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SDN-enabled terahertz x-haul network

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Abstract— **The data growth of user traffic in wireless communications requires the usage of higher frequencies in the order of Terahertz (THz) as a promising candidate to support ultra-broadband for beyond fifth generation (5G) networks. The integration of THz links for network transports requires software-based networking to improve efficiency and reduce operational costs. A preliminary design of a comprehensive SDN management architecture for joint optimization of radio and network resources is presented. The proposed architecture obtains the most added value out of use of THz technology integrated with software managed networking for mobile network beyond 5G. Seamless integration of THz radio links for increasing the overall transport capacity requires 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

The rollout of 5G started recently, and the joint development/standardization process by 3GPP/ITU-T is still ongoing. Researchers from industry and academia are already looking ahead to have an initial design of what Beyond-5G (B5G) and 6G networks. It is still premature, but experts are outlining the envisioned requirements, use cases and enabling technologies for the next-generation network landscape a decade from now. The main trends emerging and guiding the 5G development are towards higher capacity, lower energy consumption improved reliability and lower latency which will 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. 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]. As the radio access network gets denser, wideband point-to-point radio links become necessary, in addition to optical fiber, to guarantee a capillary infrastructure for the aggregation and transport of backhaul traffic up to the core. Because of the Gbps-level capacity needed for 5G backhauling links, mm-Wave and THz bands represent the viable solution, towards B5G/6G. Mobile aggregation/transport networks will support a heterogeneous mix of such traffic types, denoted as X-Haul or Mid-Haul.

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. Although technologies such as SDN or NFV have been present for some time, it is with the emergence of 5G that they will prove their true potential. First, they provide a financial advantage. It was observed that in comparison with the traditional architecture, the CAPEX would be reduced by 68%, the OPEX by 63% and the TCO by 69%. Moreover, the development of NFV management and orchestration (MANO) platforms makes it easier to manage and orchestrate virtual network function (VNF) instances or network slices. This way, these technologies could help in implementing a reliable and scalable 5G core network. The main advantage of these technologies is the ability to orchestrate and schedule the mobile core components on demand in order to deliver the required services with the proper Quality of Experience (QoE). The subsequent integration with cutting-edge analysis and control algorithms based on Artificial Intelligence (AI) and Machine Learning (ML) is believed to be the absolute defining feature for B5G/6G networks.

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. This system is designed as part of the TERAWAY H2020 project [3]. 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 also 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). In SBA, 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. In the 5G core, 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

Since its inception more than a decade ago, the SDN paradigm has progressively gained more and more adoption in disparate network environments. At first, 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. For sure, 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 feature a large number of nodes, with broad geographical distribution.
- They have a control channel with limited bandwidth and unreliable, and the real-time requirement is also difficult to meet.

These results in having the operators tied to use Network Management Systems (NMS) directly provided by equipment vendors, with specific proprietary interfaces, and independent from fixed network NMS. 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. 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, SDN is also the choice that brings highly efficient automatic O&M and end-to -end service configuration.

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 e 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. 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 in order to enable low-level operations with the hardware. The NETCONF agent whose purpose is to map high-level operations coming from the SDN Controller into low-level API commands, 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.

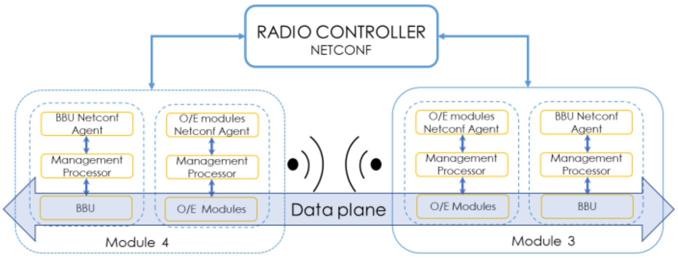

Fig. 1. Radio Management Architecture.

The radio controller maintains two databases, one for the available spectrum blocks and one for the topology of already deployed links. Assuming that the new link has been correctly aligned and the initial setup has also been performed, the first step is for the SDN controller to perform the "as-built" radio planning with the associated SLAs.

Then, the SDN controller requests periodically performance metrics such as the SINR and RSSI values, evaluates link quality [4] 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. 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. 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 [5]. 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. To this end, the SDN controller can play a vital role to the overall optimization of the radio system and consequently of the network as a whole, by drastically enhancing the operator's management capabilities by leveraging open, standard interfaces (e.g. NETCONF and ONF TR-532 yang models) and advanced AI/ML algorithms.

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. Figure 4 depicts the logical SDN management network architecture, superimposed on the TERAWAY physical network.

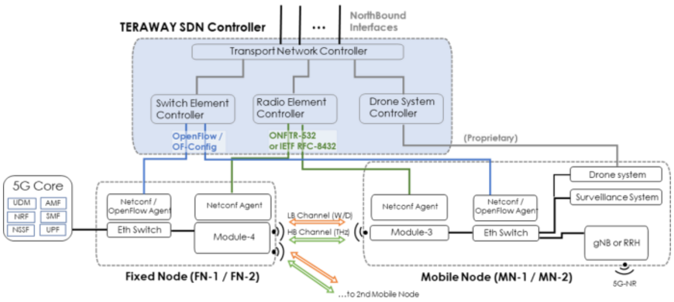

Fig. 2. TERAWAY end to end architecture.

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. The TERAWAY architecture will include an auto-scaling and self-healing mechanism built on top of Kubernetes including the following architecture.

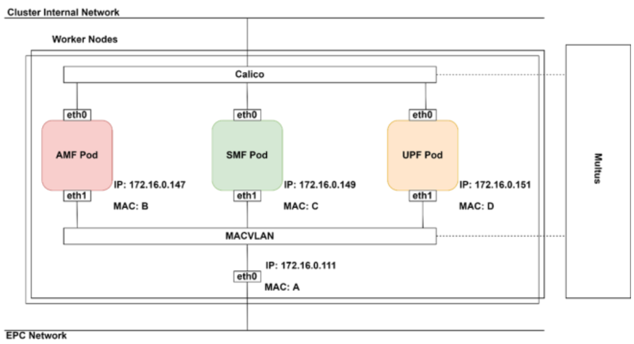

Fig. 3. Kubernetes based architecture.

For scaling up the UPF pods, we used the Horizontal Pod Autoscaler (HPA) re-source. The HPA uses Metrics API to provide the measurements based on which the scaling will be done. By default, the HPA uses for scaling metrics related to CPU and Memory utilization. The scaling of the UPF based on the in-coming packet rate on the UPF network interface. This could decrease the latency due to the queueing delay when the incoming packet rate is higher than the capacity of the interface, by forwarding the traffic from the new incoming users to a new UPF. To send more metrics to the HPA, another API must be created in Kubernetes. The following rule will be based for the scaling, where the dR represents the desired number of pods, cR is the current number of pods, cM is the measured metric and dM is the threshold specified for the metric. The ceil function is used to ensure the existence of at least one UPF pod in the system.

$$dR = \left\lceil cR \times \frac{cM}{dM} \right\rceil \quad (1)$$

The proposed scaling algorithm is evaluated for the UPF congested with UDP traffic using iperf and measured the end-to-end throughput directly from the UEs, using the Speedtest application for Android. The throughput of UEs by congesting the UPF is measured at different network load thresholds (0%, 10%, 30%, 40%, 50%, 70% and 90%). In some cases that the drop of down-link throughput is linear with network load increase, and in other cases the decreasing slope becomes steep after the 40% threshold. Two possible reasons for this behavior may be radio interference and the existence of another type of traffic in the Kubernetes node where the UPF is deployed. Nonetheless, up to the threshold of 40% we observed a throughput greater than 20 Mbps on DL and 12 Mbps on UL, and a reduction to 10 Mbps on DL and under 10 Mbps on UL when the threshold exceeded 70%. Figure 5 illustrates the scaling decision of our algorithm, using a threshold of 90%. Once the network load exceeded this threshold, another UPF was created and used by the newly attached UE.

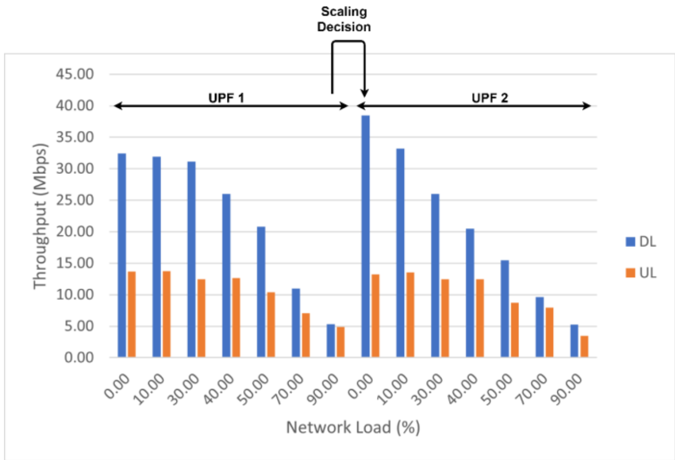

Fig. 4. Throughput variation for UE with UPF network load affected by the scaling decision.

The TERAWAY SDN controller is composed by different subsystems, where each of them is a software module that communicates with a corresponding piece of software residing in the controlled network element, which is called SDN agent. 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 will controll 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.

A. Switch Element Controller

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

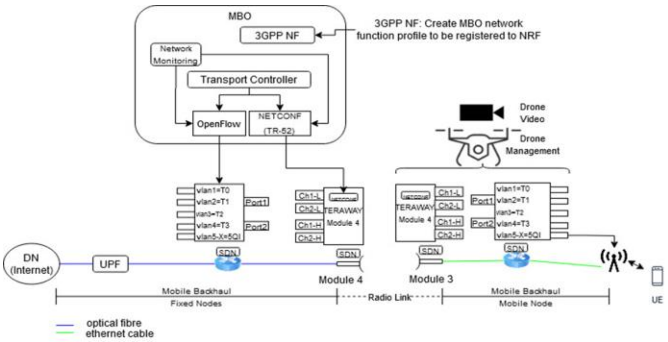

Fig. 5. TERAWAY end to end architecture.

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. The TERAWAY system should be compliant with 3GPP specified QoS specifications. Thus, when TERAWAY is used for providing backhaul or fronthaul communications, the 5G Quality Indicators (5QI) should be extended with TERAWAY specific QoS parameters to deliver the high reliability and low latency slices. 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.

B. Radio Element Controller

The Radio Element Controller is the SDN subsystem in charge of controlling the TERAWAY radio modules. The radio controller will be built with OpenDaylight that offers a generic Java platform to develop a fully customized SDN controller. This platform 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 and management solutions such as OpenStack, Kubernetes, OPNFV and ONAP SDN application projects.
For the radio part, the NETCONF protocol will be employed. Network Configuration Protocol (NETCONF) is a network management protocol defined by RFC 6241.

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, dealing 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. Moreover, the set of parameters and operations is expected to be strongly dependent on the specific commercial solution that will be adopted for the drone by TERAWAY. 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.

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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