

SDN-enabled THz Wireless X-Haul for B5G

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Abstract— With the explosive data growth of user traffic in wireless communications, Terahertz (THz) frequency band is envisioned as a promising candidate to support ultra-broadband for beyond fifth generation (5G) networks. Software based networking is being adopted in mobile communications to improve efficiency and reduce operational costs. This paper presents the design of a comprehensive SDN management architecture for joint optimization of radio and network resources. The proposed architecture obtains the most added value out of use of THz technology integrated with software managed networking for mobile network beyond 5G. In this paper, leveraging optical concepts and photonic integration techniques for an ultra-wideband and broadband wireless system is presented.

Keywords— Terahertz, Broadband, Wideband, Optoelectronics SDN, Radio management, Open Interfaces, Network Automation, NETCONF, Yang models

I. INTRODUCTION

While the rollout of 5G worldwide is just in its infancy, and the joint development/standardization process by 3GPP/ITU-T is still ongoing, researchers from industry and academia are already looking ahead to what will come next. A clear picture of what Beyond-5G (B5G) and 6G networks will be like is premature now, but experts are outlining the envisioned requirements, use cases and enabling technologies for the next-generation network landscape a decade from now. It is expected that the main trends emerging and guiding the 5G development will further grow and evolve to establish the foundation of B5G/6G [1].

The need for huge capacity at very low latencies is shifting attention to higher frequencies of the electromagnetic spectrum, where way larger bandwidths are available. This trend has already started in 5G, with the opening to mm-Wave frequencies (above 24 GHz) for the new 5G-NR air interface, complementing the traditional sub-6 GHz band shared with 4G and legacy access technologies. For B5G/6G the trend will continue up to the THz band (above 100 GHz) and infrared/visible light (optical wireless communication).

The downside is that at such frequencies the radio coverage of each antenna reduces drastically, due to the different radio propagation conditions. Thus, the number of cell sites must be increased accordingly, to ensure full coverage and uniform

spatial capacity. This trend has already started too, with the concept of heterogeneous networks, composed by macro-micro- small- and pico/femto cells and multi radio access technologies. The concept will be extended in B5G/6G to three-dimensional coverage employing non-terrestrial access points (drones, high altitude platforms, satellites) complementing traditional terrestrial infrastructures [2]. Aerial access networks show good potential as a complement of traditional terrestrial solutions in many scenarios of relevance for network operators. Ubiquitous connectivity in very low-density scenarios, or quick and ad-hoc provision of mobile connectivity to reinforce or replace terrestrial network infrastructure in temporal events, emergency or disaster recovery scenarios are some examples, typically addressed nowadays with temporal infrastructure. Adaptability to a varying target coverage area, flexibility to deploy, high probability of LOS and combination with other parallel applications as imaging, surveillance, etc., are some of the main benefits that aerial moving nodes may unlock. Many of the applications, linked to the access capacity will demand in parallel the availability of high throughput transport connectivity between the moving node and ground, aside from technologies to handle mobility, as beam steering.

Throughput needs in backhaul networks are expected to increase progressively towards the tens to hundreds of Gbps as the access networks and services evolve and extra capacity layers are implemented through network densification. As the radio access network gets denser, wideband point-to-point radio links become a necessary complement to optical fiber, especially in the last-mile section of the backhaul networks. Mainly, to enable a more flexible deployment both in terms of investment prioritization and lead time, as not all the sites can be connected via fiber cost effectively or in a time frame that may be acceptable for the launch of new services. Because of the Gbps-level capacity needed for 5G backhauling links, and the short inter-site distances which are typical in high-density high-capacity macro or small cell deployments, mm-Wave and THz bands represent the viable solution, towards B5G/6G. Moreover, inter-band aggregation also benefits applicability of these technologies to other scenarios less demanding in terms of throughput, finding compromises between the latter, availability and range.

While the establishment of different services in 5G and B5G networks will come in a progressive way, backhaul networks need to get prepared in advance. Penetration of existing mm-Wave technologies in operator networks, like E-band radios, is already showing consistent Year on Year (YoY) growth as enabler of multi-gigabit transport capabilities, backing up the need for further research and development in the field. Furthermore, mm-Wave and THz bands are also indispensable to enable the concept of X-Haul transport, in which base stations get separated between low-complexity Distributed Units (DU) located at the cell/antenna site and high-complexity Centralized Units (CU), grouped together with other CUs into a few metro sites. Radio access network architecture has been typically distributed, with all the radio processing done at site, close to the antenna.

However, 5G architecture allows for virtualization and centralization of all or part of the baseband functionality of the radio nodes. This has direct benefits (ultimately dependent on the functional split, that defines what is kept distributed and what is centralized) in terms of efficiency, scalability, latency of some radio protocols as well as simplification of the sites themselves, which eases the operation, installation and management of the radio access networks. Simplification of radio nodes also becomes key in aerial access network scenarios, where the energy consumption, form factor and weight are decisive for key applicability aspects as autonomy or regulation constraints for the operation. According to the specific split option [4], the traffic between DUs and CUs exhibits very different features and requirements in terms of capacity and latency, from the conventional Backhaul (in which no split is employed, and the CU is co-located with the DU at the cell/antenna site), up to full Fronthaul (in which the CU retains almost all the processing logic of the base station and the DU is simply a front-end for transmission/reception at the air interface). Mobile aggregation/transport networks will support a heterogeneous mix of such traffic types, denoted as X-Haul or Mid-Haul. Splits closer to fronthaul impose too stringent requirements in terms of throughput to current mm-Wave transport, and generally are only feasible with fiber connectivity, so new equipment operating in higher bands will also mean extra flexibility to implement distributed approaches via radio transport.

In general, the networks will become more complex, so harder to control and manage. The shift toward architectures based on Software-Defined Networking (SDN) and Network Function Virtualization (NFV) is therefore paramount to endow networks with “intelligence”, such that they can be autonomous, dynamic, modularizable, resilient and cost-efficient. Centralizing the control plane enables global optimized routing decisions and makes the network flow programmable to fit specific requirements and it also helps simplifying operation of multi-vendor and multi-technology networks through appropriate architectures and standard information and data models and interfaces. SDN can enable then a programmable

transport network, which is able to create multiple and isolated transport slices, where transport resources may then be allocated dynamically interconnecting physical and virtualized network functions distributed geographically.

Therefore, operators are transforming their transport networks moving to SDN-enabled architectures. Multi-operator initiatives are also in place to align vision, architectures and use cases, generating traction and development in the industry [3]. SDN implementation in live networks has already started in many networks, and stringent requirements in terms of integration in the full SDN ecosystem and support of standard models and interfaces are being derived for any transport solution under consideration for deployment. Not only because all the technical benefits, but also due to the relevance that the SDN architecture has as an enabler of slicing, key to develop new service and business models linked to differentiation of service performance and quality targets.

Motivated by all these trends, this paper presents an SDN-enabled end to end architecture for managing fixed network infrastructure integrated with ultra-wideband X-Haul network based on THz radio links. The novelty resides in the fact of using end to end SDN management system that handles both network and radio parameters. This is aligned with the concept of O-RAN where radio is fully distributed and managed through software agents. This system is designed as part of the TERAWAY H2020 project [5]. The main use case is the 5G coverage of outdoor events using moving nodes that consist in heavy-duty drones carrying gNBs or their radio parts (remote radio heads). Because of the diverse technical challenges, the project will face, we expect to gain valuable insights into the feasibility and limitations of such technologies for B5G/6G networks.

This paper is structured as follows. Section II introduces the current state of the art in 5G networks which consists of service-based architecture (SBA). Section III presents Software Defined Network (SDN) architecture for managing the mobile network infrastructure. Section IV describes the design of THz based X-haul to be integrated as part of the transport for mobile networks beyond 5G. Section V introduces the SDN-based end to end TERAWAY architecture for efficient management of fixed and THz X-haul transport. Conclusions and final remarks are in Section VI.

II. 5G SERVICE BASED ARCHITECTURE

3GPP, in its Release 15 already introduced a new architecture in the specification on the 5G Core Network, in TS 23.501 [3GPP23.501]. This architecture in 5G Core (5GC) follows several principles that are mainly targeted for reaching higher flexibility, supporting many different use cases. This includes the introduction of service-based principles, where network functions provide services to each other. A clean control plane/user plane split allows independent scaling of control plane and user plane functions and supports flexible deployments in terms of where the user plane can run (this

principle was, in fact, already introduced in EPC in Release 14). The architecture allows for different network configurations in different network slices.

The 5GC control plane is based on the Service Based Architecture (SBA) depicted in Figure 1. The network functions communicate with each other via a logical communication bus and network functions can provide services to each other. A network function instance is registered to a Network Repository Function (NRF). Using the NRF, a network function instance can find other network function instances providing a certain service. The goal of such architecture is to get a higher flexibility in the overall system, and to make it easier to introduce new services.

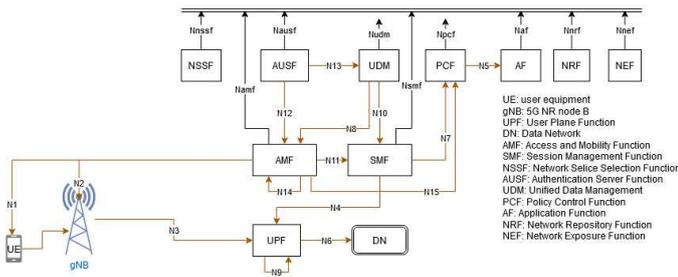


Fig. 1. 5G Service Based Architecture.

The SBA based 5GC facilitates adding new Network Functions (NF) that implement new functionality. Thus, in case of introducing new transport technologies the SBA allows to design a new NF that will handle the specific management of the new network and radio technologies to deliver end to end transport. Those NF could benefit from SDN technologies for a more effective management of the network and radio resources as described in next sections.

III. SOFTWARE BASED NETWORKING ARCHITECTURE

SDN has been widely deployed and applied in the areas from data centers to enterprise networks and WANs. Then, it has started expanding into the field of transport network, at first in IP/Optical multi-layer networks, then, in the last few years, in the microwave transport. The success of SDN in fixed networks has motivated network operators to promote similar approach for managing the microwave radio equipment and links. However, these kinds of networks have peculiar characteristics that make them differ radically from their fixed counterparts. A non-exhaustive list can be the following.

- They suffer from unpredictable impairments at the air interface, such as frequency interference, fading, and multipath. The countermeasures include adaptive modulation and coding (ACM). A change in the weather brings dynamic adjustment to air interface modulation and accordingly results in dynamic bandwidth adjustment.
- They are sensitive to bandwidth capacity, so they typically feature the technique of physical link aggregation, such that the insufficient capacity at the air interface can be addressed by binding several links together.

- They have tree or chain network topologies in most cases and ring topologies in few cases, the latter resulting in few redundant paths. For 5G backhaul, such as small cell backhaul or dense site deployment, it is expected to be more mesh networks.
- They have a control channel with limited bandwidth and unreliable, and the real-time requirement is also difficult to meet.

These criticalities are the major reasons why mobile network operators are locked in single-vendor equipment and networks operation, configuration and maintenance activities are performed manually and is difficult to change on run time. They are also tied to use Network Management Systems (NMS) directly provided by equipment vendors, with specific proprietary interfaces, and independent from fixed network NMS. Furthermore, this vendor specific NMS prevents the use of advanced applications that could provide more sophisticated features such as network slicing, dynamic power management or multi-layer coordination, among others. The SDN paradigm is thus still at its infancy for radio transport networks, but its potential is very promising. With the features of centralized control and openness, a network becomes simpler and its O&M is more efficient. The network is no longer “passive” but can have service awareness. According to service features, the network is automatically adjusted to improve its quality and ensure efficient service configuration. Open and standardized interfaces are a prerequisite for efficient management of equipment from multiple vendors, integrated in a single system/controller.

IV. X-HAUL BEYOND-5G

The TERAWAY project is developing THz transceivers that leverage optical concepts and photonic integration techniques. This allows for implementation of high-capacity radio links operating in an ultra-wide range of carrier frequency bands covering the W (92-114.5 GHz), D (130-174.8 GHz) and THz band (252-322 GHz) bands using multichannel multibeam transceivers with increased directivity due to use of optical beamforming. To that end, the project is investigating the possibility to organize the spectral resources of a network within these bands into a common pool of radio resources that can be flexibly coordinated and used for given deployment and application scenarios. In specific terms, the target of the project is to develop transceivers including a 2- and 4-channel modules with operation from 92 up to 322 GHz, data rate per channel up to 108 Gb/s, transmission reach in the THz band of more than 400 m, and possibility for the formation of wireless beams that can be independently steered in order to establish backhaul and fronthaul connections between a set of fixed and moving nodes. TERAWAY’s radio system data-plane consists of the baseband and the optoelectronic units. Each of these units is associated with and interfaces to a different management processor which runs Linux; based on this operating system, appropriate drivers will be developed to enable low-level operations with the hardware. This choice offers flexibility and increased

modularity since different combinations of baseband units and analog front ends can be tested without creating impediments to the system management. These radio modules will include a NETCONF agent whose purpose is to map high-level operations coming from the SDN Controller into low-level API commands. The control will include both OpenFlow and NETCONF to ensure integration with network switches from different vendors. This agent will serve requests and responses in the form of standardized ONF TR-532 YANG model, encoded in XML. The radio controller which initiates NETCONF sessions towards the different agents, will retrieve alarms, statistics, and performance metrics, configure radio parameters and run radio resource optimization algorithms. Finally, the radio controller itself will provide appropriate APIs to the transport network controller for joint optimization and coordination between switch and radio element controllers.

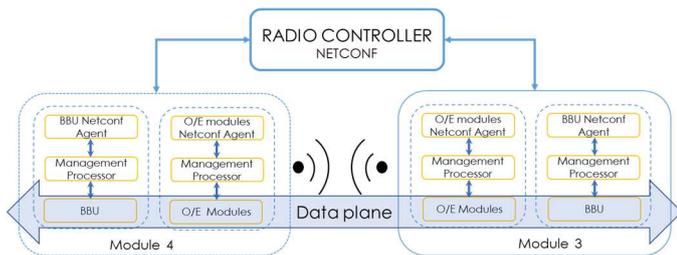


Fig. 2. Radio Management Architecture.

This SDN controller requests periodically performance metrics such as the SINR and RSSI values, evaluates link quality [6] and runs specific algorithms in order to detect interference. In case that interference is detected, an alarm occurs, and the operator input is needed on whether to allocate new licensed or unlicensed spectrum.

- In case of licensed spectrum allocation, the SDN controller runs the radio planning-based frequency selection algorithm and is in charge of triggering frequency change within the licensed spectrum block, in order to minimize interference.
- In case of unlicensed spectrum assignment, the SDN controller initiates frequency scanning and based on the results from the elements, runs a frequency selection algorithm and triggers a frequency change in order to minimize interference.

Other countermeasures to transient or permanent interference except for frequency change include: In digital/algorithm domain, re-configuration of beam-forming antennas (beam-nulling techniques). In space domain, adapting traffic distribution. In service domain, adapting some parameters (e.g. CIR and PIR rates for specific flows) to the new conditions.

The TERAWAY project is developing a new software defined networking (SDN) controller and an extended control hierarchy that will perform the management of the network resources (SDN switches) and the radio resources in a homogeneous way. These management features provide potential benefits in terms of network performance and energy efficiency enhancements, as well as the possibilities for the provision of network slices to support heterogeneous services. There is a plethora of

applications and use cases of SDN as related to millimeter wave/Terahertz communications and one of the most predominant ones related to the radio subsystem, is interference detection and frequency allocation [7]. The road to the mainstream adoption of Terahertz communications is still a long way ahead and the licensing schemes have not been defined yet, thus both licensed and unlicensed spectrum policies should be taken into account. Flexible and innovative licensing strategies combined with SDN capabilities would significantly simplify how the operators control the underlying network. To add to this, the ultra-wide range of carrier frequencies that TERAWAY’s transceivers can operate on, opens up new opportunities while creating new challenges to the network operations management. Figure 2 shows the sequence diagram between radio controller and elements, describing an interference detection and frequency allocation use case.

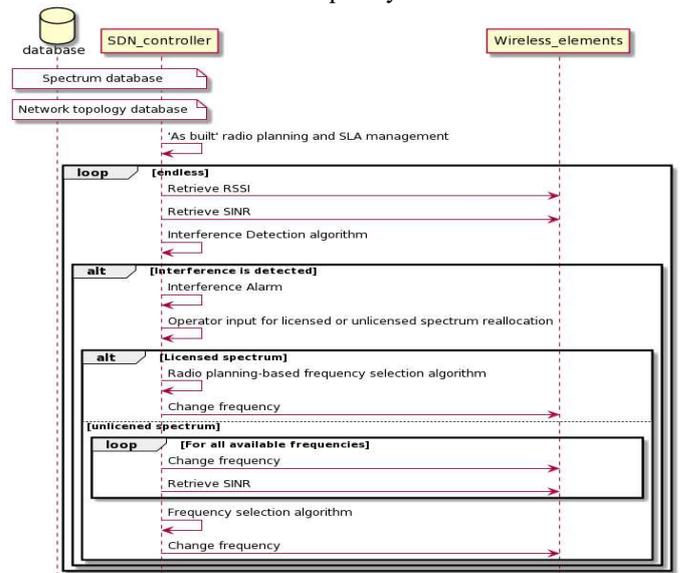


Fig. 3. Example of a figure caption.

V. TERAWAY ARCHITECTURE

TERAWAY is designing and developing an innovative SDN controller that will perform the management of the network and radio resources in a homogeneous way. The SDN controller should be an integral part of the 5G and beyond architecture to provide the required benefits for the network performance, energy efficiency, slicing efficiency. Thus, the SDN functionality would be part of network function (NF) named Mobile Backhaul Orchestrator (MBO) that would be compliant with Third Generation Partnership Project (3GPP) specifications as part of the Service Based Architecture (SBA).

The SDN controller is needed to manage the whole TERAWAY communication system in a centralized way, by receiving management requests (typically, provisioning, monitoring, fault reporting) at the network level, through the North-Bound Interface (NBI). These requests are elaborated and transformed into element-level management commands (typically, configuration, monitoring, subscription to notification events),

that are sent to the managed network elements through the South-Bound Interface (SBI) of the controller. Similarly, in the opposite direction, all responses and notifications generated by the network elements are received from the SBI and processed to be transformed to network-level messages that are sent to the NBI. It is worth noting that in general the controller exposes several different NBIs and SBIs. In the north-bound direction, there are as many NBIs as the number of higher-level controllers or orchestrators managing the overall system. Similarly, in the south-bound direction, there are different SBIs according to the different kinds of network elements that must be managed. Figure 4 depicts the logical SDN management network architecture, superimposed on the TERAWAY physical network.

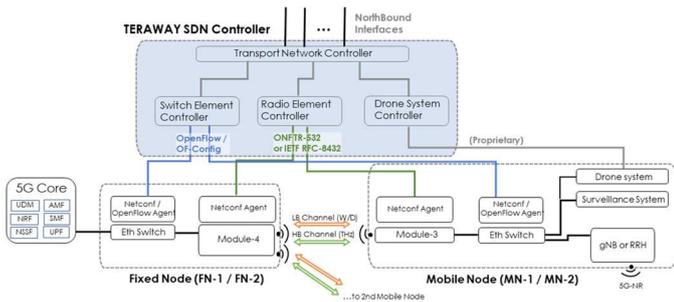


Fig. 4. TERAWAY end to end architecture.

Figure 4 highlights the relations and connections among SDN entities present in both the controller and the network devices (also known as Management Plane). However, it is important to note that this is a logical topology, where the actual SDN flows are transported on the same physical connections used for the Data Plane. In other words, the entire management traffic is in-band. The separation of management traffic from payload traffic in terms of bandwidth and Quality of Service (QoS) is performed by the network slicing techniques through the reservation of a “Slice 0” for this kind of traffic. For safety reasons, a fallback communication mechanism will be developed for the drone management traffic, employing a separate, out-of-band wireless transmission system, typically provided by the drone manufacturer.

In the TERAWAY system, three kind of network elements are managed, each paired with a different subsystem:

- *Switch Element Controller*: The SDN subsystem in charge of controlling the SDN Ethernet switches present in both the Fixed Node (FN) and the Moving Node (MN), by means of the OpenFlow protocol.
- *Radio Element Controller*: The SDN subsystem in charge of controlling the TERAWAY radio modules present in both the FN and the MN, by means of the NETCONF protocol.
- *Drone System Controller*: The Drone System Controller is the SDN subsystem in charge of controlling all the non-

telecom systems needed for the operation of the drones hosting the MNs.

Furthermore, the Transport Network Controller sits on top of those three controllers to expose one or more NBIs to higher layer SDN controllers and provides a complete network-level view of the underlying system. This makes it possible to perform all the operations related to the overall optimization of transport network resources, including, for instance, dynamic traffic re-routing and network load optimization.

A. Switch Element Controller

The switch element controller is the SDN module that handles the management of fixed switches shown in Figure 5.

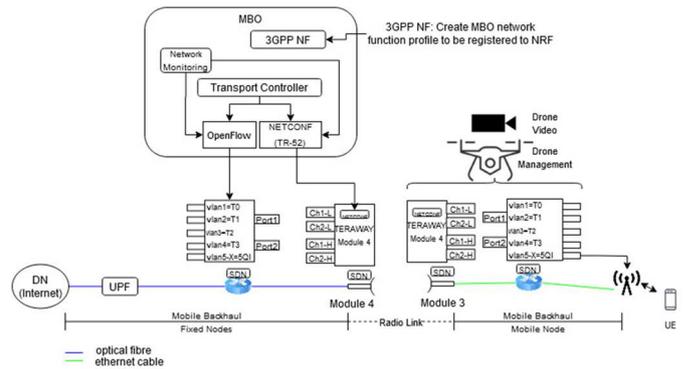


Fig. 5. TERAWAY end to end architecture.

The switch element will allocate the required network resources in the physical switches using OpenFlow. The MBO will instruct the Switch and Radio elements to reserve the required network and radio resources to support multiple network slices. The management traffic will utilize the “slice 0” with higher priority while other traffic will be routed through additional slices. TERAWAY is used for providing backhaul or fronthaul communications and the 5G Quality Indicators (5QI) should be extended with TERAWAY specific QoS parameters to deliver the high reliability and low latency slices. In TERAWAY as set of slices are defined as shown in following Table.

TABLE I. TERAWAY 5G NETWORK SLICES MAPPING

QoS	Resource Type	Bit Rate	Priority	Packet Delay	Error Rate	Usage
T0	GBR	1Gbps	100	1ms	10^{-9}	Mngt
T1	GBR	1Gbps	99	3ms	10^{-9}	High Availability & Low latency
T2	GBR	1Gbps	98	3ms	10^{-9}	High Availability (e.g. UAB Mngt)
T3	GBR	2Gbps	95	5ms	10^{-9}	Low Latency (e.g. gNB Controller)
5QI	GBR/NGBR		5QI	5QI	5QI	User traffic flows

The switch element will interact with the network switch using either OpenFlow or NETCONF to configure the different VLANs and their priority so the traffic from T0-T3 slices will be scheduled with higher priority than traffic from 5QI coming from mobile users. The integration of different applications into TERAWAY system will follow 3GPP standard mechanism

where the application utilizes NEF to register itself and request the specific network slice.

B. Radio Element Controller

The Radio Element Controller is the SDN subsystem in charge of controlling the TERAWAY radio modules. The software implementation of the TERAWAY SDN Controller will be based on OpenDaylight [8] which is used as a base component for several commercial SDN controllers (e.g.: Lumina, Inocybe, Pantheon) as well as integrated into other open-source SDN/NFV orchestration solutions such as OpenStack, Kubernetes, OPNFV and ONAP projects. OpenDaylight features a fully modular and extensible architecture, compliant to the Java component model defined in the OSGi specification [9]. As OSGi container, it uses the Apache Karaf environment, that allows loading different modules, denoted as “bundles”, dynamically at runtime. The Radio Element Controllers will be integrated into OpenDaylight as internal applications which implement the business and algorithmic logic on top of the provided south bound interface plugins. For the radio part, the NETCONF protocol will be employed. NETCONF defines configuration datastores and a set of Create, Read, Update, and Delete (CRUD) operations that allow manipulation and query on management database exposed by the element in the form of a well-defined data model, which is specified by the YANG modeling language.

There are two open radio models that are readily available for the management of point-to-point microwave network elements: TR-532, defined by the ONF and RFC-8432, defined by the IETF. These open standardized interfaces allow connecting of multi-vendor devices to an open source SDN Controller enabling the development of independent third-party applications. Both models exhibit an extensive set of parameters that can be configured and retrieved for the management of a microwave radio link.

C. Drone System Controller

The Drone System Controller is the SDN subsystem in charge of controlling all the non-telecom systems needed for the operation of the drones hosting the MNs. In this case, the kind of information that must be carried by the SBI is quite diversified, because it has to deal with the configuration and monitoring of parameters relative to different drone subsystems, like the navigation and positioning, the power management, the status of vital parameters and related alarms, and possibly others. The SBI for drone control most probably will consist a combination of proprietary protocols that must be adapted to be transported on the TERAWAY radio link. The Transport Network controller part of the Mobile Backhaul Orchestrator will allow the Drone System Controller to request additional high reliability slice dedicated to the drone control operations. A fallback mechanism shall be provided for safety

reasons, allowing drone management traffic to be transported over the proprietary wireless communication system provided by the drone manufacturer.

CONCLUSIONS

This paper has presented the TERAWAY’ SDN architecture targeting a converged ultra x-haul network. The basis of the TERAWAY architecture design adopts data model defined in ONF TR-532. The proposed architecture is based on SDN and follows SBA architecture to comply with 3GPP standards. This paper includes the proposed design for both network and radio management to deliver the x-haul beyond 5G. The proposed TERAWAY controller includes different modules for managing the network slices using OpenFlow with fixed Ethernet switches and NETCONF for managing the radio modules. In this controller design an overlay Transport Network Controller has been designed to provide a single interface for managing both fixed Ethernet switches and radio modules. The initial mapping of network slices and priorities has been defined as part of the controller design to allocate both network and radio resources. The resulting end to end x-haul management architecture will be validated after completing and integration the radio modules with commercial 5G SA.

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