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Design of cellular, satellite, and integrated systems for 5G and beyond

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5G AgiLe and fLexible integration of SaTellite And cellulaR (5G-ALLSTAR) is a Korea-Europe (KR-EU) collaborative project for developing multi-connectivity (MC) technologies that integrate cellular and satellite networks to provide seamless, reliable, and ubiquitous broadband communication services and improve service continuity for 5G and beyond. The main scope of this project entails the prototype development of a millimeter-wave 5G New Radio (NR)-based cellular system, an investigation of the feasibility of an NR-based satellite system and its integration with cellular systems, and a study of spectrum sharing and interference management techniques for MC. This article reviews recent research activities and presents preliminary results and a plan for the proof of concept (PoC) of three representative use cases (UCs) and one joint KR-EU UC. The feasibility of each UC and superiority of the developed technologies will be validated with key performance indicators using corresponding PoC platforms. The final achievements of the project are expected to eventually contribute to the technical evolution of 5G, which will pave the road for next-generation communications.

KEYWORDS
5G-ALLSTAR, millimeter-wave, multi-connectivity, new radio, satellite communications, vehicular communications

1 | INTRODUCTION

The fifth generation (5G) phase one (5G phase 1) of the mobile communication standard developed by the 3rd Generation Partnership Project (3GPP), 5G New Radio (NR) Release 15 (Rel-15), was approved in December 2017, and 2019 was the year of the first commercial launch of 5G NR services based on 5G phase 1, the 3GPP Rel-15 specification. The basic ingredients of 5G NR are (a) the use of a *new spectrum* in the range of 2.5 GHz to 40 GHz (potentially up to 86 GHz) and a common interface design for the 5G frequencies, (b) *flexible numerology* that allows subcarrier spacing and slots to be respectively scaled by $2^{\mu} \cdot 15$ kHz and $2^{-\mu} \cdot 1$ ms for a wide variety of 5G services, $\mu \in \{0, 1, 2, 3, 4\}$, (c) *flexible slot configuration* that supports not only dynamic time division duplexing but also mini-slots, (d) a *multi-antenna technique* supporting beamforming transmission assisted by a beam management mechanism to optimize the signal transmission to the intended receiver and to mitigate interference and single-user/multi-user multiple input multiple output (SU-/MU-MIMO) transmission to achieve spatial multiplexing and diversity gains, (e) *high-mobility support* providing high-quality 5G services to users traveling at speeds of up to 500 km/h (such as high-speed trains), and (f) *network densification and the use of small cells*.

Meanwhile, extensive proof of concepts (PoCs) of potential 5G technologies have been successfully delivered at local, national, and intercontinental scales since 2018 [1] to prove that 5G has the potential to provide communications for very high-bandwidth transmissions like ultra-high definition (UHD) video streaming, low-latency communications for remote control, millimeter-wave (mmWave) railway communications, and low-bandwidth communications for machine-type communications. In particular, the use of the mmWave spectrum for 5G services and use cases (UCs) has been discussed from technical [2], standardization, and economical angles [3].

Today, the 5G community is now looking to translate 5G UCs and meet vertical industry requirements, and has ambitions to adopt 5G in viable business cases. However, the support of new 5G and beyond-5G services as well as seamless connectivity across various vertical industries and highly diverse UCs still requires the integration of multiple radio access technologies (RATs) [4]. The tight interworking and integration between different RATs will be beneficial for providing improved coverage and service continuity in a cost-effective manner, especially with respect to robust, seamless, and continuous wireless services for critical applications such as public safety and emergency communications. Thanks to the wider service coverage and a significant reduction in vulnerability to physical attacks or natural disasters; satellite communications are perceived as a promising RAT that can bring significant benefits to 5G services through integration with various types of RATs. Satellite communications can also provide complementary connections to mmWave-band cellular communications, the links of which are vulnerable to line-of-sight (LoS) signal blockage or beam misalignment.

For these reasons, research on the integration of cellular and satellite networks has been actively conducted recently, and most of these studies have investigated possible integration based on the current 5G specifications. In [5], the authors proposed a dynamic hybrid terrestrial and satellite backhaul network supporting coverage expansion and capable of alleviating the terrestrial congestion by traffic offloading; they performed an initial analysis on the routing and load balancing for the networks. The authors of [6] provided a brief review of current initiatives and challenges for 5G satellite integration facilitated by software defined networking/network function virtualization (SDN/NFV) and showed the applicability of network coding in the integrated network, and the authors of [7] addressed a framework unifying satellite and 5G networks by utilizing standards-based interfaces with reuse of components in 5G core networks and a multimode user terminal. In Refs [8] and [9], possible architecture options for 5G-satellite integration were discussed. The authors of [8] further analyzed the impact of typical satellite channel impairments, which is one of the critical bottlenecks in the realization of a 5G satellite network. Moreover, they compared cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) and filtered OFDM in terms of out-of-band-emissions, and highlighted a technical challenge of hybrid automatic repeat request (HARQ) procedures due to the large delays. In [10], the authors delivered an over-the-air demonstration using a satellite backhaul network integrated with the 3GPP Rel-15 5G core network.

Meanwhile, 3GPP has been working on new releases, Rel-16 (known as "5G phase 2," to be completed in June 2020) and beyond, to introduce advanced features that include multi-RAT interoperability and NR-based non-terrestrial networks (NTNs). The scope of the NR NTN is to identify solutions for physical layer (PHY) control, random access, retransmission schemes from the RAN1 perspective, and to study medium access control (MAC), radio link control (RLC), and radio resource control (RRC) layers and handover impacts from RAN2 and RAN3 perspectives [11]. NR-based NTN standardization in the 3GPP RAN Working Group (WG) began with the approval of the Rel-15 study item (SI) for RAN plenary and RAN1 at the RAN plenary meeting (RAN#75) in March 2017 [12]. The purpose of the SI was to study the channel model of NTN, NTN scenarios, and the impact of NTN on the NR specifications, and the results were reported in technical report (TR) 38.811 [13]. In this TR, the impacts of NTN on the NR specifications were identified, which motivated the approval of the new Rel-16 SI at the RAN#80 meeting in June 2018 [14]. This SI studies the necessary functions of the NR protocol for NTN in

RAN1, 2, and 3 by March 2020, and the results are included in TR 38.821 [15]. In addition, the service and system aspects (SA) SA1 investigated the requirements for satellite access as part of Rel-16 SI from September 2017 to June 2018, which was reported in TR 22.822 [16] and was reflected as the requirements of the 5G system in the technical specification (TS) 22.261 [17]. Meanwhile, SA2 worked on TR 23.737 [18], specifying architecture for satellite access in 5G, from June 2018 to September 2019, and in SA5, the management and orchestration of integrated satellite components in 5G networks has been underway since March 2019 with TR 28.808 [19]. In addition, in 3GPP RAN3, multi-connectivity (MC) between non-terrestrial and terrestrial next-generation radio access networks (NG-RANs) as well as MC between two different NTN-based NG-RANs has been studied within the NTN SI [20], and several potential architectures and the impact on NG-RAN have been included in TR 38.821 [15]. MC can be simply defined as a scheme that allows a certain user equipment (UE) to establish at least two different traffic links. Hence, the service performance of UE can be improved by applying a dynamic load balancing over the established links.

In this context, a new joint Korea-Europe (KR-EU) project named 5G AgiLe and fLexible integration of SaTellite And cellulaR (5G-ALLSTAR) [21], which leverages the outcomes of a previous KR-EU joint project [1,22], has been launched to design, develop, and experimentally evaluate the following set of key technologies to support system interoperability, global service connectivity (such as for critical applications), and 5G applications of interest to both the EU and KR regions:

1. mmWave-band cellular access systems (ie, 5G NR-based vehicular communications) for providing users (eg, onboard passengers) with broadband and low-latency 5G services;
2. the feasibility of NR-based satellite access for providing broadband and reliable 5G services;
3. MC technology that integrates cellular and satellite networks with interoperability support controlled by the same 5G RAN to support seamless, reliable, and ubiquitous broadband services;
4. spectrum sharing between cellular and satellite networks.

This article aims to provide an overview of our latest research on the technologies listed above, mainly focusing on the architectural framework, PoC design, and key technical solutions with some preliminary results, which are the main contributions distinct from exiting studies.

The remainder of this article is organized as follows. In Section 2, we present the basic high-level architecture and representative UCs of the project. Next, in Section 3, the overall design of the PoC is presented, including the architecture and interface design of PoC platforms and further detailed descriptions of the UCs and target key performance indicators (KPIs) to be demonstrated. In Section 4, key technologies that are part of the technical concepts of the project and will be possibly implemented on the PoC platforms and the preliminary results are described. Finally, Section 5 concludes the article.

2 | OVERALL ARCHITECTURE AND REPRESENTATIVE UCs

The overall high-level 5G-ALLSTAR architecture is depicted in Figure 1. On the basis of the current vision of 5G architectures [23], it is designed to further support a flexible integration between 5G cellular access and satellite access networks with particular focus on the radio resource management (RRM) and traffic flow control.

The system architecture is composed of standardized 5G network components, which are the data network (DN), core network (CN), cloud RAN, and UEs. The DN is an entity involved in providing private and public data (eg, documents or movie content), and the CN is further designed to introduce advanced quality of experience/service (QoE/QoS) management functionality. The UE can be any device such as mobile devices carried by pedestrians or vehicle UEs (V-UEs) and can establish simultaneous connections to multiple RATs (ie, gNB-DUs) with MC capability. As shown in Figure 1, both GEO and low earth orbit (LEO) satellites are supported, and as presented in TR 38.821 [15], the satellites can be divided into two types. One is a transparent satellite in which the satellite payload is relayed by an analogue radio frequency (RF) repeater that implements frequency conversion and an RF amplifier in both the uplink and downlink, and the other is a regenerative satellite in which the satellite receives the signals from the earth station and the regenerated payload is transmitted.

With the cloud RAN, as depicted in Figures 1 and 2, the system is largely composed of a centralized RAN (C-RAN) and distributed RAN (D-RAN). As shown in Figure 1, a centralized unit (CU) of gNB (gNB-CU) in the C-RAN is interconnected with multiple distributed units (DUs) of gNB (gNB-DUs) in the D-RAN. The gNB-CU supports coordination and control capabilities, enabling a faster and efficient centralization of the traffic flows for functionalities of the control plane (CP) and user plane (UP), and the gNB-DUs are responsible for functionalities monitoring and estimating radio performance and actual QoS. Among the eight functional split options specified in TR 38.801 [24], the packet data convergence protocol (PDCP) split, identified as option 2 in the TR, is prioritized, although other options are not precluded. This split, already implemented in long-term evolution (LTE) dual connectivity, allows connection switching

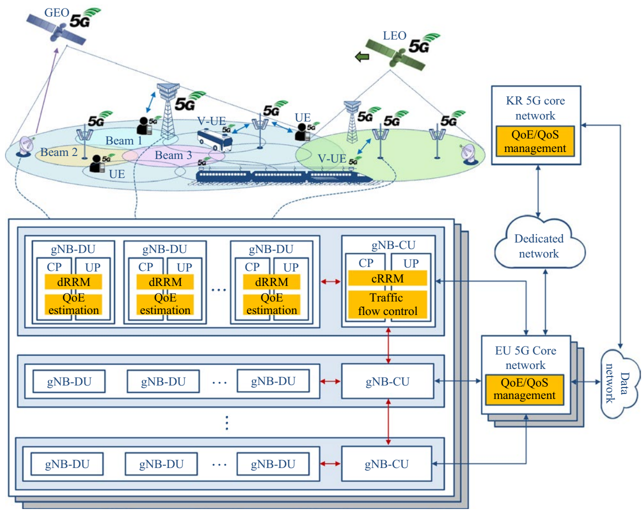

FIGURE 1 General architecture and key functionalities of the 5G-ALLSTAR system

and aggregation at PDCP level, facilitating management of the traffic load between RATs, without the low latency and high throughput required in intra-PHY or PHY-MAC splits.

The integration of the 5G-ALLSTAR MC system with the 3GPP network functionalities is one of the fundamental aspects that have been considered. As specified in [25], the 3GPP connection process includes two fundamental steps: (a) the mapping of application data (protocol data unit (PDU) session data) in QoS flows and (b) the mapping of QoS flows in the access resources. This approach, however, does not exploit user and application information in the RAN during the resource assignment, which hampers the possibility of lower-level resource assignment in a QoE fashion. Therefore,

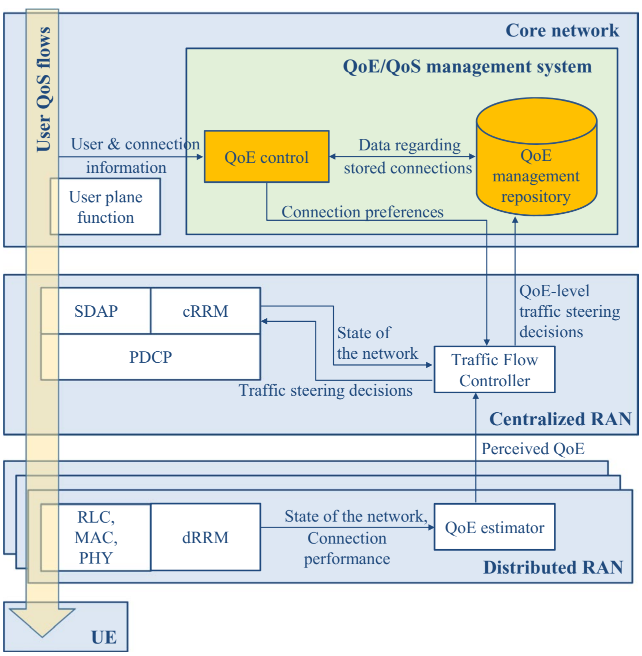

FIGURE 2 Functional architecture of the 5G-ALLSTAR MC

we improve this aspect by introducing advanced functionalities supported at CN and RAN, which are RRM both at the gNB-CU and gNB-DU, QoE/QoS management at the CN, QoE estimation at the gNB-DU, and traffic flow control at the gNB-CU. These functionalities allow the system to take advantage of user and application information in the RAN, thereby allowing provider connections and user information, typically managed in the CN and used for the PDU session-to-QoS flow mapping according to the 3GPP standard, to be processed and enriched with QoE/QoS management to facilitate resource assignment in the RAN.

More specifically, Figure 2 shows the proposed functional architecture of the 5G-ALLSTAR MC system by illustrating the flow of data through all the protocol layers [26,27]. As depicted in the figure, the RAN is connected to the CN, more specifically to the user-plane function (UPF), and the UP protocol stack in the RAN(C-RAN and D-RAN) consists of PHY, MAC, RLC, and PDCP layers [28]. The service data adaptation protocol (SDAP) located above PDCP mainly handles the mapping between a QoS flow and a data radio bearer. The SDAP layer accepts one or more QoS flows carrying IP packets according to their QoS requirements. The RRM functionalities are mainly responsible for the spectrum sharing of multi-RAT, where algorithms for interference analysis and mitigation are implemented. The RRM functionalities are deployed at both the gNB-CU and gNB-DU, respectively, as centralized RRM (cRRM) and distributed RRM (dRRM). The QoE estimator provides the estimation of the individual perceived QoE based on the information provided by the user via explicit or implicit feedback and on the measurements provided by the dRRM. The QoE/QoS management, logically located in the CN, is designed to compute/estimate the proper personalized *Connection Preferences* of each UE and assign a set of personalized parameters (in addition to the QoS Flow Identifier (QFI)) for each traffic flow depending on the learned UE needs and expectations. These *Connection Preferences* specify the user's needs not in terms of additional QoS constraints, but in terms of a personal user's preferences expressed over a set of non-standardized parameters such as battery consumption, connection cost, and mobility. The stored information, used for Traffic Flow Control, is updated based on user's feedback at the end of each connection.

To sum up, to satisfy the *Connection Preferences* of each user in the best possible way, the traffic flow control, managed by the gNB-CU, makes switching, steering, and splitting decisions in terms of traffic and network resource management based on the personalized parameters and the actual performances of the RATs, which includes

- RAT performances (network status) directly provided by the cRRM;
- the *Connection Preferences* provided by the QoE/QoS management;

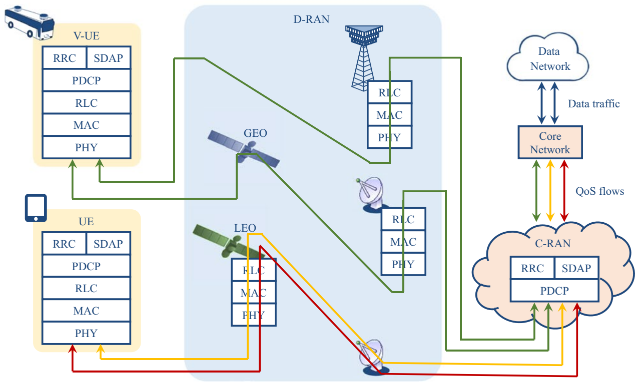

FIGURE 3 Example of an MC operational scenario

- the QoE estimated during the connection for a real-time traffic control, provided by the QoE estimator;
- the QoS requirements for each user.

The QoS requirements are the QoS parameters for a specific QFI also included within the QoS profile and delivered to the RAN with the standardized CN functionalities. The QoE level can be used by the flow control as an additional input for the selection of its access point (AP) and traffic steering decisions.

Figure 3 shows an example of an MC operational scenario. In this scenario, the functionalities of the architecture with two PDU sessions are illustrated. Based on the estimation and acquisition of parameters (eg, the network state) described above, the first PDU session (the green line in the figure) is duplicated over two different APs belonging to different RATs, so that the connection resiliency is increased. The second PDU session is made up of two different QoS flows (red and yellow lines in the figure) that they can be routed independently from one another in order to satisfy their QoS requirements accordingly.

The architecture and functionalities discussed above would be beneficial in a variety of service scenarios, as described in TS 22.261 [17], and are promising for 5G verticals such as transport, public safety, media and entertainment, eHealth, energy, agriculture, finance, and automotive applications [13]. Among the service scenarios and potential verticals, we identified several relevant UCs in [29], and the following four representative UCs were chosen for PoC:

- **UC1:** broadband moving hotspot network;
- **UC2:** simultaneous satellite and cellular MC;
- **UC3:** public safety;
- **UC4:** intercontinental interoperability.

3 | 5G-ALLSTAR PoC

The objective of the PoC is to deliver technical demonstrations verifying the feasibility of the representative UCs

TABLE 1 Overall target KPI verification during the 5G-ALLSTAR PoC stage

		Evaluation methodology	
KPI	Target performance	Simulation/ testbed	Field trial
KPI0	50 Mbps on downlink and 10 Mbps on uplink	✓	✓
KPI1	Below 10 ms for delay-sensitive traffic	✓	✓
KPI2	<20 ms	✓	
KPI3	99.999% success probability of transmission	✓	
KPI4	No service interruption[a]		✓

KPI0, User-experienced data rate; KPI1, User-plane latency; KPI2, Control plane latency; KPI3, Reliability; KPI4, Service continuity.

[a]Verifying zero service interruption when one of a link (eg, cellular) fails abruptly or disappears due to mobility (eg, in rural areas).

and the enabling technologies satisfying the KPIs listed in Table 1. Table 1 defines the overall target KPIs and their evaluation methodologies, and the KPIs are specified based on [30] as essential requirements to meet during the PoC.

The PoC is divided into two phases. During the first phase, we plan to build different types of PoC systems and use them to demonstrate the corresponding UCs. In particular, for the EU PoC, two different types of PoC systems, implemented as a testbed (EU-Testbed) and trial platform (EU-Trial), respectively, will be used to perform technical demonstrations of UCs 2 and 3, while in KR, two trial platforms (KR-Trial0 and KR-Trial1) will be developed for the demonstration of UC1. After the demonstrations of UCs 1 to 3 are complete, the second phase of PoC will be initiated to conduct the final joint PoC demonstration using an integrated KR-EU PoC platform (Joint-Trial) at a key event (eg, Roland-Garros 2021) to provide our 5G experiences to visitors.

More specifically, as summarized in Table 2, each UC is composed of two UC scenarios (UCSs). A UCS may be seen as a demonstration scenario in which the UC is realized through a set of key technologies developed in the project. Table 3 lists the technical concepts that represent the main research scope of the project and show its mapping to the corresponding UCs. A technical concept may entail one or multiple key technologies developed within the scope of the technical concept, and thus, the demonstration of a UCS also corresponds to the validation of part of the technical concepts.

Table 3 also shows the mapping of technical concepts to the PoC platforms used for its validation. The concepts will be verified by the corresponding PoC platforms with the exception of two concepts, spectrum sharing, and interference

TABLE 2 UCs and UCSs for PoC

UC	UC description	UCS	UCS description
UC1	Broadband moving hotspot network	UCS1.1	Beam switching for mmWave-band vehicular communications
		UCS1.2	Cellular and satellite MC for mmWave-band vehicular communications
UC2	Simultaneous satellite and cellular MC	UCS2.1	Simultaneous cellular and satellite access with enhanced total throughput
		UCS2.2	Simultaneous satellite non-stringent QoS services and cellular stringent QoS services delivery to UE
UC3	Public safety	UCS3.1	Unpredictable traffic switching
		UCS3.2	Predictable traffic switching
UC4	Intercontinental interoperability	UCS4.1	Virtual-Reality (VR) tennis game
		UCS4.2	VR tennis followers

TABLE 3 Mapping of technical concepts to UCs and platforms

	UC				PoC platform					
Technical concept	UC1	UC2	UC3	UC4	KR-Trial0	KR-Trial1	EU-Testbed	EU-Trial	Joint-Trial	Simulation
Spectrum sharing										✓
Interference management										✓
Beam switching	✓			✓	✓	✓			✓	
Link aggregation		✓		✓			✓	✓		
Traffic steering / switching		✓	✓	✓			✓	✓	✓	✓
Traffic splitting	✓		✓			✓	✓			✓
Inter-RAT RRM		✓	✓	✓			✓	✓	✓	✓
Prototyping for mobile backhaul	✓			✓	✓	✓			✓	
Prototyping for 5G NR-based satellite access		✓	✓	✓			✓	✓	✓	

management, which are being studied through simulations and are detailed in Section 4.3.

3.1 | KR PoC

KR PoC will be conducted to showcase two UCSs of UC1 with two trial platforms, KR-Trial0 and KR-Trial1.

3.1.1 | Use case description and target KPIs

KR PoC platforms, KR-Trial0 and KR-Trial1, aim to demonstrate UC1 by showcasing various broadband and reliable services provided to passengers on a moving vehicle. In this UC, the moving vehicle is a vehicle carrying a large number of passengers, such as a bus. The UC is composed of two UCSs, UCS1.1, and UCS1.2. UCS1.1 demonstrates mmWave-band vehicular communications with a developed beam switching technique through KR-Trial0, and UCS1.2 focuses on the feasibility and superiority of MC technology using KR-Trial1.

More specifically, UCS1.1 with KR-Trial0 demonstrates that in urban and highway scenarios, with the developed beam switching technique, broadband and reliable mobile wireless backhaul links can be maintained for moving vehicles even when overtaking or driving on a curve, which allows onboard passengers to enjoy their in-vehicle mobile services (eg, broadband Wi-Fi services and 3D/UHD video streaming). However, mmWave-band vehicular communications in KR-Trial0 are vulnerable to unexpected blockages by vehicles or/and various structures (eg, buildings) around the transceiver, which cause very critical performance degradation. In addition, in rural scenarios like highways, because of the limited deployment of network infrastructure, the quality of a terrestrial link is insufficient to provide satisfactory performance. For these reasons, UCS1.2 is demonstrated by implementing an MC technology in KR-Trial1 and evaluating the KPIs related to reliability and service continuity to show the benefits of this MC technology. The enabler for this MC technology is traffic splitting. Traffic splitting is a function that performs the duplication of a traffic flow over two (or potentially more) different RATs, which can increase the connection reliability and satisfy stricter QoS requirement for certain services.

3.1.2 | System design

As depicted in Figure 4, the KR PoC platform is mainly composed of two systems, the moving network system (MNS) and satellite system (hereinafter referred to as SAT). KR-Trial0 corresponds to the MNS, and KR-Trial1 is a trial platform that supports MC functionality by additionally integrating the SAT and traffic controller (TC) with the MNS. The KR-Trial1 includes five main subsystems, the MNS core network subsystem (MNS-CNS), MNS radio access subsystem (MNS-RAS), MNS vehicular equipment subsystem (MNS-VES), SAT-RAS (SAT-RAS), and SAT-VES (SAT-VES) as well as one system component, TC. To support the cloud RAN functionality, the MNS-RAS is designed to have a CU with multiple DUs, and the MNS is an mmWave-band 5G NR vehicular communication system, the detailed design of which is presented in Refs [31,32]. The SAT-RAS is composed of a GEO satellite and an earth station. The TC, as part of MC functionality, plays a pivotal role in switching between traffic received from the two VESs, MNS-VES, and SAT-VES. A more detailed description of the KR PoC system design is given in deliverable D2.3 [27].

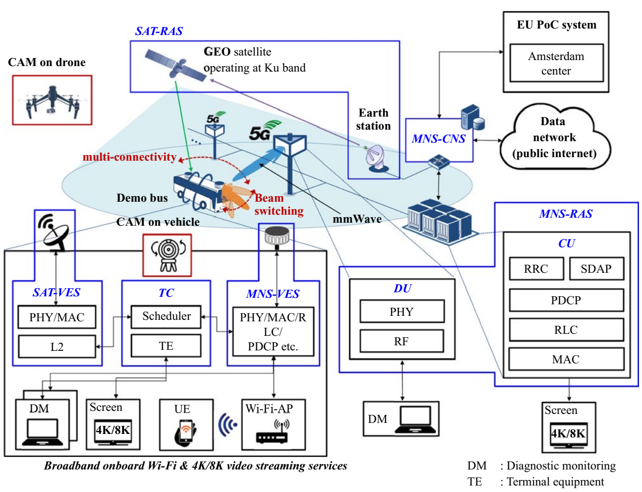

FIGURE 4 Architecture and interface design for the KR PoC trial platform

3.2 | EU PoC

The EU PoC will be conducted using two PoC platforms, the EU-Testbed and EU-Trial, to validate UCs 2 and 3. The EU-Testbed is designed to implement the 5G NR-based satellite access and MC functionalities and used for link-level and system-level evaluations by testing selected KPIs. After exhaustive tests with the EU-Testbed, the EU-Trial will be used to demonstrate the MC technologies.

3.2.1 | Use case description and target KPIs

As shown in Table 4, UC2 is composed of UCS2.1 and UCS2.2, and the EU-Testbed is used to validate UCS2.1 and its associated KPIs, whereas both the EU-Testbed and EU-Trial are used to validate UCS2.2. In UCS2.1, a UE that can benefit from dual satellite and terrestrial connectivity for the same (non-QoS stringent) service simultaneously will be demonstrated. Some packets are routed on the terrestrial RAT and others are routed on the satellite RAT, which, therefore, allows the UE to transparently benefit from more bandwidth. High-quality video (eg, 4K video) streaming is considered an application of this UC to be showcased. In the UCS2.2, the simultaneous connection to cellular and satellite RATs allows a UE to be provided with the services in which stringent QoS packets (such as voice over IP or remote conferencing) are routed over cellular RAT, whereas non-stringent QoS packets (such as video streaming) are routed over satellite RAT. The main enablers for this scenario are traffic steering and inter-RAT RRM. The traffic steering is defined as a function of distributing the traffic load optimally across different network entities and spectrum bands considering operator and user preferences.

UC3 is composed of UCS3.1 and UCS3.2, and the EU-Testbed is used to validate its enablers and associated KPIs. In the demonstration of UCS3.1, it will be shown that an unpredictable connectivity failure of cellular access due to physical attacks or natural disasters is protected by satellite access by switching the traffic to satellite access when failure is detected. Traffic switching deals with the seamless handover between two different RATs to dynamically adapt to the new network states (eg, resource scarcity, service outages, or moving UEs). In the case of UCS3.2, on the other hand, a scenario in which the cellular access protects satellite access when the UE moves to an environment where satellite access

TABLE 4 Target KPIs of PoC UCSs

UCS	Target KPI description	Value	PoC platform	Associated KPI
1.1	Average PHY data rate of cellular access link to a bus (downlink)	500 Mbps	KR-Trial0	KPI0
	Average user-experienced data rate (downlink)	50 Mbps	KR-Trial0	KPI0
	UP latency (cellular)	8 ms	KR-Trial0	KPI1
	CP latency (cellular)	20 ms	KR-Trial0	KPI2
	HO latency	4 ms	KR-Trial0	KPI4
1.2	Average PHY data rate of cellular access link to a bus (downlink)	500 Mbps	KR-Trial1	KPI0
	Average PHY data rate of satellite access link to a bus (downlink)	2 Mbps[a]	KR-Trial1	KPI0
	Reliability of cellular link: block error rate	$<10^{-1}$	KR-Trial1	KPI3
	Service continuity	No video streaming interruption[b]	KR-Trial1	KPI4
2.1	Average PHY data rate of UE access link (downlink)	100 Mbps	EU-Testbed	KPI0
2.2	Average PHY data rate of UE access link (downlink)	100 Mbps	EU-Trial/EU-Testbed	KPI0
	UP latency (cellular)	<4 ms	EU-Trial/EU-Testbed	KPI1
	CP latency (cellular)	<20 ms	EU-Trial/EU-Testbed	KPI2
3.1	Service continuity (if link failure)	Interruption time: 4 ms	EU-Testbed	KPI4
3.2	Service continuity (if both satellite and cellular links available)	Interruption time: 0 ms	EU-Testbed	KPI4
	Service continuity (if buffering)	Interruption time: 0 ms	EU-Testbed	KPI4
4.1	Latency of VR tennis game	20 ms	Joint-Trial	KPI1
	Average PHY data rate of link from trial sites 2 to 1	100 Mbps	Joint-Trial	KPI0
4.2	Average PHY data rate of link to a bus (downlink with MC)	500 Mbps	Joint-Trial	KPI0

[a] This is the target data rate to be measured under the satellite bandwidth of 2 MHz (1.6 MHz for downlink and 0.4 MHz for uplink).
[b] This can be demonstrated by showing that video streaming is maintained without interruption even when the cellular link is lost.

is not available (eg, urban areas) will be demonstrated. The main enabler for this scenario is traffic splitting. Since the unavailability of satellite connectivity may be predictable, the system can split the services and traffic to cellular access before the satellite link is lost in order to ensure zero interruption time.

3.2.2 | System design

As described in previous sections, there are two platforms for the EU PoC, the EU-Testbed and EU-Trial. According to the reference architectures depicted in Figures 1 and 2, the architectures of the EU-Testbed and EU-Trial are built up to combine satellite and cellular terrestrial accesses. Figures 5 and 6 show the functional and physical architecture and interface design of the EU PoC platforms, respectively. As depicted in the figures, the EU-Trial is essentially equivalent to the EU-Testbed except for the green dotted box in the figures. For the EU-Testbed, the channel emulator, in which proper channel models are implemented, is deployed in the green box, whereas for the EU-Trial, additional hardware and RF equipment, such as gNB up/down-converter, gNB transmit/receive antenna, UE terrestrial up/down-converter, satellite, and satellite antenna, are implemented for over-the-air demonstrations. A detailed description of the design of the EU-Testbed and EU-Trial, including hardware and software architectures, has been extensively described in deliverables D5.1 [33] and D2.3 [27].

3.3 | Joint KR-EU PoC

As part of KR and EU collaboration, UC4, a comprehensive PoC UC encompassing the concepts of UCs 1, 2, and 3 will be demonstrated using the Joint-Trial.

3.3.1 | Use case description and target KPIs

The purpose of this UC is to showcase that providing users with a seamless, reliable, and ubiquitous broadband service

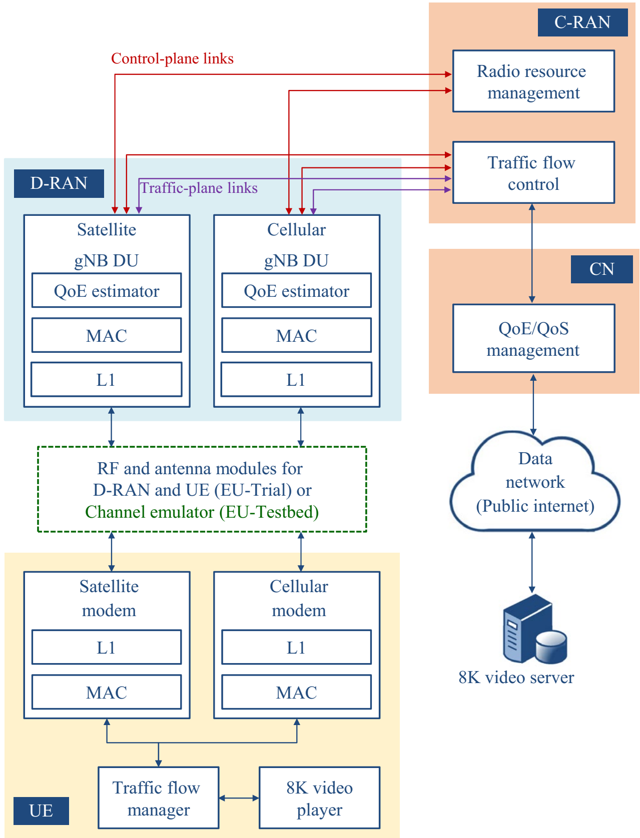

FIGURE 5 Functional architecture design for the EU PoC platforms

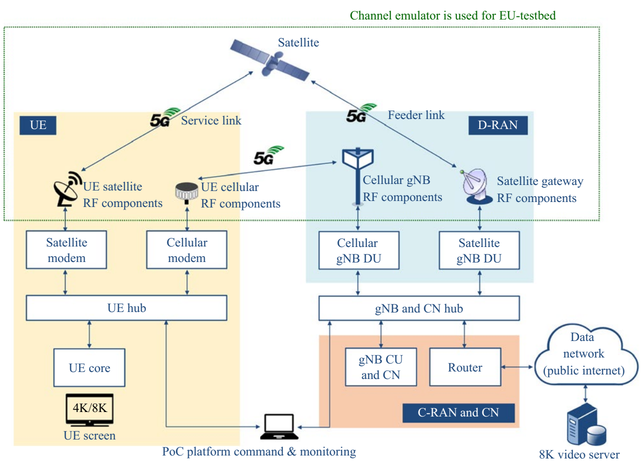

FIGURE 6 Physical architecture and interface design for the EU PoC platforms

and an intercontinental interoperability service is possible thanks to the 5G-ALLSTAR technologies.

Figure 7 illustrates UC4, the overall PoC UC of the joint KR-EU demonstration using the Joint-Trial. This UC will be conducted at three different trial sites,

- **Trial site 1:** a Roland-Garros booth in Paris, France;
- **Trial site 2:** Toulouse, France (CNES premises);
- **Trial site 3:** an automobile proving ground in Yeonggwang or Cheonan, Korea.

The demonstration on the trial sites will take place concurrently. Trial site 1, however, may be subject to change depending on whether permission for the demonstration at Roland-Garros is granted. Visitors will be allowed to experience a variety of 5G services facilitated by the 5G-ALLSTAR technologies, including delay-sensitive applications, VR online tennis game, and high-bandwidth applications such as real-time high-quality tennis game streaming.

Tennis Kings VR, which is a VR-sport game developed by a KR company called Appnori Inc., was chosen in order to link the tennis tournament and the demonstration as well as to promote the technical achievements of our project by interesting Roland-Garros visitors. As illustrated in Figure 7, two players located at trial sites 1 and 2 will be able to play the game, and at the same time, an intercontinental interoperability service will be showcased in which passengers on a moving vehicle at trial site 3 can watch the VR tennis match with their VR headsets or watch live (or recorded) 4K/8K videos through a TV screen installed on the vehicle. The TV screen can display the VR tennis players located at trial sites 1 and 2. Meanwhile, the onboard passengers and a bird's eye view of trial site 3, where the demonstration is being conducted, will be filmed by CAM3 and CAM4, respectively, and sent to both trial sites 2 and 3.

3.3.2 | System design

The Joint-Trial is a KR-EU integrated PoC platform, consisting of the EU-Trial and KR-Trial1, which will be deployed at trial sites 2 and 3, respectively, during the demonstration at Roland-Garros 2021. The high-level design of the interfaces for connecting the EU-Trial, KR-Trial1, and Roland-Garros booth is depicted in Figure 7. To support a CN-level interconnection between the EU-Trial and KR-Trial1 for the intercontinental interoperability service, two networks, KREONET and last-mile connectivity, will be used. KREONET, which is a principal national research and education network supported by the KR government and has been operated by KISTI since 1988 [34], is responsible for the interface between the KR-Trial1 and the KREONET Amsterdam network center. Last-mile connectivity is the interface between the KREONET Amsterdam network center and trial sites 1 and 2. Moreover, because the VR tennis server and 8K video server are located in the EU, it also connects the servers with the KREONET Amsterdam network center and trial sites 1 and 2. As depicted in Figures 5 and 6, the 8K video server is a part of the EU-trial platform and envisaged to provide 8K video streaming to UEs connected to RANs at the three trial sites.

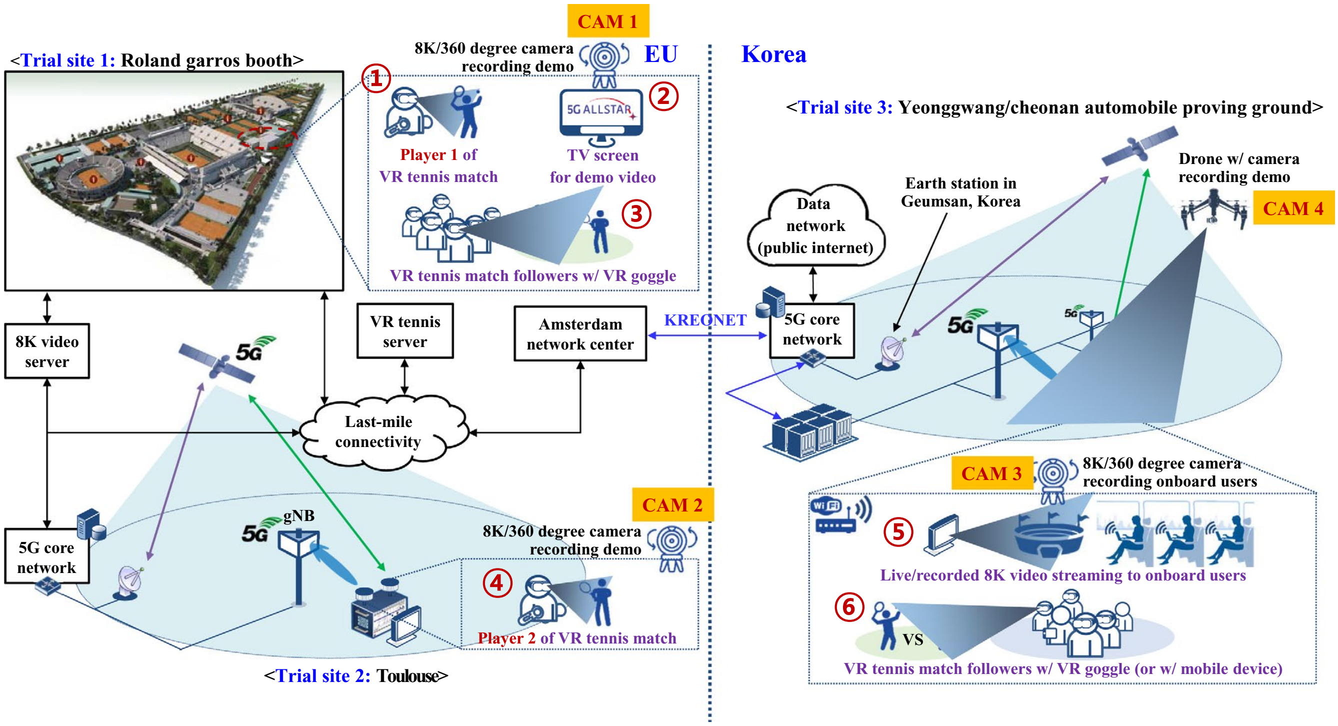

FIGURE 7 High-level interface of the Joint-Trial and the overall PoC scenarios

4 | KEY ENABLING TECHNOLOGIES

This section describes key enabling technologies currently under study within the project and the preliminary results.

4.1 | 5G satellite communications

With a greater focus on ubiquitous coverage and availability, the adoption of NTNs (eg, airborne and spaceborne based communications) interoperable with terrestrial access technologies has been identified in 3GPP study phases and standardization processes as a solution to unlock 5G connectivity in unserved or underserved areas. In this scenario, satellite access networks will turn into one of the key enabling technologies for 5G systems [35].

Within the scope of 5G-ALLSTAR, the prioritized architecture of satellite access, selected from the 3GPP pool of candidates [13], is based on a transparent satellite acting as a relay of the radio interface between the gNB and the UE (ie, the NR-Uu) from the feeder link to the service link and vice versa, thus not terminating the NR-Uu. The satellite of the EU-Trial will be operating using frequency division duplexing mode in the Ka band. With simultaneous access to both the terrestrial and the satellite access networks, the UE will be able to select the best performing technology with MC techniques [17].

In order to achieve smooth integration with the 5G RAN, an NR signal with "satellite friendly" features has to be provided through the satellite link [13]. As the propagation features of the satellite channel have a substantial impact on the standard procedures of 3GPP radio protocols, tailored adjustments to the modem design have to be taken into account. The most relevant issues introduced by the satellite propagation channel identified so far are as follows:

1. higher propagation delay, which has an impact on higher-layer (eg, MAC/RLC) procedures, PHY procedures (such as link adaptation and power control loops), and HARQ;
2. differential delay due to the larger cell size of satellite beam footprints, which has an impact on physical random access channels and random access procedures (ie, the timing advance);
3. Doppler shift (and its variation rate) on the received signals (ie, the shift of the carrier frequency) due to the simultaneous motion of the satellite and the UE, eventually producing inter-carrier interference.

4.2 | 5G vehicular communications

Within the project, we have been studying various key enabling technologies for 5G vehicular communications, and the progress made in addition to the studies presented in Refs

[31,36] is described in this section. First of all, from a system architecture perspective, various features as depicted in Figure 4 were studied and implemented to enhance the performance the MNS. The function split of MNS between the baseband (BB) units (BBUs) and remote radio heads (RRHs) is done such that the PHY functions including BB, RF, and antenna modules are located in the RRH, whereas the other functions including the MAC layer and other higher-layer protocol stack functions are located in the BBU. The BBU and RRH respectively correspond to the CU and DU of MNS-RAS in KR PoC platforms in Figure 4, and they are typically interconnected via a high-capacity fronthaul. In addition, the MNS is designed as a synchronized system, where RRHs are implemented to have the same starting time instance of a radio frame to minimize interruption time during handover [36].

Since the MNS is designed to operate in the mmWave band, RRHs with very narrow beams are deployed along the roadside for coverage enhancement, and two RRHs, $RRH_{i,1}$, and $RRH_{i,2}$, colocated at the i-th location, cover the sectors in opposite directions; each corresponds to an independent cell. However, it was found in our previous study [31] that the inter-cell interference from adjacent cells seriously degrades system performance due to the narrow beams of the RRHs. This motivated us to conduct another study to investigate three different frequency planning (FP) strategies, which are (a) **FP 1**: FP with a frequency reuse factor (FRF) of 1 in which all RRHs occupy the entire frequency band F with a 1 GHz bandwidth; (b) **FP 2**: FP with an FRF of 2, in which $RRH_{i,1}$ and $RRH_{i,2}$ occupy the frequency bands F_1 and F_2, respectively; and (c) **FP 3**: Reverse FP with an FRF of 2, in which $RRH_{j,1}$, $RRH_{j,2}$, $RRH_{j+1,1}$, and $RRH_{j+2,2}$, occupy the frequency bands, F_1, F_2, F_2 and F_1, F_2, F_2, and F_1, respectively, where $j = 2{\cdot}i$, and F_1 and F_2 are adjacent frequency bands with equal bandwidths of 500 MHz within frequency band F [36]. In this study [36], it was shown that as inter-site distance (ISD), the distance between the i-th colocated RRHs and $(i + 1)$-th colocated RRHs d_{ISD}, decreases, FP 3 outperforms the other FP strategies. In this article, we show an additional simulation result to investigate the influence of a larger ISD on the system performance. Figure 8 shows the CDF of the capacity for the three FP strategies. As can seen from the figure, when the ISD increases, the performance of FP 1 is better than that of FP 3. Hence, we can conclude that in the case of urban scenarios, where the ISD is typically smaller than 500 m, FP 3 is preferable, whereas FP 1 is preferable in highway scenarios, where RRHs are typically deployed at ISDs larger than 500 m.

Second, as presented in [31], the Flexible Access Common Spectrum (FACS), which is an unlicensed mmWave band allocated by the KR government, is utilized for the connection between the RRHs of base stations (BSs) and V-UEs. By taking advantage of the vast amount of spectrum available in

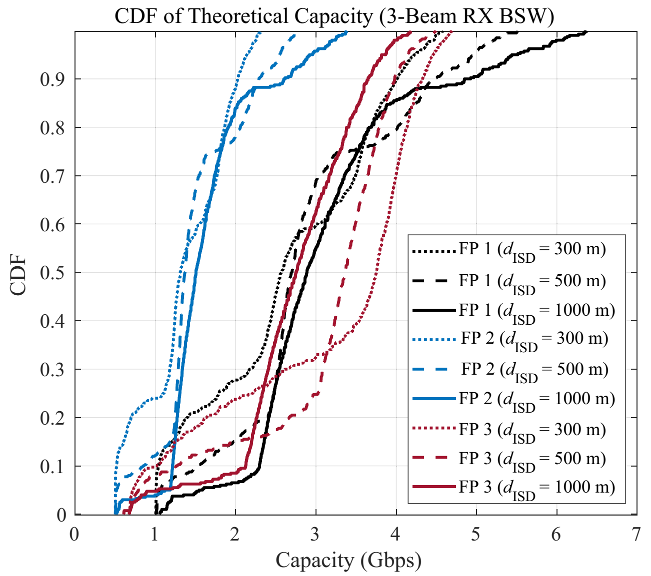

FIGURE 8 Capacity performance of three FP strategies with different ISD values, $d_{ISD} \in \{300, 500, 1000\}m$

the FACS, the targeted system can support a maximum bandwidth of 1 GHz through carrier aggregation (CA) of up to 10 component carriers (CCs). For a high-mobility support in the FACS that is close to the FR2 band in NR, the system is designed to comply with two numerologies used for the NR FR2, $\mu = 2$ and $\mu = 3$, which respectively support a large subcarrier spacing of 60 kHz and 120 kHz to combat high Doppler frequency spread For PoC, considering that $\mu = 3$ has a slot duration that is half that of $\mu = 2$, which requires high-speed data and signaling processing time both at the physical and higher layers, and that it also has a shorter cyclic prefix requiring a better beam switching capability, we decided to implement only the system with $\mu = 2$, focusing on the validation of other key functionalities such as beam switching and MC. Furthermore, efficient demodulation reference signal (DMRS) patterns for high-mobility scenario under the given numerology (as discussed in [31]) and automatic frequency control will be introduced to compensate not only for the Doppler frequency shift caused by the mobility of vehicle, but also the frequency offset caused by the local oscillator.

Third, in order to overcome the performance degradation of neighboring cell search due to the fact that the received signal strength of the serving cell is much larger than that of neighboring cells, making it hard for the V-UE to detect the synchronization signals of neighboring cells, the synchronization signals of cells that interfere with each other are designed not to overlap in the OFDM resource, as illustrated in Figure 9, thereby minimizing interference from the serving cell when the V-UE is searching for the synchronization signals of adjacent cells for handover, and minimizing the probability of handover failure due to a false alarm.

Based on the proposed frame structure for cell search performance enhancement, a seamless handover mechanism obtained by realizing the RACH-less and make-before-break protocol is designed to minimize the communication interruption time due to a handover interruption.

Lastly, the system introduces several MIMO transmission technologies for mmWave communications including array beamforming at both the RRH and V-UE, which is a key solution for dealing with serious propagation loss, and a polarization-based multi-antenna scheme, which is particularly effective in LoS-dominant channel environments. With the polarization antenna, spatial multiplexing technique of supporting up to two spatial layers is introduced to increase throughput. Moreover, with three antennas at the V-UE, each creating a beam pointing in a direction, an efficient open-loop beam switching (OL-BSW) technique was studied. This is a technology to align the TX/RX beam in the best direction to maximize the received signal quality and to combat unexpected signal blockage caused by the motion of the V-UE and/or the surroundings. Beam sweeping is performed at a specific period by measuring the received power of the synchronization signal, and measurement mechanisms such as those that measure the received power of the channel state information reference signal (CSI-RS) or DMRS can be also considered. For beam selection, the best beam is selected for the Tx or Rx at each time instance (eg, each slot). To analyze the performance gain that can be obtained by switching three beams, a preliminary study was conducted to evaluate the received power of each beam using a ray-tracing simulation [37]. In this simulation, it was observed that mmWave-band vehicular communication system with three receiving beams can achieve a power gain of up to 10 dB. The actual performance of this OL-BSW will be validated by KR-Trial0.

4.3 | Integrated RRM and spectrum sharing

To demonstrate satellite and cellular MC, we implemented the 4G and 5G RRM functions involved in interference mitigation, like the coordinated multi-point (CoMP), enhanced inter-cell interference coordination and CA with cross-carrier scheduling. The coordination between satellite gNB(s) and cellular gNB(s) as well as that between cellular gNBs relies on signal-to-interference-plus-noise ratio (SINR)

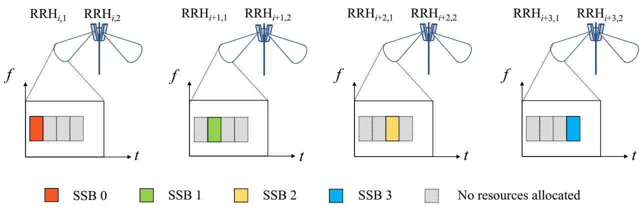

FIGURE 9 Design of MNS frame structure for improving neighboring cell search performance

measurements, on the identification of the critical regions where interference occurs and mitigation is required, on the agreement on sets of radio resource and cell regions where the coordination is required (such as cell edges), and on the setup of the shared resource in time (eg, because of almost blank subframes) and frequency domains (such as with primary and secondary CCs or by splitting the shared band into—possibly adjacent—sub-bands). Within the project, these coordination mechanisms inherited from 4G and 5G are analyzed and their adaptation to satellite and cellular MC is evaluated. The technical challenges for hybrid satellite/cellular systems are mainly due to the round-trip delay between the measurement and the command that configures the coordination, which is longer for the satellite system than it is for the cellular system, and to the fact that the coordination between the satellite gNB(s) and the cellular gNB(s) should be operated for all the cellular gNBs that experience interference within the whole satellite beam footprint.

As part of the research on integrated RRM and spectrum sharing techniques, a preliminary study was conducted using a ray-tracing simulation [38]. We studied a spectrum sharing scenario where satellite and cellular networks use the same spectrum and analyzed the co-channel interference between two links. In [38], it was shown that when the satellite is a GEO whose elevation angle with the earth's surface is 45°, the SINR of a satellite UE receiver is often less than 0 dB due to the severe interference from the cellular networks, whereas the SINR of a cellular UE receiver is basically larger than 20 dB because the impact of interference from the satellite network on the cellular receiver is negligible. Therefore, it is more important to manage the cellular link transmission for interference mitigation between the GEO satellite and cellular networks. Meanwhile, research on the development of integrated RRM and spectrum sharing techniques in various spectrum sharing scenarios is currently in progress. For the scenario described above, a beam selection-based interference avoidance technique was studied, and the preliminary result was presented in [39].

4.4 | Traffic flow control

The access traffic steering, splitting, and switching (ATSSS) was first studied in SI (FS_ATSSS [40]) conducted by the 3GPP SA WG2 in 2018 for the purpose of traffic management of 3GPP and non-3GPP access networks in a 5G system, and the results were reported in TR 23.793 [41]. By exploiting service-, network-, and user-related information available at the CN, the ATSSS enables the steering, switching, and splitting of access traffic between 3GPP and non-3GPP networks. Based on the results of the TR 23.793 [41], standard development began in 2019 and will eventually be specified in TS 23.501 [25], TS 23.502 [42], and TS 23.503 [43].

We are also developing similar traffic flow control algorithms, mainly managed by the traffic flow control module, as shown in Figures 1 and 2. As mentioned in Section 2, the traffic steering/switching/splitting in our system is implemented at the PDCP layer and performed based on a set of inputs provided by the additional functionalities introduced, thereby enabling a faster selection and efficient traffic flow control across the RATs within the area covered by a gNB-CU in order to guarantee network reliability and increase the traffic throughput of each UE.

As mentioned in Section 4.2, our previous study [37] has shown that performance gains can be achieved by switching three beams appropriately at the V-UE. Nevertheless, as in our other study [38], there is still a critical challenge that needs to be solved in the MNS. The study showed that in some cases, the received power of BS-to-V-UE link is significantly degraded because of an unexpected blockage caused by the surroundings. In this case, the traffic flow control technique can play crucial role in increasing the reliability of the link and avoiding communication interruption to improve the end-user experience. Two options for traffic flow control are considered. One is traffic splitting (TS) and the other is the joint transmission (JT) scheme of CoMP, in which the V-UE simultaneously receives the same data sent from the cellular and satellite networks. In this article, for the TS, it is assumed that the V-UE selects the stream with a higher signal-to-noise ratio (SNR) from the two duplicated traffic streams received from the cellular and satellite networks, and we assume a non-coherent JT, in which the network does not make use of channel knowledge reported by the V-UE. The received SNRs of the two traffic control schemes can be simply expressed as $\gamma_{\mathrm{TS}} = \max\{\gamma_{\mathrm{C}}, \gamma_{\mathrm{S}}\}$ and $\gamma_{\mathrm{JT}} = \gamma_{\mathrm{C}} + \gamma_{\mathrm{S}}$, respectively, where γ_{C} and γ_{S} denote the SNRs received at the cellular and satellite receivers, respectively. In addition to the GEO satellite considered in the previous study [38], we further consider an LEO satellite with an altitude of 1500 km ($h_0 = 1500$ km), which is one of the non-GEO satellites given in [13]. Then, as in Refs [13,38], the distance d between the satellite and a V-UE can be determined by elevation angle α and Earth radius R_{E}, which can be expressed as

$$d = \sqrt{R_{\mathrm{E}}^2 \sin^2\alpha + h_0^2 + 2h_0 R_{\mathrm{E}}} - R_{\mathrm{E}} \sin\alpha, \quad (1)$$

where $R_{\mathrm{E}} = 6371$ km, and considering that the elevation angles of GEO satellites in Korea are around 45°, the same elevation angle for both GEO and LEO satellites, $\alpha = 45°$, is assumed for the sake of simplifying the analysis.

Next, through ray-tracing simulations with the same framework used in [38], received signals were obtained, as shown in Figures 10 and 11. As can be seen from Figure 10, both TS and JT schemes with LEO satellite can yield a performance gain when deep fading occurs in the cellular link, and from the enlarged area of Figures 10 and 11, the JT scheme can achieve a slightly better performance than the TS scheme. It can be also observed in the enlarged area of Figure 11, the performance gains of the TS and JT schemes with the GEO satellite are negligible as compared with the cellular communication because of the low received SNR of the GEO satellite link. Nevertheless, it is sufficient for the GEO satellite to prevent a V-UE from having communication interruptions due to a cellular link blockage, as observed in Figure 10. Furthermore, we believe that the elevation of GEO satellite is close to 90°, the V-UE can achieve higher link performance gains.

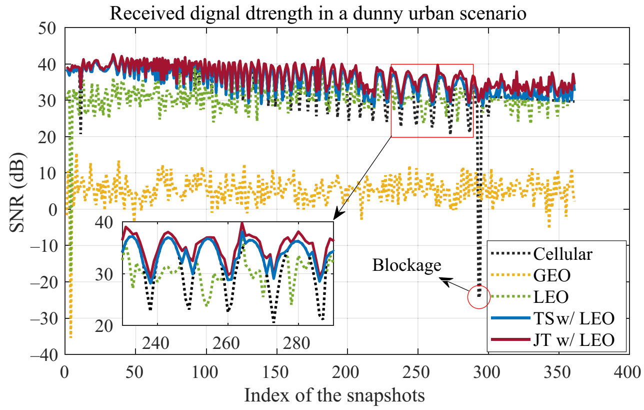

FIGURE 10 Received SNR of traffic flow control schemes

5 | CONCLUSIONS

Many countries have started to commercially launch 5G communication networks since late 2018, and 5G is at the stage of maturity of developing the key enabling technologies for extended PoCs. However, the support of new 5G services and seamless connectivity across various vertical industries and very diverse UCs still requires the integration of multiple access technologies. Motivated by this, 5G-ALLSTAR project has been launched to design, develop, and experimentally evaluate a set of technologies that can support seamless, reliable, and ubiquitous broadband services. This article presented an overview of the recent research activities of the project, mainly focusing on architectural frameworks, PoC design, and key enabling technologies with some preliminary results. Specifically, we described the overall high-level architecture of the 5G-ALLSTAR system and its basic supported functionalities as well as representative UCs. We further defined each UC into two UCSs and the associated KPIs to be verified during PoC and specified a set of PoC platforms that will be used for the demonstration of each UCS. The 5G-ALLSTAR PoC activities will demonstrate a set of technical concepts, which are specifically developed and experimentally evaluated by a two-step approach. During the first-phase PoC, UCs 1 to 3

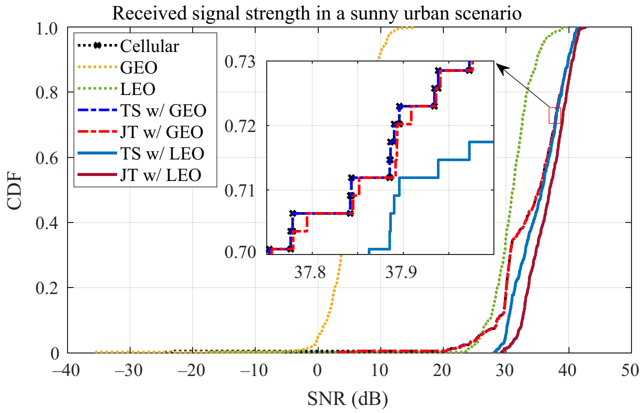

FIGURE 11 CDF of received SNRs for traffic flow control schemes

will be demonstrated by KR and EU PoC platforms. Next, during the second-phase PoC, 5G-ALLSTAR will showcase UC4 encompassing UCs 1, 2, and 3 at a key event in 2021 (eg, Roland-Garros) using an integrated KR and EU platform. In addition, we described a subset of the key technologies being developed and the relevant technical challenges. We also presented preliminary results to show the necessity of introducing FP for the MNS and the benefits of integrating cellular and satellite networks in mmWave-band vehicular communications. The outcomes of 5G-ALLSTAR project are expected to motivate and convince vertical markets, the industry, and future service providers, as well as relevant stakeholders, and eventually contribute to the technical evolution of 5G, paving the road for next-generation communications.

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