Cross Domain Orchestration and Management of Optical Links in Terrestrial-Non Terrestrial Networks

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ABSTRACT

In this contribution, we describe different levels of orchestration and management to be adopted in a cross domain Terrestrial and Non Terrestrial Network exploiting the most recent architectures defined for the Core Network since we propose to extend the control of the optical fiber links also to the ones operating in Non Terrestrial Networks, and mainly based on Free Space Optics (FSO). In particular, the NETCONF protocol is proposed for the Southbound interfaces.

Keywords: Non Terrestrial Networks, SDN, FSO, 5G, 6G.

1. INTRODUCTION

It is now recognized that Non Terrestrial Networks (NTNs) [1], made up of satellites, drones, and aerial platforms, will be fundamental in the creation of telecommunications networks to improve performance in several contexts and first of all in terms of coverage. For example, 3GPP already in *Release 17* envisaged the introduction of the Non Terrestrial (NT) segment in 5G networks [2], but it will certainly be 6G that will fully exploit the presence of the NTN domain [2]. NTN adopts wireless links operating on different radio frequencies, but also with free-air optical communications also known as Free Space Optics (FSO) [3]. On the other hand, FSO systems are becoming a reality in Terrestrial Networks (TN) both in the access and in the backhaul-fronthaul sectors. Management and control in Software Defined Networks (SDN) [4] are fundamental aspects in any networks, and currently this issue has been addressed differently for each network domain, especially regarding the Core and the Radio Access Network (RAN) segments. Indeed, various standardization bodies – as ITU, ETSI and 3GPP – put forward different methodologies, which have gradually evolved to establish mechanisms capable of managing transmission resources by controlling the elements responsible for data flow with the aim of fully satisfying the services provided by the networks. Moreover, to enhance services reliability and optimize resources allocation, it is essential to conduct thorough an analyses of network monitoring data. Such analyses are increasingly leveraging Artificial Intelligence (AI) and Machine Learning models [5]. Recently, there has been a growing attention toward the issues related to the orchestration to simultaneously manage different types of networks, or multi-domain [6], in order to optimize data path in End-to-End (E2E) connections, i.e., passing from an access through the core and up to the final access, encompassing the NTN domain (see Fig.1) [7]. Currently, it is still not clear whether NTN should be managed with more typical core or RAN methodologies. Added to this complex situation is the question of controlling the physical devices that transmit and forward information data. Specifically, a key consideration arises when distinguishing between radio and optical devices. In fact, it could be assumed that FSO devices could be managed as the elements of the core network such as WDM transmitters and receivers, OXCs and ROADMs, which can be controlled with procedures based for example on NETCONF protocol [8], very different from the procedure relatives to the mmWAVE devices. Therefore, also in terms of compatibility, a possible solution is to extend the control used in the core for FSO connections in the NTN. This is the proposal reported in this paper in the framework of the *Integrated Terrestrial and Non Terrestrial Networks* (ITA NTN) project, representing the 11-th structural project of the overall RESTART Italian PNRR research activity.

The paper is structured as follows. After this introduction, in Sec. 2 a general view of the NTN architecture is described with relevance on the role of FSO. In Sec. 3, the theme of the Orchestration & Management (O&M) is described detailing the different layers of controls from the Southbound to the Northbound, towards architectures that take into account the requirements of the service layers and adopting AI. The analysis primarily focuses on the core domain to understand the behaviour of the optical layer that could be extended to the FSO devices. However, the concept of Cross Domain O&M is also considered to analyse the role of the RAN architecture. Sec. 4 concludes the paper.

2. NTN ARCHITECTURES

The NTN domain can be seen as being composed of different elements such as drones, aerial platforms, satellites, and all the terrestrial gateways. According to a 6G-oriented scenario, 3D wireless connectivity can be defined with the ambitious goal of conceiving novel methodologies and effective solutions to provide pervasive, ubiquitous, and flexible on-demand wireless connectivity and edge computing services through the integration of TN and NTN. In this 3D TN-NTN architecture, each layer can play different roles, and, in particular, we can consider the most general case based on one (or more) intermediary node based on drones and aerial platforms and a satellite that can operate in transparent or regenerative mode, thus leading to various architecture subcategories, as shown in Fig. 1. In ITA-NTN, four different architectures were defined: i) Drone-based Relay Network, ii) Satellite-based Architecture, iii) 3D Single-Connectivity Architecture, and iv) 3D Multi-Connectivity Architecture [7]. The architecture of a *drone-based relay network* typically consists of three main components: User Equipments (UEs)/Ground Users (GUs), drones, and a ground control station, where the latter can be embedded in the g-NodeB (gNB). Indeed, drones equipped with communication systems may act as flying base stations or relays, enabling communication between distant locations. *Satellite-based architecture* facilitates communications through satellites orbiting around the Earth. While communication systems aim for sustained and stable connectivity, satellite-based architectures can encounter hurdles like signal latency due to vast satellite-to-ground distances, elevated initial setup and upkeep expenses, and vulnerability to atmospheric conditions. However, in contrast to drone-based designs, this architecture provides extensive coverage, efficiently linking geographically distant locations, including remote or rural regions. Two different configurations involving satellites can be identified, which are satellite-based access and satellite-based backhauling (i.e., direct and indirect access in 3GPP terminology, respectively). Both configurations allow for connectivity to remote areas, where laying terrestrial cables or establishing direct fiber connections is challenging or cost-prohibitive.

2.1 Optical links

FSO is being considered for access and fronthaul/backhaul connectivity since several years and is now also proposed as a fundamental technique for 6G, especially for NTN. A trend in NTN wireless system is to shift into FSO the technology already consolidated for fiber optics [9]. WDM channels are combined and amplified by a booster erbium-doped fiber amplifier (EDFA) and launched into free-space by a telescope. After free-space propagation, the beam is collected by the receiver telescope, then coupled into a single-mode fiber and amplified by a low-noise EDFA pre-amplifier. Finally, the channels are demultiplexed and the signals detected by the corresponding optical receivers. However, in an FSO system, a signal is time-variant mainly due to the fading caused by the atmosphere. Fading induces a loss that may vary in the range of tens of milliseconds, which can cause the complete loss of the signal (*deep fading*). In Fig. 1, we indicate where FSO can be adopted for wireless communications in NTN domain.

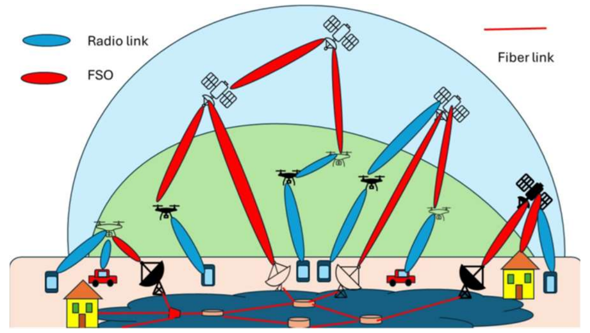

Fig.1: 3D NTN architecture

The following devices/elements can be controlled/configured and monitored: transmitters and receivers (e.g., the configuration of line rate or modulation format, depending on traffic needs and NTN state conditions), optical amplifiers (EDFAs), telescopes. Finally, fading can create outages, so to design and develop a reliable NTN, the control system should be able to predict or at least reveal outages due to fading and take the proper reactions.

We must not forget that the NTN network connects to a TN where communications are mostly carried out with optical fiber systems. Thus, we can imagine that in an E2E communication, even with an NTN segment, the communication can be done entirely or almost entirely at the optical level. This aspect also suggests that quantum communications [10] might also be used for all optical TN-NTN paths especially for security issues [11].

3. MANAGEMENT AND CONTROL

The softwarization of the network has been one of the most important evolutions in the field of the telecommunications of the last 20 years. This transformative process relies on Network Function Virtualization (NFV) and cloud-native architecture. The former allows the migration from traditional, hardware-centric infrastructures to software-defined architectures, the latter breaks down monolithic applications into smaller independent deployable microservices. Moreover, the adoption of SDN principles, introduces a centralized control and programmability to allow the dynamical and flexible orchestration of network resources. This integration of softwarization and programmability has been adopted as a fundamental aspect of the 5G core network architecture, introducing the Service Based Architecture (SBA) paradigm, that has the aim to manage and control the whole core network trying to satisfy the requirements of all the services that the network should support looking for the best E2E connections in terms of resources obtained by means of slicing procedures.

Currently, even if there are various O&M procedures with methods that increasingly leverage AI functions, it is still not clear how to carry out a complete control of the network. In fact, from a certain point of view it would be better to have a control carried out very close to the physical layer to achieve faster responses aimed to satisfy the needs of optimized information transmission; on the other hand, if you aim to improve services, a control that manages both the network and the applications is worthwhile This is shown in Fig. 2 that recall the proposal in [6], inspired to ITU-T Study Group 13, and where different levels of control and orchestrations are illustrated and in addition to the core segment, other domains are considered, (for example the RAN, and NTN). For the core domain a two layers control system (green and blue) is depicted, and O&M close to the physical layer is represented by the bleu part. For such a level we can assume that a very wide number of KPI data dedicated to the monitoring of the network are collected and elaborated by a sort of "reasoner" [12]. For an optical core network, KPI can be the Quality of Transmission (QoT) in each WDM fiber link, QoS measured by active probes and traffic monitoring by means of passive probes [12]. AI methods can be adopted to understand the state of the networks and relative anomalies [5][12]. These outcomes can be utilized for control of the core infrastructure acting on the core devices (e.g. TX, RX, OXC, OADM). To accomplish this goal, NETCONF stands out as a suitable protocol [8].

The upper layer oversees an E2E service and it can be considered as relative to the 5G SBA. These systems collectively feed data into a central monitoring system, facilitating a comprehensive analysis of the network's status from E2E perspective. This analysis serves as the foundation for optimizing E2E resource management and control according to service level requirements and user intents. The goal is dynamically and optimally allocating resources to ensure the delivery of high-quality E2E communication services. The challenge lies in delving into the details of the characteristics of all the devices present with their transmission characteristics and the protocols operating in each domain. Furthermore, it is necessary to understand which processes can remain controlled within each single domain and which instead reside in the integrated network control system, even if the trend should lean to move upward integration as much as possible.

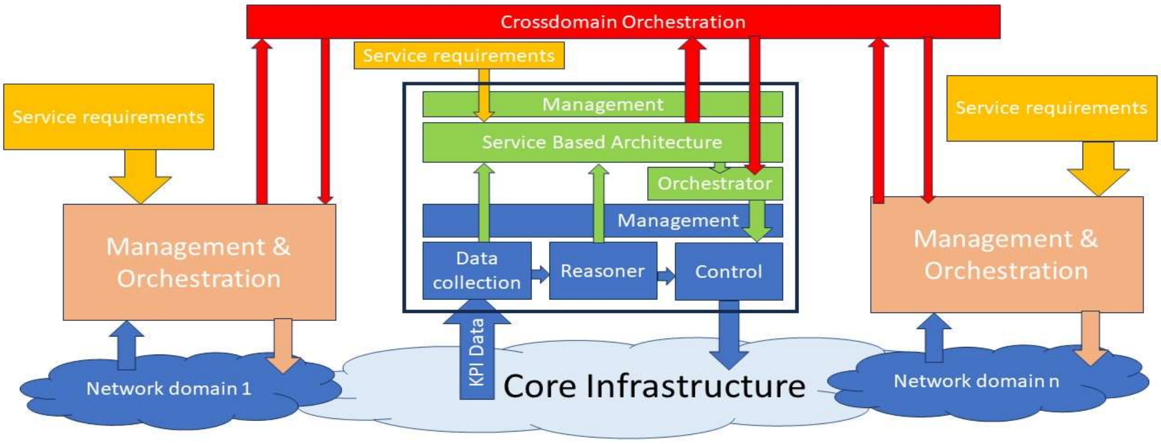

Fig. 2: Functional architecture of integrated network control system

The significance of these blocks in the figure becomes particularly pronounced when considering the integration of artificial intelligence (AI) to manage the increased complexity.

The adoption of AI in telecommunication has progressed significantly, particularly evident in the evolution outlined within 3GPP specifications. In 3GPP TS 23.501 and subsequently in 3GPP TS 23.288, a new intelligent control function, Network Data Analytics Function (NWDAF), has been introduced in the 5G core network. NWDAF can operate in a centralized or distributed model and with global or per slice scope to provide data analytics and gain insights into the overall network performance, even with control loop automation to other authorized network elements. Furthermore, 3GPP has made a more significant leap forward, by introducing other domain specific data analytics functions, such as Network Data Analytics Function (NDAF), Management Data Analytics function (MDAF), and Radio Access Network (RAN DAF). These functions play a crucial role in leveraging data analytics to enhance efficiency, performance, and management of mobile communication networks. Moreover, 3GPP *Release 18* – the first release of 5G-Advanced – includes a diverse set of study and work items dedicated to AI. On the other hand, the European Telecommunication Standards Institute (ETSI) has also taken significant steps in embracing artificial intelligence and machine learning (AI/ML) for an increasing automation of network resource management and orchestration. Two prominent groups have been established: ETSI Experiential Networked Intelligence (ENI) [13], and ETSI Zerotouch Service Management (ZSM) [5]. ETSI ENI represents a centralized framework that delineates an AI-based approach to network management, by augmenting legacy systems with on-top intelligence, without requiring substantial modifications. On the other

hand, ETSI ZSM has developed a reference architecture featuring distributed management and orchestration, including also closed loop control, aiming at a deeper AI native approach. In the realm of open-source initiatives, the Open Network Automation Platform (ONAP) stands out. Hosted by the Linux Foundation, ONAP aims to automate the management and orchestration of network services, addressing the dynamic and resource-intensive nature of 5G networks, supporting distributed and federated learning approach and closed-loop automation. Being an opensource platform, ONAP promotes interoperability by allowing different vendors to contribute and collaborate. This interoperability is crucial in a 5G and beyond ecosystem where different technologies and vendors coexist. Similarly, O-Ran Alliance (O-RAN) is gaining attention, for its efforts in disaggregating the traditional RAN architecture and enhancing RAN with AI capabilities, openness, and interoperability, [14].
However, no definitive solutions have been yet addressed and convergence and interoperability remain a critical gap to be furtherly investigated.
So far, we have described the role of the control and management both looking at the different TN-NTN environments and at the different network layers, from the one closer to the data plane (southbound layer) to the service one (northbound layer). Looking at the optical components that can be introduced in an NTN, we propose to adopt a typical control for fiber optical network in the NTN domain where FSO links are present. Therefore, it is considered the NETCONF protocol and the YANG data modeling language [9] as the basement of the content for NETCONF messages. Currently, NETCONF is envisioned for the control of core networks (e.g., based on fiber optics) and it is applied to configure transceivers (e.g., at a specific line rate or modulation format) and optical switches. In the core, NETCONF is also used to transport performance monitoring information (e.g., pre-FEC BER of an E2E connection). NETCONF can be also considered for the configuration of the gateway between the ground station and satellite enabling QoS enforcement.

4. CONCLUSION

This paper delineates various levels of orchestration and management to be deployed in a cross-domain context, incorporating both Terrestrial and Non Terrestrial Networks. It explores the latest architectures defined for the Core Network, aiming to clarify methods for extending control over optical devices within it to those deployed in Non Terrestrial environments, particularly those reliant on Free Space Optics. Specifically, the NETCONF protocol is proposed for the Southbound interfaces.

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