O-RAN based Non-Terrestrial Networks: Trends and Challenges

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***Abstract*—While 5G networks are already being deployed for commercial applications, Academia and industry are focusing their effort on the development and standardization of the next generations of mobile networks, *i.e.*, 5G-Advance and 6G. Beyond 5G networks will revolutionize communications systems providing seamless connectivity, both in time and in space, to a unique ecosystem consisting of the convergence of the digital, physical, and human domains. In this scenario, Non-Terrestrial Networks (NTN) will play a crucial role by providing ubiquitous, secure, and resilient infrastructure fully integrated into the overall system. The NTN nodes will be organized into a Multi-Layer Multi-dimensional (ML-MD) architecture. This ML-MD network will rely on the interoperability of very different network elements, enabled by the disaggregation and virtualization of network components, their interconnection by open standard interfaces and orchestrated by data-driven network Artificial Intelligence. This paradigm, which has been standardized by the O-RAN Alliance, is now being implemented in Terrestrial Networks (TNs) but has not been fully addressed in NTN, yet. Therefore, this paper aims at exploring the possible implementation of an NTN infrastructure based on the O-RAN approach. By starting with the review of the State of the Art of O-RAN in TNs and flying platforms, we identify a possible architecture solution for an O-RAN-based NTN system and we foresee the O-RAN implementation trends that will increase the NTN system efficiency.**

***Index Terms*—O-RAN, NTN, AI, B5G, 6G**

I. Introduction

All sectors of industry and society already experience the benefits of 5G networks, and research and development interests are now directed towards enhancing 5G features through 5G-Advance (5G-A), [1]. The latter is expected to bring 5G to its full potential by solving its last points of attention and by providing its connectivity to all possible scenarios and devices. The enhancement of 5G features is paving the way for 6G, the next generation of mobile communications. As defined by the International Telecommunication Union (ITU) Focus Group Technologies for Network 2030, [2], 6G is expected to support the convergence of the physical, human, and digital domains creating a fully connected world. Three classes of interaction will be possible according to 5G-PPP, [3]: *i*) *digital twinning* of systems, indeed pervasive sensors can tightly synchronize the domains to build digital twins of factories or cities; *ii*) *connected intelligence*, with trusted Artificial Intelligence (AI) functions managing digital twins in the virtual domain; and *iii*) *immersive communications*, relying on high-resolution sensory data exchanged via high throughput and low latency networks to create an immersive virtual experience. One of the enabling elements of such a system is the thorough integration of Non-Terrestrial Networks (NTN) into terrestrial ones. To offer an everywhere and every-time available service to the users. The NTN component will be organized in an ML-MD architecture, figure 1, in which a Non-Terrestrial (NT) component is added to the bi-dimensional terrestrial infrastructure obtaining a multi-dimensional network, [4].

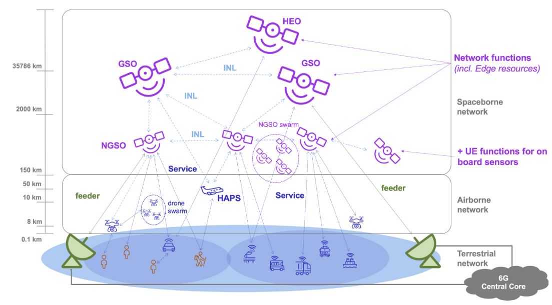

Fig. 1. The foreseen multi-layer multi-dimensional architecture.

The NT element consists of air-born nodes, such as High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAVs), and space-born network elements, *i.e.,* the satellites, deployed in different orbits (multi-layer) and interconnected by Inter-Node Links (INLs). Clearly, the third dimension of the architecture highly increases the complexity of the network, due to the required interoperability among the different nodes offering a plethora of various services. Therefore, in order to ensure its proper functionality, comprehensive and autonomous network monitoring and management is required, along with data-driven optimization of network functions enabled by AI, [3]. Both TN and NTN are still struggling to reach this level of infrastructure intelligence. Indeed, while TN operators are starting to implement the autonomous optimization of some network functions relying on open access solutions for Radio Access Network (RAN) functionalities, [5], the NTN still relies on closed systems with strictly planned architectures. The absence of flexibility in terms of optimization and interface management is a considerable obstacle to the interoperability between NTN nodes based on different technologies and hinders the comprehensive ML-MD system optimization. In this context, it is clear that to unleash the full flexibility of future 6G networks also the NTN component of the ML-MD architecture should shift towards an open access paradigm, such as Open-RAN (O-RAN) standardized by the O-RAN Alliance. The O-RAN standard is based on disaggregated and virtualized components, connected through open interfaces, and so interoperable across different vendors, [6]. In this paper, starting from the state of the art of O-RAN in TNs and HAPS we outline the importance to increase research efforts on O-RAN applied to NTNs. We then identify the functions of the NTN system that can be optimized and enhanced by fully exploiting the O-RAN concept. For each of these foreseen O-RAN implementation trends, a thorough analysis is provided highlighting their advantages along with the brought challenges. The work is organized as follows: In section II we provide a review of the state of the art about O-RAN and the identification of the scientific gaps; in section III we discuss the O-RAN architecture and its fundamental paradigms; section IV gives an overview of the system model; in section V we present the O-RAN NTN use cases with their pros and cons; finally, Section VI concludes this work.

II. State of the Art and Motivation

The idea of having an open RAN has gained a lot of interest in recent years in the TN community, which has performed a vast analysis. Its open interfaces and closed-loop control enable proactive management elements that take care of networking tasks. The research on these applications has focused on three main categories, based on their expected latency, as specified in [7]: *i*) non-real-time (non-RT) applications, with a latency larger than 1 second; *ii*) near-real-time (near-RT) applications, with latency between 10ms and 1s, and *iii*) real-time applications.

In the non-RT field, the interest has been mainly in network orchestration. The authors in [8] present a novel orchestration framework that builds upon the Open RAN paradigm. It evaluates the optimal set of data-driven algorithms and the best execution location and functional split in an automatic way, to meet the needs of the Network Operator (NO). In [9] the authors propose a reinforcement learning dynamic functional split to choose the optimal splitting point, while in [10] the same problem is solved with a heuristic algorithm.

For what concerns the near-RT applications, the research has focused on different aspects of network edge management. Handover management is tackled in [11], the authors propose a new approach to Automatic Neighbour Relationship (ANR) optimization exploiting O-RAN architecture and develop a Machine Learning (ML) based optimization technique to improve gNB handovers. A similar approach has been followed in [12], the authors optimize the handover performances through an intelligent access control scheme with Deep Reinforcement Learning (DRL). Resource allocation optimization in O-RAN is tackled in [13] where network slicing is used to study the service-aware baseband resource allocation and Virtual Network Function (VNF) activation.

Real-time applications are still not fully supported by the O-RAN standard but are gaining interest to implement specific AI algorithms in the far network edges. An example is the industrial project [14], where a cognitive Medium Access Layer (MAC) layer to predict user Equipment's mobility was built.

The O-RAN functional split architecture brings flexible and scalable network deployments, and it relies on network interfaces with limited throughput and latency performances, as underlined in [15]. Therefore, the Authors in [15] provide a survey of the Third Generation Partnership Program (3GPP) and O-RAN fronthaul compression techniques. [16] addresses the channel information aging of Mulitple Input Multiple Output (MIMO) base stations due to the fronthaul interface latency. The channel information being present at one side of the split takes time to reach the other side to implement uplink beamforming, causing air-interface performance degradation. Additionally, the work in [17] focuses on open interfaces security, since they may be exposed to a plethora of threats, emphasizing missing authentication and authorization vulnerabilities. In [18], MACsec, a standard security protocol that operates in the data-link layer bringing high datarate performance, is proposed as a potential protection solution for the O-RAN Fronthaul interface.

The exploitation of O-RAN in NTN has been analyzed but requires more research effort to reach maturity. Precisely, the O-RAN application to UAVs applications has gained more appeal compared to its exploitation in Satellite Communications (SatCom). In [19], to minimize the inter-cell interference generated by a video streaming UAV, the authors propose a closed-loop control system based on O-RAN that optimizes UAV's location and its transmission direction. The authors in [20] take into consideration a flying base station on a UAV system and propose a method to jointly optimize the UAVs trajectory and the offloading tasks based on O-RAN-enabled AI. In [21], the opportunities of exploiting O-RAN latency consciousness of the network segments to enable UAV manual real-time control and autonomous drive are analyzed.Surprisingly, the O-RAN exploitation in the SatCom field has been addressed only in a single work, [22]. Here the authors exploit closed-loop feedback and open interface standards to control the interference between congested terrestrial and non-terrestrial systems. The work presents a spectrum-sharing architecture between terrestrial 5G and Low Earth Orbit (LEO) military satellite systems based on a spectrum sensor. It is important to underline that this inter-system overall interference management would not be possible without the exploitation of the O-RAN architecture. Indeed, while O-RAN increases the system complexity, it equally increases the system design degrees of freedom and enables otherwise unreachable optimizations. This understanding, along with the recent history of O-RAN success in TNs illustrated in this paragraph, has motivated us to start this novel research branch about O-RAN exploitation in NTNs. Indeed, in our opinion, the O-RAN architecture can enhance the NTN systems with a plethora of unexplored applications. Among all use cases, we underline: *i*) the full exploitation of AI models must rely on data-collection pipelines and centralized intelligence provided by open RAN approaches; *ii*) the optimal allocation of RAN functions to the different network nodes requires the O-RAN enabled disaggregation and virtualization of the RAN, along with central network-status knowledge, and *iii*) the leveraging of the O-RAN standardized and open network interfaces to pursue NTN systems interoperability. Therefore, the motiva-

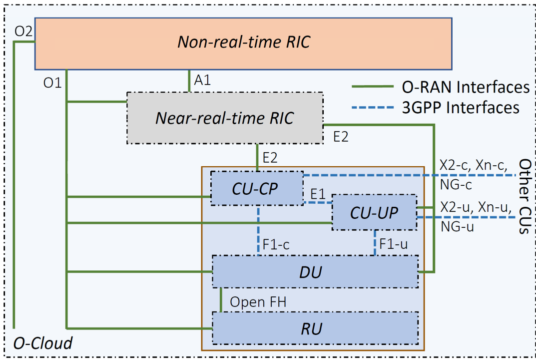

Fig. 2. High-level O-RAN architecture, [5].

tion of this article is to analyze the feasibility of exploiting O-RAN in these use cases by exploring the introduced advantages and challenges.

III. Open RAN Architecture

Current mobile networks rely on very closed architectures: network components are monolithic blocks, implementing every function of the communication protocol, [5]. This approach leads to poor network reconfigurability and efficiency. Next-generation systems require open RAN approaches to overcome these limitations. The Open RAN approaches expose system performance analytics, distribute data, and enable data-driven control and automation. The O-RAN architecture is born to accomplish these goals and it is based on four concepts [6]: *i*) disaggregation; *ii*) virtualization; *iii*) RAN Intelligent Controllers; *iv*) open interfaces.

A. Disaggregation and Virtualization

The disaggregation principle extends the functional disaggregation paradigm proposed by 3GPP for the New Radio (NR) gNB, effectively splitting base stations into different functional units. The gNB is split into a Central Unit (CU), a Distributed Unit (DU), and a Radio Unit (RU), having the CU divided also in the Control Plane (CP) and the User Plane (UP). Thanks to this logical split different functionalities can be deployed at different network elements and on specialized or general-purpose hardware platforms. Implementing the virtualization principle, all the O-RAN architecture components shown in Figure 2 can be deployed on a cloud computing platform, as stated in [6].

B. RAN Intelligent Controllers and Closed-Loop Control

In order to orchestrate the RAN, O-RAN introduces the RAN Intelligent Controllers (RICs). The latter, thanks to data pipelines that stream Key Performance Indicators (KPI) of system nodes, have an abstract and centralized point of view on the network. By processing this data and exploiting AI and ML algorithms, the RICs can optimize and apply the control policies of the RAN. With reference to Figure 2, O-RAN foresees the non-RT RIC and the near-RT RIC, differentiated on the role and on the timescale of intervention.

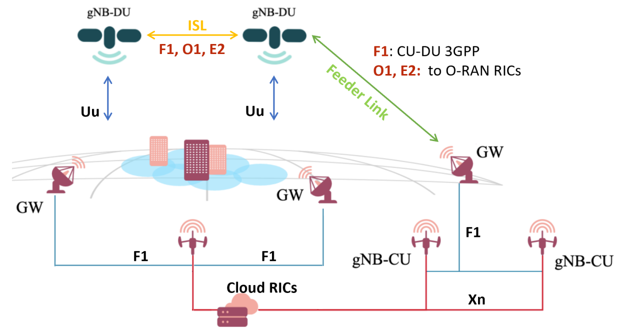

Fig. 3. High-level system architecture.

C. Open Interfaces

Finally, O-RAN introduces technical specifications of open interfaces connecting different components of the architecture. The existence of these interfaces is fundamental for the RICs to collect data from the network and to apply the control policies on the RAN. The most important O-RAN interfaces are shown in Figure 2 and are described below:

- *E2 Interface*: this interface interconnect the near-RT RIC and the so-called E2 nodes, such as the CUs or DUs. E2 enables the RIC to collect KPIs and control the procedures of E2 nodes.
- *O1 Interface*: The O1 interface role is to provide management services to all the O-RAN-managed elements, which include the O-RAN component's life-cycle management, software and file management, and performance assurance through KPIs collection.
- *A1 Interface*: This interface connects the non-RT RIC with the near-RT RIC, allowing the former to deploy guidance for the latter and to manage the used ML models.
- *Fronthaul (FH) Interface*: Distributes the physical layer functionalities between the DU and multiple RUs.
- *3GPP defined Interfaces*: The F1 interface connects the CU to the DU to exchange control and user plane Protocol Data units (PDU), the Xn interface connects different gNBs to perform handovers and to enable dual connectivity, the NG interface connects the gNB to the 5G core and, finally, the Uu interface exists between the UEs and the gNB.

IV. NTN System Architecture

The NTN system architecture is depicted in Figure 3 and it is composed by:

- The terrestrial segment, where the ground distribution network provides inter-connectivity between the gNBs, the 5G Core Network (5GC), and the on-ground gateways (GWs). The latter are uniformly distributed on the globe and connect the terrestrial network to the NTN segment.
- The access segment provides access service through NTN nodes. For the purpose of this study, we focus on regenerative nodes allowing the implementation of O-RAN in space. The coverage can be achieved with *fixed* or *moving* beams. In the former case, the on-board

antenna keeps serving the same on-ground area while the satellite moves in its orbit (steerable antennas). In the latter case, the served on-ground area is moving together with the satellite. The regenerative payload offers the possibility of embarking the full gNB or part of it. In the firs case, the NR-Uu protocols are fully terminated on-board. Therefore, the Uu air interface is only present on the user service link (the blue arrow in Fig. 3). As a consequence, the GW only terminates the transport protocols, interconnecting the 5GC network and the gNB via the Next-Generation (NG) interface. In the case of the gNB split, several options are available [23] and each one is optimized for specific use cases. Currently, those considered as the most relevant are option 2, Option 6, Option 7, and Option 7.2. However, it is worth emphasizing that only Option 2 is fully supported by 3GPP, which includes the F1/E1 interfaces; while option 7.2 is adopted in O-RAN.

  It is worthwhile highlighting that each gNB is capable of managing a few tens of beams. However, in the case of multi-beam NTN systems, each satellite may generate hundreds of beams. Therefore, in order to manage the NTN node, multiple gNBs (or part of it) might be needed on-board.
- The user segment is composed of a potentially massive number of users directly connected to the satellite.

While adapting the open RAN concept to NTN we focus on two architectural design aspects: *i*) the network entity in which the O-RAN components are implemented; *ii*) the physical links to which the O-RAN interfaces are mapped. In the context of this work, the non-RT RIC and the near-RT RIC are assumed to be implemented in the cloud, interconnected to the ground network elements through the ground distribution network. Depending on the dimension of the network slice they have to serve, they can be deployed closer to the network edge or to the central cloud. For what concerns the open interfaces, their mapping on the physical network links of this NTN architecture is a non-trivial task. In a terrestrial implementation of the O-RAN architecture, the interfaces are built upon the ground distribution network, inter-connecting all the network elements. This Internet Protocol (IP) based network is often based on reliable optic fiber links, providing stable capacity and latency. On the other hand, in NTN networks some key open interfaces have to rely on intermittent links with unstable performances.

More precisely, the NR-Uu Air Interface is implemented on the user access link, while on the feeder link, the interface depends on the type of split. Indeed, if the satellite embarks only the RU, the feeder link carries the FH and O1 interface, while if both the RU and DU are on-board the implemented Interfaces are the F1, E2 and O1. All the interfaces assigned to the feeder link are logical, *i.e.*, they can be implemented by means of any Satellite Radio Interface (SRI), such as the DVB-S2, DVB-S2X, or DVB-RCS2. Actually, the unstable performance of the feeder link is not a show-stopper problem, since the service provided by O1, E2, and F1 interfaces can be adapted to meet the instantaneous feeder link performances. On the contrary, the current standardization of these interfaces, as per 3GPP TR 38.473 [24] and O-RAN WG1 [6], do not allow their implementation upon intermittent links. As a consequence, for Non-Geostationary Orbit (NGSO) nodes with no direct visibility of the GW, the logical link with the serving gNB on-ground is ensured by INL.

V. O-RAN NTN Trends and Challenges

A. F1 Interface PDUs reliable delivery

Focusing on LEO satellites, they orbit around the earth between 11 and 16 times per day, causing a constant handover in the GW serving the satellite DU through the feeder link. However, 3GPP defines the F1 interface as a constantly available logical link between the CU and the DUs, [24]. Since the F1 interface is delivered through the feeder link, even if we assume the network is dimensioned with a sufficient number of GWs distributed on the earth's surface and INLs, such that there is always a viable route between the CU and the DUs, there will still be the need for feeder link and INL handovers. The frequent changes in the GW serving the satellite may cause the late delivery or even the loss of a consistent number of PDUs, currently not foreseen by 3GPP, [25]. To address the reliable delivery of the F1 PDUs from the CU to the DUs on the satellite, the O-RAN based NTN architecture shall enable the management of the feeder link and INLs handovers directly at the network layer, providing reliable service to the application layer on which the F1 interface relays. Indeed, an application implemented inside the near-RT RIC is able to foresee the availability of each physical link under its control and can centrally orchestrate the network elements in order to always route the F1 packets toward an active network path. In this way, no F1 packet is lost or delayed trying to deliver it on a link that is going to drop. Since we are considering an O-RAN based architecture, also the E2 and O1 interfaces will rely on the same reliable network paths used by F1. A significant work on this topic has been presented in [26], where a GW cooperation scheme is proposed to route the downlink packets to a different satellite with a most reliable feeder link trough INLs. The main challenge to be tackled while implementing this solution is to serve the DUs from different RICs while orbiting around the earth, since the near-RT RIC has not a global view of the network. This is actually a challenging architectural design to address since it implies: *i*) to implement over-dimensioned near-RT RICs to keep in memory the data and applications of all the RAN elements, even the ones not in visibility, or *ii*) to exchange the data and applications between the near-RT RICs when it is needed, causing an increased load on the non-RT RIC in charge of managing the near-RT RICs. In the latter case, it will not be efficient to implement a single instance of the non-RT RIC to manage the whole global network of near-RT RICs due to the heavy load of data and applications to be transferred. However, the current O-RAN standardization foresees an isolated implementation of the non-RT RIC inside the Service Management and Orchestration

(SMO) framework of the Mobile Network Operator (MNO), [6], thus, to enable this architecture the standardization of a distributed and synchronized non-RT RIC is needed.

B. Functional Split Optimization

The functional split concept yields many degrees of freedom to the RAN design, allowing the distribution of the network functions between different physical and virtualized resources. However, the full potential of the functional split is in its dynamic implementation, where the functions are allocated to network resources based on specific optimization rules. Indeed, implementing RAN functionalities closer to the network center implies lower complexity edge nodes, but requires a high throughput inter-connection interface and increases the service latency. Conversely, progressively shifting the RAN functions to the edge nodes requires more computationally capable devices in the edge but relaxes the interface-required performances. This concept is already exploited in [9] and [10] to maximize the photovoltaic power exploitation and the quality of service in a terrestrial RAN. Referring to the NTN system architecture, the RAN functions are split between the on-ground component and the payload component onboard the satellite. The reference functional split architecture, as defined in TR 38.821, foresees the CU implemented on-ground while the DUs and RUs implemented on the satellite. The CU-DU interface is implemented on the SRI exploiting the feeder link and the INLs. In a static system, the optimal functional split can be already determined in the design phase. On the contrary, the NTN architecture changes morphology in a highly dynamic way and must optimize its functional split in an equally dynamic way. To this respect, the O-RAN based NTN architecture shall enable a system-aware and proactive functional split optimization leveraging on its near-RT RICs capabilities. Indeed, the near-RT RIC will be in charge of computing the optimal functional split based on the collected network status data and redeploying the network functions in the CU and DU according to it. One of the main optimization objectives to be investigated is the minimization of the on-board payload energy consumption. Indeed, it has already been mentioned that the satellite has limited available power, this implies that every single watt from batteries and the photovoltaic unit shall be wisely exploited. Moreover, not only the communication payload power is a scarce resource, but also it is not constant in time since it is a function of the satellite's position in the orbit and it depends on the instantaneous power required by the other satellite subsystems. In this framework, a software application deployed in the O-RAN near-RT RIC will be able to select and implement the optimal functional split while guaranteeing an appropriate Quality of Service (QoS). Precisely, shifting RAN functions from the on-board DU to the on-ground CU frees up resources on the payload but increases the required feeder link performances and the latency of the CU-implemented RAN functions. This application operates by collecting data from the network about: *i*) type and volume of requested user traffic; *ii*) payloads computational power capabilities; *iii*) Payloads instantaneous available power, and *iv*) the CU-DU physical feeder link instantaneous throughput and latency. Furthermore, in order to provide an optimal operation, the near-RT RIC application will actually need to be an AI algorithm [9], able to foresee the future behaviors and needs of the network and optimize the functional split in advance. Additionally, in system configurations with lower restrictions on power consumption, an additional optimization objective is the maximization of the exploitation of the feeder link, following the time-varying behavior of its performances. In this regard, the near-RT RICs will exploit the same KPIs of the previous case to proactively select the best-fitting functional split. The most challenging aspect of the dynamic functional split implementation is the high functional flexibility required on the payload. Indeed, that grade of flexibility that can be met by: *i*) relying on general-purpose computing processors, or *ii*) implementing the single RAN functions on specialized and isolated hardware that can be individually activated. The general-purpose computing technology currently available requires an amount of power not compliant with the common NGSO payload implementations, [27]. Additionally, the latter case implies high complexity design and poorly exploited payload hardware. This implies the current applicability of the dynamic functional split is limited to low-capacity services, but relying on the future implementation of low-power high-performance processors its applicability can be extended to every type of service.

C. Wide-Scale Radio Resource Management

NTN is a very dynamic system due to the rapid movement of the flying platform along its orbit, causing the change over time of the users' channel parameters. Thus, to avoid taking decisions based on aged parameters, Radio Resource Management shall be performed rapidly. In this context, the most promising tools to take rapid and data-driven decisions are AI and ML, as suggested by the interesting review in [28]. Nevertheless, the current approaches based on AI/ML are inherently limited because they apply to the existing NTN architecture that was originally designed without considering the application of AI/ML. For this reason, the current optimization of the RRM problem is restricted to the point of view of a single satellite, limiting the benefits of the technique. To this respect, the O-RAN based NTN architecture will enable dynamic RRM, including beamforming and Beam Hopping (BH), performed at a constellation scale. Indeed, the O-RAN based architecture enables: *i*) the collection of the required near-RT KPIs from all the network nodes (specifically, the E2 nodes) through the open interfaces; *ii*) the exploitation of the collected data to train the AI/ML models, and, finally, *iii*) the deployment of the trained AI/ML model in the RICs, which, taking as input the KPIs data, performs fine-grained control over the CU and DU nodes to optimize the RRM. Specifically, the near-RT RIC will need to collect information about the area traffic demands and user locations, along with the satellite ephemeris to identify the best scheduling options based on ancillary information. This RIC based approach to RRM will introduce a longer latency in the scheduling computation compared to on-board implemented AI solution but allows a comprehensive optimization of the resources.

VI. Conclusion

In this paper, we investigated the exploitation of O-RAN infrastructure in NTNs. We started with a state-of-the-art analysis of the latest applications of O-RAN that underlined: *i*) the capabilities proven by O-RAN in the TN field; *ii*) the novelty of the research on O-RAN use in NTN. Consequently, we identified the NTN services that can be optimized and enhanced by fully exploiting O-RAN concept. For each of the proposed use cases, a thorough analysis is provided highlighting their advantages from the system performance and efficiency point of view, along with their limitations. The work shows that O-RAN is a promising tool to enhance the performance of NTNs in the following use cases: *i*) the full exploitation of AI models which must rely on data-collection pipelines and centralized intelligence provided by open RAN approaches; *ii*) the optimal allocation of RAN functions to the different network nodes requires the O-RAN enabled disaggregation and virtualization of the RAN, along with central network-status knowledge, and *iii*) the leveraging of the O-RAN standardized and open network interfaces to pursue NTN systems interoperability. Thus, future works foresee the evaluation of these use cases through system simulators, to quantify the actual increase of the NTN network performance and efficiency and precisely identify their limits.

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