5G ALLSTAR

HORIZON 2020

Document Number: H2020-EUK-815323/5G-ALLSTAR/D1.4

Project Name:
5G AgiLe and fLexible integration of SaTellite And cellulaR (5G-ALLSTAR)

Deliverable D1.4

Final Report

Date of delivery:	31/10/2021	Version:	1.0
Start date of Project:	01/07/2018	Duration:	40 months

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Project Number:	H2020-EUK-815323
Project Name:	5G AgiLe and fLexible integration of SaTellite And cellulaR

Document Number:	H2020-EUK-815323/5G-ALLSTAR/D1.4
Document Title:	Final Report
Editor(s):	Nicolas Cassiau (CEA), Gosan Noh (ETRI)
Authors:	Gosan Noh (ETRI), Nicolas Cassiau (CEA), Junhyeong Kim (ETRI), Seok Ho Won (ETRI), Taesang Choi (ETRI), Heesang Chung (ETRI), Emilio Calvanese Strinati (CEA)
Dissemination Level:	PU
Contractual Date of Delivery:	31/10/2021
Security:	Public
Status:	Final
Version:	1.0
File Name:	5G-ALLSTAR_D1.4.docx

Abstract

This deliverable aims at summarizing all the results obtained during the 5G-ALLSTAR project. It provides an exhaustive view of the satellite-terrestrial multi-connectivity enablers developed throughout this 40-month project. Furthermore the achievements of the European and Korean testbeds and platforms are also recalled.

Note that, for brevity and conciseness, no details are provided, the reader is referred to the relevant documents.

Keywords

Multi-connectivity; satellite; terrestrial; 5G; enablers; demonstration.

Contents

1 Introduction

The objectives of the 5G-ALLSTAR project [D2.1] were to design, to develop, to evaluate and to test via testbeds and trials, multiple access based multi-connectivity: combination of satellite and cellular access technologies for support of seamless reliable and ubiquitous broadband services. 5G-ALLSTAR not only aimed at demonstrating technical feasibility of 5G NR multiple-access, the project also actively contributed to global 5G standardization including 3GPP and ETSI focusing on multi-RAT interoperability and New Radio based satellite access and to the creation of a cross-regional lasting synergy for 5G and beyond-5G research, innovation and commercialization through value proposition assessment for vertical industries [Calvanese19][Calvanese20][Kim20.2].

This document is the final report of the project; its purpose is to provide an overview of the work done during 40 months to fulfil the above-mentioned objectives. It is not meant to describe in detail the technical accomplishments of the project. It is deliberately short to read: for each achievement the interested reader is referred to the publicly published deliverables and/or to the related project publications.

This document is organized as follows:

- Section 2 briefly describes the use cases and architecture considered in the 5G-ALLSTAR project.
- In Section 3, based on the defined use cases and architecture, key enablers to achieve the ambition of 5G-ALLSTAR concept are specified encompassing 5G NR-compatible mmW radio access, multi-connectivity support, spectrum usage and interference analysis, channel model development, and beamforming.
- Section 4 provides the demonstration efforts and results to prove the 5G-ALLSTAR concept.

- Results for the potential socio-technological and socio-economic impacts are discussed in Section 5.
- Exploration results including dissemination and standardization are presented in Section 6.
- Section 7 shows the references including deliverables, papers, and patents containing in-depth details missing in this document.

2 Use cases and architecture

In order to define use cases categories and relevant multi-connectivity use cases for 5G-ALLSTAR, 3GPP documents have been analysed in [D2.1] (TR 22.891, TR 22.891 §5.72, 3GPP SA1 SMARTER eMBB Use Cases series, 3GPP SA1 SMARTER Network Operation Use Cases series, 3GPP 5G RAN eMBB use cases for Satellite access networks wrt to TR 38.811 with extensions to support multiple access, 3GPP TR 23.793, Study on Access Traffic Steering, Switching and Splitting support in the 5G system architecture", Release 16). Relevant Key Performance Indicators (KPIs) for the chosen use cases were selected.

The specification of 5G-ALLSTAR system describing a set of architectures and associated interfaces can be found in [D2.2], refined in [D2.3]. A high-level system architecture with basic required interfaces for 5G-ALLSTAR system was designed. Then, in order to provide other technical work packages with architecture for their study, two detailed architectures that originate from the high-level system architecture – WP4-specific architecture and WP5-specific architecture – were imagined. A set of architectures and associated interfaces were defined for WP4's study on Multi-Connectivity (MC) technologies [D2.3]. The detailed architecture and interface design of testbeds and trial platforms for proof of concept (PoC) were also specified, particularly focusing on key components, functionalities, application programming interfaces (APIs), interfaces and key technologies to be implemented. Target Key Performance Indicators (KPIs) to be fulfilled by the PoC were defined [Kim20.1][Kim18].

A description of PoC service scenarios and applications with different types of testbeds based on the previously identified architectures was then provided in [D2.4].

3 Enablers for the 5G-ALLSTAR concept

3.1 5G NR mmW radio access

3.1.1 Cellular radio access

3.1.1.1 Hardware implementation of BF-OFDM

On the European side, Block-Filtered (BF)-OFDM was chosen as the waveform for the terrestrial link [Doré19]. This waveform has been conceptualized in CEA in 2016. It presents interesting properties for the 5G-ALLSTAR concept: it is fully compatible with a 5G NR receiver, the out-of-band rejections are high (allowing efficient spectrum sharing [D3.3]) and it can be configured in real-time sub-band per sub-band (hence supporting multi-service scenarios). The challenge in 5G-ALLSTAR was to provide, from scratch, a wide-band (up to 400 MHz) hardware implementation of BF-OFDM, on a Radio Frequency System-On-Chip (RF-SOC) platform from Xilinx. In order to do so, some obstacles have been overcome: (i) the support of multiple configurations and parameters, (ii) the high bandwidth with respect to the board clock frequency and (iii) the intrinsic complexity of the waveform. The solutions provided are described in [D5.2]. The architecture was the subject of a conference paper [Doré21] and a patent [Pat7]. The transceiver has been proved fully functional [D5.2][D5.5] with tunable parameters such as the bandwidth, the numerology, the Modulation and Coding Scheme (MCS) and the active sub-bands.
CEA was granted a license for over the air transmission in the 5G 26 GHz band. In order to realize this over the air (OTA) transmission RF modules were specifically designed, [D5.5],

based on Analog Device up and down converters. In [D5.6], smooth transmission of low latency Virtual Reality (VR) tennis game plus 8k video stream through the terrestrial testbed was demonstrated; with a tx-rx distance of around 3 m, using 10 dBi horn antennas.

3.1.1.2 mmWave band 5G NR vehicular communications

On the Korean side, the mmWave band 5G NR vehicular communication system, which aims to offer on-board broadband moving hotspot services on a vehicle carrying a large number of passengers, such as a bus [D2.4], is developed. To provide such a service, the system has been designed to operate at a mmWave band of around 23 GHz owing to its abundant bandwidth availability, and a vehicle equipped with a vehicle UE above the roof acts as a mobile relay to provide broadband wireless backhaul connectivity to the on-board Wi-Fi by communicating with a gNB at the frequency band [D2.2][D2.3][Kim20.2]. The air interface of the wireless backhaul basically complies with Rel-15 5G NR specifications, and the physical layer is designed to support a high subcarrier spacing of 60 kHz and a dense allocation of DMRS in the time domain in order to combat the high Doppler effect. In addition, since the target deployment scenarios of the system are highway and urban road scenarios, the system is required to maintain its wireless backhaul connectivity with the network even when the vehicle overtakes or travels on a curve. To address the challenges, the system is further designed to support an open-loop beam switching technique dedicated for vehicular communications. At each time instance (every 240 ms), one best beam set is chosen among three beam set candidates for communication based on the measurement results. Moreover, several techniques such as 2x2 MIMO transmission with linearly-polarized antennas and fast handover. Some related patents are: [Pat1][Pat3][Pat6][Pat8].

To validate the feasibility and effectiveness of the system, a prototype system is implemented, and field test were conducted in an urban and highway environments [D5.3]. The test results showed that the system with the developed technologies is capable of providing broadband wireless connectivity between the vehicle UE and gNB, which enables the realization of the target service. However, during the field test, it was observed that performance degradation occurs depending vehicle locations, mainly due to the line-of-sight (LoS) signal blockage, which is more significant in the high-frequency mmWave band. Hence, in order to complement blockage problem of the mmWave cellular system and to guarantee service continuity, supporting multi-connectivity between cellular and satellite networks is also developed, the details of which are described in Section 3.2.

3.1.2 Satellite radio access

5G-ALLSTAR aimed at providing direct satellite access to the 5G NR UE. OpenAirInterface (OAI) was chosen for the design of the satellite-friendly modem in the European testbeds and trial. OAI is an implementation of the 3GPP mobile communication standards. It currently supports LTE UE, eNB and EPC. Development on the 5G NR standards (beginning with 3GPP release 15) is ongoing. The main challenge for such a goal is the adaptation of the NR procedures of OAI to the long delay scenarios, such as GEO satellite channels. In that goal, during the project, the following features were developed [D5.2]: (i) extension of the K2 slot offset to at least twice the one-way delay between gNB and UE; (ii) introduction of an offset for UE PUSCH transmission (when receiving a PDSCH with RAR message); (iii) introduction of an offset for the transmission slot of DCI scheduled PUSCH; (iv) additional slot number, corresponding to at least twice of the one-way delay between gNB and UE; (v) extension of random access response (RAR) window; (vi) extension of UL future TTI request and UL virtual RB mapping; (vii) increase of the Timing Advance update period; and (viii) deactivation of HARQ processes.

The satellite modems are running on same HW for both UE and gNB, based on the SDR platform Ettus USRP X300 [D5.2] equipped with 1 CBX-120 daughterboard and 50 dB attenuators. The frequency range is tuneable from 1200 MHz to 6000 MHz, channels bandwidth is available up to 120 MHz (OpenAirInterface currently sup-ports up to 40 MHz) and TDD and FDD operation modes are allowed.

A press release was published [Casati21] to disseminate the successful implementation of the satellite-friendly 5G NR modem.

3.2 Multi-connectivity support

3.2.1 Traffic flow control

Traffic flow control is a key feature to support multi-connectivity. European and Korean partners have worked on architectural solutions and algorithms in WP4 and WP5.

3.2.1.1 Contribution to 5G architecture

An exhaustive state of the art of 5G Multi-Connectivity architecture and of control algorithms for addressing multi-connectivity issues has been realized in [D4.1]. Leveraging on this study, 5G-ALLSTAR conceived a Non Terrestrial / Terrestrial Multi-Connectivity Architecture, to be in line with the current vision of distributed resource control and to maximize the whole user's experience by optimizing the radio performances. In this regard, the 5G-ALLSTAR project enriched the current entities, i.e., Core Network (CN), Cloud Radio Access Network (cRAN) and Distributed Radio Access Networks (dRAN), with elements able to satisfy and control specific end-to-end Services/Applications by using both Traffic Flow Control and Quality of Experience (QoE) Control [D4.1].

The QoE/QoS Management – including QoE management repository and QoE control – is logically located into the Core Network. The 5G-ALLSTAR functionalities included in the gNB-CU are the centralized Radio Resource Management (cRRM), Cell QoS Performance Repository, In Progress Connection Repository and Traffic Flow Control. Finally, the Distributed Radio Access Network (D-RAN) hosts dRRM and QoE estimation.

The communication among the various entities, i.e., the Core Network, the C-RAN and the D-RAN are performed with specific Interfaces. The mentioned entities exchange data information concerning the user's requirement, traffic and channel performances. The communication among entities and software modules implemented in such entities is a mandatory step for enabling the network optimization and control.

These functionalities and the proposed architecture are fully described in [D4.1] [D4.2] [Choi20] [Lisi19].

3.2.1.2 Contribution to algorithms

Regarding multi-connectivity, three main processes for traffic flow control were identified by 3GPP for inclusion in its Release 16, namely traffic steering, traffic switching and traffic splitting. In the scope of 5G-ALLSTAR, these processes were referred to as "traffic flow control strategies or decisions". Traffic steering was also given the dynamical capabilities of traffic switching, so that the assignment of (a portion of) a QoS flow may change over time and hence becomes a real-time control action that impacts the network state. Traffic splitting can also be integrated into the dynamic traffic steering process, provided that the traffic flow control accounts for the different QoS requirements of the various PDU sessions. In this regard, the 5G-ALLSTAR project also integrated a so-called "personalization system" able to associate to the various PDU sessions and QoS flows, a set of unstandardized user-dependent connection preferences that may drive the behavior of the traffic flow control in a user-centric, or personalized, way.

Several control algorithms [D4.2] [DPriscoli21] [Giusepi20.1] [Giusepi20.2] [Giusepi20.3] [Ornatelli20] [Priscoli20] were developed and assessed by simulation in the project lifetime, to explore possible research directions and investigate the challenges associated with the multi-connectivity framework. The integration of the QoE functionalities into these traffic flow control algorithms solutions and, overall, with the entire 5G-ALLSTAR system is also discussed in [D4.2].

3.2.1.3 Algorithm selection for PoC

The above-mentioned algorithms have been evaluated in the context of the 5G-ALLSTAR Proof of Concept (PoC) demonstration [D4.3]. A selection of algorithms has been made. To realize such a choice, the European partners developed an open source network simulator. This simulator allows the demonstration and the study of multi-connectivity functionalities and algorithms beyond the scope of the project PoC, as it simulates a “target scenario” in which all 5G technologies are deployed and available. It has been open sourced and given a doi [https://doi.org/10.5281/zenodo.4706857]. On the Korean side, a simulator has been designed to allow the testing of load balancing algorithms in multi-RAT networks. The simulator developed allows for intra-RAT and inter-RAT traffic offloading and 5G QoS Identifier (5QI)-aware traffic steering.

The functional requirements of the algorithms were adapted to demonstrate in the final PoC the capabilities of the 5G-ALLSTAR multi-connectivity approach. The selected algorithm for European testbed is *Wardrop Equilibrium based control*, whereas on the Korean side it is *Mobility Load Balancing*.

3.2.1.4 Software development for multi-connectivity demonstration

In order to demonstrate the selected algorithms, testbeds and trial platforms were designed (see §4). In that aim, software components and functionalities were developed.

European partners worked on a 8k adaptive video streaming platform [D4.3] responsible in the PoC for: 1) the data flow generation (for the scenarios involving video streams); 2) the multi-connectivity traffic steering/control capabilities of the EU PoC (traffic control); 3) the logical reconstruction of the split traffic flows to enable a seamless multi-connectivity solution, based on custom Multipath TCP. Three modes are available for the traffic flow controller [D5.2]:

- Static. The forwarding of a traffic to one of the links is fully defined by configuration. This mode supports steering.
- Static with load balancing. The input traffic balancing to the output ports are fixed (x % of the receive traffic to satellite port and (100 – x %) to the terrestrial port. This is a form of steering+splitting.
- Dynamic. These rules take into account the offered throughput indication provided by the cRRM. It is possible to deploy rule-based or more complex control laws as described in [D4.3]. An example of such a control law could be to have preconfigured traffic rules that model certain preferences; e.g., whether traffic prefers low delay (terrestrial) or not (satellite). In this case; the allocation could operate on a strict (ordered) priority as defined by the configuration or in a load balancing and preference-aware setting.

A side mode enables a policy overrule when one link has been reported as completely failing. This triggers an immediate reaction (switching) in order to minimize packet losses at each unpredictable link loss event so that all traffic is routed to the sole working radio link.

The traffic controller (TC) developed on Korean side consists of a traffic status monitoring module, a control decision module, and a control action module [D4.3][Pat5]. Its functionality includes traffic monitoring of status of multi-channels, traffic hand-off/recovery decision making, and streaming session management based traffic control. Before integration in the final trial, the functionality was verified by the testing in a ETRI testbed that consists of a streaming server, a WAN aggregation switch, two WAN gateways for both a cellular network and satellite network, a TC, an Access Point (AP) for WiFi connectivity, a management console, and 5G and satellite user terminals in a moving vehicle.

3.2.2 Radio Resource Management

3.2.2.1 Analysis

With respect to RRM, two interference mitigation methods were studied: exclusion region design and RRM schemes coordinated in frequency, time or frequency·time.

For the former study [D3.3], the radius of the zone around the satellite earth station that may be free of cellular base station transmission was analytically derived. The proposed algorithm takes into account antenna directivity to form a non-circular-shaped exclusion zone. Computer simulations revealed that the proposed scheme outperforms the conventional circular-shaped exclusion zone design in terms of the success probability of satellite network and the performance of coverage area in the cellular network.

In the latter study [D3.3], an overview of the candidate RRM coordination schemes extended to face NTN links constraints was first provided. A NS-3 based simulator was then designed in order to evaluate the different schemes. Interferences on the terrestrial and non terrestrial entities were modelled. Conclusions were drawn and recommendations for implementation in testbeds were provided.

3.2.2.2 Simulation

Some of algorithms like intra RAT and inter RAT load balancing algorithms are very promising for the efficient RRM [D4.3]. However, in order to prove their efficiency with the implemented PoC, the system needs lots of user terminals, NTN and TN base stations, which is almost impossible to run for the PoC. Instead, the simulator for the algorithm was developed and extensively evaluated which is showed in [D4.3].

3.2.2.3 Implementation

A central Radio Resource Management (cRRM) software module has been designed for implementation in the EU testbeds and trial platform [D5.2]. It ensures a safe coexistence of both heterogeneous RATs cellular and satellite in terms of Dynamic spectrum sharing and interference prevention. It implements advanced strategies to dynamically select the appropriate radio configuration depending on the actual conditions. Radio measurements made by the UEs and gNodes (gNBs) are provided by the dRRM (distributed Radio Resource Management) software components serving to connect each gNB-DU to the cRRM located in the gNB-CU and to exchange control messages.

This cRRM implementation, on the contrary of the cRRM described for the full system in [D3.3] must respect some testbed prototyping constraints: (i) the demonstrator and its hardware does not support the notion of 3GPP cells; (ii) mainly due to the difference in delays between terrestrial links and GEO, a fast-loop PRB allocation process is not achievable and (iii) the demonstrator is limited to a single terminal. In these conditions, three cRRM algorithms were implemented [D5.2]:

- MCS management, i.e. Adaptive Mode (ACM), so that higher throughput can be delivered when conditions are favourable.
- Link throughput reports to Video and/or Generic traffic flow router.
- Bandwidth sharing profile. Satellite and terrestrial transmitters share the same band. The cRRM dynamically allocates totality or fractions of this band to either the one or the other RAT. The allocation can be based on static profile; periodic “on/off” time series or SNR-based profiles.

3.3 Spectrum usage and interference analyses

In [D3.1] the spectrum usage for cellular and satellite systems has been analysed by (i) reviewing spectrum bands and (ii) deployment scenarios and by (iii) specifying key parameters for RRM techniques to be implemented.

The spectrum band review (i) includes an overview of the overall 5G spectrum situation: IMT-2020 interfaces definition process, identification of new bands for IMT-2020, 3GPP NR frequency bands and regulatory and licensing issues of 5G satellite system use in mobile bands. A survey of the satellite frequency bands potentially eligible for 5G was also realized: L-band, S-band, C-band, FACS band, Ka-band were taken into account. This review has been included in [Cassiau20]. (ii) 3GPP reference deployment scenarios for 5G non-terrestrial networks (including beam size, gateway and space segment parameters) were studied and selected in light of the 5G-ALLSTAR concept and objectives. The same work has been done for the terminal deployment scenarios.

The effect of the interference between satellite and cellular systems was investigated in some candidate scenarios. First, theoretical outage probability analysis was conducted to assess the interference from the cellular base stations to the satellite UEs deployed on a vehicle. Considering beam direction and vehicle UE location, the outage probability of the satellite signal transmitted from GEO satellite was provided. The detailed results were demonstrated in [D3.2], [Noh20]. Second, stochastic geometry-based analysis was provided, which shows the effect of randomly deployed interferers. The metric of aggregated interference is used for the analysis. The 3D antenna modelling and circular-shaped exclusion zone were assumed for the analysis. As a result, it was shown that an increasing exclusion zone radius reduces the aggregated interference level, while an increasing BS density leads to an increased interference level. More details can be found in [D3.2], [Syeom20].

3.4 Channel models

When setting-up the project, a lack in the state of the art in modelling of satellite / terrestrial channels has been identified. In the early part of the project, big effort has therefore been made on designing such channel models. A geometry-based and a Ray Tracing (RT)-based models were developed [D3.1]. They were then used for evaluation of algorithms and interference in [D3.2].

3.4.1 Geometry-based

The 5G-ALLSTAR channel model is based on 3GPP TR 38.811 v15.0.0. The work in 5G-ALLSTAR aimed at providing an implementation and further extensions of this channel model within the QuaDRiGa channel simulator [https://quadriga-channel-model.de/]. Only the satellite part of 3GPP TR 38.811 was considered here, whereas 3GPP considers also high-altitude platforms. Hence, only outdoor conditions are considered, since performance requirements are not expected to meet the available link budget for indoor communications. Besides the satellite channel model, 5G-ALLSTAR leveraged all existing features of the QuaDRiGa channel simulator and the channel model for terrestrial communication systems specified in 3GPP TR 38.901 v15.0.0 (2018-06).

The following features were implemented:

Frequency range	Satellite model scalable from 2 – 40 GHz, terrestrial model scalable from 0.5 – 100 GHz
Simultaneous multi-frequency Simulations	Support for simultaneous multi-frequency simulations including terrestrial base stations and satellites, fully compatible with all other model components
Channel observation time	Satellite links observable for up to 30 seconds, including deterministic orbit tracking and multipath tracking; terrestrial links have unlimited observation time
Coordinate system	Supports orbit tracking of LEO satellites in accordance with ITU-R S.1503-3, transformation into local Cartesian coordinates in order to support coexistence studies between terrestrial and satellite systems
Antenna modelling	Reflector antennas and beam-steering antennas, support for wide range of antenna types
Drop-based system-level simulations	Supported by default

LOS probability model	Based on satellite elevation or BS-MT distance, support for spatial consistency based on MT and satellite positions
Path loss and Shadow fading	Model for distance and frequency-dependence, attenuation due to atmospheric gases, shadow fading scalable for whole frequency range from 2 – 40 GHz
O2I penetration loss	Supported for terrestrial links; optional for satellite links (same as in TR 38.811)
Frequency selective fading	Supported by default
Spatial Consistency	Supported
Dual-Mobility	Supported

The modified 5G-ALLSTAR Quadriga model was made available open-source to the scientific community [Jaeckel19] [Jaeckel20].

3.4.2 Ray-tracing based

The RT-based channel model is meant for millimetre wave (mmWave) simulations of wireless communication in a typical urban scenario and a highway scenario, respectively. It characterizes the target channel with consideration of the terrestrial communication link from base station (BS) to vehicle UE and the satellite-terrestrial communication link from a transmitter (Tx) on a satellite, called Koreasat 6, to a satellite UE carried by an SUV. The propagation attenuation for each link is considered. The model allows to study the interference between a terrestrial Mobile Network system and a satellite-terrestrial communication link.

The RT simulator models wave propagation and calculates all possible rays between the transmitter and the receiver by using the principles of geometric optics. Once all the rays are traced, the amplitude and the phase of each ray can be calculated by coupling with the antenna patterns and polarizations. Because of the deterministic map-based channel modelling approach, RT requires precise 3-dimensional (3D) environment model indicating the geometry of the objects and the corresponding material. It also requires an accurate propagation mechanism model. The most time consuming part of RT simulations is the tracing of rays, especially when the reflection order is higher or propagation constitution becomes complex. As a result, more accurate simulation tasks bring more complexity in tracing rays and electromagnetic (EM) calculations. 5G-ALLSTAR therefore leveraged on a publicly available high-performance RT platform (CloudRT) - developed in Beijing Jiao-tong University – to develop the satellite-terrestrial channel model.

Attenuations (due to gases, rain, clouds, fog and tropospheric scintillation) were taken into account to derive path loss, RMS delay spread and Rician K-factor for any kind of Mobile Network terrestrial - satellite scenario.

More details can be found in [D3.1] and in [Guan18] [Guan19] [Ma20.1] [Ma20.2] [Wang19] [Wu20] [Yan19] [Yan20] [Yi19] [PViet19].

3.5 Beamforming

3.5.1 Algorithm

A dual beamforming technique was studied which can mitigate the interference between satellite and cellular networks. The goal was to introduce a way of enhancing the communication quality of the cellular network while limiting the aggregate interference from the cellular base stations to the satellite Earth station to a certain level. Considering a realistic satellite-cellular sharing scenario where both satellite and cellular links operate in the downlink, a beamforming vector design was provided [D3.3][Pat2][Pat4] for the cellular base station. The objective of the proposed beamforming technique is to maximize the communication performance while limiting the amount of maximum allowable interference at the satellite Earth station to a predefined level. More specifically, a combination of ZF beamforming using null space of the interference channel and MRT beamforming which can maximize the channel gain of the cellular link is provided. The dual beamforming scheme was verified via computer simulation. The performance of the proposed dual beamforming was proved to outperform beamforming schemes based only on either MRT beamforming or ZF beamforming.

3.5.2 Implementation

As a simpler form of beamforming functionality, a UE-centric beam switching scheme, is implemented in KR testbed. The beam switching functionality is embedded in a terminal equipment (TE) within a cellular network. The beam switching not only allows to find the best beam – having the strongest received signal power – but also reduces the impact of severe interference by not selecting the transmit/receive antenna with high interference. Since the beam switching operation is based on the measurement of the synchronization signal block (i.e., primary/secondary synchronization signal and broadcast signal), the beam switching module has the ability of discriminating between the desired signal and interference. As described in [D5.3], the antenna switching at the TE periodically monitors the synchronization signal block received by each antenna, accumulate the received signal strength at each measurement instant, and select the antenna having the maximum received power strength. The beam switching operation can be done with a periodicity of 250 µs.

4 Demonstration of the concept

4.1 Korean Testbeds

On the Korean side, a step-wise approach for the final trial platform had been adopted. Two kinds of testbeds had been prepared in parallel and they were merged into the multi-connectivity testbed with the help of a traffic controller. The multi-connectivity testbed had been validated through high quality video streaming services.

4.1.1 Terrestrial testbed

A Korean cellular access testbed based on the 5G NR specification had been established [D5.3]. **Figure 1** illustrates the components of the Korean terrestrial testbed, and Table 1 summarizes the components and their functions/services and hardware specification.

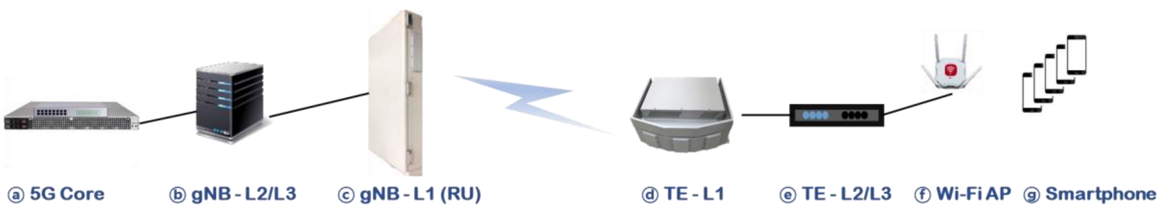


Figure 1. The components of the Korean terrestrial testbed

Table 1. List of the components and characteristics

Component	Function/Service	Hardware Specification
5G Core	UPF, AMF, SMF	Xeon server, Zynx B series 480G switching capacity with OA4 & Quagga protocol stack
gNB-L2/L3	L2/L3 protocol stacks	Xeon server (16 cores) gNB throughput of 6 Gb/s (2 cells)
gNB-L1 (RU)	Baseband, radio frequency	Dedicated hardware

		2T2R antenna configuration 600 MHz bandwidth at 22~23 GHz
TE-L1	Baseband, radio frequency	Dedicated hardware 2T2R antenna configuration 600 MHz bandwidth at 22~23 GHz
TE-L2/L3	L2/L3 protocol stacks	Xeon server (8 cores) UE throughput of 3 Gb/s
Wi-Fi AP	Wi-Fi Access Point	Netgear AX11000 IEEE 802.11ax compliant 2.5 Gb/s of data rate
Smartphone	Internet access Video streaming application Benchbee App	Samsung Galaxy S20+

These components were integrated and the integrated system had been tested. For the test, a video server was connected to the server for the 5G Core, and total seven smartphones were attached to the network. Figure 2 shows the smartphones displaying video contents from the media server at the same time.

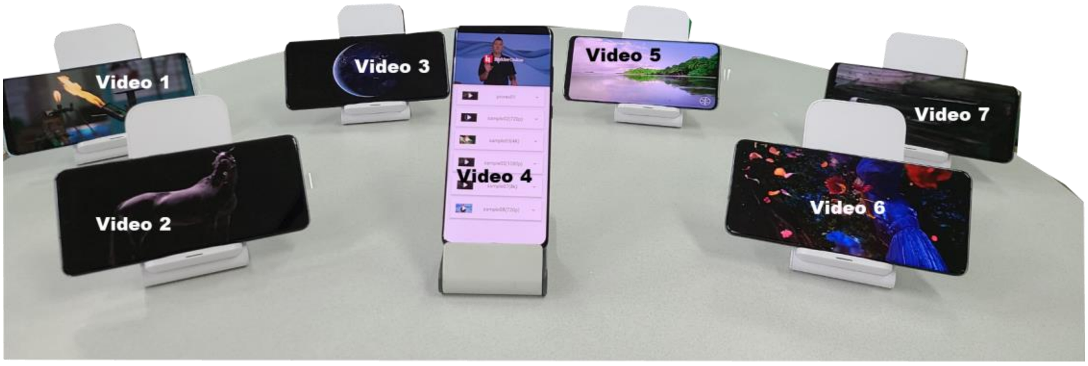


Figure 2. Video streaming service with the smartphones

4.1.2 Satellite testbed

A Korean satellite access testbed had been prepared based on the Koreasat-6 in service and a set of commercially available modem and antenna [D5.3]. Figure 3 illustrates the Korean satellite access testbed including a earth station in Kumsan and a set of modem and antenna in a test vehicle. Details on the satellite testbed is described in [D5.3].

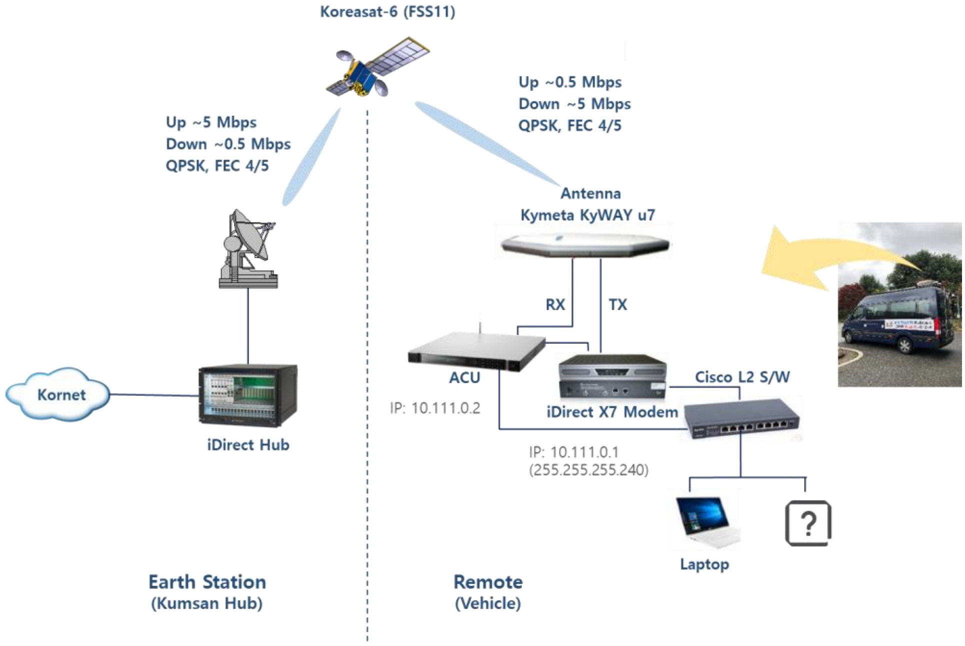


Figure 3. Korean satellite testbed

Checking three services in the vehicle, the test results are listed in Table 2. Since the satellite testbed exploits the satellite system in service, the available frequency bandwidth for the test is quite limited. The maximum available bandwidth was around 3 MHz for downlink in the vehicle user perspective. Thus, the download and upload speeds were much lower than we can expect for a 5G air interface. The VoIP and video conferencing service functions had been checked and had shown reasonable results.

Table 2. Service with the satellite testbed

Service	Check point	Result
Internet access	Download/Upload speed	Download: 3.1 Mb/s Upload: 656 kb/s
VoIP	Call using a IP phone	Good
Video conferencing	Quality check with a chat application	Good

4.1.3 Multi-connectivity testbed

The two testbeds explained had been aggregated towards the final test platform of multi-connectivity (MC). A key component is a traffic controller (TC) as in Figure 4. The TC gets input from the cellular UE modem and the satellite UE modem and selects one stream to the output port that connected to a Wi-Fi AP. Details of the MC testbed is described in [D5.4]. To validate the MC testbed, a video server was used as in Figure 4. The cellular path and satellite path were active, and the TC selected one path according to predefined conditions such as packet loss and delay. Figure 5 shows a smartphone connecting the video server.

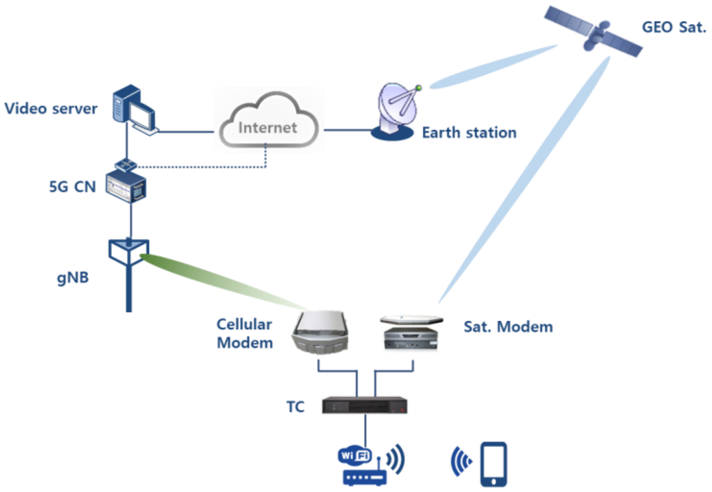


Figure 4. Korean multi-connectivity testbed

Figure 5 Video streaming with the multi-connectivity testbed

4.2 European Testbeds

On the European side, the strategy for getting to the final trial platform was to first develop independent terrestrial, satellite and multi-connectivity testbeds, in three different locations in Europe. Those testbeds were meant to validate the integration of enablers before trial.

4.2.1 Terrestrial testbed

A testbed for the terrestrial link of the 5G-ALLSTAR system was set in the CEA premises [D5.2][D5.5]. The goal was to demonstrate the enablers: (i) 5G NR mmW cellular radio access and (ii) Radio Resource Management. Two services were assessed: Virtual Reality tennis game and webcam streaming.

The MCS reconfigurability functionality of cRRM was first assessed. Terrestrial boards (see §3.1.1) were used together with a PropSim F8 channel emulator (see [D5.2]) to emulate a pedestrian transmission. The fading profile of the channel was automatically set to a “V curve”. It was observed a correct adaptation of the MCS, i.e. a lower MCS (resp. higher) is selected when the fading is high (resp. low).

The two services mentioned above were then evaluated. **Figure 6** describes the European testbed for this demonstration. The VR player and the webcam are connected to the UE boards/PCs. The link from the transmit UE board to the receive gNB board is over the air at 26 GHz (the return link is through channel emulator). The gNB is connected to the internet. The second VR player is directly connected to the internet. The webcam stream is displayed on the screen, and the to players are playing together. **Figure 7** shows a pictures of the setup.

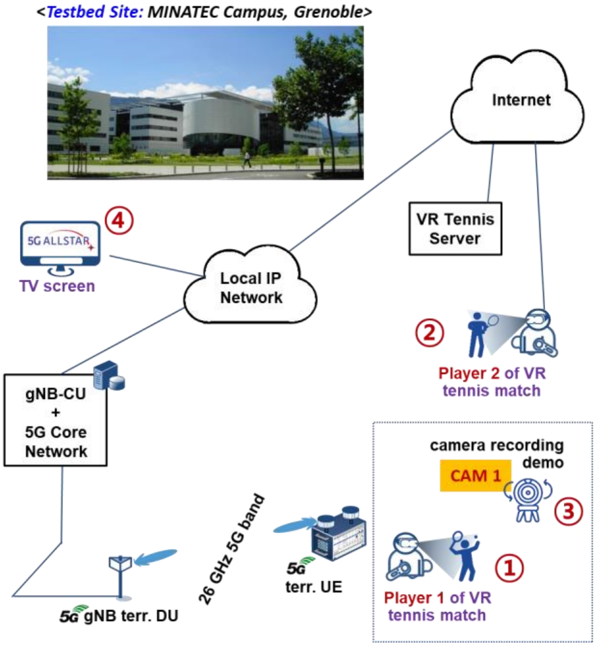


Figure 6. European testbed for terrestrial link

It was demonstrated that the game experiences no latency and that the webcam stream is smooth.

Figure 7. Terrestrial link of European testbed demonstrated

Below is a zoom on the transmit RF board and the antenna. We can see on the screen that the throughput reached in this particular case (100 MHz bandwidth, MCS 9) is 187 Mb/s. Much higher throughput has been demonstrated (>300 Mb/s) with higher MCS.

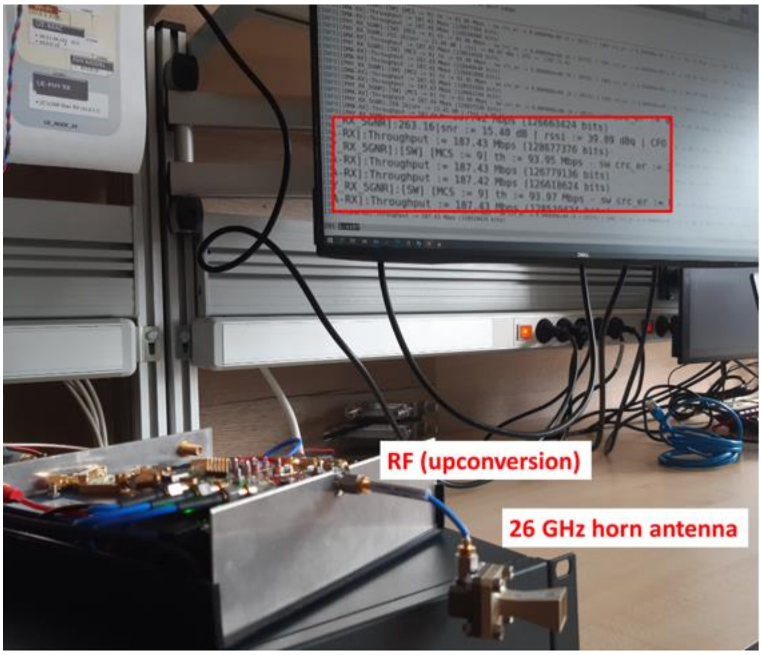


Figure 8. 26 GHz over the air transmission demonstration

4.2.2 Satellite testbed

The goal of the satellite tested, in Fraunhofer premises in Erlangen, was to validate the 5G NR satellite radio access, see 3.1.2. The bidirectional link between the satellite UE and the satellite gNB is set up by the PROPSIM F64 channel emulator [D5.2]. This channel emulator is equipped with an Aerospace Option (ASO) and Aerospace and Satellite Modelling tool for testing airborne, aerospace and satellite radio communication devices and systems in order to emulate SISO topologies with high Doppler shift (up to +/- 1.5 MHz), long propagation delay spread (up to 1.3 s) and high range rates in a laboratory environment. Figure 9 shows a picture of the testbed in the Fraunhofer IIS premises.

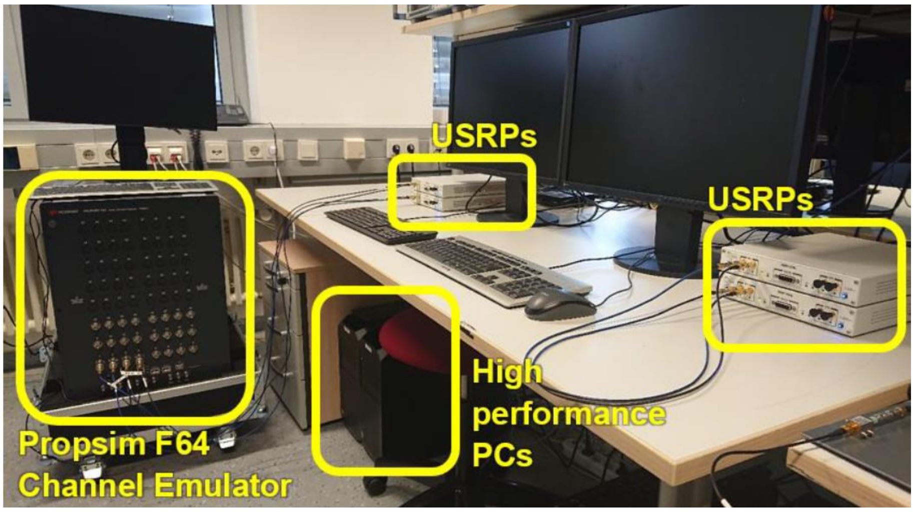


Figure 9. Lab setup of the Fraunhofer IIS Satellite Emulation Testbed

The test consisted in running the SAT OAI modems with an emulated GEO Satellite channel. The selected channel parameters were:

- Satellite channel one-way propagation delay: 240 ms
- RF and simulation center frequency: 2169.08 MHz DL, 1769.08 MHz UL
- 20 dB attenuation DL/UL

During this test an UDP Iperf throughput test was performed both in DL and UL (i.e. forward and return links). Different MCS were tested and the performance of the satellite modems proved to be stable up to MCS 16 [D5.2].

4.2.3 Multi-connectivity and cRRM testbed

For the traffic flow control and management validation in CRAT premises, adaptive Video Streaming client and server (see 3.2.1) were used; two virtual machines (VMs) were put in place (one for the server and one for the client). Both the VMs acted as OpenBACH agents (see [D5.2] for details on OpenBACH orchestration) and were connected to an OpenBACH controller, that was used to run the tests [D5.2] and show the results in the Grafana environment provided by OpenBACH. The Server VM has been connected to the Client VM with two (virtual) paths as shown on Figure 10. Furthermore, the cRRM modules (see §3.2.2) were also integrated, for validation, with the dummy dRRMs for satellite and terrestrial paths.

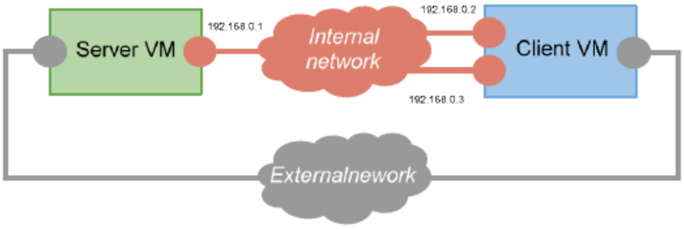


Figure 10. Validation setup for Traffic Flow Controller

It has been demonstrated [**D5.2**][**D4.3**] that the Traffic Flow Controller changes dynamically and in real-time, as expected, the MPTCP quotas and the video streaming is able to reach highest quality level.

4.3 European Trial platform

4.3.1 Multi-connectivity

The European trial platform first aimed at demonstrating multi-connectivity (see §3.2) with terrestrial and satellite boards, over the air transmission and realistic satellite delay. To that goal, the integration of both terrestrial and satellite testbeds took place in the CEA premises where the Fraunhofer hardware was shipped. All involved partners have met there during 4.5 days only, whereas several weeks of integration had been initially planned before Covid crisis.

Figure 11. Integration of EU trial platform in CEA premises

Due to the very short time allocated to the assembly of the components from all partners and to unexpected difficulties (see [D5.5]) the satellite link was not established as initially desired (i.e. as described in §4.2.2 plus over the air transmission). We nevertheless succeeded in establishing the network as shown on **Figure 12**.

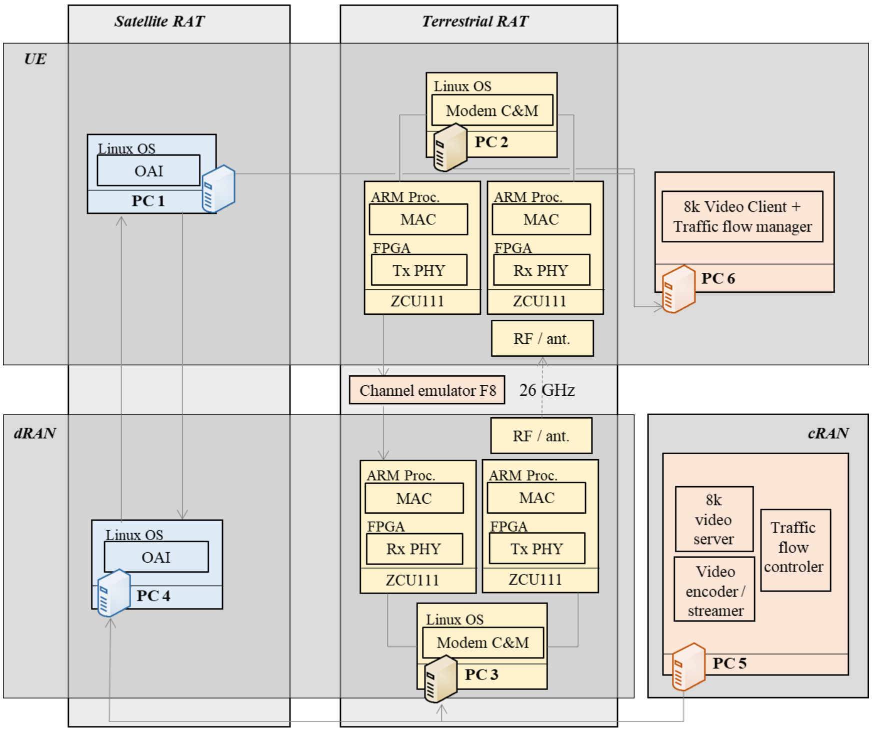


Figure 12. EU multi-connectivity trial platform

With this setup the multi-connectivity has been demonstrated in its basic concept, anyway, giving some expected results and some hints on how the complete European Trial Platform would have behaved if more time could have been dedicated to it.

In particular the validation included basic multi-path connectivity test with iperf3 tool, validation of the 8K Video Streaming system transmitting on both the two paths at the same time and validation of 8K Video Streaming with an abrupt channel interruption. Moreover, the European Trial Platform was tested running multiple services at the same time (e.g., 8K Video Streaming and Real-time Webcam Streaming) on the available paths. These validation tests (see [D5.5]) can be mapped in the following scenarios from [D5.2]:

- Scenario 5: Basic multi-connectivity
- Scenario 8: Realistic multi-connectivity, no handover, single application
- Scenario 10: Realistic multi-connectivity, no handover, multiple applications

4.3.2 Demonstration preparation

The second role of the European platform was to prepare the final demonstration [D5.6]. To this end, the hardware and the connections were re-arranged to obtain the set-up shown on **Figure 13**.

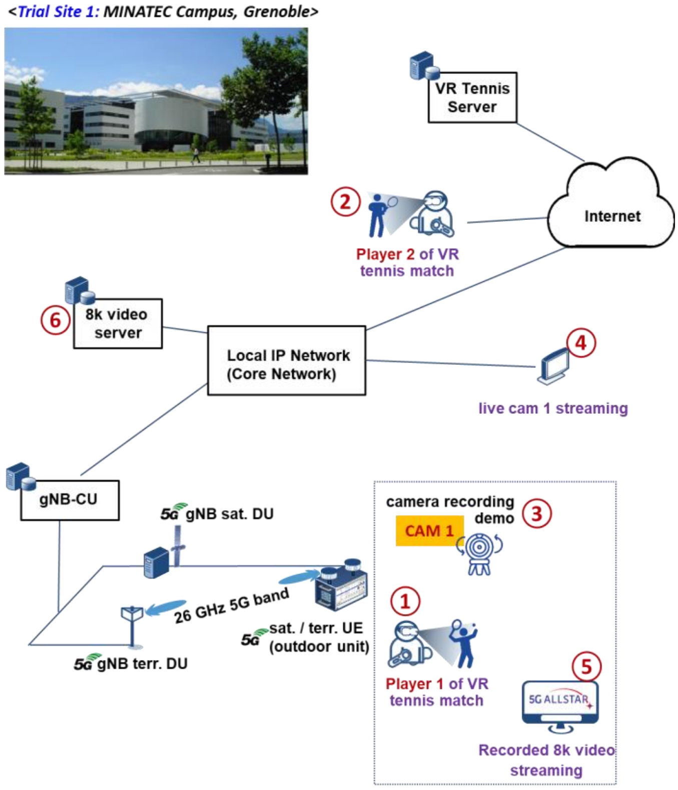


Figure 13. EU trial platform for final demonstration preparation

The flows that are exchanged are:

- From player 1 to/from the VR server on the internet, via the terrestrial link over the air.
- From player 2 to/from the VR server on the internet, via a WiFi connection.
- From webcam 1 to screen 4 via the satellite link.
- From 8k video server to screen 5 via the terrestrial link over the air. Note that in the final demonstration, this flow may go to Korea while the 8k video displayed on screen 5 may come from Korea.

All these flow have been validated with the required performance [D5.6].

4.4 Intercontinental demonstration

The intercontinental final demonstration first required to connect the Korean platform to the European platform [D5.6], as shown on **Figure 14**. The connection between both sites was realized thanks to an IPsec VPN terminated by Kreonet connection in Korea, guarantying acceptable throughput and latency.

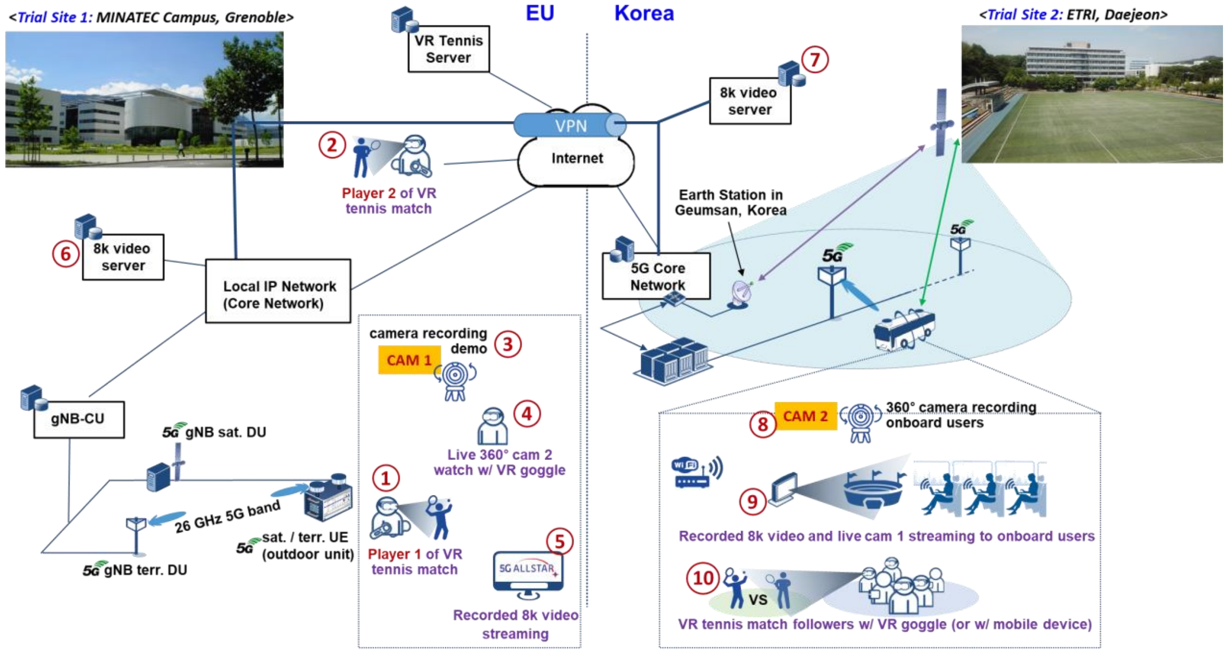
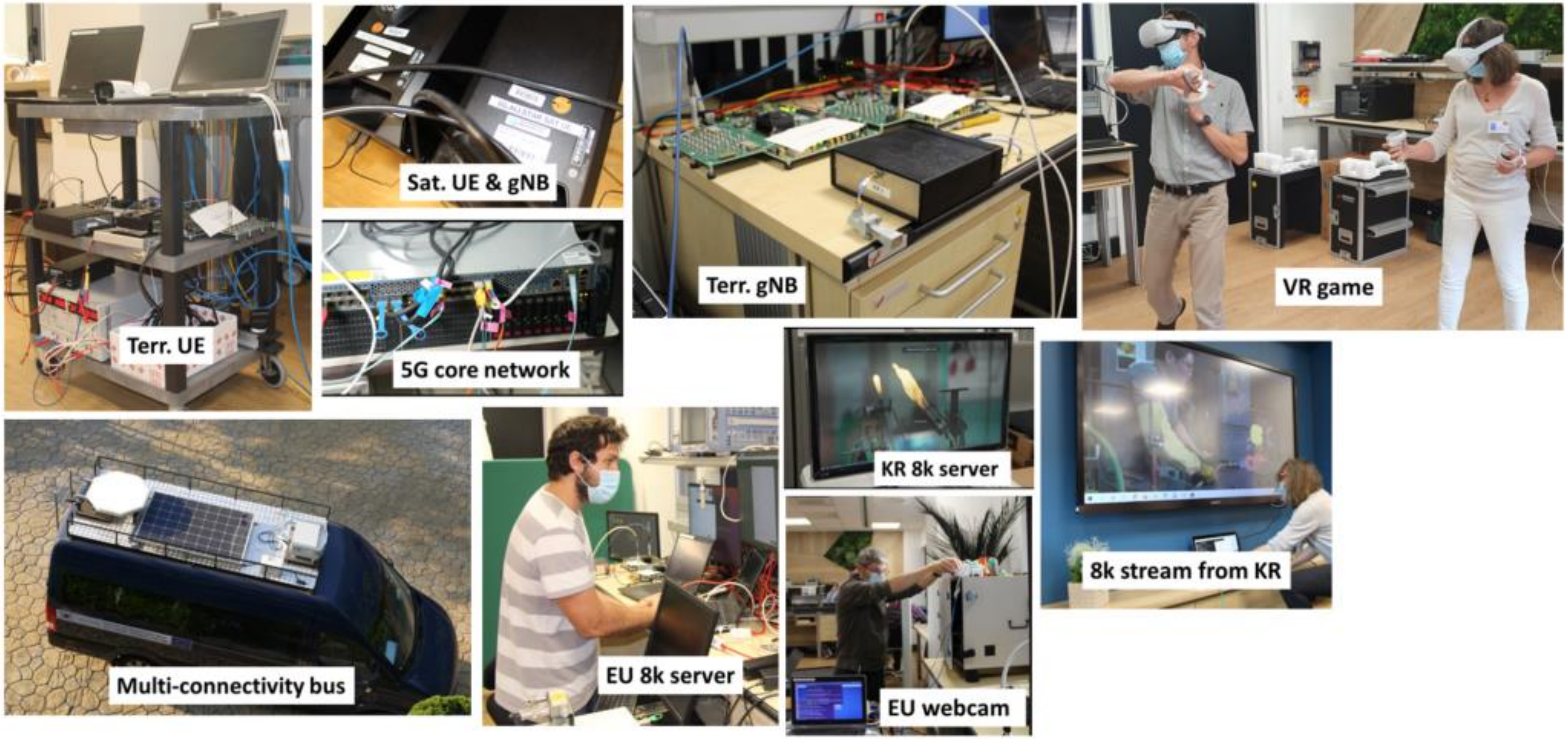


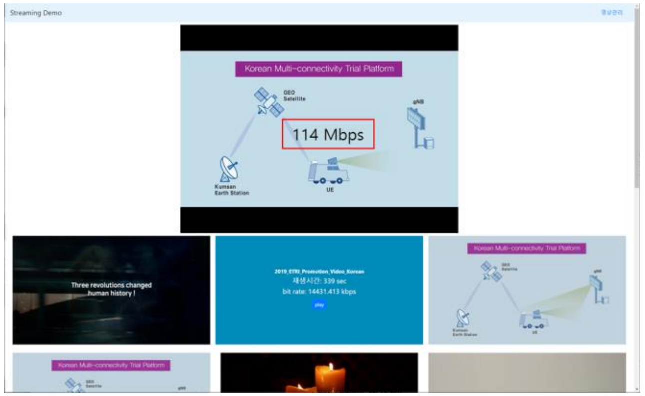
Figure 14. Intercontinental final demonstration

The scenario is the following:

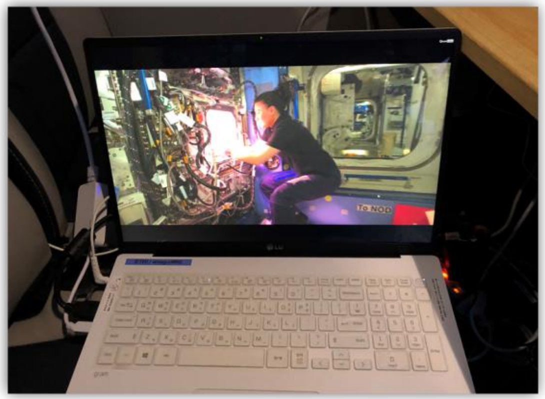
- In Europe, a player of Virtual Reality (VR) tennis game ① is at home or on the move is equipped with a multi-connectivity 5G unit (UE), able to transmit/receive via a satellite link and a terrestrial link.
- He plays with another player ② somewhere in the internet (flow goes through the terrestrial path).
- The player at home is filmed with a webcam ③ (flows goes through the satellite path).
- In Korea, people are in a bus equipped with satellite and 5G terrestrial receivers/transmitters. Some of them ⑨ are watching the VR tennis game from webcam ③, others are watching the game with VR goggles ⑩. These flows go through the best path between satellite and terrestrial.
- In the bus, people are filmed with a 360° camera ⑧. This stream is displayed in Europe ④ (through terrestrial path).
- Additionally, in order to demonstrate that high throughput can be reached, 8k videos are transmitted from Europe to Korea (via multi-connectivity receiver) ⑥⑨ and from Korea to Europe (via terrestrial path) ⑦⑤.

The final demonstration took place on Friday October 15th. The results were satisfactory and are provided in [D5.6]. Some pictures of the demonstration can be find below.

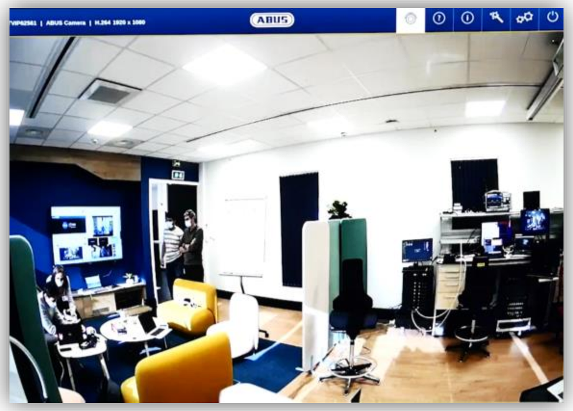

Terr. UE
Sat. UE & gNB
5G core network
Terr. gNB
VR game
KR 8k server
8k stream from KR
Multi-connectivity bus
EU 8k server
EU webcam



KR 8K video server manager



8K video streaming in a KR vehicle



EU webcam streaming

EU-KR VR tennis match

360° webcam streaming

5 Potential socio-technological and socio-economic impacts

Part of the effort of 5G-ALLSTAR was dedicated to 5G business assessment and exploitation towards vertical stakeholders [Colombero21] [Chatelain21.1] [Chatelain21.2] [Colombero20] [Colombero19].
In [D2.5] we first provided an overall summary of the current state of 5G market in 2020. We note that overall adoption of 5G is still very limited; even industry presents itself in its early stages. Shortcomings and issues that are structuring the current offering and market, of which some may concern possible applications emerging from 5G-ALLSTAR innovations, were identified.
In a second part we discussed the emerging configurations based on both a desk analysis of available literature and studies, and direct interviews we conducted with key informants. Two rounds of interviews were conducted from our panel of experts who were selected based on criteria such as relevant experience in field, expertise, knowledge of 5G and business models and an insight of trends within 5G for B2B and consumer markets. Our first round of interviews included general, open ended, exploratory questions that were further improved upon within the second round based on responses received to the first set of questions. This allowed us to understand 5G networks and frame our discussion around key dimensions of the business models in terms of balancing risks with promises while managing tensions and synergies to provide a holistic overview of what we expect within the upcoming 5G business models in industry. For data analysis, we coded our interviews through Nvivo coding. These codes were re-assembled to develop concepts that led to the identification of the main themes of discussion elaborated within the findings.
Based on the joint analysis literature, available cases, and interviews we finally discussed the opportunities for 5G-ALLSTAR technologies in the identified vertical markets describing effects of the different dimensions of business models (transport, public safety, rural area), helping the definition of viable strategies.

6 Exploitation results

6.1 Dissemination

Big effort has been done to disseminate the results of 5G-ALLSTAR. This resulted in:

- 14 journal papers and 24 conference papers issued, see §7.2.
- 8 patents applied, see §7.3.
- 6 workshops organized.
- 3 radio, 1 TV presentations and 1 press release.
- Twitter and LinkedIn accounts.

6.2 Contribution to standardization

5G-ALLSTAR included standardization activities for incorporation of technologies developed by the project in the 5G system definition, mainly at 3GPP. One of the project’s objectives was indeed to contribute to the definition of 5G system as part of the release 16 and beyond with the inclusion of 5G satellite access, mobile wireless backhaul and multiple access/connectivity.

The plan, as defined in [D6.5] was to leverage on going standardization on eMBB and 5G satellite access. Additional standardization activities in bodies such as ETSI, IEEE and ITU, have been considered in complement to 3GPP activities. Contributions have been provided to selected groups in order to support product adoption and interoperability developed in the context of the project [D6.7].

- Activity at 3GPP level. The 5G-ALLSTAR partners actively participated in the different 3GPP working groups that are working on V2X and on the integration of Non-Terrestrial Networks into future 5G Systems. Contributions to 3GPP included the submission of Temporary Documents (TDOCs), focusing on different topics in the relevant 3GPP working groups. Involved partners participated in RAN1, RAN2 and RAN3 activities. Also, contributions to SA working group 5 were submitted.
- Activities at ITU-R level. At 3GPP RAN Meeting #84, a liaison document on the integration of satellite solutions into 5G networks, was drafted to be sent to ITU-R Working Party 4B in response to ITU expressed interest to continue collaboration with 3GPP on this topic. The liaison document mentioning all the activities lead at this level by both RAN and SA Technical Specification Groups was co-signed by TAS.

6.3 Future collaborations

5G-ALLSTAR was the opportunity to consolidate the links between the European and Korean partners created during the 5GCHAMPION project. After the end of the project, the collaborations are expected to continue, through standardization actions, dissemination (organization of conferences, publications) or industrial partnerships, see [D1.4].

7 Bibliography from 5G-ALLSTAR

7.1 Deliverables

All public deliverables [Dx.x] are available https://5g-allstar.eu/results/deliverables/

[D1.5]	Impact report and future EU-KR collaboration plan
[D2.1]	5G-ALLSTAR vision document: Vision, Scope and Goals
[D2.2]	Preliminary document of 5G-ALLSTAR architecture, API and interface specifications
[D2.3]	Final document of 5G-ALLSTAR architecture, API, interface specifications and KPIs for PoC
[D2.4]	Final document of service scenarios/applications for PoC
[D2.5]	Business assessment for vertical markets empowerment
[D3.1]	Spectrum usage analysis and channel model
[D3.2]	Interference analysis for terrestrial-satellite spectrum sharing
[D3.3]	Interference mitigation techniques
[D4.1]	Mapping of multi-connectivity functions onto the 5G network architecture
[D4.2]	Design and simulation of the multi-RAT load balancing algorithms
[D4.3]	Implementation of the multi-RAT load balancing algorithms and technical specifications of the relevant interfaces
[D5.1]	Specification of the European testbed of 5G cellular and satellite access networks
[D5.2]	Integration and system level testing for European testbed of 5G cellular and satellite access networks
[D5.3]	Integration and system level testing for Korean testbeds of 5G cellular and satellite access networks
[D5.4]	Integration and system level testing for Korean multi-connectivity

[D5.5]	Integration and system level testing of proof-of-concept phase 1
[D5.6]	Integration and system level testing of proof-of-concept phase 2
[D6.5]	Standardization Action Plan
[D6.7]	Report on standardization activities Y2

7.2 Papers

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[Pat3]	G. Noh, S. Kim, I. Kim, J. Kim, J. Lee, H. Chung, D. Cho, S. Choi, S. Choi, and J. Choi	Method and apparatus for transmitting and receiving synchronization signal in communication system
[Pat4]	B. Jung, G. Noh, I. Kim, H. Chung, J. Yeom, and J. Yoon	Method and apparatus for interference mitigation based on beamforming
[Pat5]	S. Won, I. Kim, and H. Chung	Method and Apparatus for Adaptive Multi-Connectivity Selection based on Machine Learning Algorithm fitted to Radio Network
[Pat6]	J. Kim, S. Kim, I. Kim, G. Noh, H. Chung, D. Cho, S. Choi, S. Choi, and J. Choi	Method and apparatus for relay communication based on zone
[Pat7]	N. Cassiau, M. Laugeois	OFDM modulator for block-filtered OFDM transmitter, related block-filtered OFDM transmitter and transceiver system
[Pat8]	G. Noh, J. Kim, S. Kim, I. Kim, and H. Chung	METHOD OF SHARING ASSISTANCE INFORMATION BETWEEN SIDELINK UES