

Review

Simultaneous Utilization of Multiple Radio Access Networks in Ubiquitous 6G Connectivity for Autonomous Ships: Opportunities and Challenges

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Abstract: The growing significance of ubiquitous 6G connectivity within the maritime sector is a consequence of its evolution into an era characterized by the adoption of autonomous ships. This evolution necessitates the development of adaptable communication capabilities, even in the face of increasing heterogeneity in Radio Access Networks (RANs). This heterogeneity is a consequence of the extended lifespans of maritime communication technologies used by both legacy and emerging ships at sea, in contrast to the generational shift seen in terrestrial communication technologies. This paper undertakes a comprehensive examination and provides an insightful overview of communication technologies within the framework of 3rd Generation Partnership Project (3GPP) standards with the aim of preparing for the forthcoming 6G standardization to enable ubiquitous 6G connectivity in the maritime domain. The primary focus of this paper is the mobile RAN entities (e.g., satellites and uncrewed aerial vehicles (UAVs)) positioned for integration into the 5G and beyond systems. These entities are distinguished by their differences from conventional terrestrial RAN entities, which are typically stationary on land. This integration enables User Equipment (UE) to connect to various RAN entities, including mobile RANs, interconnected with core networks, thereby granting UE secure access to external internets through 5G and beyond systems, enabling them to enjoy a diverse range of application services, even in areas beyond terrestrial coverage, such as at sea. This paper further conducts an in-depth analysis of a transport layer-level solution known as the Access Traffic Steering, Switching, and Splitting (ATSSS) feature enabling a concurrent connection to multiple RANs for data-traffic delivery. Furthermore, this paper explores opportunities and challenges for future research in the realm of forthcoming 6G standardization within 3GPP, especially when combined with the ATSSS features for the success of autonomous ships within the maritime sector. These considerations encompass the concept of autonomous ships as mobile RAN entities, the integration of legacy maritime communications into the 6G framework, and the variability in maritime channel measurements, generally employed as one of the criteria for selecting an appropriate RAN among multiple options, influenced by uncontrollable factors such as climate change.

Keywords: heterogeneity; concurrent connection; maritime communication; simultaneous utilization; 6G; autonomous ship; mobile RAN



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1. Introduction

Traditional analog maritime communications still remain a dominant means of communication at sea, primarily serving voice communication, distress calls, and critical navigational functions. These systems leverage their extensive communication coverage, a characteristic derived from their unique frequency properties. However, as maritime communication requirements evolve, these systems reveal limitations in radio performance. This evolution necessitates the adoption of high-performance and secure communication technologies tailored to the specific challenges of maritime environments.

Satellite communication has emerged as a prevalent method for maritime communication, particularly for vessels navigating globally. This shift began with the adoption of the convention on the International Mobile Satellite Organization (formerly known as Inmarsat) by the International Maritime Organization (IMO) in 1976. This convention was established to oversee and regulate the provision of specific satellite-based maritime distress communication services, primarily integrated within the Global Maritime Distress and Safety System (GMDSS) [1]. Presently, the IMO is in the process of reviewing the GMDSS, with plans for its modernization expected to take effect in 2024. However, existing maritime communication systems prove inadequate in meeting the performance requirements necessary to support imminent advancements in the maritime industry. These advancements encompass the operation of autonomous ships on extended ocean voyages and the development of intelligent offshore aquaculture, etc. Despite offering broader communication coverage than terrestrial cellular communications, current satellite communications, which rely on proprietary solutions tied to manufacturers, are inadequate in meeting the evolving demands of the maritime sector due to their lack of global interoperability, unlike 3GPP standards-based products and solutions with a dominant economy of scale in the market.

In stark contrast, first-generation (1G) analog terrestrial communication has become obsolete. Second-generation (2G) and third-generation (3G) digital communication technologies, such as Global System for Mobile Communications (GSM) and Universal Mobile Telecommunication System (UMTS), have been globally phased out. Fourth-generation (4G) communication, represented by LTE, has achieved widespread deployment. Furthermore, fifth-generation (5G) communication is exerting its influence by driving the digitalization and mobilization of various industries while catalyzing the evolution of the Information and Communication Technology (ICT) sector [2].

In addition, the 3rd Generation Partnership Project (3GPP) [3] has been actively engaged in the systematic development of advanced and promising evolutionary features, custom-tailored to meet the stringent requirements of industries venturing beyond the boundaries of 5G [4–6]. Notably, a diverse range of industry sectors, including automotive, factory automation, and public safety, has persistently advocated for enhanced coverage. This expanded coverage extends across both network infrastructure and off-network scenarios, encompassing indoor and outdoor environments.

In response to these persistent demands, 3GPP has embarked on a rigorous standardization process, characterized by an unwavering commitment to enhancing performance and optimizing user experiences. This comprehensive effort includes the extension of communication coverage, such as the introduction of satellite components as part of 5G New Radio (NR), and the integration of various advanced features aimed at improving reliability and reducing latency. This groundbreaking initiative commenced with the introduction of Release 15, representing a pivotal milestone in 3GPP's specifications for 5G. Release 15 established the foundational architecture capable of accommodating the diverse requirements of multiple industries [7].

Furthermore, the dynamic and evolving requirements originating from these industry sectors continue to exert a profound influence on the trajectory of ongoing standardization efforts within 3GPP. This transformative journey began with the introduction of Release 18, marking the inaugural version of 3GPP specifications for 5G-Advanced [8]. These cutting-edge technologies operate seamlessly within a globally harmonized communication framework, strategically positioned to deliver benefits across multiple industries by leveraging the economies of scale inherent in 3GPP standards-based products and solutions. Moreover, these advancements are poised to effectively address evolving needs within the forthcoming standardization framework, often referred to as 6G. This framework is anticipated to closely align with the framework and overall objectives of the future development of International Mobile Telecommunications (IMT) for 2030 and beyond, encompassing six distinct usage scenarios, including the realization of ubiquitous connectivity, and four overarching aspects, notably the imperative of connecting the unconnected [9]. These

objectives hold particular significance for the maritime sector, given its distinctive and evolving communication demands.

It is clear that various industry sectors share common demands in terms of enabling technologies within the context of 3GPP standardization, and some of these demands may have relevance within the maritime sector. This relevance is particularly evident when considering the need to enhance communication coverage at sea, which can be achieved through the adoption of cutting-edge enabling technologies and solutions within the 3GPP framework. The inclusion of the maritime domain within the 3GPP standardization framework, starting from Release 16 [10–12], has brought a wealth of enabling technologies from 5G and beyond into the scope of maritime transformation. However, it is crucial to acknowledge that these technologies may require further optimization to seamlessly align with the specific challenges posed by the maritime environment. This recognition emphasizes the need for additional work within 3GPP to address maritime-specific requirements, which should be carefully formulated with significant input from key stakeholders representing the global maritime sector, including maritime safety aspects. These requirements are poised to assume a pivotal role in the forthcoming 6G standardization, with a core objective of delivering evolved performance and tailored user experiences customized to meet the distinctive challenges of maritime environments.

Consequently, there is substantial value in conducting a comprehensive review of standardized 5G enabling technologies, with a particular focus on integrating mobile RAN entities like satellite access components into 5G and beyond systems and supporting the concurrent utilization of multiple Radio Access Networks (RANs) including those mobile RAN entities. This effort takes into account the extended operational lifespans of the maritime communication technologies, which result in a diverse landscape of multiple access networks within the maritime sector. Effectively, harnessing multiple RANs simultaneously and efficiently is crucial for achieving ubiquitous connectivity, which is an essential foundation for the successful deployment of autonomous ships in the maritime sector. The key contributions of this paper are summarized as follows:

- This paper contributes to the insightful analysis of Access Traffic Steering, Switching, and Splitting (ATSSS) features, which enable the simultaneous resource utilization of multiple RANs including mobile RANs within the 3GPP standardization framework. This transport-layer solution offers substantial advantages to the maritime sector, preparing for impending shifts, including the adoption of autonomous ships that require ubiquitous connectivity during their voyages.
- In addition, this paper makes a significant contribution by conducting a thorough examination of standardization trends and technologies within 3GPP, with a specific focus on the integration of satellites and low-altitude Uncrewed Aerial Vehicles (UAVs) as mobile RAN entities. These mobile RAN entities, integrated into 6G systems, are poised to play a crucial role in ensuring uninterrupted connectivity and optimizing concurrent resource utilization across multiple RANs when combined with ATSSS features, given the anticipated increase in RAN heterogeneity in the near future as the maritime sector undergoes digitalization and mobilization, including the introduction of autonomous ships.
- Finally, this paper contributes significantly by exploring opportunities and challenges for future research within the context of ATSSS features in the maritime communication scenarios in terms of three aspects encompassing the concept of autonomous ships as mobile RAN entities, the integration of legacy maritime communications into the 6G framework, and the variability in maritime channel measurements, generally employed as one of the criteria for selecting an appropriate RAN among multiple options, influenced by uncontrollable factors such as climate change.

This paper is organized as follows: in Section 2, we present an overview of related work from academic research and global standardization trends, with a particular focus on ITU-R [13] and 3GPP, for the provision of seamless connectivity over 6G systems for the evolution of the maritime sector including autonomous ships. Section 3 provides

a comprehensive exploration of integrating satellite and low-altitude UAVs as mobile RAN entities into 5G and beyond. Following this, Section 4 explores transport-layer solutions for efficiently distributing data traffic across two access networks, catering to various applications within the 3GPP standardization framework. In Section 5, we navigate the opportunities and challenges that warrant further investigation in the ever-evolving landscape of providing ubiquitous connectivity optimized for autonomous ships in the maritime sector. Finally, Section 6 offers our conclusions.

2. Related Works

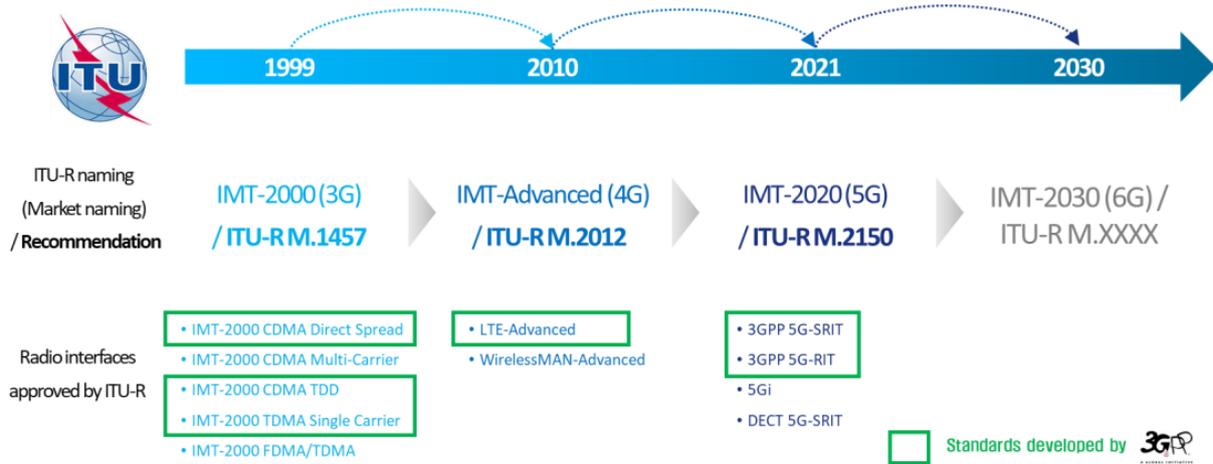
2.1. Academic Research

Since the advent of wireless communication technologies, achieving seamless communication has been a fundamental objective pursued by nearly all communication technologies. Conventional wireless communication networks incorporate radio access network selection algorithms, including handover mechanisms, which predominantly prioritize signal strength as the key determinant in network switching decisions, with the overarching objective of maintaining device connectivity throughout transitions [14]. In the trajectory of mobile communication systems progressing beyond 5G, often referred to as 6G, considerable academic research has been conducted to formulate frameworks and protocols that facilitate seamless provisioning of wireless communication anywhere, anytime [15–23]. This pursuit seeks to not only enhance throughput and bolster reliability but also to optimize radio resource utilization across various radio access technologies (RATs) within a unified communication ecosystem.

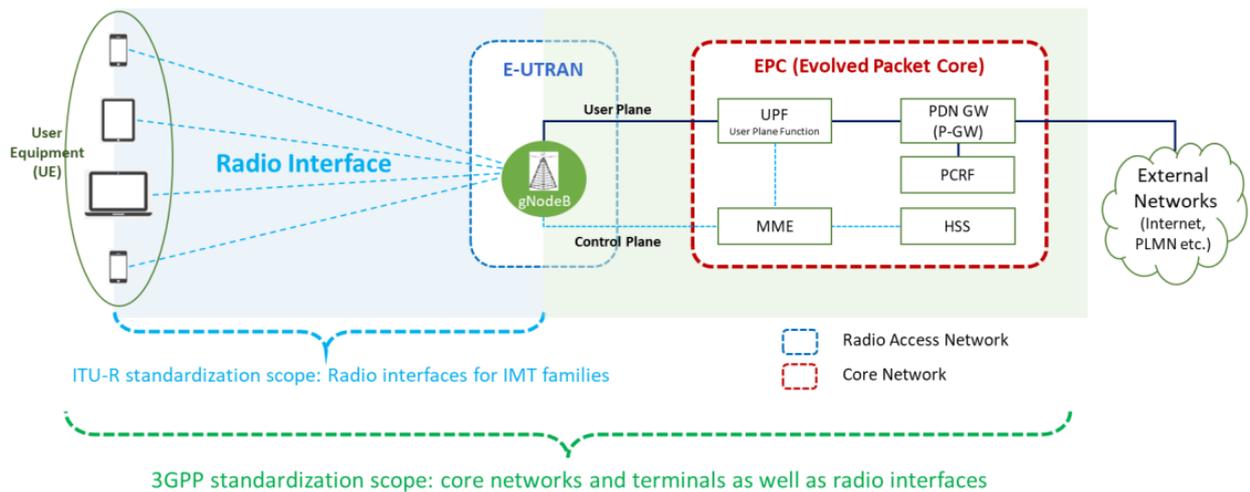
Within the realm of maritime communication, pertinent related works elucidate approaches for incorporating autonomous ships into a cohesive communication framework, encompassing advancements like 5G and its evolutionary successors (i.e., 6G) with AI-aided solutions for ubiquitous connectivity in the maritime communication environment [24–29]. The investigation into the harmonious coexistence of autonomous and conventional vessels has also been explored, aiming to facilitate the autonomous ships' effective conveyance of their operational status and intentions to traditional ships via diverse maritime communication methods [30].

2.2. Global Standardization in ITU-R and 3GPP

ITU-R and 3GPP have a cooperative relationship in the development of global mobile communication standards. ITU-R establishes comprehensive guidelines and recommendations to steer the evolution of IMT families, and ITU-R Working Party 5D (WP 5D) bears the responsibility for the comprehensive radio-system aspects of the terrestrial component within IMT systems, which encompass IMT-2000, IMT-Advanced (referred to as 4G or LTE), IMT-2020 (commonly known as 5G), and IMT-2030 (indicative of the forthcoming 6G) [31]. 3GPP is responsible for crafting standards for radio interfaces of IMT families, aligning them with requirements stipulated by ITU-R. Figure 1a summarizes the ITU-R Recommendation and corresponding radio interfaces based on 3GPP standards for IMT families. Furthermore, 3GPP undertakes the formulation of technical standards for core networks and terminals, expanding upon ITU-R's recommendations as shown in Figure 1b. This collaborative effort ensures the worldwide compatibility and efficiency of communication systems, optimizing the utilization of allocated radio frequencies, which contribute to establish the unified communication ecosystems based on 3GPP standards prevalent in the market.



(a) ITU-R Recommendation and corresponding radio interfaces based on 3GPP standards for IMT families



(b) Standardization scope: ITU-R Recommendation for IMT-families vs. 3GPP standards with the example of LTE system

Figure 1. Relations between IMT systems and 3GPP systems.

2.2.1. Standardization Trends for IMT-2030 System in ITU-R

In June 2023, ITU-R WP 5D reached a consensus on the draft new recommendation titled “Framework and overall objectives of the future development of IMT for 2030 and beyond” that addresses the trends, usage scenarios, and capabilities of IMT-2030, serving as the basis for the forthcoming standardization efforts in the development of the next generation of IMT standards [9]. ‘Ubiquitous connectivity’ and ‘connecting the unconnected’ have been incorporated into the IMT-2030 framework. Their inclusion aims to facilitate the extension of communication coverage beyond terrestrial networks, spanning into integrated networks that encompass space, air, ground, and sea, transitioning from the conventional terrestrial-based paradigm. Upon the approval of this draft new recommendation during the fourth quarter of the year 2023 by ITU-R Study Group 5 (SG5), the subsequent standardization efforts will encompass the specification of precise requirements according to the IMT-2030 standardization timeline in ITU-R [32]. This undertaking involves elaborating on exact technical specifications, functionalities, and performance requirements. These particulars will serve as guiding principles for the advancement of IMT-2030 standards and their practical implementations in 3GPP.

2.2.2. Standardization Trends for 5G and Beyond in 3GPP

For seamless communication and the improvement of communication quality, a range of features including multi-connectivity solutions have been developed in 3GPP across successive generational advancements [9,33,34]. Preceding the establishment of 5G standards, the prevalent approaches to enable multi-connectivity predominantly stemmed from assessments within RAN domains. These approaches were designed to ascertain the optimal selection of radio channels, both within a communication system with a single connection to a certain RAN and in interworking scenarios involving 3GPP systems (e.g., LTE) and non-3GPP systems (i.e., Wi-Fi) [35]. With the integration of satellite access components as part of the 5G landscape in 2022 [36–38], a critical challenge has arisen concerning the efficient utilization of multiple RANs within a cohesive communication framework. This challenge aims to harness the potential for augmented throughput, enhanced reliability, and diminished energy consumption in the context of 5G and subsequent standardization efforts [39,40]. The forefront of 5G technology pertaining to the efficient resource utilization of multiple RANs will undergo continuous advancement in the subsequent generation. These capabilities are of paramount importance in meeting the demands for ubiquitous connectivity within the IMT-2030 system. A comprehensive exploration of these features will be presented in the forthcoming sections.

3. Mobile RAN Entity Integrated into 5G and Beyond

In contrast to its predecessors, 5G has been designed to cater to the diverse requirements stemming from various industries, including the automotive, railway, public safety, broadcasting, and maritime sectors. Furthermore, continuous efforts are devoted to advancing these technologies, facilitating seamless communication across diverse deployment scenarios that are indispensable for the mobilization and automation of various industries. It is crucial to delve into the cutting-edge advancements in 5G technologies related to the efficient utilization of multiple RANs, which assume a pivotal role in providing ubiquitous connectivity to autonomous ships within the maritime sector considering the increase in the heterogeneity in RANs, spanning the 5G and beyond systems.

Traditionally, RAN entities based on 3GPP standards were perceived as stationary and lacking mobility, while User Equipment (UE) was recognized as a mobile entity, transitioning between different spatial points. This dichotomy necessitated solutions such as handovers for UE in connected mode or cell reselection for UE in idle mode to ensure uninterrupted communication as the UE moves. However, with the advent of the 5G and beyond era, mobile entities like satellites and UAVs are poised to be integrated into RAN equipment, despite the myriad challenges arising from their departure from conventional assumptions concerning the mobility capabilities of both RANs and UE. This section provides a comprehensive exploration of the integration of satellites and UAVs into the 5G and beyond system, formulated within the framework of 3GPP standardization.

3.1. Integration of Satellite Components into the 5G and Beyond Landscape

The incorporation of satellite components into the 5G system began with its inclusion in the specifications of 3GPP Release 17 in 2022. As outlined in Figure 2, after this pivotal integration, a series of investigations and initiatives followed, aiming at further enhancement. The initial design objective primarily aimed at establishing the connectivity between traditional mobile phones and a satellite component intricately woven into the architecture of the 5G framework depicted in Figure 3, functioning within the sub-6GHz frequency band. This integration sought to extend 5G's reach to mobile users situated in geographically challenging areas, such as maritime expanses. The satellite component, illustrated in Figure 3a as a transparent payload, was designed to serve as a repeater, limited to radio frequency (RF) processing tasks, including frequency conversion, amplification, and beam management [36–38].

Study Phase (Release 16)	5GSAT Phase 1 (Release 17)	5GSAT Phase 2 (Release 18)	5GSAT Phase 3 (Release 19)
Study on using Satellite Access in 5G (FS_5GSAT) - Completion date: June 2018	Work on using Satellite Access in 5G (5GSAT) - Completion date: September 2018		Study on satellite access - Phase 3 (FS_5GSAT_Ph3) - Completion date: September 2023 Satellite Access Phase 3 (5GSAT_Ph3) - Completion date: December 2023
Feasibility Studies Normative Works Stage 1 Studies/Works Stage 2 Studies/Works Stage 3 Studies/Works	Study on architecture aspects for using satellite access in 5G (FS_5GSAT_ARCH) - Completion date: June 2022 Work of Integration of satellite components in the 5G architecture (5GSAT_ARCH) - Completion date: September 2021	Study on 5GC enhancement for satellite access Phase 2 (FS_5GSAT_Ph2) - Completion date: September 2022 5GC/EPC enhancement for satellite access Phase 2 (5GSAT_Ph2) - Completion date: June 2023 Study on Support of Satellite Backhauling in 5GS (FS_5GSATB) - Completion date: March 2023 Stage 2 of 5GSATB (5GSATB) - Completion date: June 2023	(1) The main Rel-17 Stage 3 normative works for NR NTN solutions have been completed in June 2022 and remaining on radio performance parts and device conformance are scheduled to be completed by December 2022 and 2023 correspondingly. (2) The work for the support of NB-IoT and eMTC via satellite access over LTE is not included here.
	CT aspects of 5GC architecture for satellite networks (5GSAT_ARCH-CT) - Completion date: March 2022	CT aspects of 5GSAT_Ph2 (5GSAT_Ph2) - Completion date: March 2024 CT aspects of 5GSATB (5GSATB) - Completion date: December 2023	
Study on solutions for NR to support non-terrestrial networks (FS_NR_NTN_solutions) - Completion date: December 2019	Solutions for NR to support non-terrestrial networks (NR_NTN_solutions) - Completion date: December 2023	NR Non-Terrestrial Networks enhancements (Core / Perf parts) (NR_NTN_enh) - Completion date: June 2024	

Figure 2. Studies and works for satellite access as a 5G New Radio and a backhaul entity in 3GPP.

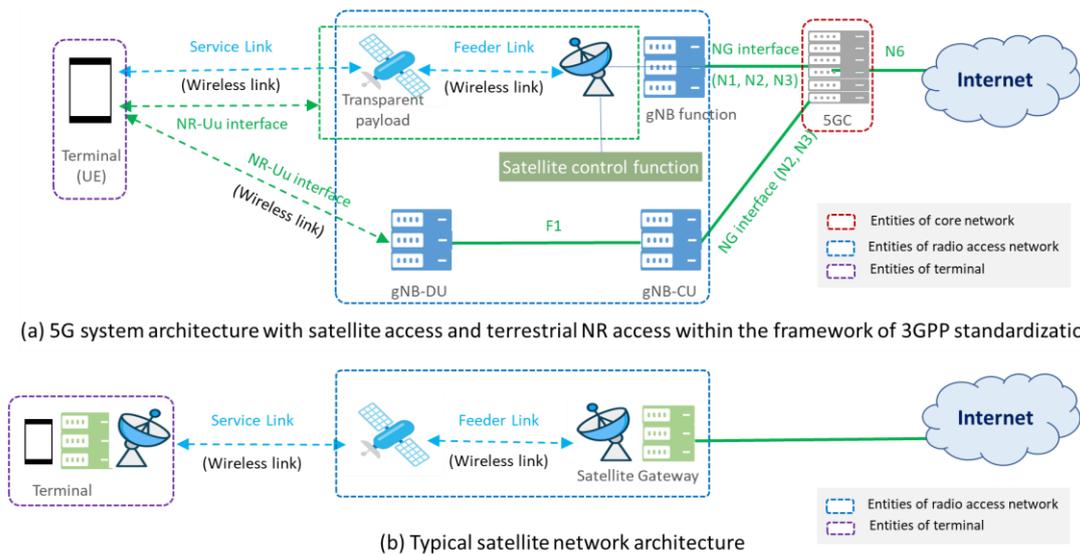


Figure 3. Comparison between 5G system architectures with transparent satellite access and with terrestrial NR radio access and typical satellite network architecture.

However, since the inception of 5G’s design in 3GPP Release 15 specifications, operating under the presumption of a terrestrial-based radio interface environment [7,33], numerous challenges emerged due to the unique characteristics associated with satellites. Within the framework of conventional 3GPP standards-based communication systems, these challenges encompass various critical dimensions [41,42]. They include significant considerations like the substantial round-trip delays inherent to especially Geostationary Earth Orbit (GEO) satellites. Additionally, complexities have arisen from rapid Doppler Shift and intricate mobility patterns not typically encountered in terrestrial-based RAN equipment, particularly evident within the realm of Low Earth Orbit (LEO) satellites. Moreover, a formidable obstacle has emerged in the form of establishing communication coverage across geographical regions that extend beyond the boundaries of a single country. As delineated in Release 17 [34], the solution adopted has illuminated suboptimal

design principles from the perspective of satellite components. These principles have been implemented through the adaptation of key procedures, notably encompassing aspects such as timing advance, hybrid automatic repeat request (HARQ) operations, and tracking area management. Importantly, this adaptation has been executed while concurrently preserving established procedural norms that have conventionally underpinned radio interfaces within the framework of 3GPP standardization.

Furthermore, ongoing advancements are currently under way within 5G-Advanced standardization [43–45]. Aligned with the goals of the IMT-2030 framework including ‘ubiquitous connectivity’ and ‘connecting unconnected’, it is anticipated that satellite components will be seamlessly and comprehensively integrated into the foundational design of the 6G communication system within the framework of 3GPP standardization [36,46,47].

3.2. Integration of Low-Altitude UAVs into 5G and Beyond

The integration of low-altitude UAVs and Uncrewed Aerial System (UAS) traffic management into 5G systems has become a prominent research focus in both academic and global standardization communities [48–51]. As illustrated in Figure 4, UAS Phase 1 defines the architecture and protocols for the UAS application layer, encompassing UAS application enablers within the 3GPP standardization framework [52–56]. UAS Phase 2 is currently under standardization, with a specific focus on meeting regulatory requirements for broadcast remote ID and detect and avoid (DAA) solutions [57,58]. Concurrently, UAS Phase 3 is in the process of standardization to develop additional service requirements.

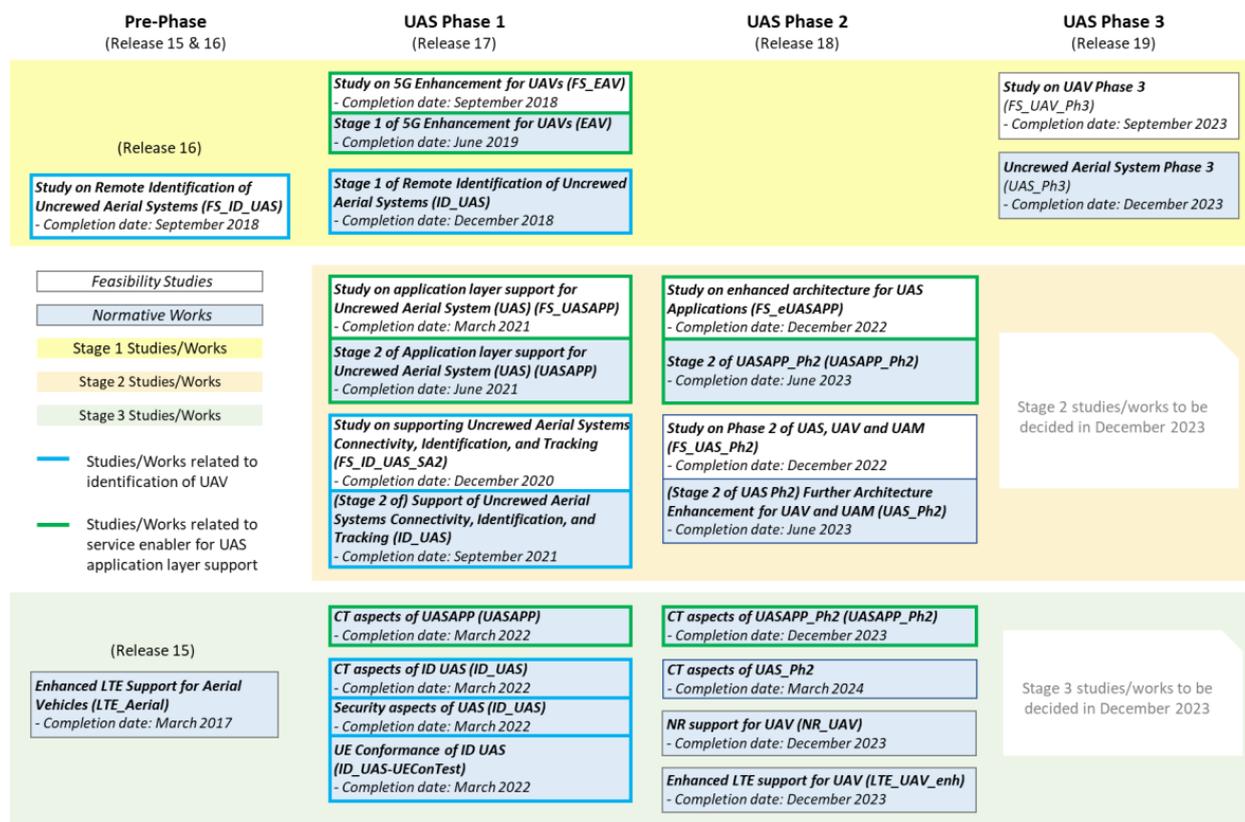
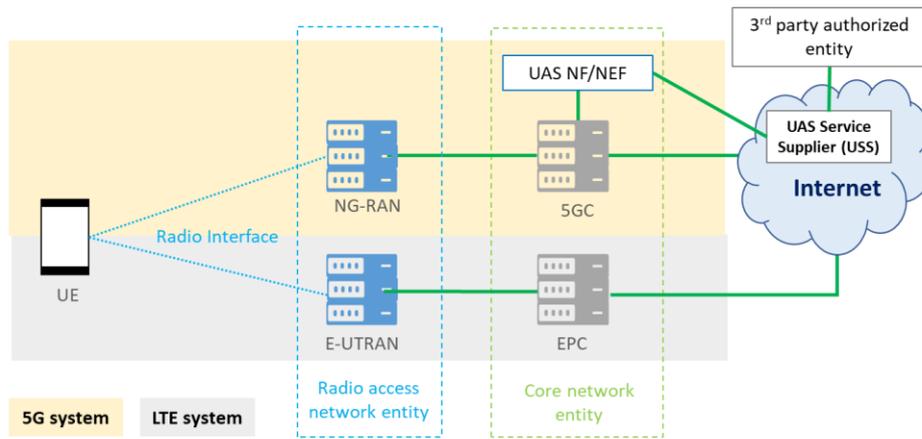
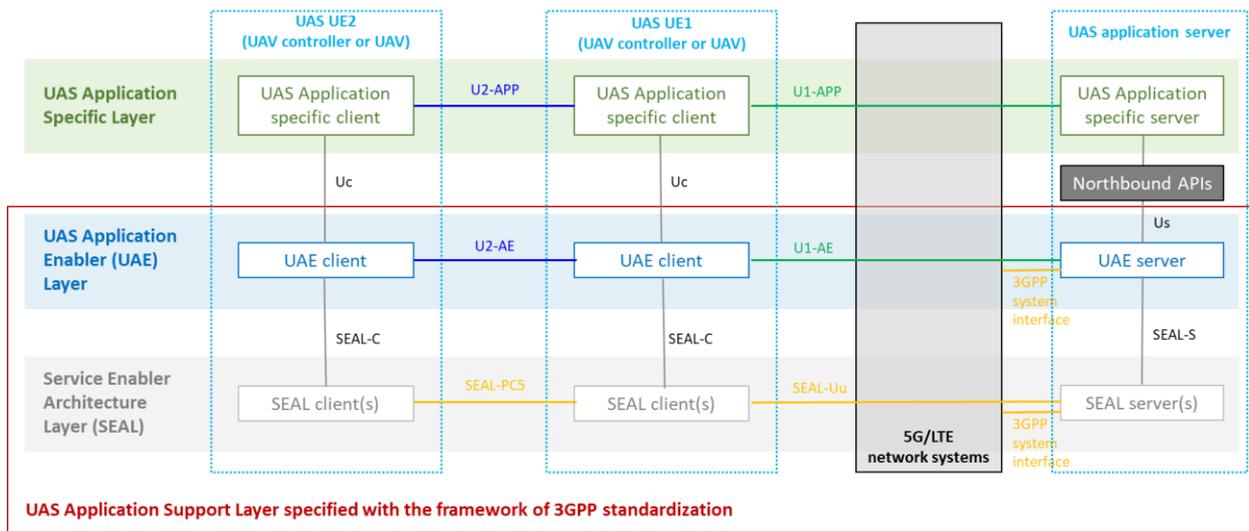


Figure 4. Studies and works for Uncrewed Aerial Systems (UAS) in 3GPP.

As depicted in Figure 5, within the context of 3GPP standardization, UAS Phase 1 comprehensively outlined the functional architecture, procedures, and information flows that govern the integration of the UAS Application Enabler (UAE) layer with 5G/LTE systems. This integration effectively harnessed the capabilities offered by the Service Enabler Architecture Layer (SEAL).



(a) 5G/LTE system architecture for UAS



(b) Architecture for UAS application layer over 5G/LTE systems

Figure 5. System architecture and UAS application enabler layer for UAS over 5G/LTE system in UAS Phase 1.

The following functionalities were specified within the UAS Phase 1 framework, contributing to the enhancement of precision and versatility in UAV monitoring within the network:

- UAV remote identification—Incorporated into 5G/LTE systems, the civil aviation administration (CAA)-Level UAV ID serves as a globally unique and easily readable identifier for UAVs. This identification plays a crucial role in ensuring the accurate routing of requests to the designated UAV service supplier (USS) for the retrieval of UAV-related information. During the initial registration of a UAV by its owner with the USS, the CAA-Level UAV ID is assigned to the UAV. It encompasses essential aviation-level data, including the UAV’s serial number, pilot information, and UAS operator details. Subsequently, this information is transmitted to the USS for meticulous record keeping and management;
- UAV USS authentication and authorization (UUAA)—After successful 3GPP authentication of the UE using the credentials of a mobile network operator (MNO), a dedicated UUAA procedure is established to verify the UAV’s registration with the USS. This procedure relies on the CAA-Level UAV ID for USS authentication. In 5G systems, it can occur during 3GPP registration or packet data unit (PDU) session setup for

UAS services and in LTE systems, it is during packet data network (PDN) connection establishment. The UUAA procedure comprises a service-level-AA container, a Service-level-AA procedure for authentication/authorization, and an API-based method. Security material specifics are considered outside the scope of 3GPP as they are application layer concerns;

- Command and Control (C2) communication over 5G/LTE—To facilitate C2 communication over 5G/LTE systems, specifically involving a UAV user plane connection with the UAV controller, it is imperative to obtain authorization from the USS. This authorization encompasses several key aspects, including permission for the UAV and UAV controller pairing and, optionally, flight authorization for the UAV, a process overseen by the USS. To support these vital functions, the existing non-access stratum PDU session establishment and modification procedures have been expanded. These enhancements enable the inclusion of critical elements such as the CAA-level UAV ID and other application-layer authorization information within the service-level-AA container, ensuring a robust framework for secure and controlled cellular communication in UAV operations;
- UAV location reporting and tracking—The specification of UAV location reporting and tracking extensively relies on the reuse of existing location procedures [59]. In this framework, the UAS network function (UAS NF/NEF) engages with network functions such as the gateway mobile location center and the mobility management functions (e.g., access and mobility management function (AMF) in the case of 5G systems, mobility management entity (MME) in the case of LTE systems). Various UAV tracking modes have been established to cater for diverse operational scenarios:
 - (1) UAV location reporting—The USS subscribes to the UAS NF, specifying preferences for accuracy and timing, to receive continuous UAV location updates;
 - (2) UAV presence monitoring—The USS subscribes to event reports triggered when a UAV enters or exits a defined geographical area;
 - (3) List of aerial UEs—The USS can request the UAS NF to provide a comprehensive list of UAVs within a geographical area served by the PLMN. This multifaceted tracking system enhances the precision and versatility of UAV monitoring within the network.

These efforts are aimed at strengthening network support for UAVs, encompassing aspects such as predictive monitoring, flight-path planning, reliable communication, and enhancing UAV operational control and safety. This includes the ability to detect connected UAVs, manage flight paths, and identify non-3GPP flying objects. Notably, the incorporation of UAVs into the 5G and beyond systems to extend coverage is currently outside the scope of consideration within 3GPP. However, ongoing research endeavors are actively exploring the integration of UAVs as a mobile RAN entity into the forthcoming 6G system, with the goal of extending communication coverage beyond regional boundaries [48,60–62].

4. Simultaneous Utilization of Multiple RANs within a 3GPP Framework

The effective utilization of radio resources has become a significant focal point in academic research and global standardization efforts, increasingly incorporating machine learning algorithms [63–65]. With the emergence of 5G and beyond systems, a multitude of RANs have become accessible, expanding their coverage even to non-terrestrial regions, thanks to the addition of satellite components such as mobile RANs integrated into 5G and beyond. Furthermore, UAVs are poised to play a pivotal role as a mobile RAN, facilitating expanded coverage in the forthcoming 6G standardization. Traditionally, cellular networks like LTE connect to just one access network at a time [14] or utilize unlicensed spectrum bands as part of 3GPP-based radio access resources for offloading wireless data traffic [66,67], alongside a range of radio access interface-level solutions [68]. However, the simultaneous connection and utilization of multiple access networks now empowers the distribution of data traffic [69,70]. This section explores transport layer-level solutions for

efficiently distributing data traffic simultaneously across two RANs for several applications in the context of 3GPP standardization, as outlined in Table 1.

Table 1. Summary of ATSSS functions in the context of 3GPP standardization.

Function	ATSSS Phase 1 (Release 16)	ATSSS Phase 2 (Release 17)	ATSSS Phase 3 (Release 18)
Steering functionality	<ul style="list-style-type: none"> MPTCP functionality for TCP traffic ATSSS-LL functionality for all types of traffic 	<ul style="list-style-type: none"> Same as ATSSS Phase 1 	<ul style="list-style-type: none"> Same as ATSSS Phase 1 MPQUIC steering functionality over HTTP
Steering Mode (SM)	<ul style="list-style-type: none"> Active-standby SM Smallest delay SM Load-balancing SM with pre-defined or fixed split percentages Priority-based SM 	<ul style="list-style-type: none"> Same as ATSSS Phase 1 	<ul style="list-style-type: none"> Same as ATSSS Phase 1 Redundant SM
	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Steering Mode Indicator indicating either autonomous load-balance indicator or UE-assistance indicator for load-balancing SM Threshold Values indicator in case of load-balancing SM with fixed split percentage or priority-based SM 	<ul style="list-style-type: none"> Same as ATSSS Phase 2
Performance measurement function (PMF) to assist access selection	<ul style="list-style-type: none"> Round Trip Time (RTT) measurement in case of smallest delay mode in use UE's reporting on access availability/unavailability to UPF 	<ul style="list-style-type: none"> RTT measurement same as ATSSS Phase 1 Packet Loss Rate (PLR) measurement for a service data flow (SDF) over both accesses 	<ul style="list-style-type: none"> Same as ATSSS Phase 2
	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Access performance measurement over a certain QoS flow 	<ul style="list-style-type: none"> Same as ATSSS Phase 2
Combination of two access networks and core networks	<ul style="list-style-type: none"> a 3GPP access path over 5GC/a non-3GPP access path over 5GC 	<ul style="list-style-type: none"> Same as ATSSS Phase 1 a 3GPP access path (e.g., E-UTRAN) over EPC/a non-3GPP access path over 5GC 	<ul style="list-style-type: none"> Same as ATSSS Phase 2 a 3GPP access path over 5GC/a non-3GPP access path over ePDG/EPC

4.1. Simultaneous Utilization of 3GPP-Based and Wi-Fi Access Networks over 5GC or EPC

Commencing with Release 16 and onwards, a transport layer-level solution referred to as ATSSS was initially introduced to integrate non-3GPP access networks (e.g., Wireless Local Area Network (WLAN)) into the 3GPP ecosystem. This innovation facilitates the distribution of data traffic related to multiple applications through various pathways, encompassing both a 3GPP access network (e.g., NG-RAN) and a non-3GPP access network (e.g., WLAN) within the framework of the 5G system. In the subsequent sections, we delve into the distinct functions of ATSSS in each phase, enabling the simultaneous distribution of data traffic across both 3GPP and non-3GPP access networks, integrated into either 5G Core (5GC) or Evolved Packet Core (EPC) network.

4.1.1. ATSSS Phase 1

Incorporating the ATSSS Phase 1 feature into the 5G system involves the introduction of a Multi-Access PDU (MA PDU) session into the existing 5G network functions. This integration is designed to ensure alignment with the foundational structure of the 5G system architecture, as depicted in Figure 6. The MA PDU session enables the seamless exchange of PDUs between the UE (application client) and the internet (remote application server host) for a wide range of applications. This exchange is made possible by simultaneously

utilizing both a 3GPP access network and a non-3GPP access network, each operating within two independent N3/N9 interfaces. Regarding the MA PDU session type, ATSSS Phase 1 exclusively accommodates structured types, including IPv4, IPv6, IPv4v6, and Ethernet, while it does not provide the support for unstructured types of a MA PDU session.

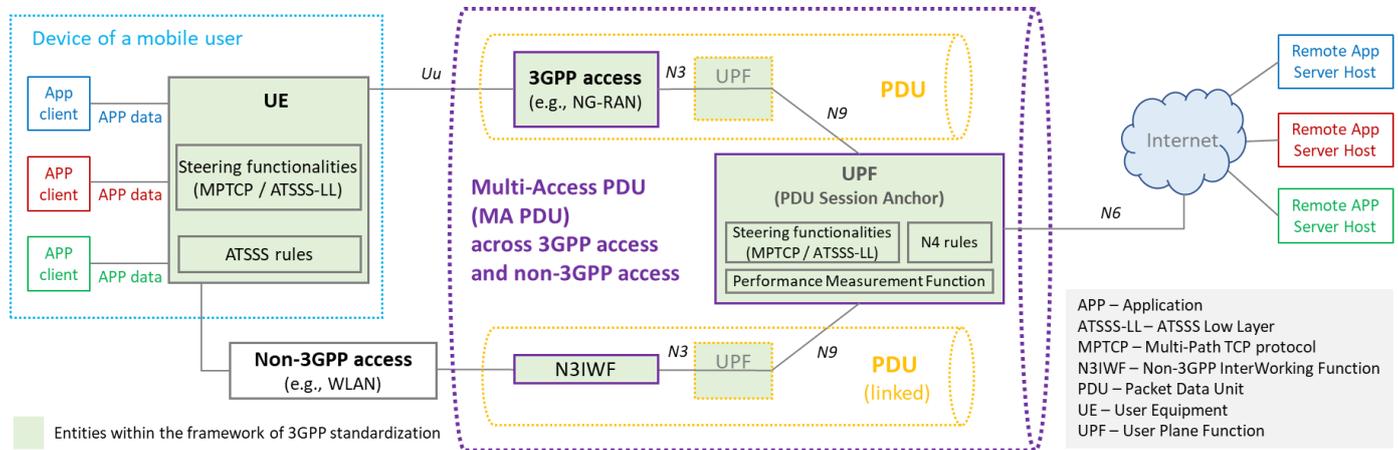


Figure 6. Multi-Access PDU (MA PDU) session with user-plane resources across both 3GPP access and non-3GPP access networks (The figure does not show entities related to the control plane in a 5G system).

The three following procedures are defined in the context of an ATSSS Phase 1 feature, which is applicable between one 3GPP access and one non-3GPP access.

- ATSSS traffic steering—This procedure is employed to select an access network for a new data flow to transfer the data traffic of this data flow over the selected access network;
- ATSSS traffic switching—This procedure is employed to seamlessly transition all data traffic of an ongoing data flow from one access network to another access network;
- ATSSS traffic splitting—This procedure is employed to split the data traffic of a data flow across two access networks. This splitting allows some data traffic of the data flow to be routed through one access network, while simultaneously directing other data traffic of the same data flow through another access network.

The network-provided policy, which includes ATSSS rules for UE and N4 rules for UPF, is derived by the UE’s serving Session Management Function (SMF) within the 5GC. Concurrently, the UE reports the availability of the access network. In light of the network-provided policy and the access network availability reported from the UE, the UPF determines the appropriate procedure for distributing downlink data traffic across the two access networks. Simultaneously, the UE governs uplink data-traffic distribution, selecting the appropriate procedure based on the network-provided policy, access network availability, and local factors, including signal strength, user preferences, and signal loss.

The ATSSS Phase 1 feature encompasses two steering functionalities: Multi-Path Transmission Control Protocol (MPTCP) functionality for TCP traffic, facilitated by an MPTCP proxy in the UPF, and ATSSS Low Layer (ATSSS-LL) functionality, which extends to all types of data traffic, including TCP, User Datagram Protocol (UDP), Ethernet, and more. Furthermore, four distinct steering modes, included in ATSSS rules, have been defined to guide UE in routing data traffic for MA PDU sessions, and three steering modes, except for active standby, are applicable only to non-Guaranteed Bit Rate (non-GBR) [71,72] data flow:

- Active-standby steering mode: When an access network, indicated as ‘active’, is available, all data traffic for the MA PDU session is routed through this active access network. If the active access network becomes unavailable while another access network, indicated as ‘standby’, remains accessible, the data traffic for the MA PDU

session is then directed through the standby access network. The determination of the active or standby status of the 3GPP access network and non-3GPP access network is conveyed through the ATSSS/N4 rules;

- Smallest delay steering mode: The data traffic for the MA PDU session is routed through the access network with the smallest RTT if two access networks are available;
- Load-balancing steering mode: Data traffic within the MA PDU session is intelligently distributed across both 3GPP and non-3GPP access networks, with a specified percentage allocation when both access networks are concurrently accessible. This distribution of data-traffic percentages between 3GPP and non-3GPP access networks is communicated via the ATSSS/N4 rules;
- Priority-based steering mode: Data traffic within the MA PDU session is primarily directed over a high-priority access network, unless the high-priority access network experiences congestion or becomes unavailable. In instances of congestion on the high-priority access network, new data traffic is redirected to the low-priority access network. In the event of the high-priority access network being unavailable, all data traffic for the MA PDU session is seamlessly rerouted to an alternative low-priority access network if available. The designation of which access network holds the high-priority status is specified within the ATSSS/N4 rules.

In addition, for the assistance of access network selection, the Performance Measurement Function (PMF) is introduced to support two types of measurements, i.e., Round Trip Time (RTT) measurement per access network from the UE and UPF in the case of the smallest delay steering mode, and access network availability measurement from the UE to report it to the UPF. Moreover, the 5G Quality of Service (QoS) model designed for a single-access PDU session is extended to the MA PDU session. This ensures that the same QoS Flow Identifier (QFI) is employed by the SMF for both 3GPP and non-3GPP access networks, thereby facilitating consistent QoS support across both access networks.

4.1.2. ATSSS Phase 2

In ATSSS Phase 2, two significant advancements have been achieved: the refinement of steering modes and the integration of MA PDU session support with a 3GPP access network connected to the EPC, which serves as the LTE system's core network.

In the realm of steering-mode enhancement, a new indicator, referred to as the Steering Mode Indicator, has been incorporated into the ATSSS/N4 rules [73], specifically designed for the load-balancing steering mode. This indicator signifies that the UE is empowered to modify the default steering parameters and autonomously adjust traffic steering based on its own decision making. In situations where ATSSS/N4 rules do not provide predefined split ratios for the load-balancing steering mode, this innovation allows both the UE and the UPF to independently and autonomously determine the data-traffic split percentage between two access networks. To indicate the absence of predefined or fixed percentages, the parameter called the autonomous load-balance indicator [74] is included within the Steering Mode Indicator. The primary goal of this enhancement is to optimize data flow throughput in both the uplink and downlink directions. It operates under the assumption that the UE and UPF typically select percentages that maximize aggregate throughput, considering RTT measurements that can vary depending on the radio environment in which the UE is situated. In ATSSS Phase 1, data-traffic distribution policies across two access networks were primarily controlled by the network infrastructure, irrespective of the specific circumstances encountered by the UE, regardless of their criticality. ATSSS Phase 2 has effectively addressed this limitation by including the parameter called the UE-assistance indicator [74] within the *Steering Mode Indicator*. This indication empowers the UE to make informed decisions regarding data-traffic distribution based on its internal status, such as battery consumption. Furthermore, the UE can request the UPF to consider its preferences when determining data-traffic distribution in the downlink direction, thereby providing increased control and flexibility to the UE in optimizing its network experience.

It is important to note that the *Steering Mode Indicator* from ATSSS/N4 rules includes only one parameter, either the autonomous load-balance indicator or the *UE-assistance indicator*.

Furthermore, ATSSS Phase 2 introduces a new element called *Threshold Values* within the ATSSS/N4 rules. This information establishes specific conditions for adjusting the data-traffic distribution for the load-balancing steering mode with fixed split percentages and the priority-based steering mode. A threshold value can represent either an RTT value or a Packet Loss Rate (PLR), and it applies to both access networks. Both the UE and the UPF utilize these threshold values. For instance, in the load-balancing steering mode with fixed split percentages, if at least one measured parameter (either RTT or PLR) on one access network surpasses the designated threshold value, the UE and UPF may cease sending data traffic on that access network or reduce the data traffic on that access network in a manner specific to the implementation. Consequently, the reduced data-traffic amount is redistributed to the other access network. Importantly, it should be noted that the *Steering Mode Indicator* and the *Threshold Values* are not concurrently included within the ATSSS/N4 rules.

To enhance the precision of QoS flow control, ATSSS Phase 2 introduces the capability to conduct performance measurements, such as RTT and PLR measurements, over the same QoS flow used to carry the data flow. This improvement addresses the challenges associated with less-optimized control that stem from relying on rough estimates of RTT/PLR, which are obtained through measurements over the default QoS flow in ATSSS Phase 1. The network determines whether measurements are conducted ‘over the default QoS flow’ or ‘over a certain QoS flow’ during MA PDU session establishment.

Regarding the configuration of the connectivity between access networks and core networks, ATSSS Phase 1 establishes connections between both access networks and the 5GC, which serves as the core network for the 5G system. ATSSS Phase 2 extends support for a different connectivity scenario, where a 3GPP access network is linked to the EPC, the core network of the LTE system, while a non-3GPP access network is connected to the 5GC.

4.1.3. ATSSS Phase 3

ATSSS Phase 3 feature is currently undergoing standardization within the 5G-Advanced framework in 3GPP, with a target completion date set for March 2024. The architectural aspects have already been fully specified in Stage 2 specifications, which were finalized in June 2023. Building upon the achievements in architectural specification, this section provides an in-depth exploration of the four noteworthy enhancements introduced in ATSSS Phase 3 [75,76].

First, ATSSS Phase 3 introduces a new steering mode known as the redundant steering mode integrated into both the UE and the UPF. This steering mode enables the distribution of duplicated data traffic between both a 3GPP access network and a non-3GPP access network. It offers the flexibility to seamlessly suspend or resume this distribution through a message transmitted via the user plane of any available access network within the MA PDU session. Additionally, this steering mode operates efficiently, whether configured with or without *Threshold Values* for RTT and PLR. It is specifically designed for non-GBR service data flow and is not configured with ATSSS-LL steering functionality.

The roaming scenario involving network entities (i.e., Non-3GPP InterWorking Function (N3IWF) or Trusted Non-3GPP Gateway Function (TNGF)) among non-3GPP access networks is designed to facilitate the transition of data-traffic distribution within the MA PDU session. This transition shifts the data flow from the user-plane resource of an existing non-3GPP access network to that of a new non-3GPP access network, while keeping the data-traffic distribution over the 3GPP access network connected for the MA PDU session. When both the UE and the 5G network components (i.e., AMF, SMF) have the capability to switch the non-3GPP access path, such path redirection becomes achievable through the procedure of the mobility registration update initiated by the UE over the user-plane resource of the new non-3GPP access network. Furthermore, this capability for non-3GPP

access-path switching extends to the user-plane resources of non-3GPP access networks, even in the context of a single-access PDU session.

In pursuit of enhancing the configuration of connectivity to the core network, ATSSS Phase 3 introduced additional improvements aimed at facilitating the MA PDU session over a 3GPP access network linked to the 5GC and non-3GPP access network connected to the evolved Packet Data Gateway (ePDG) [77,78] via the EPC.

In addition to two steering functionalities introduced in ATSSS Phase 1, namely MPTCP functionality and ATSSS-LL functionality, a new steering functionality referred to as Multi-Path Quick UDP Internet Connection (MP-QUIC) has been defined to steer, switch and split UDP traffic flows according to ATSSS/N4 rules based on policies decided by the Policy Control Function (PCF). The MP-QUIC steering functionality consists of three components as follows:

- QoS flow and steering mode selection: Following the establishment of an MA PDU session, this component within the UE initiates the setup of one or more multipath QUIC connections. The UE and UPF components then determine the QoS flow, steering mode, and transport mode based on ATSSS/N4 rules, respectively;
- HTTP/3 layer: It supports the HyperText Transfer Protocol version 3 (HTTP/3) HTTP/3 protocol [79], along with extensions for UDP proxying over HTTP [80], HTTP datagrams [81], and extended CONNECT [82]. This layer selects a multipath QUIC connection to be used for each UDP flow and allocates a new QUIC stream on this connection linked with UDP flow;
- QUIC layer: It supports the QUIC protocol [83–85] and the extensions [86,87] defined by the Internet Engineering Task Force (IETF) [88].

As depicted in Figure 7, the MP-QUIC steering functionality within the UE communicates with a corresponding MP-QUIC proxy steering functionality in the UPF. This communication employs the QUIC protocol and its multipath extensions over the HTTP/3. Furthermore, a new indicator, called Transport Mode, is introduced exclusively for MP-QUIC steering functionality. ATSSS/N4 rules specify one of three transport modes to determine how a UDP flow is transmitted between the UE and UPF according to the selected transport mode:

- Datagram mode 1 (An extension of the mode defined in [80]): This mode encapsulates UDP packets within QUIC Datagram frames, providing unreliable transport with sequence numbering and packet reordering/duplication;
- Datagram mode 2 [80]: This mode encapsulates UDP packets within QUIC Datagram frames, offering unreliable transport without sequence numbering or packet reordering/duplication;
- Stream mode: This mode encapsulates UDP packets within QUIC Stream frames, delivering reliable transport with sequence numbering and packet reordering/duplication. It ensures strict reliability and in-order delivery with retransmission, which is particularly suitable for applications lacking their own reliability mechanism.

4.2. Simultaneous Utilization of Two 3GPP Access Networks and Future Enhancements

The ATSSS feature was initially designed as a transport-layer solution with a specific focus on concurrently utilizing user-plane resources across both a 3GPP access network (such as NG-RAN or E-UTRAN) and a non-3GPP access network (like WLAN), all without causing any disruptions to the underlying radio access networks. This concept of optimizing user-plane resources across multiple RANs with different RATs can be extended to encompass access networks specified exclusively within the framework of 3GPP standardization. The demand for this expansion has become more pressing due to the limitations of non-3GPP access networks such as WLAN in enhancing communication coverage with secure reliability and Quality of Experience (QoE) in certain use cases (e.g., maritime usage). Moreover, as the market evolves, there is an expectation of the coexistence of multiple 3GPP access networks, including NG-RAN, E-UTRAN, and 5G LEO/GEO satellite access networks, within the framework of 5G-Advanced and future systems.

From the perspective of the maritime sector and considering the diverse wireless communication environments that ships encounter during global navigation, the imperative of simultaneously utilizing radio resources of multiple RANs, including LEO/GEO satellites, E-UTRAN, and NG-RAN, becomes even more pronounced, as illustrated in Figure 8. This is a fundamental requirement for the digitalization of the maritime sector, including autonomous ships, to ensure the secure provision of seamless ubiquitous connectivity within a single subscription provided by a mobile operator with roaming services, facilitated through mutual agreements with other mobile or satellite operators.

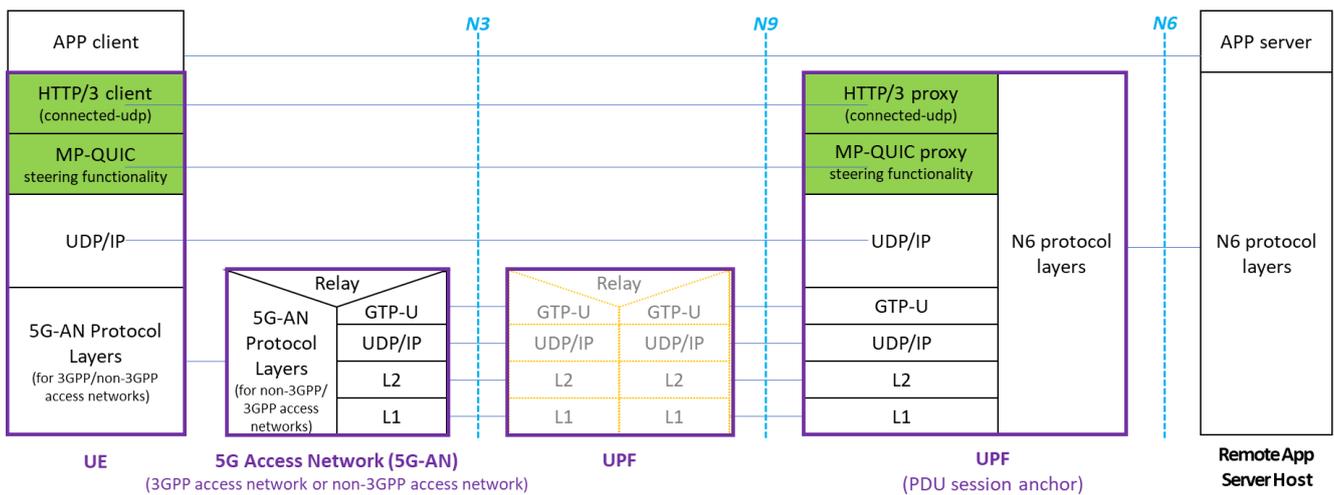


Figure 7. Protocol stack of the user plane with MP-QUIC steering functionality within the Release 18 framework of 3GPP standardization (Adapted from Figure 5.32.6.2.2-1 of 3GPP TS 23.501 V18.1.0 [89]).

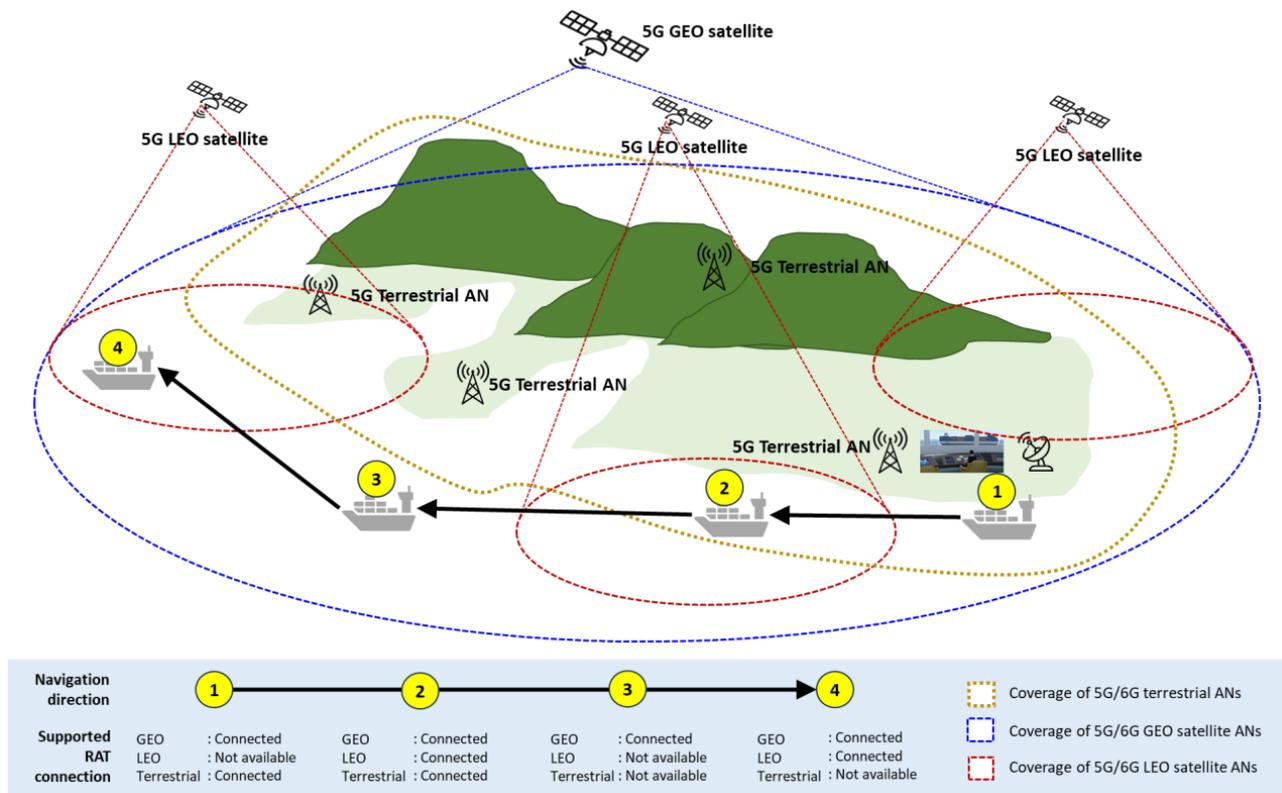


Figure 8. Example of available multiple 3GPP access networks including 5G satellite access ((Adapted from Figure 5.10-1 of 3GPP TR 22.841 V2.0.0 [90]).

Lately, 3GPP has been investigating pertinent use cases that bring about new service requirements, requiring corresponding transport-layer solutions to support the utilization of user-plane resources across two 3GPP access networks [91]. With a single subscription, it is considered that two 3GPP access networks are connected to the same Public Land Mobile Network (PLMN) [92–94], two different PLMNs, or a PLMN and a Non-Public Network (NPN) [95] called a private network on the market. In addition, two 3GPP access networks may involve combinations such as NG-RAN and 5G LEO satellite access networks, E-UTRAN and 5G LEO satellite access networks, or 5G LEO and GEO satellite access networks.

In the traditional approach, data-traffic distribution within the 3GPP standardization framework relies on the utilization of user-plane resources from a single-access network. This implies that existing procedures may need to be reconsidered to enable the simultaneous utilization of user-plane resources from two separate 3GPP access networks without disrupting RAN entities. Looking ahead to the progress of 3GPP standardization in Release 19, there is an expectation of further enhancements. These enhancements are expected to continue into Release 20, which is considered the inaugural version of the 6G communication system within the 3GPP framework.

5. Opportunities and Challenges

The simultaneous use of multiple RANs within a unified communication system offers distinct advantages for autonomous ships navigating in the maritime environment with heterogeneous multiple RANs. This becomes especially pronounced during global navigation, where the secure connectivity to on-land entities assumes a pivotal role in monitoring vessel status, tracking location or enabling remote control. The significance of this connectivity is further underscored by the variations in network infrastructure capabilities across different countries. The 6G communication systems are poised to provide a decisive advantage by offering both terrestrial and non-terrestrial networks, serving as indispensable components for ensuring ubiquitous connectivity in the maritime communication landscape.

However, it is important to note that legacy maritime communications, such as VHF-based communication, have endured well beyond legacy cellular communications. This longevity can be attributed to their extended communication coverage capability stemming from their frequency characteristics, despite their relatively low performance. This extended lifespan presents a unique set of challenges that demand meticulous consideration during the transition from traditional maritime communication methods to the cutting-edge realm of 6G communications. The latter enables continuous advancements in the concurrent utilization of multiple 3GPP access networks over 5G and beyond systems, optimizing the distribution of data traffic for autonomous ships during their navigation in the ocean, in port areas, or on inland rivers.

As the maritime sector embarks on this transformative journey, thoughtful planning and collaboration among relevant stakeholders, technology providers, and regulators will be essential to explore these opportunities and address challenges. In this section, we provide insightful exploration about opportunities and challenges for further research in this continually evolving landscape.

5.1. Integration of Autonomous Ships as Mobile RAN Entities into the 6G Framework

The incorporation of autonomous ships into mobile RAN entities leveraged by ATSSS features presents a substantial opportunity to enhance maritime communication environments, particularly in cases where deploying essential network infrastructures is challenging compared to terrestrial communication environments. This integration contributes to extending network coverage and capabilities, fostering a more adaptable and interconnected communication ecosystem in the maritime environment in addition to the inclusion of UAVs [48,49] and more enhanced satellite components as mobile RAN entities within the framework of forthcoming 6G standardization. Moreover, autonomous ships can be

integrated as network nodes serving as a relay node, like vehicles acting as mobile RAN entities which are exemplified by the mobile Integrated Access and Backhaul (IAB) nodes mounted on vehicles, as outlined within the 3GPP standardization framework [96,97].

Mobile objects like UAVs and vehicles initially served as UE and later evolved into mobile RAN entities to enhance coverage and connectivity in the 3GPP framework. Similarly, autonomous ships are poised to revolutionize the concept of RAN entities in maritime communication environments, albeit with distinctive challenges compared to UAVs and vehicles, primarily stemming from the various sizes of ships, their specific movement patterns, and the intricacies of their navigation route, including the number of people on board.

The conventional cellular network model, known for its characteristic communication coverage areas resembling hexagons or circles, with signal strength gradually diminishing from the center outward, has long served as the foundation for maximizing network capacity. When integrating autonomous ships into the realm of mobile RAN entities, applying this traditional approach becomes intricate. Within the maritime communication environment, especially with ships of substantial length (e.g., several hundred meters), relying on the traditional hexagonal or circular shape-based approach may prove suboptimal. Furthermore, the bulk of data traffic may primarily take place within the confines of a ship, with minimal data traffic extending beyond the ship's boundaries especially for ships navigating in oceans such as cruise ships. This suggests a potential need for high capacity of the network infrastructure in specific areas of the ship, and temporarily along the navigation route, like a stadium where tens of thousands of people watch concerts together for a few hours, using their mobile phones for various data exchanges with friends in the stadium or with family members at home. This can give rise to challenges such as sudden surges in data traffic along the ship's navigation routes. Consequently, the adoption of advanced technologies, such as ATSSS features enabling the simultaneous and efficient utilization of multiple RANs, including mobile RAN entities such as satellites, UAVs and autonomous ships, becomes critically necessary to efficiently manage the temporary data-traffic surges that occur along the ship's route, within the framework of 3GPP standardization.

5.2. Integration of Legacy Maritime Communications into the 6G Framework

Given the enduring presence of legacy maritime communications, it is evident that multiple RANs are poised to coexist within the maritime sector, leading to an escalation in RAN heterogeneity. Thus, it becomes imperative to harness these legacy maritime communications as non-3GPP access networks, enabling the concurrent use of them together with 3GPP RANs available within the context of the 6G framework. This linkage can empower autonomous ships to establish connections with external networks, such as the internet, thereby facilitating access to a diverse range of services during their navigation. The integration of legacy maritime communications into the context of the 6G framework presents a landscape brimming with both promising opportunities and formidable challenges.

One of the most compelling prospects lies in the potential to significantly enhance connectivity at sea. Traditional maritime communication systems have often grappled with limitations in bandwidth and coverage. However, integrating them into the 6G ecosystem, alongside mobile RANs with the capability of ATSSS features, enables ships to harness ultra-high-speed data transmission and reliable communication, even in the open ocean. This enhancement serves as a cornerstone for modern maritime operations, spanning shipping, fishing, research endeavors, and emergency response initiatives. Another noteworthy opportunity arises from the convergence of the Internet of Things (IoT) and sensor technologies within the maritime sector. This synergy, facilitated by the seamless amalgamation of legacy systems with 6G capabilities, paves the way for real-time data transmission and monitoring. Ships can seamlessly gather and analyze multifaceted data, encompassing aspects such as weather conditions, equipment status, and cargo management. This data-centric approach holds the potential to significantly enhance safety, fortify security measures, and streamline operational efficiency. Furthermore, the integration process can be orchestrated

with minimal disruption to the existing infrastructure. This approach ensures a seamless transition, allowing maritime organizations to harness their previous investments while reaping the benefits of 6G connectivity. Moreover, the potential of 6G to deliver 'ubiquitous connectivity' and 'connecting unconnected' carries profound implications for the maritime sector. Ships can maintain uninterrupted communication, irrespective of their location, thereby promoting safer navigation and more streamlined logistics.

However, in tandem with these opportunities, a series of notable challenges emerges. Foremost among these is the critical issue of interoperability. The integration of legacy maritime communications into the 6G framework presents a formidable task in terms of achieving seamless communication between different generations of technology. Older equipment may necessitate adjustments or upgrades to ensure compatibility with the 6G infrastructure. Navigating the complex regulatory landscape stands as another substantial challenge. The maritime sector operates within a multifaceted regulatory framework, and adapting to the intricacies of 6G may demand alterations in spectrum allocation, licensing protocols, and compliance with international maritime regulations. Effectively addressing these regulatory challenges is pivotal to a successful integration. Additionally, as connectivity intensifies, an augmented need for cybersecurity becomes apparent. Safeguarding maritime communication networks against cyber threats takes on paramount significance to uphold the safety and integrity of sea operations. Legacy maritime communications may lack the robust security features intrinsic to 6G, necessitating a meticulous approach to planning and executing cybersecurity upgrades.

5.3. Variability in Maritime Channel Measurements Affected by Climate Change

The channel measurements such as RTT or PLR are used to select RANs among multiple RANs simultaneously utilized in the context of ATSSS features despite having no impact on RAN aspects. In the realm of communication systems, channel measurement metrics such as RTT serve as standard criteria for assessing the suitability of one method over another. Moreover, statistical channel models often stem from these fundamental channel measurements. In the context of 6G communication within the maritime sector, several studies explored the development of 6G channel models, considering the distinctive characteristics that arise from the maritime communication environment, which differs significantly from terrestrial communication environments [3,98–100]. When examining the data in [101] (Figures 16 and 18), it becomes apparent that wireless channel conditions in the maritime communication environment tend to stay relatively stable on sunny and calm days. In contrast, they show significant variability on windy days, primarily attributed to the presence of high waves, even in coastal regions. This variability implies that channel models may not sustain consistent effectiveness, even within the same maritime region geographically. The outcome of channel measurements is intrinsically dynamic, influenced by specific conditions like weather or the increasingly unpredictable temperature patterns resulting from the significant effects of climate change currently experienced by the global community. This highlights a disconnect between the current communication environment and what lies ahead in the maritime sector. As a result, channel models developed based on channel measurement during the research phase may not be optimally suited for real-world deployment scenarios of the maritime communication environment, which usually come to be implemented in at least five years to a decade after the research phase.

In recent times, there has been a remarkable surge in interest surrounding the utilization of Artificial Intelligence (AI) technologies for channel modeling within the academic research community [102–104]. Additionally, the 3GPP standards body has undertaken the exploration of AI and Machine Learning (ML) technologies to enhance the overall functionalities of 5G and beyond systems. This exploration encompasses AI/ML-based network energy conservation, data-traffic load balancing, and mobility optimization within 3GPP systems, while considering the dynamic nature of air interfaces [105,106].

Emphasizing the critical nature of acquiring a substantial volume of actual channel-measurement data for AI/ML-based approaches is imperative. In the maritime sector,

autonomous ships can play a pivotal role in collecting this data, spanning diverse weather conditions, including severe weather situations when conventional navigation is typically constrained. Furthermore, it is worth noting that the maritime communication environment varies significantly across different regions, such as polar sea regions, earthquake-prone areas, open-ocean expanses, and coastal regions. This variability underscores the challenges of creating a single universal channel model of a 6G communication system capable of providing ubiquitous connectivity in all locations, either terrestrial or non-terrestrial areas. The availability of a comprehensive global dataset of real channel measurements collected in the maritime communication environment becomes increasingly crucial. It will enable the development of optimized channel models integrated with AI/ML technologies for the maritime sector within the context of the 6G framework. These models can be considered when global standards bodies like 3GPP work towards establishing comprehensive 6G channel model frameworks, catering to scenarios encompassing space, air, and sea as well as terrestrial environments.

6. Conclusions

As we embark on the journey towards the next generation of mobile communication systems, notably 6G, it has become imperative to seamlessly integrate the demands of digitalization and mobilization within the maritime sector, particularly for autonomous ships, within the framework of 6G standardization. This integration holds paramount significance due to the myriad of advantages that the 6G framework offers, centered around the establishment of unified communication ecosystems, built upon the widely embraced 3GPP standards that have come to dominate in market for the digital revolution of various industries since the advent of 5G. Notably, the realization of ‘ubiquitous connectivity’ in 6G is poised to play a pivotal role in expanding communication coverage with secure reliability and optimal QoE in the maritime communication environment, a critical requirement for autonomous ships.

This article contributes significantly by providing a comprehensive overview of the integration of satellites and UAVs as mobile RANs into 5G and beyond systems, which are envisioned as integral components of the 3GPP access networks supporting the simultaneous utilization of multiple RANs in the forthcoming 6G era, within the framework of 3GPP standardization. Additionally, we have explored the ATSSS features within 3GPP as a transport layer-level solution enabling the seamless steering, switching, and splitting of data traffic across multiple access networks over the core networks of 5G and beyond systems.

Given the unique characteristics arising from the maritime communication environment and the ships themselves, we have highlighted the opportunities and challenges for further exploration and research as we look ahead to the forthcoming 6G era. To succeed in the 6G-based maritime evolution, it is imperative to foster close collaboration among maritime stakeholders including authorities responsible for vessel traffic management and control, and maritime safety. Additionally, the collaboration between maritime stakeholders and 3GPP experts is vital in developing the relevant requirements that align with the maritime sector’s needs. These requirements should be meticulously formulated with substantial input from key stakeholders capable of representing the global maritime sector, including authorities in charge of vessel traffic management and control, and maritime safety, etc., considering both maritime safety and commercial usage perspectives. This collaborative effort serves as a pivotal milestone towards establishing more efficient, adaptable, and reliable communication within the 6G ecosystem for the maritime sector.

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