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5G-ALLSTAR: Beyond 5G Satellite-Terrestrial Multi-Connectivity

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Abstract—This paper presents a summary of the results of the 5G-ALLSTAR project. It describes the enablers that have been developed and validated and will help make 5G and beyond satellite-terrestrial multi-connectivity (MC) a reality in the near future. We proposed and evaluated solutions for critical aspects of the integration of non-terrestrial networks into a 5G and beyond terrestrial network. The OpenAirInterface implementation of the 5G physical layer (PHY) has been upgraded to meet the satellite radio channel constraints. We addressed the issue of co-tier interference between satellite and terrestrial systems. We designed and implemented customized 5G Physical layer, specifically adapted for terrestrial-satellite spectrum sharing. On top of the dedicated beam-forming and hardware design, we validated the full potential of MC by conceiving and testing our proposed resource allocation algorithms based on a custom multipath TCP protocol. The contribution of MC in vehicular use cases has been demonstrated onsite by implementing a terrestrial 5G PHY in conjunction with a satellite/terrestrial traffic controller. Finally, radio resource management solutions were examined. Thanks to these tools, the presence of industry partners in the consortium and to an active participation in standardization, the 5G-ALLSTAR project is an accelerator for the integration of non-terrestrial networks in 5G and beyond.

Index Terms—5G; multi-connectivity; UE satellite 5G direct access; terrestrial 5G access; traffic control.

I. INTRODUCTION

The European-Korean joint research project 5G-ALLSTAR (5G AgiLe and fLexible integration of SaTellite And cellular), 2018-2021, aimed to demonstrate satellite-terrestrial multi-connectivity (MC), a key feature to ensure 5G performance anywhere and anytime.

The integration of non-terrestrial networks (NTN) into terrestrial communication standards has been studied since the

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development of 4G. Today, after having released the first generation of 5G networks and planning research for 6G networks [1], convergence of these standards could not be achieved yet. The advent of 5G changed the game. Industry and academia reached the consensus that NTN will play an fundamental role in 5G and beyond standards: satellite, aerial, and terrestrial platforms will jointly enable connectivity and support of on-demand edge cloud and intelligence services also on rural areas and in the three-dimensional space [1].

Research activities and engineering of technology for making an operational reality the integration of satellite and terrestrial networks is recently exploding. Among these, the demonstrator in [2] and [3], from the ESA ARTES AT project SATis5, uses the 5G network core. Another ESA ARTES project, ASCENT [4], has conducted field trials of a system sharing satellite-terrestrial spectrum. The authors use interference measurements to free up occupied frequency resources that can be used by a predefined primary user. The H2020 5G-PPP project SaT5G [5] [6] demonstrates through measurements the possibility of 5G connectivity to mobile platforms (such as aircraft).

In contrast to the above-mentioned projects, which only consider the satellite as a backhaul link, and building on the 5GCHAMPION project findings [7], the 5G-ALLSTAR project focuses on demonstrating MC in the direct user-to-satellite access. Therefore, here we present original solutions and tools specifically dedicated to this goal.

The structure of the paper is as follows. Section II introduces the concepts of the project and how they translate into technological requirements. In the third section, each enabler developed in the project is described along with its means of demonstration. Finally, Section IV looks at the impact of the project.

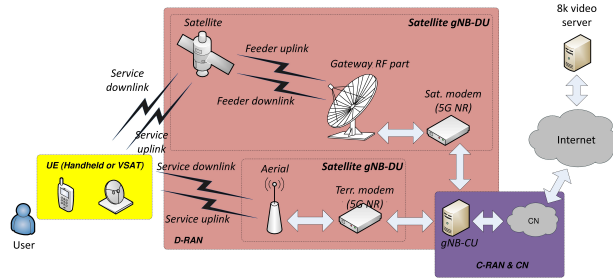


Fig. 1: 5G-ALLSTAR concept architecture

II. PROJECT CONCEPTS

5G networks are intended to be a mix of heterogeneous radio access technologies (RATs) and a variety of services/applications defined by the needs of vertical players (e.g. energy, transport, healthcare, content delivery, public safety/emergencies, etc.). Possible application domains comprise autonomous cars, massive wireless sensors, virtual/augmented reality (VR/AR), industrial automation, etc. These new services/applications are characterized by very different end-to-end requirements and each application entity has customized quality of experience (QoE) specifications based on context and user feedback. For example, VR/AR applications need to achieve high data throughput with minimal latency; Supporting large numbers of wireless sensors requires the ability to create and manage a multitude of links; Automotive and industrial automation applications need to be supported by a highly reliable and very low latency link.

These emerging services/applications will be enabled by a mix of tightly coupled existing and new RATs, encompassing cellular access such as 5G New Radio (NR), 4G LTE and WiFi, as well as non-terrestrial access such as satellite. Therefore, the tight integration and inter-working of various RATs, combined with the design of appropriate resource sharing algorithms, can enable the end-to-end needs of each application instance to be met while maintaining network efficiency, security, and scalability with the integration of 5G and non-5G RATs. This is referred to as an integrated multi-RAT network. In order to make such a network a reality, a number of concepts were identified in the project. These concepts are illustrated in Fig. 1, details and challenges are provided below.

A. Broadband and reliable access to 5G services for users

The first concept is 5G access everywhere. To this end, the feasibility of NR-based satellite direct access in the millimeter wave (mmWave) band to provide broadband and reliable 5G services will be demonstrated. Besides verifying the defined 5G satellite access architecture, which is currently being developed in the standardization organization 3GPP, works, the various challenges arising from the mobility of satellite and the propagation delay have to be solved appropriately. As for the terrestrial physical (PHY) layer, it needs to be designed to cope with mobility and should allow spectrum sharing with satellites.

B. Resource sharing

Due to the differences between terrestrial and non-terrestrial RATs, an important point should be to carefully select the most appropriate RAT layers and RAT network nodes in which the resource sharing functionalities should be embedded. In this regard, two concepts have been identified: resource sharing capabilities at Packet Data Convergence Protocol (PDCP) and higher layers referred to as multi-connectivity, and resource sharing capabilities at the PHY/Medium Access Control (MAC) layer, referred to as spectrum sharing.

1) *Multi-Connectivity*: MC enables a User Equipment (UE) to connect to multiple base stations simultaneously and thus user-plane data aggregation. MC can be realized through the same access links, between different access links, or even between different access technologies. In 3GPP LTE, a dual connectivity feature has been integrated in Release 13, allowing a UE to connect to two eNodeBs. This dual connectivity framework can be extended to inter-RAT aggregation, e.g., LTE-WLAN interworking. In the PHY layer and higher layers, dual connectivity affects synchronization, power control, and scheduling. Support for MC between 5G and LTE air interfaces has also been studied. The tight integration of 5G and LTE air interfaces is expected to meet several 5G requirements, including faster mobility and resource management [8]. A study was also conducted on inter-RAT MC between, for example, 2G/3G, LTE, and 5G networks. Identified new functionalities related to inter-RAT MC include among others RAT selection, operating mode selection, traffic management, control and data flow routing [9]. MC was also studied in ETSI TR 103 272 (Satellite Earth Stations and Systems ; Hybrid FSS satellite/terrestrial network architecture for high speed broadband access) and in TR 103 351 (Satellite Earth Stations and Systems ; Multi-link routing scheme in hybrid access network with heterogeneous links). The challenge is to manage unbalanced access links in terms of Quality of Service (QoS) including bandwidth, latency, error rate and jitter.

2) *Spectrum sharing*: To enable spectrum sharing, dynamic technologies and algorithms should be analyzed, designed and implemented. These include advanced MAC layer functionalities to handle the band overlap between different systems using the same or adjacent frequency bands and advanced PHY layer functionalities to manage interference, with the aim of ensuring a robust service thanks to advanced signal processing techniques.

C. Mapping to enablers

The above-mentioned concepts were mapped to technological enablers, see Table I. The goal of the project was to implement and verify these enablers in order to validate the concepts. The table shows how the enablers were demonstrated, either through software simulations, through implementation in local testbeds or in the final trial platform. Section III describes the work done for each enabler.

III. ENABLERS AND THEIR DEMONSTRATION

A. Satellite 5G direct access

5G-ALLSTAR provided direct satellite access to the 5G NR UE by developing a satellite-friendly modem based on OpenAirInterface (OAI). OAI is an implementation of the 3GPP mobile communications standards. It currently supports LTE UE, evolved NodeB (eNB) and Evolved Packet Core. The development of the 5G NR standards, starting with 3GPP Release 15, is ongoing. The main challenge for implementing the satellite-friendly modem was adapting OAI's NR procedures to the long-delay scenarios, e.g. for geostationary (GEO) satellites. For this purpose, the following features were developed during the project: (i) Extension of the K2 slot offset (i.e., the offset between the downlink (DL) slot for uplink (UL) scheduling and the corresponding UL data slot) to at least double the one-way delay between 5G Base Station (gNB) and UE; (ii) Introduction of an offset for UE Physical Uplink Shared Channel (PUSCH) transmission; (iii) Introduction of an offset for the transmission slot of DL Control Information scheduled PUSCH; (iv) Additional slot number equal to at least twice the one-way delay between gNB and UE; (v) Extension of the random access response window; (vi) Extension of the UL future Transmission Time Interval (TTI) request and the UL Virtual Resource Block (VRB) mapping; (vii) Increasing the Timing Advance update period; and (viii) disabling Hybrid Automatic Repeat Request processes.

The satellite modems were implemented on the same hardware (HW) for both UE and gNB, based on the Ettus USRP X300 Software Defined Radio platform equipped with a CBX-120 daughter board. The frequency range is tunable from 1200 MHz to 6000 MHz, channels bandwidth is available up to 120 MHz, and both Time and Frequency Division Duplex modes of operation are allowed.

Over-the-air tests were conducted using a GEO satellite. The UE performed the initial connection setup to the gNB using a specifically adapted random access method for 5G over satellite. After successful connection establishment, the 5G UL and DL transmission signals were decoded with QPSK and 16-QAM modulations. In addition, a smoothly functioning 5G timing advance procedure was tested to keep the UE synchronized to the gNB [10].

B. Terrestrial 5G access

1) *Waveform for spectrum sharing*: In the European testbed, Block-Filtered (BF)-OFDM was chosen as the wave-

form for the terrestrial link. This waveform was designed by CEA in 2016 [11]. The following characteristics made it a good candidate 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) and it can be configured in real-time per sub-band (hence supporting multi-service scenarios). The challenge in 5G-ALLSTAR was to provide a broadband (up to 400 MHz) HW implementation of BF-OFDM on a Xilinx Radio Frequency System-On-Chip (RF-SOC) platform from the ground up. In achieve this, a number of obstacles were overcome: (i) the support of multiple configurations and parameters, (ii) the high bandwidth in terms of board clock frequency and (iii) the intrinsic complexity of the waveform. The provided solutions are described in [12]. The transceiver has proven to be fully functional with tunable parameters such as bandwidth, numerology, Modulation and Coding Scheme (MCS) and active sub-bands.

The smooth transmission of a low-latency VR tennis game plus an 8K video stream through the terrestrial testbed was demonstrated over-the-air in the 26 GHz band with a tx-rx distance of around 3 m using 10 dBi horn antennas [17].

2) *mmWave vehicular communications air interface*: Our Korean partners have developed a mmWave 5G NR vehicular communication system that provides a mobile broadband access point on board a vehicle for a large number of passengers such as a bus. The wireless backhaul air interface basically conforms to the specifications of 5G NR Release 15. Considering the mobility of the vehicle, the physical layer is designed to support a high subcarrier spacing of 60 kHz and a dense allocation of the Demodulation Reference Signal in the time domain to compensate for the high Doppler effect [18]. Maintaining backhaul connectivity between the vehicle and the network is made more difficult in the considered highway and urban road target deployment scenarios, since the vehicle's direction of travel can change, for example during overtaking maneuvers or when driving around a curve. To address these challenges, the system is further designed to support an open-loop beam switching technique dedicated for vehicular communications. The details of beam switching are discussed further in Section III-E. In addition, several techniques such as 2x2 Multiple Input Multiple Output transmission with linearly-polarized antennas and fast handover have been implemented.

To validate the feasibility and effectiveness of the mmWave vehicular communication system, a prototype system was implemented, and field tests were conducted in urban and highway environments. The tests results showed that the

TABLE I: Project concepts, enabling technologies and means of demonstration

Concept	Enabling technology	Sim.	Testbed	Trial
Provide broadband and reliable direct to UE 5G services.	Satellite friendly 5G NR PHY & MAC		✓	
	5G NR terrestrial PHY		✓	✓
Implement multi-connectivity support and integrate 5G Terrestrial and Satellite access systems.	Traffic Load Balancing	✓		
	Traffic Control		✓	✓
Enable Terrestrial and Satellite access to share the same spectrum.	Dual beamforming		✓	✓
	High OoB rejection waveform	✓	✓	✓
	Radio Resource Management	✓		

NOTE: Sim., Testbed and Trial respectively stand for demonstration by software simulations, by implementation in a local testbed and by trials.

system with the developed technologies is capable to provide broadband wireless connectivity between the vehicle UE and the gNB, enabling the realization of the target service [17]. However, during the field testing, it was observed that there is performance degradation depending on vehicle locations, mainly due to line-of-sight signal blockage, which is more significant in the high-frequency mmWave band. Therefore, to complement blocking problem of the mmWave cellular system and to ensure service continuity, the support of MC between cellular and satellite networks is also realized, the details of which are described in Section III-D.

C. Traffic load balancing

Resource sharing at the PDCP and higher layers are made possible by MC functionalities. The 5G-ALLSTAR project analyzed, designed and simulated multi-RAT load-balancing algorithms that decide about traffic steering between the available RATs. These algorithms are:

- Cognitive (i.e. context-aware), since they are expected to take their decisions on the basis of the present performance in terms of the Key Performance Indicators - defined for the various use cases - measured in the candidate RATs; thus proper sensing (i.e. monitoring) functionalities able to provide real-time measurements on the present RAT status should be foreseen.
- Personalized, since they need to make their decisions to meet the specific end-to-end Service/Application Requirements as well as the personalized end-to-end Quality of Service/Quality of Experience requirements of the running applications (the latter are reduced by an ad-hoc Personalization System).
- Dynamic, since they are expected to change their decisions in real-time depending on the current RAT state and the dynamics of the traffic generated by the running applications they support.

Load balancing algorithm decisions are made by adopting sophisticated methodologies such as optimization techniques and learning algorithms [13] [14]; These decisions concern link aggregation (i.e., the use of multiple RATs to support a specific flow, e.g., to enhance the throughput), the split of each flow among the selected RATs in appropriate percentages, the triggering of vertical (inter-RAT) handovers induced by interference and/or traffic, the QoS requirements to be satisfied by each underlying RAT for each specific flow, etc.

Adaptive Video Streaming clients and servers were used to validate the algorithms [19]; Two virtual machines (VMs) have been set up (one for the server and one for the client). The Server VM was connected to the Client VM via two (virtual) paths emulating satellite paths (with high delay) and terrestrial paths. Developing such functionality required addressing several issues, including adapting the open standard Multipath TCP (MPTCP) mechanism. To prove that a Multipath implementation makes it possible to determine the quota of data to be sent over multiple links in user space (satellite and 5G), a modified version of MPTCP's round-robin scheduler was implemented in the project. It has been shown

that the Traffic Flow Controller dynamically changes and the custom MPTCP satellite / terrestrial quotas in real-time, as expected, and that the video streaming is able to reach highest quality level.

D. Traffic Control

The MC functionality of the Korean testbed is based on an Internet Protocol (IP) layer traffic aggregation of heterogeneous networks consisting of a satellite network and a cellular network. An active GEO satellite (i.e., Koreasat-6) is used for the MC tests, using a digital video broadcasting waveform common to commercial satellite service networks. The cellular network adopts the 3GPP Release-15 standards as the basis for implementation. The cellular and satellite networks are integrated with an IP layer traffic controller (TC) located at the UE side.

The MC functionality operates on a vehicle UE associated with the TC. Note that the TC module is located at the UE side to provide uninterrupted connectivity with the vehicle UE. In TC configuration, all the packets are duplicated from an application server to the TC over both satellite and cellular links, and one stream is selected from two output streams of the TC. With the redundancy from duplication, the overall reliability in transferring data is improved, facilitating service continuity in video streaming, for example. To further improve data throughput or reduce latency, in addition to the TC functionality at the UE side, sophisticated algorithms for load balancing or packet splitting at the network side can also be considered.

Another feature of the Korean MC concept concerns the asymmetry in data throughput between the cellular and satellite networks. The cellular access network can allocate a total bandwidth of 300 MHz to a vehicle UE, whereas the satellite access network can only allocate up to 2 MHz, which is proportional to the available budget for the commercial service. With the above difference in allocated bandwidths, the cellular access path can support high-definition video streaming services like 4K, whereas the satellite access path has some video quality and latency limitation. Therefore, the service scenarios of this use case have taken this reality into account.

The MC concept was validated in trials with a mini-bus connected simultaneously to a 5G gNB and an operating satellite [20]. Voice over IP (VoIP) and video conferencing services have been tested and satisfactory results have been shown.

E. Beamforming

The project investigated a dual beamforming (BF) technique that can mitigate interference between the satellite and cellular networks. The goal was to introduce a way to improve the communication quality of the cellular network while limiting the overall interference from the cellular base stations to the satellite Earth station to a certain level. Considering a realistic satellite-cellular sharing scenario with both satellite and cellular links operating in the DL, the proposed BF

technique attempts to maximize communication performance while the amount of maximum allowable interference at the satellite Earth station is limited to a predefined level. More specifically, a combination of Zero Forcing (ZF) BF using the null space of the interference channel and Maximum Ratio Transmission (MRT) BF is provided, which can maximize the channel gain of the cellular link. The proposed dual BF has been shown to outperform BF schemes based on either MRT BF alone or ZF BF alone [15] [16].

As a simpler form of BF functionality, a UE-centric beam switching scheme was implemented in the Korean testbed. The beam switching functionality is embedded in a vehicle UE within a cellular network. Every 240 ms, based on the measurement results, the best beam is selected from three beam set candidates for communication. In addition, beam switching not only makes it possible to find the best beam that delivers the strongest received signal power, but also reduces the effects 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 to discriminate between the desired signal and interference.

F. Radio Resource Management

With 5G-ALLSTAR, a concept was researched that is based on a dynamic coupling of both cellular and satellite access at Radio Resource Management (RRM) in order to ensure safe coexistence of both systems. This required investigating the parameters (e.g. spectrum partitioning, flux density, transmission power, antenna characteristics) to be exchanged between the RRM schemes of both access technologies concurrently accessing the same spectrum. The RRM has been defined considering the most relevant interference scenarios related to the typical satellite system deployment foreseen for 5G system (3GPP TR38.811). Great care has been taken to integrate joint RRM schemes into the 5G system/radio access network architecture and comply as much as possible with the relevant protocols/interfaces specified by 3GPP (e.g. F1, X2 interfaces). A possible extension of Enhanced Inter-Cell Interference Coordination, an interference control technology, to Hetnets that takes satellite components into account was considered to mitigate interference from inter-access (cellular/satellite) technologies and the need to modify the relevant protocols was evaluated.

An NS-3 based simulator was developed to evaluate different schemes [21]. Interference on the terrestrial and non terrestrial entities were modelled. Conclusions were drawn and recommendations for implementation in testbeds were provided.

IV. IMPACT

A. Socio-technological and socio-economic impacts

Part of 5G-ALLSTAR's efforts have been devoted to 5G business assessment and exploitation towards vertical stake-

holders. We have first provided an overall summary of the current state of 5G market in 2020. We have found that mainstream adoption of 5G is still very limited; even industry presents itself in its early stages. The gaps and challenges structuring the current supply and market, some of which may be related to possible applications from 5G-ALLSTAR innovations, have been identified. A second time, we discussed the emerging configurations based on both a desk analysis of the available literature and studies, and direct interviews conducted with key informants while implementing qualitative methods. Two rounds of interviews were conducted by our panel of experts, selected based on criteria such as relevant experience in the field, expertise, knowledge of 5G and business models and an insight into trends within 5G for Business to Business 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 and promises while managing tensions and synergies to provide a holistic view of what the upcoming 5G business models in industry is to be expected. For data analysis, we coded our interviews with NVivo. These codes were reassembled to develop concepts that led to the identification of the main topics of discussion elaborated in the results. Finally, based on the Joint Analysis literature, available cases, and interviews, we discussed the opportunities for 5G-ALLSTAR technologies in the identified vertical markets (transport, public safety, rural area), and helped to define viable strategies with regard to the different aspects of business models. The interested reader is referred to [22].

B. Standardization

5G-ALLSTAR included standardization activities to incorporate technologies developed within the project into the 5G system definition, mainly at 3GPP. Indeed, one of the goals of the project was to contribute to the definition of the 5G system as part of Release 16 and beyond by including 5G satellite access, mobile wireless backhaul and multiple access/connectivity. The plan was to leverage ongoing standardization for eMBB and 5G satellite access. Additional standardization activities in bodies such as ETSI, IEEE and ITU, have been considered in complement to 3GPP activities. Submissions were made to selected working groups to support product adoption and interoperability developed within the project, e.g. R1-1908811 and R1-1908810 focus on physical layer techniques and sidelink synchronization for NR V2X.

V. CONCLUSION

The tools discussed in this paper were presented during a final intercontinental proof-of-concept demonstration, see Fig. 2. Players ①② and spectators ④ enjoyed a VR tennis game in France and Korea while being filmed ③⑤. Both sites benefited from terrestrial / satellite dual-connectivity (emulated satellite in France). Details on the demonstration can be found in

[17]. This scenario enabled the validation of low latency (VR tennis game) and high-throughput (8K video streams ⑥⑦) 5G transmission in real-world conditions, leveraging the best of both networks.

Thus, over a period of forty months, the 5G-ALLSTAR project has designed, developed and demonstrated technological building blocks that have validated the original concept of satellite-terrestrial multi-connectivity for 5G and beyond. This work paves the way for full seamless and transparent three-dimensional coverage of the globe.

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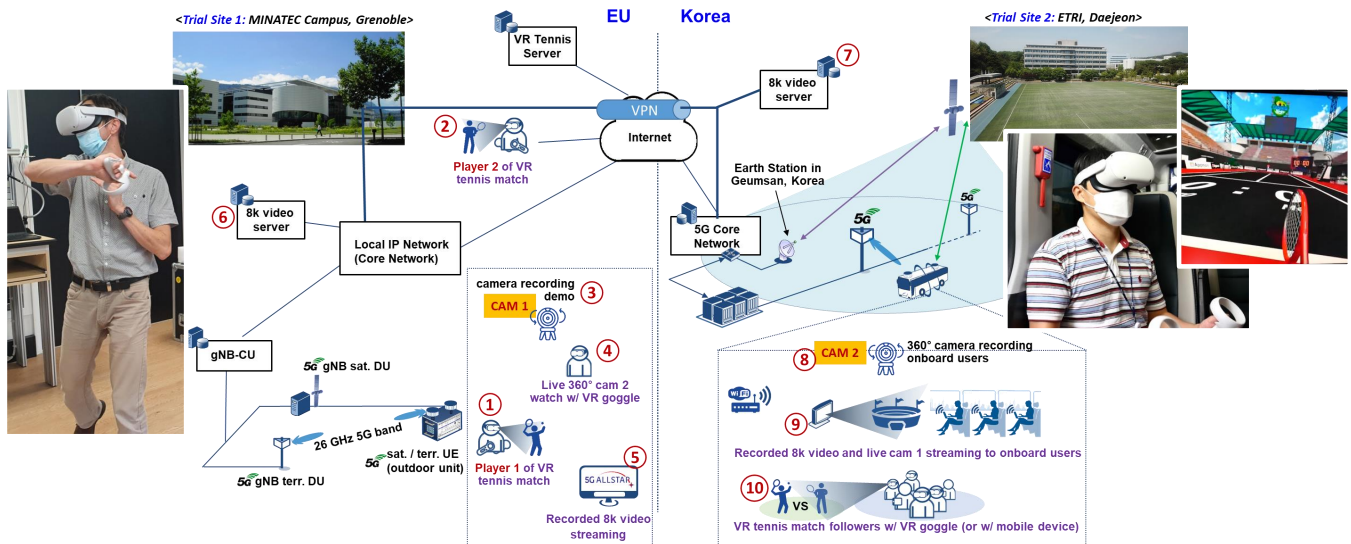


Fig. 2: 5G-ALLSTAR final demonstration scenario