Network Slicing in Fiber Wireless Fronthaul for 5G Networks

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Abstract— **Network slicing is a key feature of 5G networks to realize the vision of tailored quality characteristics per service or application over a shared physical infrastructure. This is challenging considering the various network segments involved, and the plethora of networking technologies that are used. In our work, we propose the joint allocation of fiber and wireless (FiWi) resources in the fronthaul, from massive Multiple-Input and Multiple-Output (mMIMO) antennas and Time and Wavelength Division Multiplexed Passive Optical Networks (TWDM-PONs). In this way, a network slice is composed of a virtual PON that is a wavelength shared over time from the Optical Line Terminal (OLT) to a set of Optical Network Units (ONUs) and a number of antenna elements controlled by the ONUs to transmit a beam towards a small cell or an end-device. The respective problem is formulated as an Integer Linear Programming (ILP) and simulation experiments are performed to illustrate the benefits and the trade-offs of the joint allocation of the FiWi resources.**

Keywords—5G, network slicing, Fiber-Wireless, PON, mMIMO

I. INTRODUCTION

5G networks are set to address the demands of a fully connected and mobile society, enabling a wide variety of applications over the same physical infrastructure, fulfilling their strict and heterogeneous requirements [1]. They are expected to carry 45 % of the total mobile traffic, while serving up to 65% of the world's population [2]. To unlock the full potential of 5G services, a flexible network operation is required.

Network slicing is a key enabler for the realization of the desired flexibility in 5G networks. In network slicing [3], the network is divided into multiple virtual networks called slices, which are multiplexed over the same physical infrastructure, with each one providing an isolated end-to-end virtual network. Thus, each slice serves the demands of a particular usage scenario, while the slices' performance requirements can vary significantly. For example, a network operator can provide a dedicated slice for handling applications like Internet of Things, autonomous driving or telemedicine, while in a multi-tenant scenario, the slices can be leased from the infrastructure provider to different virtual network operators.

A number of wired and wireless networking technologies have been proposed for serving traffic from the operators' Central Office to the end-device. In the wireless domain, operators plan to make use of optical beamforming and massive Multiple-Input and Multiple-Output (MIMO) antennas that transmit over the mmWave bands, in order to increase network efficiency [4]. Massive MIMO (mMIMO) antennas, equipped with a large number of radio antenna elements are capable of transmitting beams of different pattern, performance and characteristics, tailored to the user needs, minimizing network interference, utilizing just enough of the available MIMO antenna resources. In the wired domain, Time and Wavelength Division Multiplexed Passive Optical Networks (TWDM-PONs) are a candidate solution to transport efficiently the increased fronthaul traffic generated by the 5G wireless access network [5]. In that case, the data are transmitted over an optical distribution network that consists of WDM multiplexers/demultiplexers and optical splitters. In a TWDM-PON transport network, Optical Network Units (ONU) transmit at specific wavelengths and time slots, assigned by the Optical Line Terminal (OLT). Lastly, the notion of virtual PONs (VPONs) has also been proposed [6] for isolation and quality of service purposes. In that case a wavelength is assigned to one or more ONUs, depending on the requirements of the carried traffic.

The importance of optimizing the resource usage both in the wireless and wired domain in 5G and beyond networks is boost by the Centralized Radio Access Networks (C-RAN). In that architecture, the execution of the baseband processing is moved from the antenna site, called the Remote Radio Unit (RRU) to a centralized Baseband Unit, namely the BBU, while other functional splits and more hierarchical architectures are also possible [7]. Common Public Radio Interface (CPRI) and enhanced CPRI (eCPRI) define an interference and provide specifications for transferring information from the RRU to the BBU.

In our work, we formulate the network slicing problem in the Fiber - Wireless (FiWi) fronthaul, in which the resources from the wavelength, radio, and time domains over the different network segments are jointly allocated to form a network slice. Towards this end, we propose an optimal Integer Linear Programming ILP algorithm for beam-based slicing in 5G networks. It makes use of mMIMO antennas in the wireless part and virtual TWDM PONs to transport the CPRI/eCPRI signals. Thus, a slice is assigned to a V-PON, with the V-PON wavelengths being shared among the slices and end to the desired ONU's, which in turn control specific antenna elements of the mMIMO antennas to finally form the beams of specific pattern towards the destination point. The created network slices are able to fulfil the diverse requirements in terms of bandwidth or/and latency as requested by a particular application or a

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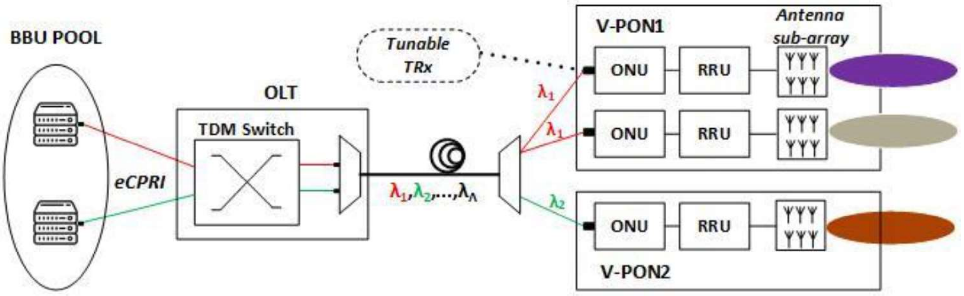

Figure 1. Fronthaul network model, consisting of a TWDM PON and massive MIMO antennas.

virtual network operator, making efficient use of the network's infrastructure resources and reducing cost.

The rest of our work is organized as follows. In Section II we comment on the related work. In Section III we describe the network model under consideration. In Section IV we present the problem formulation and the respective ILP mechanism, while simulation results are discussed in Section V. Finally, our work is concluded in Section VI.

II. RELATED WORK

A number of research works and network slicing methodologies have been proposed, assuming generic models of the underlying infrastructures. The authors in [8] describe some of the challenges in network slicing, viewing a slice as a virtual network on top of the physical infrastructure. In [9], the authors coordinate the reservation of computing and networking resources among different network flows so as to minimize queuing latency. In [10] a hierarchical edge cloud fronthaul slicing framework is proposed that considers jointly bandwidth and computing resources, so as to satisfy the latency constraints of the demands. The authors in [11] studied the virtual network embedding problem in a generic formulated Fiber-Wireless (FiWi) network. In [12], the problem of joint resource fiber wireless resource allocation in a TWDM-PON based fronthaul architecture is studied. The authors propose a time-slot model for the sharing of the wireless resources and interference mitigation. In our work we consider a different model of the mMIMO resource performing sub-band allocation to serve the static demands considering also different modulation schemes and their respective reach.

FiWi fronthaul networks are usually based on Passive Optical Networks (PONs) and a variety of wireless technologies, like WiFi, WiMAX, LTE and 5G. PONs provide high capacity, flexible resource allocation and low cost implementations. 5G networks will increase the provided capacity, mainly through the utilization of the mmWave and Multiple-Input Multiple-Output (MIMO) communication schemes [13].

The slicing of the radio resources of the fronthaul infrastructure is a challenging task considering the inherently shared nature of the medium. The respective mechanisms have to decide the appropriate slices for serving the demands, to enforce these slices in practice and minimize the interference between them. [14] surveys cellular network sharing and also presents a spectrum sharing method to achieve radio access network (RAN) virtualization. In [15], the authors present a number of RAN slicing approaches and evaluate them in terms of the granularity used in the assignment of radio resources and the achieved isolation and customization. [16] shows that the RAN slicing enforcement problem is NP-hard and presents a number of approximation algorithms. In [17], a network virtualization substrate is proposed, based on a slice scheduler that allocates radio resources to the tenants, and a flow scheduler that schedules data transmission for the users in each network slice. [18] describes a network slicing scheme for cloud radio access networks, consisting of macrocells overlaid with small-cells.

Passive Optical Network (PON) are used to transfer traffic between a BBU pool and multiple RRUs through shared fibers [19]. The authors in [20] propose a bandwidth allocation scheme for converged 5G mobile fronthaul and IoT networks on a TDM-PON. [21] proposes a unified control and network-slicing architecture for a multi-vendor multi-standard PON-based 5G fronthaul network and experimentally demonstrate its flexible resource management and slicing capability. In [22] bandwidth allocations mechanisms are presented for enabling PON multi-tenancy. Authors in [23] investigate how TWDM PONs that are logically-separated in Virtual PONs (VPONs) can serve different types of traffic by either assigning each type to a separate VPON or by aggregating different types of traffic in the same VPON. [24] proposes a hybrid cloud-fog radio access network (RAN) architecture and presents mechanisms for the joint BBU placement and the formation of VPONs over TWDM PONs.

Most of the above works however, either consider only the wired or wireless part of the mobile fronthaul or consider them both but separately. In order to achieve higher flexibility and better resource utilization in mobile fronthaul network slicing, the resource allocation mechanisms developed should consider the respective wired and wireless resources jointly. This is the focus of our work where the slicing of a PON in virtual PONs and the radio slicing operations are performed jointly.

III. NETWORK MODEL

A. Overall Model

Our network model is based on a converged computing and networking infrastructure that operates in the mobile fronthaul (Figure 1). We consider a Centralized Radio Access Network (C-RAN) architecture were all the baseband processing is performed in the BBU. A Time and Wavelength Division Multiplexed Passive Optical Network (TWDM-PON) is used to transfer the fronthaul traffic between the BBU and the remote radio units (RRU). The wireless part of the 5G fronthaul consists of RRUs equipped with massive MIMO (mMIMO) antennas.

In TWDM-PONs, each ONU is served by a dedicated wavelength for downstream and upstream traffic. We assume that the traffic carried by each wavelength is served by a BBU, that possesses particular performance characteristics (e.g., in terms of computation capacity). Different ONUs can also be served by the same wavelength over different time periods, turning off the linecards of the unused wavelengths in the OLT. The sharing of wavelengths between ONUs over time, is part of the optimization problem that will be formulated in Section IV. Each set of ONUs that share the same wavelength in a TDM manner, form a Virtual PON (VPON), served by a particular BBU. We also assume that the OLT and ONUs' transceivers are based on tunable lasers and modulators with typical supported transmission rates ranging from 10 to 50 Gbps and transmission reaches that vary between 20-60 km [25]. The configurations in ONUs, OLT and the optical distribution network to support the formation of VPONs can be performed in a Software Defined Networking (SDN) manner.

RRUs are connected to mMIMO antennas, which are composed of large arrays of antenna elements that transmit beams of different pattern based on the active antenna elements. Beam-steering refers to the capability to direct the electromagnetic wave radiated/received from/to an antenna to a desired direction and beamforming is probably the best-known beam-steering method. To form a beam of specific pattern and direction and serve a user device, the beamforming technique controls the phase and relative amplitude of the signal at each selected antenna element, while utilizing a specific sub-band.

The use of beamforming enables the mMIMO antenna to transmit different data to different recipients at the same time, thus practically increasing network capacity by a factor equal to the number of beams transmitted in parallel. As a result, the wireless capacity increases without the use of extra spectrum. Additionally, in order to lower the antenna's cost, the radio antenna elements can be grouped into the so-called antenna subarrays, each one controlled by a radio chain that drives the generation of a beam with particular characteristics (direction, phase, amplitude). Multiple subarrays can also be clustered to provide a beam that serves a particular end-device. Thus, the transmission reach of the resulting beam is increased, decreasing at the same time the angle coverage and also the interference to other beams. This introduces an interesting trade-off between antenna subarrays interference and transmission reach.

Overall, in our network model a FiWi network slice consists of a VPON and a set of antenna subarrays. Such a slice has the following particular characteristics:

- a VPON utilizes one or more ONUs
- an ONU is connected to a single RRU
- antenna elements are grouped into an antenna subarray
- a RRU drives a set of antenna elements in a mMIMO antenna, that is a subarray
- one or more subarrays create(s) a beam
- an end-device is served by one or more beams

B. *mMIMO antenna architecture and beam's transmission rate*

The maximum number of beams that a mMIMO antenna can transmit in parallel depends on the number of the antenna sub-arrays and thus the number of radio chains it is equipped with. In cases where there is a need for higher transmission rates to serve a demand with a beam, more than one antenna subarrays can be allocated. The antenna elements of these subarrays are used to create narrower beams and transmit at longer distances, utilizing the same sub-band.

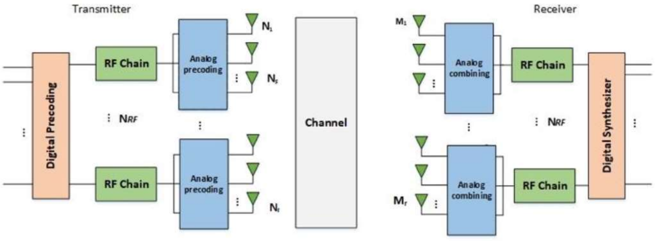

Figure 2. The block diagram of a mMIMO beamforming transmitter/receiver.

Figure 2 illustrates the elements that make up a mMIMO beamforming antenna system. The transmitter consists of N_t antenna elements that are divided into several analog antenna sub-arrays, where each antenna sub-array includes N_s antenna elements and is connected to an RF chain. Each subarray is connected to a baseband processor via a digital-to-analog convertor (DAC) in the transmitter or an analog-to-digital convertor (ADC) in the receiver.

To avoid high interference among neighboring beams, the allocation of antenna sub-arrays to beams must be performed carefully. A beam transmitted from an antenna at node n to an antenna placed at node m is subject to interference caused: (i) from other beams that are transmitted from an antenna at m, (ii) from other beams that are received at the antenna at n, (iii) from beams sent by neighboring nodes of antenna at n and (iv) by Additive White Gaussian Noise.

For a mMIMO transmission with beamforming between antennas placed at node n and m respectively, the achievable transmission rate is:

$$r_{n,m}(W) = W * log_2\left(1 + \frac{P_{n,m}\left|(w^r_{n,m})^H H_{n,m} w^t_{n,m} g_{n,m}\right|^2}{I_{n,m} + W \cdot N_0}\right) \quad (1)$$

where $w^r_{n,m}$ and $w^t_{n,m}$ are the receiver and transmitter beamforming vectors, $H_{n,m}$ is the channel matrix, $g_{n,m}$ is the pathloss, $I_{n,m}$ is the interference power that the beam between antennas at nodes n and m is subject to, N_0 is the power spectral density of the Additive White Gaussian Noise and W is the sub-band spectral width over which the transmission is performed.

Assuming that the channel matrix remains constant during the transmission and that the beamforming matrices are known to the transmitter and receiver before the transmission, the interference terms $I_{n,m}$ are not properly matched to the channel matrix $H_{n,m}$. As a result, we can assume that when $I_{n,m} \leq I_{limit}$, where I_{limit} is an upper bound on the acceptable interference, the interference factor can be eliminated from Eq. (1).

IV. PROBLEM FORMULATION

To model the *FiWi slicing*, we represent the 5G network with a directed graph $G=(V, E)$. The set of nodes V describes the location of the different network elements that are placed in the network. Specifically, let the subsets $V_{BBU}, V_{ONU}, V_{RRU}, V_{UE} \subseteq V$ describe the set of nodes where the BBUs, ONUs, RRUs and user demands (UE) are placed respectively. The set of links E includes the possible connections between nodes equipped with transmitters and receivers either in the wireless or the optical domain. Each network link $e \in E$ is characterized by the physical distance l_e between the corresponding nodes.

We assume that a RRU, placed at node n, is equipped with a mMIMO antenna that consists of M antenna sub-arrays and can thus transmit simultaneously up to M beams in parallel, with the total power P_n of the RRU at node n, to be equally split among the antenna subarrays. We also assume that the available wireless spectrum is divided into F sub-band channels of equal width W. Each network slice $s \in S$ is described by the tuple $s=(B_s, h)$, where B_s is the set of beams that serve slice s and h the fronthaul bandwidth provided by the respective VPON.

The fronthaul bandwidth h required for uplink and downlink communication between the BBU-OLT and the ONU-RRU is specified by the eCPRI protocol, based on the II_D physical split [26]. Each beam $b \in B_s$ transmitted by one or more mMIMO antennas placed at nodes in set N_b, is described by the tuple $b=(s_b, h_b)$, where s_b is the number of the utilized antenna subarrays and h_b the fronthaul traffic of b. Note that it is possible a user device to be served by more than one antenna sub-arrays from antennas located at different nodes. In these cases, the same signal is copied and sent to the ONUs, a process that is is performed by the BBU. Then it is transmitted to the RRUs and the antenna radio elements. Let $R=\{R_1, \ldots, R_m\}$ be the set of the ONU-RRU pairs. Each ONU is equipped with a tunable transceiver that can transmit and receive at rate D. We also assume that the OLT of the TWDM-PON used to transport the fronthaul traffic supports a total of Λ wavelengths.

Let Q be the set of the demands, with each demand $q_n \in Q$ at node $n \in V_{UE}$ describing the required transmission rate. The network slices serve the demands by assigning part of their resources. Specifically, each slice s, consists of wired and wireless resources that include a VPON with a wavelength λ, the ONU-RRU pair(s) served by the VPON and the antennas' beam(s). Note that the offline scenario is examined, in which the demands are known in advanced. Such scenarios play a crucial role in ultra-dense environments in which the mMIMO antennas serve the small cell antennas. Such demanding environments can certainly not rely exclusively on fiber connections reaching every antenna, as this would require expensive new fiber deployment. Relying on both wireless and fiber-based fronthauling as two independent fronthaul approaches is the mainstream solution, with the bandwidth and latency requirements of extreme cell densification to benefit from their cooperative and synergistic use.

In what follows, we present the problem formulation for the FiWi slicing. The objective function used, considers both the number of served demands and the utilization of the wavelengths and antenna subarrays. To reduce the search space and make our calculations faster we use a pre-processing phase. In this phase we calculate the set B with the possible antenna configurations b that can be used to transmit beams and serve each request q. For this purpose, for the antennas $\tau_{a,b}$ that are used by configuration q, we use Eq. (1) to calculate the number of the required antenna subarrays that form the beam and transmit with the demanded rate utilizing $g_{a,b}$ antenna sub-arrays from the antenna placed at $a \in V_{RRU}$. Next, based on all the possible beam configurations B, for every pair of beams $b, b' \in B$ we calculate the interference parameter $I_{b,b'}$. This parameter takes under consideration the physical distance of the antennas, the direction of the beams b and b', and the transmitting power of the beam in order to calculate the interference parameter which is used to keep the interference at acceptable levels up to I_{limit} and prohibit the transmission of beams that result in high interference and QoS degradation.

Variables

$y_{q,b,f}$: Boolean variable equal to 1 if demand q is served with beam set $b \in B_q$, over sub-band f.

$x_{i,\lambda,b}$: Boolean variable equal to 1 if ONU-RRU pair i, uses wavelength λ to serve antenna beam b.

$\delta_{b,b'}$: Boolean variable equal to 1 if both beams b and b' are both active.

u_λ: Boolean variable equal to 1 if wavelength λ is used.

z_q: Boolean variable equal to 1 if demand q is served.

v: Total number of utilized antenna subarrays.

$$max \sum_{q \in Q} z_q - \left[\sum_{\lambda \in [1,\ldots,\Lambda]} u_\lambda + v \right]$$

Subject to the following constraints.

- Select at most one set of beams to serve the demand

$$\forall q \in Q, \sum_{b \in B_q} \sum_{f \in [1,\ldots,F]} y_{q,b,f} \leq 1 \tag{C1}$$

- Limit interference from neighboring beams

For each pair of beams $b, b' \in B$, with $b \neq b'$ and $q \neq q'$:

$$\delta_{b,b'} \geq \sum_{q \in Q} \sum_{f \in [1,\ldots,F]} y_{q,b,f} + \sum_{q \in Q} \sum_{f \in [1,\ldots,F]} y_{q,b',f} - 1 \tag{C2}$$

$$\delta_{b,b'} \geq \sum_{q \in Q} \sum_{f \in [1,\ldots,F]} y_{q,b,f} + \sum_{q' \in Q} \sum_{f \in [1,\ldots,F]} y_{q',b',f} - 1 \tag{C3}$$

$$\sum_{b,b' \in B} \delta_{b,b'} \cdot I_{b,b'} \leq I_{limit} \tag{C4}$$

- Antenna sub-array allocation

$$\forall a \in V_{RRU}, \sum_{q \in Q} \sum_{b \in B} \sum_{f \in [1,\ldots,F]} y_{q,b,f} \cdot g_{a,b} \leq M \tag{C5}$$

-Total sub-band allocation constraint

$$\forall a \in V_{RRU}, \sum_{b \in B} \sum_{f \in [1,\ldots,F]} y_{q,b,f} \cdot \tau_{a,b} \leq F \tag{C6}$$

-ONU and wavelength allocation for each beam

$$\forall b \in B, \sum_{q \in Q} \sum_{f \in [1,\ldots,F]} y_{q,b,f} \leq \sum_{i \in R} \sum_{\lambda \in [1,\ldots,\Lambda]} x_{i,\lambda b} \tag{C7}$$

- Wavelength capacity constraint that serves fronthaul traffic

$$\forall \lambda \in [1,..,\Lambda], \sum_{i \in R} \sum_{b \in B} x_{i,\lambda,b} \cdot h_b \leq D \quad \text{(C8)}$$

- Total number of utilized antenna subarrays

$$v \geq \sum_{q \in Q} \sum_{b \in B} \sum_{f \in [1,..,F]} y_{q,b,f} \cdot g_{a,b} \quad \text{(C9)}$$

- Served demands

$$\forall q \in Q, b \in B, f \in [1,..,F], z_q \leq y_{q,b,f} \quad \text{(C10)}$$

- Utilized wavelengths

$$\forall i \in R, l \in [1,\ldots,\Lambda], b \in B, u_\lambda \geq x_{i,\lambda,b} \quad \text{(C11)}$$

The objective used in the aforementioned problem formulation maximizes the number of the served demands with the minimum network resources. It is closely related to the revenue maximization, when considering the revenue generated by the served demands and the expenses related to the use of the network resources.

Constraint 1 is used to ensure that one at most of the possible beam combinations is used to serve the demand. Constraints (2), (3) are used to calculate the pair of active beams and then constraint (4) is used to ensure transmission with acceptable interference. Constraints (5), (6) are related to the antenna capabilities installed at each node and limit both the available number of antenna subarrays and the total power that is divided among the active beams. Constraints (7), (8) are used to ensure that only one ONU-RRU pair is used to serve a beam that is transmitted from a Base Station and the wavelength assigned to transport the fronthaul traffic has enough capacity. The rest of the constraints are used to calculate the number of served demands and antenna subarrays and wavelengths, which are used by the objective function.

V. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed FiWi Slicing methodology in comparison to the Static Slicing, in which antennas are connected to the BBU pool via a WDM PON network. In a WDM PON, each wavelength is statically assigned to an antenna and only its subarrays can be used to serve the demands. We implemented the proposed methodologies in Matlab and used it with the IBM ILOG CPLEX optimizer [27] to evaluate their performance. For our simulations, we considered a multi-cell scenario of 5 RRUs equipped with mMIMO antennas with each antenna divided to 8 subarrays. Each antenna subarray consists of 64 antenna elements and is controlled by an ONU. For our TWDM PON, we assumed a tree topology. The PON's OLT can handle up to 5 wavelengths, while the ONU is equipped with tunable transceivers that transmit at 50 Gbps.

We assume that the antennas are placed at distances that vary from 50 to 200 m and so there are cases where more than one antenna can be utilized to serve a demand. Each antenna is omnidirectional and creates beams with different sector degrees. Particularly, the sector degree can vary from 22.5 to 90 degrees, depending on the number of the combined antenna subarrays that are used to form a beam. The transmission is performed on the mmWave band and the sub-band channels have 400 MHz width. In order to calculate the achievable transmission rate over a specific distance, the Free Space Path Loss Model was used.

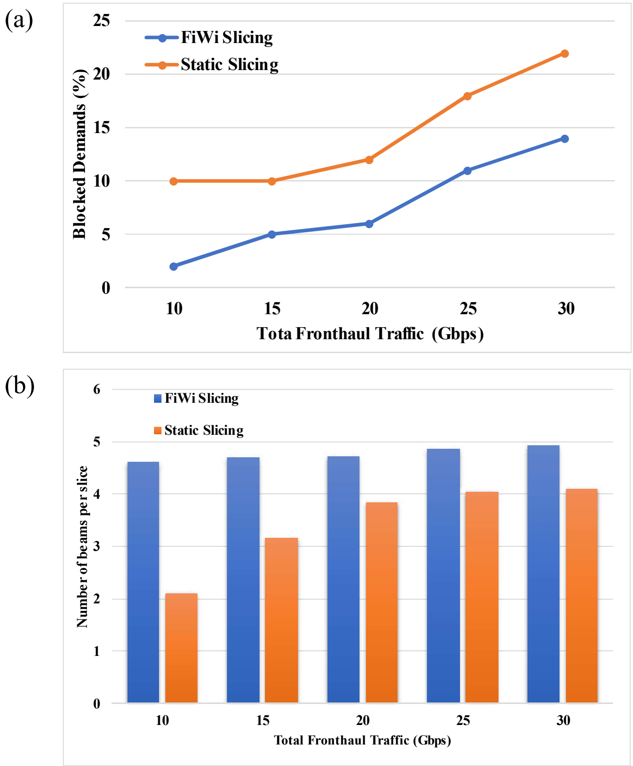

Figure 3. FiWi slicing versus Static Slicing regarding the number of (a) the blocked requests and (b) the number of beams that make up a slice.

For the fronthaul traffic, we considered offline demands with total traffic requirements up to 30 Gbps which are known in advance and drawn from the uniform distribution on the interval [0-2] Gbps, distributed uniformly among the antennas up to 100 m distance. For the eCPRI protocol traffic requirements, we assumed them to vary in the close interval [1-20] Gbps according to the demanded rate. We performed a number of simulations to examine the performance of the FiWi slicing approach that utilizes in a flexible manner both the PON wavelengths and the antenna resources to form slices that serve the demands.

Initially, as Figure 3 illustrates, we examined for the different offline traffic scenarios the blocking ratio performance for the two examined approaches. We observe that for low and medium traffic at each RRU site, the capacity of wavelengths is underutilized since a smaller number of beams are assigned to each slice. Moreover, in the static scenario each demand is served by only one antenna and consequently it lacks of the flexibility offered by a transmission that combines more than one antenna subarrays placed even at different nodes. For this reason, it uses more antenna sub-arrays to serve the demands with high rates that are placed at longer distances which results in higher blocking probability for all the examined cases.

To demonstrate the difference in the wavelength utilization, we present in Figure 3.b the average number of beams used to make up a slice. As we observe, the number of beams used in the FiWi slicing scenario is higher which leads to better slice utilization for all the examined traffic scenarios. At the same time, the static slicing uses more wavelengths, which are underutilized for low and medium traffic. As traffic increases, they end up with utilization close to the FiWi slicing, but WDM PON slice falls short in the number of the served requests. In all examined cases, the FiWi Slicing approach manages to achieve almost equal utilization of the wavelengths, for the different traffic scenarios. Thus, a smaller number of wavelengths is utilized, offering reduction in the cost of our approach compared to the static one. Note also that for high traffic their performance is close, which showcase the ability of the FiWi Slicing methodology to adapt better to the different traffic scenarios, an important requirement of 5G applications due to their heterogeneous characteristics.

VI. CONCLUSIONS

5G network slicing requires the proper reservation of computing and networking resources. In a C-RAN based network fronthaul these include BBU resources, network resources that connect BBUs to RRUs and radio resources. In our work, we assume the use of TWDM-PONs for the wired fronthaul BBU-RRU communication and massive MIMO antennas for the wireless part. We propose a methodology, namely FiWi Slicing that jointly allocates wired and wireless resources to form slices in the fronthaul as opposed to other works that usually consider them separately. The created network slices are composed of a virtual PON, assigning a wavelength from the OLT to a set of ONUs and matching each ONU to particular antenna elements of massive MIMO antenna that form a beam towards an end-device. A number of simulation experiments are performed that illustrate the benefits of the FiWi Slicing methodology in comparison to the static slicing, in terms of the number of offline demands served and the number of beams used. These results showcase that high efficiency is achieved by the joint allocation of wired (e.g., wavelengths) and wireless (e.g., antenna elements) resources for network slicing in a 5G fronthaul.

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