Innovative Multi-Layer Approaches for 6G Integrated Terrestrial And Non-Terrestrial Networks

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***Abstract*—This paper explores the integration of Terrestrial Networks and Non-Terrestrial Networks (T/NTNs) as a critical enabler for the 6th Generation (6G) of communication systems. Starting from the 3rd Generation Partnership Project (3GPP) specifications and roadmap, this article investigates cutting-edge aspects of architectural designs, advanced transmission techniques, and cross-domain management strategies. In particular, in order to address challenges in seamless connectivity and optimized resource utilization, the proposed multi-layer approach combines terrestrial, aerial, and satellite components for improved coverage, scalability, and adaptability. Key and innovative contributions include modular waveform designs, efficient management of free-space optical links, and a comprehensive NTN framework.**

***Index Terms*—6G, Integrated Terrestrial and Non-Terrestrial Networks, Multi-layer Architecture, Modular Waveform Design, T/NTN Management, Free-Space Optics.**

I. Introduction

Building on 5th Generation (5G) and 5G-Advanced (5G-A), 6th Generation (6G) promises to further revolutionise the connectivity landscape, by achieving ultra-high data rates and low-latency communications integrating Artificial Intelligence (AI) in a sustainable ecosystem that will merge the human, physical, and digital worlds [4]. While the activities related to the definition of 6G systems recently started within International Telecommunication Union (ITU) and 3rd Generation Partnership Project (3GPP), it is globally recognised that a native Non-Terrestrial Network (NTN) component will be a pivotal element in the global end-to-end infrastructure to achieve the challenging objectives set forth for 6G.

This work builds upon the recent advancements in 5G NTN integration with Terrestrial Networks (TNs) and it extends them toward 6G by outlining innovative multi-layer approaches (meaning that they affect different levels) that have been studied within the Italian Integrated Terrestrial And Non-Terrestrial Networks (ITA NTN) project [3], which is included in the "RESearch and innovation on future Telecommunications systems and networks, to make Italy more smart (RESTART)" program and funded by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of Next Generation EU. The ITA NTN project assumes a 6G-oriented scenario and is focused on: the design of a 3D multi-layered communication architecture for integrated T/NTNs; the evaluation of the link budget of free-space, optical, and Radio Frequency (RF) communication links; the design of advanced transmission techniques and innovative methodologies for the orchestration of communication and computational resources; performance evaluation in some reference use cases through simulations and Proof of Concepts.

In line with the 6G standardization process, the paper addresses various aspects: i) it reviews the 3GPP process of standardization for integrating T/NTNs; ii) it proposes a multi-layer NTN architecture combining terrestrial, aerial, and satellite systems to enable global connectivity with dynamic adaptability for diverse use cases and requirements; iii) it introduces modular waveform design for NTN physical layers, allowing flexible adaptation to varying data rates, latencies, and environmental conditions; iv) it focuses on the multi-faceted challenges of network management and orchestration, including resource allocation, traffic steering, and QoS enforcement across heterogeneous domains; v) it investigates the integration of Free-Space Optics (FSO) technologies into NTN for enhanced throughput, which can conveniently exploit the advancements in fiber-optic systems.

II. 3GPP Overview of the NTN Standardization

This section outlines the 3GPP overview of the NTN standardization.

After the successful integration of NTN in 5G in Rel. 17 [5], the 3GPP normative activities introduced further enhancements and functionalities to support space-/air-borne components

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in 5G-A within Rel. 18, finalised earlier in 2024 [6]; in this framework, 3GPP also submitted two NTN-based Radio Interface Technology (RIT) documents to ITU Radiocommunication sector (ITU-R) for its inclusion in International Mobile Telecommunications-2020 (IMT-2020 standard), reported in Technical Report (TR) 37.911. The allocations in Frequency Range 1 (FR1), i.e., S-/L-band, have been extended and Frequency Range 2 (FR2) operations, i.e., Ka-band, for Very Small Aperture Terminal (VSAT) receivers have been included; the latter foresee fixed VSAT for Geosynchronous Orbit (GSO) and Non-Geosynchronous Orbit (NGSO) platforms, while mobile terminals are only allowed for GSO systems. In all allocations, the system is operating in Frequency Division Duplexing (FDD) mode, as also in Rel. 17. Within the System and Service Aspects (SA) and Core Network and Terminals (CT) Technical Specification Groups (TSGs), two important Study Items (SIs) were finalised: i) 5G systems with satellite backhaul, which focused on the support of dynamic (latency, bandwidth, capacity) backhaul solutions and the inclusion of the User Plane Function (UPF) on-board GSO platforms; and ii) enhancements for satellite access in discontinuous coverage scenarios. With respect to the former, several challenges were identified within TR 23.700-27, identifying three major key issues related to: i) Policy and Charging Control (PCC) and Quality of Service (QoS) management with dynamic backhaul, for which new service categories and their management have been included in the specifications; ii) the support of local data switching via an on-board UPF, aimed at reducing the use of satellite backhauls, which called for enhancements related to on-board User Equipment (UE)-to-UE traffic routing; and iii) the support of satellite edge computing via on-board UPFs. The related enhancements are reported in many documents of the 22 (Service Aspects – Stage 1), 23 (Technical Realisation – Stage 2), and 28-29 (Signalling protocols – Stage 3) series. At Radio Access Network (RAN) level, the enhancements focused: i) on uplink coverage, aimed at improved estimation of the DeModulation Reference Signals (DMRS) and repetition schemes in the HARQ-ACK procedure; ii) network-verified location, in which the 5G Core network (5GC) requests a verification procedure to confirm that the User Equipment (UE) in connected state is indeed in the location that it provided; iii) NTN-TN and NTN-NTN mobility and service continuity. As for the latter, several enhancements have been introduced, including an extension to the functionality of System Information Block (SIB) 19 and 25 to broadcast cell coverage areas, ephemeris data, and frequency allocations to ease the transition from a terrestrial to a non-terrestrial cell, and vice versa, the support of enhanced handover procedures (without Random Access and more conditional handover scenarios), and operations for satellite switch-over.

Currently, 3GPP is working on Rel. 19, which will be finalised at the end of 2025. It is worthwhile mentioning that the enhancements that are being discussed will provide a bridge to 6G communications, for which the study phase will start in Rel. 20 (normative in Rel. 21+). In Rel. 19, the NTN component will be allowed to operate in extended S-/L-/Ka-band allocations, but also Ku-band ranges are being evaluated. However, the most relevant improvement is definitely related to the architecture: in Rel. 19, regenerative payloads with a full Next Generation Node B (gNB) on-board are considered. This leads two additional scenarios that are being defined in terms of the related procedures and operation and management (O&M) aspects: i) Store & Forward (S&F) operations for delay-tolerant communications, an NTN operating mode in which the 5G system can provide a certain level of service when the satellite connectivity is intermitted or temporarily unavailable; ii) UE-Satellite-UE communications, in which some UEs are allowed to communicate using the satellite access without the need to go down to the ground network (for the User Plane), thus avoiding large latencies and limited data rates, as well as reducing the resource consumption on backhaul links. In addition, operations without Global Navigation Satellite System (GNSS) capabilities at the UE are being defined, which are particularly challenging due to the mandatory requirement for the UEs to pre-compensate time/frequency shifts during the Initial Access procedure. The architecture enhancements are being reported in TR 23.700-29, and it shall be mentioned that Inter-Satellite Links (ISLs) and feeder links are assumed to only act as transport layer links, meaning that they will not be specified by 3GPP, for the moment being. Another relevant step in Rel. 19 is that Integrated Access and Backhaul (IAB) nodes are being deprioritised also for TN systems, in favour of the newly defined Wireless Access Backhaul (WAB) approach, in which the NTN component is only included as a backhaul solution. Finally, other RAN studies are focusing on downlink coverage and uplink capacity enhancements, and, clearly, on all the required modifications to support the massive modifications related to the NTN system architecture.

The 3GPP NTN roadmap which has been thoroughly described in this paragraph is summarized in Fig. 1.

III. Multi-layer NTN architectures

While 5G-A maximizes the potential of current infrastructures, 6G aims to integrate TNs and NTNs into a unified, fully optimized multi-layer system. The envisioned Multi-Band Multi-Layer Multi-Dimensional network architecture will incorporate terrestrial components, aerial components, such as Unmanned Aircraft Systems (UASs) including drones or Unmanned Aerial Systems (UAVs) and High Altitude Platforms (HAPs), and spaceborne components, such as Geostationary Earth Orbit (GEO) (included in GSO category) and Non-Geostationary Earth Orbit (NGEO) satellites. This approach enables seamless global connectivity and adaptability for various use cases, from regional low-latency applications to long-range delay-tolerant communications [9]. As shown in [3] there are suitable architectures for each use case depending on the requirements in terms of latency, reliability, and other specific functional Key Performance Indicators (KPIs). Moreover, scalability can be achieved by leveraging orchestration approaches based on Software-Defined Networking (SDN) and Network Function Virtualization (NFV) paradigms and AI integration, in order to enhance automation and flexibility.

Rel. 16 introduced IAB nodes. The IAB architecture is based on the Centralized Unit (CU)/Distributed Unit (DU) split of the gNB. New advancements are expanding NTN's role in 5G, leveraging high-throughput satellites, mega-constellations, and improved NTN specifications to support Internet of Things (IoT), data offloading, and multimedia broadcasting. Carefully selected integration options include satellite-enabled access and backhaul architectures aligned with 3GPP specifications and standards [4], [10]. Feasible configurations exclude impractical scenarios, such as placing the entire core network on satellites without terrestrial radio access components.

Four primary multi-layer NTN architectures demonstrate the potential of T/NTN integration [3], [9]. They are summarized in Fig. 2, where the non-terrestrial and terrestrial segments are depicted with the main entities and interfaces [3], [10]:

- UAS-based Relay Network,
- Satellite-based Architecture,
- 3D Single-Connectivity Architecture,
- 3D Multi-Connectivity Architecture.

Note that: the NR-Uu interface connects the UE to the gNB over the air; the F1 interface provides a means for interconnecting the gNB-CU and the gNB-DU of a gNB within the 5G RAN; the NG interface connects the gNB to the 5GC. Furthermore, the dotted line represents the feeder link between the NTN gateway (NTN-GW) and the satellite.

In the *UAS-based Relay Network*, UASs, including drones, act as relays, offering flexible data routing options and localized user service.

The *Satellite-based Architecture* provides consistent coverage via satellites, supporting both direct access and backhauling. In particular, satellite-based direct access refers to the utilization of satellites to directly connect end-user devices, establishing a direct link between the satellite and the UE (also through a functional split option with an onboard gNB-DU and an on-ground gNB-CU). Satellite-based backhauling solution is possible through IAB specifications, i.e., IAB Donor and Satellite Access Node (SAN), which is connected with the NTN-GW through the feeder link.

For the *3D Single-Connectivity Architecture*, intermediate aerial nodes (i.e., relays) route user traffic to satellites, enabling communication in areas without terrestrial infrastructure.

Finally, the *3D Multi-Connectivity Architecture* combines terrestrial, aerial, and satellite layers for enhanced reliability, offering backup routes and higher network resilience. It can be deployed between a terrestrial node and a non-terrestrial node, i.e., without ISL with gNB-DU on satellite and gNB-CU on earth or gNBs on satellites, or between two non-terrestrial nodes (with ISL). It is worth noting that a key aspect that defines the overall architecture is the option to deploy transparent or regenerative payloads for the non-terrestrial (space/air) segment, giving rise to various subcategories [3].

IV. Advanced Transmission Techniques

In the 6G vision, connectivity should be guaranteed everywhere, at all times, and for everyone/everything [7]. The fulfillment of such a fundamental requirement has a significant impact on the policies of PHY-layer standardization, also considering the emerging role of NTNs. 5G inherited the PHY design philosophy of LTE, focused on Multicarrier Orthogonal Frequency Division Multiplexing (OFDM) transmission and orthogonal Multicarrier multiple access, i.e., Orthogonal Frequency Division Multiple Access (OFDMA) and Single-Carrier Frequency Division Multiple Access (SC-FDMA), adapted to the heterogeneous connectivity requirements typical of the new standard. In such a framework, it was spoken about "OFDM-inspired" waveforms, meaning with this term things like Filter-Bank Multicarrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), and Universal Frequency Multicarrier (UFMC). The two basic 4G waveforms, namely: OFDM and DFT-spread-OFDM (DFT-s-OFDM), were retained as legacy, adding flexibility by introducing some kind of numerology [7]. The most recent trends are going toward an holistic radio design by emphasizing the importance of creating the radio as an integrated, cohesive system rather than as an interconnection of individual components [1].

In such a perspective, the evolution toward 6G will require a step forward in terms of a renewed standardization process involving the waveforms to be adopted. The key points to be addressed are as follows [8]:

- need to support a plethora of services, characterized by heterogeneous requirements of data rate and latency;
- extension of New Radio (NR) FDD mode to frequency bands beyond 10 GHz, e.g., Ka-band for VSAT devices;
- coverage enhancement for low-data rate and Voice-over-IP (VoIP) services in LEO NTN scenarios.
- improvement of UE mobility in NTN earth-fixed and earth-moving cells;
- support of high-mobility scenarios, characterized by significant Doppler effects.

In addition, FSO technology is emerging as a relevant component for NTN links, leveraging optical devices (e.g, transceivers) to achieve ultra-high-speed data transmission. This capability is further explored in the management and control strategies discussed in Sections V and VI. FSO integration with fiber infrastructures could enhance the reliability of connections as well as the coverage. As an example, FSO links (e.g., for space communications) may redound fiber links so that if a fiber cut occurs (e.g., in sub-marine cables), traffic can be switched into the FSO link. Such an integration will rely on electronic layer2/layer3 interfaces, performing the switching from the TN to the NTN. In few cases, TN-NTN integration might also avoid electronic interfaces, integrating telescopes directly with the fiber-based TN (with relevant issues of power budget). Data plane integration is still an open field which strongly depends on the application (e.g., due to the involved propagation distance and latency).

Given the diverse and complex requirements of 6G networks, the standard waveform design should become more flexible and adaptive to the multifaceted application requirements. To this aim, it is of paramount importance to have a *modular* waveform design as proposed in [7]. Starting from the Lattice theory, each transmission format is implemented by assembling various combinations of processing slices:

- *Reshaping*, which organizes the modulated symbols into a lattice of $\frac{N}{L_2} \times \frac{M}{L_1}$ elements, M and N being the number of resources in the frequency (subcarriers) and in the time domain respectively, while L_1 and L_2 accounts the reshaping granularity.

- *Precoding* converts the symbols mapped in the multi-dimensional lattice to PHY-layer resources in the T-F grid. The conversion is performed by transforming and/or combining symbols localized at different points of the lattice.
- *Windowing* multiplies the signal by a window function leading to a signal scaling or rotation, depending on some specific requirements.
- *Transform* converts the T-F signal in the time domain by operating a pulse-shaped transformation of the samples in the grid. A typical example of such an operation is the I-FFT used in Multicarrier modulations.
- *CP + filtering* is devoted to physically transmitting the time-domain signal onto the channel. It substantially adds the Cyclic Prefix (CP) and, optionally, filters the signal before the D/A conversion.

Adding (or removing) processing slices to the chain it is possible to obtain various kinds of waveforms, namely:

- *OFDM* and *DFT-s-OFDM*, used by LTE and NR.
- Multi-Carrier Spread Spectrum (*MC-SS*), whose multi-user version is known as Multi-Carrier Code Division Multiple Access (MC-CDMA).
- *Filtered-OFDM*, used by LTE-A.
- OFDM-inspired waveforms: *FBMC* and *GFDM*.
- Constant-Envelope (CE) Multicarrier waveforms, i.e., *CE-OFDM* and Constant-Envelope Single-Carrier FDMA (*CE-SC-FDMA*), obtained by applying a nonlinear phase modulation to a real-valued Multicarrier signal [15]. They are employed in satellite communications and mmWave 5G transmission.
- *LoRA chirp*, used in satellite-based IoT applications.
- Delay-Doppler grid waveforms, namely: Orthogonal Time-Frequency Space (*OTFS*), Orthogonal Time-Sequency Multiplexing (*OTSM*), and Orthogonal Chirp Division Multiplexing (*OCDM*) [7] that represent the last frontier of 6G waveform design, characterized by robustness to multipath and Doppler.
- Non-Orthogonal Multiple Access (*NOMA*), which will be one of the leading multi-user transmission formats of 6G thanks to its flexibility, ease of deployment, and augmented spectral efficiency. NOMA is actually implemented in the *power domain* and as Resource Spread Multiple Access (*RSMA*)/Direct Sequence CDMA (DS-CDMA).

An idea of standardized modular waveform design for 6G NTNs, inspired by [7] and [8], can be sketched as in Fig.3, where the acronyms DFT and IDFT stand for Discrete Fourier Transform and Inverse Discrete Fourier Transform, respectively, ISFFT stands for Inverse Sympletic Finite Fourier Transform, DZT for Discrete Zak Transform, WHT for Walsh-Hadamard transform, and F_{ov} is the oversampling factor applied to the real-valued IDFT transform required to generate the CE Multicarrier signals.

The modular implementation shown in Fig. 3 can pave the way to a Software-Defined Radio (SDR) implementation of the NTN PHY-layer, as proposed in [8].

V. Management of Integrated T/NTNs

Integrated T/NTNs assume multifaceted challenges related to the cross-domain control plane, orchestration, and management because they involve very different domains, from terrestrial to drones to satellites, and because they can use different transmission systems and different frequency bandwidths introduced by 3GPP from Rel. 17 to Rel. 18, with a foundational set of features to facilitate the spectrum exploitation. Furthermore, the resource management, in a satellite network, has to take into consideration satellite mobility, variable propagation conditions (e.g., due to fading), and continuous handovers among terrestrial gateways and satellites. Coordinating resource allocation and management across these dynamic and heterogeneous environments while taking into account QoS is a challenging task. In particular, efficient routing and traffic engineering across TN and NTN domains require mechanisms to optimize end-to-end path selection, considering factors like latency, bandwidth availability, and network congestion. This involves also developing algorithms and protocols for inter-domain routing and traffic steering. In addition, it is also necessary to keep in mind spectrum management policies, developing regulations and standards for efficient frequency allocation and management to accommodate the diverse requirements of TNs and NTNs, avoiding interferences and ensuring equitable access and optimal utilization.

First of all, it should be noted that there is still a very heated debate on whether to have a single management and orchestration that simultaneously manages both the Core Network (CN) and RAN. Furthermore, it is still to be established whether the NTN can be assimilated into a RAN or whether it needs its own management model. Clearly, in order to achieve a rapid definition of the management models of such a complex network, it would be advisable to try to exploit the regulations already in place as much as possible.

Standards Development Organizations (SDOs) such as ITU Telecommunication Standardization Sector (ITU-T), European Telecommunication Standard Institute (ETSI), 3GPP, and Open Radio Access Network (O-RAN) [13] have proposed different approaches to address various challenges associated with unified management and control for different domains. However, no definitive solutions have been addressed yet and convergence and interoperability remain critical gaps to be further investigated. Advanced analytics capabilities are essential and crucial to achieving effective orchestration and management in this context. These capabilities empower control loops and automation, enabling the system to adapt and respond efficiently to changing conditions. 3GPP Rel. 18 has included a diverse set of study and work items dedicated to AI, and the 3GPP Service and System Aspect 5 working group (3GPP SA5) has introduced the Management Data Analytics Function (MDAF) to address these needs also in a cross-domain scenario, gathering data from various sources such as Operations And Management (OAM) systems, intelligent elements within the 5GC, i.e., 5G NetWork Data Analytics

Function (NWDAF), and access networks, i.e., Non-Real-Time (Non-RT) RAN Intelligent Controller (RIC), RT RIC, where RIC is a key component of the O-RAN architecture. However, the detailed design of each functional component, the orchestration of the resources and functionalities, interface, protocol and algorithm, and pipeline has to be further studied and discussed in the different standardization organizations and towards the scenario envisaged in ETSI Zero-touch network and Service Management (ZSM) [11]. This entails developing intelligent algorithms and protocols capable of efficiently balancing traffic loads, mitigating interference, and adapting to changing network conditions, introducing a reference architecture featuring distributed management and orchestration, including also closed-loop control, aiming at a deeper AI native approach. Concerning Management and Orchestration (M&O), a particular aspect would be required for the introduction of FSO systems that will be a novelty in the 6G environment and that can have a different control with respect to radio systems. This is the reason why in the framework of the ITA NTN project particular attention is devoted to M&O of FSO links. The challenge of coordinating and optimizing the integration of multiple fibers, FSO, and radio links was investigated in [9] considering different terrestrial and non-terrestrial paths within a unified network. A possible strategy could be based on the treatment of the whole optical layer, including optical fibers for TN and FSO for NTN, with the same kind of control, already affirmed for optical fiber networks [2]. Independently of M&O adopted either in the core, the access segment, or in a cross-domain orchestration, the configuration of the optical devices could be achieved by means of the NETCONF protocol, thus extending the control system and the procedures already adopted for the optical part in the TN domain. Indeed, considering that the main and consolidated components (e.g., transceivers) for fiber-optics networks are going to be re-used in FSO, similarly, it is possible to expect that NETCONF could be considered for the control of FSO transceivers as well. In fact, currently, NETCONF is envisioned for the control of core and metro networks (e.g., based on fiber optics) and it can be applied to configure transceivers (e.g., at a specific line rate or modulation format) and optical switches. NETCONF is also used to transport performance monitoring information, e.g., pre-forward-error-correction bit error rate (pre-FEC-BER) of an End-to-End (E2E) connection. NETCONF can be also considered for the configuration of the gateway between the ground station and satellite enabling QoS enforcement [2].

Therefore, the concept of a high-level architecture framework of integrated network control systems for T/NTN convergence starts to be defined such as the one shown in Fig. 4, which recalls the proposed in [12], inspired by ITU-T Study Group 13. In Fig. 4, it is supposed to have a 3GPP 5GC with different NT domains operating according to O-RAN model. NWDAF operates in the 5GC and provides analytic outputs both in terms of statistics and predictions, based on ML models and algorithms embedded in it. In 3GPP TR 23.791, the list of analytics services provided by NWDAF is detailed to provide support for different use cases as UE mobility management customization, supporting in policy management and enhanced management and orchestration capabilities, slide load computation and predictions to efficiently allocate resources, security prevention attacks by abnormal or anomaly user equipment behavior. For the O-RAN Non-RT RIC and Near-RT RIC are responsible for data analytics. All the elements dedicated to data analytics communicate with the common MDAF that can operate both with the 5GC M&O and the Service Management Orchestration (SMO) related to O-RAN. All the M&O interact with the controls of the device configurations. The complete integrated T/NTN architecture of Fig. 4 serves as the foundation for optimizing E2E resource management and control according to service level requirements and user intents. Its objective is to dynamically and optimally allocate resources to ensure the delivery of high-quality E2E communication services.

VI. FSO Control

FSO technology is currently regarded as the most promising option for enabling ultra-high-speed NTN links. The recent trend in FSO is to shift mature technologies for fiber optics (e.g., transceivers, amplifiers, multiplexers and demultiplexers) into the FSO system and several demonstrations have been performed accordingly, in terrestrial FSO links and recently in satellite links [14]. This is possible thanks to the use of transparent optical terminals, which can support Wavelength Division Multiplexing (WDM) and actually allow the "fiber to the sky" concept. Regarding possible protocols for FSO control, as already anticipated in Sec. IV, a similar tendency of the FSO data plane could be assumed for the control. In today's optical fiber networks, NETCONF is a widely used configuration and management protocol. NETCONF is based on a highly-readable data modeling language named YANG. Currently, there is a huge effort within the industry to define YANG data models for *configuration* (e.g., laser central frequency) and *state* (e.g., performance monitoring) parameters of devices, such as transceivers, in optical-fiber networks. An example is the OpenConfig consortium[1], involving some of the most relevant global operators and service providers.

The OpenConfig data model for terminal devices – designed to describe transponders for fiber-optics networks – has been extended in [2] to describe transceivers in a FSO system. Part of the traditional OpenConfig terminal-device YANG data model is shown in Fig. 5. Each $< \mathrm{optical}-\mathrm{channel} >$ consists of two main branches: (i) the $< \mathrm{config} >$, representing configurable hardware parameters, (ii) the $< \mathrm{state} >$ for state information. The $< \mathrm{config} >$ parameters include frequency, target output power, and Operational (OP) modes (i.e., a given combination of modulation format, symbol rate, and coding), and the line port. The $< \mathrm{state} >$ parameters include pre-FEC-BER, post-FEC-BER, and the electrical signal-to-noise ratio (ESNR). A state parameter is then associated to instant, average, minimum, maximum, and other values (for space reasons, shown only for output power).

Configuration parameters (frequency, power, OP mode) are confirmed in FSO. Differently, the OpenConfig model is extended to describe the state parameters associated with a

[1] https://www.openconfig.net/

FSO system, including the telescope and Adaptive Optics (AO) (which is a module introduced to mitigate the distortions due to propagation in the atmosphere), as shown in Fig. 5 (b) and (c), respectively. Indeed, a SDN controller might monitor the functionalities of both the telescope and AO, e.g. to localize where a malfunction is experienced. It is assumed that the external SDN controller does not configure the telescope and AO, since both they are self-configured based on local control loops: e.g., the telescope at the receiver can be self-oriented to maximize the received optical power.

The model for the telescope includes the orientation (elevation and azimuth angles) and a related tracking speed. Then, the model for AO infers its behavior through the input/output power at/after the AO, respectively.

Finally, besides protocols, SDN controllers should also be envisioned: likely, dedicated controllers for TN and NTN, respectively, can be considered. They have been developed for TN and could be extended to NTN: e.g., the TeraFlow controller (https://www.teraflow-h2020.eu/), recently emerged within ETSI, based on a modular architecture, where each component is responsible for specific tasks (e.g., the "Optical" component for resource allocation in fiber infrastructures). A specific component managing FSO might be designed and integrated into this controller architecture.

VII. Conclusions

This paper has presented a comprehensive investigation of the new paradigm of integrating terrestrial and non-terrestrial networks for upcoming 6G communications as considered in the standardization process. By addressing key challenges in multi-layer architectures, advanced transmission techniques, and network management, this contribution provides a roadmap for achieving seamless global communication. The integration of modular waveform designs and advanced FSO management highlights the potential for optimized resource utilization and system flexibility. Future research will focus on implementing these solutions in real-world scenarios, even for heterogeneous use cases, and refining cross-domain orchestration to meet the evolving demands of 6G networks.

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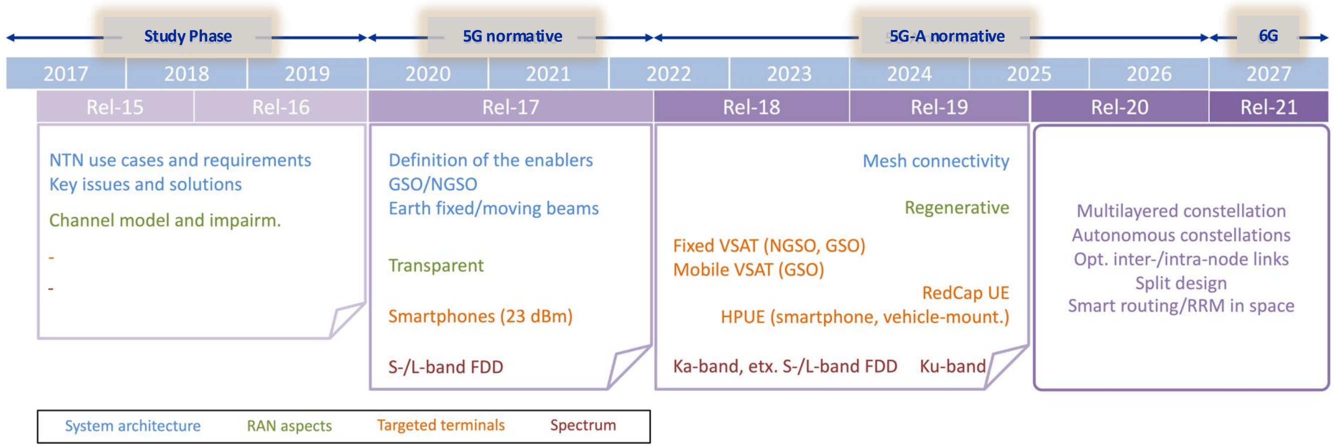

Fig. 1. 3GPP NTN roadmap.

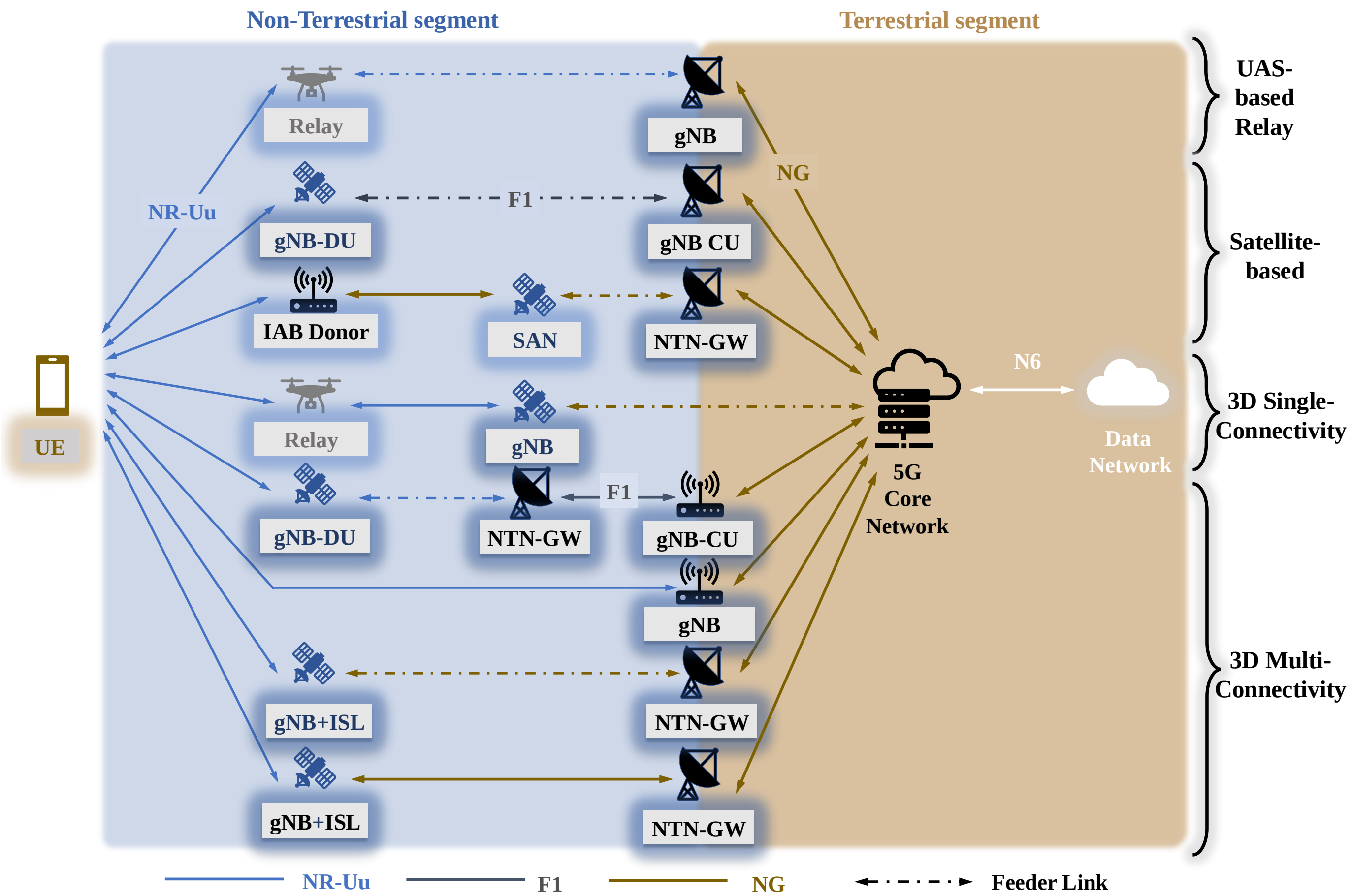

Fig. 2. Main integrated T/NTN architectures with components and interfaces: UAS-based Relay Network, Satellite-based Architecture, 3D Single-Connectivity Architecture, 3D Multi-Connectivity Architecture.

Waveform	Reshaping	Precoding	Windowing	Transform	CP + filtering
OFDM	Mx1 (S/P)	None	None	M-point IDFT	CP+
DFT-s-OFDM	M/L₁ x 1 (L_1>1) (S/P)	M/L_1 point DFT	(M-M/L_1) zero-padding	M-point IDFT	CP+
MC-SS	Mx1 (repetition)	WHT	None	M-point IDFT	CP+
Filtered-OFDM	M/L_kx1 (k=1,..,K, L_k>1) (S/P)	None	None	M/L_k-point IDFT	Sub-band filtering, CP+
FBMC	Mx1 (S/P)	None	None	M-point IDFT	Subcarrier filtering (filter bank)
GFDM	Mx1 (S/P)	None	None	M-point IDFT with pulse shaping	CP+
CE-OFDM	Mx1 (S/P)	None	2F_{ov} (M+1) x1 (zero-padded conjugate symmetric vector)	2F_{ov} (M+1)-point IDFT	Nonlinear phase modulation, CP+
CE-SC-FDMA	Mx1 (S/P)	M-point DFT	2F_{ov} (M+1) x1 (zero-padded conjugate symmetric vector)	2F_{ov} (M+1)-point IDFT	Nonlinear phase modulation, CP+
LoRA chirp	1 x 1 + M-1 zero-padding	None	Chirp transform	M-point DFT	CP+
OTFS	MxN buffering (L_1=1, L_2=1)	ISFFT	None	Heisenberg transform	CP+
OTSM	MxN buffering (L_1=1, L_2=1)	N-point WHT and M-point DFT	None	M-point IDFT	CP+
OCDM	MxN buffering (L_1=1, L_2=1)	DZT	Chirp transform	Heisenberg transform	CP+
Power- domain OFDM (NOMA)	M/L₁ x 1 (L_1<1) (S/P)	None	None	M-point IDFT	CP+
RSMA/ DS-CDMA (NOMA)	1xM/L_1 (L_1<1)	Direct Sequence Spread Spectrum spreading	None	Pulse-shaped single carrier	None

Fig. 3. Modular waveform design mapping for 6G NTNs.

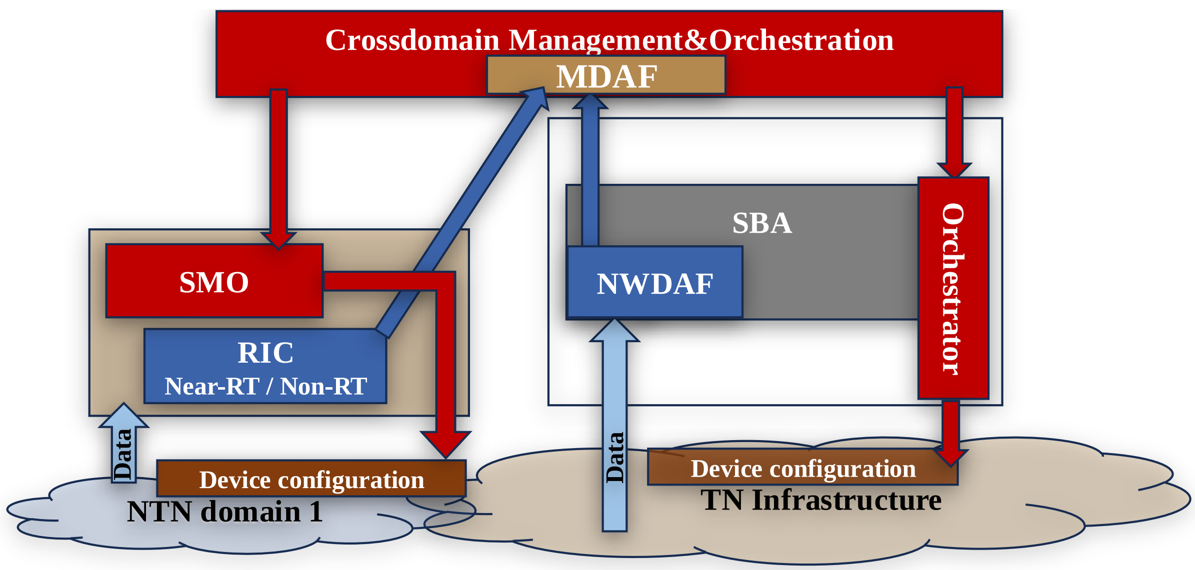

Fig. 4. Functional architecture of integrated network control system.

module: openconfig-terminal-device

```
augment /oc-platform:components/oc-platform:component:
    +--rw optical-channel
      +--rw config
      |   +--rw frequency?                  oc-opt-types:frequency-type
      |   +--rw target-output-power?        decimal64
      |   +--rw operational-mode?           uint16
      |   +--rw line-port?                  -> /oc-platform:components/
component/name
      +--ro state
          +--ro frequency?                  oc-opt-types:frequency-type
          +--ro target-output-power?        decimal64
          +--ro operational-mode?           uint16
          +--ro line-port?                  -> /oc-platform:components/
component/name
          +--ro group-id?                   uint32
          +--ro output-power
          |    +--ro instant?               decimal64
          |    +--ro avg?                   decimal64
          |    +--ro min?                   decimal64
          |    +--ro max?                   decimal64
          |    +--ro interval?              oc-types:stat-interval
          |    +--ro min-time?              oc-types:timeticks64
          |    +--ro max-time?              oc-types:timeticks64
          +--ro input-power
               ...
          +--ro laser-bias-current
               ...
          +--ro chromatic-dispersion
               ...
          +--ro polarization-mode-dispersion
               ...
          +--ro polarization-dependent-loss
               ...
          +--ro osnr
               ...
          +--ro carrier-frequency-offset
               ...
          +--ro fec-uncorrectable-blocks? yang:counter64
               ...
          +--ro pre-fec-ber
               ...
          +--ro post-fec-ber
               ...
          +--ro q-value
               ...
          +--ro esnr
               ...
```

a

module: openconfig-telescope

```
augment /oc-platform:components/oc-platform:component:
  +--rw telescope
      +--rw orientation
      | +--rw state
      |     +--rw elevation_angle?    decimal64
      |     +--rw azimuth_angle?      decimal64
      |     +--rw timestamp?          yang:timestamp
      +--rw speed
        +--rw state
+--rw elevation_speed?  decimal64
            +--rw azimuth_speed?    decimal64
            +--rw timestamp?        yang:timestamp
```

b

module: openconfig-ao

```
augment /oc-platform:components/oc-platform:component:
  +--rw ao
      +--rw received-power-pre-top
      | +--rw state
      |  +--rw input-power
      |     +--rw instant?          decimal64
      |     +--rw avg?              decimal64
      |     +--rw min?              decimal64
      |     +--rw max?              decimal64
      |     +--rw interval?         oc-types:stat-interval
      |     +--rw min-time?         oc-types:timeticks64
      |     +--rw max-time?         oc-types:timeticks64
      +--rw received-power-post-top
        +--rw state
            +--rw input-power
            +--rw instant?          decimal64
            +--rw avg?              decimal64
            +--rw min?              decimal64
            +--rw max?              decimal64
            +--rw interval?         oc-types:stat-interval
            +--rw min-time?         oc-types:timeticks64
            +--rw max-time?         oc-types:timeticks64
```

c

Fig. 5. (a) OpenConfig YANG model; augmentations (b) for the telescope, and (c) for Adaptive Optics (AO).