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Non-Terrestrial Networks for 6G: Integrated, Intelligent and Ubiquitous Connectivity

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***Abstract*—Universal connectivity has been part of past and current generations of wireless systems, but as we approach the sixth generation (6G), the subject of social responsibility is being built as a core component. Given the advent of Non-Terrestrial Networks (NTN), reaching these goals will be much closer to realization than ever before. Owing to the benefits of NTN, the integration of NTN and Terrestrial Networks (TN) is still at its infancy, where the past, the current and future standard releases within the 3rd Generation Partnership Project (3GPP) provide guidelines to adopt a successfully co-existence/integration of TN and NTN. Therefore, in this article, we illustrate, through 3GPP guidelines, how NTN and TN can effectively be integrated. Moreover, the role of beamforming and Artificial Intelligence (AI) is highlighted to achieve this integration. Finally, the usefulness of integrating NTN and TN is validated through numerical analysis.**

***Index Terms*—6G standardization, 3rd Generation Partnership Project (3GPP), Non-Terrestrial Networks (NTN), Artificial Intelligence (AI), Beamforming.**

I. INTRODUCTION

Every generation of cellular communications is expected to surpass its predecessor by a fair margin, providing enhanced throughput, extremely low latency, seamless coverage, and ubiquitous connectivity. Among them, providing ubiquitous connectivity is a challenging aspect, as there are still 2.6 billion people without mobile connectivity. Usually, the deployment of the cellular infrastructure directly relates to the population density, which in return limits the reach of advanced cellular technology to remote areas. Moreover, the cost of providing cellular services stays homogeneous throughout the whole country, which also limits the provisioning of a comparable service to sparsely populated areas. The 3rd Generation Partnership Project (3GPP) Release 17 marks a significant milestone in overcoming these issues by integrating Non-Terrestrial Networks (NTN) and Terrestrial Networks (TN).

The term NTN is often associated with satellite communications (always available NTN) as the fight for space communications supremacy has captured everyone's attention over the last few years. Other platforms that can provide communication services including Unmanned Aerial Vehicles (UAV) and High-Altitude Platforms (HAP) (on-demand NTN), come under the broader definition of NTN. In general, NTN provide connectivity in areas where TN are unavailable or challenging to deploy, and are becoming mainstream as their role in supporting ubiquitous connectivity grows. There are a number of services that can be implemented utilizing NTN, *e.g.*, disaster recovery, search and rescue operations, and firefighting [1].

On the one hand, NTN are important in providing ubiquitous connectivity integrating them with TN. On the other hand, some design challenges, such as the transmission delay, path loss, Doppler shift, and interference management, need to be overcome for the seamless integration of NTN and TN [2]. Owing to these challenges associated with NTN, this article presents an extensive overview of the latest academic and industrial advancements in integrating NTN and TN to facilitate intelligent and ubiquitous connectivity. More specifically our contributions are summarized as follows:

- We provide a detailed overview of how NTN can be integrated with TN, based on 3GPP guidelines, covering past, present and future releases. Moreover, we highlight the key issues in the co-existence of TN and NTN, and introduce the 3GPP-based proposed solutions.
- We provide a detailed overview of how user centric beamforming techniques can overcome the interference arising from integrating TN and NTN.
- We present a detailed overview of how Artificial Intelligence (AI) can be exploited to successfully integrate TN and NTN. Further, we highlight key limitations of AI for

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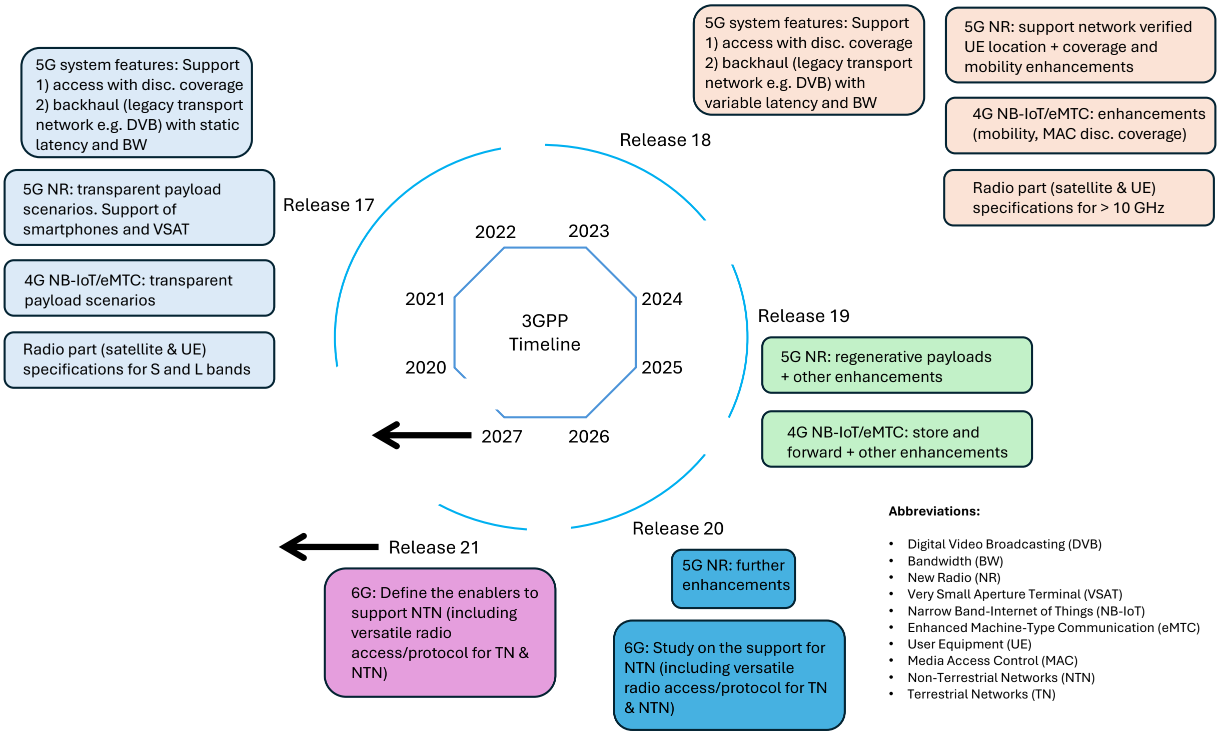

Fig. 1: Timeline of the 3GPP standardization activities related to NTN.

TN/NTN systems.

- We present two use case demonstrations of NTN: 1) In an airborne scenario, *i.e.*, by using UAV to improve the Energy Efficiency (EE) of User Equipments (UEs). 2) In a satellite-based scenario, *i.e.*, by using Low Earth Orbit (LEO) satellites to improve system capacity.

II. NTN UBIQUITOUS CONNECTIVITY: A 6G VISION

6G and NTN-TN integration are two emerging concepts in the realm of telecommunications and wireless technology, with some potential intersections and synergies. Although the final definition of 6G is still being formed, it is generally agreed that the social impact of 6G has to be a key tenet of the evolution of communication networks. A component of this social impact is universal broadband connectivity where the fusion of TN and NTN will play an enabling role. The integration of NTN with 6G networks holds the promise of creating a highly connected world with ubiquitous, high-speed, and reliable communication services. In 5G, the integration of NTN has been at the higher layers; for 6G, the expectation is that this integration will be native.

The 3GPP standardization activities are represented in Fig. 1. Building on the success of Release 17, the work is now directed to the finalization of Release 18 and the beginning of Release 19, *i.e.*, 5G-Advanced. In particular, regenerative payloads and operations in the Ka-band are now being considered, in addition to different mobility and coverage enhancements. It is worthwhile mentioning that the activities in ITU-R for IMT-2023, not represented in the figure, have now started with the definition of the framework for TN; the plan is to initiate the standard for terrestrial and non-terrestrial components in 2027. As for Release 20, the 3GPP Service and System Aspects 1 (SA1) Working Group (WG) has started activities on service requirements. In this release, SA1 divides the work into 2 parts: part 1 will study and develop normative service requirements for the continued enhancement of 5G-Advanced; and part 2 will conduct a 6G study for preparing the normative work in Release 21, which will be the first 3GPP release for 6G. In the 3GPP SA1 #105 meeting held in May 2024 a new study item on satellite access —Phase 4 for Release 20 part 1 —was approved. The objective of this new study includes (S1-240312):

- Enhanced support for emergency communications and mission critical services using satellite access.
- Support multi-orbits satellite access for multiple services.
- Support the ability to notify the user that a mobile terminated communication has failed when the UE is unreachable in satellite access.
- Support IP Multimedia Subsystem (IMS) voice calls using Geostationary Equatorial Orbit (GEO) satellite access.

As for the part 2 of the 6G preparation, native support of both terrestrial and satellite network components to address a set of common goals and higher Key Performance Indicators (KPI) requirements for 6G (S1-233201) was proposed. It is still a bit early to arrive at a general conclusion on how NTN will be integrated with Public Land Mobile Networks (PLMN) in 3GPP, but it is certain that these networks will be an integral part of the future communication infrastructure and of 3GPP's 6G focus.

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A. NTN & Standards

Over the last couple of years, there have been several agreements between the traditional Mobile Network Operators (MNO) and Satellite Network Operators (SNO) aimed at providing extended service between the two networks. This arrangement allows MNO to expand service coverage in places where the cost of deploying and operating a full terrestrial infrastructure may not be compensated by revenues. Satellite communications can be considered for home/office connectivity, backhauling of isolated Base Stations (BS), or direct-to-smartphone connectivity. The first two scenarios are already quite widely deployed, *e.g.*, in Latin America and Middle East and North Africa (MENA) countries, mostly based on proprietary solutions for satellite connectivity. The last scenario is also gaining attention, and the first compact terminals integrating the capabilities of smartphones and satphones have been launched on the market. 3GPP recognized the added value of NTN, and particularly satellite communication networks. This step forward in this ecosystem has raised significant interest. Indeed, it offers network interoperability, can favor the entry of new stakeholders in the market, limit vendor lock-in and reduce costs in a general manner.

3GPP targets different scenarios for NTN, from the support of non-3GPP satellite access to fully 3GPP-compliant systems for 5G and beyond, and significant work has been pursued in this direction. Given this tie up between TN and NTN, it is critical that some level of standardization takes place. Starting with Release 17, 3GPP work in supporting NTN has focused on ensuring seamless connectivity and interoperability between the two. Although NTN include other non-satellite-based (*e.g.*, UAV and HAP) networks, 3GPP System and Architecture (SA) WG, so far, mainly focus on satellite-based NTN.

1) ***Satellite Access Through Unmodified 4G Smartphones****:* In parallel with the 3GPP efforts towards standardized NTN, several satellite companies, such as AST SpaceMobile, Lynk or Starlink, have demonstrated 4G capabilities, in partnerships with MNO. Proprietary solutions have been developed to enable satellites to operate using the same 3GPP standards utilized for TN, and to transmit 4G Long-Term Evolution (LTE) signals from space to off-the-shelf smartphones, and vice versa. Initially, these services were limited to messaging type applications, but more recent efforts cover more advanced voice and data capabilities. However, from a commercial perspective, such systems are not widely available yet. Firstly, this satellite connectivity needs to use spectrum in bands allocated to terrestrial mobile services and is thus subject to the approval of national regulatory authorities. In addition, further clarifications are still required concerning the sharing of responsibilities between the MNO and the SNO, to ensure the proper use of these frequency bands. Secondly, the interference remains a major issue, as it is necessary to protect the terrestrial users of the same MNO, as well as the cellular networks of neighboring countries. Indeed, the large footprint of satellites makes border management quite complex, especially in Europe, for example, where countries are generally smaller compared to North America. Finally, dedicating TN bands to NTN services is also a question of spectrum efficiency and business sustainability.

2) ***Integration of non-3GPP Satellite Access into 5G****:* The support of non-3GPP access has already been specified in Release 15 to allow 5G to manage new types of access, with interoperability and reliability. To this end, different network functions have been defined, *i.e.*, N3IWF (Non-3GPP Inter-Working Function) for untrusted access, TNGF (Trusted Non-3GPP Gateway Function), TWIF (Trusted Wide Local Area Network (WLAN) Inter-Working Function) and W-AGF (Wireline Access Gateway Function), for trusted access, depending on the considered UE scenario and capabilities. These mechanisms have targeted primarily Wireless Fidelity (Wi-Fi), fixed access, and mobile UEs with limited support of 5G Non Access Stratum (NAS) signaling, but adapting these functions to satellite-based scenarios has attracted significant interest [3]–[5]. Moreover, there are numerous technical challenges, as highlighted in [6], [7]. Indeed, is necessary to rework these mechanisms to accommodate the specificities of space-to-ground links (*e.g.*, long delays and lower capacity) and to adapt to various satellite protocol stacks, often based on proprietary technologies and generally tailored for specific use-cases.

3) ***5G-NTN: A First Complete Framework****:* 3GPP Release 16 is the first release in which 3GPP SA WGs tried to introduce the integration of satellite access technology into the overall 5G SA. Unfortunately, in Release 16 time-frame, only Stage 1 use cases and service requirements (TR22.822) were completed, as well as the normative service requirements defined in TS22.261. The subsequent study for SA level solution (TR 23.737) and the following normative standardization work based on the SA1 requirements were postponed and completed in Release 17. In Release 17, satellite NTN were integrated into 5G TN in the SA with new 5G features covering the aspects of mobility management, incorporating the impact of delay, 5G system Quality-of-Service (QoS) with satellite backhaul, and Radio Access Network (RAN) mobility with Non-Geostationary Satellite Orbit (NGSO) regenerative-based satellite access.

4) ***NTN Systems in 5G-Advanced & Beyond****:* In Release 18, 5G SA with satellite integration was continued to be studied and enhanced to consider satellites as an access technology (TR 23.700-28) and as 5G system backhaul (TR23.700-27). The results of those two studies were incorporated into the final normative Release 18 Stage 2 specifications of TS23.501 and TS23.502. As for the case study of satellite-based NTN as an access technology, Release 18 mainly focused on the mobility management enhancement and power saving for UE with discontinuous satellite coverage. As for satellite-based NTN as a 5G system backhaul, new 5G solutions were developed to cover QoS control enhancement considering dynamic satellite backhaul and using on board User Plane Function (UPF) to provide support of satellite edge computing and local data switching to overcome the delay. Finally, the 3GPP Release 19 aims at studying key issues for satellite integration (TR23.700-29), such as providing support for regenerative-based satellites, store and forward satellite operations, and supporting communication between UEs under the coverage of one or more serving satellites without the user plane traffic

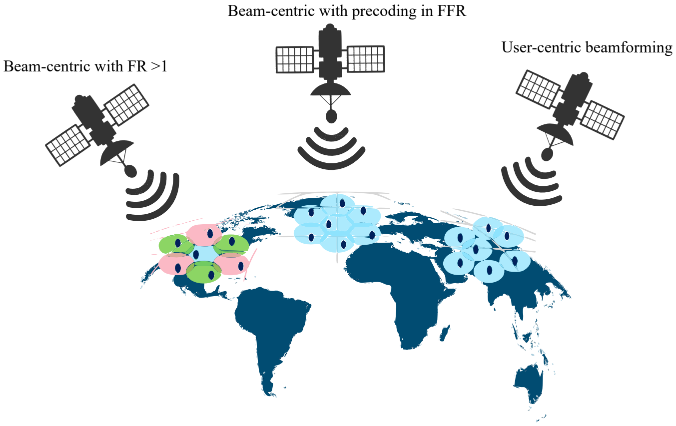

Fig. 2: NTN beamforming and precoding schemes.

going through the ground network.

III. ADVANCE BEAMFORMING TECHNIQUES TO IMPROVE FUTURE 6G NTN CONNECTIVITY

Legacy satellite communication systems are typically based on Frequency Reuse (FR) schemes, for instance 3 or 4 colours, in which the available bandwidth is split into multiple non-overlapping channels differentiated in the frequency and polarization domains. Then, these channels are assigned to the on-ground coverage on a geographic basis to limit interference, by mapping them to specific beams of the desired beam lattice. This can be achieved by means of advanced spectrum usage paradigms, such as Cognitive Radios (CR), Dynamic Spectrum Access (DSA), or by aggressively allocating the resources through Full Frequency Reuse (FFR) schemes, in which the FR factor is decreased to one. Focusing on the latter approach, effective interference management techniques are required to cope with the massive co-channel interference, such as precoding. In this case, for a pre-determined on-ground beam lattice, Multiple-Input-Multiple-Output (MIMO) algorithms, such as Zero Forcing (ZF) or Minimum Mean Square Error (MMSE) are applied to a channel matrix at the beam level.

The implementation of these solutions via NTN is already possible with the current Release 17-18 specifications, subject to a few conditions, such as: i) the number of simultaneous beams cannot exceed the number of Synchronisation Signal Blocks (SSB) that can be broadcasted by the Next-Generation Node B (gNB) (8 below 6 GHz and 64 above 6 GHz), allowing the UE to identify and synchronize to the best serving beam [8]; and ii) the algorithms shall operate at the beam level. In addition, one key aspect that still has to be addressed and agreed within 3GPP is related to beam management solutions, which define the mapping between the NTN beams and the cell/NR beams managed by the gNB [9]. Figure 2 depicts different coverage solutions: beam-based with FR schemes, beam-based with precoding supporting full FR, and user-centric beamforming, in which the beams are generated in the direction of the users instead of being determined a priori on a geographic basis.

Beam-level solutions, such as precoding, show good performance, but do not yet exploit the full potential of MIMO via NTN. In fact, the beam lattice is usually defined to geographically limit co-channel interference, rather than exploiting it. In this framework, user-centric beamforming, *i.e.*, beamforming algorithms that dynamically generate beams in the direction of the served users, are recognised as the next evolution; however, these are not yet defined at the standard level.

A first aspect to be taken into account is related to the ancillary information that is exploited to compute the beamforming coefficients, which classifies the user-centric algorithms as [10]: i) Channel State Information (CSI)-based, when the channel coefficients are estimated by the users and reported to the network; and ii) location-based, in which the users estimate their location and then the network infers the channel coefficients exploiting this information and the NTN node. The implementation of CSI-based solutions requires that each user is able to estimate the channel coefficient between its receiving antenna and each radiating element on-board. Currently, CSI estimation in 3GPP NTN allows to estimate quantized information on the Channel Quality Indicator (CQI) at the beam level, by exploiting the CSI-Reference Signal (RS) defined in the 3GPP specifications. Thus, to support these techniques, future releases shall provide the means to implement pilot-aided estimation algorithms for each radiating element level, which might increase the signalling overhead. This is a challenging task, in terms of both computational complexity (the number of radiating elements is usually large, *e.g.* 512 or 1024) and signalling overhead. A possible solution is exploiting the current CSI-RS to estimate the common portion of the channel coefficients (everything occurring between the NTN node and the terminal), while leaving at the gNB the task of superimposing the terms related to the known antenna array geometry. As for location-based solutions, in 5G the users are equipped with Global Navigation Satellite System (GNSS) capabilities and they can report their location; however, the location information is not available at the RAN level, *e.g.*, at the on-board gNB, but in the 5G Core Network (5GC). More specifically, the Access and Mobility Management Function (AMF) interacts with the Location Management Function (LMF) to provide location services. Thus, also location-based solutions would need adaptations, in order to make the location information available in the RAN and not only in the 5GC.

More recently, the implementation of Cell-Free MIMO via NTN is also receiving an increasing attention, [10]. In this scenario, multiple close NTN nodes organized in a flying swarm can cooperate to generate a virtual antenna array in space, aimed at implementing more flexible and advanced user-centric beamforming solutions. In addition to the above-mentioned evolution that is to support standalone beamforming, the major challenge is related to the tight time and frequency synchronization requirements on the Inter-Switch Link (ISL). In fact, for distributed (or federated) user-centric beamforming solutions to be effective, and not detrimental, the non co-located transmissions from the NTN segment shall be ideally perfectly aligned in time and frequency. Notably, this requirement is particularly challenging to be achieved. This is one of the main reasons for which these solutions, denoted as Coherent Joint Transmission (C-JT) were de-prioritized in favour of Non-Coherent JT (NC-JT) approaches such as

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multiple transmission/reception point or Multi-Connectivity (MC) in the past.

IV. AI FOR SEAMLESS CONNECTIVITY IN 6G NTN

The seamless integration of NTN into 6G networks provides another level of complexity to an infrastructure that is already characterized by dense BS deployments, with an exponentially increasing number of terminals, each with heterogeneous QoS requirements and random mobility patterns. The conventional model-based designs cannot deal with such complex network management, as they usually lack mathematical tractability and involve significant computational cost. In this context, data-based tools can provide speed-up inference procedures by learning the patterns and relationships of complex algorithms, assuming they have been previously trained with relevant datasets. Offline training is often complemented by updating the AI model based on new evidence, which can significantly improve the adaptability of the model to changes on the environment of operation.

The 3GPP Release 18, which is the first standard of 5G-Advanced, includes discussions on a suitable framework for the integration of AI in the NR air interface targeting automation of networks [11]. Few study items identified areas and use-cases where AI can definitely have an impact. These include: (i) AI for network management and orchestration; (ii) AI-enabled RAN intelligence (with a focus on energy efficiency); and (iii) AI-native air interface (with different collaboration levels between gNB and UE), including CSI, beam management and positioning. 3GPP has also identified procedures to perform data analytics functions and to interact with the 5GC (*i.e.*, 5G network data analytics function).

In the next sub-sections, we first present the applications of AI in integrated 6G-NTN networks and subsequently, we discuss the related challenges and limitations.

A. AI Applications in Integrated 6G-NTN

6G-NTN optimization and management is one of the areas with highest potential for AI-oriented solutions. With a combination of ground BS and multiple flying satellites with overlapping coverage areas, space and ground operations need to be strictly coordinated for seamless service towards their users. The network shall be optimized such that the resource efficiency is maximized and the service agreements with customers are met. AI provides the solution to flexible and autonomous network adaptation to wireless channel changes, rapid traffic demand variations, as well as mobility patterns. The most common approach is to use deep learning architectures to emulate computational-stringent algorithms, in an attempt to find a suitable trade-off between performance and speed of convergence. If environment testing is allowed, reinforcement learning can be considered, where different configurations are tested in a trial-and-error fashion until convergence.

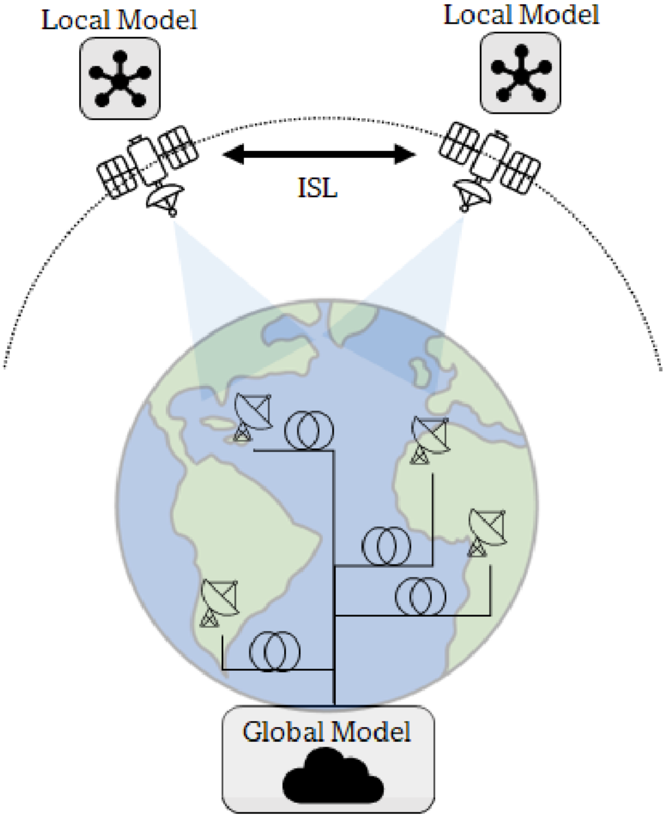

Fig. 3: Schematic of a distributed AI model over a constellation of satellites.

As discussed, pro-activity to network congestion and failures is critical, and requires continuous monitoring and analysis of network performance data. AI-tool devoted to anomaly detection (*e.g.*, interference and/or link failure detection) as well as the prediction of network metrics (*e.g.*, demand, trajectory of terminals, congestion) have been shown to provide an advantage to network management procedures, allowing to take corrective actions before the users' QoS deteriorates. Such procedures become relevant in NTN scenarios, where the spectrum is congested due to the many LEO satellites being launched, and interference cannot be ignored. Link congestion is also a characteristic of NTN, as the wide coverage area of a single satellite encompasses many more users than a terrestrial BS. Furthermore, the fact that satellites revisit the same area several times can be exploited as depicted in Fig. 3, where the satellite AI local models are collected at a cloud via optical interconnected ground stations and updated based on shared experience. ISL may become useful in forming cluster-based models with nearby satellites, *i.e.*, by exploiting the experience of neighboring satellites to build stronger models.

B. Limits of AI-enabled TN/NTN Systems

One of the key aspects of the O-RAN architecture is that it is natively designed for AI-empowered RAN. Radio Resource Management (RRM) can be optimized at the near-real-time scale ($<$ 1sec) for efficient gNB radio configuration, and at the non-real-time scale (minutes or hours) for dynamic TN/NTN load balancing (including management of satellite beam Equivalent Isotropic Radiated Power (EIRP) or on-board data routing). To this end, the O-RAN Machine Learning (ML) framework consists of: 1) several interfaces to collect data at

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the gNB (Radio Unit (RU)/Control Unit (CU)/Distributed Unit (DU)/RAN Intelligent Controller (RIC)), the UE, the Core Network (CN), but also different application functions; 2) the ML training host for online and offline training; and 3) the ML interference host, used for execution, including hosting the ML model and providing outputs to the actor of the ML-assisted solution.

Firstly, the location of these ML model components has significant impact on the system performance but NTN raises specific challenges, yet to be fully explored. Different functional splits can be envisaged for NTN, *e.g.*, the transparent mode (full gNB on the ground), but also RU on board, RU/DU on board or full gNB on board. Each case implies different practical constraints for deploying and running the ML framework. The right balance still needs to be found between long propagation delays (compared to the TN scenario), potentially high number of served UEs (due to the large satellite footprint) and, above all, the limited computational capabilities of the satellite payload. Furthermore, the moving topology of LEO mega-constellations is another major challenge to practical implementation. Secondly, the AI efficiency may be restricted by the availability, quantity and quality of data. Data is often collected at different entities (UEs or network) in a fully distributed manner and at very different space/time scales, such that the current O-RAN architecture, interfaces, and orchestration capabilities require adaptation. By introducing new AI generative models, the lack of data availability may be overcome by generating synthetic entries that emulate realistic environments. Traffic modeling and prediction are additional key aspects shaping ML models for optimized resource management and will significantly impact the choice of the best option for AI-empowered TN/NTN systems.

Finally, a large number of AI algorithms proposed in the literature are often considered as theoretical (yet valuable) upper bounds, due to the underlying assumption that the whole TN/NTN system is operated by a single stakeholder. Due to their different technical architecture, historical ecosystem evolution, regulation landscape and geographical footprint, TN and NTN will probably be organized differently from a business perspective. The main solutions for TN/NTN interconnections are roaming, multi-connectivity with converged core (as detailed in Section II-A2), RAN sharing and all their variants. Each case corresponds to a different level of network interworking, with limited information sharing, such that part of data sources may remain inaccessible, due to confidentiality. Investigating the gap between theoretical upper bounds (with full data knowledge) and constrained ML frameworks could provide a good performance indicator of AI applied to practical TN/NTN architecture options and business models.

V. NTN DESIGN AND ANALYSIS

A. Airborne NTN Connectivity

In this section, we analyze through simulations, a public safety use case of NTN. As illustrated in Fig. 4a, consider a scenario where the UEs are unable to communicate with the BS due to a natural disaster. We optimize the limited energy levels of the UEs available in a disaster region, by relying on Non-Orthogonal Multiple Access (NOMA), AI and a UAV. As presented in [12], firstly the usefulness of NOMA is exploited by performing user grouping and subcarrier allocation of devices by collectively using the k-means, F-test and elbow methods. Afterwards, power allocation is performed using iterative methods, to improve the EE of UEs. We consider 128 subcarriers, a bandwidth of 1 MHz and the path loss model defined in [13]. In Fig. 4b, the EE obtained by the UAV-AI solution is illustrated as a function of the transmitted data, whereas the uplink power level, circuit power and number of UEs are fixed to 0.2 Watts, 1.4002, and 70. In general, by increasing the amount of data transmitted for a fixed number of UEs, the total EE decreases, which shows a proper functioning of the UAV-AI solution. In comparison to a modified version of the greedy algorithm, which does not maintain fairness among all the UEs, the UAV-AI algorithm improves the EE consistently for all amounts of data transmitted. Approximately, the performance gap remains the same in Fig. 4b, which is due the fixed circuit power value.

B. LEO Satellites based NTN Connectivity

In this section, we show numerical results for the implementation of user-centric beamforming via NTN from a single LEO satellite. The antenna model and system configuration are detailed in [10]. Fig. 5b shows the system capacity with an available transmission power of 38 dBW, transmitting in the Ka-band at 20 GHz and assuming a 400 MHz bandwidth (the maximum allowed for NTN in Ka-band) for Very Small Aperture Terminal (VSAT) receivers. The beamfomring algorithms are CSI-based MMSE and Location-Based MMSE (LB-MMSE) and their performance is compared against legacy beam-based schemes with FR3 and FR4. As for the MMSE and LB-MMSE schemes, the maximum power constraint is considered as the power distribution strategy, which ensures that the orthogonality in the beamforming vectors is maintained and the power limitations are met. Two channel models are considered: clear-sky and 3GPP, which refers to the system-level channel model in 3GPP TR 38.811, [14] and TR 38.821, [15]. As shown in Fig. 5a, during the estimation phase, the users estimate their CSI or location to allow the gNB to compute the beamforming matrix. However, the actual transmission occurs after a misalignment time Δt: the longer this interval, the less accurate the ancillary information is for user-centric beamforming. In the considered example, $\Delta t = 16.7$ ms is computed assuming a LEO satellite at 600 km and minimum elevation angles to the users and the gateway of 30° and 10°, respectively.

It can be noticed that the advantage in applying user-centric solutions is massive, with a relative gain of approximately $160-170\%$ and $230-240\%$ compared to FR3 and FR4, respectively. In general, the achievable spectral efficiency is larger with FR3 and FR4, thanks to the reduced co-channel interference. However, the exploitation of the entire bandwidth through full FR with beamforming yields such large gains. It can also be noticed that, in the 3GPP channel that considers additional losses (scintillation, shadowing, atmospheric loss),

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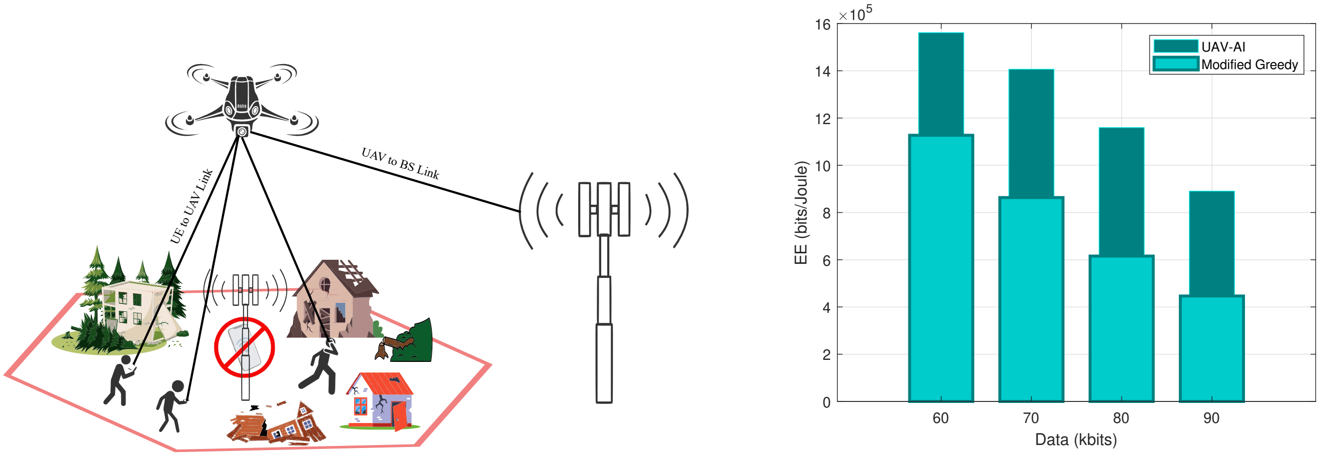
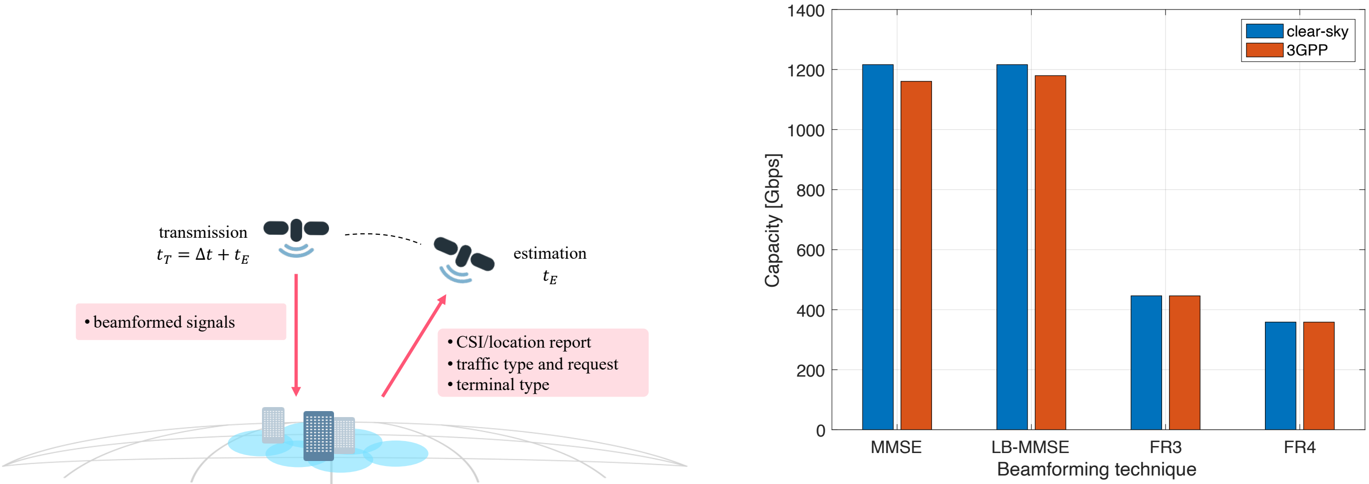


(a) System model, where a UAV is employed for disaster management.

(b) EE versus the transmitted data size for a fixed number of UEs.

Fig. 4: Public safety use case demonstration of NTN, jointly using AI and NOMA.



(a) System model for user-centric beamforming.

(b) System capacity with user-centric beamforming.

Fig. 5: Illustration of a user centric beamforming use case, while utilizing LEO satellites to improve the system capacity.

LB-MMSE performs better than the CSI-based solutions. This is in line with the considerations reported in [10]. In fact, location-based techniques infer the channel coefficients based on the users' positions and do not take into account additional losses. Also, CSI-based algorithms take the entire estimated channel, which is however different from the channel encountered when transmitting the signals and this misalignment degrades the performance.

VI. CONCLUSION

The integration of NTN and TN will play a key role in fulfilling the ITU 2030 objective of providing universal access and connectivity. This integration still faces numerous open research questions and challenges that are yet to be addressed. In this article, we have provided an overview of how 3GPP is making efforts towards addressing such issues. We have also showcased how AI and beamforming techniques can play a role in achieving this successful integration. Finally, through experimental validation, we have demonstrated how airborne NTN connectivity can improve the EE of UEs in a disaster region, and how the use of user-centric beamforming via satellites can improve the total system capacity of TN.

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