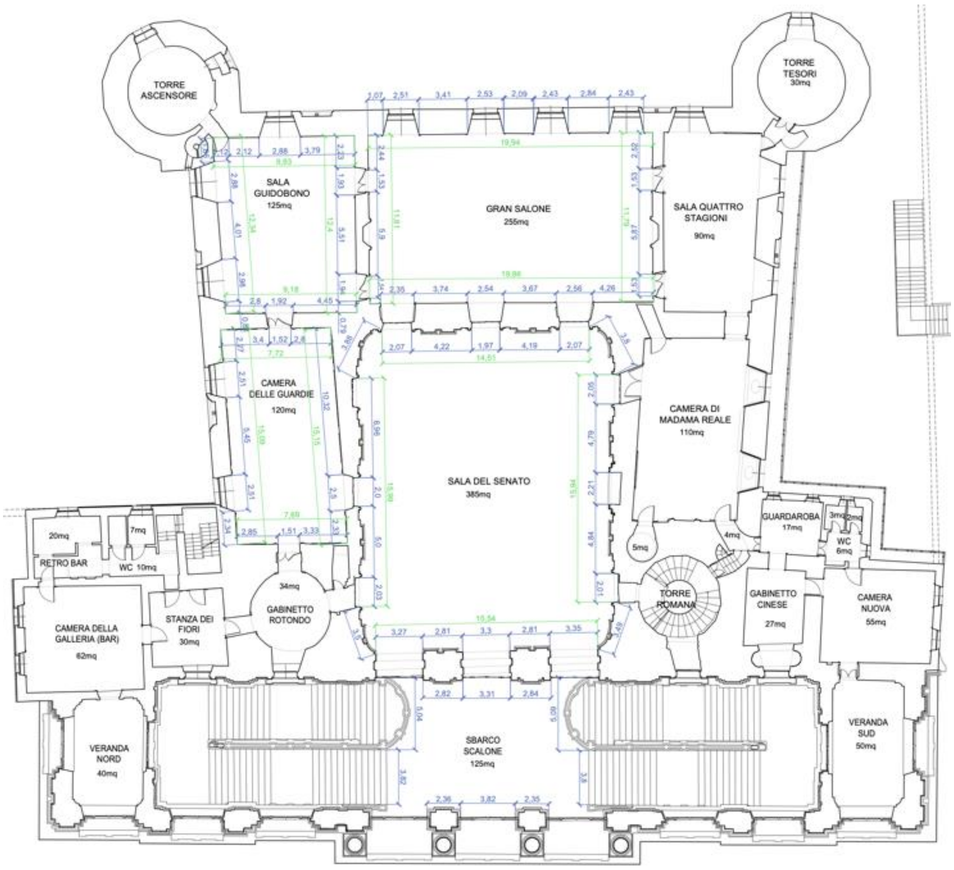


Figure 12. Museum map showing room surface.

The capacity of each room is evaluated with the following formula:

$$\boldsymbol{Capacity} = \left\lfloor \frac{\boldsymbol{Room\ surface}}{\mathbf{5}} \right\rfloor$$

By using beacons and the mobile app is possible to monitor how many people are present in a room and the crowding percentage:

$$\boldsymbol{Crowding\ percentage} = \frac{\boldsymbol{capacity}}{\mathbf{100}} * \boldsymbol{number\ of\ people}$$

Four crowding levels has been defined using crowding percentage:

- Low – less than 30%
- Medium - from 30% to 70%
- High - from 70% to 100%
- Critical – more than 100%

When the «Critical» level is reached an alarm is generated to the guardian dashboard of UC2c. This information can be used to monitor COVID-19 restrictions in real-time. The picture below shows how crowding information are conveyed to users.

Figure 13. Crowding levels.

Smart City Services (back-end)

As described in the previous deliverable D4.2 [2], Smart City Services are used during step 5 at the end of the visit.

Open data are exposed, using APIs, to offer information regarding the following five categories:

- Museum and historical sites
- Bike Sharing Station
- Bus stops and lines
- Car sharing stations
- Commercial activities

For each category, APIs allow retrieving all items in the city of Torino or filtering by using the current GPS position and a distance, allowing to find only the nearest.

Due to administrative authorization issue to deploy IoT devices outside Palazzo Madama, because of cultural heritage restrictions, we decided to reduce the number and type of IoT devices. Only one pollution sensor has been used, just to show the concept of the use case (it will sense real data).

Information related to weather conditions has been obtained using the OpenWeather API instead of deploying a weather station.

Resources Management APIs

This module works as a bridge between the multimedia content and the client app services that need them, making it easier to retrieve all the multimedia files related to a specific artwork or room.

Open-Data repositories

In addition to the dataset mentioned in deliverable D4.2 [2], also weather information is retrieved from an external source of data. In fact, the OpenWeather APIs are used instead of deploying a real weather station. This simplifies the setting of the trial due to administrative authorization issues.

Multimedia Contents Repository

These module storages all the Multimedia content and make it available to the app. The contents may be 3D models, video, audio, and pictures.

2.2.2 Terminal Equipment components

UC1.a. AR: In the very heart of Turin

As mentioned in the previous paragraph, the IoT infrastructure uses three kinds of IoT devices:

1. Temperature, humidity, fire: deployed on every room covered by this UC.
2. Earthquake: this kind of vibration sensors are deployed in some tower of the Museum.
3. Pollution: deployed on top of Torre Nord, already described in D4.1 [1].

UC1 (and UC2) also relies on Bluetooth beacons to implement indoor localization (also described in D4.1[1]). To sense temperature humidity and detect fires we use a Sodaq AFF development board (Figure 14) equipped with two grove sensors: a temperature and humidity sensor (Figure 15) and a flame sensor (Figure 16).

Figure 14. Sodaq SARA AFF R410M.

This prototyping board, designed with the standard Arduino form factor, comes with a powerful 32 bits micro-controller, two grove sockets to easily connect any sensor, two JST connectors to connect a battery and a solar panel, onboard charge circuit, accelerometer, GPS, and NB-IoT or Cat M1 connectivity modules. We use NB-IoT to send values to our IoT Platform.

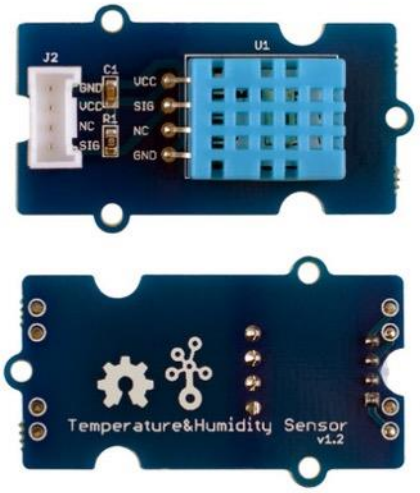


Figure 15. Grove Temperature and Humidity Sensor.

Figure 16. Grove Flame Sensor.

Earthquakes detection is performed using the Arduino MKR 1500 (Figure 17) as prototyping board and the Breakout019 board (Figure 18) as seismic sensor.

Figure 17. Arduino MKR NB 1500.

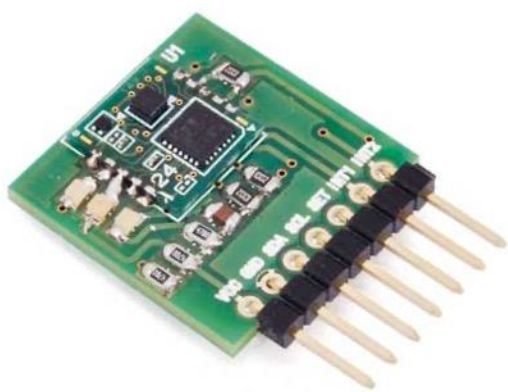


Figure 18. Breakout019 earthquake sensor.

The Breakout board is based on the D7S produced by Omron, the world's smallest seismic sensor. The D7S is composed of a three-axis accelerometer, of which only two are used during the detection of an earthquake and are selectable either by the user or automatically with respect to the inclination of the sensor.

Samsung Galaxy S10 is used in this UC. It is powered by a Snapdragon 855 5G processor (octa-core CPU at 2.84 GHz) and is equipped with 8GB RAM, enabling multitasking and fast switching between apps. S10 uses 5G frequencies below 6GHZ and falls back to LTE when there is no 5G service, while being to automatically fall back to LTE when 5G service is not available. Although the smartphone can attain speed over 1Gbps via a mm wave small cell, it cannot exploit the low band 600 MHz FDD (frequency division duplex) 5G service. Lastly, it is equipped with a non-removable LiIon 4500 mAh battery and supports super-fast charging with its 25-watt adapter.

UC1.a. VR: In the very heart of Turin

The VR experience is based on:

- The involvement of a minimum of two users;
- Originally, we developed Single application that users can wear a VR headset (Destek) using a 5G Samsung phone as a display (5G enabled S21+). Destek's Bluetooth controller does not provide a 6DOF experience and all the interactions were possible only via head movements/transitions and a single button on the headset (the select/release functionality – providing possibilities to interact with objects – select menu items or pick up, drag and release them at desired destination). After initial tests of experience, the FTM team decided to go with the Oculus VR headset. The OS is a modified Android shipped with WebXR enabled Oculus Browser (and other vendors browser apps like Firefox and Wolvic). Additionally, HMD comes with two (Left, Right) hand controllers (for hand motion tracking and hand gestures recognition) enabling user's interactions and movement within the environment virtually projected to the virtual guardian. Users can also use the device in a stationary mode, sitting.
- Users' simplified avatars (spherical semi-transparent head with attached model of Headset VR (HMD - Head Mounted Displays), simplified limbs with ray casting and models of controller) is present; a user is able to see their controllers or hands and also avatar(s) of the second or more players.

UC1.b: GAM and Edulab – Gamification, let's play artist

The compact multisensory prototyping platform, the Nordic Thingy 5, originally planned, was not used at the end being this device not well known.

Several controllers were tested and only a few were able to fit our requirements. After numerous tests, the Nintendo Wii controller was selected. Wiimote allows to get gyroscopic information, acceleration, vibration, multiple buttons and most importantly the pointed direction of the remote controller on the wall. The Wiimote uses a complex set of operations, transmitted through HID Output reports, and it returns a number of different data packets through its input reports, which contain the data from its peripherals. Wiimote's precision and missed clicks are worse than for instance "normal" mouse, but target re-entry much higher.

For the 2D tasks throughput is 41,2% lower than using the mouse, target re-entry is almost the same, and missed clicks count is three times higher. For the 3D tasks throughput is 56,1% lower than using the mouse, target re-entry is increased by almost 50%, and missed clicks count is sixteen times higher.

Figure 19. Wiimote is motion controller and human input device.

This controller guaranteeing an interactive experience where users can intuitively rotate, scale, move, add animation, and change the color of the different shapes inspired by the composition of De Maria art style.

The gestures recognition is based on kinematic interaction where the applied animation of the shape follows the intention of the user. The pointed direction of the remote controller on the wall is calibrated by the source of infrared light emitted by the array of LEDs from the sensor (Myflash W010 Dolphin Bar) bar placed above or at the top of Interactive Wall.

Figure 20. IR sensor bar as the source of calibrating light.

2.2.3 Interfaces

UC1.a AR: In the very heart of Turin

Several examples of the interface screens can be found in Figure 1 to Figure 6.

UC1.a VR: In the very heart of Turin

The interface is immersive real-time 3D world rendered by java script virtual machine of the WebXR enabled browser. There is possibility to experience the initial 3D and 2D layer UI without VR headset. To enter the WebXR API there is a simple button [ENTER VR] and additional features for those who can assist at the same time.

Figure 21. Two tabs of Oculus Browser for the VR entry and OBSERVATION mode.

During the VR experience there are several gamification modules focused on the Art exploration and possibility of picking up artworks and moving them around in the room by more than one user at the same time. UI elements are temporary displayed blocks of information and buttons (they appear as single elements or grouped in a kind of drop-down list). Some elements display interactive features like Clock, Date, Countdown, Game Result and Scoreboard list. There is also possibility to watch an instructional video on a temporary created video player. User has also possibility to provide profiling nickname which will be placed on the Scoreboard with a calculated result.

Figure 22. Free Play: User can interact with random objects.

Figure 23. Single Player: Virtual keyboard for profiling and instructional video.

Figure 24. “Something happened”: Player needs to place the paintings back on the walls.

Figure 25. Paintings are laying on the floor and user can pick them up using controller.

Figure 26. The time left and indicated amount of collected items are displayed on the wall.

Figure 27. Painting is successfully moved and placed to its original location.

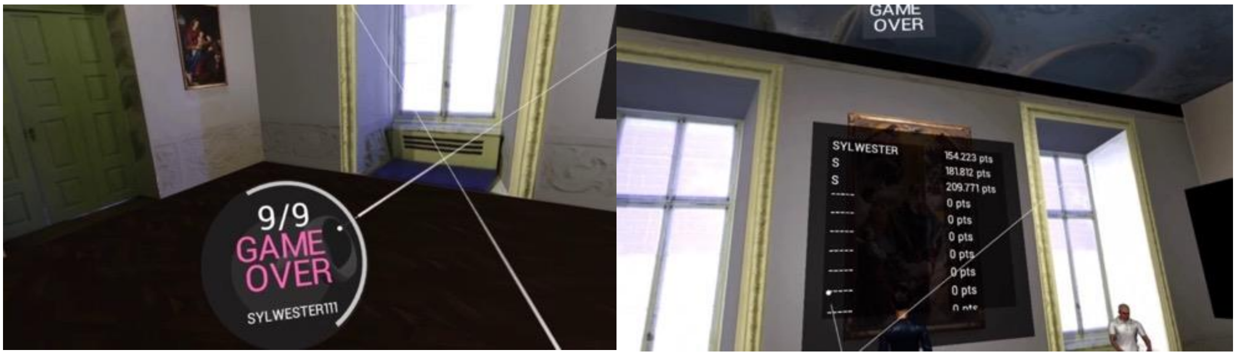


Figure 28. The GAME is over. The result is displayed on the SCOREBOARD.

UC1.b: GAM and Edulab – Gamification, let’s play artist

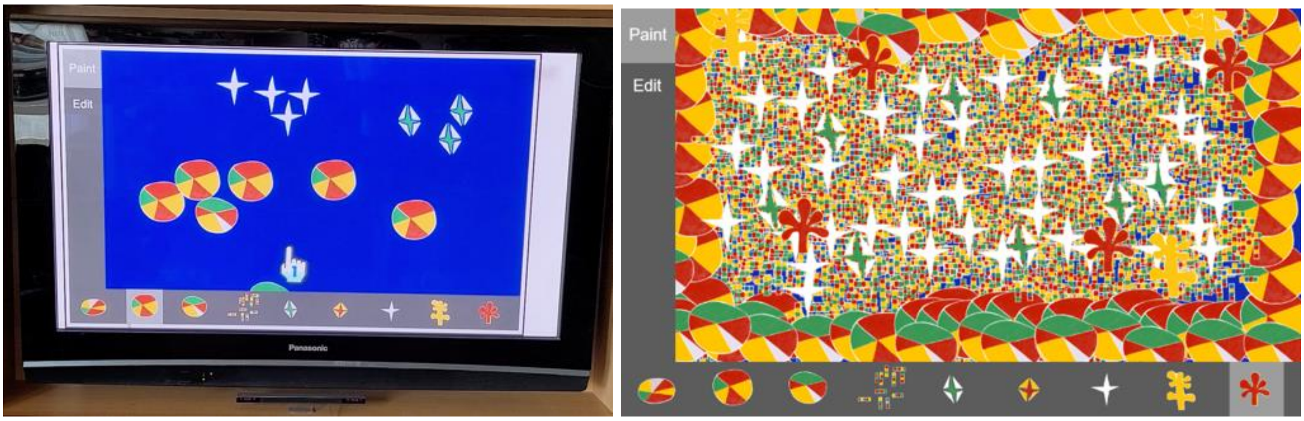


Figure 29. UC1.b GAM UI: early phase prototype. The artwork on the right has been created during the tests by 8 years old girl.

Figure 29 presents the prototyped first UI that we were using for the development of the project which rapidly evolved into next phase of UIs.

The final implementation consists of two UI views. The first one is projected UI on the big screen at the GAM. This could be also a smaller typical living room setup (PC connected to TV – see photo below).

Because of use of multiple controllers by “creators” there is required some sort of distancing between participants of experience for their safety.

Figure 30. PC with WebHID API web application connected to the Display (TV-Set or Projector) and Wiimote player playing the UC1.b Interactive Wall at home (Flexible portability and scalability of the system).

We connected and tested up to 5 Wiimotes. The Bluetooth Web HID API allows to pair many more devices with PC Browser – depends on the hardware (tested on Windows, MacOS, Android, Android Wearable, iOS). The main UI at the beginning provides at the center of UI dynamically generated QR code.

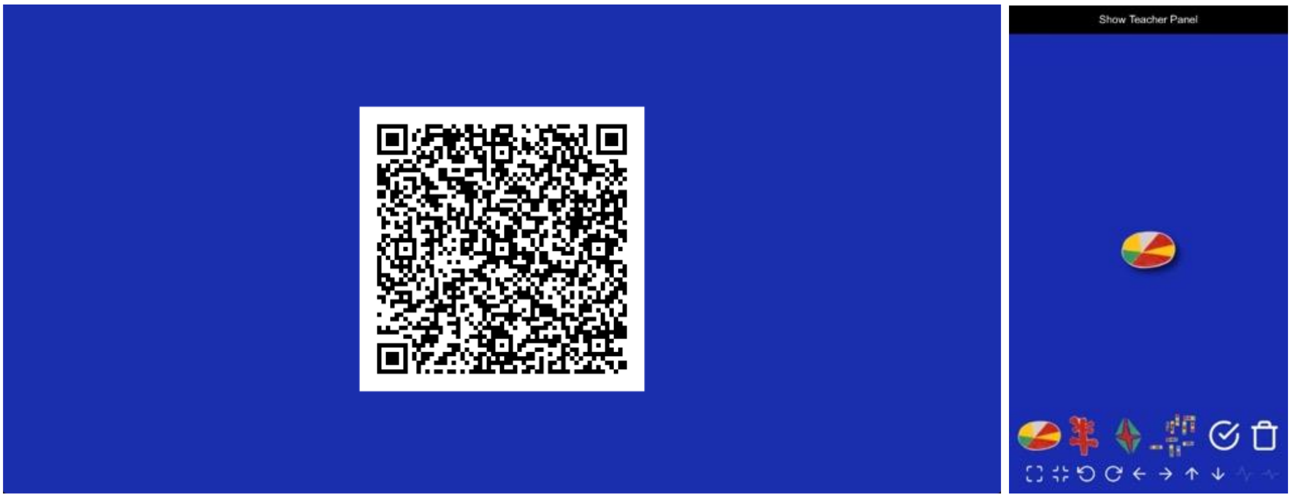


Figure 31. QR code on the main screen allows to open Teachers Desk on the mobile device.

It allows seemingly open Teachers' desks and access to the main screen. The interaction between both screens is bilateral. Teachers Desk has two modes: 1) Teacher Panel 2) Real-time Canvas. Users can switch between them by clicking the label at the top of the UI.

Teacher Panel has five buttons: Pause, Clear, Save, Save Alpha, QR. They allow the teacher to pause the animation of the shapes and Save Them as Images. The image is saved to the server (the naming convention: filename + timestamp +. extension) and also displayed at the center of Teacher Panel mode (so the teacher can easily save the image using the operating system dialog UI – "save as image"). Also, the teacher can completely clear the canvas. QR code allows to toggle on/off the display of the initial QR code on the main screen.

Figure 32. The Teacher's Desk UI on the mobile device.

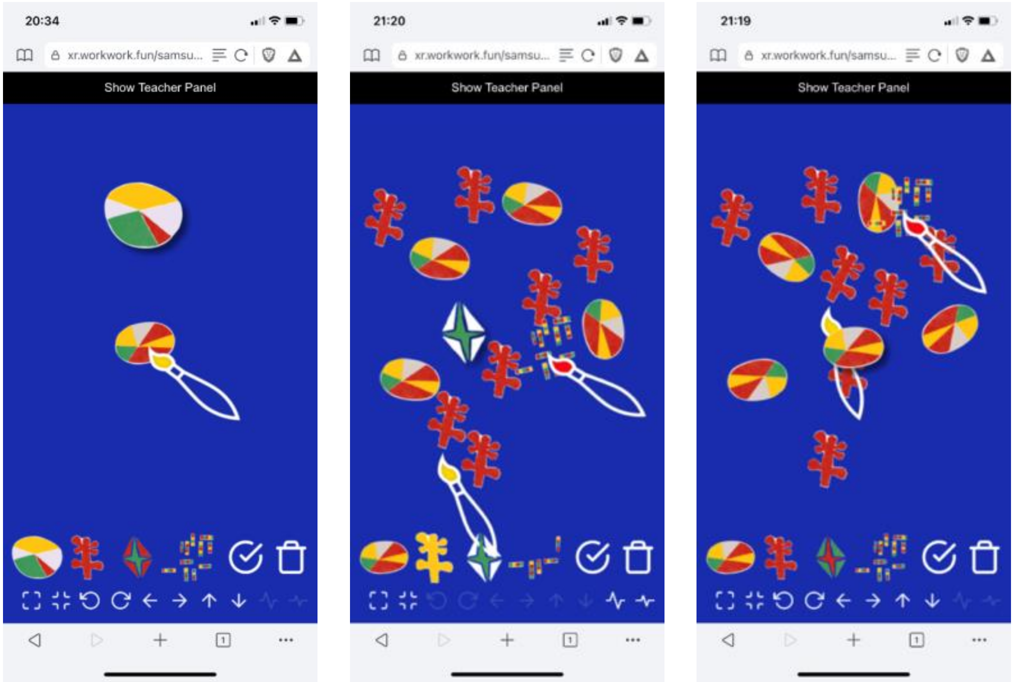


Figure 33. In Real-time Canvas.

In real time canvas the teacher can observe the creativity of multiple users connected to the main UI. Their presence is visible as pointer brushes which are manipulating the shapes, change the characteristics of their animations, and place them anchored to the canvas.

Real-time Canvas gives the teacher creative possibilities to add and manipulate shapes applying specific animation and scale. There are four main groups: Planets, Flowers, Stars and Seeds. These shapes have multiple color variants. Teacher can choose one and move it to desired location, apply animations (rotation, bouncing, swinging, pulsation), scale up and down.

There is also multi-level undo feature. Shapes previously placed by the teacher can be removed in inverted order. Such action of the teacher is visible in real-time bidirectional on main UI by the users.

2.3 Integration and test in labs

UC1.a AR: In the very heart of Turin

Due to COVID-19, laboratory tests have been essential. However, the restriction issue has been mitigated by a close collaboration among partners.

The flow of the app has been tested using both Wi-Fi and 4G network. All the functional tests have been performed using a Samsung S20 device, trying to mimic also the conditions (light, markers size…) to be similar to the ones present in Palazzo Madama. To simulate the physical beacon in the lab, an Android app has been used. It has been installed in another smartphone and it emits a Bluetooth signals exactly like the ones emitted by the beacons. The app has been integrated with the different services for crowding control, warning of fire or earthquake, and Smart Cities services. In addition, e-meetings between the partners were organized in order to debug specific functionalities of the application.

WebSocket's Latency:

The stress on the general latency has been specifically shifted to the assessment of quality of bilateral WebSocket's communication between multiple users. We have implemented overlay display to gain access to real-time data provided by WebSockets server and simply measuring differences between timestamps sent to/back ("ping-pong") from the VR app client and WebSocket connection session. The same method was used for UC1b. For example websocket stats on average public WiFi network were: rss 99.76 MB, heapTotal 52.69 MB, heapUsed 50.93 MB, external 3.81 MB, arrayBuffers 2.44 MB, CLIENTS: 1 and a very variable and unstable LATENCY measured between 50ms and few seconds).

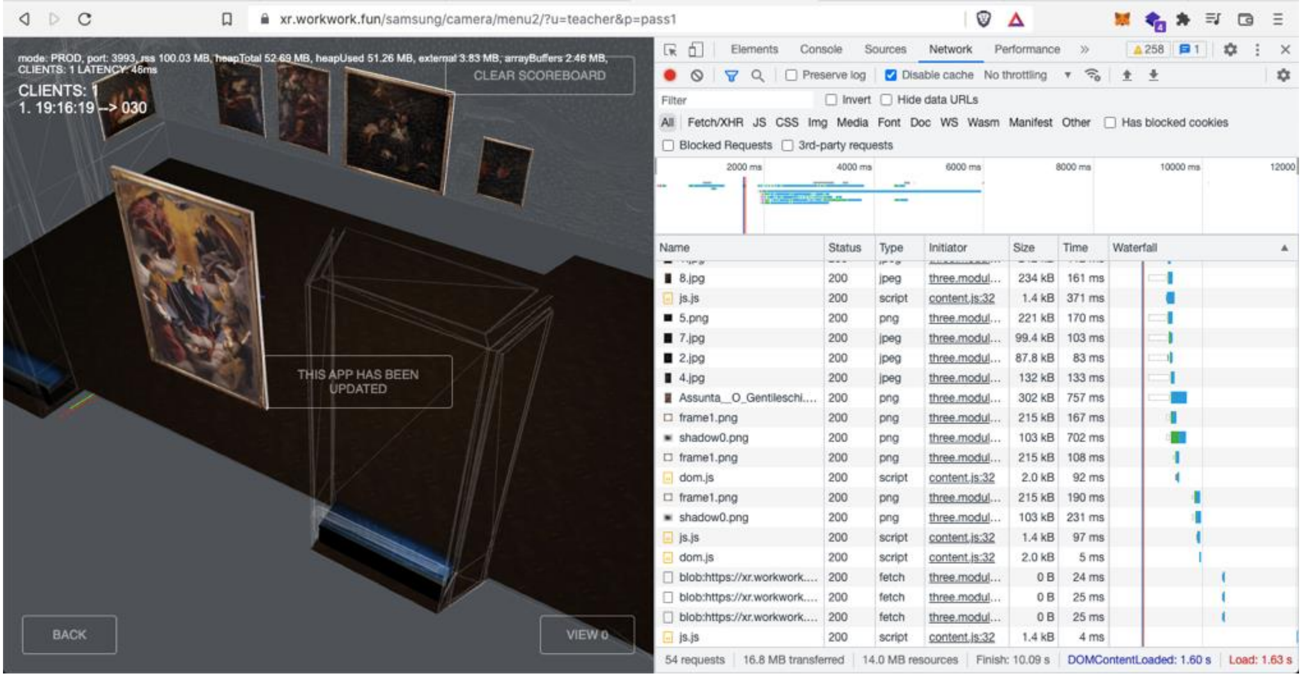


Figure 34. WebSocket Performance – example of OBSERVATION mode stats overlay.

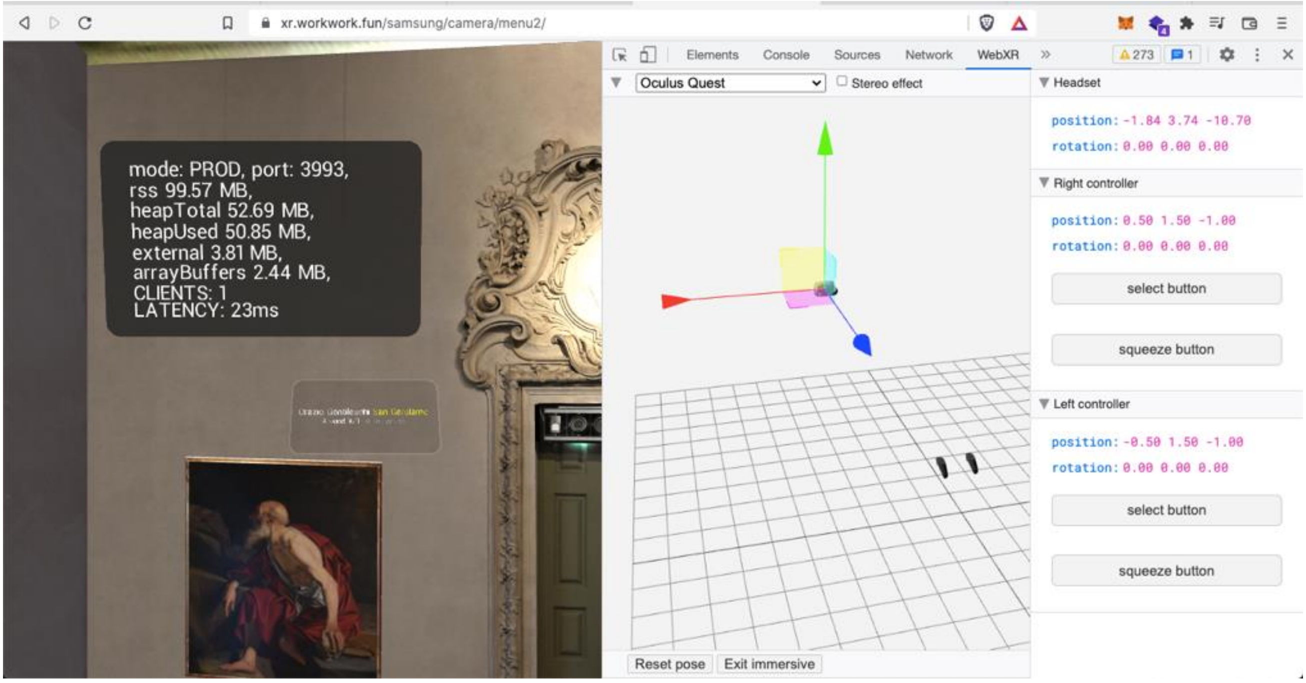


Figure 35. WebSocket Performance – example of stats available inside VR app (WebXR API emulator).

Payload:

The app has size 13.4MB and for instance has been served on the average public WiFi app in less than 3 seconds. The measurement of payload time has insignificant impact on the user overall experience and is not able to provide more specific data.

Figure 36. UC1.a initial payload

Motion Sickness reduction:

The use case 1.a VR test was focused on latency and bandwidth delivered to and from the device. Initially we focused on the solution to reduce motion sickness (aka cyber-sickness) which is understood as conflict between senses when the inner ear feels things while what you're seeing doesn't correlate with it. The 5G network reduced the latency between what the users' sight can experience and virtual sense of real motion. We hoped that low latency solves significantly this issue but did not design any tests to collect any data to confirm nor deny that.

The positive anti-motion sickness result has been achieved by the simplistic reduction of transitions (point-to-point teleportation). However, it's still possible to experience mild motion sickness by slow rotation of user camera or and all controller's joystick movements. Above features are not obligatory to traverse the virtual space also they might be confusing the sense of objective direction while used by multiple users at the space of shared guardian.

UC1.b: GAM and Edulab – Gamification, let's play artist

Real time gestures recognition by the input server.

The UC1.b shares most of the requirements of UC1.a VR. The stress point idea was focused on delivering assets dynamically on the screen projected wall while having users continuing their art piece work. Most of the web-apps are designed to have low initial payload and possibly small but larger chunks of progressive assets (on demand like video). Modern web applications are not designed to load extra assets anymore if the whole initial assets base can be reduced to minimum at initial payload, also it reduces drastically.

Payload:

Figure 37. UC1.b initial payload.

The idea of sophisticated centralized gesture recognition was scrapped as it would require advanced machine learning backend engine and/or not web-based access to native SDK. That would make the app development extremally difficult to develop in a short span of time without access to the team of machine learning engineers.

The assessment of bilateral WebSockets communication between two web interfaces (Teachers Desk and Students Screen) is exactly the same as for VR app (UC1.a.) Additionally we have implemented two methods measuring the latency from User's Desk to Students UI and vice-versa ([video](#) – directional latency test).

Figure 38. The overlay displaying FPS (frames per second - WebGL performance indicator) and LAT: WebSocket latency on both interfaces of Interactive Wall.

2.4 Test in the network

With reference to D2.3 [14] and regarding network KPIs, the table of Telepresence network requirements is reported below for all the UC1 sub use case. All collected data and results will be reported in D7.4 [9].

Table 1. UC1a – Augmented Tourism Experience AR (mMTC & eMBB)- network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(Reviewed) UC1a : AR - Augmented tourism experience (in Palazzo Madama)			Priority	Range	
			URLLC	mMTC	eMBB		Min	Max
General Vertical Use cases requirements								
1	Latency (in milliseconds) - round trip - Min/Max	msec		100	100		20	100
2	**RAN** Latency (in milliseconds) - one way	msec		25	50		25	50
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps		30Kbps - 130Kbps	400Mbps - 600 Bbps		30Kbps	600Mbps
4	Reliability (%) - Min/Max	%		99,99%	99,9999%		99.99%	99,9999%
5	Availability (%) - Min/Max	%		99,999%	99,99%		99,99%	99,999%
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h		N/A	10		0	10
7	Broadband Connectivity (peak demand)	Y/N or Gbps		No	0.08		0.08	0.08
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N		No	50		50	90
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N		Y (Baseline)	Y			
10	Capacity (Mbps/m^2 or Km^2)	Mbps/Km^2		1*	12**		1	12
11	Device Density	Dev/Km^2		20+	400		20	400
12	Location Accuracy	m		N/A	1		1	1

(*) 1 Mbps/Km^2 = 0,000001 Mbps/m^2

(**) 12 Mbps/Km^2 = 0,000012 Mbps/m^2

Table 2. UC1a – Augmented Tourism Experience VR (URLLC) - network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(Reviewed) UC1a : VR - Augmented tourism experience (in Palazzo Madama)			Priority	Range	
			URLLC	mMTC	eMBB		Min	Max
General Vertical Use cases requirements								
1	Latency (in milliseconds) - round trip - Min/Max	msec	20				20	100
2	**RAN** Latency (in milliseconds) - one way	msec	10				10	50
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps	100				80	100
4	Reliability (%) - Min/Max	%	99,9999%				99.99%	99,9999%
5	Availability (%) - Min/Max	%	99,99%				99,99%	99,999%
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h	10				0	10
7	Broadband Connectivity (peak demand)	Y/N or Gbps	0.08				0.08	0.08
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N	50				50	90
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N	Y					
10	Capacity (Mbps/m^2 or Km^2)	Mbps/Km^2	12				1	12
11	Device Density	Dev/Km^2	400				20	400
12	Location Accuracy	m	<1				1	1

Table 3. UC1b – Augmented Tourism Experience (URLLC) - network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(Reviewed) UC1b : Augmented tourism experience (in in GAM)			Priority	Range	
			URLLC	mMTC	eMBB		Min	Max
General Vertical Use cases requirements								
1	Latency (in milliseconds) - round trip - Min/Max	msec	20				20	100
2	**RAN** Latency (in milliseconds) - one way	msec	10				10	50
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps	80				30	80
4	Reliability (%) - Min/Max	%	99,9999%				99.99%	99,9999%
5	Availability (%) - Min/Max	%	99,99%				99,99%	99,999%
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h	10				0	10
7	Broadband Connectivity (peak demand)	Y/N or Gbps	0.08				0.08	0.08
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N	50				50	90
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N	Y					
10	Capacity (Mbps/m^2 or Km^2)	Mbps/Km^2	12				1	12
11	Device Density	Dev/Km^2	400				20	400
12	Location Accuracy	m	<1				1	1

The relation between sub-use cases and slices is the following:

- UC1.a AR, running in Palazzo Madama, is eMMB and mMTC.
- UC1.a VR, also running in Palazzo Madama, is URLLC.
- UC1.b is URLLC and running in GAM.

UC1.a AR: In the very heart of Turin

UC1.a mobile app has been tested on field with 5G network during two sessions organized in November 2021 and March 2022. Several tests have been performed with all features involving high bandwidth requirements such as multimedia content download, 3D object download. In relation to the smart city services, during the first test session the following activities have been performed:

- Definition) of the position where beacons and IoT devices has to be installed.
- First tests of the mobile app with 4G network, of the beacon location system and of IoT devices.
- Created a list of improvements and bugs to fix of the application.

After this test session the following enhancements were performed:

- Beacons tuning of transmission power and transmission interval to improve the signal coverage.
- IoT devices firmware bug fixing and improvements related to battery life as some of them are not continuously powered.
- IoT kit setup: to protect IoT devices (except for Pollution sensors) a custom kit with a robust case has been realized, as shown in the picture below.
- Improving the look and feel of the overall solution
- Integrating further multi-media contents (Videos, Pictures, audio script, 3D artifacts, etc.).
- Laboratory test with "external to the project" users to validate the usability of the interfaces implemented so far.

Figure 39. IoT custom kit.

During the second session of tests performed in March 2022 the following activities have been performed:

- Deploy of Beacons, IoT kits and air quality device.
- Final tests of beacon location system and IoT devices.
- Test of the mobile app with 5G network with 3D scans and AR Markers, assessment of beacon location system.

Figure 40. Beacon in Gabinetto Cinese.

Figure 41. IoT kit in Sala Acaja.

Figure 42. Air quality device in Torre Nord

At the time of writing this deliverable, the UC1.a AR trials activities are still ongoing. Therefore, the achieved results and performances over the 5G network at Palazzo Madama will be reported in D7.4 [9].

UC1.a VR: In the very heart of Turin

At the time of writing this deliverable, the UC1.a VR trials activities are still ongoing at Palazzo Madama. The results and performances will be reported in D7.4 [9].

UC1.b: GAM and Edulab – Gamification, let's play artist

At the time of writing this deliverable, the UC1.b trials activities are still ongoing at GAM. The results and performances will be reported in D7.4 [9].

3 UC2 – Telepresence

3.1 UC2 definition

The main goal of this use case is to test and employ a robot located inside the museum and controlling it from a remote location. Telepresence robots have the potential to contribute to accessibility and inclusiveness by extending access to previously excluded audiences. UC2 is divided into three subcases:

UC2.a: Palazzo Madama exclusive exhibitions for all

The idea of this sub-use case is to enlarge the public for selected exhibitions in order to make these experiences more accessible to all for a longer period as well as to use virtual exhibition as a promotional activity to attract foreign visitors or tourists. In particular, the specific sub-use case is set in Palazzo Madama and is characterized by a remote visit to the museum basement and underground, an area normally closed to the public and difficult to reach, at present time only visible through the glass floating floor of the main hall at ground floor.

UC2.b: Play and visit modern art from museum to school

The objective of this sub-use case is to offer enhanced educational activities to students at school. The target audience for this application is children aged from 6 to 13 years old. The selected location links students located at the Edulab premised with GAM. As for UC1.b, and because of the UC's target, gamification is used throughout the creation of a virtual "Treasure Hunt".

3.2 UC2 implementation

Compared to the previous deliverable D4.2 [2], the main part of the development is focused on the creation of the GUI used for trials open to the public. The activity was carried out with the participation of the staff of the Fondazione Torino Musei who was directly involved in the trial activity, to create a system of immediate understanding and with an integrated aesthetic component with respect to the existing sites and portals.

The robot piloting activity is reserved to trained museum operators, therefore the graphical interface will be used only by them (but displayed by tourists who will use the services in the rooms designated for remote visits or treasure hunts). As far as remote surveillance is concerned, the end-users will be the security personnel of the museum system, but also in this case it was decided to give homogeneity to the pages of the navigation and data display interface.

The web application developed has a common home page that allows the users to choose one of the three implemented sub use cases, and the project's credit information. From this, the three specific applications described below are then activated. The three pages have however been developed with a homogeneous structure, in which an information frame completes and contains the navigation page of the robot, obtained by integrating the navigation and piloting platform available for the robot.

From the point of view of the application requirements, the final definition of the content of the trial allows them to be simplified, because the need for remote visiting stations in which the pilot and the public are physically separated has disappeared. Although the platform could allow, outside the context of the project, further developments and extensions of the UCs consolidated today, the previously described software components, which would be used for these further developments, have been removed because they are currently outside the context of the project.

UC2.a: Palazzo Madama exclusive exhibitions for all

After a set of visits and tests in the museum, according also to the 5G coverage shared with other UCs, the areas of Palazzo Madama involved by UC2.a are the ground floor, the «Piano Nobile» and underground floor (a restricted access area not accessible by the public) as depicted in chapter 7.

The trial application for UC2.a is a guided tour, from an equipped room inside the museum (bookshop), to the underground spaces of the museum that are not accessible to the public for safety reasons. In a future work, after the end of the project the remote visit can take place in different areas of the museum.

As previously described in D4.2 (5G-TOURS, “D4.2 First Touristic City use case results”, December 2020) from the user perspective level, four types of required endpoints needed to cover the different scenarios foreseen for the UC2.a. have been defined. A detailed description of these endpoints is available in D4.2. To allow the use of the visit to the undergrounds, given that the pilot and the public use the same station, which is a totem positioned on the ground floor of "Palazzo Madama" inside the Bookshop, endpoints 3 and 4 are not used and, consequently, the application architecture is simplified and limited to first two endpoints types described below:

- **Endpoint type 1:** The robot inside the museum, with bidirectional audio/video communication with the other subsystem (connected with 5G mobile indoor coverage);
- **Endpoint type 2:** The pilot of the robot, that controls the robot via UI, plus (optionally) one or more people in the same room that look at the robot video, and interact with bidirectional audio/video with the robot side of the system (connected with a broadband cable);

On the server side, the consolidation of the requirements allows the use of a single architecture for the three sub-UCs involving the Double3 robot, as described in the following paragraphs.

From the point of view of the GUI, the application is composed of a modular structure that contains a navigation toolbar at the top, a retractable information sidebar on the left side, and the main area that contains the connection and navigation interface to pilot to view the contents transmitted by the robot.

Detailed information on the current visit is available in the information area, which can be used by the guide conducting the visit to provide more information to the public. The area is structured on two levels of web browsing, one used as an index and one of information pages containing useful texts and images.

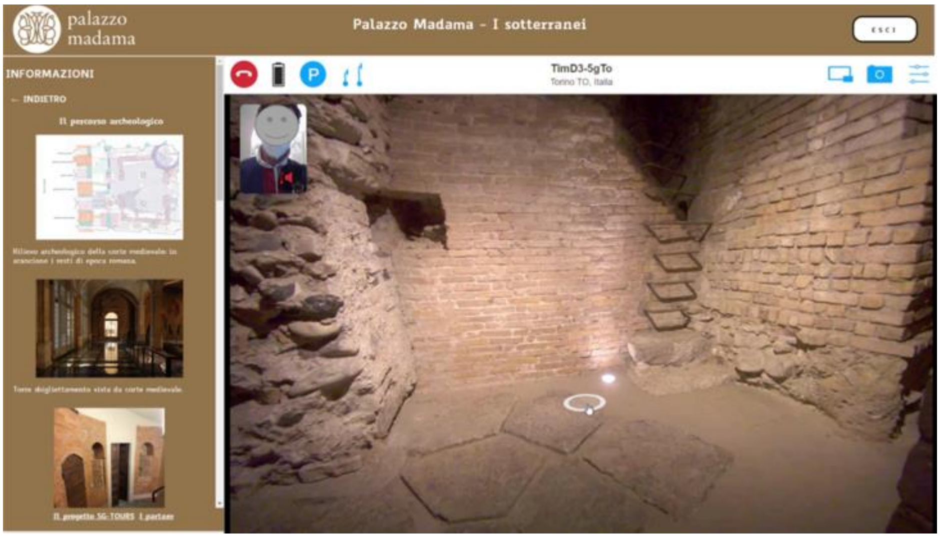


Figure 43. UC2.a application screenshot.

UC2.b: Play and visit modern art from museum to school

In the previous phases of the project, as described D4.2 (5G-TOURS, “D4.2 First Touristic City use case results”, December 2020), the candidate areas inside the GAM involved in the UC2.b were identified, according to the map reported in Chapter 7. The location inside GAM is the permanent collection area on the first floor.

As already expressed in the previous deliverables, the preliminary test of the robot movement and speed capability highlighted the need to reduce the area involved in the "treasure hunt" to avoid long movements of the robot that would waste time and reduce the level of attention and usability of the service. The area called “Manica Lunga” on the first floor was chosen as the location for UC2.b implementation.

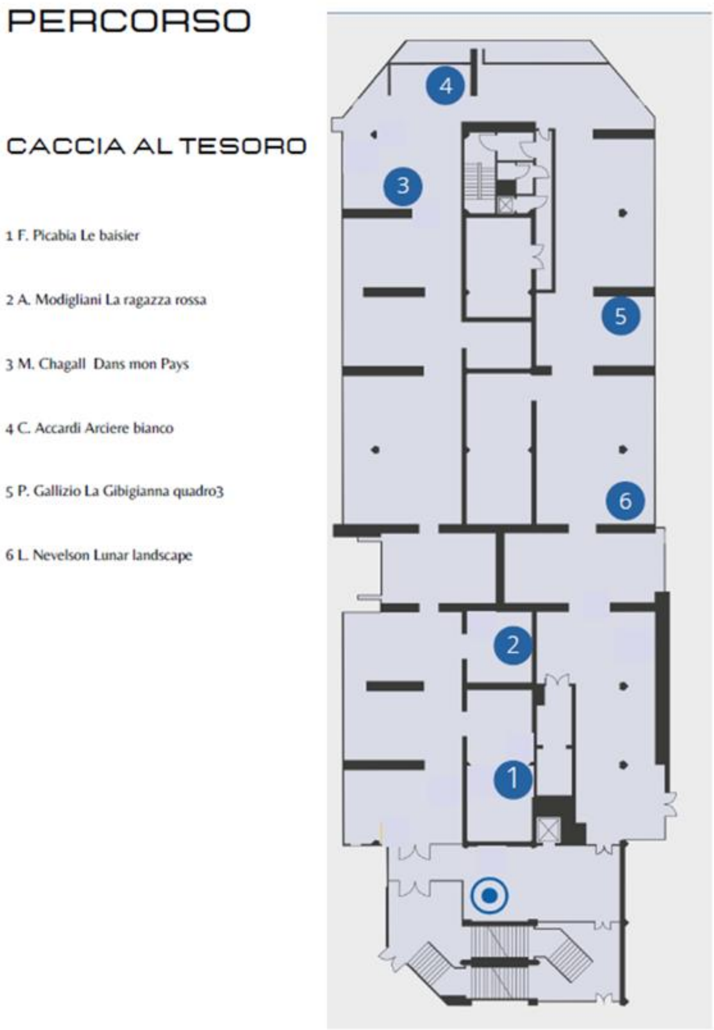


Figure 44. UC2.b Treasure hunt map.

During the previous phase of the project, the path used for the treasure hunt and the artworks involved have been defined in more detail, paying particular attention to the clues to be used, and their visibility through the robot's video tools.

During the tests, it was confirmed the need to have the robot driven by a person with an appropriate training and not directly by the public. The service can therefore be enjoyed by the public in the same room as the guide (who is the pilot). The premises inside Edulab have been chosen as the visitors room, where both the educator (and the pilot) and the schoolchildren (the public) can take advantage of the UC2.b service.

As in D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) from the user perspective level they have been defined three types of required endpoints needed to cover the different scenarios foreseen for the UC2.b. The last one, however, is not used in the current implementation of the UC, so the endpoints used are the ones described in UC2.a.

On the server side, the consolidation of the requirements allows the use of a single architecture for the three sub-UCs involving the Double3 robot, as described in the following paragraphs.

From the point of view of the GUI, as in UC2.a, the application is composed of a modular structure that contains a navigation toolbar at the top, a retractable information sidebar on the left side, and the main area that contains the connection and navigation interface to pilot to view the contents transmitted by the robot.
The information area shows the steps of the treasure hunt and the related clues, accompanied by texts and images useful to guide the museum to conduct the treasure hunt by helping the public to identify the various artworks and search for them in the museum through the robot. All the contents and appearance of the GUI were shared with "Fondazione Torino Musei" staff during the design and development process.

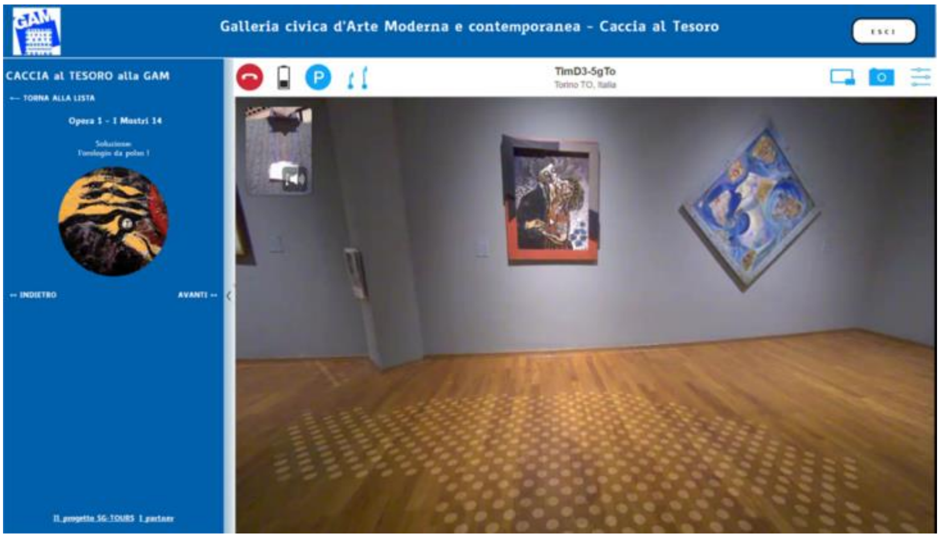


Figure 45. UC2.b application screenshot.

UC2.c: Surveillance of the museum

The location for UC2.c was defined after the consolidation of UC2.a, UC2.b and UC3, and it consists of the "piano Nobile" and the "Sala Ceramiche", where most of the IoT sensors used for UC1 are located. The control room is in Palazzo Madama. Surveillance UC is implemented using two different robots, which provide a different level of autonomy: from pure teleoperation (Double3 robot) to mixed teleoperation/autonomous navigation (R1 robot).

Double3 robot

The Double3 robot solution is a teleoperation only system, usable during daytime or in rooms where a sufficient level of artificial illumination is available.

As previously described in D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) from the user perspective level they have been defined only two types of required endpoints needed to cover the very simple scenario of UC2.c daytime.

On the server side, the consolidation of the requirements allows the use of a single architecture for the three sub-UCs involving the Double3 robot, as described in the following paragraphs.

The integration of UC2.c with the data of the IoT platform takes place through the use of the API made available by UC1, to find and display the necessary data within the GUI. All integration is done in the web application directly from the frontend, as indicated in the next paragraph.
The data of the IoT platform used are:

- Reading of temperature and humidity data from environmental sensors
- Reading and notification of the fire alarm status
- Reading and notification of the earthquake alarm status
- Position reading via the beacon network

The application running on the mobile terminal on board of the robot also checks for the presence of beacons and notifies the IoT platform of the change of position.

From the point of view of the GUI, as in UC2.a and b the application is composed of a modular structure that contains a navigation toolbar at the top, a retractable information sidebar on the left side, and the main area.

Unlike the other UCs, the content of the main area changes according to the activity carried out by the surveillance staff:

- When the application is started, the map of the museum is shown with graphic information about the status of the sensors. In the information area, the sensor data and their status are displayed in table format. In the lower part, there is a button that allows the user to start the remote connection to the robot and start the remote surveillance session.

- When in surveillance mode, the main area contains the connection and navigation interface used to pilot and view the contents transmitted by the robot. The information area shows the status and values reported by the IoT sensors installed in the museum in a table format, and a mini-map of the palace, reporting graphically the position and the status of the sensors, and the rooms in which the robot is located, based on the beacon data collected by the on-board mobile phone.

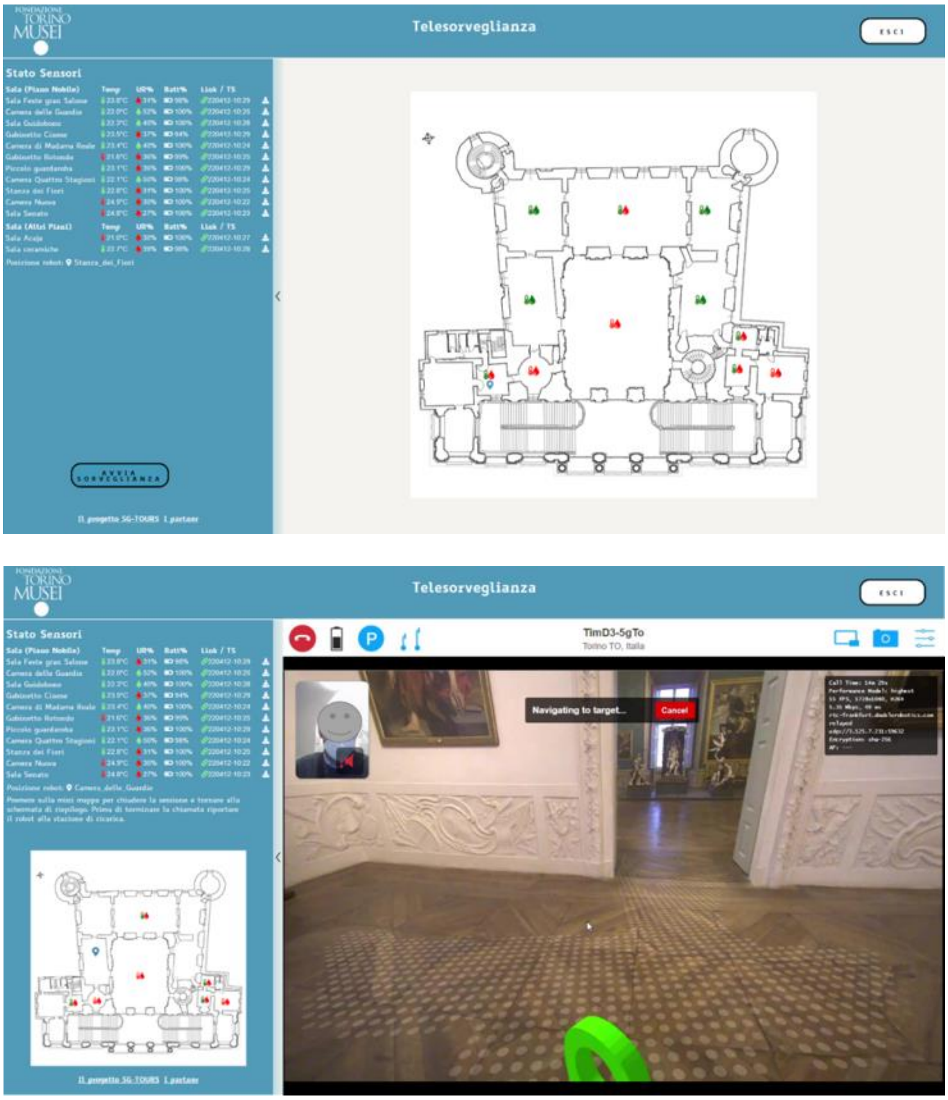


Figure 46. UC2.c application screenshots.

R1 robot

The R1-based surveillance application is a "mixed" solution that combines teleoperation and autonomous navigation (patrolling) using a complete map of the environment, which reduces the effort required by the operator for controlling the robot. Some of the work is therefore common between UC2.c and UC3. This includes both hardware upgrades for 5G connectivity and the integration of new sensors for indoor localization, as well as the development of some software components which are, in some cases, used even more extensively in UC3. The autonomous navigation system is an example of such a module. Advancements on these common tasks are reported in UC3, sections 3.2.2 and 3.2.3.

During the teleoperation task the robot is required to:

- transmit to the operator large amounts of data (the video stream and the lidar/3D sensors data);

- receive from the operator small amounts of data (the control commands) but with minimum latency.

It must be noticed that in this UC we do not transfer video streams from the surveillance operator to the robot, so the downlink bandwidth required on the robot side is basically limited to the robot control commands (whose size is extremely small compared to a standard video stream). For this reason, this sub UC mainly stresses the 5G upload bandwidth.

Regarding the teleoperation GUI, we integrated the navigation application of the R1 robot in the same GUI of the Double3 robot, in order to provide a homogenous experience of operation to security personnel. One note-worthy difference, however, is the login page, whose engine is different for the two robots and requires different accounts. This difference become a major issue during the final tests, since, due to security restrictions on the public server on which the portal runs, it was not possible to redirect the user from the main login page to the R1 navigation page. To overcome this problem, during the final trials, we run the R1 robot teleoperation web page onto a different server but using a page layout similar to the one used by the Double 3 robot.

3.2.1 Application Components

Double3 robot

As previously mentioned, the system architecture has been simplified as result of the consolidation of the sub UCs and their convergence on a single platform. Regarding the Double3 robot solution, a scheme of the application components required by UC2.a/b/c is described in Figure 47.

Not all the parts are used in all the sub UC scenarios, but the most complex architecture necessary to implement UC2 may include all the shown components. The platform also allows the creation of even more articulated and complex scenarios, as initially described in the previous deliverables. The components involved in these scenarios have been removed from this document as they have not been used in the trials (for their description see the previous D4.1 138[1] and D4.2 [2].

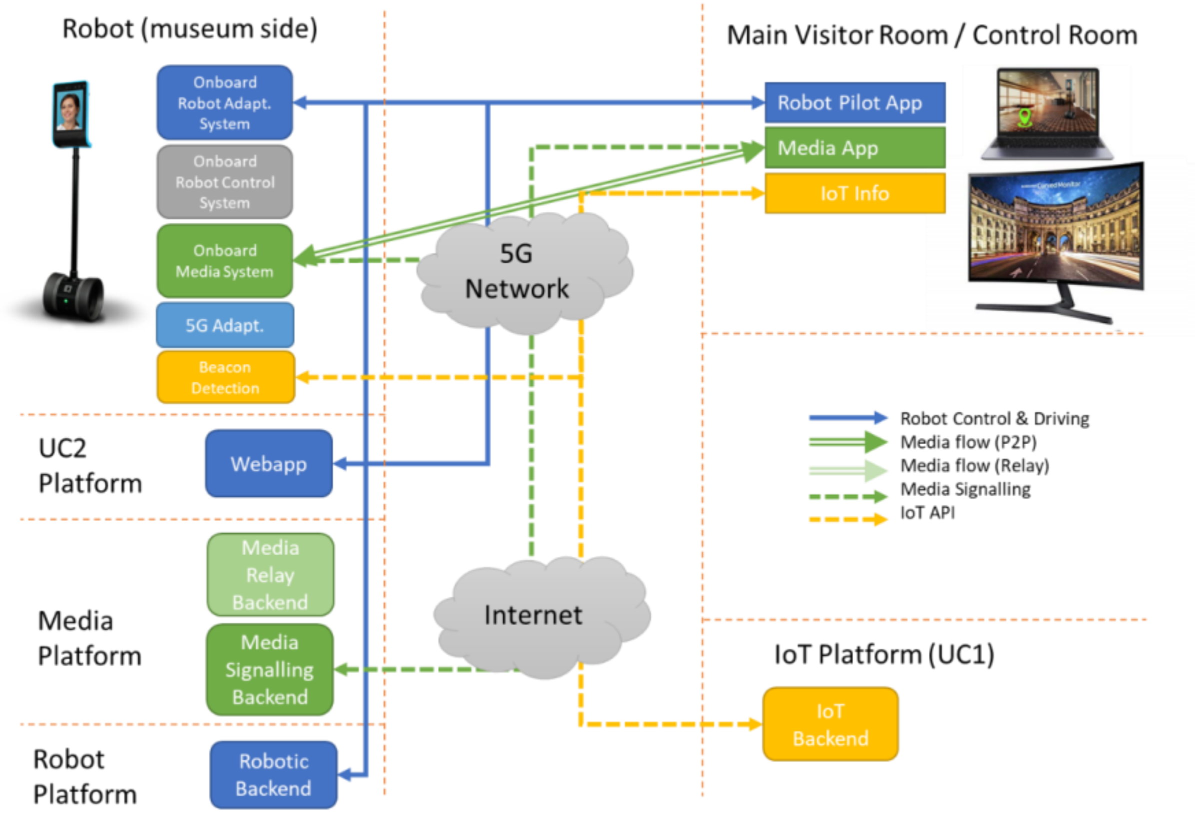


Figure 47. Scheme of the application components required by UC2.a/b/c.

The application is distributed and it allows robot access and control plus the establishment of the multimedia session necessary to give the telepresence experience for the Use Case. The different logical blocks can be described as follows:

- **Robot side:**
  - **Onboard Robot Control System**: is the main OSS of the robot containing all the software components necessary to control the robot movement (wheels, stand, pole) and the devices of the robot (camera, pan-tilt-zoom controls, microphone, navigations sensor);
  - **Onboard Robot Adaptation System**: is the application interface between the robot system and the service application, that allows robot remote connection and operation establishing a peer to peer control channel between robot and pilot application;
  - **Onboard Media System**: is the multimedia system (web-rtc audio video streaming function) that enables bi-directional audio video connection between the robot and the other endpoint involved in the use case. This part handles the signaling and call setup functions interacting with the Media Control Layer in the backend, and it handles the peer-to-peer multimedia flow streaming and receiving;
  - **5G Adapter**: is composed by the tools and driver necessary to give the robot the ability to connect to a 5G network, since the robot doesn't support natively the 5G connection but only the Wi-Fi connection.
  - **IoT Integration**: is composed by a foreground service Android application, running on the mobile phone used to provide 5G connections to the robot. It scans the IoT beacon network deployed in the museum to detect the room occupied by the robot, and it transmits this information to the IoT backend.
- **UC2 Platform / Webapp**: is the server that hosts the UC2 web app used by all sub UCs.
- **Robot Platform**: is the server platform involved in the application. Localization of this server does not influence the latency, because it is directly involved only during the connection/call setup, while during the telepresence session the control message is transmitted peer to peer between robot and pilot application
  - **Robotic Backend**: performs all the platform-related server functions, such as user authentication, robot connection, and discovery, robot management, and mediation.
- **Media Platform:**
  - **Media Signaling Backend** handles all the media-related signaling and session operation needed to setup the media flow, directly in peer to peer mode (preferred solution to reduce latency) or via MCU/SFU function. If necessary, based on the architecture of the network used, it can also perform the functions of STUN / TURN server;
- **Main visitor room / Control room**: is a web browser-based application that allows the pilot to perform all the necessary operations to discover and connect to the robot remotely, move it in the space of the museum using the point and click enhanced navigation interface, control the camera pan-tilt-zoom functions:
  - **Robot/Media pilot application**: full control application with robot control and remote audio video visualization;
  - **Media application**: visualization only application to give the public a better vision experience without the superimposed graphical interface used for navigation;
  - **IoT info:** integration of IoT data (shared between UC1a and UC2) to give a comprehensive digital view of the museum. The following information is available:
    - Temperature and humidity and crowding level of each room;

- Alerts, if some thresholds are exceeded (regarding the parameter above) or in case of emergency (fire, earthquake).

- **IoT Platform / Backend:** shared with UC1, provides IoT back-end to integrate IoT sensors data in the UC2.c scenario.

To achieve the best performance in terms of low latency and band performance of the 5G network, the main media flow (between the robot and the visitor/control room) was peer to peer. Also the main control data flow between the robot and the pilot application was handled in peer to peer mode, in order to minimize the delay and maximize the user driving experience.

To better clarify the components involved in the different UC2 sub scenarios reported in Figure 47 shows the architecture implemented by a remote visit to the underground floor (UC2.a), in which the museum guide (who was also the pilot) was in the same room with the visitors. The same architecture was used for UC2.b, the remote treasure hunt at GAM, where the educator was also the pilot and was in the same room with the students.

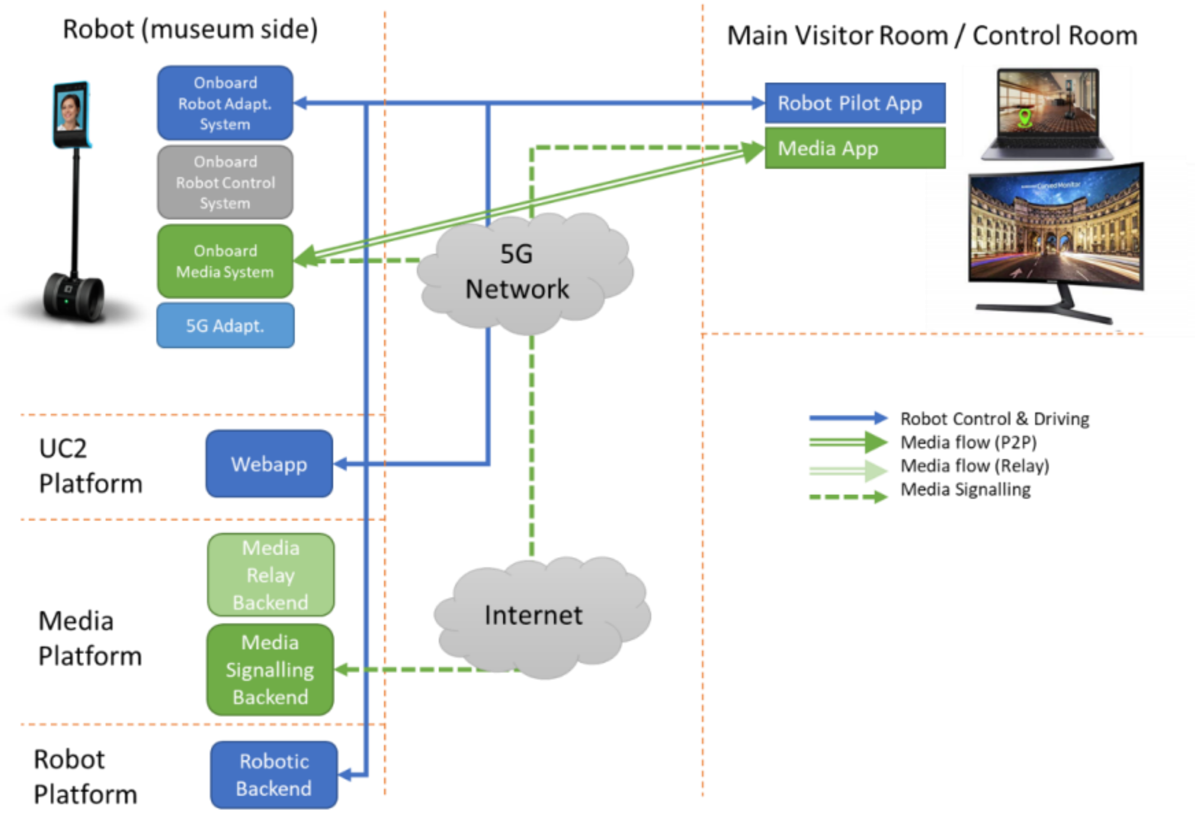


Figure 48. Schema of the application components required by UC2.a and UC2.b.

Finally, the case of UC2.c remote surveillance used the whole architecture shown in Figure 48. Schema of the application components required by UC2.a and UC2.b. in which the IoT part is highlighted.

R1 robot

The R1-based surveillance application consists of three main blocks, depicted in Figure 49.

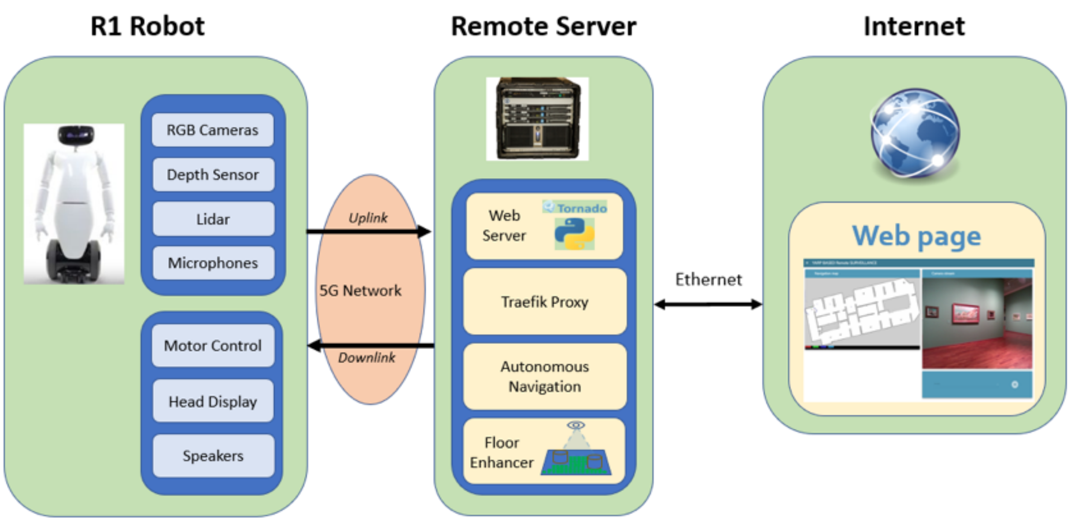


Figure 49. The R1-based surveillance application main blocks.

1. **The robot**: R1 is a network composed of multiple computational units. Each machine controls a specific hardware subsystem (e.g. motors, cameras, etc.) and it communicates with the others. A 5G connection toward the mobile network allows the robot to exchange data with a remote server located in the museum control room or in TIM premises.
2. **The remote server**: it consists of multiple machines which:
   - Allow a human operator to monitor the museum environment seen by the robot cameras;
   - Perform the required computations transforming the goal provided by the operator into an autonomous navigation plan (including obstacle detection and avoidance);
   - Enhance the camera view via augmented reality. AI algorithms can be plugged into the video processing pipeline for highlighting specific areas of the scene, for example performing object recognition and people detection;
   - Perform system management, checking periodically the status of the robot (both hardware and software), monitoring the data flows, and triggering alarms.
3. Run a webserver and proxy which exposes the application public ports, allowing users to connect to the robot and teleoperate it. **The web page:** it is the application frontend, used by the museum operators to control the robot. It can run on the browser of a standard PC or smartphone connected to the internet.

3.2.2 Terminal Equipment components

Double3 Robot

5G connection on board the Robot: the initial solution involved the use of a 5G USB dongle device to connect the Double3 robot to the 5G network. Pending the availability of a 5G device, initial testing and development was carried out with a 4G device. Due to the continued unavailability of this type of devices on the 5G network during the second part of 2021, not being able to wait any longer to finalize the developments and tests of the UC, a more secure solution was opted for using a 5G terminal connected via USB tethering to the robot, to minimize the delay introduced. This required finding a solution for fixing the terminal to the robot that was robust, stable, light, and did not interfere with the balance of the robot itself, and with the navigation sensor system. After several tests (as described in previous document) a solution was found, consisting of a support bracket for mountain-bikes, in silicon and plastic, fixed to the robot pole, immediately under the attachment of the head, so that the terminal is as close as possible to the axis of the robot (to avoid imbalances) and behind the head itself, where there are no position sensors (see Figure 50).

Figure 50. Details of mobile phone support and connection.

R1 Robot

A solution similar to the one implemented on Double3 was adopted also by the R1 robot with one major difference: in this case the robot is not constituted by a single PC, but by a network of multiple machines. Having multiple 5G terminals connected to the individual PCs was not a viable solution, since it would imply sending and receiving data to the network also for internal communication. For this reason, we chose to equip the robot with an internal router which manages the internal traffic, and, when required, routes it to the 5G network through a 5G terminal connected via USB. The internal robot private network and the remote servers are then connected through a VPN tunnel. Additional details about this network configuration are provided in UC3, Section 4.2.2. In order to provide easy accessibility to the control interface, the 5G terminal was attached to the R1 robot arm using a standard sport arm band (Figure 51).

Figure 51. The 5G phone attached to the left arm of the R1 robot.

IoT device

The IoT platform used in UC2.c is the same used in UC1.a. For a detailed description of the equipment involved refer to the corresponding paragraph in the UC1.a chapter. 2.2.1 Application Components of D4.2 [2].

3.2.3 Interfaces

Double3 Robot

The integration of the Double Robotics platform was done at the application level, without the need to interact with the API of the native platform, so the description of these interfaces is omitted as it is not relevant.

For the integration of IoT platform data into the GUI used for UC2.c, the REST API and Websocket interfaces made available for UC1.a were used, which allow to:

- Read the status of the sensors installed in the museum;
- Download historical data of the sensor installed in the museum;
- Read the detected position of a terminal based on readings from nearby Beacons;
- Subscribe to the notification of alarms received by the sensors;
- Receive notification of subscribed alarms on the application WebSocket.

As for the detection of the position of the robot, on the application residing in the mobile terminal used for the connection, another REST interface of the IoT platform is used, which allows to:

- Notify the platform of the last Beacon identified by the device.

Through these interfaces, the remote surveillance application can retrieve and present IoT data aside the remote surveillance video window. For more details on these interfaces, please refer to the corresponding paragraph of the chapter relating to UC1.a (2.2.3Interfaces).

R1 Robot

To control the robot R1, we used YARP, a middleware developed by IIT. Also in this case, the platform interfaces used for UC2.c are the same as UC3, hence they are described in details in the corresponding paragraph of UC3, Section 4.2.3.

Since the whole robot is connected to the remote control through a VPN, we used additional commercial software, Traefik by Treafiklabs, to publicly expose a subset of ports used by teleoperation application, while keeping private the other ones. The public ports are: the port which streams the video captured by the robot cameras and the port used to receive the commands (movements or actions) from the operator. The WebScoket protocol is used to connect these ports to the teleoperation GUI, which is embedded into a web page running on a Tornado Web Server.

UC2.c: Surveillance of the museum

Robots are used for tele-surveillance of the museum both during day and night hours. The selected test bed is Palazzo Madama. The use case shares IoT data collected in UC1.a through sensor networks about the crowding level of rooms, safety conditions (fire and earthquakes alerts) and other information like temperature and humidity inside each room (to preserve artworks).

3.3 Integration and test in labs

Double3 Robot

The testing and development activity related to the Double3 robot was carried out as a continuation of what was previously described D4.2 (5G-TOURS, “D4.2 First Touristic City use case results”, December 2020).

All the development and in labs test were performed in smart working environment due to COVID-19 pandemic that lasted during most of the project time. Different rounds of on-field tests were carried out since the beginning of July 2020 to July 2021.

These tests, focused on the Double3 robot, took place at Palazzo Madama to test the capability of the robot to move in the spaces of the museum on the different kinds of floors and rooms, to check the automatic obstacle avoidance system behaviour in front of glasses, mirrors and other precious and fragile artworks present in the museum, and also to check the reaction of the robot in the narrow spaces of the basement of the building. In the same period, the field test took place also at GAM to check the interaction of the robot with the museum spaces and artworks, and also to evaluate the movement speed of the robot in the wide space of the gallery.

In both museums, the video capability of the robot was also checked, in order to better identify the artworks and the details that can be used during the remote visit and to finalize the storyboard of the UC2.a and UC2.b trials.

Some issues related to the behavior of the robot on shiny floor such as the one of the GAM were found and solved.

The tests confirmed the need to plan the remote visit in detail, and to define the storytelling for both locations. To speed up the movements and positioning of the robot in the best points for the visibility of the works, a placeholder was placed on the floor to be used by the staff driving the robot during the visit/treasure hunt.

During the first quarter of 2022, other round of on-field tests took place, to check the path defined for the UC2 sub use case, simulating a visit to evaluate the overall time of the activities in relation to the relative "slowness" of the movements of the robot in the wide spaces of the GAM, to maintain a good level of interactivity and interest in the visit.

During the last round of on-field test in March 2022 the whole architecture for UC2 was tested, checking the web application, the 5G coverage in both museum, the integration of the IoT sensors data and beacon. Finally a dry-run test was performed, simulating the path and story of the three subs UCs.

Numerous laboratory tests were carried out with different types of connections, to evaluate both the performance and the connection methods used by the robot, in particular as regards the management of the NAT (Network Address Translator) present in the connection between the robot and the pilot's PC.

Figure 52. Media flows – Single point peer-to-peer. shows the network media flows involved in a single point telepresence session when the NAT traversal allows the establishment of peer-to-peer connection.

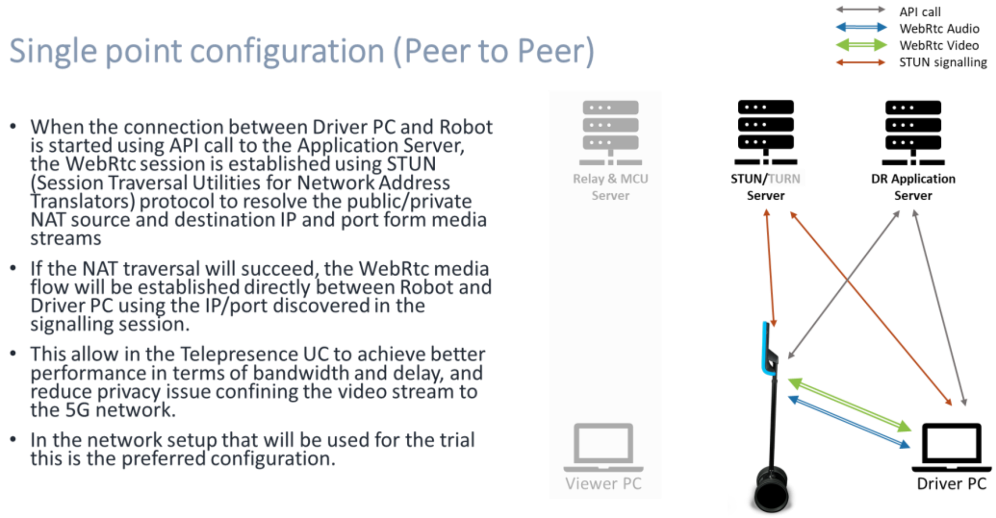


Figure 52. Media flows – Single point peer-to-peer.

The resolution of the NAT and the possibility of using a peer to peer connection between the robot and the pilot PC simplify the architecture by eliminating the need to have the Media Relay Backend and the Media Signalling Backend connected close to the 5G network.

As already mentioned, for reasons of unavailability of 5G USB dongle devices, the connection between the robot and a 5G phone is performed via tethering using a USB cable. The direct connection via USB was chosen because it allows the transmission delay to be reduced to a minimum and to be kept constant, compared to a WiFi connection with the same 5G terminal.

Switching from a USB Dongle to a 5G phone in USB tethering required finding a good solution for fixing the phone to the robot. Several tests were carried out with different types of fastening systems. These are mobile phone holder brackets normally sold as motorcycle or mountain bike mounts.

At the end of the tests, the best positioning turned out to be behind the robot's head, using a very light and not very protruding bracket. The bracket is fixed to the mobile part of the pole of the robot.

Regarding the location, during the preliminary on-field test the need to find a protected area (not accessible by visitors) where to install the Robot charge docking station, with a power supply socket and a good level of 5G radio coverage was addressed. During the subsequent tests at GAM, the location was identified in the atrium at the first floor near the entrance of the exhibition area of the permanent collection, involved in the treasure hunt. At Palazzo Madama the remote visit took place in the underground part of the museum that is not accessible to the public, so the robot was safely placed in the area, near to the electric plug available. Since the area involved in UC2c, remote surveillance, was the first floor of Palazzo Madama, the recharging station was located in a service area near to the Veranda Nord room, a location which is not accessible to the public during the opening time of the museum.

R1 Robot

About the R1 robot different solutions were tested to efficiently encode the camera's video stream and transmit it on the mobile network. Particularly, the Mjpeg, H264 and H265 encoders, made available by the FFmpeg library, were integrated with the robot software. To validate the performances of YARP (i.e. the robot software infrastructure), latency tests were performed in ERI-IT E2E Lab in Genoa. These tests, initially performed using a 4G-LTE network, were repeated at ERI-IT premises, using a fully functional 5G network that replicates the one available in Turin. Since the software infrastructure is common between both UC2.c and UC3, the results of these experiments are reported in the corresponding paragraph of UC3: 3.2.1.

Additionally, a graphical interface for the teleoperation of the robot was also developed and tested in simulation and in laboratory environment, see Figure 53. The interface shows an augmented reality view of the environment in front of the robot, as seen from its cameras. On the top of the video stream, the free areas (i.e. areas without obstacles) are highlighted in green. The user is thus visually notified of the areas which the R1 robot is able to reach and he can send navigation commands by clicking on the image. In this way, the robot can be safely tele operated in an unknown environment, without the risk of colliding with walls or other obstacles.

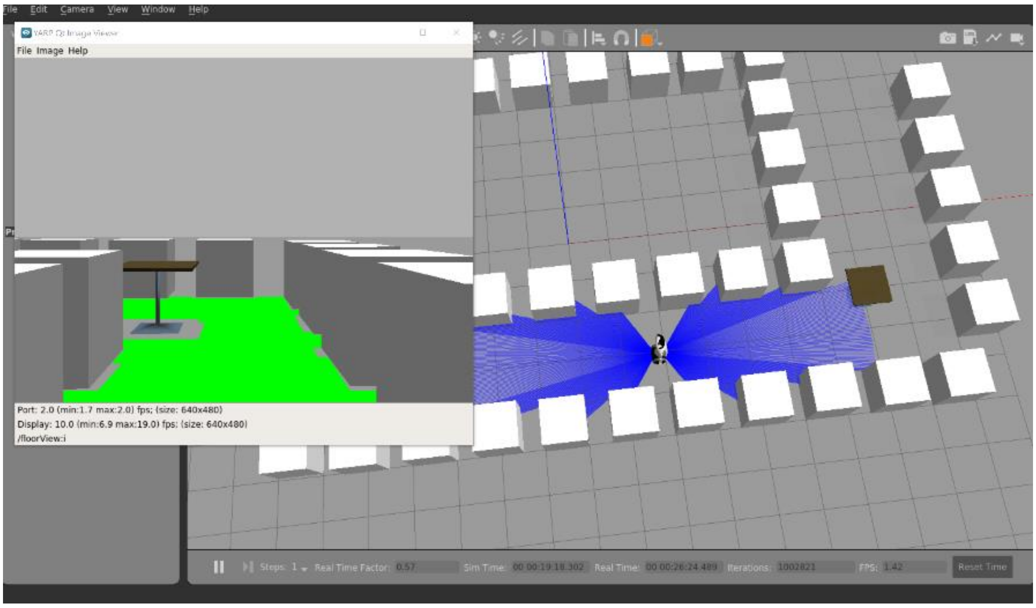


Figure 53. Graphical interface for the robot teleoperation (in simulation).

Thanks to the modularity of YARP, additional layers of image processing can be plugged into the video processing pipeline and further augment the view. For example, Figure 54 shows another YARP module, *yarpOpenPose* which wraps the Openpose library to detect humans through an ad-hoc trained neural network.

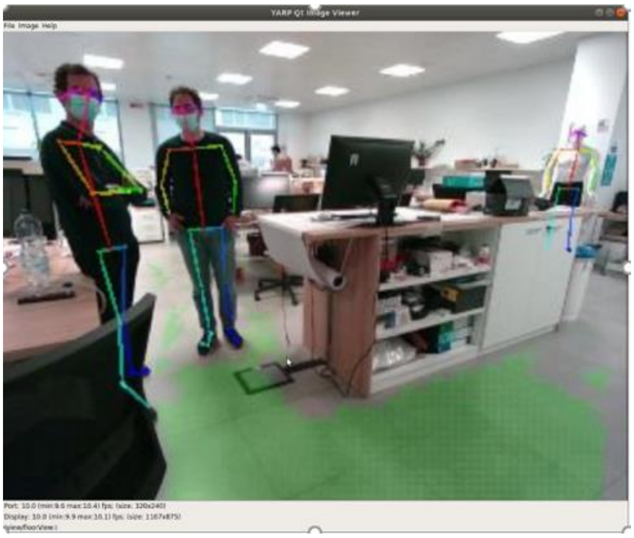


Figure 54. Additional video processing for human detection, during the robot teleoperation.

In order to integrate the R1 surveillance application into the web portal developed by TIM and TOR, IIT developed a WebSocket carrier for YARP which allows viewing the camera video stream and controlling the robot from a standard browser, instead of using a stand-alone executable running on a desktop PC. The developed web page can be eventually displayed also by a smartphone browser, thus allowing the robot to be controlled virtually from everywhere.

3.4 Test in the network

After the definitive installation of the 5G coverage in the two museums, in March 2022 functional tests were carried out for UC2 in the areas planned for the trials.

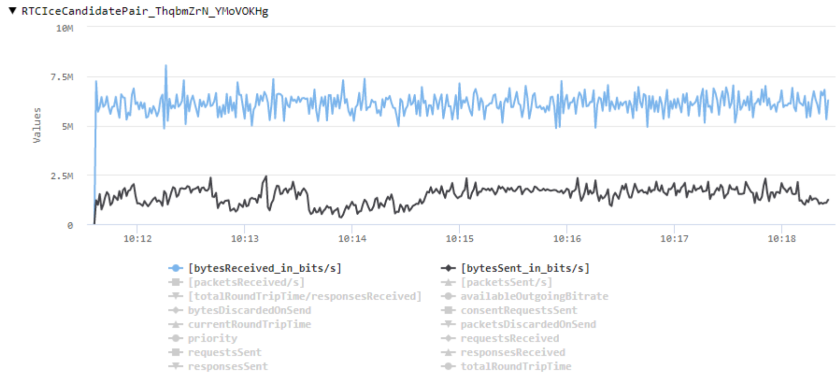
The tests allowed to subjectively evaluate the real performance of the system, in terms of video quality, smoothness of movements, end-to-end delay of audio and video streams.

Comparative tests were also carried out using the project's dedicated 5G connectivity, existing 4G connectivity, and where available an infrastructural WiFi connection. The performance tests were carried out on the “Piano Nobile” of Palazzo Madama, the area used for UC2.c, and on the first floor of the GAM, the area used for UC2.b.

Through the statistics of the WebRTC audio video streams at the application level, measurements of bitrate, round trip time, jitter, etc. were collected. These data provided useful numerical indications of the behaviour of the system with the different types of networks.

The results show a marked improvement in both qualitative and quantitative performance using mobile networks compared to WiFi. The RTT with the Robot on WiFi connection, varies from values below 100 ms up to peaks of 0.5 s and more, with great variance. Even the bitrate under these conditions undergoes large fluctuations giving a very poor perceived video quality. On the other hand, on the mobile network, the variations of RTT are much more contained, with values between 80 and 150 ms for the 4G network, and between 60 and 100 ms for the 5G network. The difference between 4G and 5G is evident above all on the stability of the quality throughout the area where the tests were carried out.

The graphs below show an example of the data collected during testing at the GAM. The test was carried out by piloting the robot from a PC located in the first room of the exhibition connected by cable to a 5G CPE, while on the robot the connection was in USB tethering with the S10 5G mobile phone. In the two cases, the project’s indoor 5G network and the commercial 4G network were used. The route taken in the museum is always the same, approximately half of that envisaged for the treasure hunt. The data is collected by the client application on the driving PC and shows the uplink and downlink bitrate, the overall RTT on the webrtc stream, and the detail of RTT and Jitter on the incoming video and audio streams.

<table>
<tr><td>Robot 5G – Driver PC 5G: uplink and downlink bitrate, and overall RTT on the webrtc stream</td><td>Robot 4G – Driver PC 4G: uplink and downlink bitrate, and overall RTT on the webrtc stream</td></tr>
<tr><td>
</td><td>
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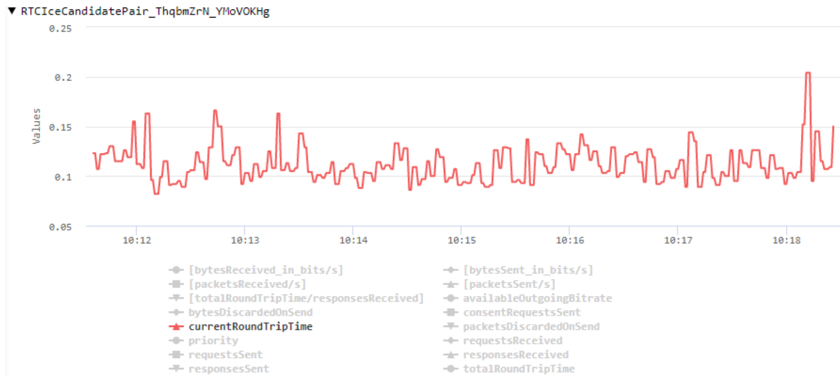
</td><td>
</td></tr>
</table>

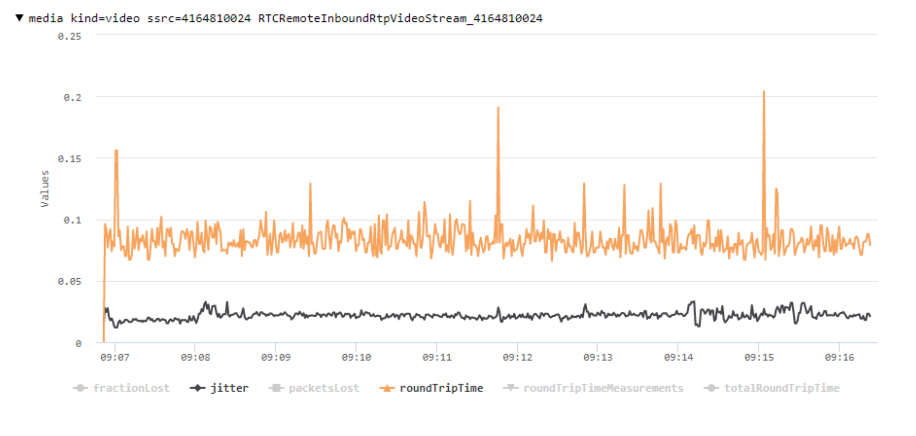
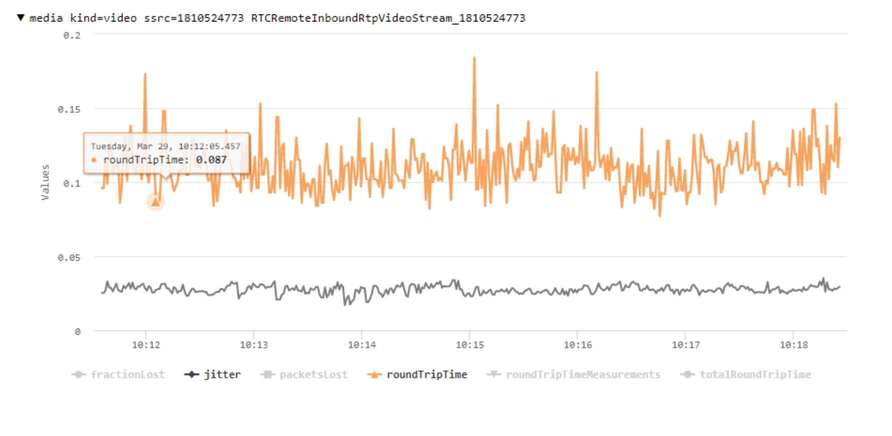
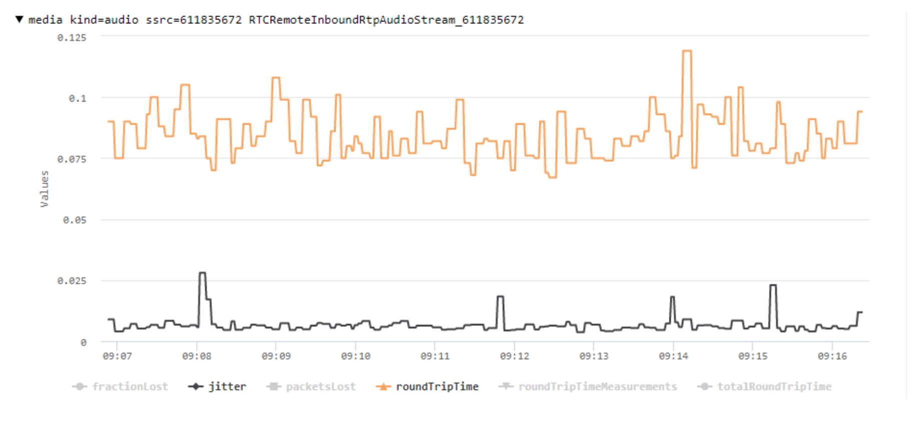
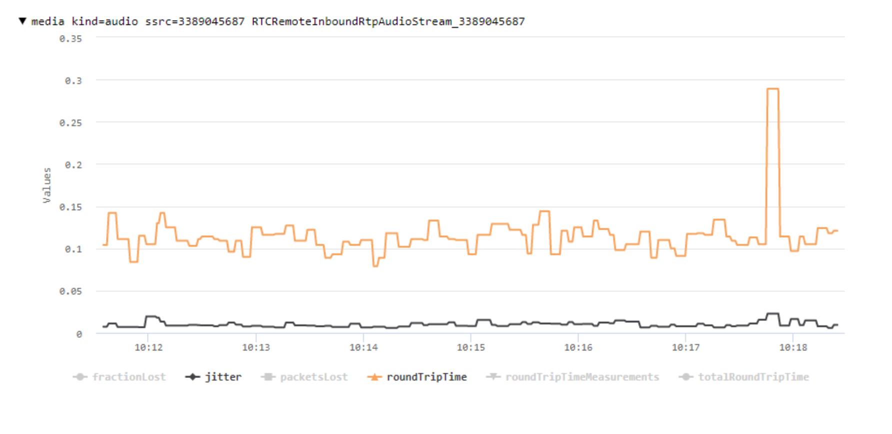
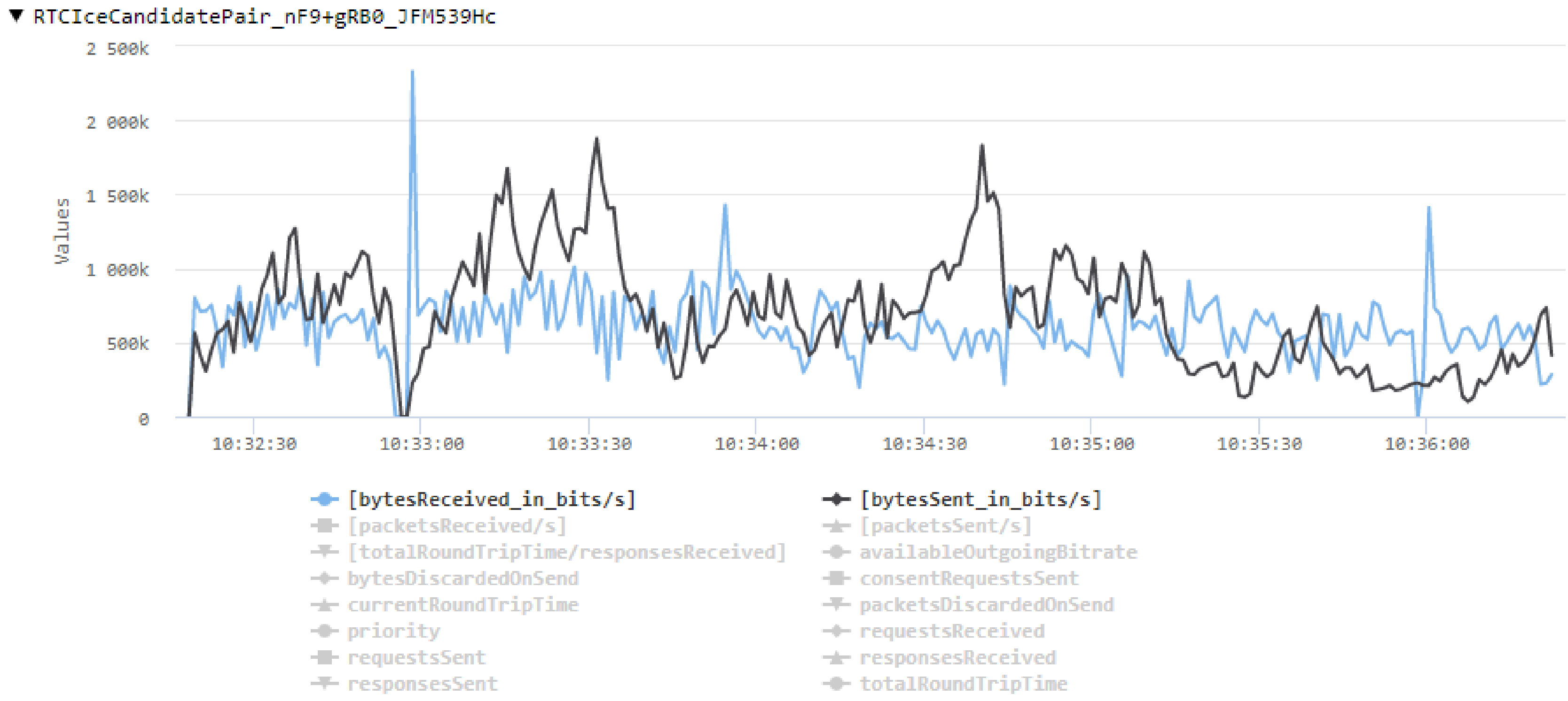
Robot 5G – Driver PC 5G: detail of RTT and Jitter on the incoming video and audio streams	Robot 4G – Driver PC 4G: detail of RTT and Jitter on the incoming video and audio streams
	
	

Figure 55. Sample performance data from WebRTC media session – 5G vs 4G connection comparison considering jitter and RTT.

For reference only, the graphs of the bitrate and the overall RTT are also shown for a test carried out with the robot connected to the free WiFi network present in the GAM. It can be noticed the very high variability of the RTT and of the band due to the low stability of the connection while the robot is moving.

Robot WiFi – Driver PC 5G


Robot WiFi – Driver PC 5G

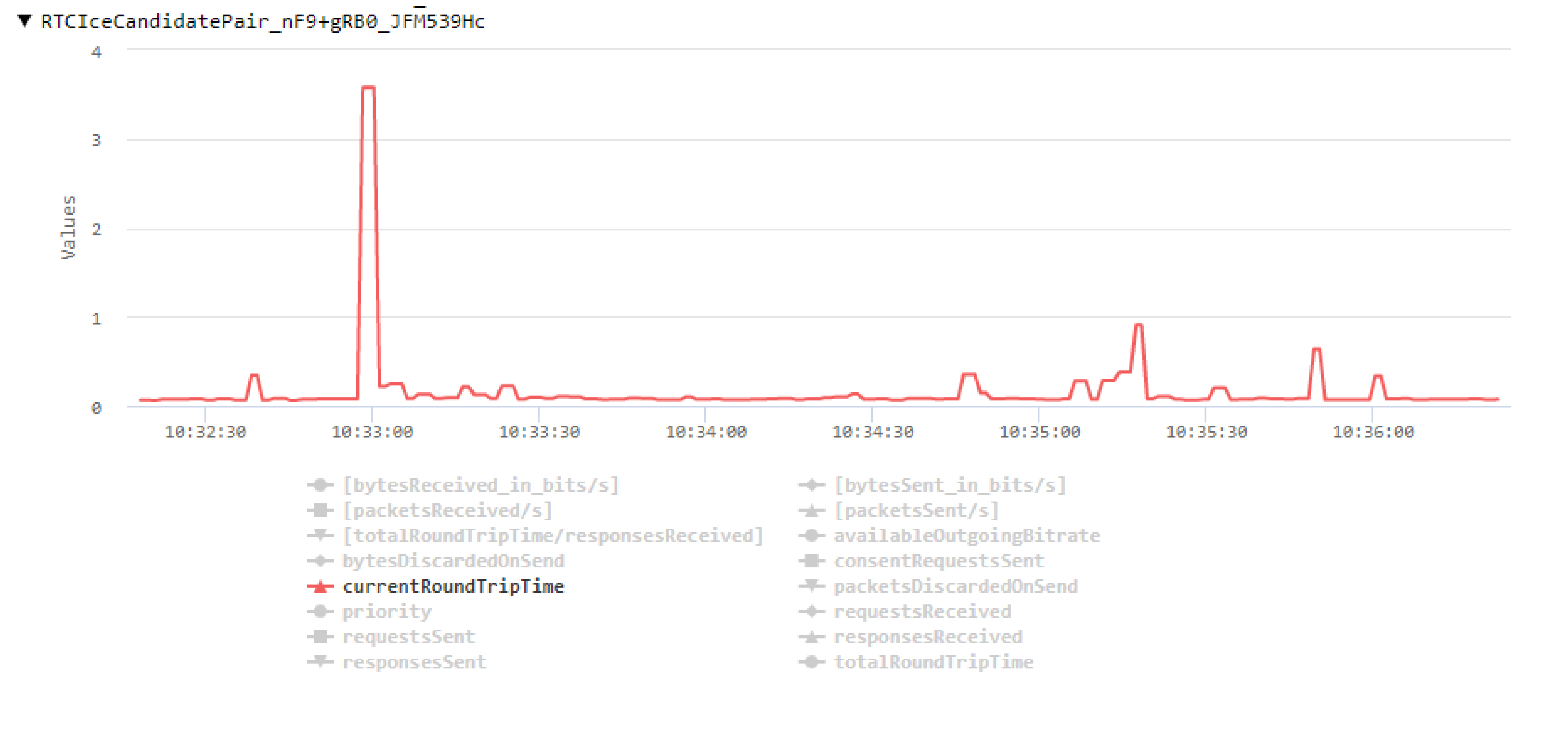
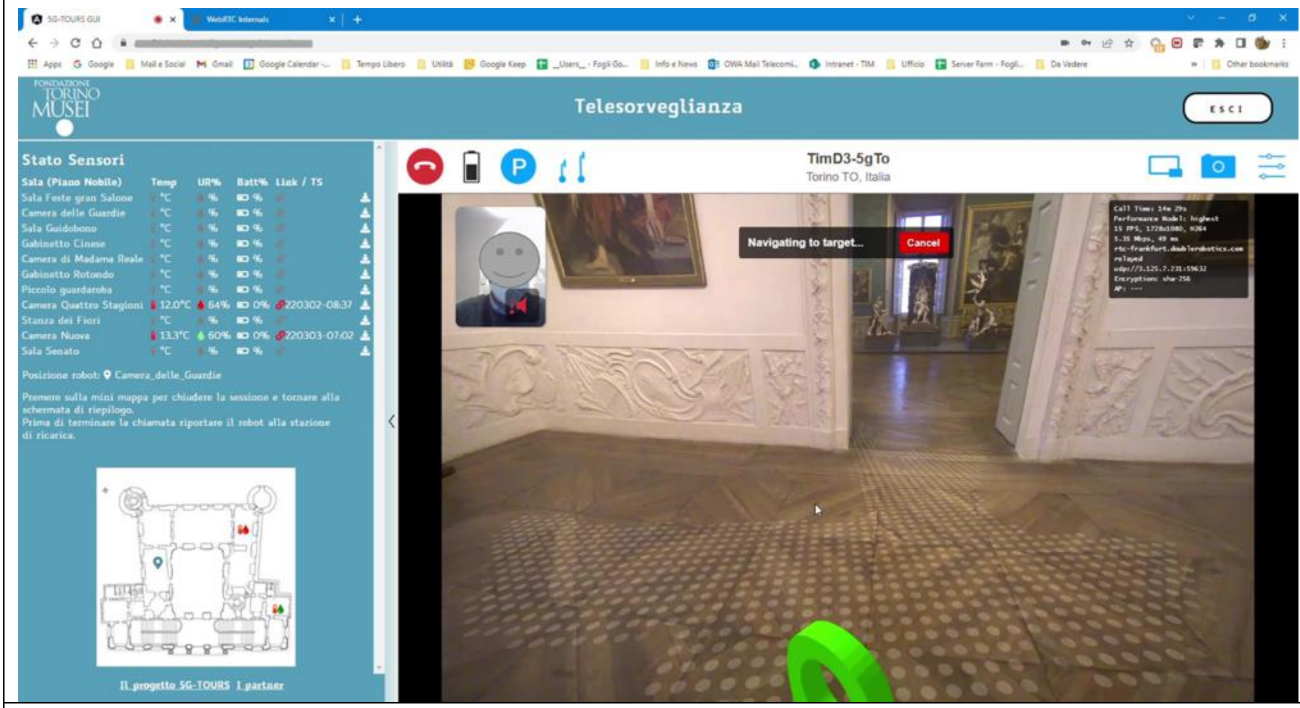


Figure 56. Sample performance data from WebRTC media session – WiFi connection.

From a qualitative point of view, the 5G connection provides a video stream with higher definition and fewer encoding artifacts and transmission errors. As an example, some images captured from video recordings acquired on the PC driver are provided. The test was performed in Palazzo Madama “Piano Nobile” using the indoor 5G coverage of the project, or the available 4G commercial coverage, on both robot and driver PC connection.

Robot 5G – Driver PC 5G



Robot 4G – Driver PC 4G

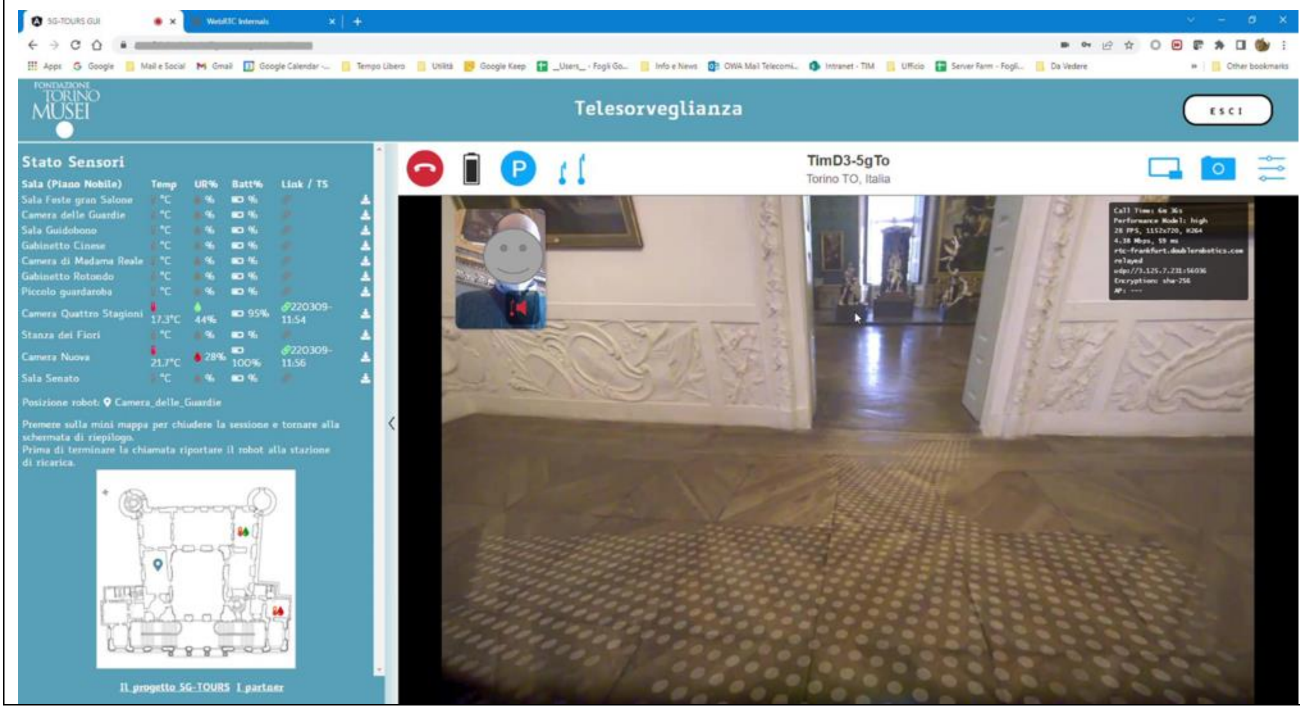


Figure 57. Sample video quality screenshot - 5G vs 4G connection comparison.

The qualitative comparison with the video in the Wi-Fi case is not very significant, due to the numerous transmission errors and the reduced bandwidth available.

R1 Robot

In May 2022 we performed the final trial of the remote surveillance application with R1 at Palazzo Madama. The robot was successfully teleoperated by the museum operators from the museum control room, using both a laptop connected to the internet (via wi-fi or via 5G) and directly a 5G smartphone. The results of the trial were very positive from the technical point of view and a positive feedback (collected through the WP7 questionnaires) was also received from the museum operators, which also suggested future improvements, both hardware and software. For example, they suggested the integration on the robot of a thermal imaging camera and the possibility of comparing the current lidar scan with a prerecorded database, to check if some plaster decorations on the walls and doors have been moved from the original position or damaged.

A picture of the teleoperation web page used during the final trial is provided in Figure 58. On the left, a representation of the whole floor map, is provided. The map is not a static drawing, indeed it is the same map used by the robot localization system and previously built using the robot lidar. On this map, the current position of the robot is shown, as well as its coordinates, its status, the user location markers and the current navigation plan. The map is also interactive, since the operator can click on it to require the robot to autonomously move to a specific location. On the right, instead, the video stream generated by the robot cameras is provided.

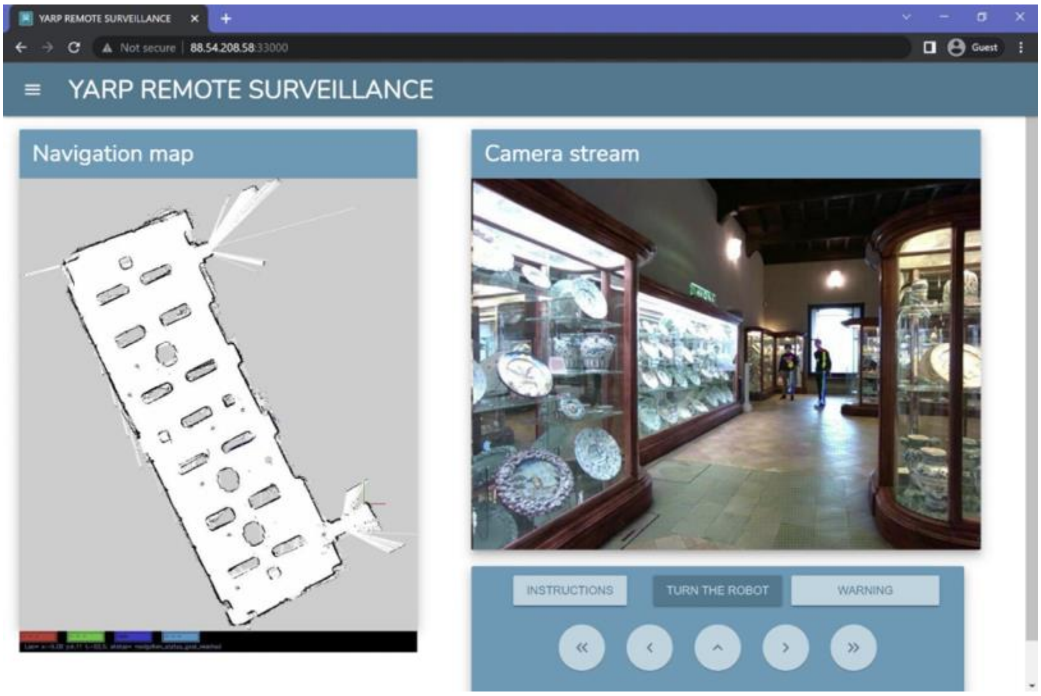


Figure 58. The teleoperation web page.

This is an enhanced view, which also highlights in green the open floor space in which the robot can move by clicking on the image. By dragging the mouse cursor, the operator can also move the robot head without moving the mobile base. Finally, under the video display, there is a third panel, which includes several control buttons to rotate the robot base, an instruction manual and a drop-down menu which allows to perform predefined actions with the robot, such as reproducing a speech text. The movements of the robot can be also controlled by using the arrow keys on the control PC keyboard.

As previously mentioned, during the final trial, the robot was tele operated by the museum operators through a 5G smartphone or through a laptop (also connected to the 5G network). In both these configurations, we measured a bandwidth of 5 Mbit/s in download and few Kbits/s in upload. These values must not be confused however with the upload bandwidth from the robot to the server, which was indeed the key requirement in this sub Use Case. In particular, approx. 20Mbit/s of data, containing the camera, the lidar and the depth sensor streams, were constantly uploaded from the robot to the remote server. It must be noticed, however, that lidar and depth sensor data are used internally for computing the robot path, so they are not displayed to the human operator. Additionally, the video stream received by the operator laptop was running at 10 frames per second, which is a smaller value with respect to the camera acquisition rate, which is 30 frames per second. This difference is independent of the network limitation, instead 10 fps is just the computational bottleneck of the server GPU (NVidia 2080RTX) and it represents the maximum framerate achievable by the neural network responsible for providing video augmentation through people and object detection.
With reference to D2.3 [14] and regarding network KPIs, the table of Telepresence network requirements is reported below. All collected data and results will be reported in D7.4 [9].

Table 4. UC2 – Telepresence network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(Reviewed) - UC2 – Telepresence			Priority	Range	
			URLLC	mMTC*	eMMB		Min	Max
General Vertical/Use Case Requirement								
1	Latency (in milliseconds) - round trip - Min/Max	msec	50	100		High	50	200
2	**RAN** Latency (in milliseconds) - one way	msec	10	25		High		25
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps	30	1<		High	~10	~30
4	Reliability (%) - Min/Max	%	99,99%	99,99%			99%	99,99%
5	Availability (%) - Min/Max	%	99,99%	99,999%			99%	99,999%
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h	1	N/A			0,1	1
7	Broadband Connectivity (peak demand)	Y/N or Gbps	0,1	No				0,1
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N	N	No				
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N	Y (Baseline)	Y (Baseline)				
10	Capacity (Mbps/m^2 or Km^2)	Mbps/Km^2	30**	1 ***				
11	Device Density	Dev/Km^2	2	20+			10	100
12	Location Accuracy	m	2	N/A			1	5

(*) mMTC: mMTC requirements are needed for IoT sensors

(**) 30 Mbps/Km^2 = 0,00003 Mbps/m^2

(***) 1 Mbps/Km^2 = 0,000001 Mbps/m^2

Regarding the system latency, during the final trial in Palazzo Madama we performed tests at three different levels. At the ping level, we measured a RTT of 29.2ms (SD=18) between the robot and the remote server. At the application level, we measured a mean latency of 35.9ms (SD=22) between the robot and the remote server using an ad-hoc developed application. We also obtained similar values at the user level, i.e. after the Traefik layer which publicly exposes the YARP ports outside the VPN, thus confirming that Traefik does not negatively impacts on the system latency. For a detailed description of the performed latency tests, please refer to UC3, section 3.4.

4 UC3 - Robot-assisted Museum guide

4.1 UC3 definition

In this use case robotic technology is used to provide an enhanced visit experience both in Palazzo Madama and GAM museums.

More in particular, the humanoid robot R1, developed by IIT, is employed to: a) provide basic information about collection highlights and temporary exhibitions; b) guide visitors moving autonomously through the museum and describing the artworks. In both cases, the 5G network is exploited to partially relocate the "intelligence", i.e. the computation load, from the robot to an external workstation.

4.2 UC3 implementation

In this section we describe the structure of the application and its software components, such as the dialog system and the navigation. The robotic guided tour consists of several 'points of interests' spread through the museum galleries, which are autonomously reached by the robot and where it stops to describe the artworks to the visitors. While the robot is navigating and speaking, its microphones are turned off, in order for the speech recognition system to be not activated by the own voice of the robot. After the description, the robot is ready to answer additional questions coming from the visitors that may ask for additional details about the artworks. All the dialogues with the robot were designed together with TOR, which also provided all the texts in Italian and English languages.

4.2.1 Application Components

The application is similar to the one described in UC2.c and it re-uses some of its components. However, in this UC no teleoperation is required. The robot is indeed autonomous, and it does not receive its commands not from a human operator but from specific software modules which run externally to the robot.

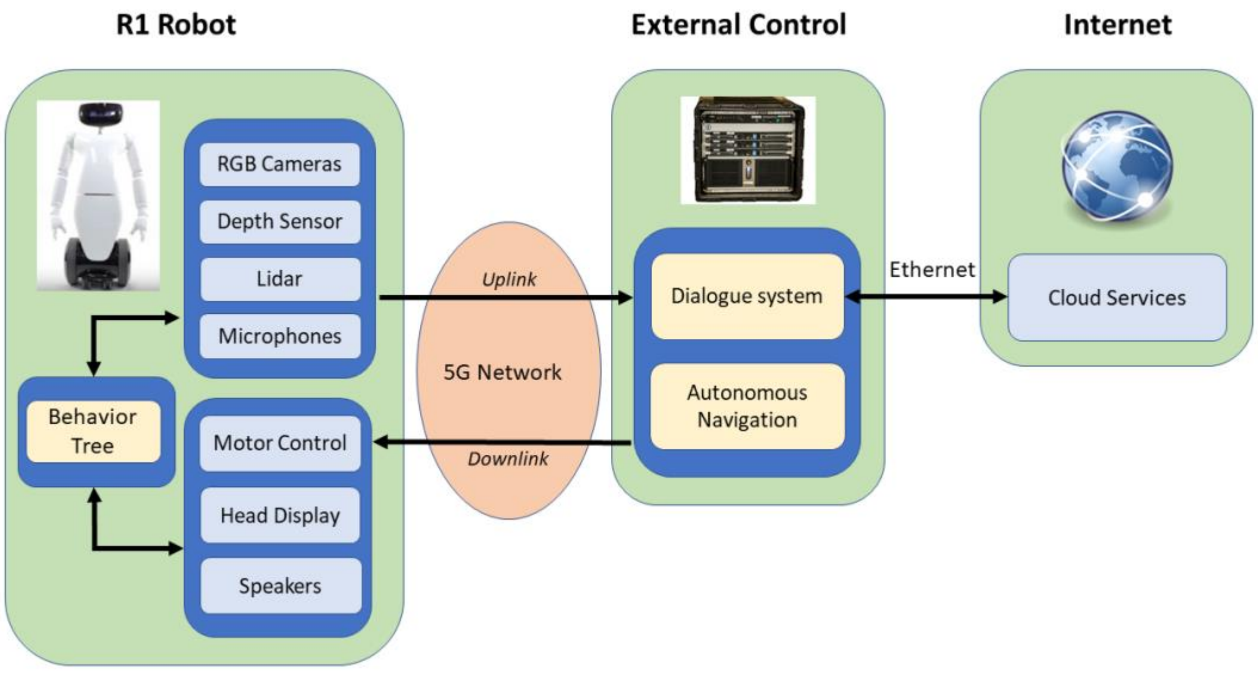


Figure 59. The Application Components.

The three main components which constitute the application are the behavior tree, the dialogue system, and the navigation system. As shown in Figure 60, the dialogue system and the navigation system run externally to the robot and communicate with it through the 5G network. On the contrary, the behavior tree executes locally on the robot, in order to maintain control of the system also if it gets temporary disconnected from the mobile network.

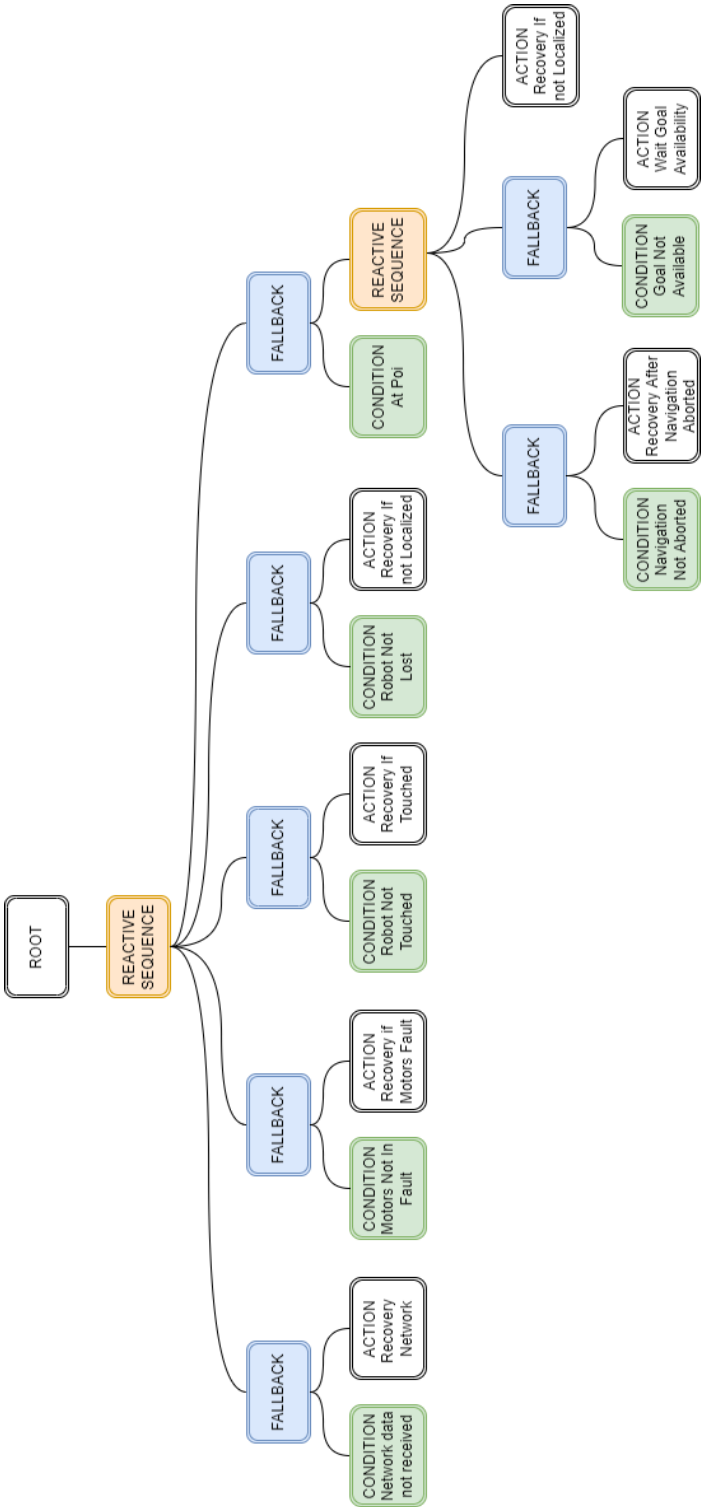


Figure 60. The application behaviour tree.

The *behaviour* tree (Figure 60) is responsible for the high-level control of the application status, e.g. if the robot has to move to a specific goal, describe an artwork or perform a specific action. The tree is organized hierarchically, with its leaves which constitute either *actions* or *conditions* (e.g. triggers for specific behaviors). The conditions are small executables which run in parallel. If a condition is verified, the status of the behavior tree changes accordingly, inhibiting specific actions and activating other ones. For example, if during the navigation a visitor or an obstacle touches the arm of the robot, then the navigation halts immediately and a warning sentence is declared by the robot. Other notable reactive behaviors include: a check if the navigation path or the goal is occupied by people; the internal diagnostics that monitor the status of the motors, sensors, and battery charge; a redundant control which checks if the robot is correctly localized in the environment. . The *dialogue component* is constituted by three main blocks, the *speech recognition system*, the *dialogue manager*, and the *speech synthesizer*. The *speech recognition system* is activated by specific actions of the robot behavior tree, e.g. when the robot is asking the visitors if they have questions about the artwork they are currently observing. A *Voice Activity Detector* (VAD) runs locally on the robot and is used to cut candidate sentences from the continuous audio stream captured by the microphone, which may contain long silences and background noise. The extracted audio chunk is then transmitted to the *google speech application* which forwards the analysis request to the cloud. The reply is a textual transcription of the sentence, which is analyzed by the second block of the processing pipeline, i.e. the *dialogue manager*. Also in this case we use a cloud application provided by Google, i.e. Dialogflow. Dialogflow is similar to a finite state machine, whose transition between the different states is trigged by *intents*, i.e. the sentences received by the transcribed text received from the speech recognition system, see Figure 61, where on the left, the branch of the dialogue activated at the beginning of the tour and on the right, the branch used when the robot is front of an opera. The main advantage of using Dialogflow is that intents are recognized by the system through machine learning techniques, even if the text does not match exactly. For example, questions such as “Please tell me who is the author?” and “What’s the name of the author?” correspond to the same intent, and the system can be trained to extend its database of knowledge by providing additional examples of sentences to recognize. One limitation of the system is that it has to know a-priori the language on which the intent analysis has to be performed: it cannot automatically detect the language of the interlocutor and switch to it. We thus decided to support only Italian and English languages and to manually add to Dialogflow the same set of intents for both languages. The final block of the pipeline is the *speech synthesizer*, which is also provided by Google cloud services. The component simply generates an audio stream from the text which is associated with each state included in the Dialogflow agent. The speech synthesizer is also invoked when the robot has to describe an artwork and is synchronized with the behavior tree so that some specific actions (e.g. the movements of the arm to indicate something) are synchronized with the speech.

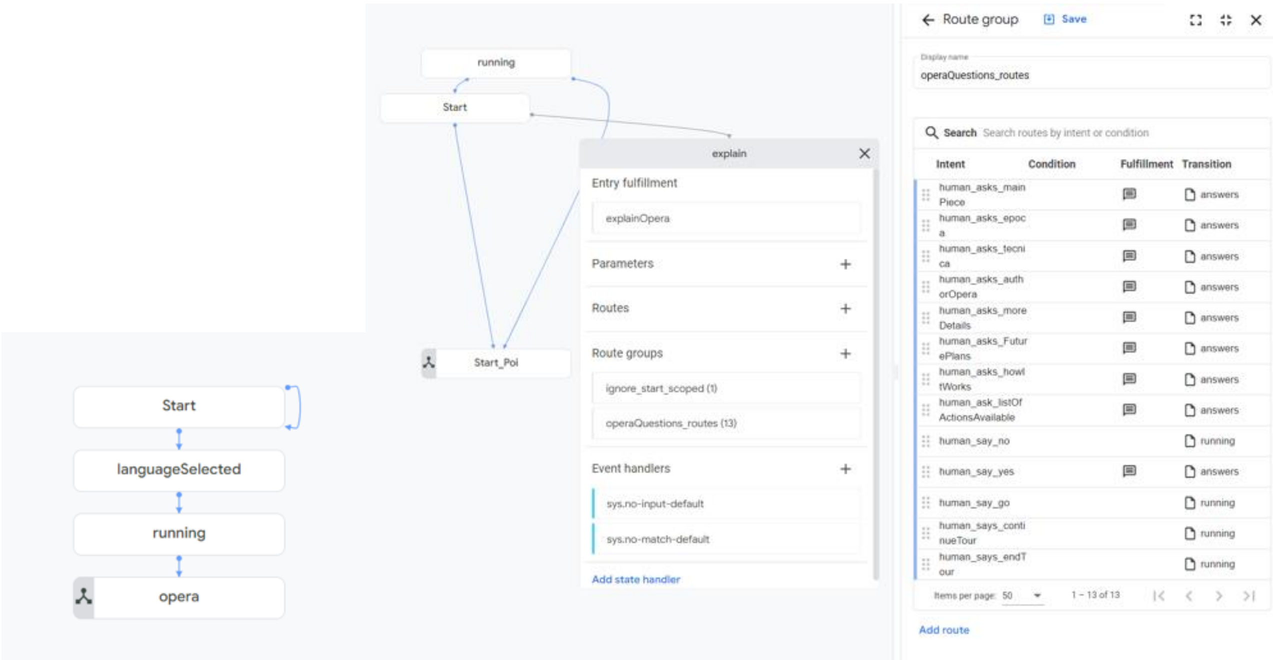


Figure 61. The Dialogflow agent developed for the robot guided tour.

The *autonomous navigation* component can be divided into two subcomponents: the *localization system* and the *trajectory planner*. The *localization system* is responsible for estimating the position of the robot in the environment. It is based on a state-of-the-art technique, called *AMCL,* constituted by an adaptive particle filter which takes into input the robot's odometry and it corrects it through the lidar measurements, matching them against a stored map of the environment. Since during the development phase we were not sure about the algorithm performance in large and possibly crowded environments, we performed various tests in a simulated environment based on the museum planimetry. These tests were generally successful, nevertheless we added an extra layer of security by implementing *a redundancy check*. This check verifies if the robot position estimated by AMCL is similar up to certain threshold with the result of other different localization algorithms, e.g. visual slam techniques. If a mismatch is detected, a reactive condition of the behavior tree is triggered, the navigation is halted and a recovery strategy is executed, so that the robot tries to re-localize itself in the global map.

The *trajectory planner* is the module that computes, instant by instant, the direction in which the robot has to move to reach the goal, avoiding potential obstacles along the path. Our implementation is based on ROS *Dynamic Window Approach* (DWA) algorithm, with some specific customizations to manage *keep-out areas*. Since the field-of-view of each of the robot lidars is limited to an angle of 100 degrees, we also implemented a *control strategy* that rotates the head of the robot towards possible obstacles during the navigation. The 3D measurements obtained from the head depth sensor are then projected into the map plane. In this way, we not only virtually increase the field of the robot lidar, but we also become aware of suspended obstacles (e.g. display cases) that cannot otherwise be detected. The head and the torso of the robot are also moved to clear the navigation *local costmap* after that a recovery behavior is triggered, i.e. when the robot cannot find any available path to reach the destination. In this case, the robot stops its movements and begins looking around, waiting for a clearance of the path. Also, in this case, the navigation system is synchronized with the application behavior tree, receiving from it the sequence of goals and notifying the application when they are reached or if a problem occurred.

4.2.2 Terminal Equipment components

During the project, the design of the robot was modified to host additional hardware, in particular new sensors, a new computational unit and a new router. On the head of the robot (Figure 62), we added an additional RGBD camera, the Realsense D455, and a stereocamera with tracking capabilities, the Realsense T265, to improve the mapping/localization capabilities of the robot. On the back of R1, instead, we integrated an extra computational unit, the Nvidia Jetson Xavier AGX (Figure 63), for acquiring and process cameras data, and a new router, the Mikrotik hAP ac[3] (Figure 64). The latter is the central router that provides network connectivity to all the machines inside the robot; additionally it is equipped with an USB port to which a 5G smartphone (S21, provided by Samsung) is connected. During the project we also investigated, unsuccessfully, if more compact solutions were available, i.e. if it was possible to employ an integrated router-5G modem, thus eliminating the need of USB tethering (which it also constitutes a bandwidth bottleneck). Unfortunately, given our design constraints, no alternatives to Mikrotik hAP ac[3] were found. The router also provides VPN capabilities, even if we decided not to use them, because of some issues, described in Section 4.2.3.

Figure 62. The head cover of the robot modified to mount the additional sensors for localization and mapping.

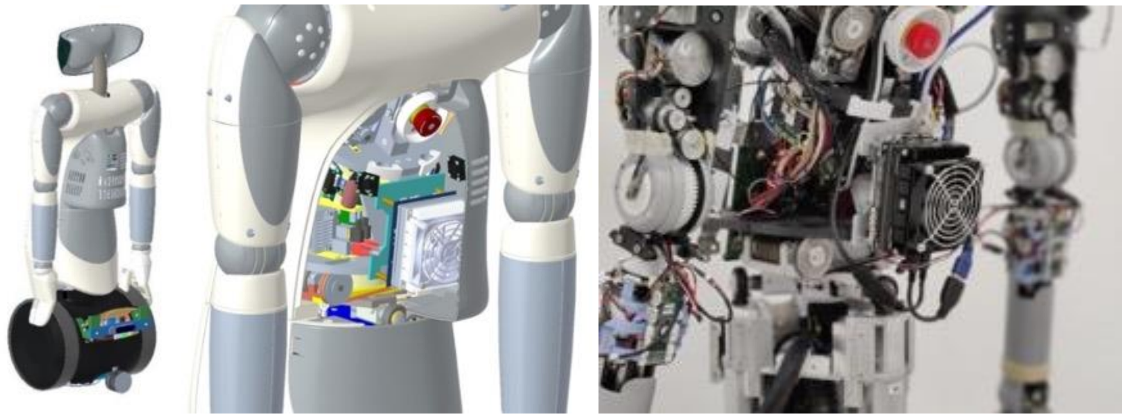


Figure 63. The back cover of the robot redesigned to host the additional Xavier AGX and the router.

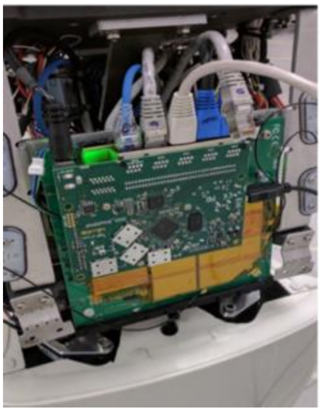


Figure 64. The Mikrotik router inside the robot and the 5G smartphone attached to the arm of the robot.

4.2.3 Interfaces

From the software point of view, the R1 humanoid robot is based on a middleware developed by IIT called *YARP*. All the application software employed in this UC, running both in the robot and on external machines, is built on top of the YARP libraries, which are responsible for managing the data exchange across the network. YARP implements communication through special objects, called ports, which deliver messages to any number of observers (other ports). The computation can thus happen locally, i.e. on a single machine, or can be distributed across any number of machines, each of them running multiple processes, using any of several underlying communication protocols. In order to allow YARP to work properly, all the machines must belong to the same subnet and have a reachable IP address. This condition is normally achieved in a laboratory private network, but this is difficult to achieve on a commercial mobile network. To overcome this difficulty, we initially setup a VPN tunnel based on OpenVPN software between the robot's internal network and the remote computational unit, as shown in Figure 65.

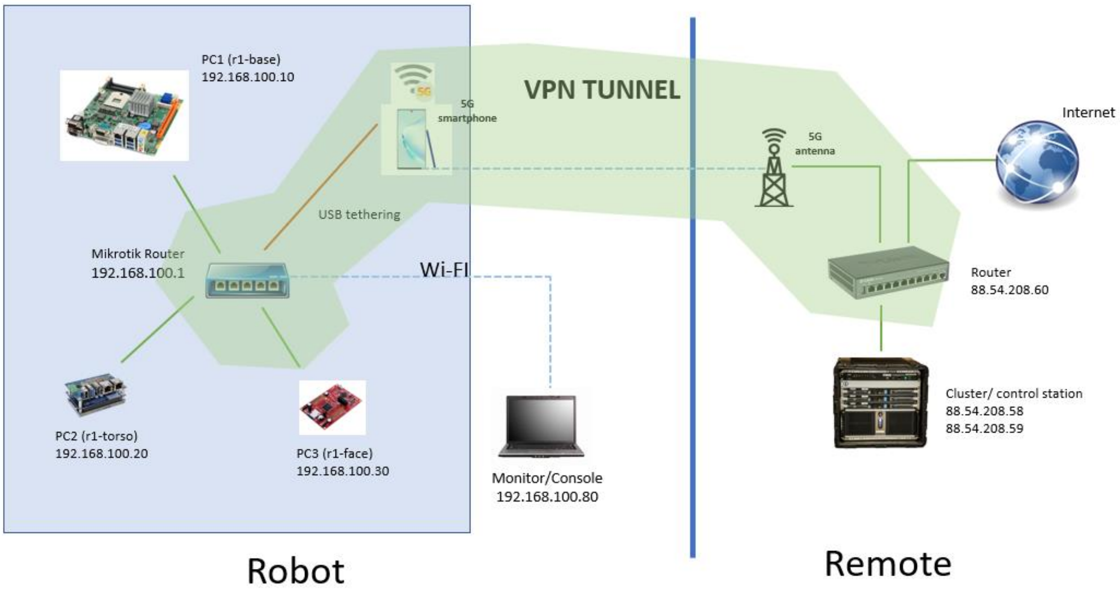


Figure 65.The VPN tunnel. The endpoints are managed by the routers.

As shown in the picture, our initial idea was to employ a router with VPN capabilities to manage the VPN so that no additional configuration parameters need to be modified on the robot machines. We evaluated several routers with OpenWrt capabilities, however, we observed that all of them, including the Mikrotik hAP ac[3] installed on the robot, introduce severe *limits on the maximum network bandwidth* (~100Mbit/s). We suppose that this limitation comes from a computational limit of the CPUs of the routers, which are not optimized to manage a large amount of data traffic, especially if encryption/decryption operations are performed[1].

Unable to find a solution, we choose to move the VPN management from the routers directly to the computers that are part of the network. This network architecture, shown in Figure 66, consists of an *openVPN* server, running on the remote side (ip address 10.8.0.1), and multiple openVPN clients, one for each machine belonging to the network (both the ones inside robot and the external ones, ip addresses 10.8.0.x).

[1] During our research, we eventually found some routers which potentially fulfill our requirements, but these hi-performance models are dedicated to the industrial market and they cannot easily integrated as a compact solution inside the robot due to their large chassis.

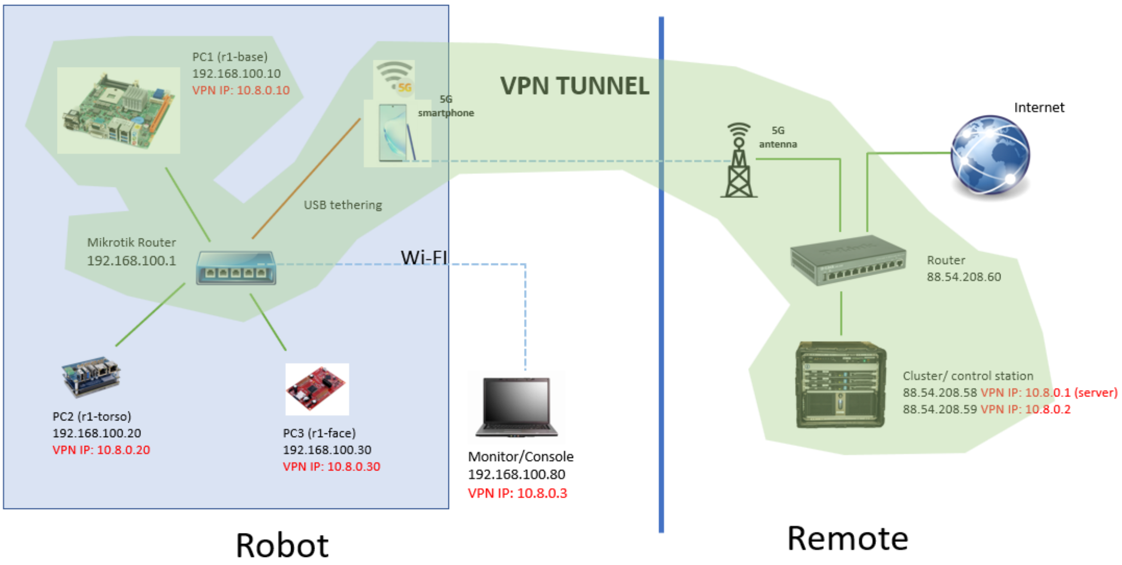


Figure 66. The VPN tunnel. The endpoints are individually managed by the individual machines.

It must be noted that, while this solution solved the problem of limited bandwidth previously described, it is sub-optimal from the computational point of view, since each CPU has to dedicate part of its computational power to route traffic through the VPN.

An additional issue we faced was the *latency* increase due to the introduction of the VPN. This is particularly problematic in this UC, in which the communication between the robot and the external control server must happen as fast as possible. Indeed, the closed-loop control of the robot is negatively affected if feedback is received with a latency greater than one hundred of milliseconds. We were able to successfully tune the VPN parameters for the requirements of our application through a set of experimental measurements, performed in collaboration with ERI-IT. Details are reported in section 4.2.3.

4.3 Integration and test in labs

Due to the pandemic restrictions, the guided tours application was developed and tested mainly in a simulated environment (Figure 67) and, with the real robot, in the IIT lab, using an Ethernet cable or a Wi-Fi connection.

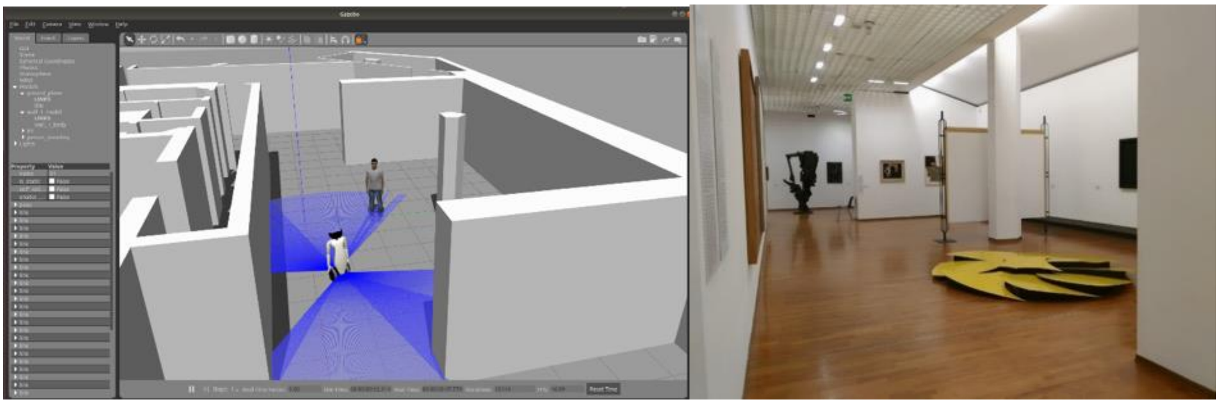


Figure 67. A simulation of the guided tour using Gazebo simulator.

In May 2021, with the relaxation of some COVID-19 restrictions, we were finally able to perform the first trial in GAM, even if no 5G network was yet available at that time (Figure 68). This was indeed the very first time we carried out the R1 robot to Turin and the trial allowed us to obtain a large amount of information about how the robot behaves in the real museum environment.

Figure 68. R1 robot in GAM.

The first problem we faced was the localization of the robot in the environment. Indeed, the museum rooms were very large, and in some cases (e.g. in the corridors, or in the middle of the rooms), the range of the lidar installed on the robot was not enough to detect the perimetral walls. This eventuality was expected and taken into account in the testing phase performed with the robot simulator, but it turned out that in the museum the system odometry suffers from extra errors due to wheels slippage, that was confusing the localization system. The problem was mitigated by refining the odometry model to take into account this error. We succeeded in building an accurate map of the gallery by placing in the halls some obstacles which the lidar system and the SLAM algorithm were able to detect and consider as strong landmarks (Figure 69). It is worth stressing that these landmarks were only used to build the map, and were later removed during the robot operation. This problem was then completely solved by replacing the lidar on the robot with new models with an extended range.

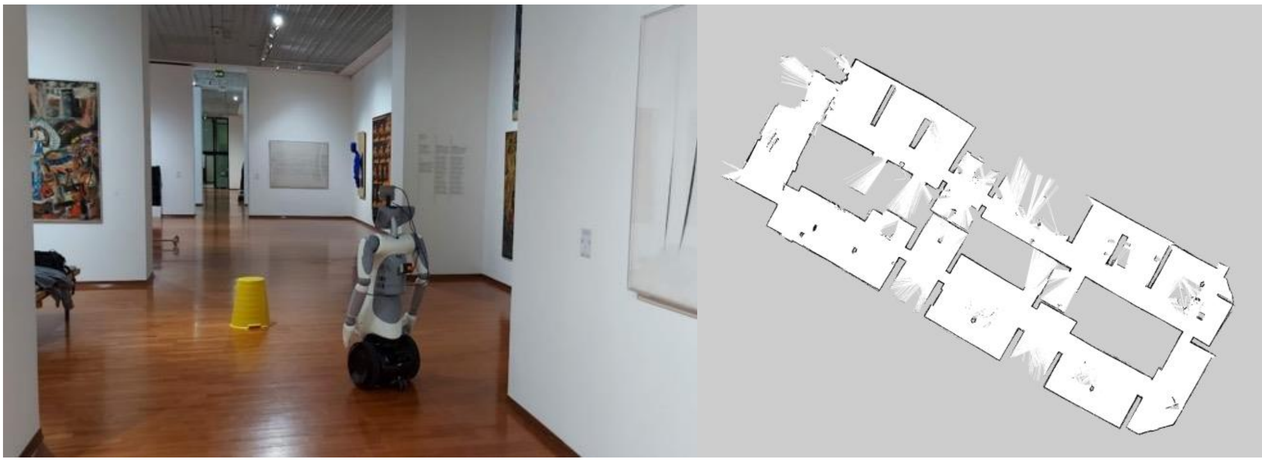


Figure 69. On the left: R1 robot during the mapping session in GAM: yellow buckets were placed on the floor as landmarks. On the right, the obtained map.

Another issue we faced was navigation instability, which arises when multiple paths are available to reach the desired goal. Indeed, several halls of the museum include central columns or walls on which the artworks are exposed. When the robot navigates, it may choose to follow a path that suddenly becomes unavailable because it is obstructed by visitors who are passing in front of the robot. Since the robot knows that a different path to reach the goal is available, it interrupts its current plan and starts to move to the newly computed waypoint even if this new path is longer. Then, if the visitors move away, and the original path becomes available again, the robot resumes the previous navigation plan, which was shorter. To overcome this problem, we implemented in the planner a new cost map layer which is responsible for handling the keep-out-areas, i.e. areas that are marked on the map in which the robot cannot enter. We then placed these virtual walls in order to have always a single available "virtual corridor" in which the robot can navigate. This solution also increased the safety of the navigation system by guaranteeing that the robot always stays away from some artworks which are placed on the floor and may elude in some conditions the obstacle detection sensors (Figure 70).

Figure 70. Some specific areas corresponding to the presence of artworks on the floor have been marked as keep-out areas on the navigation map.

In order to keep the duration of the tour limited to a reasonable amount of time, we decided together with TOR to choose only six points of interest in which the robot stops to describe the artwork and interact with the visitors. This number was chosen by running a pre-test in which we measured the time required by the robot to complete a full tour. Figure 71. The six artworks chosen for the guided tour. shows the location on the GAM map of the six points of interest that were chosen. TOR also created the text for a description of the artworks and for the visitors' questions.

Figure 71. The six artworks chosen for the guided tour.

In order to simplify the dialog, we decided to limit to three the number of possible questions for each artwork. Additionally, all the intents were chosen to be the same for each artwork. More specifically, the three possible intents are: "additional information about the author", "additional information about the historical period" and "additional information about the artwork". In this way, we were able to reuse the same dialog agent for each point of interest. In addition to these three, extra intents were added when the robot is located near the entrance and it is not performing the tour. The exact location of this point was indeed chosen to have the robot able to answer to visitors' questions while it is recharging its battery. These intents include additional information about the duration and the availability for the next tour, as well as extra details on the robot itself and the 5G-TOURS project.

As previously mentioned, all the preliminary integration tests carried out in IIT labs and at GAM in Turin were performed either using an ethernet cable or with a standard wi-fi connection, with the robot configured as a client and an external router configured as an access point. Indeed, the goal of all these tests was to tune the navigation algorithm parameters and to evaluate its performances in ideal conditions.

After this preliminary phase, we performed a large amount of tests in ERI-IT labs located in Erzelli, Genoa, to assess the performance of the system from the network point of view, using a 5G network which mirrors the one deployed in Turin. In these tests, we measured the end-to-end latency at the application level, which considers the base latency of the network, plus the overhead introduced by the VPN and by our communication software YARP.

To measure the application latency, we wrote a *YARP-based testing application*, composed by a client and a server connected through one of the available YARP carriers. This testing application works as follows. Initially, the client sends a request to the server including a timestamp. The server then responds by sending back the original request and adding an additional dummy payload, whose size can be defined by the user. By comparing the original timestamp and the received timestamp it is thus possible to produce a plot showing the system latency vs. the data payload. Figure 72 shows the results for such a test in the reference case in which two machines communicate through a wired Ethernet connection and no VPN is involved.

Figure 72. Application latency for two machines connected through an Ethernet cable.

The plot shows a similar performance for two different *yarp carries*, called tcp and tcp_fast. These carries are specific YARP implementations of communication protocols and should be not confused with the TCP internet protocols which operate at a lower level. Indeed, the *yarp* TCP *carrier* aggregates multiple TCP network packets and, in addition to the individual acknowledgments sent by a receiver for each TCP packet, it sends an extra application-level ACK to confirm the reception.

YARP offers multiple carriers, and some of them can be more suitable for specific types of data with respect to others. More specifically, we can distinguish between *command data* and *sensors data*.

Command data are typically sent from an external controller to the robot and can be *sporadic* or *streaming*. Sporadic commands or Remote Procedure Calls (RPCs) are used to set the value of a specific control parameter and require an acknowledge/status reply, since their loss could cause a catastrophic failure of the system. For this reason, sporadic commands typically employ the yarp TCP carrier. Streaming commands are used to control the movement of the robot and are repeatedly transmitted by the external controller to the robot. Only the most recent one should be considered by the robot. Missing a command may cause a glitch, but the system will recover when the next command will be successfully received. Streaming commands typically employ the *yarp* TCP*_fast carrier*. Both two types of command data are typically small in size, in the range of 10-50 bytes, and should have the lowest possible latency.

Sensor data are sent by to robot to the external controller at a constant rate. Only the last received value is meaningful: similarly to streaming commands, data packets can be sporadically lost, without causing a catastrophic failure of the system. It is worth noting, however, that only a sporadic packet loss is acceptable and that a prolonged communication failure (e.g. 100ms) may cause severe issues as well. The transmission of sensor data typically relies on a UDP carrier, with the only exception of compressed image data which may use different protocols, depending on the specific compression algorithm. MJPEG *carrier*, for example, is based on *get HTTP requests* and use a TCP network protocol at a lower level. Different sensors generate different types of traffic: the size of the array of encoders measurements ranges between 800 and 2.000 bytes, a LIDAR scan between 1.000 and 20.000 bytes, a compressed camera frame between 50.000 and 500.000 bytes. It can be easily observed that these range of values are very different with respect to the ones of the control commands: the data associated with the sensors are responsible for most of the network traffic and bandwidth usage in this UC.

To investigate the latency of our application on the 5G network, we tested the configuration previously reported in Figure 66, i.e., with the VPN endpoints running on the individual machines.

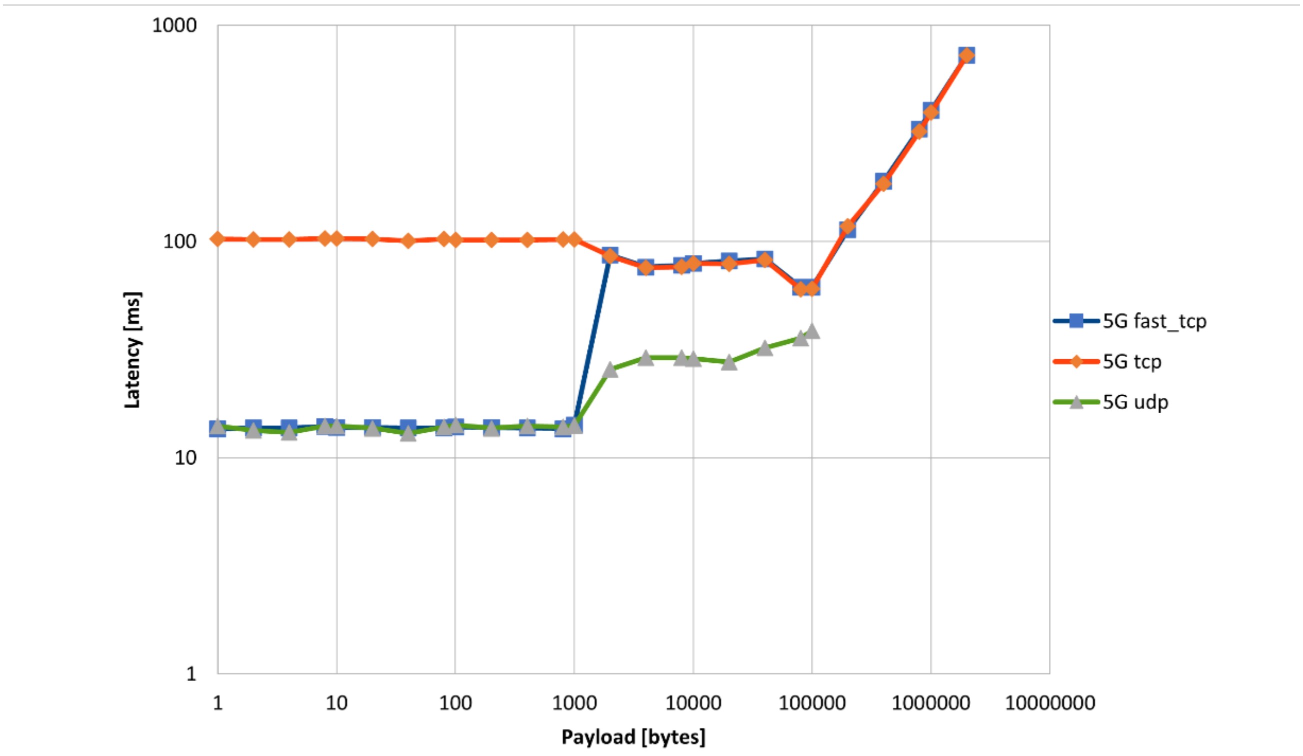


Figure 73. Application latency for two machines connected through 5G network (default openVPN configuration).

The result of our initial tests, obtained with a default openVPN configuration, are shown in Figure 73. It immediately stands out that the plot is very different with respect to the one obtained using the local Ethernet connection (Figure 72). Both the yarp fast_tcp carrier and the udp carrier exhibit a latency of ~15ms when is the payload is smaller than 1000 bytes. This result is consistent with the value coming from a simple ping test and it can be considered near to the intrinsic network latency. However, when the payload increases, some differences can be noticed. While the latency simply increases with the udp carrier, the fast_tcp exhibits an abrupt jump to a value near 100 milliseconds. The YARP tcp carrier, which requires the extra ack, performs even worse, with latency values in the range of 100 milliseconds even for small payloads. Finally, the plot of the udp carrier is interrupted when the payload reaches a value of 100.000 bytes. Beyond this value, YARP is no more able to reconstruct the transmitted data, since the datagrams into which the large data packet is fragmented, arrive unordered and they exceed the memory allocated in the internal buffer.

Investigating the issue, we observed that the performance of the system heavily depends on the VPN settings, and that its parameters must be carefully chosen. One of the key parameters we set on our VPN was the flag TCP_NODELAY, which is a socket option which disables the internal Nagle's algorithm, by sending data as soon is available instead of accumulating data waiting until receiving a TCP ACKTCP ack from previously sent packets (Nagle's algorithm, enabled by default, is designed to minimize the number of small packets through the network). In addition to this flag, we also optimized the values of MTU, MSS and we chose UDP as preferred VPN transport protocol. Results of these optimizations are shown in Figure 74. As shown in the plot, the latency of the application data was greatly reduced for the YARP TCP carriers, with values that almost match those of the UDP protocol.

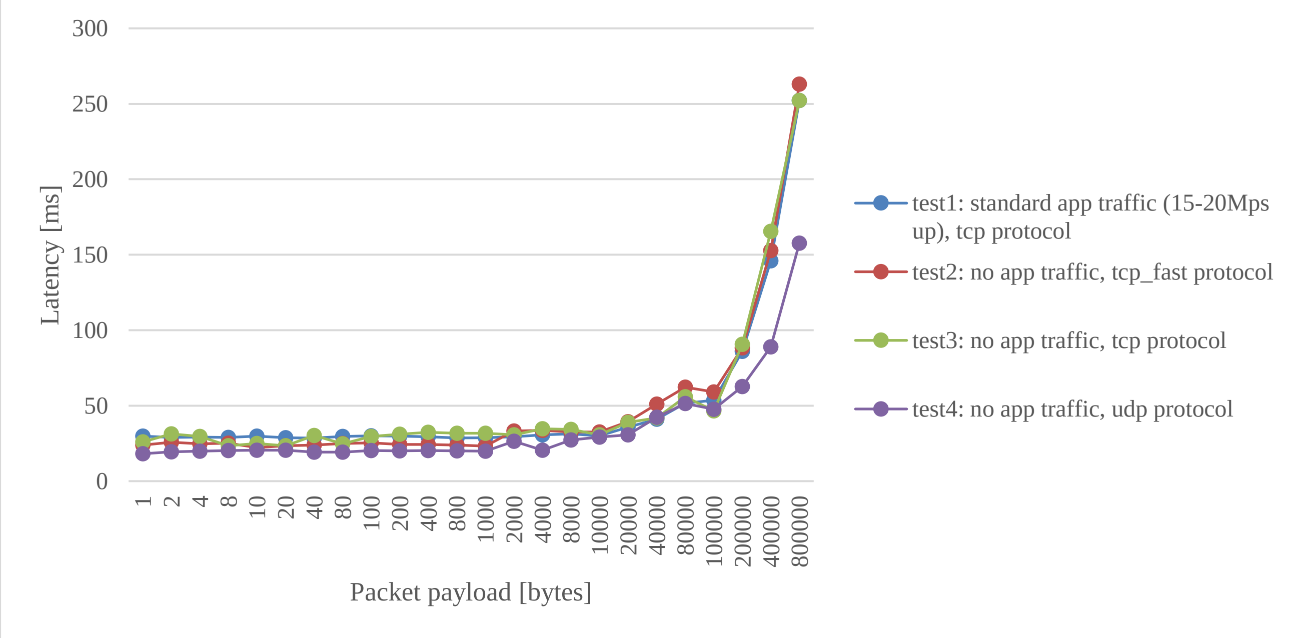


Figure 74. Application latency for two machines connected through 5G network (optimized openVPN configuration).

4.4 Test in the network

In April 2022 and May 2022 the final trials with the robot in Turin were performed.

The first trial was performed in GAM, since the environment was already well tested in the previous integration trials. The guided tour consisted of the same six points of interest previously defined with TOR (Figure 71) with some minor improvements to the contents of the dialogues, following the feedback of both museum operators and of the public. The total duration of each tour was ranging from 20 to 40 minutes, depending on the number of questions done to the robot, for linear path of approximately 150-200 meters (Figure 75). The trial was very successful: many individual visitors and schools enjoyed following the robot and interacting with it. A minor difficulty in the interaction was due to speech recognition system that sometimes failed to recognize the questions from the visitors due to background noise. The feedback from the public response was collected at the end of each tour through the questionnaire defined together with WP7.

Figure 75 The robot interacting with some public during the final trial week at GAM.

The second trial was performed in May 2022 in the ceramics gallery, at palazzo Madama. The structure of the dialog used in Palazzo Madama in Sala Ceramiche was substantially identical to the one in GAM: in this case the robot was programmed to follow a path consisting of eight operas. For each of them the robot was programmed to provide a main artwork description plus three additional contents (i.e. details about the author, about the historical period, about the technique) if explicitly requested by the visitor. The path of the whole tour is shown in Figure 76. A major difference between GAM and palazzo Madama was the environment in which the robot had to move. At first sight, it could seem that the environment of the ceramics gallery is more complicated than the one of the GAM, due to the presence of many glass display cases in the centre of the room (Figure 77). However, their presence was not actually affecting the navigation system of the robot, since its LIDARs are placed at a sufficiently low height respect to the ground to detect the wood basements of the display cases. The successful detection of the display cases was a key factor for the success of the trial, since they provide a the large amount of features, resulting in a stronger and more accurate estimate of the robot position in the environment respect to the one observed during the trial in GAM. Another difference between of the two tours was their length. The gallery of the ceramics was a much smaller environment respect to the large artwork collection of GAM, therefore also the travel time from a specific location to the next one was much smaller, giving the impression of a more dense and detailed tour. The duration of a tour in the ceramics galley was approximately 20 minutes (up to 45 with questions from the visitors) for a total length of 70 meters. Also in this trial a questionnaire was given to the public and to the museum operators at the end of the tour to evaluate their experience with the robot. The results are discussed in D7.4 [9].

Figure 76. The artworks chosen for the guided tour at Palazzo Madama.

Figure 77. The robot navigating through the ceramics gallery.

From the network point of view, we collected measurements about the performance of the 5G connection during both the trial at GAM and at Palazzo Madama. For better understanding the behaviour of the system, we performed tests at different levels, i.e. on the smartphone, on the robot without using the VPN, and on the robot using the VPN.

We used the standard speed test by Ookla to measure the network performance at the smartphone level (i.e. measuring the traffic from the smartphone to the internet). The results were similar for both Gam and Palazzo Madama, with a measured data bandwidth ranging from a minimum of 400Mbit/s to a maximum of 1 Gbit/s in download, and from 35 to 60 Mbit/s in upload. This variance was depending mostly on the strength of the signal and the location of the 5G terminal, which was in some cases was also able to perform 4G+5G carrier aggregation, resulting in the additional bandwidth (up to 110Mbit/s).

The second test we performed was an iperf test between a machine located on the robot (thus connected to the 5G network through the internal router and the USB-tethered smartphone) and the remote servers, using their public IP address (thus without using the VPN). In this scenario, we measured a maximum throughput of 400Mbits/s in download and the same previous values (35 to 60 Mbit/s) in upload. We thus concluded that the router negatively affects only the download performance, capping the maximum bandwidth to a value that, however, is far beyond the requirements of our application.

The final test was running iperf through the VPN. In this configuration we observed a different behaviour between UDP data transmissions, which were substantially behaving like in the previous case, and TCP data transmissions. In this latter case, we observed an additional drop of the available bandwidth, with a maximum download throughput of 300Mbit/s and a maximum upload of 30-35 Mbit/s.

With these values in mind, we tuned our application, throttling down the refresh rate of some highly bandwidth-consuming data flows, slightly sacrificing the navigation responsiveness/accuracy. As an example, we had to quantize the accuracy of the depth camera to 0.01 meters and reduce its refresh rate from 10 to 5Hertz6. This compromise, required to maintain the stability of the system in case of rare gaps of the network (e.g. below 20Mbit/s of upload bandwidth), were nevertheless not noticeable from the visitor point of view and did not affected at all the guided tour experience.

With reference to D2.3 [14] and regarding network KPIs, the table of Robot-Assisted Museum Guide network requirements is reported below. All collected data and results will be reported in D7.4 [9].

Table 5. UC3 – Robot-Assisted Museum Guide network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(Reviewed) - UC3: Robot-assisted museum guide and monitoring			Priority	Range	
			URLLC	mMTC	eMMB		Min	Max
General Vertical/Use Case Requirement								
1	Latency (in milliseconds) - round trip - Min/Max	msec	30			High		35
2	**RAN** Latency (in milliseconds) - one way	msec	12,5			High		15*
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps	40			High	~15	~50
4	Reliability (%) - Min/Max	%	99,99%				99%	99,99%
5	Availability (%) - Min/Max	%	99,99%				99%	99,999%
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h	0,5				0,1	1
7	Broadband Connectivity (peak demand)	Y/N or Gbps	N					
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N	N					
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N	Y (Baseline)					
10	Capacity (Mbps/m^2 or Km^2)	Mbps/Km^2	40**				~15	~50
11	Device Density	Dev/Km^2	1				1	1
12	Location Accuracy	m	0,1				0,1	0,5

(*) Although the robot is autonomous, moving part of the computation from the robot to the network in order to have higher computational power is needed. Hence sensory data should be sent from the robot to the external machines with a maximum delay of 15ms. Similarly, the maximum delay for the control action (from the network to the robot) should be ~15ms. Larger delays in the control loop (or packets loss) may cause instability/failure of the navigation system.
(**) Capacity = 40 Mbps/Km^2 = 0,00004 Mbps/m^2

Regarding the system latency, we performed ping tests from the robot to different target machines. Results are reported in Figure 78. It can be noticed that the values are very similar when the robot communicates with the remote server using its public IP address and when it is using the VPN. We can thus conclude that the VPN is not really affecting the latency of the system during the ping tests.

from:	robot 192.168.100.10	robot 192.168.100.10	robot 192.168.100.10	robot 192.168.100.10
to:	5G phone ip 192.168.205.230	google public ip 8.8.8.8	server public ip 88.54.208.59	server VPN ip 10.8.0.2
min	0.452	14.8	22.7	23.53
mean	0.749	29.8	36.4	39.8
max	2.842	195.8	125.8	126.9
std	0.305	14.4	13.1	14.7

Figure 78. ping time (in milliseconds) from the robot to different target machines.

An additional note regards the particular case of network congestion (i.e. if the requested bandwidth exceeds the network availability). When this happens, the ping time obviously increases and it can reach peaks of hundreds of milliseconds of even seconds. Of course, this is not the normal operating condition, and during the trial it just happened few times, when the smartphone switched automatically to 4G due to a bad connection/network coverage in some specific locations of the room.

A final observation regards a similar failure condition of the system which was occasionally observed. In a few cases, during the tour, the smartphone switched to the 4G network even in areas of good network coverage, thus dropping the upload throughput to 1-2Mbit/s and causing a general system deadlock. Interestingly enough, in these cases the smartphone was not able to reconnect to the 5G network, even if disconnected to the robot and moved near the 5G antenna. Indeed, switching it to airplane mode (or a general reboot) was the only way to fix the issue. While we did not investigate the issue further, we speculated that it may be due to the fact that the device was not designed to sustain heavy traffic for several hours continuously[2]. These kinds of issues, in addition to the performance limitations and the intrinsic complexity of a system relying on a USB-tethered connection, strengthen our plan for the future to opt for a new modem-router with embedded 5G capabilities. Indeed, many manufacturers are now starting to release on the market new models with 5G capabilities and this solution would be very interesting to pursue in future developments.

[2] During the trial activity, about 100 Gigabytes per day of data traffic were consumed.

5 UC4 - High Quality video service distribution

5.1 UC4 definition

This use case targets the distribution of enhanced high-quality video and immersive services for tourists to enhance the user experience when visiting a city. It is directly related to the media and entertainment vertical. Users have been able to use their smartphones, tablets, or VR devices to receive educational and informative content during their visits to the city and museums. Video sources has been produced in collaboration with the RAI Television Production Center. This audio/video (A/V) product has been used for the demos in 5G-TOURS and it will serve as promotional activities about the city and its culture at the same time.

UC4 was initially divided into three sub-use cases: (a) transmission of mixed unicast/broadcast services using TIM's laboratory network (*b*) use of 5G broadcast delivery services using RAI's broadcasting network, and (*c*) development of a 5G core multicast component in UPV's laboratory.

The first sub-use case, as reported in D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) was cancelled. LTE eMBMS was never rolled-out on TIM network since it requests a huge amount of network resources (impacting on the other services) and without any consistent commercial demand. eMBMS requires an additional and consistent effort (and budget) that couldn't be provided since TIM is focused on the 5G network deployment: an activity targeting a legacy feature on a legacy system (involving both radio and CN parts) that is not going to be implemented in the network cannot justify such a type of investment. On such basis, it was decided to cancel the UC4a.

The two active sub-use cases are described below.

UC4.b: 5G Broadcast delivery to massive audiences

This sub use case aims at the transmission of high-quality content in a downlink-only mode by means of the 3GPP Broadcast network provided by RAI and UPV. The video content used in the final demo has been produced inside the itinerant orchestra, Use Case 5, and it has been broadcasted to all the tourists in Palazzo Madama.

The use of broadcast capabilities, such as 3GPP EnTV (Release 14) and Release 16 novelties with a High-Power High-Tower (HPHT) topology allows the reception of the signal regardless of the number of devices. This approach doesn't impact in the user quality of experience and in the performance of the demo. The trials have been divided into two phases.

- Phase 1- EnTV Rel-14. This stage consists of transmitting 3GPP enTV Rel-14 services to all users by using a broadcast tower. RAI already tested this technology under different scenarios, such as the European Championships 2018 in Aosta Valley, the Feast of San Giovanni, or the RAI-CRITS tests mobile TV broadcast demonstrator.
- Phase 2 - EnTV Rel-16. In this stage, the consortium has been committed to update LTE based 5G Broadcast to 3GPP Rel-16 and explore the advantages that this technology brings to real users such as citizens or tourists. Expected improvements are a larger coverage or higher mobility speeds. It had been envisioned to use the multimedia content produced in the itinerant orchestra (UC5).

UC4.c: 5G Core Multicast

This use case entails the development of a multicast component in the 5G core available in UPV premises. The implementation of a multicast/broadcast capable 5G Core software was not completely finished in the mark of this project due to some difficulties and the delay they costed. The goal was to implement, develop and validate a set of enhancements that will provide the 5G Core open-source software with multicast capabilities aligned with Release 17. The system has been implemented into UPV premises using Open5GCore that is an open-source software implementing 3GPP 5G Core whose last version is Release 16 compliant.

UC 4.c trials will include Service Layer modules in the system. The work of the Service Layer for broadcast/multicast support focuses on two actions: the support of the new network functions being specified in the

3GPP work and the enhancement of the transport delivery stack. In the trials, the main functionality implemented by the Service Layer is the media content injection point.

The implementation aims for a 5G-TOURS adapted architecture, whose reference is TR 26.802 (3GPP , 2021) proposed architecture, shown in Figure 79**.**

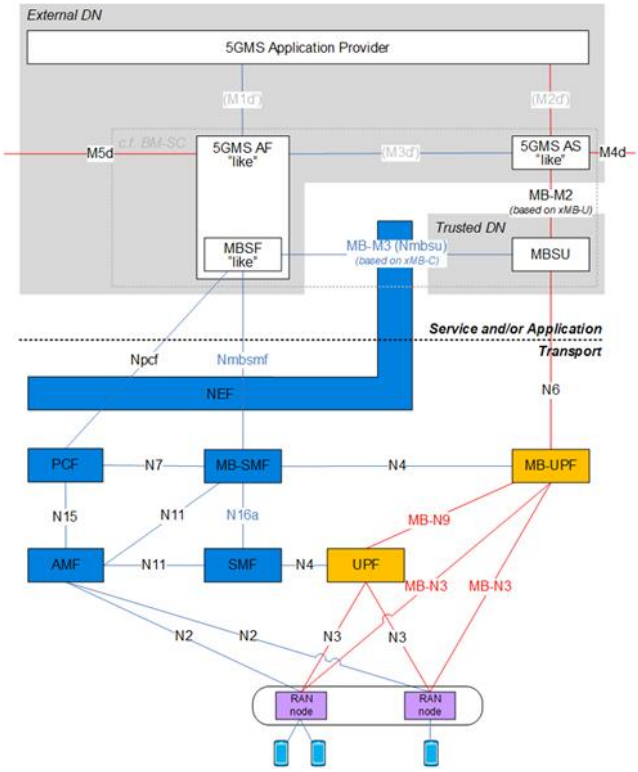


Figure 79. 5G-TOURS adapted proposed architecture.

In addition, the multicast 5GC system includes an application layer forward error correction (AL-FEC) technology to improve the transmission protection implemented by Raptor codes. Raptor codes are the first known class of fountain codes with linear time encoding and decoding. Raptor codes perform software-implemented Forward Error Correction (FEC), thus, there is no need to integrate any additional dedicated hardware in the system to perform AL-FEC. The increment of reliability in data transmission derived from Raptor Codes determined its standardization for MBMS AL-FEC. In this system, the latest and most improved version of Raptor codes, called RaptorQ, is used. The combined integration allows reliable and efficient downlink broadcast communications even in the most challenging environments.

5.2 UC4 implementation

5.2.1 Network Deployment

UC 4.b: 5G Broadcast delivery to massive audiences

In the framework of the UC4.b, the testbed of Turin is used to transmit a program to all users at once via the broadcasting network of RAI in a downlink-only mode. As described in the previous section, the trial has been split into two phases: due to the pandemic, the first one has been carried out in the RAI laboratories, providing additional measurements and test results about 5G broadcast transmitting simulations according to the Rel. 14, while in the second one the transmitter and the receiver equipment set up a real 5G broadcast experience according to Rel.16. Immersive services have been showcased in this phase to highlight the capabilities of the 5G network in terms of bandwidth resources.

The trials to be held during the second phase have been rescheduled, following the precarious situation introduced by the health emergency:

- Indoor scenario (Palazzo Madama or RAI CPTO premises) and Wi-Fi multicast distribution to a large panel of users of a live or pre-recorded video signal.
- Mobile in-car scenario in the city center and unicast Wi-Fi distribution in the car of a live or pre-recorded video signal.

During a special event performed in November 2021 (joint demo with UC5), a video live signal have been generated by a direction located in the surrounding of Palazzo Madama. The SDI signal has been then compressed in HEVC with an Encoder by Elemental. The chosen bit rate was decided on the basis of the modulation scheme (MCS) adopted during the trial and depending on the scenario that has been considered for the live demo.

UC4.c: 5G Core Multicast

Initially, the new 5G Core multicast capabilities were planned to be tested only in UPV's laboratory. However, in order to focus the implementation of the 5G-Native Multicast Core on the demonstration on the 5G-EVE-based 5G-TOURS trial, the trial was not limited to laboratory testing into UPV premises but extended to involve 5G-EVE. In this sense, the trial was restructured and enlarged to 4 different phases.

Phase 1:

The first phase of the UC4.C implementation does not involve 5G-EVE premises. The complete system has been placed in the UPV laboratory (Valencia). In addition, Enensys' Service Layer implementation has been deployed in Valencia and connected to Amarisoft, which will perform 4G Core and eNB tasks. To validate this phase of the use case Enensys' Mobile Cube Agent application has been deployed into an eMBMS capable user equipment provided by Samsung that will act as endpoint.

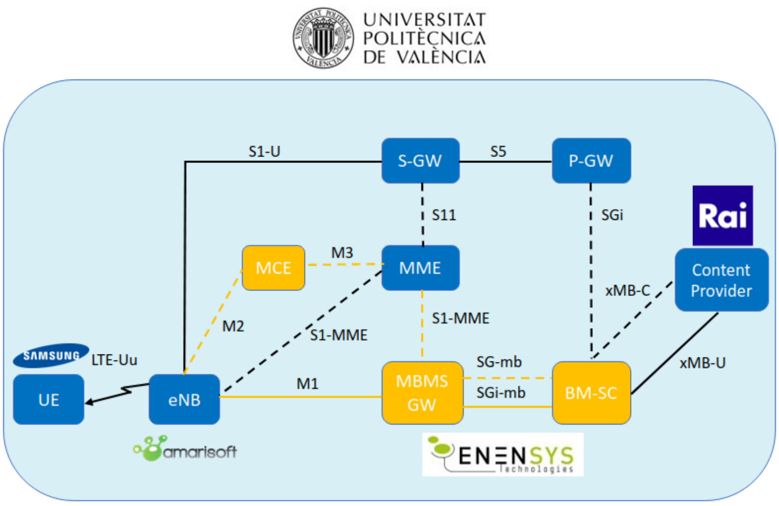


Figure 80. Use Case 4.C Phase 1 Deployment.

The architecture shown in Figure 80 allows multicast end-to-end tests using 4G technology as an initial trial. This deployment aims to test the correct connection and combined functioning of the Service Layer modules into UPV's laboratory.

Phase 2:

Phase 2 architecture, Figure 81, enhances Phase 1 deployment including 5G-EVE premises in the trials, where Service Layer modules have been placed. This deployment proves the performance of the UPV-5G-EVE connection involving both unicast and multicast/broadcast interfaces between both sites.

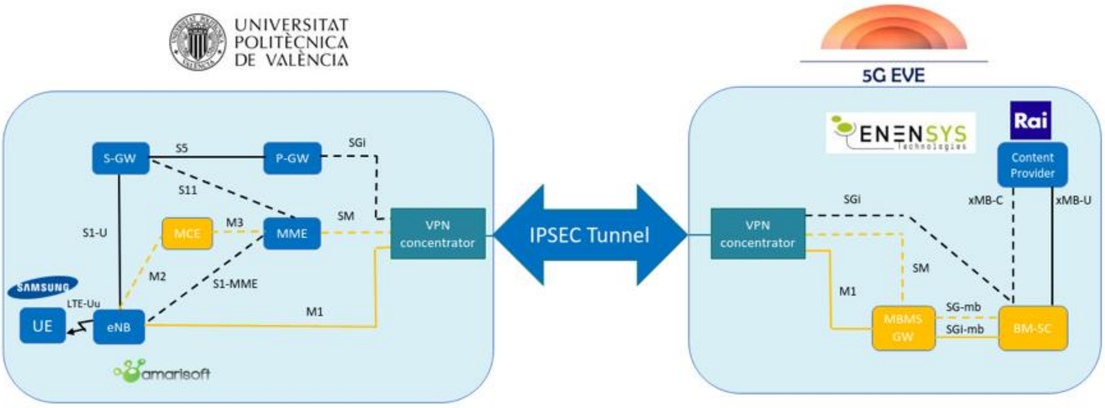


Figure 81. Use Case 4.C Phase 2 Deployment.

Figure 81. Use Case 4.C Phase 2 Deployment. The first trials done with the architecture of phase 2 were done using a demo video provided by Enensys. However, after the video from UC5 was supplied to the partners the trial was updated to use this video instead.

Phase 3

The Phase 3 architecture included the Release 17 multicast capable 5G Core developed in UPV as well as the implementation of RaptorQ FEC codes. The implementation focuses on the two new entities defined by the 3GPP and the northbound interface. The two new entities are:

- **Multicast-Broadcast SMF (MB-SMF):** the MB-SMF is used for session management (including QoS control), and control of multicast transport, configuring the MB-UPF and RAN (via AMF) for multicast/broadcast flows transport based on the policy rules for MBS services from PCF or local policy.
- **Multicast-Broadcast UPF (MB-UPF):** The MB-UPF is used for delivery of MBS flows to RAN (or UPF for individual delivery) and QoS enforcement for MBS services. The MB-UPF performs the following functions to support MBS:
    - Packet filtering of incoming downlink packets for MBS flows.
    - Distribution of MBS data packets to RAN nodes (or UPF nodes).
    - QoS enforcement and counting/reporting based on existing means.

The system was going to be completely deployed into UPV premises as an initial step as it was done in Phase 1. The architecture is illustrated in Figure 82.

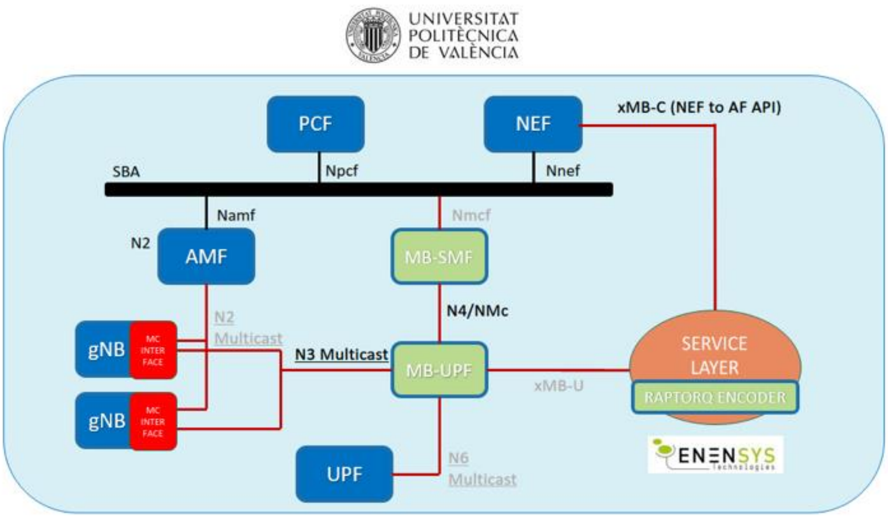


Figure 82. Use Case 4.C Phase 3 deployment.

This trial would test the correct functioning of the beyond state-of-the-art 5G Core, including its connection with the Service Layer and the implementation of the RaptorQ based FEC system. However, due to the lack of Release 17 compliant radio equipment, the multicast/broadcast transport only covers the communication inside of the core, reaching to the gNB.

Phase 4:

5G-TOURS intended architecture would have been deployed in Phase 4. In this architecture, the Service Layer was placed in 5G-EVE premises, similarly to the Phase 2 system. The connection would use the interfaces created for Phase 2. The Phase 4 system is illustrated in Figure 83.

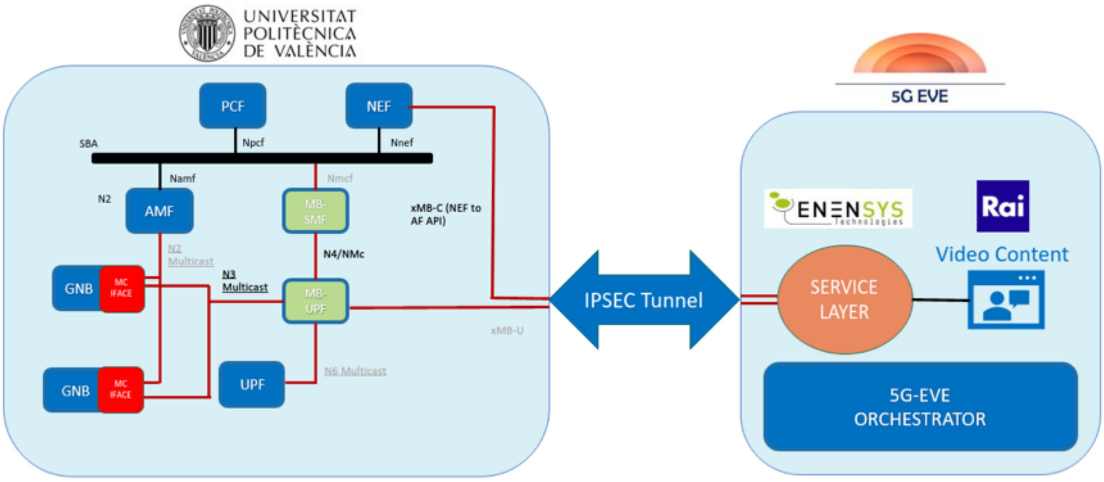


Figure 83. Use Case 4.C Phase 4 deployment.

Unfortunately, as stated in the first section of these use case, the development was not able to be finished with all the required parts for a Rel-17 Broadcast 5G Core. Instead, a demo to highlight the accomplished parts of the development has been made and is explained in later sections.

5.2.2 Network Equipment

UC 4.b: 5G Broadcast delivery to massive audiences

The network scheme used during Phase 2 of the trials is shown in Figure 84.

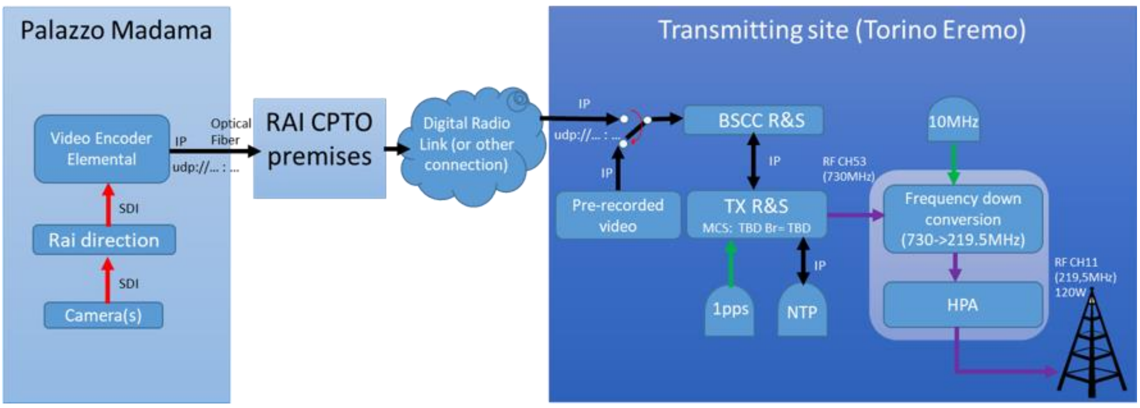


Figure 84. Phase-2 trials configuration.

The Rel. 16 signal is transmitted from Torino-Eremo towards the city of Torino and received both in indoor (at either Palazzo Madama or RAI premises) and mobile scenario (in the city centre).

UC4.c: 5G Core Multicast

As stated previously, the system of this use case has used an Amarisoft equipment to perform phases 1 and 2 of the use case.

5.2.3 Application Components

UC 4.b: 5G Broadcast delivery to massive audiences

Since 5G broadcast terminals are not yet available in the market, the signal reception at the end user still needs be achieved by using special hardware/software defined receiver (SDR), for both indoor and mobile in-car scenarios.

Since the SDR has been upgraded in order to receive 5G broadcast signals according to the Rel. 16, a successful lab session has been organized at RAI laboratories.

UC4.c: 5G Core Multicast

As explained in the use case description, the system has been implemented into UPV premises and included inside the software Open5GCore (O5C). The modification consists in the creation of MB-SMF, MB-UPF and NEF modules implemented by adding some enhancements to the original SMF, UPF and NEF modules provided by O5C. In addition, to test the successful functioning of the multicast/broadcast communication, the system requires Enensys ' Mobile CubeAgent installed into the eMBMS capable UEs to be able to employ the available multicast/broadcast services.

5.2.4 Terminal Equipment components

UC 4.b: 5G Broadcast delivery to massive audiences

The RAI transmitting and receiving chain has been upgraded to Rel. 16 in July-August 2021.

The equipment involved in the trials has then been updated as in the following table:

Table 6. UC4b list of the equipment.

Reference name	Number	Model	Minimum specifications (CPUs, RAM, storage, etc.)	Public/private IP	VPN required	Provided by
Broadcast Service and Control Center (BSCC)	1	R&S (BSCC2.0 for Live Tv)	Rel-16 Compliant	private	no	RAI
Broadcast Transmitter System	1	R&S (TMU9C)	Rel-16 Compliant: includes SDE900, TCE901 and PMU905 (UHF amplifier band IV-V, DTV 400 W rms, Doherty)	private	no	RAI
RF converter and amplifier	1	ONEtastic – ONECOMPACT HV		private	no	RAI
VHF antenna	2	OffelE11Y6,R&S TSMDVB-Z2 antenna magnet mount		_	_	RAI
SDR receiver	1	R&S FEMBMS receiver	Rel-16 Compliant: includes TX9-B82 (single CPU, DekTec interface), DTA-2131 UHF/VHF multistandard RX	private	no	RAI
SDR receiver	2-3	USRPs B210				UPV
Measurement receiver	1	Kathrein		private	no	RAI
Server and access point	2	Global Invacom BX-WiFi, D-Link DIR-615		private	no	RAI
Smartphones	2	Galaxy S10 5G		_	_	SRUK
Smartphones	3	Samsung Galaxy S10, LG V40, Sony Xperia XZ4		_	_	RAI
Video Encoder	1	AWS Elemental Live		private	no	RAI

UC4.c: 5G Core Multicast

Regarding the implementation of the core network and its trials, most of the updates are software-based, so only a few hardware components are used, most of them test the integration for Phase 1 and Phase 2 architecture. However, due to the high processing capabilities requirement of the task, a VMWare platform is used to deploy different Virtual Machines either for Open5GCore implementation or to deploy Service Layer modules. The equipment involved in this trial is shown in the following table:

Table 7. Equipment involved in the trial.

Component	Quantity	Model	Requirement
Service Layer modules	1	Linux Virtual Machine (redhat 7.9 or Fedora 30 /32)	1 CPU/4 cores/2.4 GHz, 16 GB RAM, 80 GB storage, 2 network interfaces Gbps.
VMWare platform	1	*Supermicro sys-1029p-wtrt*	
Smartphones	3	Galaxy S21+ 5G	eMBMS support with Exynos chipset.
Amarisoft	1	AMARI Callbox Ultimate	

The beyond state-of-the-art scope of Phase 3 and 4 architectures derives in a lack of commercial equipment capable to perform the task. For that reason, the components of both deployments have been performed using simulated equipment.

5.2.5 Interfaces

UC 4.b: 5G Broadcast deliveries to massive audiences

The interfaces used by different devices were reported in the previous deliverable D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) in which both the network scheme to be used during the phase 1 of the trials and the DASH configuration is shown.

UC 4.c: 5G Core Multicast

The connection with the Service Layer modules is performed using an xMB interface, as it was done in 4G technology. However, some updates were needed. After an internal discussion, IGMP IPv4 was chosen as the best option to implement multicast variants of N3 and N6 interfaces. Additionally, some enhancements were needed into the N2 interface to adapt the system for multicast traffic accommodation. However, the N2 interface update could not be completed to consummate the intended architecture.

5.3 Integration and test in labs

UC 4.b: laboratory test (Rel.14)

The results regarding the Rel.14 have been already reported in D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020).

UC4.b: SDR prototype

During the project, the UPV has been working with the OpenAirinterface (OAI) open source platform. This platform offers an end-to-end solution, which at the time of the development of the SDR prototype, offered a FeMBMS solution, compatible with Rel-14 3GPP specifications. The UPV has been working on the upgrading and adaptation of the OAI FeMBMS solution, in order to introduce the Rel-16 specifications.

However, the OAI code has presented a series of instabilities and issues, that made it impossible to continue working with it. The OAI transmitter has shown some very large instabilities, high power variations, which are linked with reception problems. Sync issues between the user (UE) and the cell (eNB) have also been reflected, causing packet and synchronisation loss. Carrying out a real-time demonstration with all the basic problems presented by the OAI platform has made it possible to move to another platform.

The chosen platform has been the SRSRAN one. At the time of the change, the ORF group (Österreichischer Rundfunk), which is a member of the 5G-MAG (Media Action Group), developed a functional FeMBMS receiver (Rel-14). The UPV, recently a member of the 5G-MAG, has developed a 5G Broadcast transmitter, Figure 85, which is 3GPP Rel 14 compliant and has some Rel-16 capabilities, being the first 5G Broadcast LTE-Based SDR prototype (transmitter and receiver).

Figure 85. 5G Broadcast SDR prototype system architecture.

UC 4.b: laboratory test (Rel.16)

Before the scheduled demo in November, as in previous Phase 1, preliminary lab tests have been carried out in order to check the performance of the entire Tx-Rx chain after the upgrade to Rel. 16 upgrade (completed in July 2021), compared with its former 3GPP Release 14 FeMBMS broadcast profile.

The lab tests of the new release have been carried out at Rai CRITS laboratory in August 2021: all the elements in the transmitting chain and those in the receiver one (based on Rohde&Schwarz/iFN SDR receiver, access point and smartphones) have been tested in presence of the following conditions:

- Additive White Gaussian Noise (AWGN)
- Single echo
- Mobile reception condition (COST206-Typical Urban 6 taps)
- Single Frequency Network (SFN)

Figure 85. 5G Broadcast SDR prototype system architecture. reports the test equipment running the Rel. 16. A pre-recorded and encoded video signal is sent to the R&S BSCC. The block diagram of the adopted test bench that is reported in Figure 87. Laboratory set-up block diagram for phase 2.

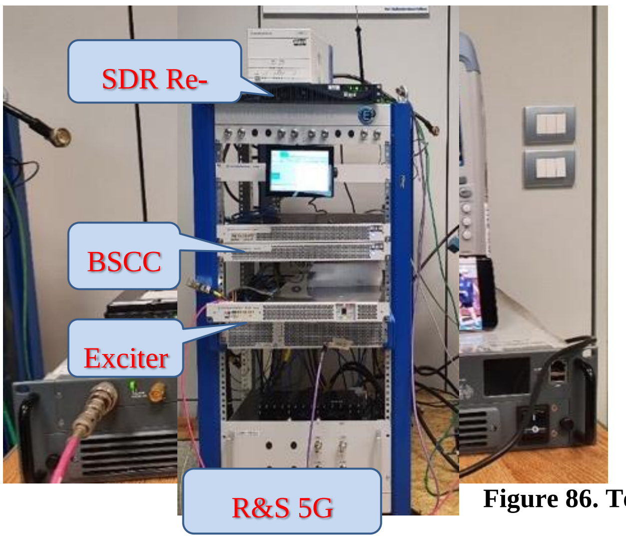


Figure 86. Test equipment running the Rel. 16.

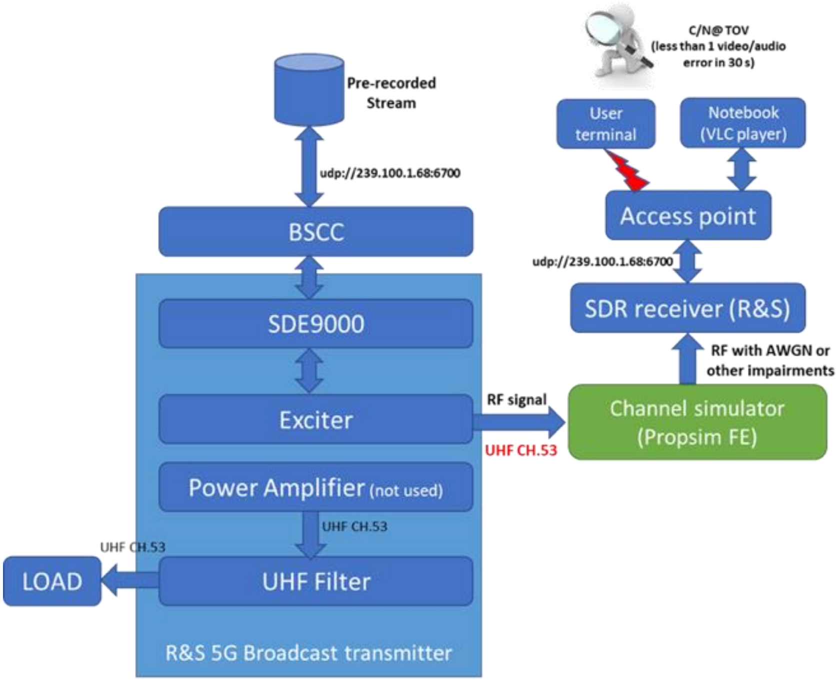


Figure 87. Laboratory set-up block diagram for phase 2.

a. Additive White Gaussian Noise (AWGN)

A pre-recorded stream has been played through a Dektec DTA2162 card and controlled by StreamXpress software. The multicast output stream has been sent to the BSCC, suitably configured, and then to the SDE900 and the exciter. The RF output from the exciter has been directly used, since the power amplifier block has been disconnected for our lab tests purposes, and the central output frequency has been the one of channel 53 UHF (730 MHz).

The generated the RF signal has been sent to the Anite Propsim FS8 channel simulator where a white Gaussian noise has been added. The noised signal has been finally sent to the SDR receiver, whose output (IP multicast) was sent to a PC with a VLC player to display the video.

A measurement has been then carried out for each MCS, noting the C/N value at the Threshold Of Visibility (TOV), defined as the condition at which less than one audio/video error occurs during at least 30 seconds of observation. Figure 88 reports the measured values during our tests.

			Rel. 16		
		Rel. 14	SCS 1,25 kHz CAS Rel. 16	SCS 2,5 kHz CAS Rel. 16	SCS 7,5 kHz CAS Rel. 16
MCS	Modcod	C/N@TOV [dB]	C/N@TOV [dB]	C/N@TOV [dB]	C/N@TOV [dB]
0	QPSK 0,11	NA	NA	NA	NA
1	QPSK 0,15	NA	NA	NA	NA
2	QPSK 0,18	NA	NA	NA	NA
3	QPSK 0,24	NA	NA	NA	NA
4	QPSK 0,30	-0,2	-1,1	-0,6	-1,1
5	QPSK 0.37	-0,1	-0,2	0,4	-0,1
6	QPSK 0.43	0,6	0,7	1,3	0,6
7	QPSK 0.52	1,5	1,7	2,4	1,7
8	QPSK 0.59	2,6	2,5	3,4	2,5
9	QPSK 0.67	3,7	3,8	4,6	3,7
10	16QAM 0.34	4,0	4,0	4,7	4,2
11	16QAM 0.37	4,4	4,7	5,3	4,7
12	16QAM 0.42	5,1	5,5	6,4	5,7
13	16QAM 0.48	6,5	6,4	7,3	7,2
14	16QAM 0.54	7,7	7,7	8,7	>40
15	16QAM 0.59	8,4	8,7	9,8	>40
16	16QAM 0.64	9,3	9,6	10,7	>40
17	64QAM 0.43	9,8	10,1	11,1	>40
18	64QAM 0.46	10,2	10,4	11,5	>40
19	64QAM 0.51	11,6	11,8	12,8	>40
20	64QAM 0.55	12,4	12,5	14,0	>40
21	64QAM 0.60	13,7	13,5	14,9	>40
22	64QAM 0.64	14,3	14,3	15,6	>40
23	64QAM 0.71	15,7	15,7	17,5	>40
24	64QAM 0.76	16,8	16,5	18,1	16,1
25	64QAM 0.79	17,9	17,2	19,3	16,8
26	64QAM 0.85	19,4	18,5	21,4	22,5
27	64QAM 0.89	19,7	19,0	26,1	23,5

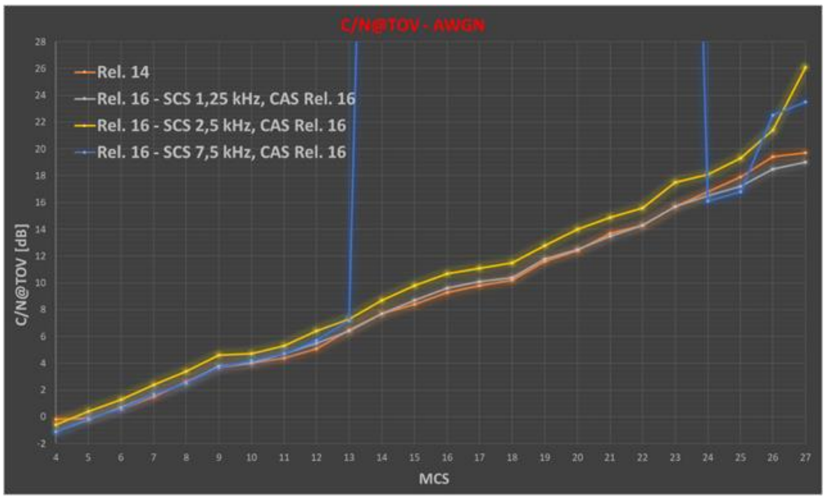


Figure 88. C/N@TOV with AWGN (Bw= 5 MHz, SCS= 1.25 kHz, 2.5 kHz, 7.5 kHz).

The results obtained with the AWGN channel are summarized in the following:

- With SCS = 1.25 kHz (the same as Rel. 14) the results are in line with what has been already found in the previous measurement campaign on Rel. 14 and then they are well aligned with the expected theoretical ones.

- With SCS = 2.5 kHz there is a slight degradation ranging from 0.5 dB with the most robust MCS up to about 2 dB with the most efficient MCS. This indicates that the receiver has not yet been perfectly optimized to operate in this new mode envisaged by Rel. 16
- With SCS = 7.5 kHz the results are in line with what obtained with SCS = 1.25 kHz from MCS4 to MCS12; they are better than SCS = 1.25 kHz for MCS 24 and 25. However, there are some MCS (MCS 14 to MCS 23) where the receiver is not working at all despite the receiver indicates a "Synced" status (the VLC video continuously shows errors). The remaining MCS are worse compared to their performance with than SCS = 1.25 kHz (on average 1-2 dB).

b. Single echo

The single echo test is used to evaluate the robustness of the system in the presence of an echo which can be either natural (reflection against an obstacle) or artificial (signal coming from another transmitter operating at the same frequency, SFN). Typically, a “robust” echo (equal to or slightly below the main signal) causes a degradation in performance compared to the presence of AWGN only; this degradation can be quantified between a few dB fractions and a few dBs as long as the delay is within the cyclic prefix. Outside the cyclic prefix, on the other hand, the echo behaves as an interfering one and therefore the system quickly collapses.

During these tests, the performance of the MCS7 (QPSK 0.52) and MCS12 (16QAM 0.42) modes have been checked, since they are considered as particularly significant modes in case of mobile reception. The echo has been generated using the Anite Propsim FS8 channel simulator. The delay of the echo, having a power of 1 dB lower than the main signal (C/I = 1 dB), has been changed from 1µs up to over the CP (see **Figure 89**): 33µs for SCS = 7.5 kHz, 100 µs for SCS = 2.5 kHz, 200 µs for SCS = 1.25 kHz. SCS = 0.37 kHz, which has a CP of 300 µs is not currently supported by the R&S receiver and it has not been tested.

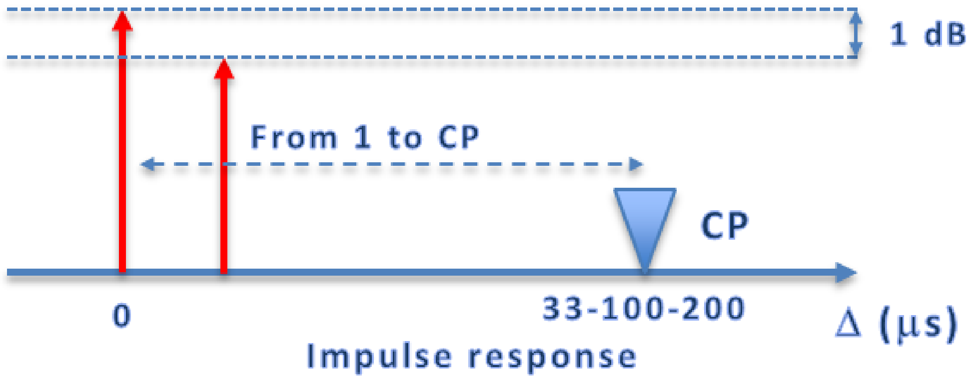


Figure 89. Impulse response with one echo.

For each delay, noise has been added until the TOV has been reached: the results are reported in the tables below (see Figure 90). The tests refer to a transmission at 730 MHz.

	SCS 1,25 kHz	
	C/N@TOV [dB]	
Δ [µs]	MCS 7	MCS 12
1,0	2,6	6,4
2,0	3,4	7,0
3,0	3,5	6,9
4,0	3,4	7,0
8,0	3,4	7,0
10,0	3,7	6,9
15,0	3,7	7,0
16,0	3,7	7,2
20,0	No sync	No sync
30,0	4,5	7,3
40,0	3,6	7,0
50,0	4,8	7,3
100,0	4,8	7,0
150,0	4,8	7,2
190,0	4,8	7,5
200,0	30,0	30,0
220,0	No video	No video

	SCS 2,5 kHz	
	C/N@TOV [dB]	
Δ [µs]	MCS 7	MCS 12
1,0	3,8	7,2
2,0	4,5	8,3
3,0	6,6	8,1
4,0	4,9	8,1
8,0	5,0	8,1
10,0	4,7	8,0
15,0	4,7	8,3
16,0	4,7	8,0
20,0	No sync	No sync
30,0	4,7	8,2
40,0	4,8	8,2
50,0	17,0	17,2
70,0	5,0	8,1
90,0	5,2	8,3
100,0	No video	No video
110,0	No video	No video
150,0	No video	No video

	SCS 7,5	
	C/N@TOV [dB]	
Δ [µs]		MCS 12
1,0	3,7	8,2
2,0	6,5	9,0
3,0	4,7	9,0
4,0	4,5	8,6
8,0	5,1	8,6
10,0	5,2	9,0
14,0	13,5	13,8
16,0	No sync	No sync
20,0	No sync	No sync
25,0	No sync	No sync
30,0	40,0	No sync
33,0	11,0	No sync
35,0	No video	No video
40,0	No video	No video
50,0	No video	No video

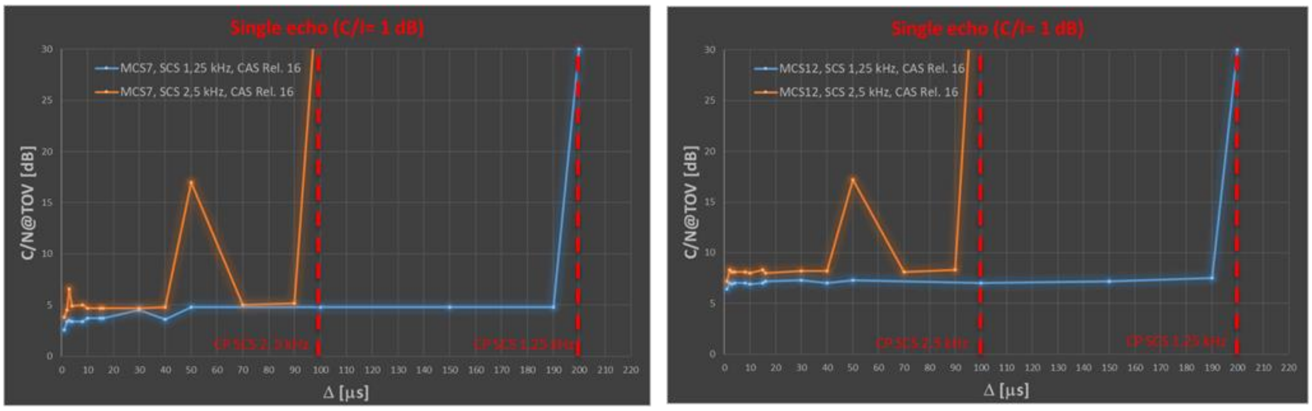


Figure 90 . C/N@TOV with one eco with C/I=1 dB (CAS mode = "Rel. 16").

As it can be easily observed from the graphs in, the behaviour of the receiver, concerning the duration of the CP, is in line with what is theoretically expected. However, for all SCS some problems with echo delays ranging from 16 to 30 µs have been observed. It is assumed that this malfunction is in some way correlated with the duration of the cyclic prefix of the CAS which is 16 µs. This hypothesis needs to be investigated by R&S and TUBS who have been informed.

Outside this critical range, the following observations can also be made:

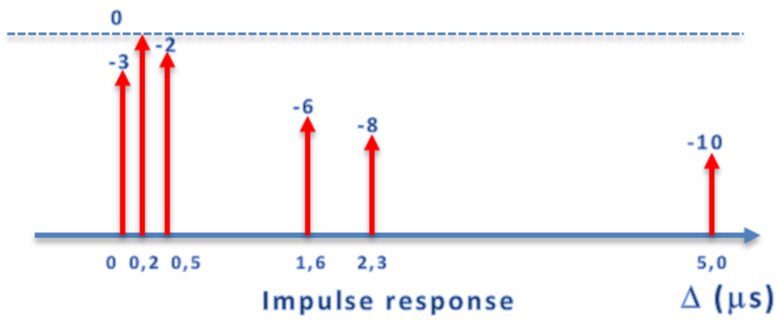
- With SCS = 1.25 kHz the results are in line with what was expected.
- With SCS = 2.5 kHz the results are in line with what was expected, except for an anomalous point at 50 µs (still under investigation).
- With SCS = 7.5 kHz the results are quite far from the expected values. This result is not surprising considering the problems in case of AWGN: the receiver must certainly be optimized for this carrier spacing.
- Using «CAS Rel. 14» there are no appreciable differences.

c. Mobile reception condition (COST206-Typical Urban 6 taps)

Tests with Doppler shift allow to have an initial evaluation of the performance of the system in mobility. Typically, by using a channel simulator, echo profiles typical of mobile outdoor reception are generated. These profiles are defined in COST 206 and are:

- Typical Urban (TU6)
- Hilly Terrain (HT6)
- Rural Area (RA6)

During the tests, the Typical Urban profile was used whose echo profile and the corresponding impulse response are shown in Figure 91.



TU6 channel model			
Path	Amplitude [dB]	Delay (μs)	Doppler
1	-3	0	Classical
2	0	0.2	Classical
3	-2	0.5	Classical
4	-6	1.6	Classical
5	-8	2.3	Classical
6	-10	5.0	Classical

Figure 91. Typical Urban TU6: echo profile and impulse response.

Also in this case the MCS7 (QPSK 0.52) and MCS12 (16QAM 0.42) modes have been tested.

During the tests, the speed (and the Doppler shift consequently) has been increased starting from 1 km/h and noise has been added until reaching the TOV.

The results are reported in Figure 92.

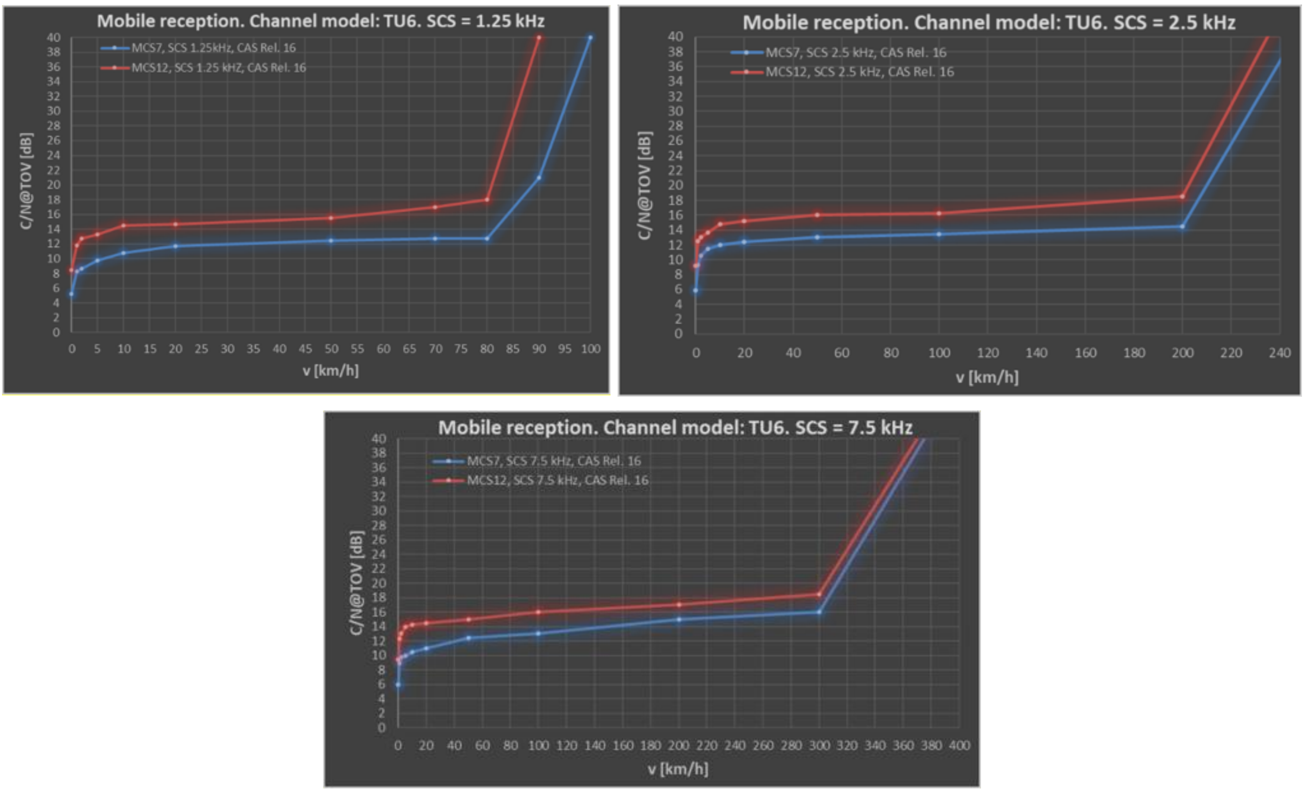


Figure 92. Typical Urban TU6: echo profile and impulse response.

Taking into account that the receiver has not been designed specifically for the mobile channel, the results look promising, also having in mind the field measurement campaign. In particular, with SCS = 2.5 kHz the maximum speed at 730 MHz is about 200 km/h, acceptable for most mobile use cases. SCS = 2.5 kHz seems to be the best compromise between robustness against the Doppler effect and the length of the CP (100 µs, distance of the transmitters up to 30 km). Also in case of the mobile channel, no differences were found using «CAS Rel. 16» or «CAS Rel. 14».

d. Single Frequency Network (SFN)

Having two transmitters available, a single frequency network has been set up in the laboratory in order to verify its correct operation in this mode, according to the measuring bench illustrated in Figure 93.

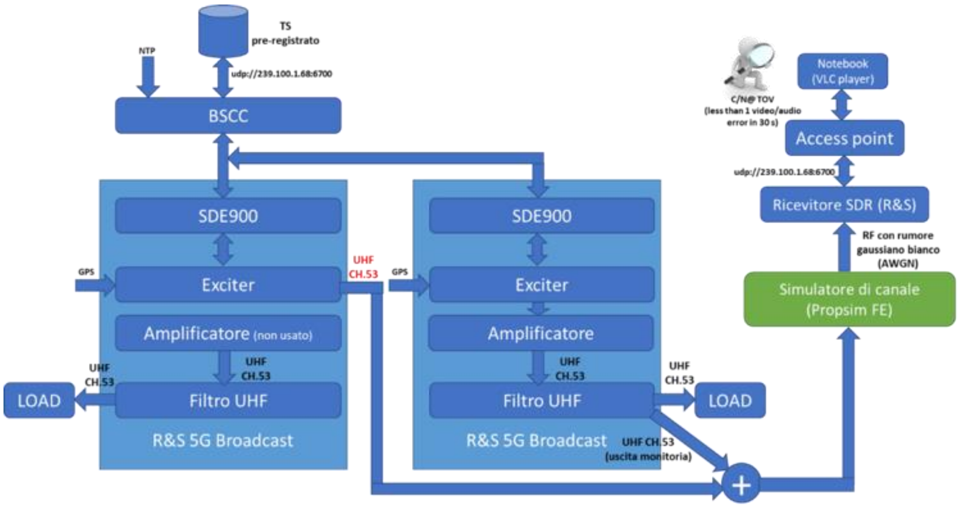


Figure 93. Measurement bench for Single Frequency Network.

The BSCC has been then set in SFN mode and the output sent to both SDE900s. Both transmitters, connected to a GPS signal, receive the flow coming from the BSCC and set the parameters according the instructions received from the BSCC.

As a first test, a static delay of 1 µs has been inserted on one of the two transmitters and the two outputs have been placed at a power difference equal to 1 dB (ratio C1/C2). After summing the two outputs, the presence of the classic "holes" in the resulting spectrum has been verified by means of a spectrum analyser. The result of this test is shown in Figure 94.

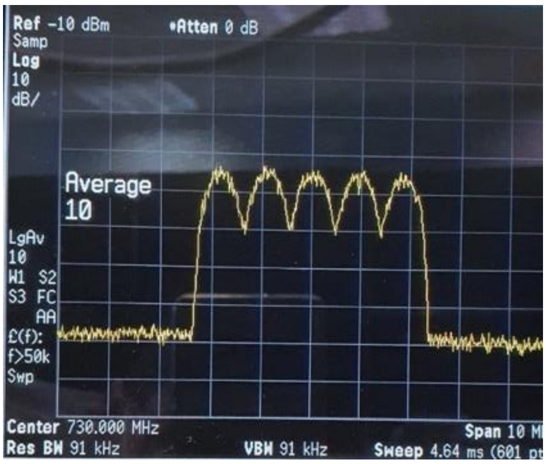


Figure 94. Transmitters in SFN (delay 1 µs, C_1/C_2= 1dB).

The tests carried out in the single-frequency network with the rel. 14 have produced a rather poor result: without AWGN and with delay between the signals within the cyclic prefix (for example 1 µs, 5 µs, 10 µs ....), with signals that differ by less than 10 dB in terms of signal strength (C1 / C2 <10 dB), the video on the PC and / or smartphone was frozen and the R&S receiver showed the "Unsync" status. With a level difference greater than 8-10 dB, the receiver worked correctly and the video stream flowed without errors.

According to R&S, the introduction of the CAS rel. 16 would also solve this problem.

The tests led to results congruent with what has been obtained in case of a single echo at C/I = 1 dB. The two configurations, strictly speaking, should be perfectly coincident: the only difference should be that in SFN there is a slight movement back and forth of the holes in the spectrum due to the sliding of the time references in the two transmitters, which is null in the long term while in the short term it can be easily observed looking at the signal spectrum.

The results, obtained by varying the static delay of one of the two transmitters from 1 μs up to beyond the CP, are shown in Figure 95:

	SCS 1,25 kHz CAS Rel. 16	
	C/N@TOV [dB]	
Δ [μs]	MCS 7	MCS 12
1,0	3,3	6,8
10,0	3,4	6,9
20,0	No sync	No sync
50,0	4,8	6,9
100,0	4,8	6,9
190,0	4,8	7,2
200,0	No sync	No sync
220,0	No sync	No sync

	SCS 2,5 kHz CAS Rel. 16	
	C/N@TOV [dB]	
Δ [μs]	MCS 7	MCS 12
1,0	4,8	7,8
10,0	5,2	7,9
20,0	No sync	No sync
40,0	5,6	8,2
90,0	6,1	8,2
100,0	No video	No video
110,0	No video	No video

Figure 95. C/N@TOV in SFN (delay 1 μs, C_1/C_2= 1dB).

The results are slightly worse than those obtained in case of a single echo (Figure 90) an explanation could be that in case of SFN, as mentioned before, the echo has a slight slip which leads to a degradation in performance, compared to the case when the echo is perfectly static.

Furthermore, in SFN, as in the case of a single echo, in all tested modes (SCS 1.25kHz and 2.5kHz) some problems with echo delays between 16 and 30 μs have been observed.

The test has been then repeated using the CAS Rel. 14 and in this case the results were completely similar to what was found when we tested the Rel. 14 on the transmitters (reception problems with C1/C2 <10 dB as indicated above).

UC4.c: 5G Core Multicast

To integrate the Service Layer modules into UPV premises, Enensys has been enabled to use UPV's network. BMSC and MBMS Gateway have been implemented in a virtual machine placed in Valencia. In the scope of the Phase 1 architecture, the connection of both modules with the Amarisoft 4G system was accomplished.

In addition, the networks from UPV and 5G-EVE were modified in order to successfully connect with each other. In this sense, an IPSec connection was between both sites and the proper test were performed.

The newly created solution for Phase 1 and 2 architectures was going to be reused and integrated into Phase 3 and 4 deployments. Instead, it has been used in the backup demo trial.

5.4 Test in the network

UC 4.b: 5G Broadcast delivery to massive audiences. Field test (Rel.16) in Torino

In October 2021 Rai CRITS and Rai Way activated a 5G Broadcast Rel. 16 test bed in Torino on VHF channel 11 (219.5 MHz), in order to test the potential of the new system. The goals of the testbed can be summarized in the following:

- To validate the main system technical features
- To evaluate the coverage with a single transmitter in Torino and in its first suburban areas, including the ring road (motorway), for an automotive reception (antenna mounted on the roof of the van)
- To record the RF signal in different conditions for off-line evaluations on the mobile reception availability
- To evaluate the EMF availability
- To identify a "threshold" in terms of EMF for the mobile reception

The set-up included the activation of one transmitter with a Pout=150W located on the main transmitting site around Torino, called Torino-Eremo: it is located on a hill 600 m asl (above sea level) and 400 m agl (about ground level) at about 6 km in line of sight from the city centre (Figure 96).

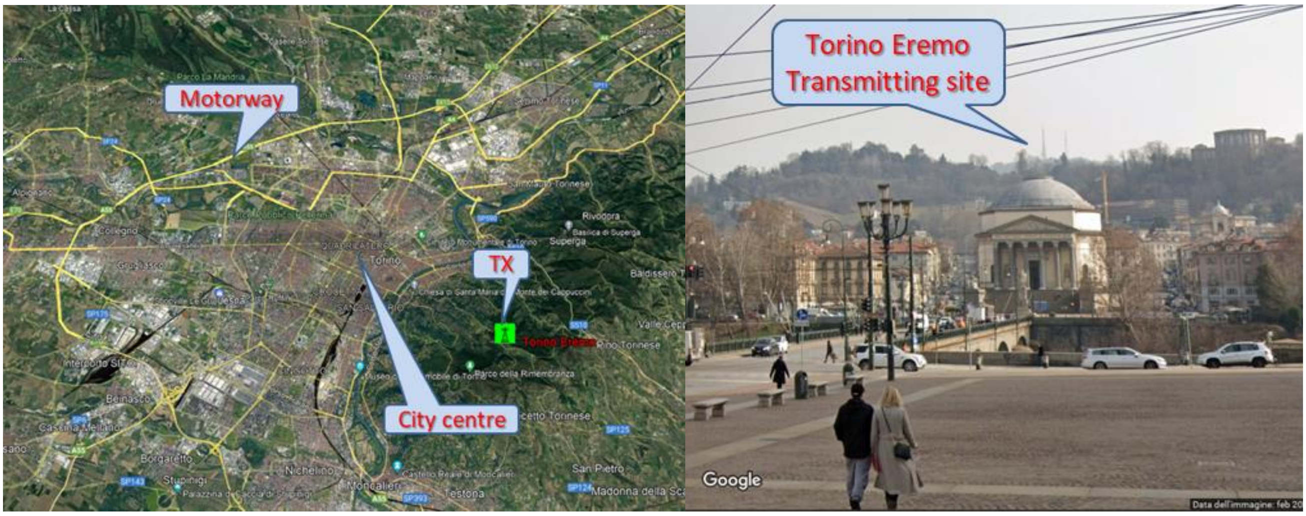


Figure 96. Torino-Eremo transmitting site.

Considering the tests carried out in the lab, in order to guarantee a good trade-off between the robustness in mobile reception and the bit-rate availability, the following modulation scheme has been adopted:

- MCS12 (16QAM, rate 0,42)
- SCS= 2.5 kHz (cyclic prefix = 100 μs)
- Bw = 5 MHz
- CAS Rel. 16
- Available bit rate = 4.83 Mbit/s

A pre-recorded signal (a promo of the 5G-TOURS event "Itinerant Orchestra") has been played in the Rai Production Centre premises of Torino (CPTO). The SDI signal coming from the play-out has been used to feed an Encoder for the generation of a TSoIP at a desired bit-rate. The multicast IP has been sent to the transmitting site via an optical fiber connection. At the transmitting site both the BSCC and the transmitting chain by Rohde & Schwarz have been placed. The set-up of the test bed is reported in Figure 97.

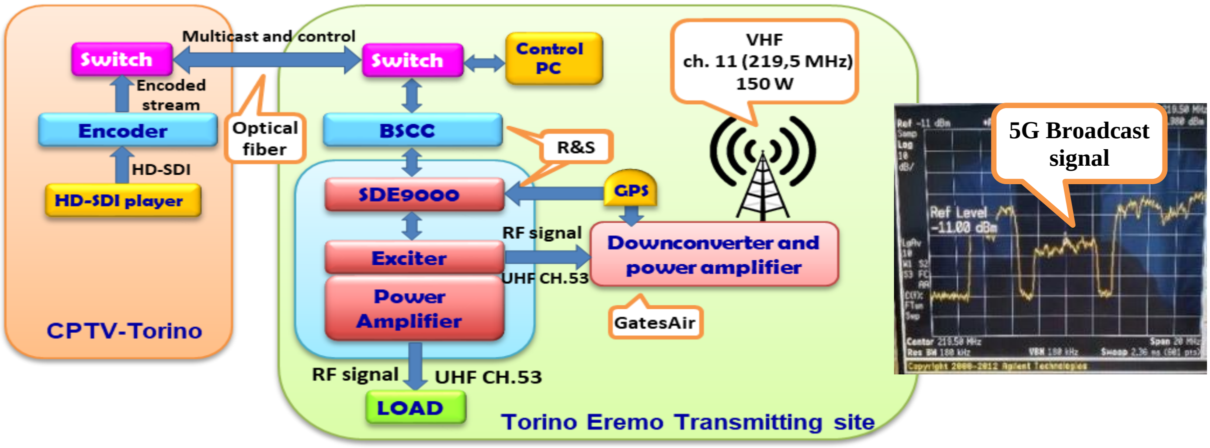


Figure 97. Test-bed set-up.

To carry out the tests in the service area, a van (Figure 97) equipped as follows has been set up:

- Omnidirectional VHF receiving antenna on car roof, vertical polarization
- 5G Broadcast receiver
  - R&S SDR receiver (not optimized for mobile reception)
- Labview software
  - Data logging: position, speed, video/audio errors
- Field-strength measurement
  - Power level at the receiver input and field strength using the antenna's parameters. GPS position
- RF grabber
  - RF recording, tracking of the position and the speed of the car

Figure 98. Measurement van.

The measurements, carried out mainly in the night to avoid the city traffic, have been divided into "routes" including both the urban and suburban parts of the Turin area, trying to include the most significant and popular places in the city (city center, airport, stadiums, railway stations, ring road etc.). Thus 18 routes have been identified for a total of almost 250 km traveled, as illustrated in Figure 99.

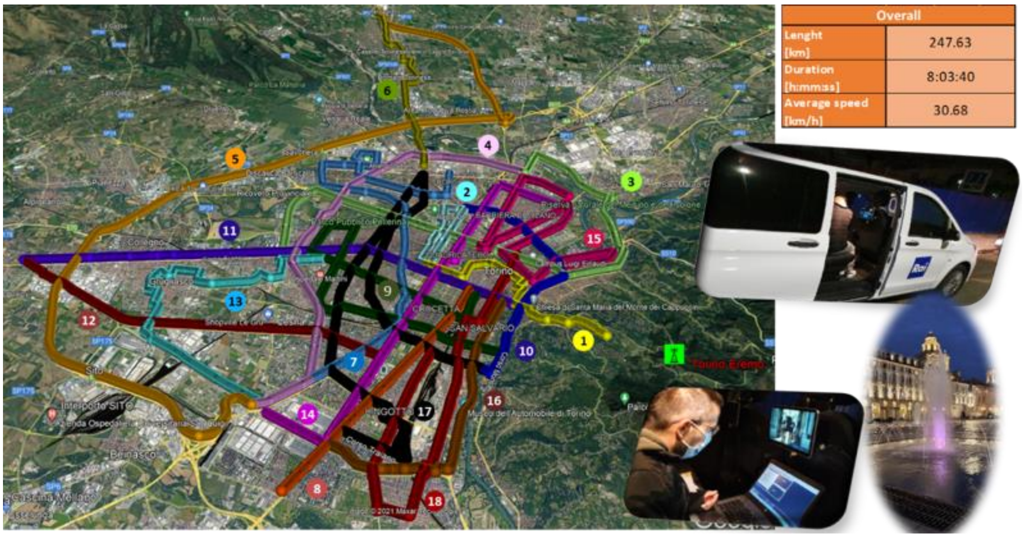
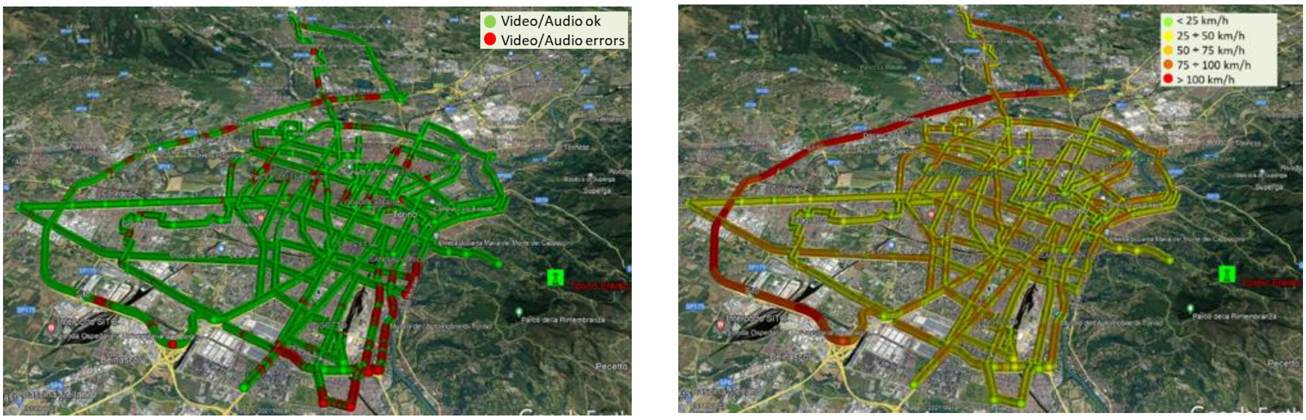


Figure 99. Torino's 5G «subway» - The routes.

The post-processing of all this huge amount of acquired data made it possible to assess the coverage of the "5G Broadcast" service transmitted by the Torino-Eremo broadcasting center.

Figure 100 shows the service coverage based on the video / audio errors detected during the measurements (a) and the speed of the van during the measurements (b).



(a) **(b)**

Figure 100.(a) Coverage of the Torino's area. (b) Speed of the van.

The estimated overall coverage has been 92,2%: every 100 s, more than 92 s have been correctly received while 8 s have shown some video and/or audio errors. This coverage estimation also includes some area of Torino generally considered outside the service area (for example the south-west area of the town, which is located at the base of the hill with the HPHT and for this reason affected by shadowing effects).

In Figure 101 the detailed coverage for each route is reported.

Routes	Name	Lenght [km]	Duration [s]	Errored seconds [s]	Coverage
01	01_Collina_Cavalli	6,82	1563	29	98,1%
02	02_Cavalli_Cavalli	5,68	1190	111	90,7%
03	03_Marche_Derna	19,00	2202	58	97,4%
04	04_Oxilia_Reni	14,63	1512	133	91,2%
05	05_Tangenziale_Caselle	33,39	1373	174	87,3%
06	06_Caselle_Borgaro_Torino	10,62	1030	126	87,8%
07	07_Casteldelfino_Orbassano	18,41	2430	34	98,6%
08	08_Unione_Sacchi	7,00	753	51	93,2%
09	09_Nizza_Dante	15,24	1795	75	95,8%
10	10_Zara_Baldissera	8,02	891	114	87,2%
11	11_Vittorio_Francia	13,37	1668	17	99,0%
12	12_Allamano_Sebastopoli	10,08	1014	5	99,5%
13	13_Grigliasco_Portone	11,84	1704	66	96,1%
14	14_Settembrini_Se,pione	13,59	1888	202	89,3%
15	15_Botticelli_Antonelli	16,81	2449	148	94,0%
16	16_Massimo_Vigliani	7,76	955	360	62,3%
17	17_Traiano_Zara	21,91	2781	162	94,2%
18	18_Bruno_PioVII	13,46	1822	405	77,8%
	TOTAL	247,63	29020	2270	92,2%

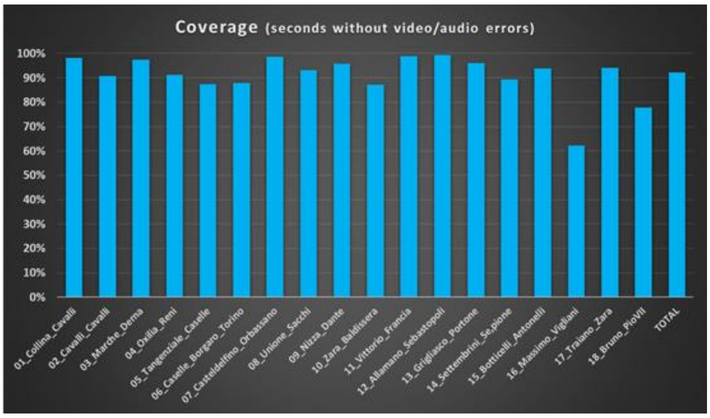


Figure 101. Coverage for each route.

Starting from the power measurements at the input of the receiver and taking into account the Rx antenna parameters, the electromagnetic field (EMF) at approximately 2 meters (height of the van) has been calculated.

Looking at Figure 102, please note that the colours system has been chosen in order to create a correlation between the evaluated field values and the corresponding measured power levels, thus, to be able to fix a kind of *operating threshold* in mobile reception. This threshold is also useful for off-line simulations: in fact, changing the modulation scheme, the transmitting power or other parameters (i.e. in the receiving antenna) we would have the possibility to "forecast" the service coverage for a certain area.

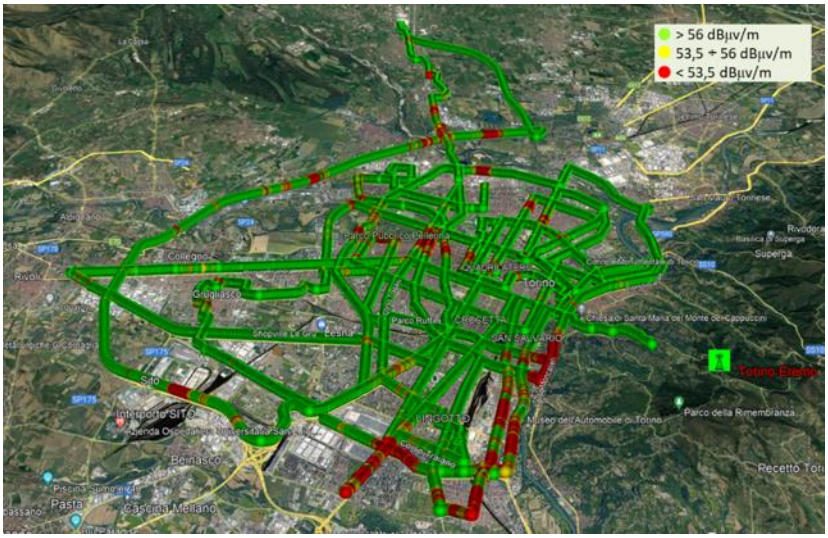


Figure 102. EMF in service area.

Tests have revealed a field strength threshold of 53.5 dBμv/m should be used as a criterion for the planning: considering this threshold, the points containing video/audio errors and the points "under threshold" are well aligned as can be appreciated in Figure 102.

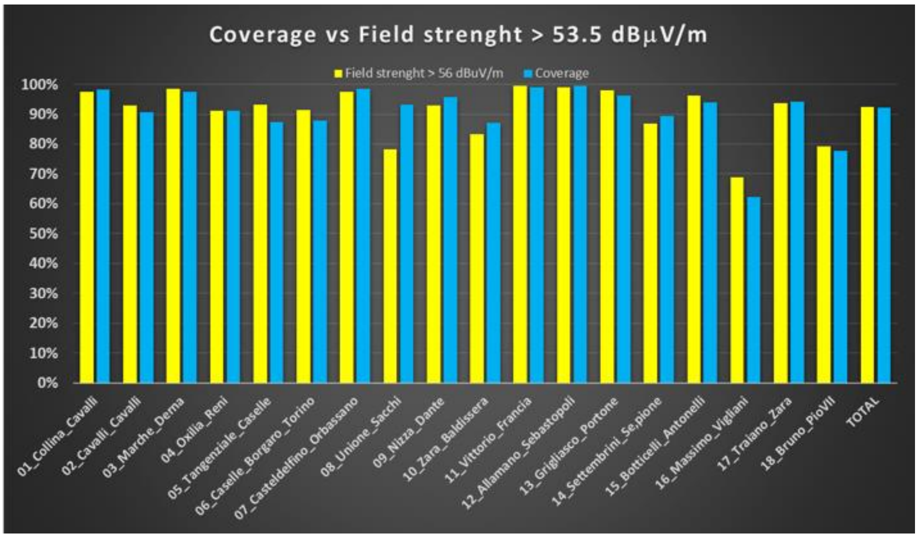


Figure 103. Coverage and EMF threshold.

As a final consideration, please note that the audio/video errors related to the measurements have been revealed by an human operator, by clicking a kind of "red button" every time he was seeing some issues in the car monitor placed in front of him. Therefore it is not misleading to assess that the identified threshold of 53.5 dBµv/m can be seen as a sort of criterion for the Quality of Experience definition (QoE) on customer's side.

UC 4.b: 5G Broadcast reception during the show "The Garden of Forking Paths"

RAI-CRITS, during the show "The Garden of Forking Paths" directed by *Maestro* A. Molino, has experienced the diffusion of high definition images to 5G mobile phones in broadcast mode, using the most recent 3GPP-Release 16 standard.

The production of the event, including traveling musicians and performers connected live with the central control room located inside Palazzo Madama, in the central Piazza Castello, has been supervised by the Turin Production Centre, in cooperation with the City of Turin, the RAI Research Centre, Ericsson, Torino Musei Foundation, LiveU and TIM.

The RAI Research Centre took care of the experimental transmission in 5G broadcast technology by the Rai Way transmitter in Torino-Eremo and the footage was available to the public in Piazza Castello, where a Rai equipped vehicle offered to the visitors the opportunity to experience the performance of 5G Broadcast through the use of a receiving chain specifically created for the event.

The set-up of the demonstration is reported in Figure 104.

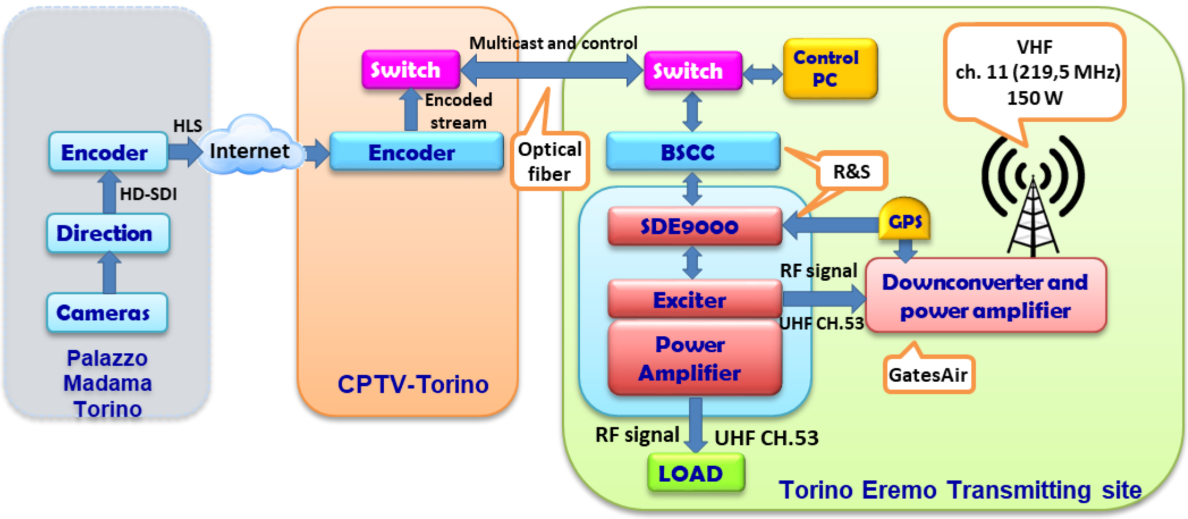


Figure 104. Set-up of the demonstration.

The demonstration illustrated to a large number of visitors, both technical and non-technical, the potential of 5G for television reception on future generation mobile phones and tablets. The quality of the service and the potential advantages of this new technology were globally appreciated.

UC4.c: 5G Core Multicast

After the accomplishment of the integration of the components from all the partners involved in the use case the proper tests were performed.

Regarding phase 1, Enensys created a script inside of the Amarisoft Ultimate Callbox placed in Valencia with the necessary settings to perform the EPC and eNB tasks. The following step consisted in the configuration of a SIM card with the required parameters according to Enensys' settings. With the achievement of the connection among all the components Enensys created a file download service to validate the first phase.

For the second step of the trial, the cross-sited version of the phase 1 of the trial involving UPV and 5G-EVE with the VPN mentioned in previous sections was implemented. At this point, Enensys handed the Service Layer deployment to be deployed in 5G-EVE premises. The initial trial was performed using Enensys' demo streaming as UC5 video production was still ongoing. However, once received the 5G-TOURS original video, it was used to create the DASH service.The Figure 105 and Figure 106 show the phone receiving the test streaming successfully.

Figure 105. UC 4C Phase 2 demo. Phone not receiving multicast data (UC5 demo).

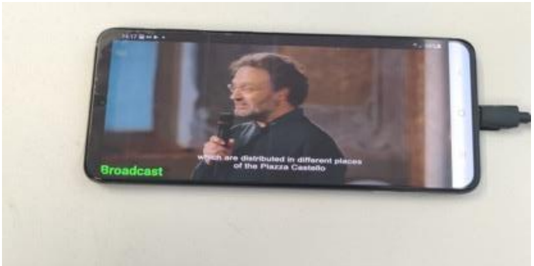


Figure 106. UC 4C Phase 2 demo, Phone receiving multicast data (UC5 demo).

The aforementioned architecture proposals for phases 3 and 4 provided a complete deployment proving the successful multicast/broadcast downlink reliable transmission of a professional streaming over a Release 17 5G Core involving both UPV and 5G-EVE sites. Unfortunately, due to some delays in the development the complete system could not be finished. The deployment lacks the necessary control signalling between AMF and gNB. For this reason, the system is unable to perform the standard procedures along the end-to-end chain.

As an alternative, a demo trial was implemented in order to highlight the completed parts of the development. The demonstration consists in the transmission and reception of a video content in emulated user equipment. The solution used in this demo had to be started manually inside of the gNB system because of the lack of the control signalling in the N2 interface. Nevertheless, this issue will be solved in future versions of the system.

Regarding the distributed content, this demo uses FFmpeg to create the video streaming and forward video chunks to the UEs. In the UEs namespaces there are instances of netcat and FFplay allowing the reception and reproduction of the video. The implementation of the RaptorQ FEC system will perform encoding tasks before the injection of the video traffic. The RaptorQ encoder provides reliability enhancements in the application layer with near-optimal properties, providing great efficiency and flexible functioning adding minimum overhead. The encoded symbols will be created inside of the gNB and will be decoded in the simulated UE. Finally, the graph of the demo trial is shown in the following figure:

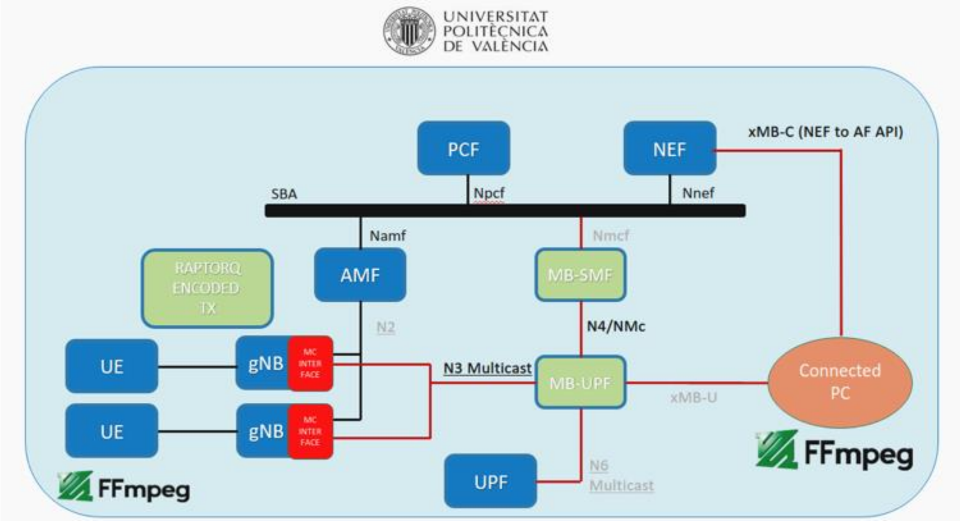


Figure 107. UC 4C Phase 2 demo, Phone receiving multicast data (UC5 demo).

As an additional testing component, UPV has acquired some Landslide licenses. Spirent Landslide is professional Core Network Testing software for 4G and 5G. It can emulate several UEs, RAN and Core Network from several technologies (3G, 4G, 5G) in order to verify the correct behaviour of the element under test in several scenarios e.g. handover, service discovery, attach/disconnect. This toolkit will be crucial in the testing of the different required KPIs of the system.

With reference to D2.3 [14] and regarding network KPIs, the table of High-quality video services distribution network requirements is reported below. All collected data and results will be reported in D7.4 [9].

Table 8. UC4 – High quality video services distribution network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(Reviewed) - UC4: High quality video services distribution			Priority	Range	
			URLLC	mMTC	eMMB		Min	Max
General Vertical/Use Case Requirement								
1	Latency (in milliseconds) - round trip - Min/Max	msec			10 ms	Medium	10 ms (bi-directional)	None (broadcast)
2	**RAN** Latency (in milliseconds) - one way	msec			5 ms	Low		
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps			25 Mbps	High	5 Mbps	25 Mbps
4	Reliability (%) - Min/Max	%			99,9995%	High	95%	99,9995%
5	Availability (%) - Min/Max	%			99,9%	Medium		
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h			100	Medium	10	100
7	Broadband Connectivity (peak demand)	Y/N or Gbps			0,1	-	0,05	0,1
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N			Y (60)	Medium	60 min	120 min
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N			N	-		
10	Capacity (Mbps/m^2 or Km^2)	Mbps/m^2			-			
11	Device Density	Dev/Km^2			N/A (multicast/broadcast)	Low		
12	Location Accuracy	m			-	-		

6 UC5 - Remote and distributed video production

In this chapter we present a novel approach of distributed video production, with a description of the system used to realize a concert with remote musicians playing together with fixed orchestra. The opera composed for such experiment is called: “The Garden of Forking Paths”.

6.1 UC5 definition

As also described in D4.1[1] and D4.2 [2], the main objective of the use case is to exploit the 5G-TOURS network features for remote television production, analysing how 5G networks could support various scenarios in which high-quality video is generated and transmitted.

Recalling the main definition of the use case, in a distributed TV video production context, the content needs to be produced by mixing local and remote audio and video contributions in the TV studio. The remote contributions are thus delivered to the main editing site via the 5G network in real-time.

The implementation for the use case is the itinerant orchestra in which some musicians located in the main concert hall play together with some other itinerant musicians walking in the streets while approaching the concert hall. Each itinerant musician is followed by one (or more) cameraman shooting their performance and providing cues to stay in synch with the main orchestra performance. The high-quality AV signal is transmitted via the 5G network to the main editing facility where it is properly processed and mixed with both the rest of the itinerant musicians and the orchestra located in the concert hall.

The spectators in the concert hall will watch the itinerant musicians playing and walking in the streets towards the Palazzo Madama (as real-time virtual presence) on one or more LED walls and listen to their performance via an amplification system, mixed to the local orchestra until they enter the concert hall and join the orchestra.

This chapter, starting from the integration and preliminary verification in the network, outdoor and indoor in Palazzo Madama, executed in December 2020 (see Figure 108), contains the new features and tests done in the following period of the project, in terms of new remote contribution chain, application components, terminal equipment, integration in lab and test in the network.

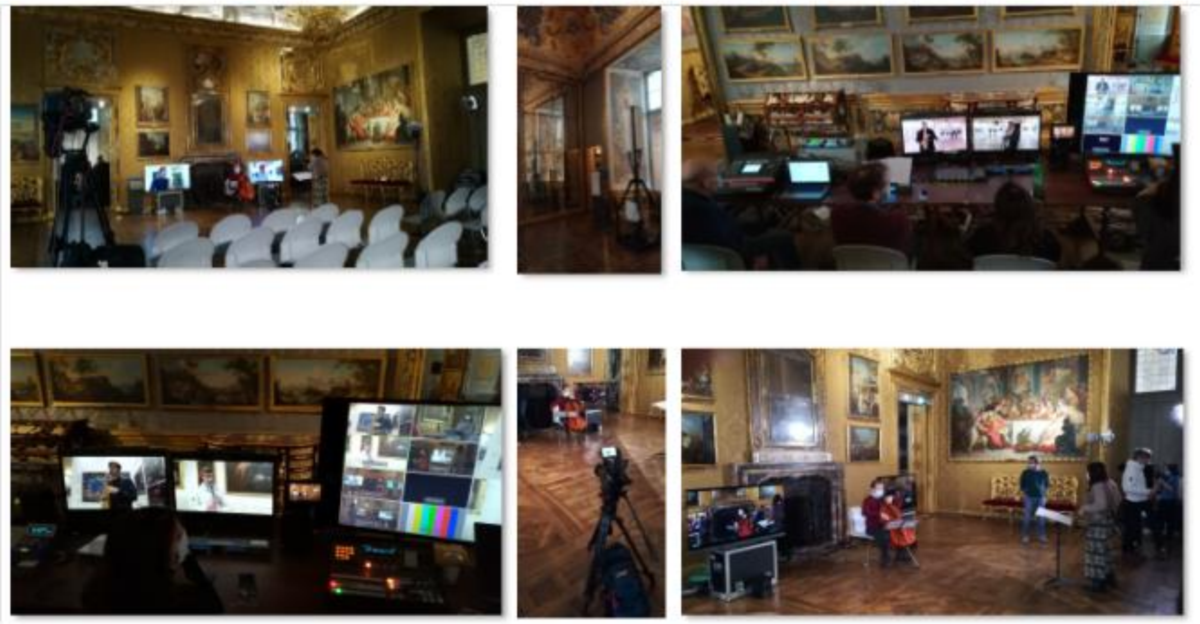


Figure 108. Itinerant Orchestra Trial – December 2020, Turin, Palazzo Madama.

6.2 UC5 implementation

During the final trial of the UC5 we were able to deploy the system and the master control room (MCR) at Rai premises and at Palazzo Madama, which is the location where the event took place. We had to make minimal updates to the system since it was already well designed during the previous iterations.

6.2.1 LiveU contribution chain

During the first months of 2021, we were able to deploy and test the LiveU chain at Rai premises. This work involved the CRITS and ICT Rai departments. We worked together to deploy all the network requirements to be able to receive streams at Rai R&D labs in order to be able to solve bugs quickly and upgrade and test the system on the fly. In Figure 109. The MCR at Rai Labs. the deployment at RAI labs is shown.

During the next debug session, the UC5 team with RAI and LiveU were able to fix the intercom issue that emerged during the first trial phase at Palazzo Madama in December 2020. We also were able to run a test for the new IFBv2 version, the two-way communication intercom between remote operators and MCR.

The deployment at Rai Labs was very useful because it allowed us to quickly identify and solve any possible issue regarding the contribution chain, and test new features together with the LiveU team from remote.

Figure 109. The MCR at Rai Labs.

The audio video setup tested during 2021 is the same we used during the 2022 trial session at Palazzo Madama. Basically, we decided to maintain the same setup in order to provide the same reliability during the show and allow the video mixer operators to work with the same instrument used during the past tests.

6.2.2 Interfaces

In Figure 110. a refined schema about interfaces between solution modules for the content production is presented. The schema shows basic data types exchanged in the context of the implementation of the Itinerant Orchestra between the on-field part (musician and cameraman) and the control room.

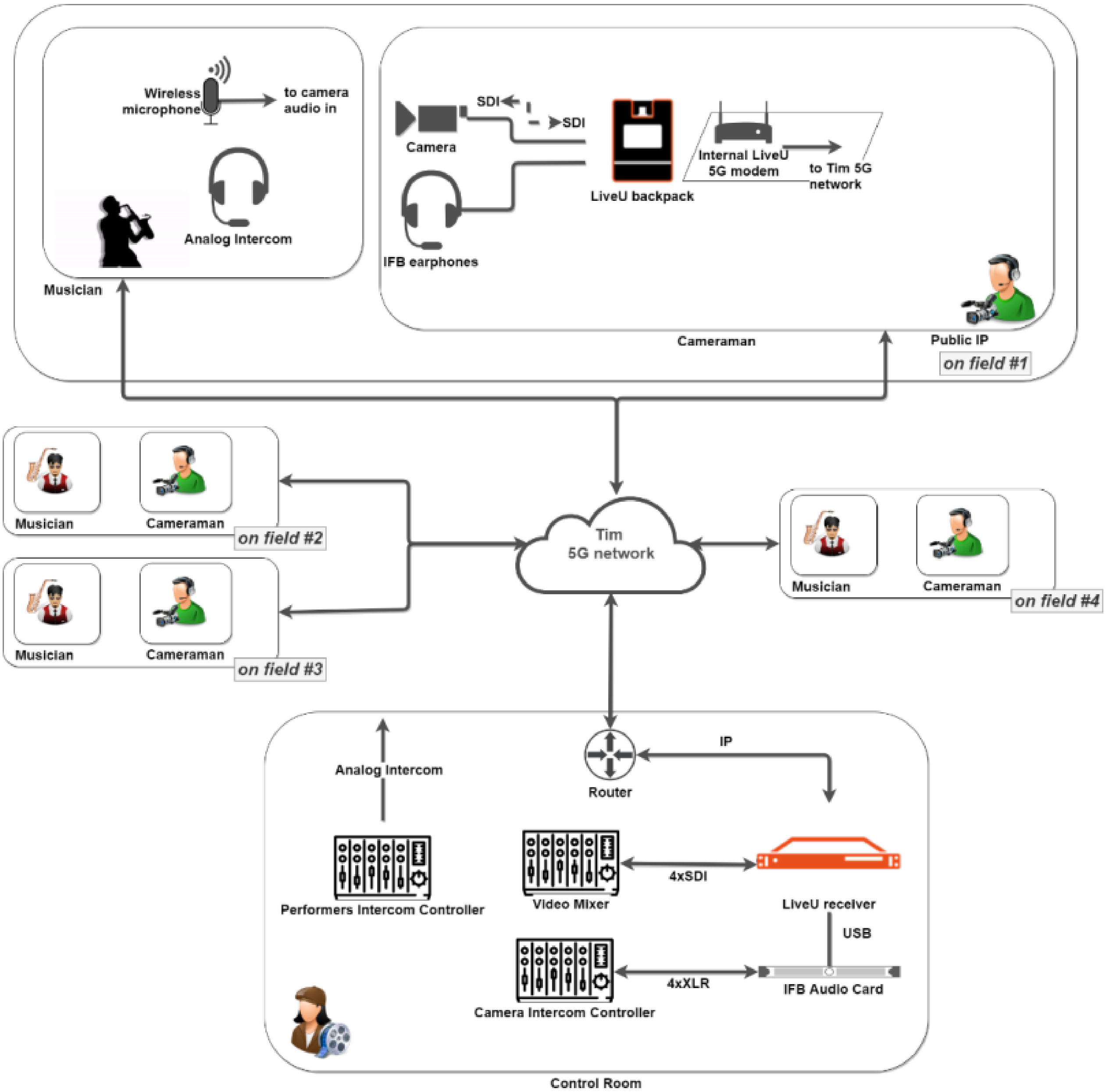


Figure 110. interfaces of Itinerant Orchestra.

In this new version the 5G modem connected to the backpack unit was successfully tested during the first trial and it is the current solution used in the project. The setup is the same described in past deliverable 4.3 and to complete de description of the MCR audio matrix used to send the cue signal to remote musician was an ADAM RTS, associated with a Soundcraft Vi1 audio mixer visible in Figure 111.

Figure 111. Soundcraft Vi1 Audio Mixer.

6.3 Integration and test in labs

The itinerant orchestra test trial took place in Turin at Palazzo Madama museum in December 2020, and during this preliminary test, it was possible to measure the glass-to-glass latency of the system and the throughput provided by the LiveU 5G LU600 backpacks.

The scenario foresaw only two of four remote musicians and a part of a fixed orchestra inside Palazzo Madama. Differently from the planned setup the connection between MCR (master control room) and remote musician were provided by an RF analog professional intercom system (RTS Adam).

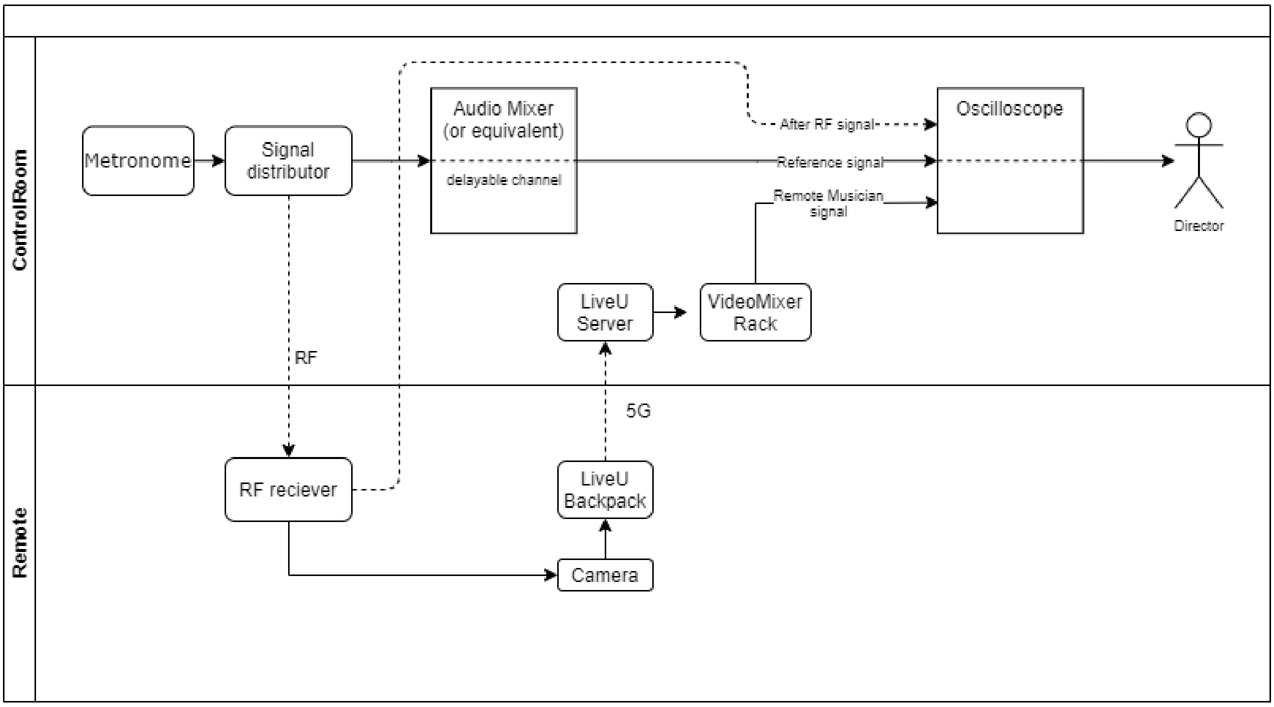


Figure 112. UC 5 glass-to-glass measure setup.

In order to measure the glass-to-glass latency we used a metronome click track sent as a reference signal with the signal distributor. We split the click-track into two tracks, one sent directly to the audio mixer and the other one sent into remote chain through RF-intercom receiver and then passing into the camera to reach the LiveU server. From the LiveU server, we de-embeded the audio click track from the video signal and we send it into an oscilloscope. In order to calculate the latency introduced by the system, we compare the misalignment with respect to the click-track sent directly to the mixer. This kind of measure is not only more reliable but it also granted us a wide range of measures. In fact, with audio, we can measure the latency of the overall system, presented in a schematic in Figure 112. An example of the measurement process is reported in Figure 113 where there is the peak coming from the reference signal (yellow) and the delayed one (lower in amplitude in pink. The device used for the measures is Tektronix MSO 3034 Mixed Signal Oscilloscope.

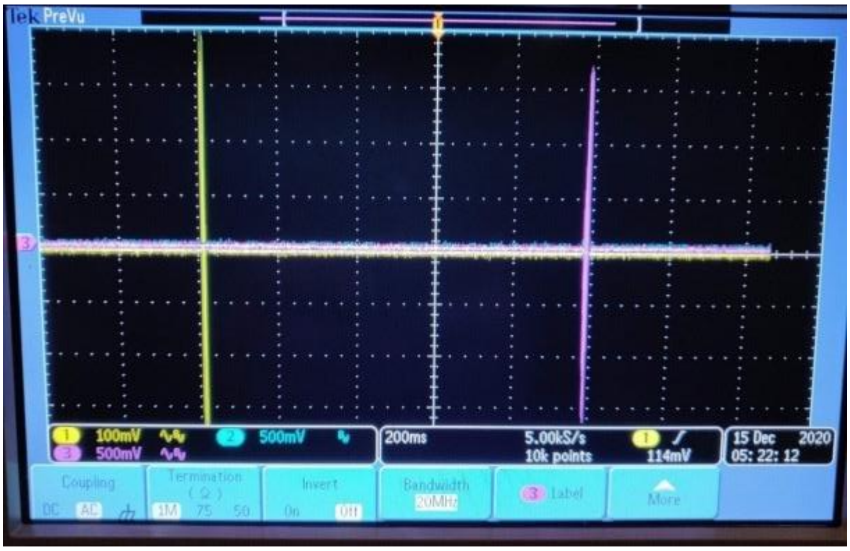


Figure 113. UC 5 oscilloscope measure setup.

During the two days at Palazzo Madama we were able to test multiple times the overall latency of the system, the measured delay compared also with the previous test performed in TIM laboratory tells us that the value is pretty constant in time Table 9.

Table 9. UC5 glass-to-glass measure.

Delay measure	AVG (ms)	MIN (ms)	MAX (ms)	STDEV
Tim lab (sep2020)	900	900	900	-
Trial Palazzo Madama (dec2020)	970	960	980	10

This not negligible amount of delay is generated by various factors: codec latency (especially during the codification on backpack side), the buffering as a source of delay, the buffering is introduced to reduce the effect of the jitter on the video streams, the network contribution. To deal with such amount of latency, and to make possible the ensemble music we used a delayable chain. With the overall delay measure, we can predict how much is the delay between the concert hall and a remote musician. Based on this delay amount measure we can arbitrarily delay the start for the main concert hall orchestra in order to shift the start of the main orchestra room of the measured delay (in this specific case 970ms), the remotes and the fixed orchestra with this setup will seem to play synchronized.

On the second day, we performed a different type of test with multiple backpacks involved. The main objective of the second day of test is to calculate the interstream synchronization of the backpacks, in particular if the same subject recorded by different backpacks was displayed with different delay on the receiving server. The interstream synchronization was important during the operations of a live event. The results of this experiment told us that we have some offset between backpacks, which can be partially explained and related to the routing of the UDP streams in the network.

The setup of interstream synchronization does not involve the same schematic presented in Figure 112 because we have only 4 inputs in the oscilloscope device, so we measured just 4 feedback audio signals as input in the oscilloscope, without the reference signal. In this way we checked the delay between each backpack signal. Using the same configuration, we sent an audio (metronome signal) reference signal in the system, and the result is visible in Figure 114.

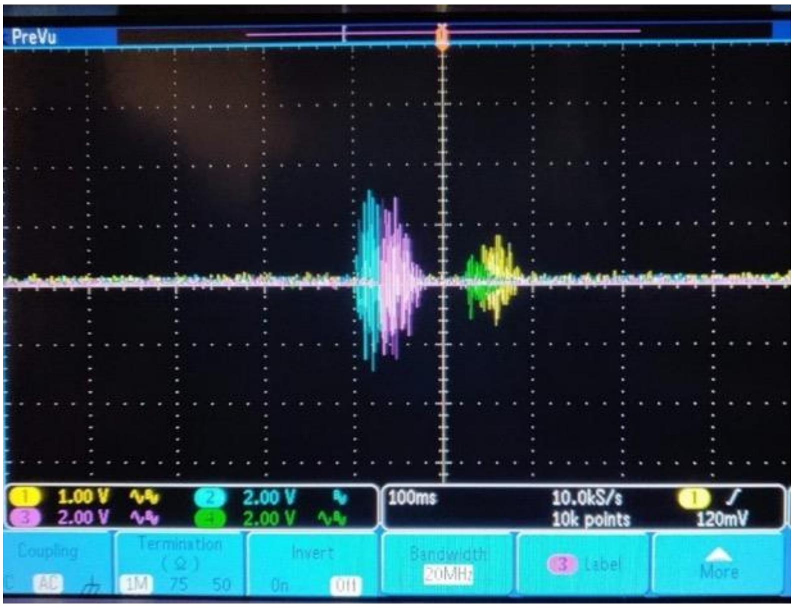


Figure 114. UC5 interstream delay.

The difference between delays was pretty constant during the tests, the maximum value of this latency offset is around 150ms. In Figure 114. It is possible to see the 4 audio metronome signals coming back from the backpack divided into two couple of signals with a difference of around 150ms. It's important to note that during this test we placed the 4 backpacks on the desk in order to avoid any problems with coverage and connectivity.

Finally, thanks to LiveU logs, it was possible to retrieve information regarding the bandwidth, latency, and packet loss rate.

In the following chart, we have multiple axis: bandwidth [kbps] uses the left primary Y axis; latency [msec] and loss rate [%] use the right secondary Y Axis. Each point is 5 secs snapshots. In case the transmission used two interfaces, they are both on the same graph, not aggregated, one point adjacent to the other one (so the total bandwidth at each point is the aggregation of both).

The "extrapolated latency" shown in the graphs is part of the overall 600 (or 800 ms in this case "end-to-end") msec latency. The charts are made by application logs system present into LiveU unit. This system can log a snapshot of the current state of the backpack with a granularity of 5 seconds; the "extrapolated latency upstream delay" plot is what LiveU application estimates/predicts/believes/anticipates the network latency is (for example, also including any latency within the 3rd party cellular modem, based on its own packets exchange between unit and server.

In Figure 115 we can see the chart related to a field unit during the trial.

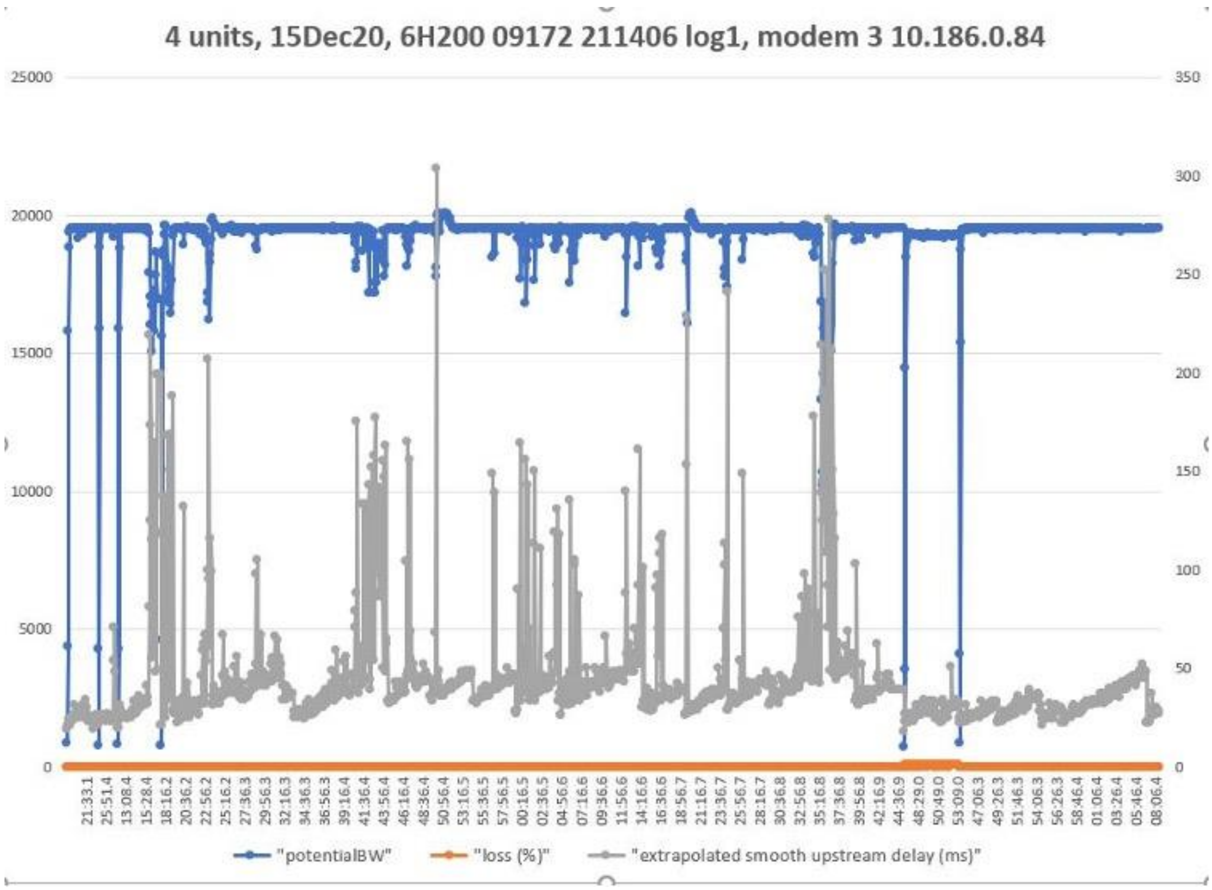


Figure 115. UC5 LiveU LU600 trial statistics.

6.4 Test in the network

The Main Event took place in November 2021 at Palazzo Madama. In the following sections we are going to describe the operations involved in the organization of the event.

6.4.1 Pre-Event operations

During the week before the event, it was necessary to establish a place where the video mixer control room could be potentially deployed and the orchestra and the remote musician teams could try the opera freely. We identified the location at RAI premises. During these days it was possible to further test the setup and coordinate the remote teams in Piazza Castello from RAI premises.

Three days before the event and on the day of the main rehearsal, November 5–November 7, the master control room (MCR) was assembled and tested. Some pictures of the testing days before the event:

Figure 116. Orchestra testing at Rai premises.

Figure 117. Master Control Room at Rai premises.

Thanks to this Pre-Event days we were able to test the entire video mixer system and intercom system before running the actual test in place at Palazzo Madama. During these days we tested successfully also the sync track system with AKAI APC mini and the audio mixer chain to the remote musicians and orchestra.

6.4.2 Event operations

UC 5 event took place in Turin at Palazzo Madama museum the 9th of November 2021, and involved more than 30 operators from RAI Crits and Rai Turin Production Centre.

A total of 16 people were involved only in the technical remote groups, which included 2 performers with microphones, an actor, a saxophonist, a cameraman with an assistant. There were 4 remote groups in total. A view of MCR in Figure 118 below.

Figure 118. Master Control Room at Palazzo Madama.

Figure 119. Remote teams operating near Palazzo Madama

We were able to test the overall latency and measure the so-called Glass-to-Glass latency with the musical ensemble and the remote quartet of saxophonists. We did it by using the method described in the previous chapter and shown in Figure 112.

It was crucial to set the computer delay on the click signals provided to the main orchestra of the event according to our measure of the glass-to-glass latency, therefore we performed this measure multiple times during the day in order to set properly also the interstream synchronization, between the 4 backpack signals.

In the following image the concert hall with the performers in place during the exhibition.

Figure 120. Top left one of the 4 actors, top right detail of the Saxophonist quartet, bottom the whole orchestra with the public.

6.4.3 Glass-to-glass comparison

A constant delay is required by the music director. The feedback signal coming back from musicians to MCR should be consistent throughout the entire event. As long as it is constant over time, the amount of delay is not particularly important.

According to our measurements the glass-to-glass delay was consistent during the whole show time.

Another important point to consider is that we measured slightly different delays from each LiveU unit, the so called *interstream synchronization*. This can be problematic since all audio/video signals from remote musicians must be synchronized with each other, with the same amount of delay, therefore faster audio/video signals should be delayed and aligned with the delay of the slowest signals.

The alignment of the different glass-to-glass latencies was performed before the measure of the overall latency in order to obtain stable and certain values.
With reference to D2.3 [14] and regarding network KPIs, latency, throughput (UL/DL), the table of Distributed video production network requirements is reported below.

Table 10. UC5 – Distributed video production network requirements.

5G-Tours - Use Cases: direct specific Technical requirements		Units	(reviewed) - UC5 – Distributed video production			Priority	Range	
			URLLC	mMTC	eMMB		Min	Max
General Vertical/Use Case Requirement								
1	Latency (in milliseconds) - round trip - Min/Max	msec	10		<50	Med	10	50
2	**RAN** Latency (in milliseconds) - one way	msec	1		1	Low	1	5
3	Throughput (in Mbps) - Min/MAX - sustained demand	Mbps	180		100	High	50	200
4	Reliability (%) - Min/Max	%	99,9999%		99,9999%	High	99,0000%	99,9999%
5	Availability (%) - Min/Max	%	99,9999%		99,9999%	Med	98,0000%	99,9999%
6	Mobility (in m/sec or Km/h) - Min/Max	Km/h	3		3	Med	0	10
7	Broadband Connectivity (peak demand)	Y/N or Gbps	0,25					
8	Network Slicing (Y/N) - if Y service deployment time (min)	Y/N	Y (5)		Y	Low	5	15
9	Security (Y/N) - if Y grade i.e. "Carrier Grade"	Y/N	Y		Y	Low		
10	Capacity (Mbps/m^2 or Km^2)	Mbps/Km^2	360 *		360	Medium	180	900
11	Device Density	Dev/Km^2	12		12	hi	12	15
12	Location Accuracy	m	n.a.		n.a.	n.a.	n.a.	n.a.

(*) Capacity = 360 Mbps/Km^2 = 0,00036 Mbps/m^2

We were able to perform numerous measurements of the overall latency, and we did not find any significant changes with this measure over time. For sake of completeness, we report here the previous measurement (with different conditions), performed at TIM labs in September 2020 and during the previous demo event in December 2020 see below results reported in the tables:

Table 11. delay comparison.

Delay measure	AVG (ms)	MIN (ms)	MAX (ms)	STDEV
Tim lab (sep2020)	900	900	900	-
Demo Palazzo Madama (dec2020)	970	960	980	10

The results of Glass-to-glass latency tell us that the system is quite constant during the operations see Table 12 below:

Table 12. Main Event measured latency.

Delay measure	AVG (ms)	MIN (ms)	MAX (ms)	STDEV
Trial Palazzo Madama (dec2021)	1030	1010	1050	16.90

We were able to also perform the alignment of the 4 signals in order to perform the interstream synchronization. The maximum value recorded during this operation was 80ms and was recorded the day of the show. Thanks to this kind of alignment, we stabilized the overall system delay at 1050ms. With this delay the performance of the ensemble and the remote musicians was completely synchronized. See in Figure 114, the example of *inter-stream synchronization* issue. In this case it is visible that we have a shift of around 100 ms between the faster blue signal and the slower one the yellow.

LiveU Logs has been collected during the field trial. In the following are presented bandwidth usage and latency of unit 1 during the performance.

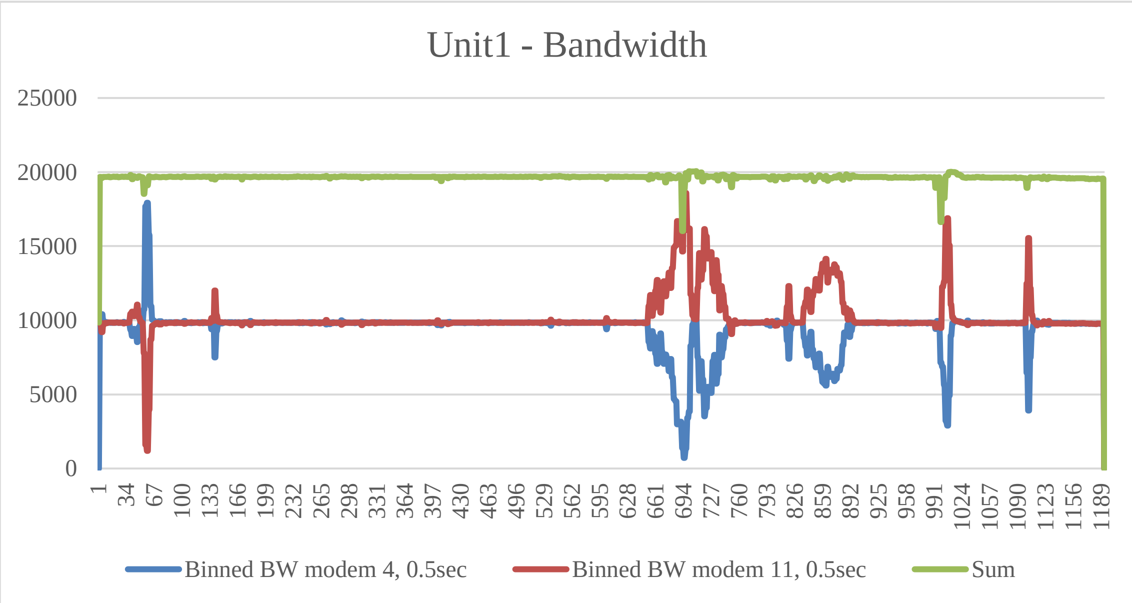


Figure 121. LiveU unit log bandwidth during the event.

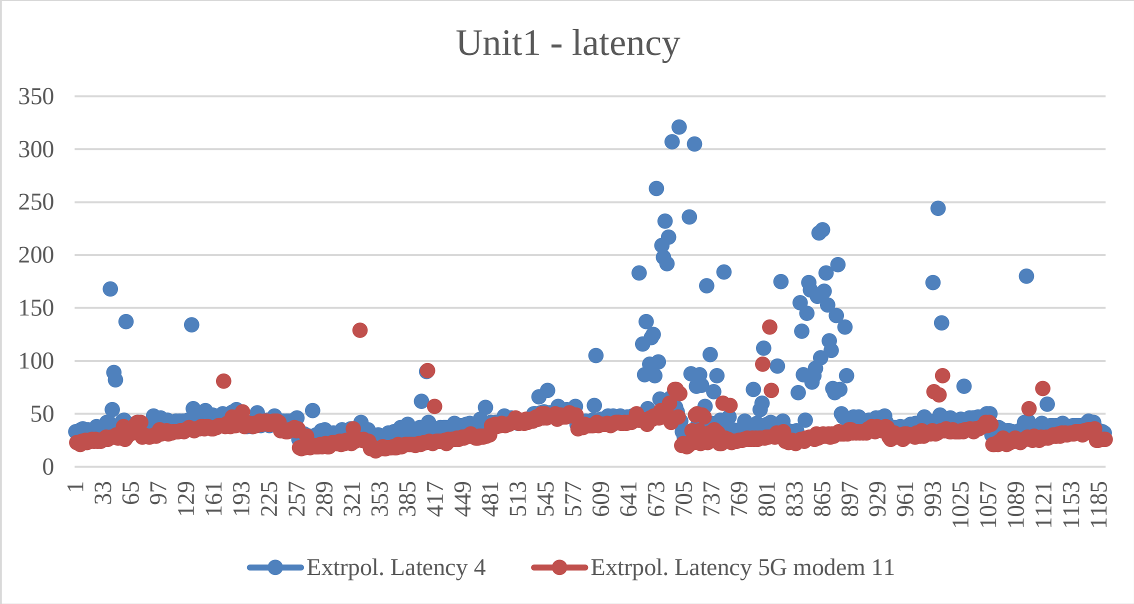


Figure 122. LiveU unit log latency during the event.

All collected data and results will be reported in D7.4 [9].

7 5G-TOURS network implementation aspects for Turin site

This section provides an update of the 5G-TOURS network implementation for the Turin site and shows the final solution implemented as finalization on what was reported in D4.3 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) and D3.4 (5G-TOURS, Technologies,architecture and deployment advanced progress) The general scheme, on which the 5G-TOURS network deployment is based, consists in the provisioning of a network composed by the combination of (i) commercial deployments based on infrastructure owned by TIM , and (ii) laboratory facilities deployed to test Rel-16 equipment and functionalities as well as 5G-TOURS innovations. In addition to that, another important aspect that has to be considered is the integration of the use cases with the 5G-EVE infrastructure and platform as a consistent support in the two contexts described above. At this stage the phased approach for the 5G-TOURS network implementation described in D4.2 (5G-TOURS, "D4.2 First Touristic City use case results", December 2020) is completed and the solution is up and running.

In terms of project objectives, the need of 5G (OBJ1), is addressed by the implementation, now completed, of an on-field extension of the TIM commercial network, to cover with the Ericsson technology the indoor areas of two selected Torino Museum: Palazzo Madama and GAM. The two networks solution have been connected to the CN (Core Network) node located in Milan and based on an NSA (Non Stand-Alone architecture).

The experimental branch (OBJ2), is instead addressed by a solution provided by 5G-EVE at the TIM laboratory, based on a NSA end to end solution: innovations are experimented through the use of the EVER orchestrator provided by Ericsson. At the time of writing this deliverable the experimental activities are still ongoing, therefore the related results will be reported in D7.4 [9].

7.1 Network equipment and coverage

As previously anticipated, the physical installation of the equipment after the network design has been completed, addressing the authorization process with the concerned private parties (e.g. the entity owner of the museum) as well as the local authorities (e.g. Soprintendenza Archeologia Belle Arti E Paesaggio). The main aspects that have been taken into account during the Network Design phase were essentially the environmental impacts as on one side it is fundamental that the electromagnetic emissions respect the limits imposed by the regulatory body, and on the other side, is mandatory to preserve the architectural and decorative aspects of the museum. In the case of Palazzo Madama and GAM, locations where the radio have been installed, the type of equipment used, are part of the Ericsson Radio System (ERS) portfolio with an ad hoc masking solution. In the following sections, the installed solutions for the two museums are reported.

7.1.1 Palazzo Madama

The solution active in Palazzo Madama is based on the Ericsson R4422 Radio unit coupled with the Cellmax CMAX-DFM3-43 CI53Atenna System, which allowed an effective masking solution thanks to the small size (210x210x48mm). Figure 123 shows an installation detail for Radio 4422 in the seat and antenna masking in the pole.

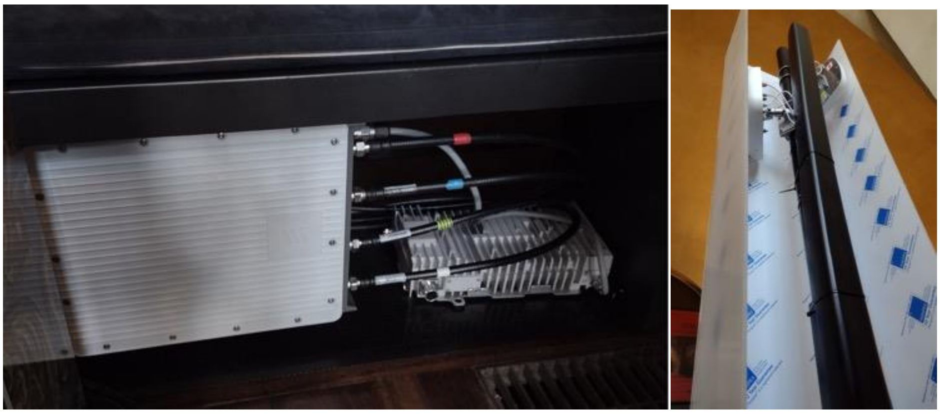


Figure 123. Installation detail in Palazzo Madama.

The fiber optic infrastructures necessary for the connection of the radio stations with the star centre present in the museum (which allows connection with the TIM control units) have been identified using non-visible passages in the pre-existing arrangements of the system in the museum. The power supply of the radio stations was provided through connections to the existing system without the addition of dedicated electrical panels.

As regards the technical solutions, in the following sections are reported the pictures of the real installation currently active at Palazzo Madama.

Figure 124. represents the positioning of the radios in Sala Acaja and the bookshop on the ground floor of Palazzo Madama.

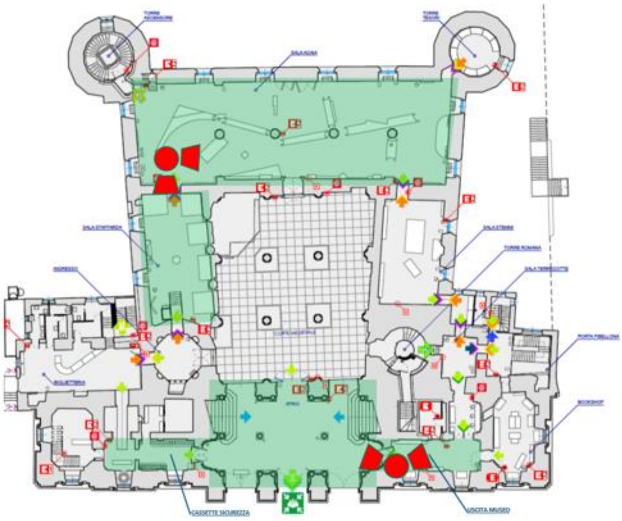


Figure 124. Palazzo Madama Ground Floor.

At the end of the installation, the resulting effect on the ground floor is shown in the following figures. In Figure 125. shows the solution implemented in the bookshop, in which the technology is inserted in an invisible way inside an information post.

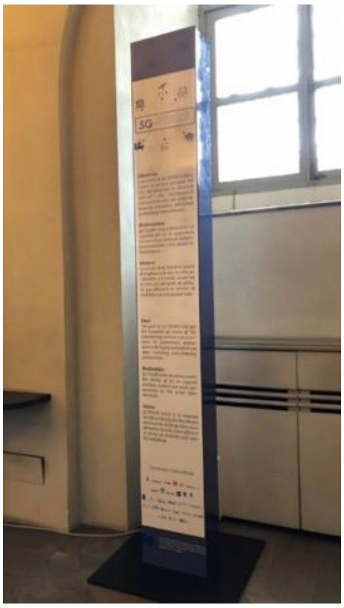


Figure 125. Radio station in the book shop

In Figure 126 the radio solution implemented in Sala Acaja is represented, integrated within the existing plasterboard structure.

The installation, as foreseen in the installation authorization request, was removed in December 2021 following the demonstration concert "The Garden of the forking paths" held on November 9, 2021.

Figure 126. Radio station integrated in the exposition wall at Sala Acaja.

Figure 127 shows the positioning of the radios on the first floor, in the Round Cabinet and the Quattro Stagioni room.

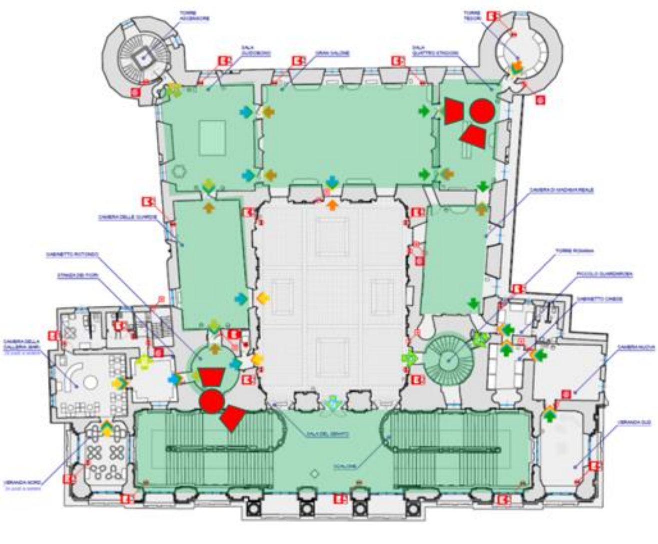


Figure 127. Palazzo Madama Frist Floor.

At the end of the installation, the resulting effect on the first floor is represented in the following figures.

Figure 128 represents the solution implemented in the Round Cabinet, in which radio technology has been integrated into the existing seats of the museum, flanked by information poles.

Figure 128. Radio installation inside seat and pole – Gabinetto Rotondo.

Figure 129 represents shows the radio solution implemented in Sala Quattro Stagioni; the basic solution uses the same approach adopted in the Round Cabinet, that is, it integrates radio technology within the existing seats of the museum, flanked by information poles. The screen printing on the pole is contextualized to the contents of the room.

Figure 129. installation inside seat and pole – Sala Quattro Stagioni.

Figure 130 represents the positioning of the radio station on the second floor for the coverage of the Sala Ceramiche. For this installation, the walkway outside the room was used for the positioning of radios and antennas (painted in brick red), using the windows to ensure the effectiveness of the coverage inside. The installation is represented in Figure 131**.**

At the end of the installation, the presence of the radio station is not perceived inside the Sala Ceramiche. The resulting effect inside the room is shown in Figure 132.

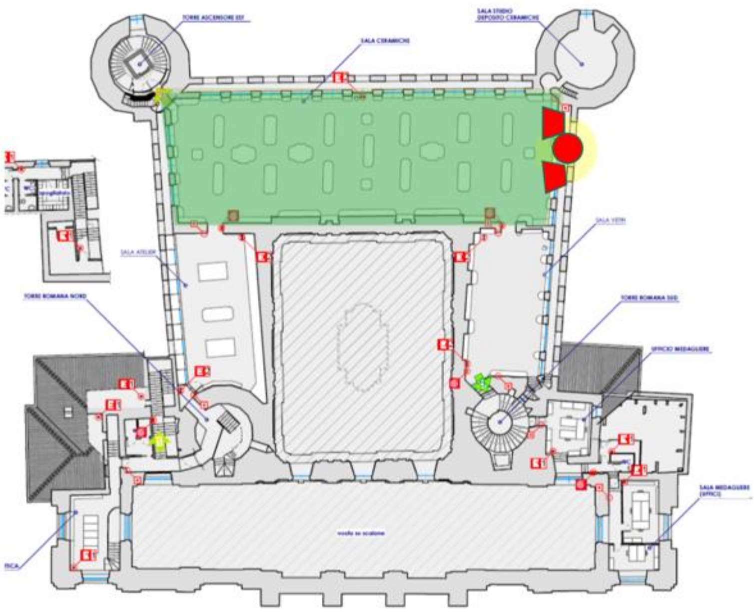


Figure 130. Palazzo Madama - Second Floor.

Figure 131. Installation in the external walkway around Sala Ceramiche.

Figure 132. View of Sala Ceramiche.

In terms of network performances, the network deployed at Palazzo Madama took advantage from the two-phase implementation. As reported in D4.2 (5G-TOURS, “D4.2 First Touristic City use case results”, December 2020) the initial network solution to perform the test of the UC5 was deployed using a temporary setup that was not addressing the restrictive requirements coming from the Soprintendenza Archeologia Belle Arti E Paesaggio. As reported at the mid-term review, for the **phase 1** the measured network performances were **900 Mbps in DL**, **75 Mbps in UL** and an average **end-to-end latency of 15 ms**. The network solution deployed for the **phase 2 (from October 2021 onwards)** provided improved performances showing up to **1.2 Gbps downlink** speed and up to **120 Mbps uplink** speed thanks to some improvement in the museum network architecture and RAN functionalizes such as the configuration of EN-DC functionality allowing the aggregation of 5G and LTE carriers. From the NSA perspective an optimization of the LTE Anchor was also introduced allowing a stable service. Overall, in terms of **latency**, the best measured time was **10ms**.

7.1.2 GAM

The solution implemented at the GAM is based on the Ericsson Radio Dot System as it was identified as the optimal solution to match the technical solution and the aesthetical requirements received from Soprintendenza of Turin. The Radio Dot System, with its distributed architecture, enables coverage and capacity throughout a variety of indoor venues. The solution provides indoor connectivity through remotely powered active antenna elements using standard enterprise LAN cabling while sharing centralized baseband and radio resources. The DOT4479 Antenna (Figure 133.) introduces support for NR technology and offers an innovative and high performing solution that effectively connects indoor users to the whole mobile eco-system. The Indoor Radio Unit IRU 8846 (Figure 134.) provides connectivity to the 8 Radio Dot 4479 single-band 4x4 MIMO radios over industry-standard twisted pair IT cabling. The Indoor Radio Unit is connected to the same baseband used for Palazzo Madama (see D4.2 (5G-TOURS, “D4.2 First Touristic City use case results”, December 2020) and D3.3 (5G-TOURS, Technologies,architecture and deployment advanced progress) for additional details).

Figure 133. Radio DOT4479.

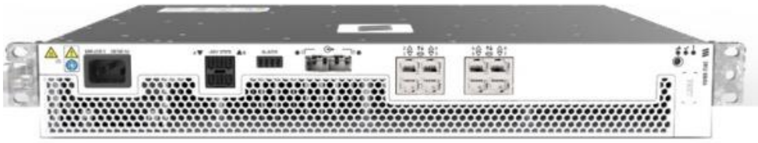
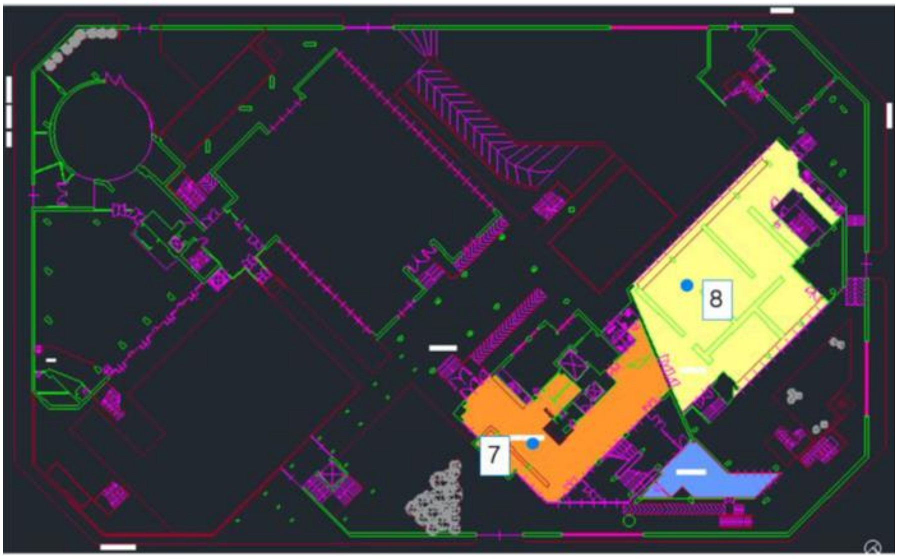


Figure 134. Internal Radio Unit 8846.

Figure 135 reports the DOT positioning inside the GAM.



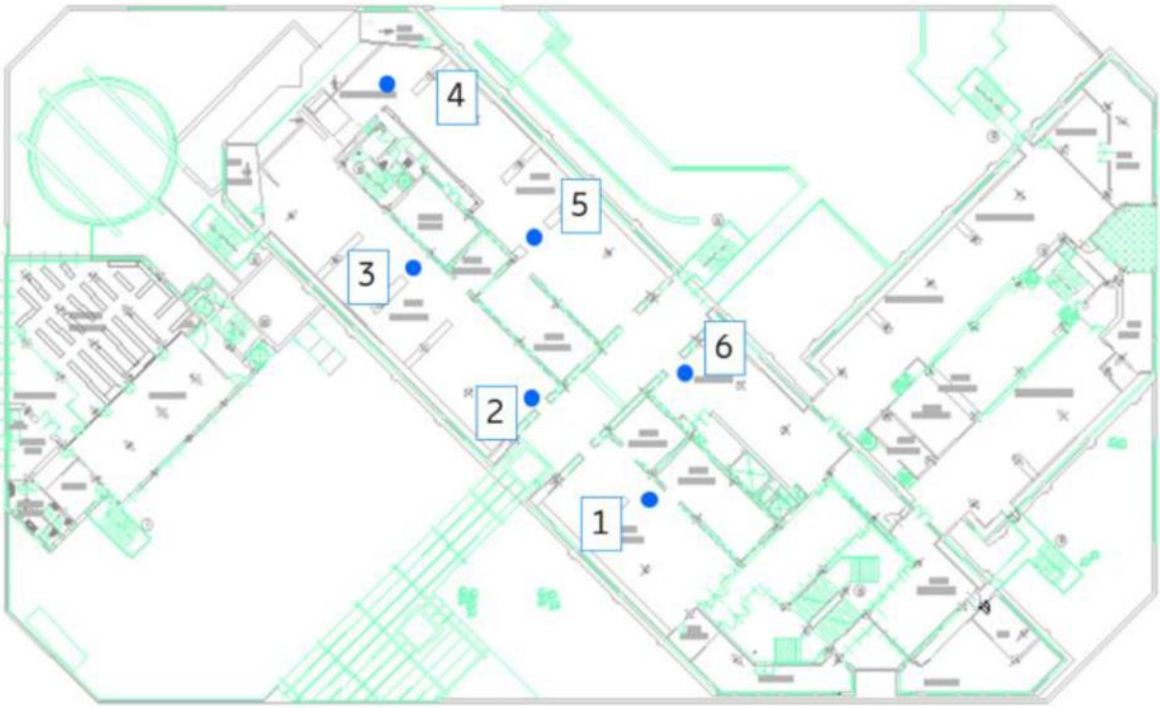


Figure 135. Indoor coverage at GAM - ground floor (UC1.b and UC3) and first floor (UC2.b/c and UC3).

As regards the technical solutions, Figure 136. First Floor DOT Installation, shows the real installation currently implemented at the GAM first floor.

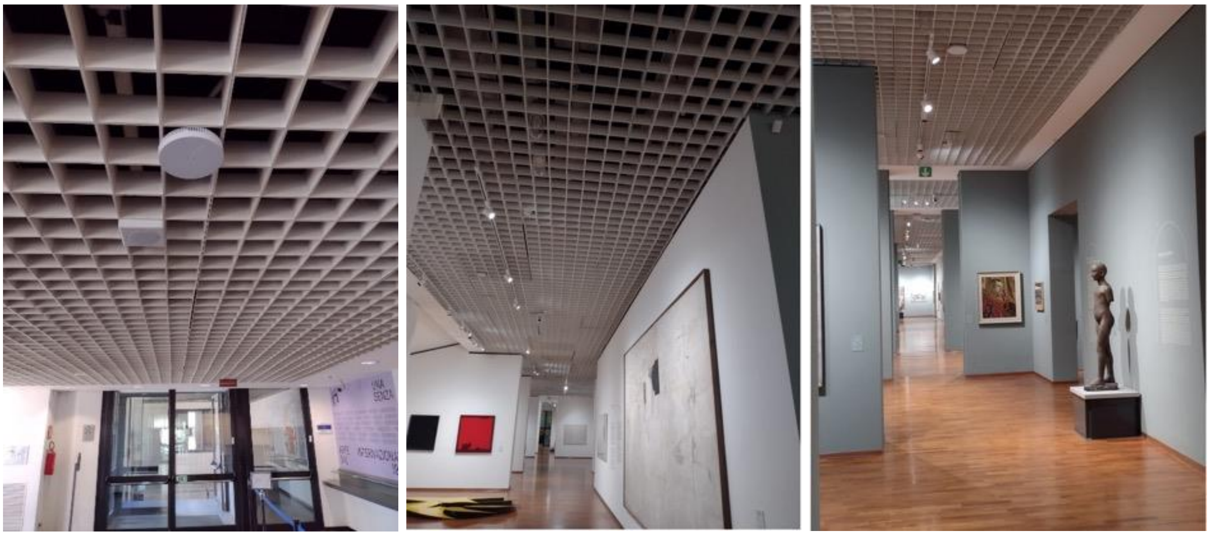


Figure 136. First Floor DOT Installation.

In terms of network performances, the measured average throughput in the GAM was **900 Mbps for the downlink** and **90 Mbps for the uplink**. In term of **latency**, the best measured time was **10ms**. These results were achieved after the optimization of the LTE outdoor anchors configuration, to fit the NR DOT needs, and using the EN-DC feature. This solution allowed to guarantee this Network performances also inside the exposition rooms close to the corridors. Compared to the performance measured at Palazzo Madama, the lower values are because the LTE signal inside the GAM was attenuated by the concrete infrastructure of the building thus not providing the best performances in terms of throughput for the LTE EN-DC component, lower than the one that can be obtained in line-of-sight or through the windows (as in case of Palazzo Madama).

7.2 Network integration

In order to integrate and onboard the network functions related to the different use cases developed by the project we had to design the 5G-EVE blueprints (5G-EVE) that were used to on board the functions on the infrastructure. The 5G-EVE blueprints are composed by a set of files that have to be designed to perform the full on boarding operation, as discussed next.

- 5G-EVE VSB file: this file provides the high-level description of the Vertical Service, indicating all the VNFs that compose the service and their arrangement.
- 5G-EVE NSB file: this file contains the low-level specification of the VNFs matching interfaces and subnet to the high-level VSB.
- 5G-EVE TCB file: this file contains the Test Case definition for each experiment. In here, the context conditions such as the background traffic or the commands to enable the data exposure towards the service layer are defined.

In this phase, we just compiled the VSB and NSB file for one exemplary use case. Other use cases and their TCBs will be filled in conjunction with the QoE / QoS evaluation methodology and the test cases defined in WP7. We selected Use Case 1 (including all of its sub use cases) for this analysis.

Before entering the details of the blueprint, we depict Figure 137. below the high-level infrastructure instantiation of the Use Case.

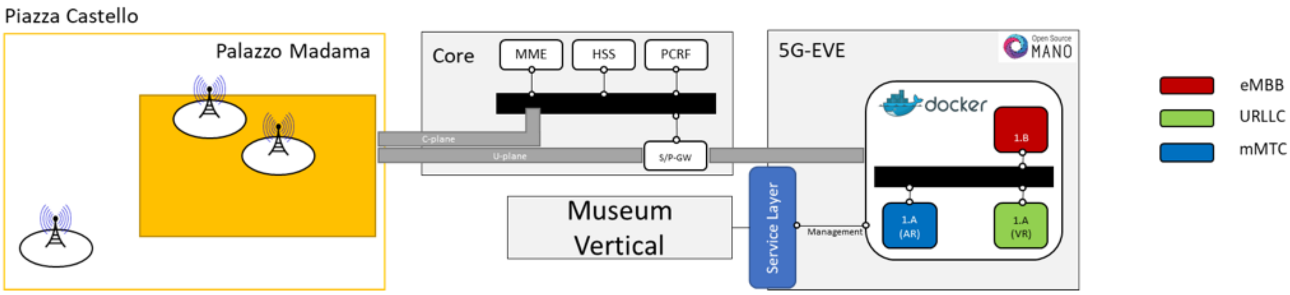


Figure 137. UC1 high-level infrastructure instantiation.

On the left-hand side, the Radio Deployment, as described in Section 7.1.1, is providing wireless coverage inside and outside the Palazzo Madama building, and it is connected via fiber with the rest of the 5G-EVE infrastructure, especially the Core Network available in the TIM Lab. The three slices used for UC1 (eMBB and URLLC for AR and VR respectively, and mMTC for the sensors deployed in the city) are then onboarded using the 5G-EVE portal and the Service Layer on the 5G-EVE NFVI infrastructure.

In 5G-TOURS we adopted a cloud native architecture, still owing to the implementation choices made by the 5G-EVE project, that provides in Turin an NFV Infrastructure based on VM and Orchestrate with the Open Source MANO software. Hence, we host our Container based solutions for vertical applications into a fully-fledged VM containing the VNF. More specifically, three containers are hosted in the VNF:

- The HTTP Server for the AR server, will serve the rendered object to the terminal
- The AR server for the UC1.a
- The data gathering server for the Internet of things scenarios of UC1.b

All of them use the docker-compose engine to orchestrate the cloud native part, into a single VNF which is then orchestrated, through the 5G-EVE portal. In the following, we briefly discuss the main part of the blueprints we created for UC1.

```
nsdIdentifier: "5G-TOURS-UC1-NSD"
designer: "NSD generator"
version: "1.0"
nsdName: " NSD for 5G-TOURS UC1 VR and AR"
nsdInvariantId: "5G-TOURS-UC1-NSD"
```

This part includes the main signatures of the file, which is used by the 5G-EVE portal to identify the Network Slice (or the Vertical Service).

```
parameters:
- parameterId: number_of_user_equipments
  parameterName: Number of user equipments
  parameterType: number
  parameterDescription: Number of User Equipments requesting con-
tent from the AR and VR
  applicabilityField: User Equipments
```

The VSB files offer the possibility to specify parameters associated with the vertical services. In this case, we identify the number of UEs in the network.

```
- componentId: vrar_vm_1
  serversNumber: 1
  endPointsIds:
  - cp_vrar_vm_1_mgmt # ssh, web interafaces
  - cp_vrar_vm_1_data # for the real app
  - sap_vrar_vm_1_mgmt # to the portal / outside
  - sap_vrar_vm_1_data # to the portal / outside
```

The VSB file lists the component in the vertical service. As previously discussed, at VM level, we just have one instance (which contains the docker images providing the services). The component has different endpoints (interfaces) that provide connectivity either to the terminals or the management services and portals.

```
- endPointId: cp_vrar_vm_1_data
  external: true
  management: false
  ranConnection: true
```

Each endpoint has different attributes which specify whether they are used for management (e.g., a web interface or ssh connections), external (i.e., with connection to the Internet), or connected to the RAN (hence to the UEs).

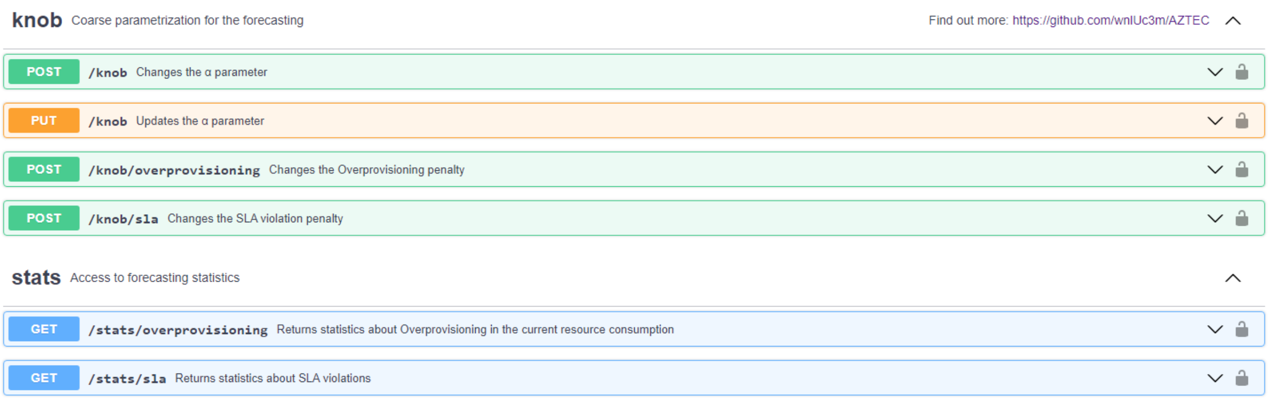
The different low level details of the interfaces are then specified in the NSD blueprint, as follows:

```
sapd:
  - cpdId: "eth1" # from the VNFD
    layerProtocol: "IPV4"
    cpRole: "ROOT"
    addressData:
      - addressType: "IP_ADDRESS"
        iPAddressAssignment: false
        floatingIpActivated: true
        management: true
        iPAddressType: "IPv4"
        numberOfIpAddress: 1
    sapAddressAssignment: false
    nsVirtualLinkDescId: "vl_vrar_vm_1_mgmt"
```

Here, the low-level details such as the interface name or the number of IP addresses are specified in this section. This version of the file will be further amended in case of needed changes in the structure of the implementation.

Integration with the Service Layer. In the context of the Service Layer integration of the SDK, WP4 provided the API definition that the vertical service provider may use to steer the network resource provisioning performed by the AI algorithm, as thoroughly discussed in [6] and [7]. This work has also been performed in the context of the ETSI ENI PoC #9 [8].

The API representation is performed with Swagger [10], using the OpenAPI [11] definition, as done by other SDOs such as 3GPP SA5 for the management system [12]. The list of API is available in [13].



The API provides two main endpoints: knob and stats. The first one is used to setup the values for the cost related to the possible SLA violations and the resource overprovisioning. It is possible to directly setup the ratio between the two values. The second one is dealing with the statistics associated to the AI algorithm operation. By polling these endpoints, the vertical can know, at any times, which are the achieved performance.

7.3 Network and Application Innovations Aspects

The 5G-TOURS architecture implemented in Turin tackled the issues related to the provisioning of high speed and low latency access for all the UCs implemented in the museum, as well as the broadcast and multicast functionality that was needed for the development of UCs 4.

The network deployment scenario has been quite homogeneous for all the UCs: UC1 to 3 uses the network deployment discussed in section 7.1, integrated with the 5G-EVE infrastructure discussed in 7.2. UC4 leverage ad-hoc network deployments to support the latest releases of the 3GPP multicast standard (see Section 5), although part of the integration has also been performed by using the 5G-EVE infrastructure.

In general, all UCs, fully or partially leverage the 5G-EVE infrastructure through the portal, although some advanced functionality is leveraging the direct connectivity to the MANO.

Due to the extensive leveraging of the TIM commercial network for the realization of the UCs it has not been possible due to the restrictions that this network has with respect to the addition of the new functionalities. So, the trialing of extended functionality such as the Integration of AI and the corresponding Service Layer (as discussed in Section 7.2) has only been performed in a Lab environment (see also D3.4 [7] for a complete evaluation of these tests).

Nevertheless, all the UCs were successfully trialed in these conditions and offered a sustained amount of the needed KPI, as defined in D2.3 [14]. The details related to the KPI analysis and their relations with the experienced QoE, collected through questionnaires. This, together with the evaluation of the network slicing performance, will be fully covered within the upcoming D7.4.

Conclusion

This deliverable, D4.4, aims to report the implementation of the Touristic City use cases in the museums, including onsite tests and the related feedbacks and results. Tests open to the public took place during the months of April and May 2022, while UC4.b and UC5 were already completed in November 2021. The document reports at several levels the work performed by technical partners and verticals in planning and implementing trial performance before making it available and testable to a general public of users.

While the use cases were successfully deployed and trailed from the network point of view and from the user point of view, it is fundamental to understand how the verticals technology providers and the relevant stakeholders perceive the advantages brought by the 5G technology. Below for each use case we report the feedback of the verticals, gathered after the first trials and on-site tests performed.

- UC 1 - Augmented tourism experience

The tests were split in different sessions: the APP was tested with focus groups of highly engaged museum visitors, while the VR experience was open to the general public. He most liked feature of the APP concerned the 3D models, which were the most enjoyed, also because they allowed to have an insight on the artworks that is not possible to get when looking at the vitrines. It is easy to foresee actual applications of these services in the day-to-day museum offer.
The VR experience was mostly appreciated by the younger public, engaged in the experience of reconstructing “Camera delle Guardie”; however, this latter test underlined how the general public is still not completely at ease with this new way of fruition of cultural heritage and would require further developments from the museum. This further work is not only on the technical aspects, but also on how to empower the public to an independent fruition of this kind of content.
The feedback on the gamification experience was positive, even though the first approach was slowed down by the fact that for many testers it was the absolute first try of a VR experience; therefore, in order to be able to play the game, some training to use the oculus gear was necessary.
The interactive wall based on Nicola De Maria’s artworks installed at the GAM was tested with school groups. Also for this use case, the feedback has been very positive. The wall was used during the laboratorial activities as a mean to understand the creative process of the artist: museum educators guided the children/teenagers in understanding the main features and elements of De Maria’s compositions and the wall gave them the opportunity to test in real time the combination of different element to create a shared virtual canvas. The teachers who accompanied the classes testing the wall were satisfied by the possibility to understand a concept while trying it out in an interactive activity. Museum educators were satisfied to see the level of interaction between the students working on the wall.

Figure 138. UC1.a AR trial at Palazzo Madama.

Figure 139. UC1.a VR trial at Palazzo Madama.

Figure 140. UC1.b Interactive Wall trial at GAM.

- UC2 – Telepresence

The telepresence experience has been a major asset both in Palazzo Madama and in GAM. It is perceived as a non-threatening technology and more as mediation with the human presence of the educator/guide.

Figure 141. UC2.a Underground visit trial at Palazzo Madama

The test in Palazzo Madama was well received by the public, who had access to the Roman Area in the basement which is not physically accessible: the possibility to use the robot while having a guide explaining both the project and the archaeological area were much appreciated.
During the testing period, a pop-up station has been installed just outside the exit of the museum, so that visitors who had finished their tour, could also enjoy this last part of the visit: while Telecom personnel guided the robot in the archaeological area, a museum educator explained what the camera was framing. This mixed experience of robot mediated visit with a human guide has been most appreciated by the public. For the museum educators the interaction with the public was quite fluid, while the possibility to guide the robot in the archaeological area

while describing the site was not really easy and required TIM's assistance..
In GAM the tests were run in cooperation with Turin Edu Lab: different school groups were invited to join GAM's educator to use the robot for a remote treasure hunt in the galleries and students were very involved both by the game-like structure of the visit and also by the possibility of driving the robot in the museum. Other visitors in the museum, who saw the telepresence robot moving around, were very curious about the project.

Figure 142. UC2.b Treasure hunt trial at GAM/EduLab.

Figure 143. UC2.c Surveillance trial at Palazzo Madama.

- UC 3 - Robot-assisted museum guide

FTM evaluated the robot assisted museum guide as a very good experience, both for the public and for the museum staff who had the opportunity to observe the interaction of the robot in the galleries.
One main aspect of the overall enthusiasm for this use case has been its innovative aspect. For many visitors it was the absolute first time to interact with a humanoid robot and this certainly contributed to a positive evaluation of the experience. However, some visitors were also slightly concerned by this new presence in the galleries. Museum staff observed that while children and teenager were immediately drawn to the robot and tried to touch

and interact with it spontaneously, adults were curios as well, but the ones that decided to interact with the robot kept a higher interpersonal distance than during the visit with a human guide. From the museums point of view, the test clarified that robot-assisted guide could possibly have a more substantial application in auxiliary services more than in a content-based tour.

Figure 144. UC3 experience in GAM.

- UC 4 - High-quality video services distribution

RAI has successfully collaborated with other partners of the project for the creation of state-of-the-art television products in order to exploit 5G-TOURS technologies in the area of distribution, taking into account UHD content and Immersive experiences. Exploiting the new features offered by the 5G broadcast transmission mode, technical partners involved in the use case managed to achieve content transmission of innovative live streams over 5G broadcast and, for the touristic cities and museums, new ways to present their cultural heritage.

Figure 145. UC4 trial at Palazzo Madama during "The Garden of Forking Path event".

- UC 5 - Remote and distributed video production

Thanks to this remote production experiment over mobile network, a remote and distributed production with an extremely challenging low and stable delay was successfully demonstrated. An ultra-reliable capability and a very large bandwidth capacity have been achieved in order to reach a good final result. On a more general aspect, the introduction of 5G could contribute to the valorization of cultural events taking place within the territory of the city introducing a new way to cover live events, while at the same time building a more efficient and cost-effective way to produce television content.

Future work on remote production could also involve a deep correlation with the new IP video standards like SMPTE ST2110 and other technologies used in this area. The technological solution developed by 5G-TOURS in terms of remote television production system and 5G network coverage has not only allowed the resolution of fundamental technical problems, such as the live synchronization of performers who are also very distant from each other and the need for extremely precise communication between of them and the central direction, but, consequently, it has made available situations and possibilities up to now in fact never usable and capable by opening up a new and unexplored world to artistic thought. The audience attending the event provided enthusiastic feedbacks about the experience and the echo over the media has been also really relevant (around 30 press releases, web and TV news), demonstrating the impacts and the effectiveness of the work performed by 5G-TOURS.

Figure 146. UC5 Itinerant orchestra concert: The Garden of Forking Path held in November 2021 at Palazzo Madama.

The implementation and trials of the UCs has been possible thanks to the ad-hoc 5G solutions that 5G-TOURS have deployed inside Palazzo Madama and GAM museums, each one with its specific peculiarities that in some cases provided really challenging requirements to be fulfilled.
For Palazzo Madama, the fact of having to install it inside a UNESCO heritage site, required a considerable innovative effort in terms of design to cope with the intrinsic complexities of the environment in which the solution would operate. From this perspective, for the insertion of the technological components within the museum context, the design had to take into consideration and balance different needs: the requirements with respect to the positioning and choice of the appropriate transparent radio materials to house the antenna system, the technical constraints relating to the possibility of powering the equipment safely, the technical difficulties of cabling for the fiber optic connection of the radio units in a building with multiple historical stratifications and, last but not least, the aesthetic requirements necessary to integrate the equipment inside the rooms. All these factors made it necessary to identify an extremely flexible radio solution also in terms of used equipment, which could be installed without supports or wiring on the wall and ceiling; this particular requirement has resulted in the creation of an ad-hoc mechanical system for fixing the radio unit combined with the choice of designing new room furnishings, coordinated with those existing and in use, which practically re-functionalized the room seating and panels with the curatorial texts.
Thanks to the modular infrastructure of the ceilings, the 5G indoor coverage at GAM has been implemented using the 5G DOT radio access system, consisting of different irradiation points that allowed a capillary coverage of the museum in the interested areas. As per Palazzo Madama, also GAM is a building under the supervision of the Soprintendenza, but thanks to the use of the DOTs it has been possible to enable a flexible installation and positioning that permitted to meet the fundamental requirement of guaranteeing the maximum integration within the environment from the visitors' point of view.
In general, the work carried out for the 5G network solutions, resulted in an innovative and "zero impact" indoor 5G radio solution within both museums (the first ones in Italy) and in recognition of which the Soprintendenza has granted a permission for a permanent installation until the end of the project. The theme of "friendliness" with the environment of radio solutions (5G and future ones) in terms of visual-architectural impact is considered of fundamental importance and, in this sense, the 5G network solution implemented by 5G-TOURS can undoubtedly be considered the state of the art.

The results achieved for WP4 use cases are to be considered as a starting point for upcoming experiments and collaborations, as demonstrated by the feedbacks collected during the events organized on a local scale. The last event named “The Art meets 5G” took place at GAM on 25 May and foresaw the presentation of WP4 case studies together with a direct demonstration of some of them (UC1, UC2 and UC3).

The event was attended by local experts, Museums and political representatives of the Culture sector who were able to experience firsthand the work carried out during the last three years and evaluate possible connections and new collaborations.

Overall the WP4 activities has been successfully carried out, collecting valuable information of the usefulness of the offered 5G services, the network performance, and the user quality of experience. Further and more detailed consideration on the network deployment KPI validations will be provided in the upcoming D7.4.

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