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A network slicing architecture for SDM and ARoF-based 5G fronthaul networks

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The blueSPACE project focuses on the study of innovative technologies to overcome the limitations of the current fronthaul networks. The key technology proposed is the Spatial Division Multiplexing (SDM) which allows to increase the capacity available in conventional single-mode fibers (SMFs), effectively encompassing this capacity to the forecasted bandwidth demands imposed by 5G mobile communications. In this article we present the innovative optical fronthaul infrastructure proposed in the project, and the tailored extensions to the ETSI NFV MANO architecture for this enhanced infrastructure together with practical implementation considerations.

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1. INTRODUCTION

5G requires low-latency and high-capacity optical networks in order to support the forecasted sub-millisecond end-to-end latency and 1000x growth in the mobile data traffic. This requirement introduces very stringent constraints in terms of high-bandwidth and low-delay in the optical fronthaul network segment (i.e., between the BBUs and the RRUs), due to the functional splits currently used in radio access networks where most of the signal processing is moved towards the Central Office (CO).

Traditionally, Digitized Radio over fiber (DRoF) transceivers based on Wavelength Division Multiplexing (WDM) are used to transport the 4G fronthaul interface (e.g., common public radio interface – CPRI). The main drawback of CPRI is that it does not scale, in terms of bandwidth requirements, for the massive multiple-input multiple-output (MIMO) antenna deployments foreseen in 5G and beyond [1]. Currently, 3GPP is defining the next generation fronthaul interface (NGFI) to reduce the 5G bandwidth requirements. It is based on a functional split of the RAN, by performing the lowest processing of the radio physical layer in the RRU [2]. This approach targets the packetization of the fronthaul interface (e.g., Ethernet) in order to provide a more efficient network utilization based on statistical multiplexing.

In this paper we focus on an alternative 5G fronthaul network solution developed in the blueSPACE project that is based on combining Space Division Multiplexing (SDM) and Analog Radio over Fiber (ARoF) technologies [3]. SDM is the key technology to overcome the capacity requirements for the 5G fronthaul transport between the RRUs and the BBUs [4]. SDM can be deployed by making use of the already deployed bundles of single mode fibers, or by exploiting the spatial dimension of the multi-core fibers (MCF). ARoF transceivers enable to reduce the bandwidth and latency requirements, by directly modulating the radio onto light for connecting analog BBUs and RRUs.

5G is adopting the ETSI Network Functions Virtualisation (NFV) Management and Orchestration (MANO) framework [5] as the reference architecture to provide efficient and end-to-end: i) resource orchestration (both at the network and computing level); ii) network service orchestration, and iii) network slice management for multi-tenancy (e.g., vertical industries). This is a key enabler to deliver virtual mobile infrastructures customized for the specific requirements of multiple vertical industries, while efficiently sharing the physical resources available in the mobile networks. Introducing the novel optical fronthaul architecture proposed in this paper brings many challenges in the whole management plane and in particular in the NFV MANO platform that need to be faced:

- ARoF and SDM technologies must be integrated in the

Transport Software-defined Networking (SDN) controller in order to manage optical transport connections in the advanced SDM fronthaul network with ARoF transceivers.

- The NFV Orchestrator (NFVO) from the NFV MANO platform must be extended to be able to manage the analog BBUs and RRUs as Physical Network Functions (PNFs) to enable their dynamic configuration and implement effective resource allocation strategies at the RAN level. This means that the provisioning of end-to-end NFV network services needs to jointly involve Virtual Network Functions (VNFs) and PNFs.
- The NFVO must be able orchestrate MEC apps in order to be transparently used as part of the Network Services (NS).
- The Transport SDN controller must be integrated with the NFVO through an open Application Programming Interface (API) that enables to manage the advanced optical connections and have a complete view of the optical resources to develop efficient allocation algorithms.
- A Network Slice Manager (NSM) must be deployed on top of NFVO in order to deploy end-to-end network slices for vertical services.

This paper is organized as follows. First, in section 2 we elaborate the challenges and the proposed target for a new NFV service platform architecture and the novel fronthaul optical infrastructure supporting the 5G services. In section 3 and 4 we detail the optical fronthaul and orchestration architectures and solutions aiming to address the challenges identified in section 2 for the optical, NFV and slice domains, and finally in 5 we establish our concluding remarks.

2. BLUESPACE NETWORK INFRASTRUCTURE AND ORCHESTRATION CHALLENGES

blueSPACE envisions a centralized radio access network (C-RAN), where all functionality is transferred to central units (CUs) hosted at the central office (CO), which in turn enables the deployment of RRUs with minimal functionality — ideally only amplification of the RF signals — that translates to minimum cost, both for deployment and operation. This C-RAN approach relies heavily on BBUs deployed in pools and connected to the RRUs via the fronthaul segment. The centralization of all processing and the resulting transport of radio waveforms to the RRUs places a heavy burden on the fronthaul network in terms of required capacities and sets stringent limits to the allowable latency. The blueSPACE high-level architecture and infrastructure description in [6], together with the related orchestration challenges, are detailed in more depth in this article with a comprehensive report of the 5G fronthaul infrastructure and network slicing orchestration and control approach.

A. Optical Technologies for 5G Fronthaul Infrastructure

Fibre optics have been the foundation of core and metro networks for many years and in the last decade have increasingly spread into the (radio) access network segment, to the point where fibre-based backhaul is rapidly supplanting traditional microwave and copper based backhaul solutions and, in many markets, already holds a majority market share. In addition, the fronthaul segment of C-RAN is predominantly based on fibre networks due to the required data rates [7]. With the increased bandwidths and denser deployment expected for 5G, however, a new set of challenges is posed to the underlying fibre networks. Especially in the fronthaul segment, where traditional digitized radio-over-fiber (DRoF) solutions do not scale well to larger signal bandwidths, a need for alternative optical (transport) technologies has emerged.

Analog radio-over-fiber (ARoF), where the desired radio waveform is directly transported over the fronthaul segment as an analogue signal, rather than in digitized form, is the key candidate for solving the capacity faced by DRoF in an efficient and cost-effective manner. From an architectural perspective, ARoF maintains and maximizes the centralization of network functionality, achieving full processing at the CO and avoiding an – at least partial – return to a distributed radio access network as foreseen with the introduction of different functional splits in the evolution of DRoF fronthaul schemes. By further removing the need for CPRI (or next generation DRoF) processing and framing, ARoF aids in minimizing fronthaul latency.

When considering the transport of an analog signal over optical fiber networks, a number of possibilities can be considered, differing mainly in the frequency of the transported analog signal and the upconversion strategy to the targeted radio band at the RRU. The analog waveform that is destined for the air interface, i.e., that is to be radiated towards the end users, can be transported as analog signal over the optical fiber either at baseband (potentially with separated I and Q streams), at an intermediate frequency (IF) or as RF signal at the target radio frequency. While for the traditional radio bands below 6GHz the use of RFoF is common and easily possible within the available modulation bandwidth of optical modulators, for the mm-wave bands introduced in 5G this is not necessarily the case and intermediate frequency over fiber (IFoF) becomes the preferred option to limit the required modulator bandwidths and minimize spectrum usage [4]. At the RRU, therefore, a final upconversion is required to the targeted RF frequency, which can be performed by electrical upmixing or – as proposed in blueSPACE – through the use of optical heterodyning. The latter not only allows easy generation of high-frequency RF signals, but also enables full centralization – and thus possible sharing or pooling – or frequency sources and references.

SDM in the optical transport medium, i.e., spatial multiplexing of signals on different modes or cores of a fibre, has been introduced as a mean to increase the capacity of fiber optic networks and has been suggested for radio access networks to alleviate the fronthaul capacity crunch. In addition, this technology introduces an additional degree of freedom for switching and routing and to enable the transport of related signals through tightly correlated channels for, e.g., optical beamforming [8–10]. Few- and multi-mode fibres typically encounter significant mode-mixing and thus require multiple-input multiple-output signal processing to separate the signals. Instead, the use of multi-core fibres (MCFs), in which the individual cores can be designed to match the transmission properties of standard single mode fiber (SMF), allows for practically independent channels that can be easily separated by passive and low-loss optical devices, while maintaining very similar channel behavior between cores [11]. SDM is further fully compatible with wavelength division multiplexing (WDM) and may offer more cost-effective solutions than an more dense wavelength grid.

In blueSPACE, MCF is proposed for the fronthaul segment to enable remote optical beamforming and to allow highly densified deployments with minimum fibre footprint and seamless sharing of the same optical fibre infrastructure for radio access and other services.

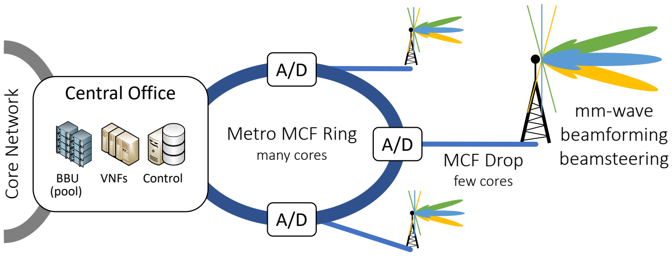

Fig. 1. blueSPACE fronthaul architecture based on ARoF fronthaul, SDM using MCF and optical beamforming for mm-wave multi-beam transmission.

The use of antennas with a large number of antenna elements, as proposed especially for the mm-wave frequency ranges of 5G New Radio (5G NR), poses the question of what beamforming strategy to use. That is, whether analog beamforming through differential delays between the signals radiated from the antenna elements or digital beamforming via MIMO processing of the signals or a hybrid thereof is preferred. Analog beamforming performed in the electrical domain typically suffers from significant beam squint for large signal bandwidths and often comes at the cost of significant footprint and power consumption. Optical beamforming, i.e., the optical conditioning of signals before conversion to the radio domain, may alleviate these issues and further allows for the implementation of full beamforming matrices, rather than the conventional banks of phase shifters. Through the implementation of full beamforming matrices, optical beamforming allows true multi-beaming, i.e., the parallel and independent transmission of multiple beams from the same antenna array, and thus allows an increase in cell capacity and by concentrating the emitted signal in a small area also enables increased frequency re-use.

blueSPACE proposes the combination of these optical technologies into a novel, SDM based fronthaul network with ARoF transport, optical heterodyning at the RRU and optical beamforming for multi-beam transmission, as shown in Fig. 1.

B. Challenges for end-to-end orchestration and slicing

The current ETSI NFV MANO architecture, adopted to manage service and resource orchestration in 5G networks, is composed of three main functional blocks: (i) the Virtualized Infrastructure Manager (VIM), responsible for the management of physical and virtual resources; (ii) the VNF Managers (VNFMs), handling the lifecycle of the single virtual functions, and (iii) the NFVO, in charge of orchestrating and deploying the overall network services.

In this model, the VIM is responsible of handling compute, storage and some network related resources and is usually implemented using the already available controllers designed for cloud computing environments (such as OpenStack). Most of these solutions, however provide limited or no functionalities to provision and configure the network and computing resources in a coordinated manner across different network segments. This is a strong limitation in the NFV environments, where a tight integration between the NFV based service life cycle actions and the network configuration is required. In a similar manner, the NFVO should be able to exploit the usage of edge resources available at the CO and manage PNFs, like BBUs and RRUs, to adopt more efficient and cross-technology resource allocation strategies. In practice, the orchestration procedures inside the NFVO should be able to combine edge, cloud, transport network and PNF information to take the allocation decisions and interact with the corresponding controllers to enforce the end-to-end QoS parameters.

The ETSI NFV MANO framework already acknowledges and tries to address the joint network and compute allocation challenge with the introduction of the WAN infrastructure Manager (WIM) as a special kind of VIM. This particular VIM is responsible for providing the connectivity among the NFVI Points of Presence (PoPs). There are already several software defined network (SDN) controllers (e.g. OpenDaylight, ONOS, Ryu) which provide software defined interfaces to configure the underlying network infrastructure, and therefore could be used as the WIM in this scenario. The problem with this approach has two main drawbacks. First, the level of maturity of the interface between the NFVO and the WIM which results in a low level adoption on the current NFVO and WIM implementations. Most of the current NFVO implementations blindly assume the WIM will provision the connection pipes between the different end points (either pre-provisioned or dynamically created) without interacting with it. Second, a single SDN controller would not be able to fit all the diverse technologies and vendors present in the transport networks.

In addition to the transport network connectivity problem, the current ETSI NFV MANO architecture is also limited in terms of the assets considered as part of the orchestration domain. Up until now, exisiting NFVO MANO tools are limited to the orchestration of VNFs, while PNFs and Mobile Edge Computing (MEC) apps are considered out of the scope of the orchestration logic or are not yet fully integrated.

In this paper we propose an extended ETSI NFV MANO architecture aiming to tackle these two challenges. In particular, the proposed NFV MANO platform integrates the management of PNFs and MEC apps and adopts an enhanced NFVO WIM interface to interact with a hierarchical Transport SDN controller in charge of managing the fronthaul network resources. The novel architecture also provides a new level of flexibility, by decoupling the logic of the resource orchestration algorithm. Current NFVO platforms use resource allocation algorithms which are tightly coupled to the core of the NFVO itself. In blueSPACE we developed extensions which allow the NFVO to send all the information available from the infrastructure, transport networks and PNFs to external services and receive back resource allocation decisions. Furthermore, while current NFV MANO platforms still lack of slicing functionalities, the architecture we present in this article also provides network slicing capabilities on top of the enhanced NFV MANO platform, in order to optimize the usage of the physical resources through the network slice sharing concept.

3. OPTICAL FRONTHAUL ARCHITECTURE

A. blueSPACE ARoF Fronthaul Architecture Options and Components

The blueSPACE ARoF scheme combines a flexible IFoF link with optical beam-forming and remote photonic up-conversion to the mm-wave frequencies (n258 band) at the RRUs. The fronthaul link thus includes the ARoF BBU and IF unit as well as optical ARoF transceivers with two-tone generation at the CO, an SDM based optical distribution network (ODN) and a simplified RRU with only photodiodes and amplification. The inclusion of optical beamforming is foreseen in two alternatives, placing the optical beamforming network (OBFN) either at the CO or the RRU, where the former allows maximum centralization, while

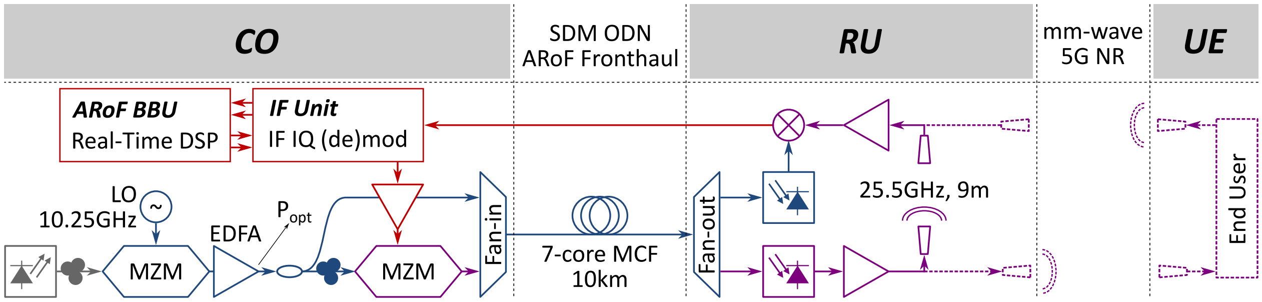

Fig. 2. ARoF architecture and setup overview with blueSPACE BBU and IF unit, IF ARoF transport over MCF and optical heterodyne for mm-wave upconversion.

the latter relaxes requirements on the ODN. blueSPACE intends to demonstrate both options and to experimentally evaluate their comparative advantages and disadvantages.

The blueSPACE BBU constitutes the interface from the ARoF fronthaul to the backhaul. The BBUs perform the baseband processing and generate baseband I and Q signals following an extended version (4bs) of the 5G NR standard numerology 4[12] [13] supporting high bandwidths — up to 800MHz — to showcase the achievable capacities with ARoF fronthaul and mm-wave transmission and to prove optical beamforming for large bandwidths. The outputs of the BBUs are up-converted by the IF unit, using IQ modulators, and are amplified to drive optical modulators in the ARoF transceivers. In uplink direction, the IF unit downconverts the received signal and passes the resulting I and Q signals to the BBU for digitization and processing.

The novel ARoF fronthaul transceivers developed in blueSPACE will minimize optical bandwidth usage and allow maximization of network hardware at the CO through the use of optical heterodyning for mm-wave generation at the RRU. The ARoF transceivers feature integrated two-tone generation and allow modulation with up to four separate IF signals targeted at different beams from the same RRU. Implemented in a single photonic integrated circuit, the four channels of the blueSPACE ARoF transceivers are coherent and thus allow the use of a single coherent OBFN to achieve true multi-beam transmission.

In the case of maximum centralization with the OBFN at the CO, the ARoF transceiver is directly coupled to the OBFN, which translates each of the four input signals to all its output signals while applying differential shifts between the different signal copies and hence defining the beam direction. Such OBFN placement at the CO places stringent requirements on the ODN, as the resulting output signals from the OBFN must be transported with minimal temporal skew in order to preserve beam shape. It further imposes limitations on the number of antenna elements used, as the number of channels required in the ODN linearly scales with the number of antenna elements. If such time synchronous transport cannot be guaranteed, or if network scaling with the number of active beams rather than the number of antenna elements is desired, the OBFN can be placed at the RRU at the cost of increased complexity at the remote side.

In either case, the modulated optical two-tone signals are spatially multiplexed onto different cores of the MCF for optical transport in the SDM based ODN.

At the RRU, the optical signals beat on high-bandwidth photodiodes to produce the mm-wave RF signals that are amplified and radiated through the antenna elements. A remote local oscillator (LO) signal also provided by the ARoF transceivers is used at the RRU for down-conversion of the received uplink radio signals to the same IF, before transmission to the CO for IF and baseband processing by the IF unit and BBU.

The use of SDM in the RAN augments capacity and allows for an additional degree of freedom in RAN design and operation — e.g., allowing the use of the same wavelength for related signals transmitted through different cores. Optical beamforming supports large RF bandwidths and allows multi-beam transmission from a single antenna with narrow beams, minimizing interference and increasing frequency reuse capabilities. Combing these three technology enablers, ARoF, SDM and optical beamforming, blueSPACE demonstrates a viable alternative for ultra-high capacity, densely deployed mm-wave RANs seamlessly supporting multi-beam transmission.

B. Experimental ARoF Transmission Results

The experimental setup for verification of the functionality of the blueSPACE ARoF BBU and IF unit and for performance analysis of the proposed ARoF fronthaul over MCF is shown in Fig. 2. It should be noted that this setup is based on bulk optical components, rather than the integrated blueSPACE transceivers as the latter are currently in fabrication. The setup can nonetheless serve to both verify the blueSPACE ARoF BBU and estimate the performance achievable for an ARoF link over MCF with a remote-fed LO.

The setup includes an ARoF transmitter based on two-tone generation in a Mach-Zehnder modulator (MZM) biased at its null point and driven with a sinusoid at half the targeted tone separation. The two-tone signal is amplified and modulated in a second MZM with an 800MHz extended 5G NR cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) signal [12] from the BBU and IF unit. The modulated signal and a second, unmodulated copy of the two-tone signal are multiplexed onto different cores of the MCF and transmitted to the RRU, where they beat on separate photodiodes, generating the RF signal to be transmitted and the LO for electrical downconversion of the received signal, respectively. The experimental setup performs a loop at the RRU to emulate a realistic case with single-pass through MCF and mm-wave segments, however in a full implementation the downlink signal would be downconverted and decoded by the UE, while the uplink signal coming from the UE would be downconverted with the help of the remote-fed LO, before being transmitted to the CO through the MCF.

The transmission results obtained with the system shown in Fig. 2 are shown in Fig. 3. The spectrum of the transmitted RF signal after heterodyning and amplification at the RRU is shown in Fig. 3(a), while Fig. 3(b) compares the transmitted and received IF spectra showing a degradation in signal-to-noise

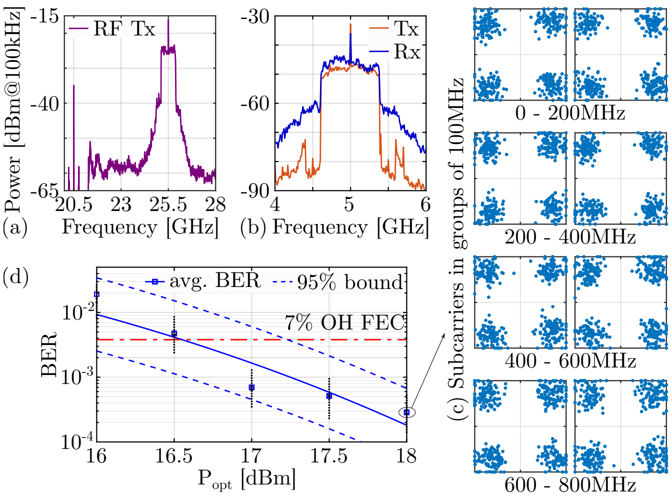

Fig. 3. Initial experimental results for real-time ARoF transmission over MCF with the blueSPACE BBU and IF units: (a) transmitted RF spectrum, (b) IF spectrum at transmit and receive sides of the IF unit, (c) received signal constellations separated in eight groups of 100MHz each, (d) measured BER for different optical powers.

ratio as expected after transmission through the optical and mm-wave wireless system as well as a small imbalance between signal components above and below the carrier. The decoded constellations and shown in Fig. 3(c), with subcarriers separated into eight groups of 100MHz bandwidth each for easier visualization, showing consistent constellations across the spectrum, with exception of small degradations in the first and last two groups. Finally, Fig. 3(d) shows the obtained bit error rate (BER) performance after 10km MCF and 9m mm-wave transmission at 25.5GHz, i.e., in the n258 5G NR band, showing real-time processes BER measurements for different optical powers – and thus different transmitted RF powers and LO drive levels for electrical down-conversion, where a 1dB reduction in optical power is estimated to correspond to a 2dB reduction in both RF and LO levels. The observed BER performance remains clearly below the limit of 3.8×10^{-3} for a commercial hard-decision forward error correction (FEC) with 7% overhead. Furthermore, the maximum optical power was set to avoid saturation of the power amplifier employed for wireless transmission; a further improvement of performance or available distance may be achieved by upgrading this amplifier and/or increasing optical power.

The obtained results not only validate the functionality of the ARoF BBU and IF units with real-time signal processing, but also shows the viability of ARoF fronthaul with optical heterodyning for mm-wave upconversion. By remotely feeding the LO required for electrical downconersion of the received signal, the proposed ARoF scheme further maximizes centralization and removes the need for any frequency generation or reference at the RRU.

4. NETWORK SLICING AND SERVICE ORCHESTRATION IN OPTICAL FRONTHAUL

A. blueSPACE NFV MANO Platform

This section provides a high level overview of the different functional blocks composing the blueSPACE NFV MANO platform (shown in Fig.4). Following a top-down approach, the NFV MANO platform is composed by the Network Slice Manager (NSM), the resource allocation algorithms, the NFV Service Platform, and the Transport SDN controller (WIM). The NSM manages the life-cycle of the network slices by translating their QoS requirements into NFV network service instantiation requests or scale operations towards the NFV service platform.

The resource allocation algorithms are the centralized point where all the fronthaul resource allocation decisions take place, based on the information provided by the NFVO from the WIM, the VIM and the available PNFs (BBUs and RRUs).

The NFV service platform manages the NFV network service operations by means of an enhanced NFVO. This implies: (a) the orchestration of the resources available at the WIM (by means of a novel Transport SDN controller), (b) the control Edge computing resources (through an enhanced the VIM), and (c) the management of VNFs/PNFs (by means of the PNF/VNF Managers (PNFM and VNFMs respetively). Finally, the WIM, as mentioned before, enables to manage the network resources through a novel API The following subsections provide a more finer-grained detail about each architectural block.

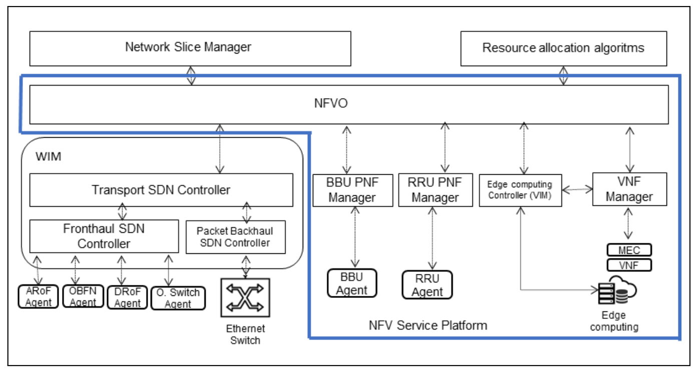

Fig. 4. blueSPACE NFV MANO platform high level functional blocks and interfaces.

B. Hierarchical Transport SDN control framework

The control of the optical network is delegated to the transport SDN controller acting as WIM, under the global coordination of the NFVO. The transport SDN controller is responsible for configuring and monitoring all network elements in order to manage the overall life cycle of the connectivity services (CSs) in the fronthaul and backhaul segments. It relies on a hierarchical approach with two different levels of hierarchy as shown in Fig.4. In the hierarchical architecture, one SDN controller acts as global orchestrator of multiple SDN controllers with a parent/child hierarchy [14]. The hierarchical architecture requires to use a common API between the parent SDN controller (southbound interface) and the child SDN controller (northbound interface) to deliver the end-to-end transport services. Each higher level has the potential for greater abstraction and broader scope of the network services from the lower levels. However this abstraction prevents the parent SDN controller to perform optimal allocation, and it has to rely on the child SDN controllers for performing the intra-domain path computation, while the parent SDN controller is mainly responsible of the SDN domain selection. It is worth to highlight the considered architecture can be applied recursively enabling the cascading of the SDN controllers.

In particular, two child SDN controllers are deployed, one for the optical fronthaul segment and another for the packet backhaul segment (between the BBU and the edge computing server in the central office). On top, a parent SDN controller is orchestrating, at a higher, abstracted level, the end-to-end transport connectivity services across the child SDN controllers. The interface between the child and parents SDN controllers is based on the Transport API (TAPI) [15]. This TAPI defines a common YANG data model for the SDN control plane functions (e.g., path computation, topology and connection provisioning) and uses RESTconf as protocol. TAPI enables to uniformly interact with heterogeneous SDN controllers, regardless of the specific implementation of the child SDN controller. Therefore this hierarchical approach based on TAPI enables to support different SDN domains owned by different providers.

Currently, the interface between the NFVO and the WIM still lacks standardization and there, it is not widely implemented as southbound interface for the WIM by any of the reference NFV service platform. We propose to use TAPI for the communication between the NFVO and the parent SDN controller, with extensions to deal with the specific optical technologies used in the optical fronthaul. In general, a TAPI client (i.e., an NFVO) gets a TAPI context from the parent Transport SDN controller. It is defined by a set of service interface points (SIP), which enables a NFVO to request connectivity services between any pair of SIPs. The parent Transport SDN controller (i.e., the TAPI provider) may expose one or more abstract topology within a shared Context [16]. The topology is expressed in terms of nodes and links. Nodes aggregate node edge points (NEPs) acting as node ports. Links interconnect two nodes and terminate on NEPs, which may be mapped to one or more SIPs at edge of Network where the ARoF and DRoF transceivers are located. An example of the blueSPACE TAPI abstracted topology is given in Fig.5.

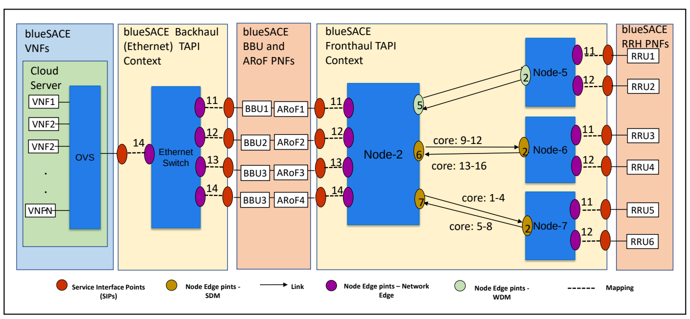

Fig. 5. Example of blueSPACE TAPI abstracted topology for fronthaul and backhaul

TAPI data models can be extended, showing a flexible modularity. Extensions for OTSi, ODU, and photonic media channels are already included in official release. We have followed the same approach in order to define two new TAPI data models, one for ARoF transceivers (tapi-arof.yang) and another for DRoF transceivers (tapi-bvt.yang). We have defined two new supported layer protocol qualifiers, one for ARoF and another for DRoF. It enables to request connectivity services configuring these two different kinds of transceivers. In short, we have extended the service-interface-point-spec and the connection-end-point-spec in order to define the capabilities and the configured parameters of the ARoF/DRoF transceivers. Previously, we also defined another TAPI data model for SDM (tapi-sdm.yang) in [17], which allows the control of super-channels in the SDM networks. The extended YANG models for TAPI are published online in a public repository [18, 19].

The child SDN controller for the backhaul network is based on a regular SDN controller for packet networks using OpenFlow at the southbound interface to configure the backhaul packet switch. On the fronthaul network, the fronthaul SDN controller is extended with a dedicated transponder manager to interact with the ARoF and DRoF transceivers (both at the CO and RU) through dedicated SDN agents. The SDN agent's purpose is to map high-level operations coming from the child SDN controller into low-level, hardware-dependent operations using the proprietary protocols. This involves defining a data model for the ARoF and DRoF transceivers, and the optical SDM/WDM aggregation elements, and agreeing on a protocol, with the corresponding message formats and encodings. We have defined data models for the ARoF and DRoF transceivers, and use RESTful protocol for communication between the child SDN controller and the ARoF agents, and NETCONF protocol between the child SDN controller and the DRoF agents.

As regards the ARoF agents, only two parameters are controlled: 'arof_id', that identifies the ARoF transceivers to configure and 'enable' that is supported for turning on and off the laser devices employed in the ARoF transceivers. Optional parameters are the nominal central frequency to configure the laser in case it is tuneable. Each ARoF agent is composed with a RESTful application that contains four operations: POST/PUT (configuration of the operations in the laser), GET (request of the operations configured in the lasers) and DELETE (removal of the operations configured in the laser).

On the other hand, DRoF transceivers are implemented using bandwidth variable transceivers (BVTs). BVT implements a range of advanced functionalities, such as different bit rates and a dynamic variation and adaptation of modulation format and symbol rate. The BVTs are based on OFDM with 512 subcarriers spaced by 39 MHz featuring adaptive modulation [20]. The parameters able to be configured at the BVT are status (active, off, standby), nominal central frequency, FEC (hard-decision or soft-decision), equalization (zero-forcing or minimum mean square error), and constellation. Constellation is set in a per subcarrier basis by means of two vectors: one containing the bits per symbol (e.g., from L=2 up to L=8, corresponding to 2L-QAM), and another one with the normalized power per symbol for each subcarrier. In addition, the BVT has a couple of monitored parameters; the overall BER, giving a general view of the connection performance, and the SNR per subcarrier, used to estimate the channel profile and enable adaptive modulation of the OFDM subcarriers. BVT agent is composed of a NETCONF server based on Python (pyang and pyangbind) that contains a modular YANG-based data store for the configuration and operational state data. The defined YANG data model is available at [21].

C. NFV Service Platform

The blueSPACE NFV service platform extends the traditional NFVO NFV-NS orchestration domain by two different means. First, traditional NFVO platforms only orchestrate common VNFs, but in blueSPACE we extended this orchestration domain to embrace PNFs and MEC apps. At the same time, blueSPACE introduces a new set of fronthaul infrastructure transport technologies in which the service platform relies to deploy the NFV-NS with QoS guarantees, which effectively extends current list of technologies supported. On top of these extended orchestration capabilities, the blueSPACE service platform also provides support for the resource allocation algorithms, further discussed in subsection E, for the joint allocation of computing

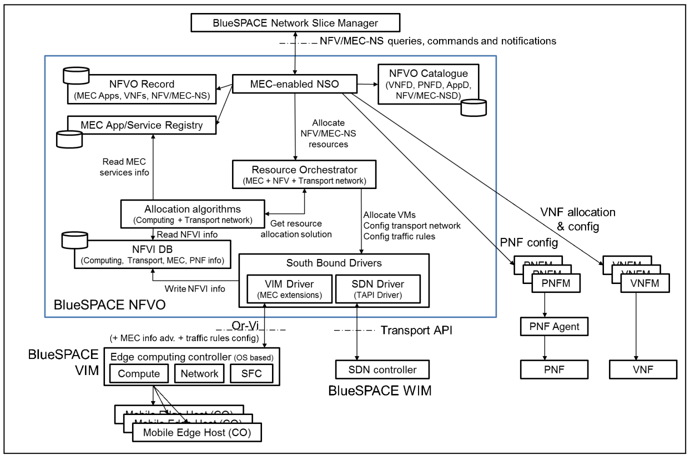

Fig. 6. blueSPACE NFV Service Platform.

and networking resources. The implications of these extensions affect several architectural blocks of the ETSI MANO architecture. The code of the blueSPACE service platform has been released under the Apache Licence 2.0 [22] and is available at [23].

In Fig. 6 we show the main functional blocks of the enhanced architecture. As shown in the figure, the northbound interface offers instantiation and management of MEC enabled NFV-NS. This means the operations of this interface use NFV-NS descriptors enriched with references to MEC apps.

The NFVO catalogue of the ETSI NFV MANO architecture holds the information of the assets to be orchestrated: the traditional NFV-NS and VNFs. The novel architecture uses MEC enabled NFV-NS, which we refer to as NFV/MEC-NS, and the PNFS. For the NFV/MEC-NS the existing catalogues were updated with references to the MEC apps, and a new catalogue was added to hold the MEC app information. The PNF support, on the other hand, required the addition of two new catalogues: one for the PNF descriptors (PNFDs) and one for the PNF instances. Furthermore, the PNFDs defined in [24] were extended to support the configurable parameters, the capabilities and network connectivity information. The network service instance records inside the NFVO record catalogue were also extended to be able keep to track of the MEC apps used by the network service instances.

The southbound drivers towards the NFVI infrastructure, were updated to add the support the new transport technologies and to extend the VIM interface. The new SDN drivers introduced interact with the blueSPACE transport network using a TAPI client that allows to retrieve the topology and create connectivity services (specifying the required parameters). In the blueSPACE NFV platform architecture, the VIM controller was extended to be a fully fledged MEC Edge Computing Controller, which manages the Mobile Edge Hosts, placed at the Central Offices (CO) where to allocate the MEC apps and to configure the traffic rules affecting them. The Or-Vi interface was also updated to support the PNF information retrieval from the VIM. In this sense, the VIM inside the blueSPACE platform exposes the PNFs available and its connections to the network.

All the new information available from the NFVI (i.e PNFs, MEC hosts, transport topology, etc) is stored in an extended NFVI catalogue, which is used by the resource allocation algorithms to compute the allocation solutions and by the orchestration related functionalities for internal procedures. Therefore, the resource allocation algorithms are fed with all the NFVI information available, including the status of the compute and transport domains and the PNF instances with their corresponding configuration and monitoring information. It is important to highlight that the resource information in this case just aims to reflect the infrastructure capacity in order to correctly determine the resource allocations. SLA enforcement and other monitoring information based decisions should rely on different mechanisms as explained in [25].

In terms of life cycle management, the NFVO resource orchestrator functions were extended to provide the functionalities of the Mobile Edge Application Orchestrator (MEAO) [26] in support of the life cycle management of the individual MEC apps. Furthermore, to support the full life cycle management, the platform has to be able to discover the MEC services available, in order to support the dependency between MEC apps and services. In the MEC architecture [26] it is up to the Mobile Edge Platform (MEP) to discover and register the MEC services. Therefore, in blueSPACE we included some of MEP functionality inside the NFVO, and in particular we included the MEC app/service registry to store this information. Another possible way of addressing this, also supported by the project, is to let the NFVO manage the life cycle of an external NFV-NS based MEP and interact with it.

The blueSPACE NFV service platform was extended to embrace PNFs as part of the orchestration domain. Besides the impact already mentioned on the NFVO and NFVI catalogues, the platform introduces the PNF manager (PNFM) and the PNF agent as two new functional blocks. The PNFM interacts with PNF agents to manage the PNF life cycle (taking into account the available actions for that PNF) and extract configuration and monitoring data. The PNF agent, in this scenario, translates the PNFM requests into the PNF-specific protocols. A particular reference point, Or-PNFM, has been established at the blueSPACE architecture implementing a subset of the Or-VNFM methods.

D. Network Slice Management for 5G Vertical Services

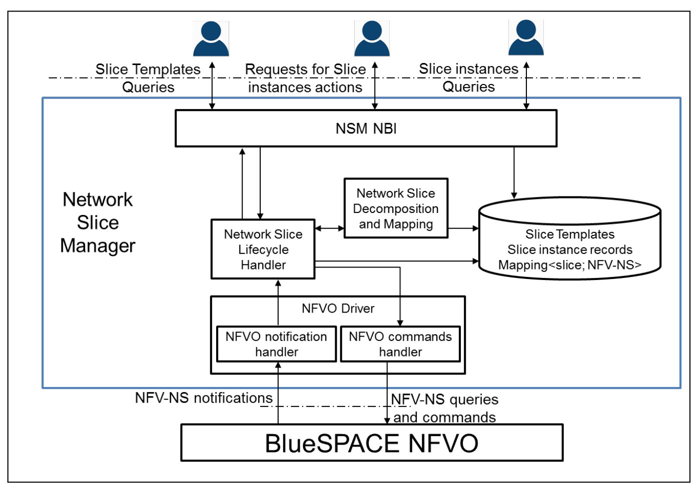

Fig. 7. blueSPACE Network Slice Manager high level functional blocks.

The blueSPACE NFV service platform adopts network slicing concepts, which is one of the key new concepts associated with 5G. Network slicing enables the creation of multiple isolated networks on top of a shared infrastructure. These isolated networks can belong to different tenants and have their own set of requirements in terms of QoS for heterogeneous vertical services to be deployed on top. Furthermore, network slices can span across different segments of the network and therefore provide end-to-end support for different kind of services. The proposed architecture, shown in Fig. 7, has a special functional block to provide the network slicing capabilities: the Network Slice Manager (NSM).

The network slices in this scenario combine a set VNF, PNFs, MEC apps and running on the blueSPACE shared physical infrastructure, which includes the computing and storage resources at the CO and the networking resources of the SDM/WDM fronthaul and the packet-based backhaul domains. As detailed in [27], the northbound interface (NBI) of the NSM uses Vertical Service Blueprints and Descriptors (VSBs and VSDs) to provide a high-level description of the services. The Network Slice Lifecycle Handler translates the high-level lifecycle actions (i.e. instantiate, terminate, etc) into network slice and network service lifecycle actions by means of the Network Slice Decomposition and Mapping. The NFVO driver in this scenario acts as mediator between the NSM and the NFVO for the NS lifecycle management.

The reference implementation of the blueSPACE NSM is released under the Apache Licence 2.0 [22] and is available at [28]. The blueSPACE NFV service platform has already been showcased in [29] and [30]. In [29], the visitors of the demo were able to deploy, operate and use a virtual Content Delivery Network (vCDN) service by means of the NSM. The vCDN service, in this scenario, consisted of a virtual Evolved Packet Core (vEPC) connected to a BBU, and a variable number of VNFs (depending on the requests from the visitors) to represent a two level hierarchy of video caches. The NSM transparently translated the visitor requests into network slices and network services. For this latter, the NSM relied on the blueSPACE NFVO for the management. In this demo, the NFVO was capable also of automatically scale up and down the network service based on the amount of users connected to the vCDN. The demo in [30], demonstrated vertical slice life cycle control for energy-efficient broadband services in scenarios with user mobility. The focus was set in showing how to dynamically orchestrate 5G Network Slices together with their Network Services and optical paths in the 5G fronthaul when users move across the network. The demo control loop integrated, among other, the NSM, the NFV Orchestration and novel transport control API to dynamically reconfigure the optical fronthaul network based on ARoF.

E. Resource allocation algorithms for 5G fronthaul

In the blueSPACE architecture, the resource allocation algorithms are directly interacting with the NFVO by receiving information about the requested services and the current resources status (originated from VNF and PNF agents) and returning the allocation of specific resources to specific services. The actual assignment of the allocated resources is performed by the NFVO, which also communicates with the SDN controller, similarly to the concept presented in [31].

The respective process addresses all involved types of system resources, which are of multiple dimensions and concern all domains from the radio access domain to the MEC domain through the ODN. Fig. 8 provides an abstract example, where the resource slots (or resource units) of the three domains are depicted. It is noted that the use of weakly couple MCF is considered. Aligned with this architecture, the allocation of resources for each service request takes place in three consecutive phases: a) allocation of radio access resources, b) allocation of optical networking resources, c) allocation of MEC resources. A modular modelling design is adopted considering these three domains. In that manner, allocation is composed of three optimization phases, corresponding to the aforementioned three types of resources. These phases are executed sequentially and ensure optimal allocation of resources within each one of the respective domains. At this point, it needs to be clarified that the considered telecommunication system typically operates on an admission control basis. Hence, in case there are no sufficient resources available to be allocated to a requesting service, then the service is not admitted. In such a case, the service may have defined alternative descriptors which correspond to requests of lower specifications (e.g. lower resolution requiring reduced data rate), increasing their opportunity to be admitted.

In particular, the first allocation phase focuses on the over-the-air resources, which are directly assigned to the 5G mobile users. The key entities for radio access are the RRUs, which are placed at the edge of the network fronthaul and provide wireless communication slots to the User Equipment (UE). In line with the beamforming capabilities of the blueSPACE OBFN architecture, which allows simultaneous and independent transmission of multiple beams, each RRU is able to support multiple directed beams to provide high quality targeted coverage. The resource allocation scheme is responsible for assigning subchannels within specific beams to address the bandwidth requirements of the requested services. The translation from the requested data-rate and the allocated bandwidth is based on the characteristics of the extended NR numerology 4bs that blueSPACE introduces.

With the completion of the first allocation phase, the optical resource allocation phase is initiated. The blueSPACE architecture consists of a fully flexible ODN exploiting the cutting-edge capabilities of Spectrally Spatially Flexible Optical Networks (SS-FON) [32]. In this context, the allocator considers the spectral and/or spatial multiplexing features of the optical nodes for performing elastic switching [33]. The aim is to establish complete optical routes (lightpaths) from the radio access domain to the Central Office (CO). In particular, the output of the first phase is utilized to determine end-to-end fiber-based connections between BBUs (or Digital Units (DUs) in case of DRoF) and beams. The formulated optimization problem (a low complexity ILP) is able to model any type of network topology and provide optimal paths to dynamic demands according to the available optical domain resources. Power saving is achieved by minimizing the number of the optical elements used for building the required lightpaths.

The last allocation phase assigns MEC resources to the blueSPACE virtual Content Delivery Network (vCDN) and the Evolved Packet Core (vEPC). The services request MEC resources to offload computationally demanding tasks (such as real-time multimedia processing) and the allocator is responsible to make optimal decisions for the hosting of the required VM instances. The formulated ILP provides such a fast decision-making mechanism, while averting the scattering of allocated resources to numerous physical servers in order to conserve energy. Specifically, the goal of this process is the aggregation of allocations to MEC servers, towards minimizing the total required physical servers, hence, allowing the conservation of the overall energy used for computing tasks. In more detail, the respective analysis considers the defined specifications of the requested VM instances and the available physical MEC resources to perform optimal deployment of VMs to the existing servers,

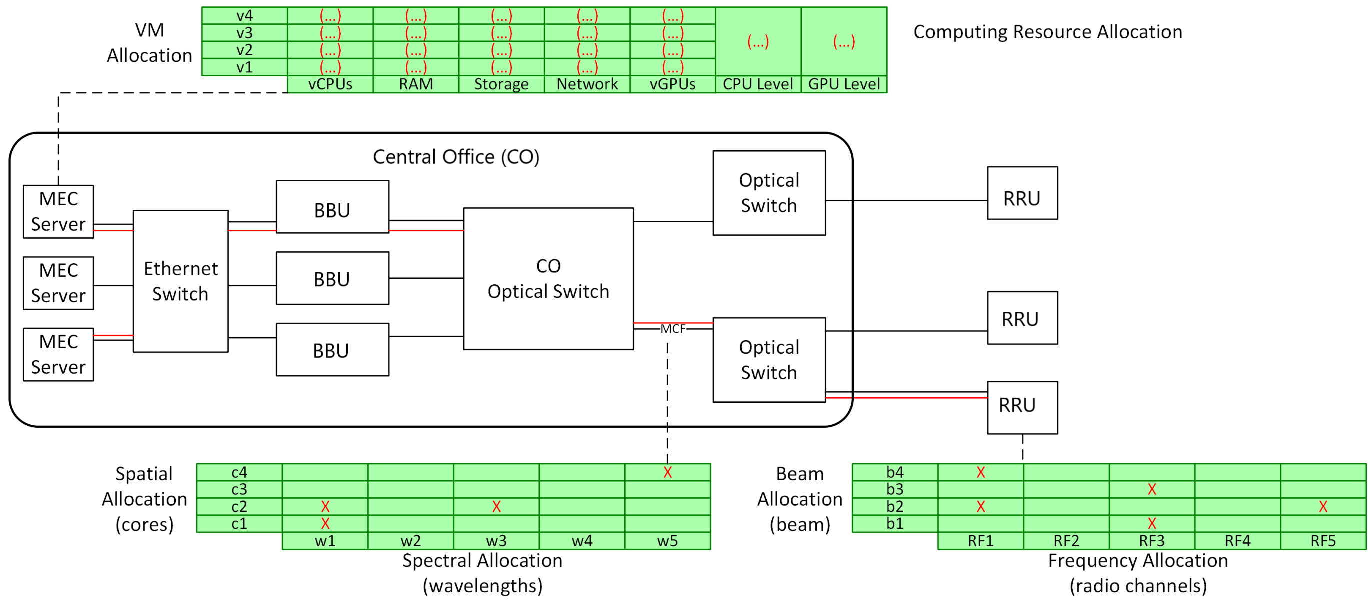

Fig. 8. Abstract resource architecture modelling for blueSPACE.

while fulfilling all related computing requirements (i.e. required CPUs, RAM, storage, data rate, and GPUs if any). Apart from the number of requested CPUs and GPUs (which are realized as virtual components), the CPU and GPU levels are also considered. The "Level of CPU" is a quantified identifier of the processing power of the specific CPU type. It is realized as an integer variable, where higher values indicate higher processing power. In the context of a MEC service request, it shows the minimum acceptable processing power that the virtual CPU of the deployed VM should possess. When characterising a MEC server, the CPU level indicates the processing power of the included CPUs. Similarly, the "Level of GPU" is a quantified identifier of the processing power of the specific GPU type. The decision variables of the formulated ILP are finally mapped to the output allocation slots that correspond to VM instances requested by services and are deployed in MEC servers. Since optimization is modelled as an integer linear problem, it exhibits lower complexity than the respective non-linear model (for instance, when the objective function is defined as a second degree polynomial representing variance), so it is allows dynamic allocations even for multi-dimensional resources. In specific, the size of each problem instance is set as the number of available physical servers by the number of VM instances required by a service request. This even allows simultaneous solving of the optimization problem for numerous concurrent requests. It is also noted that the problem size is eventually further reduced due to preprocessing which allows shortening sparse matrices. Indicatively, for the two simulation scenarios described next, the solving time was in the order of a couple of seconds in a computer with a first-generation Intel i7 920 CPU and 15 GB RAM. With the termination of this third phase, all required network and computing resources are fully allocated for serving dedicated enhanced Mobile Broadband (eMBB) slices.

The aforementioned resource allocation algorithms are implemented and simulated in MATLAB. For the evaluation process, two real-world simulation scenarios are considered to assess the allocation effectiveness and energy conservation capabilities for changing traffic requests. In more detail, we simulate a 5G deployment over a football stadium and another deployment over a city park. Specifically, in the first scenario, we simulate a topology of 35 4bs NR-enabled RRUs forming a ring and connected to a pool of 70 BBUs in total at the CO, through a PON which includes 1 central optical switch and 5 end optical switches of full spectral and spatial switching capabilities, and attached to 50 MEC physical servers. The park scenario assumes a topology of 4bs NR-enabled RRUs placed at the nodes of a 7-by-7 grid (49 nodes) and connected to a pool of 196 BBUs in total at the CO, through a PON which includes 1 central optical switch and 49 end optical switches of full spectral and spatial switching capabilities, and attached to 50 MEC physical servers. In both scenarios, the NSM receives a service request containing high-level service parameters (i.e the number of simultaneous users) and a geographical area, where the service should be available. The NSM uses this information to translate the request into NS instantiation request which contains: the computing resources required by the VNFs/MEC apps and the network resources required (including the resources required from the fronthaul optical path, and from the radio). During the simulations we considered varying service requests formed by a varying number of mobile users (up to 10,000) resulting in average requested data rate of about 16 Mbps, while each service request requires on average 2.5 VM instances of the MEC resources.

The results reveal that the developed algorithms succeed on allocating all radio, optical, and computing resources to all services. Furthermore, the energy efficiency capabilities of the introduced resource allocation are demonstrated in all domains, in comparison with a default unweighted allocation approach. In more detail, the benchmarking strategy considered in our work is based on the execution of the corresponding ILP (for each one of the three domains) without applying the introduced weighting scheme which ensures aggregation of the allocated physical resources. In that sense, the reference scheme performs allocation of available resources to fulfil the service requests without realizing the criteria for scattering avoidance. In that manner, we ensure fair evaluation, utilizing the same ILP modeling for the same inputs and the exact same infrastructure, assessing only the efficiency of the induced weighting scheme which enables physical resources aggregation towards conserving energy consumed by system physical assets (e.g. RRUs, antenna elements, optical switching elements, computing hardware elements). Specifically, in the "Stadium" scenario we achieve 50% savings in activated RRUs and beams, while in the "City Park" scenario this metric reaches 67%. In respect to the allocation of optical networking resources, our optimization approach achieves conservation of up to 11% of optical ports and 14% of optical cores. The corresponding results for the "City Park" scenario are 9% and 16%, respectively. Lastly, regarding the MEC resource allocation, the conducted simulations in the context of the "Stadium" scenario have shown 22% average reduction of the activated physical MEC servers (reaching up to 38%), while in the "City Park" scenario these savings average even higher to 68% (reaching up to 91%).

5. CONCLUSIONS

This article provides an in-depth description of the challenge the 5G adoption, and details the technological means to overcome these limitations with a novel fronthaul optical infrastructure. The results 3 for the setup described in 2 confirm the functionality of the setup and at the same time asses the viability of ARoF fronthaul with optical heterodyning for mm-wave upconversion. We also prove that is possible to further maximize the centralization and at the same time remove the need for any reference signal at the RRU by remotely feeding the LO required for the electrical down conversion of the received signal.

Furthermore, we present a enhanced NFV platform service which is tightly coupled with this new 5G optical fronthaul and at the same time allows to embrace MEC apps and PNFs as part of the orchestration ecosystem. We foresee this enhanced platform as the enabler for the 5G network service adoption.

6. ACKNOWLEDGMENTS

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REFERENCES

1. T. Pfeiffer, "Next generation mobile fronthaul and midhaul architectures," J. Opt. Commun. Netw. **7**, B38–B45 (2015).
2. I. Chih-Lin, H. Li, J. Korhonen, J. Huang, and L. Han, "RAN revolution with NGFI (xhaul) for 5G," J. Light. Technol. **36**, 541–550 (2017).
3. R. Muñoz, R. Vilalta, J. M. Fàbrega, L. Rodríguez, R. Martínez, R. Casellas, G. Landi, and M. Capitani, "blueSPACE's SDN/NFV architecture for 5G SDM/WDM-enabled fronthaul with edge computing," in *2018 European Conference on Networks and Communications (EuCNC),* (IEEE, 2018), pp. 403–9.
4. S. Rommel, D. Perez-Galacho, J. M. Fabrega, R. Muñoz, S. Sales, and I. T. Monroy, "High-capacity 5G fronthaul networks based on optical space division multiplexing," IEEE Transactions on Broadcast. **65**, 434–443 (2019).
5. "ETSI GS NFV-MAN 001 V1.1.1, Network Functions Virtualisation (NFV); Management and Orchestration," .
6. G. Bernini, M. Capitani, G. Landi, and G. Carrozzo, "End-to-end network slicing and orchestration in 5G infrastructures with SDM-based fronthaul," in *OSA Advanced Photonics Congress (AP) 2019 (IPR, Networks, NOMA, SPPCom, PVLED),* (Optical Society of America, 2019), p. NeT1D.3.
7. GSM Association, "Mobile backhaul options: spectrum analysis and recommendations," (2018).
8. W. Klaus, B. J. Puttnam, R. S. Luís, J. Sakaguchi, J. M. Delgado Mendinueta, Y. Awaji, and N. Wada, "Advanced space division multiplexing technologies for optical networks," J. Opt. Commun. Netw. **9**, C1–C11 (2017).
9. T. Nikas, E. Pikasis, and D. Syvridis, "Static skew compensation in multi core radio over fiber systems for 5G mmwave beamforming," in *2018 Photonics in Switching and Computing (PSC),* (2018).
10. M. Morant, A. Trinidad, E. Tangdiongga, T. Koonen, and R. Llorente, "Experimental demonstration of mm-wave 5G NR photonic beamforming based on ORRs and multicore fiber," IEEE Transactions on Microw. Theory Tech. **67**, 2928–2935 (2019).
11. S. Rommel, J. M. Delgado Mendinueta, W. Klaus, J. Sakaguchi, J. J. Vegas Olmos, Y. Awaji, I. Tafur Monroy, and N. Wada, "Few-mode fiber, splice and SDM component characterization by spatially-diverse optical vector network analysis," Opt. Express **25**, 22347–22361 (2017).
12. 3GPP TS 38.211, "NR: Physical channels and modulation," (2017).
13. blueSPACE, "D2.2 – physical architecture, system and network requirements," https://bluespace-5gppp.squarespace.com/s/D22-D8-Physical-architecture-system-and-network-requirements.pdf.
14. R. Muñoz, J. Fàbrega, R. Vilalta, M. S. Moreolo, R. Martínez, R. Casellas, N. Yoshikane, T. Tsuritani, and I. Morita, "SDN control and monitoring of SDM/WDM and packet transport networks for 5G fronthaul/backhaul," in *2018 IEEE Photonics Society Summer Topical Meeting Series (SUM),* (IEEE, 2018), pp. 151–152.
15. O. technical recommendation, "Functional requirements for transport API," ONF TR-527 (2016).
16. R. Muñoz, R. Vilalta, J. Fàbrega, R. Casellas, R. Martínez, N. Yoshikane, T. Tsuritani, and I. Morita, "SDN/NFV control and orchestration for SDM networks," in *2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC),* (IEEE, 2019), pp. 1–3.
17. R. Vilalta, R. Muñoz, G. Landi, L. Rodriguez, M. Capitani, R. Casellas, and R. Martínez, "Experimental demonstration of the blueSPACE's NFV MANO framework for the control of SDM/WDM-enabled fronthaul and packet-based transport networks by extending the TAPI," in *2018 European Conference on Optical Communication (ECOC),* (IEEE, 2018), pp. 1–3.
18. "TAPI AROF and DROF extensions," https://github.com/CTTC-ONS/bluespace/tree/master/TAPIext. Accessed: 2019-06-28.
19. "TAPI SDM extensions," https://github.com/CTTC-ONS/SDM/. Accessed: 2019-10-25.
20. J. M. Fabrega, R. Muñoz, M. S. Moreolo, R. Casellas, L. Nadal, R. Martinez, R. Vilalta, and F. J. Vilchez, "Hybrid WDM/SDM mobile fronthaul traffic delivery using SDN-enabled sliceable bandwidth/bitrate variable transceivers," in *2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB),* (IEEE, 2018), pp. 1–5.
21. "Bvt data model," https://github.com/CTTC-ONS/BVT. Accessed: 2019-10-25.
22. "Apache license 2.0," https://www.apache.org/licenses/LICENSE-2.0.
23. "Nextworks timeo," https://github.com/nextworks-it/timeo.
24. "ETSI GS NFV-IFA014 (V2.3.1): Network Functions Virtualisation (NFV) Release 2; Management and Orchestration; Network Service Templates Specification," .
25. G. Landi, P. Giardina, M. Capitani, K. Kondepu, L. Valcarenghi, and G. Avino, "Provisioning and automated scaling of network slices for virtual content delivery networks in 5g infrastructures," in *Proceedings of the Twentieth ACM International Symposium on Mobile Ad Hoc Networking and Computing,* (ACM, 2019), pp. 397–398.
26. "ETSI GS MEC 003 v2.1.1: Multi-access edge computing (MEC); framework and reference architecture," .
27. C. Casetti, C. F. Chiasserini, T. Deiß, P. A. Frangoudis, A. Ksentini, G. Landi, X. Li, N. Molner, and J. Mangues, "Network slices for vertical industries," in *2018 IEEE Wireless Communications and Networking Conference Workshops (WCNCW),* (IEEE, 2018), pp. 254–259.
28. "Nextworks slicer," https://github.com/nextworks-it/slicer.
29. G. Landi, P. Giardina, M. Capitani, K. Kondepu, L. Valcarenghi, and G. Avino, "Provisioning and automated scaling of network slices for virtual content delivery networks in 5G infrastructures," in *Proceedings of the Twentieth ACM International Symposium on Mobile Ad Hoc Net-*

working and Computing, (ACM, New York, NY, USA, 2019), Mobihoc '19, pp. 397–398.

30. R. Muñoz, J. M. Fàbrega, R. Vilalta, R. Casellas, L. Nadal, R. Martínez, M. S. Moreolo, M. Capitani, G. Landi, S. Rommel, I. T. Monroy, G. Otero, J. D. López, C. Vázquez, D. Larrabeiti, D. Sánchez, and E. Grivas, "SDN/NFV 5G fronthaul networks integrating analog/digital rof, optical beamforming, power over fiber and optical SDM technologies," in *2019 European Conference on Networks and Communications (EuCNC),* (2019), pp. 459–463.
31. P. Sarigiannidis, T. Lagkas, S. Bibi, A. Ampatzoglou, and P. Bellavista, "Hybrid 5G optical-wireless SDN-based networks, challenges and open issues," IET Networks **6**, 141–148 (2017).
32. M. Klinkowski, P. Lechowicz, and K. Walkowiak, "Survey of resource allocation schemes and algorithms in spectrally-spatially flexible optical networking," Opt. Switch. Netw. **27**, 58–78 (2018).
33. D. Klonidis, F. Cugini, O. Gerstel, M. Jinno, V. Lopez, E. Palkopoulou, M. Sekiya, D. Siracusa, G. Thouénon, and C. Betoule, "Spectrally and spatially flexible optical network planning and operations," IEEE Commun. Mag. **53**, 69–78 (2015).