5G-ALLSTAR: An Integrated Satellite-Cellular System for 5G and Beyond

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***Abstract*—This paper provides an overview of recent research activities of the 5G AgiLe and fLexible integration of SaTellite And cellulaR (5G-ALLSTAR) project which aims to develop Multi-Connectivity technology that integrates the cellular and satellite accesses to provide seamless, reliable and ubiquitous broadband services. 5G-ALLSTAR also entails developing millimeter-wave (mmWave) 5G New Radio (NR)-based cellular access system and investigating the feasibility of NR-based satellite access for providing broadband and reliable 5G services. In addition, spectrum sharing between the cellular and satellite access is studied. With all these technologies developed in the project, the 5G-ALLSTAR will showcase the first fully integrated satellite/cellular prototype system for 5G and beyond 5G (B5G) services at a big event (e.g., sporting event like Roland-Garros) in 2021. This paper also provides a preliminary techno-economic analysis on potential use cases targeting vertical markets, and introduces recent standardization activities of relevance.**

***Index Terms*—5G-ALLSTAR, New Radio, multi-connectivity, satellite communications, vehicular communications, millimeter wave**

I. Introduction

The phase one of a fifth generation (5G) mobile communication standard, known as 5G New Radio (NR), appeared in the 3rd Generation Partnership Project (3GPP) Release 15 (Rel-15), was approved in December 2017. Today its key enabling technologies are at the stage of maturity of developing and testing. The main ingredients of 5G NR are: (i) the use of *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, (ii) *flexible numerology* that allows subcarrier spacing and slot to be respectively scaled by $2^{\mu} \cdot 15$ kHz and $2^{-\mu} \cdot 1$ ms for a wide variety of 5G services, (iii) *flexible slot configuration* that supports not only dynamic Time Division Duplex (TDD) but also mini-slots, (iv) *multi-antenna technique* supporting beam-forming (BF) transmission assisted by 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 gain, (v) *spectrum sharing techniques*, (vi) network densification and use of small cells. Meanwhile, extensive proof-of-concepts (PoCs) of potential 5G technologies have been successfully delivered at local, national and inter-continental scale since 2018 [1] to prove that the 5G is able to provide communications for very high-bandwidth transmissions like ultra-high definition (UHD) video streaming, low-latency communications for remote control, millimeter-wave (mmWave) vehicular communications as well as low-bandwidth communications for machine type communications. In particular, the use of mmWave spectrum for 5G services and uses cases has been discussed from technical [2], standardization and economical angle [3].

2019 is the year of the first commercial launch of 5G NR services based on the second phase of 5G, the 3GPP Rel-16 specification. The 5G community is now looking for translating 5G use cases, vertical industries requirements and ambitions in adopting 5G into viable business cases. However, the support of new 5G services and seamless connectivity across various vertical industries and very diverse use cases still requires the integration of multiple radio access technologies (RATs) [4]. The tight interworking and integration between cellular and Non-Terrestrial Networks (NTNs) (e.g., satellite) will be beneficial in providing improved coverage and service continuity in a cost effective manner, especially in providing robust, seamless, and continuous wireless services for critical applications such as public safety and emergency case communications. Moreover, satellite communications can be utilized to improve reliability of communications by providing complementary connections to mmWave-band cellular

The research leading to these results has received funding from the European Union H2020 5GPPP under grant n.815323 and supported by the Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No.2018-0-00175, 5G AgiLe and fLexible integration of SaTellite And cellulaR).

communications, in which the link is vulnerable to line-of-sight (LoS) signal blockage or beam misalignment.

In this context, a new joint Korean-European (KR-EU) project called 5G-ALLSTAR [5], leveraging the outcomes of the previous Korean-EU joint project, 5GCHAMPION [1] [6], has been recently launched to design, develop, evaluate and trial the following set of key technologies to support system interoperability, global service connectivity (e.g., for critical applications) and 5G applications of interest to both EU and KR regions:

(i) mmWave-band cellular access system (i.e. 5G NR-based vehicular communications) for providing users (e.g., on-board passengers) with broadband and low-latency 5G services,
(ii) feasibility of NR-based satellite access for providing broadband and reliable 5G services,
(iii) multi-connectivity (MC) technology that integrates the cellular access and satellite access with interoperability support controlled by the same 5G RAN to support seamless, reliable and ubiquitous broadband services,
(iv) spectrum sharing between the cellular and satellite access.

Meanwhile, 5G-ALLSTAR is also actively participating in global 5G standardization including 3GPP and European Telecommunications Standards Institute (ETSI) focusing on multi-RAT interoperability (i.e. MC technology), mmWave-band NR Vehicle-to-Everything (V2X), and NR-based satellite access, and it will eventually contribute to creation of a cross-regional lasting synergy for 5G research, innovation and commercialization through value proposition assessment for vertical industries.

The remainder of this paper is organized as follows: in section II, we provide a general overview of the 5G-ALLSTAR system including its overall system architecture and key functionalities. Next, key enabling technologies are presented in section III. In section IV, a preliminary plan for the final PoC and the target KPIs are described to validate the key technologies with the system architecture. Moreover, this paper discusses the potential use cases and relevant standardization activities in section V and section VI respectively. Finally, section VII concludes the paper.

II. 5G-ALLSTAR System

A. System Architecture

Fig. 1 shows the 5G-ALLSTAR architecture designed to foster the merging between the current vision of 5G network architectures [7] and the 5G-ALLSTAR project needs, with particular attention on the MC functionality assisted by spectrum sharing and traffic flow control. In this regard, the 5G-ALLSTAR network architecture is represented to be composed by standardized 5G network components: i) Data Network (DN), ii) Core Network (CN), iii) Cloud RAN (C-RAN) and iv) User Equipments (UEs). The DN is considered to be the entity involved in providing private and public data (e.g., documents, movie contents); the 5G-ALLSTAR CN is enriched with Quality of Service/Quality of Experience (QoS/QoE) advanced functionalities to bring penalization of services in 5G networks; C-RAN centralised units (i.e., gNB-CU) are equipped with coordination and control capabilities for enabling a faster and efficient centralization of the traffic flows with both control and user-plane functionalities; the distributed units (i.e., gNB-DU) are enriched in 5G-ALLSTAR with monitoring functionalities in terms of radio performances and actual QoS estimation. The UE is considered as any device able to be connected to the access network with the dual-/multi-connection capability involving more than one RAT.

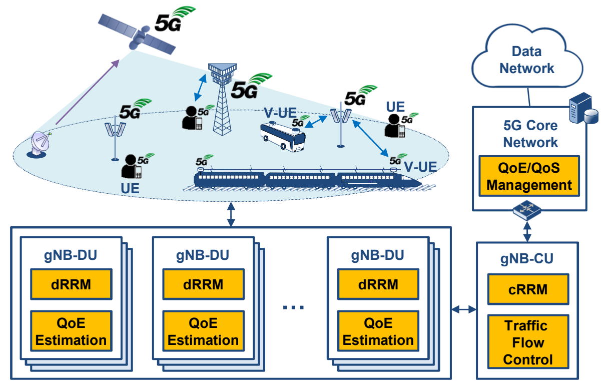

Fig. 1: General architecture and key functionalities of 5G-ALLSTAR system.

B. Functionalities

Based on the architecture proposed in Fig. 1, 5G-ALLSTAR develops the following advanced CN and RAN components:

- the Advanced Radio Resource Management (RRM) functionalities that are able to implement spectrum sharing, where algorithms for interference analysis and mitigation will be developed. The RRM functionalities can be deployed in both gNB-CU and gNB-DU as shown in Fig. 1,
- the QoE/QoS Management functionalities that enrich the standardized CN functionalities by computing/estimating the proper personalized *Connection Preferences* of each UE on the basis of a set of learned parameters concerning the UE needs and expectations. The *Connection Preferences* are directly deployed to the Traffic Flow Control,
- the QoE Estimation that provides the estimation of the individual perceived QoS on the basis of the information provided by the user via explicit or implicit feedback and on the measurements provided by the distributed RRM (dRRM),
- the Traffic Flow Control that is placed in the gNB-CU and performs the traffic switching, steering and splitting functionalities for the traffic and network resource management issues. The Traffic Flow Control solutions will be performed taking into account the (i) network status provided by the central RRM (cRRM) (ii) the Connection Preferences provided by the QoE/QoS Management, (iii) the QoE estimated during the connection for a real-time traffic control, which is provided by the QoE Estimation

module, and (iv) the QoS requirements for each user. The QoS requirements are the QoS parameters for a specific QoS Flow Identifier (QFI) also included within the QoS profile and delivered to the RAN with the standardized CN functionalities.

In addition, 5G-ALLSTAR further develops Artificial Intelligence (AI)-based solutions for the advanced CN and RAN components, and verifies the feasibility with simulation approach. The details will be presented in a future work.

III. Key Enabling Technologies

This section describes key technologies of 5G-ALLSTAR currently under study, which enable 5G satellite communications, 5G vehicular communications and MC functionalities.

A. 5G Satellite Communications

Networks leveraging on airborne or spaceborne vehicle for transmission, referred to as NTN, will bring added value to 5G networks, specially in un-served or under-served areas, in terms of scalability, service reliability and continuity. With a higher focus on ubiquitous coverage and availability, efforts have been made to include NTN access technologies in 3GPP studies and standardization processes. As a consequence, satellite communications are deemed to be one of the key enablers for 5G systems which will require both next generation RAN (NG-RAN) and non-3GPP satellite access networks to be interoperable with terrestrial access technologies [8]. Selection of the most appropriate access technology for a service will be achieved with MC techniques [9].

Different architectures for NTN access in a 5G system are currently under study and will be part of future 3GPP releases [10]. Within the scope of 5G-ALLSTAR, the candidate architecture is featuring a transparent satellite acting as a relay of the radio interface between the gNB and the UE (i.e. NR-Uu) from the feeder link to the service link (operating in Ka band with frequency division duplexing access scheme) and vice versa, thus not terminating the NR-Uu.

In order to cope with key RAN protocols, the signal relayed by the satellite has to be an NR signal with ”satellite friendly” features [11]. Potential impact on standard procedures of radio protocols shall be taken into account. The most relevant issues identified are:

- higher propagation delay introduced by the satellite, which can impact on MAC/RLC procedures, physical-layer (PHY) procedures (e.g. link adaptation and power control loops) and hybrid automatic repeat request (HARQ),
- differential delay introduced by larger cell size of satellite beam footprint, which can impact physical random access channel and random access procedure (i.e. the timing advance),
- Doppler shift (and its variation rate) on the received signals (i.e. the shift of the carrier frequency due to the motion of receiver/transmitter or both) which would be impacted simultaneously by the motion of UE and of the satellite, eventually producing inter-carrier interference (ICI).

B. 5G Vehicular Communications

5G-ALLSTAR also aims to study various key enabling technologies for 5G vehicular communications. First of all, as presented in [12], Flexible Access Common Spectrum (FACS), unlicensed mmWave band allocated by Korean government, is utilized for the connection between Remote Radio Heads (RRHs) of base station (BS) and vehicle UE (V-UE). By taking advantage of a vast amount of spectrum available in the FACS, the targeted system can support the maximum bandwidth of 1 GHz through carrier aggregation (CA) of up to 10 component carriers (CCs). For high-mobility support in the FACS that is close to 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 large sub-carrier spacing of 60 kHz and 120 kHz to combat high Doppler frequency spread. For PoC, however, a prototype with $\mu = 2$ is prioritized to be implemented. Furthermore, efficient Demodulation Reference Signal (DMRS) patterns for high-mobility scenario under given numerology as discussed in [12], and automatic frequency control (AFC) will be introduced to compensate not only Doppler frequency shift caused by the mobility of vehicle, but also frequency offset by local oscillator.

Secondly, the system introduces several MIMO transmission technologies for mmWave communications including array BF at both RRH and V-UE, which is one of the key solutions to deal with serious propagation loss, and polarization-based multi-antenna scheme, which is particularly effective in a LoS dominant channel environment. With the polarization antenna, spatial multiplexing technique of supporting up to 2 spatial layers is introduced to increase throughput. Moreover, with multiple antennas at V-UE, each creating a beam pointing a direction, an efficient open-loop fast beam switching (OL-BSW) technique is studied, and its performance will be validated by the PoC prototype. This is a technology to align TX/RX beam in the best direction in order to maximize the received signal quality and to combat unexpected signal blockage by motion of V-UE and/or the surrounding. Beam sweeping is performed at a specific period by measuring the received power of synchronization signal, and measurement mechanisms like measuring the received power of Channel State Information Reference Signal (CSI-RS) or DMRS can be also considered. For beam selection, the best beam is selected for Tx or Rx at each time instance (e.g. slot). Lastly, an efficient scheduling and RRM schemes enabling higher system throughput and a seamless handover mechanism minimizing the communication interruption time are studied.

C. Integrated RRM in MC

Aiming at demonstrating satellite/cellular MC, 5G-ALLSTAR builds on the 4G and 5G RRM functions involved in interference mitigation, like Coordinated Multi-Point, Enhanced Inter-Cell Interference Coordination or CA with carrier-cross-scheduling. The coordination between satellite gNB(s) and cellular gNB(s), and between cellular gNBs, relies on signal-to-interference-plus-noise ratio (SINR) measurements, on the identification of the critical regions where interference occur and need mitigation, on the agreement on sets of radio resource and cell regions where the coordination is required (e.g. cell edge) and on the set up of the shared resource in time (e.g. thanks to Almost Blank Sub-frames) and frequency (e.g. with Primary and Secondary CCs or by splitting the shared band into – possibly adjacent – sub-bands) domains. In 5G-ALLSTAR, these coordination mechanisms inherited from 4G and 5G are analysed and their adaptation to satellite/cellular MC is evaluated. The key issues that 5G-ALLSTAR faces for hybrid satellite/cellular systems are mainly due to the round trip delay between the measurement and the command that configures the coordination (longer for the satellite system than for cellular systems) 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.

D. Traffic Flow Control in MC

5G-ALLSTAR is investigating Traffic Flow Control algorithms, integrated into the Traffic Flow Control module as shown in Fig. 1. Such algorithms provide traffic steering, splitting and switching decisions on the basis of a set of inputs (e.g., QoS profile and requirements, personalized Connection Preferences, actual network performances), thus coping with MC issues by selecting the most promising RATs/cells within the area covered by gNB-CU in order to guarantee network reliability and increase the whole traffic throughput for each UE.

IV. 5G-ALLSTAR Proof of Concept

5G-ALLSTAR aims at showcasing the very first joint EU-KR PoC of a 5G system with the MC functionality integrating NR-based satellite and terrestrial radio accesses. The PoC demonstration will deliver 5G experience to users with no service interruption, thus proving, for the first time, the service continuity and the feasibility of high-bandwidth and low-latency applications through the combined access to terrestrial and non-terrestrial networks. In addition, as depicted in Fig. 2, KR trial platform further aims to validate the performance of mmWave-band 5G NR V2X communications with the proposed OL-BSW technique, which will show the applicability of mmWave for 5G vehicular communications. Several KPIs (based on [13]) have been identified as essential requirements to meet during 5G-ALLSTAR development stages, with the final aim to satisfy each considered use case. During the PoC stage user-experienced data rate, user-plane latency and service continuity will be verified. Validation of control-plane latency and reliability will occur at simulation and testbed stages. The overall target KPIs and their mapping to 5G-ALLSTAR deployment stages are displayed in Table I.

As shown in Fig. 2, the concept system also entails global interoperability at CN level between two different trial platforms located in Korea and Europe, which delivers multimedia services like UHD video streaming (enhanced Mobile Broadband-type, eMBB) to users (fixed UE in Europe and moving V-UE in Korea) served by the MC of satellite link and static/mobile mmWave cellular link. For the multimedia service, a 8K video server, which is a part of the EU trial platform, is envisaged to provide 8K video streaming to UEs connected to both EU and KR trial platforms. A tentative plan for the final demonstration of 5G-ALLSTAR is to showcase the first fully integrated satellite/cellular prototyping system for 5G and beyond 5G (B5G) services at a big event (e.g., sporting event like Roland-Garros) in 2021. Visitors can experience a variety of 5G services facilitated by the 5G-ALLSTAR technologies, including delay-sensitive applications (e.g., Virtual-Reality (VR) tennis game or any other games) and high-bandwidth applications (e.g. real-time high-quality tennis game streaming from tennis stadium to Korea). However, the detailed demonstration plan is still subject to change the prior to being finalized.

TABLE I: Targeted MC KPIs to be validated by 5G-ALLSTAR PoC

KPI	**Target performance**	**KPI validation through**	
		Simulation & Testbed	***Field Trial***
User-experienced data rate	50 Mbps on downlink and 10 Mbps on uplink	✓	✓
User-plane latency	Below 10 ms for delay sensitive traffic	✓	✓
Control-plane latency	$<$20 ms	✓	
Reliability	99.999% success probability of transmission	✓	
Service continuity	No service interruption[a]		✓

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

V. Analysis on Potential Use Cases and Vertical Markets

This section mainly investigates and identifies the various potential use cases and associated KPIs that receive benefits from the technologies to be developed in the 5G-ALLSTAR project. It also provides a preliminary techno-economic analysis on the use cases and the targeting vertical markets, which is expected to give valuable insights into developing potential business models/markets for vertical stakeholders.

A. Vehicular Communications

5G developments have increasingly advanced V2X communications, making it one of the first opportunity for 5G technologies to tackle vertical markets. The preliminary evidence we obtained from our Delphi study ([14]) converges with investors' short-term vision of the 5G opportunity (e.g.,

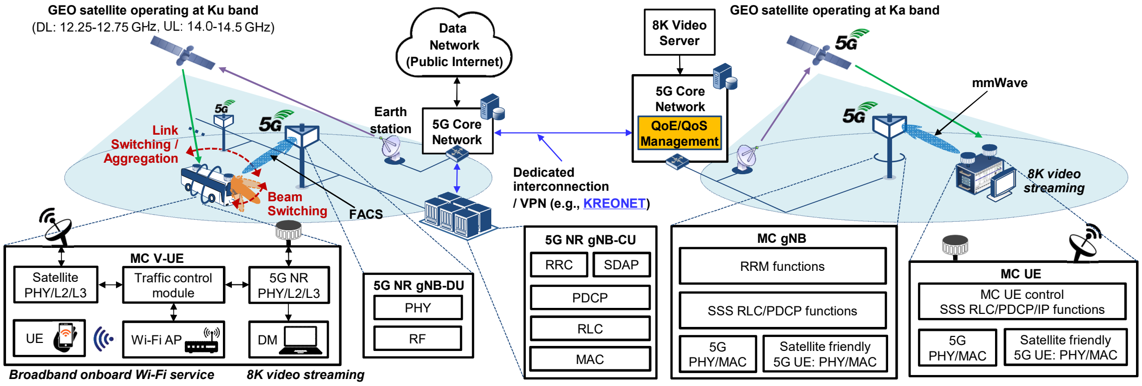

Fig. 2: Preliminary design of KR and EU PoC system and interfaces.

[15]), suggesting that 5G will impact business incrementally compared to what 4G technologies already achieve.

In the consumer market, customers' perception of 5G remains vague and coalescence around the notion of a more stable and faster 4G [16]. While the 5G potential is scenarized and designed in existing studies (e.g., [17]), the disruptive potential of 5G brought by radical applications of the technology is set to emerge only on the long-term. Nevertheless, beyond the recognized technological gap between 4G and 5G, respondents agreed on the strategic relevance of 5G innovation, affecting business models design [18] and the cognitive representation of how firm create, and capture value. In our study, we observe the convergence of informants views on scenarios characterized by the emergence of new actors and the repositioning of incumbents leveraging new value creation opportunities. More precisely, 5G deployment is set to reconfigure market opportunities by creating more value to be financially captured among the involved actors, fostering the emergence of new platforms and multi-sided markets as illustrated in the following scenarios [19]:

1) the diffusion of broadband Wi-Fi service on public transportation, affecting the perceived quality of transportation services for the final customers,
2) the development of an infrastructure for road-safety and advanced V2X systems, reshaping transportation, affecting perceived service quality, and insurances,
3) the improvement of safety and traffic control with, for instance, bus video streaming and connected cars, Cooperative Intelligent Transport (C-ITS) and autonomous driving.

The effects of these emerging scenarios have profound implications. In South Korea, for example, the simple mobile Internet enabled through public Wi-Fi (e.g., on buses, trains, subways) has become the second most popular way to be connected to the network after home [20]. Nevertheless, most public transportation in Korea do not provide free Wi-Fi services, and even if they do, Wi-Fi service quality, in general, is inferior to cellular. Therefore, most Korean citizens use mobile Internet services through this latter. The diffusion of 5G service is expected to become the core broadband wireless connection in transportation allowing users to consume more consistently online services based on broadband and reliable on-board mobile connectivity. Also, new revenue models are expected to impact the relevant household and business connectivity spending.

B. Multi-Connnectivity

Owing to 5G satellite connectivity that has capability to provide direct or complementary connections to UEs, several new use cases, as listed in TABLE II, are expected to emerge, and potential business models of the MC-related use cases are summarized as:

- Provide a worldwide availability of the network through satellite connection: both free and paid access are possible. Telecommunications service providers may offer new services like frequent flyers program;
- Provide requested network access to remote areas: new markets will thus be available. In case of disaster, better access to the network to NGOs, victims, companies ... could help to overcome crises;
- Develop the Internet of Things as a large amount of objects, irrespective of their location, could be connected
- Create new nodes, both human and digital, therefore new business and new actors/activity because of the increase of the networks;
- In terms of new industrial practices: the use of robots through the MC will highly increase as it will replace manpower in case of danger or poor human efficiency;
- Forecast of new start-ups, for instance in e-health, which will compete with large companies because of the ubiquitous connectivity and better reliability and validity;
- Examples of new services: improved security, better traceability, new ways of travelling, tactile Internet, virtual reality, multi-person video call.

VI. Relevant Standardization Activities

5G-ALLSTAR devotes to a number of targeted, interrelated and closely coordinated standardization activities, mainly on 3GPP Rel-16 and Rel-17. These activities are derived from the architecture aspects as well as the research pillars.

In the 3GPP RAN#80 plenary meeting, several Rel-16 Study Items (SIs) and Work Items (WIs) were discussed. Among them, NR NTN and NR V2X items are closely related to the research topics in 5G-ALLSTAR, as discussed in detail in the following subsections.

A. NR V2X

The NR V2X targets standardization of 5G NR in the area of vehicle applications with specific goals of road safety, accident-free cooperative autonomous driving and in-car infotainment. The related use cases are vehicles platooning, extended sensors, advanced driving, remote driving, tethering-via-vehicle, and so on. The SI for NR V2X (V2X phase 3) approved in the RAN#80 meeting started its first meeting at RAN1#94 meeting in August of 2018, and officially ended at RAN1#96 meeting in February of 2019. Subsequently, NR V2X WI has started since RAN1#96-Bis meeting in April of 2019. The objective of NR V2X includes sidelink design, Uu enhancements for advanced V2X use cases, Uu-based sidelink resource allocation/configuration, RAT/Interface selection for operation, QoS management, and coexistence, spanning over RAN1, RAN2 and RAN3 [21]. As aforementioned, since 5G-ALLSTAR PoC entails the development and validation of a 5G NR-based vehicle communications system using mmWave band, its outcomes are expected to contribute to the development of the NR V2X specification.

B. NR NTN and MC

The scope of the NR NTN is to identify solutions for physical-layer control, random access, retransmission schemes from RAN1 perspective, and to study MAC, RLC, RRC, handover impacts from RAN2 and RAN3 perspectives [22]. In addition, MC between NTN-based NG-RAN and terrestrial NG-RAN or between two different NTN-based NG-RAN have been studied within NTN SI. More specifically, several architecture proposals for MC were provided and its impact to NG-RAN were studied in 3GPP RAN3 [23]. Since the satellite support and MC are the main research topics of 5G-ALLSTAR project, we are participating in the NTN standardization activities. We have already contributed with 5G-ALLSTAR's views on physical-layer solution for NTN and MC-related architecture perspectives to the NTN technical document, the final version of which will be a useful reference for the 5G-ALLSTAR system design and implementation.

TABLE II: MC Use Cases

Use case	Description
Backhauling for eMBB and narrow-band services	Providing efficient multicast, broadcast services delivery to fixed platforms (such as home/office) or moving platforms
Hybrid multi-play for eMBB and narrow-band services	MC satellite/cellular to serve broadband & narrow-band services to fixed platforms (e.g. small home / small office) or moving platforms (e.g. high-speed trains/buses) to ensure service reliability
Network resilience for network operation and/or public safety	In a multi-access cellular / satellite context, each access attempts to protect the other one
ATSSS functions, flexibility and scalability	Access traffic steering, splitting and switching (ATSSS)-related use cases and scalability and flexibility can be demonstrated by ATSSS functions

VII. Conclusions

This paper presented an overview of 5G-ALLSTAR, which is a joint KR-EU collaboration project that aims to develop not only 5G NR-based cellular and satellite systems, but also an integrated cellular/satellite system with MC technology for a variety of broadband, reliable, and ubiquitous 5G and B5G services that has recently emerged. To this end, firstly, study was conducted to define the basic system architecture and necessary functionalities, and several detailed key technologies for each targeted use case were discussed. Secondly, we discussed a preliminary PoC architecture and target KPIs for the final demonstration at a big sporting event (e.g., Roland-Garros). In addition, we presented potential use cases of 5G-ALLSTAR technologies as well as a brief analysis on the market/business aspects. Lastly, we also gave a brief overview of relevant standardization activities mainly led by 3GPP.

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