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5G/NGPON Evolution and Convergence: Developing on Spatial Multiplexing of Optical Fiber Links for 5G Infrastructures

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ABSTRACT

The offering of demanding telecommunication services as promised by the 5G specifications raise the necessity for high capacity, flexible, adaptive, and power conserving fronthaul. Toward this goal, the role of the passive optical network which is responsible for interconnecting the central office (CO) with the cell-sites is crucial. Among the latest related technologies that need to be integrated in the context of the next generation passive optical networks (NGPONs), the most promising for increasing the provided bandwidth, is the optical spatial multiplexing. In this paper, we present the key 5G technologies, focusing on spatial division multiplexing, which constitutes the main innovation of the blueSPACE 5G Infrastructure Public Private Partnership (5G PPP) project. Exploiting the recent developments on multicore fibers (MCFs), optical beamforming networks (OBFNs), analog radio over fiber (ARoF), and spatial-spectral resources granularity in the context of Spectrally Spatially Flexible Optical Networks (SS-FONs), we describe a complete approach for the 5G fronthaul, emphasizing on the efficient allocation of optical resources while aiming at minimizing energy consumption. The modeled optimization problem is thoroughly presented, and the introduced scheme is evaluated through a real-world based simulation scenario, exhibiting quite promising results.

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5G fronthaul; optical SDM; NGPON; ODN granularity; spatial and spectral dimensions; power saving optimization

1. Introduction

One of the key challenges for the modern telecommunication systems toward coping with the exponentially increasing demands is to efficiently integrate cutting-edge communication technologies. Undoubtfully, a bottleneck in the current telecommunication infrastructure can be found at the sector that interconnects the radio access domain to the network core, known as fronthaul. The adoption of high-performance fiber optical networking constitutes the only viable solution and is expected to play a leading role in building the future fronthaul infrastructure. At the access part of the system, the growing need for mobility and agility while wireless traffic keeps skyrocketing is now answered by New Radio (NR) [1] standards and modern radio access features, namely beamforming, millimeter wave links, small-cells, and massive Multiple Input Multiple Output (MIMO)

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transmissions. The seamless combination of the latest radio access and optical communication hardware technologies at the fronthaul domain along with the use of state-of-the-art network control and management techniques, such as Software Defined Networking (SDN) [2], are expected to enable covering the notably elevated requirements of the overall 5G vision.

Latest trends in network traffic set advanced requirements, due to its high-quality multimedia nature, the increased traffic variability, and the demand for real-time communications. The ability to effectively serve this kind of traffic by fulfilling its demanding specifications while conserving energy was considered until recently possible only for small-scale local area wireless networks, where mobility is not a key factor, so it is quite limited [3, 4]. However, the proliferation of highly capable mobile devices along with the tremendous growth of multimedia network services and the significant developments in video streaming quality have necessitated the full support of modern mobile network services, such as autonomous vehicles connective, which require significantly low latency. The 5G networks promise to cover all related requirements with their advanced specifications in terms of throughput and latency; however, this does not concern only the radio access part. Interconnecting the numerous mobile devices to the core network and efficiently driving the links through the fronthaul is an essential part of the overall architecture for the delivery of high-quality modern telecommunication services to vast numbers of users. Toward this goal, some very promising multiplexing techniques for managing fiber connections in Passive Optical Networks (PONs) have risen besides Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM), with the latest approaches being Ultra Dense WDM (UDWDM) and SDM (Space Division Multiplexing) in the context of the Optical Distribution Network (ODN) at the fronthaul domain [5], frequently combined with the very promising Analog Radio over Fiber (ARoF) technique.

Apart from the technical improvements in the telecommunication hardware infrastructure, the efficient provision of a variety of services with various requirements to numerous different types of users requires optimized network management and resource allocation [6]. In 5G systems, these tasks are performed through the orchestration of resources using SDN and Network Function Virtualization (NFV) that can provide efficient network slicing to support different services and users within the same infrastructure, as well as power saving schemes for lowering the overall energy consumption.

This paper summarizes 5G enabling technologies, focusing on the fronthaul optical domain. It presents new schemes for the realization of Next Generation Passive Optical Networks (NGPONs), emphasizing on the use of spatial multiplexing. Moreover, it discusses the respective solutions introduced by the blueSPACE (Building on the use of Spatial Multiplexing 5g Network Infrastructure) project [7, 8], emphasizing on the optimization of optical resource allocation and presenting related scenario results.

The rest of the paper is organized as follows. Section 2 discusses key enabling technologies for 5G systems, while Section 3 presents new solutions that elevate the SDM paradigm. The introduced resource allocation optimization scheme for the optical fronthaul is described in Section 4. This scheme is evaluated in Section 5, where related results are provided through a simulation scenario. Finally, Section 6 concludes the paper.

2. 5G enabling technologies

The enabling technologies for 5G systems aim at revolutionizing mobile user experience and allowing a totally new set of network services.

2.1. *Key features and KPIs*

5G features cover various parts of the system architecture, while Key Performance Indicators (KPIs) are mainly expressed in relation to the performance of existing 4G systems. Below, we have listed the main 5G features and we explain how they help or hinder the realization of the related KPIs. Each one of the features is described in the following list.

- CP-OFDM: Cyclic-Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) has deemed as one of the best candidate waveforms for NR, since it is able to support a large number of simultaneous transmissions while requiring low complexity transceivers from both ends.
- Massive MIMO: The use of MIMO schemes that rely on a large number of antenna elements at the base station (e.g. 64, 96, 128 or more) allows significant improvement of the available bandwidth for each user, increasing, however, the Total Cost of Ownership (TCO) regarding the telecommunication infrastructure (as with most state-of-the-art technologies).
- Beamforming: As a very promising technique for RF spatial selectivity, it can significantly increase bandwidth per user and per area.
- Shortened TTI: Shortening the Transmit Time Interval (TTI) leads to latency reduction, which constitutes a challenging 5G KPI.
- Flexible Band Sizing: This feature refers to the ability of 5G systems to operate in different parts of the sector. Sub-millimeter and millimeter wave bands are considered to allow sufficiently large portions of bandwidth.
- CoMP: Coordinated Multipoint (CoMP) is a very promising type of Cooperative MIMO, which enables the distributed processing of received signals and in that manner notable increase of bandwidth even in noisy environments.
- Small Cell: The adoption of cells of limited range (small cells or micro cells or femto cells) in 5G systems allows dense deployments which leads to higher quality links and bandwidth sharing among less subscribers.
- 5G-NR in Unlicensed: The use of unlicensed spectrum by 5G-NR can make even more bandwidth available and allow new types of services, such as local private 5G networks.
- C-RAN: Cloud Radio Access Network (C-RAN) architectures concentrate the BaseBand Unit (BBU) functionality in a BBU pool for centralized control
- NFV/SDN. The NFV and SDN techniques, as it is already discussed in the introduction section, provide flexible management through the softwarization of network resources, so they enable respective agile schemes, such as network slicing.
- MEC: Mobile Edge Computing (MEC) refers to the third type of resources (after radio and optical resources) that can be found in a 5G systems. It allows computing resources to be positioned in a flexible manner closer to the end user contributing in that way to the lowering of the overall experienced latency/

- Massive IoT: The Massive Internet of Things (Massive IoT) describes the huge number of IoT devices, which can be interconnected through the 5G infrastructure. The respective specifications set notably high density for IoT devices, which is many times higher than the standardized 4G devices' density.

From the operators' point of view, all these new features require significant investments; however, they promise high returns as they allow achieving the notably demanding 5G KPIs.

2.2. Converged 5G C-RAN network

The dominant architecture which is adopted for 5G systems is C-RAN [9], which actually integrates the radio access, fronthaul, and backhaul sectors of the telecommunications infrastructure. The Remote Radio Heads (RRHs) are the entities where the mobile devices are wirelessly connected. Over the PON of the ODN fronthaul, the collected traffic is delivered to the BBUs, which according to the C-RAN architecture are not co-located with the RRHs (traditional approach) but centrally implemented as a BBU pool at the consolidated Central Office (CO), following the Virtual Network Function (VNF) paradigm. In that manner, the system exhibits advanced scaling capabilities, since the fronthaul network resources can better adapt to dynamic traffic conditions.

In more detail, the CO, where the BBU pool is hosted, can support multiple services and utilized by multiple operators, while it may also host other optical networking entities, such as an Optical Line Terminal (OLT). Given that ODN is based on high capacity SDM, the CO equipment should be capable of serving many Tbps of network traffic. On the other end of the architecture, there are numerous terminal points that are interconnected to the CO through multiple passive Remote Nodes (RNs) that are parts of a dense ODN. The goal is to be able to reach each RRH with a dedicated fiber, as illustrated in Figure 1. This creates tremendous requirements in the deployment of very dense fiber links, which leads to the necessity of a next generation PON, capable of providing numerous optical resources.

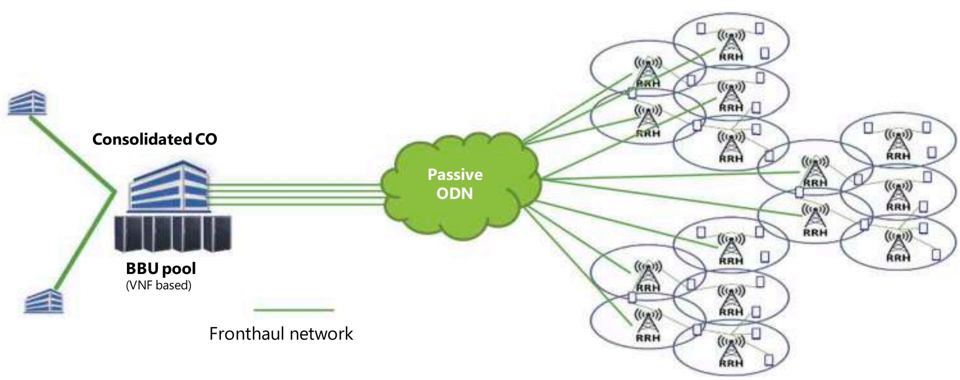

Figure 1. Consolidated C-RAN architecture.

2.3. Fronthaul design options – DRoF and ARoF

The C-RAN architecture allows the migration of the tasks traditionally processed at the RRH to the CO, lowering in that manner the overall complexity, energy consumption, as well as the experienced end-to-end delay. The approaches where the wireless data are processed at the baseband and are transmitted encoded over the optical fibers are known as Digital Radio over Fiber (DRoF). In 5G systems, DRoF solutions are packet-based and move away from the traditional Common Public Radio Interface (CPRI). The most promising new DRoF standards are the evolved CPRI (eCPRI) [10] and the Next Generation Fronthaul Interface (NGFI) [11] that allow advanced functional splitting. However, the DRoF solutions require Medium Access Control (MAC) layer processes to be added to at the Remote Radio Unit (RRU) sites with a notable impact on the overall cost, complexity, and power consumption. It is noted that the term RRH is also widely used in the literature to denote the exact same component that RRU represents, hence, in this work, the two terms (RRU and RRH) are used interchangeably.

The approach that essentially lifts the need for any processing task at the RRU site is the ARoF, since it allows the analog modulation of carriers with radio signals over fibers to the CO. This means that ARoF does not require any signal processing for line encoding and for converting the initial radio signals to baseband. As a result, the optical/electronic equipment at the RRU is simplified, lowering in that manner costs and consumed energy. Probably the most notable drawback of ARoF is its inability to maintain high performance when transmitting in long distances. Furthermore, the increase in radio bandwidth leads to more complex and costlier ARoF components. Figure 2 depicts the distribution of processing tasks in the DRoF and ARoF cases.

2.4. Fronthaul of 5G networks utilizing SDM solutions

The C-RAN architecture poses a heavy load on the fronthaul sector, since it centralizes all the baseband processes. Addressing this issue with traditional methods, such as CPRI, is not really an option, because they have low scalability for denser deployments, since they require tremendously high data rates even for limited radio bandwidth. Hence, as a very promising solution for the ODN rises the adoption of SDM-based techniques.

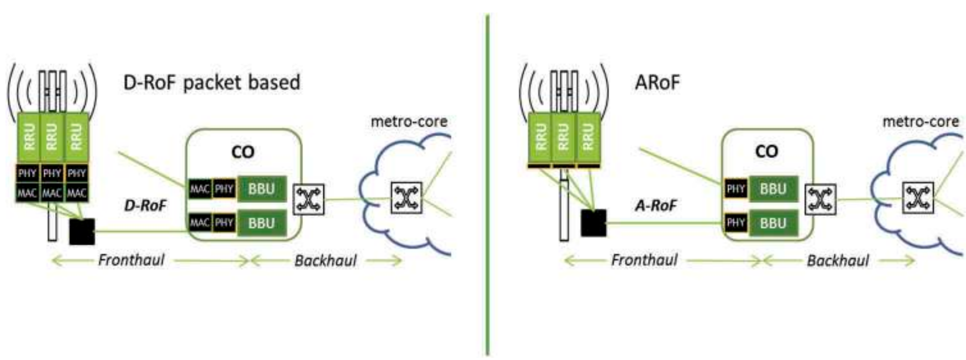

Figure 2. Processing tasks distribution in DRoF and ARoF.

2.4.1. *"Integrated fibers" for SDM-based optical networks*

As it becomes evident, the employment of SDM solutions for the ODN is crucial for the appropriate network dimensioning and the provision of adequate capacity for the 5G fronthaul. Regarding the various alternatives for the type of integrated fibers, there are three main spatial modes [12], which are listed below:

(1) "Uncoupled/Weakly-coupled" spatial modes for SDM: There are two types of supporting integrated fibers, namely the bundles of Single-Mode Fibers (SMFs) and the uncoupled Multi-Core Fibers (MCFs), as depicted in Figure 3.
(2) "Strongly coupled" spatial modes for SDM: There are two types of supporting integrated fibers, namely the strongly coupled MCFs and the Few-Mode Fibers (FMFs), as depicted in Figure 4.
(3) "Coupled spatial sub-groups" of modes for SDM: There are two types of supporting integrated fibers, namely the uncoupled groups of coupled-cores and the Few-Mode Multi-Core Fibers (FM_MCFs), as depicted in Figure 5.

It should be noted that bundle fibers can be considered as an extra multiplex hierarchy and allow they introduction of new optical elements that enable bundle splitting. Also, summarizing the characteristics of the different fiber types, it becomes clear that the main drawback of coupled fibers is the increased interference; however, this is not a major problem for the limited distances covered in the fronthaul.

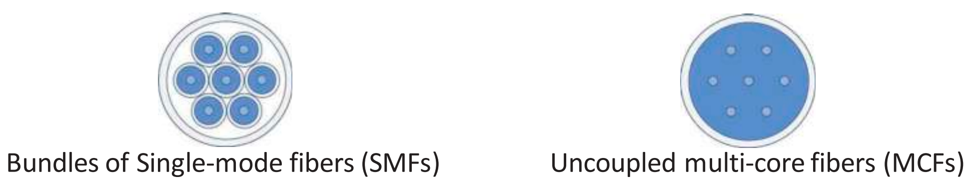

Figure 3. "Uncoupled/Weakly-coupled" spatial modes for SDM.

Figure 4. "Strongly coupled" spatial modes for SDM.

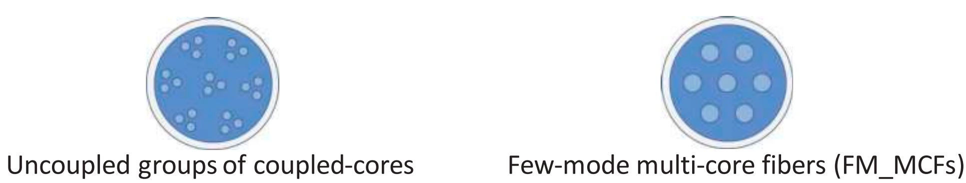

Figure 5. "Coupled spatial sub-groups" of modes for SDM.

2.4.2. *SDM-based ODN fiber types*

The most promising fiber types for supporting SDM in ODN are the MCFs and the Bundles of Single Mode Fibers (B-SMFs). The former type (MCF) may contain various numbers of cores, ranging from 2 to more than 30 cores, which can be coupled or uncoupled. MCF is considered a long-term option for SDM-based ODN, since it is a technology that has just recently entered the market. One of the key benefits it provides is the almost synchronized data among its cores. However, it suffers from scalability issues, in the sense it is difficult to be further extended to even higher core numbers.

On the other hand, SMFs constitute a mature technology that is widely available with deployments in most optical access networks. This is of course considered as a major advantage. Nevertheless, SMFs exhibit notable synchronization problems [13]. The delay variation among the different fibers may be significant, hence, it has to be closely examined. Specifically, the application of phase correction techniques is required for effectively handling those variations. At this point, it should be mentioned that a key difference in the case of B-SMFs is that the fibers are treated (i.e. switched) not separately, but as a single entity (known as joint switching).

3. Other optical technologies alongside SDM

SDM supports new forthcoming technologies such as flexible allocation of frequency resources, adaptive use of different Modulation Formats (MFs), and multi-carrier (super-channel, SCh) transmission [14–16]. The blueSPACE project adopts cutting-edge techniques to build on SDM and provide efficient solutions for the 5G optical fronthaul. On this ground, it focuses on the ARoF approach (while also supporting DRoF), where the BBUs generate baseband/Intermediate Frequency-over-Fiber (IFoF) Orthogonal Frequency Division Multiplexing (OFDM) NR signals for different target RF beams. In summary, we identify and build on three main technologies: (a) ARoF, which lowers latency and costs, (b) optical beamforming, which provides higher targeted datarate and/or coverage, and (c) SDM, which increases the multiplexing capabilities and the overall capacity.

3.1. *ARoF fronthaul and optical beamforming*

A promising strategy alongside SDM in 5G systems to provide higher bandwidth to targeted users/areas in a flexible way is optical beamforming. According to the related concept, the ARoF transmission bank modulates optical carriers with analog signals from BBUs and performs parallel transmission in fiber cores. The result is the formation of an Optical Beamforming Networks (OBFN) positioned in-between the CO and the cell-sites, which performs mapping of all inputs to all outputs, by properly introducing phase-shifts, as depicted in Figure 6. It is noted that in this scheme, the up-conversion of the RF signals takes place optically through a photodiode (PD) array rather than electronically.

3.1.1. *Comparison among different options for placement of the OBFN along the fiber link*

Regarding the exact placement of the OBFN, there are three main options: OBFN at CO site, OBFN at cell site before the receiver array (Rx), and OBFN at cell site after

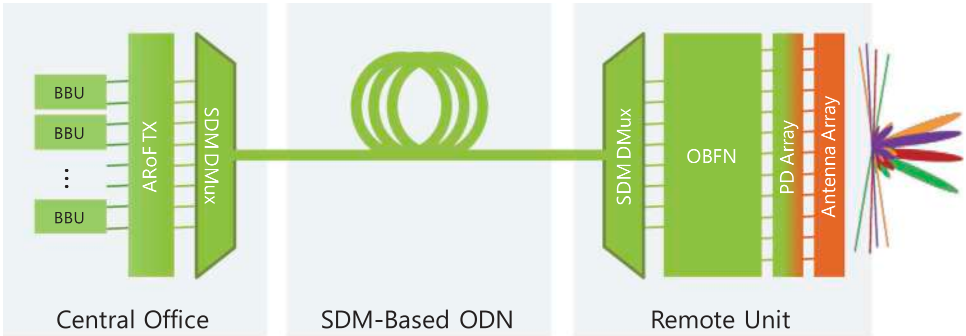

Figure 6. OBFN for the 5G fronthaul relying on SDM.

the receiver array (Rx). These placement options present different characteristics, advantages and limitations, which are listed in Table 1. For comparison purposes, we also include two beamforming options, the electronic beamforming (eBF) at the RRH and the electronic beamforming network (eBFN) at the RRH, which are electronic-based and not optical. As it can be seen, the key objective of low power consumption and low cell-site complexity (hence, low cost) is more satisfactorily achieved by placing the OBFN at the CO site. However, it should be noted that in case of unresolvable synchronization issues, the second and third options (OBFN at cell site before RN and OBFN at cell site after Rx) are the only viable solutions for optical beamforming.

3.1.2. *OBFN at CO site in detail*

At this point, we examine in more detail the first option of the OBFN placement (i.e. at the CO site), which seems to be the most promising for the 5G fronthaul, and schematically presented in Figure 7. Specifically, at the CO site, a number of data streams, with each one carrying the traffic for one beam of the same cell site, are generated, assigned a specific phase shift and split to all outputs of the OBFN element. Each OBFN output port is driven over a fiber/core of the ODN to a different antenna element of the destined RRH. At the cell-site, a simple opto-electronic array (PIN – TIA – PA) receives the transmissions, amplifies the signals and drives the antenna array. The phase shifts that the OBFN initially assigned cause a different beam for each data stream.

The key benefit of placing the OBFN at the CO site is the ability to keep the downlink receiver at the cell-site as simple as possible, just by utilizing an antenna array, amplifiers, and PDs. In that manner, the energy consumption is at the lower levels, compared to the other options. The most notable limitation of this approach is to keep the signals synchronized over the ODN, which is needed to keep the initially assigned phase shifts intact along the path to the cell-site. For that reason, it is necessary to adopt MCF connections, in order to keep the phase differences that are dynamically introduced while transmitting at the lowest levels. This objective, that is the efficient control of phase variations when using MCF connections for realizing this OBFN placement options, is open to further investigation.

Table 1. Comparison of beamforming placement options.

	OBFN at CO site	OBFN at cell site before Rx	OBFN at cell site after Rx	eBF at RRH	eBFN at RRH
Supported RoF scheme	ARoF	ARoF	ARoF & DRoF	ARoF & DRoF	ARoF & DRoF
Transmission over the fiber	RF (or IF + carrier)	RF (or IF + carrier)	IF or Baseband	IF or Baseband	IF or Baseband
Supported type of fiber links	MCF	M-SMF, MCF	M-SMF, MCF	M-SMF, MCF	M-SMF, MCF
Scalability of RRH deployment	Limited	Limited	Scalable	Fully scalable	Partial
Scalability of optical channels	Limited (technology advancements required)	Limited	Fully scalable	Fully scalable	Fully scalable
RRH complexity	Very low	Moderate	Moderate	High	Very high
Special technical requirements	Mitigating small sync mismatches	Polarization tracking	No	No	eBFN power, size and degradations
Main advantages	Cell-site simplicity Low Energy	Moderate cell-site simplicity	Better power budget Scalability Applicable in all cases	Tech maturity Scalability Applicable in all cases	Applicable in all cases
Main limitations	Synchronization works for ARoF with MCF links	Polarization tracking at cell-site	Added complexity at cell-cite	Cost, Energy	Cost, energy
Further investigations required	Sync correction SDM-MCF joint switching	Efficient polarization tracking	Low cost/energy electronic-optical-electronic conversion at cell-site	-	eBFN performance improvements

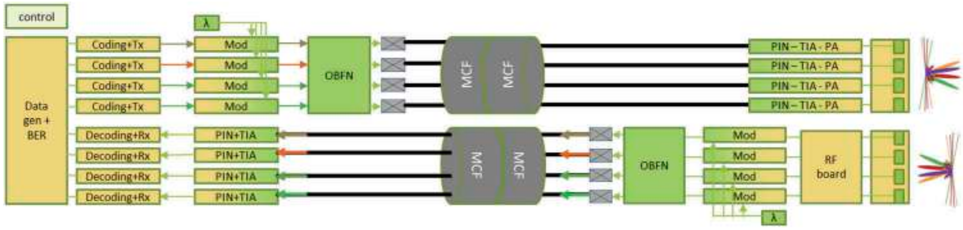

Figure 7. OBFN at the CO site end-to-end illustration.

3.2. *Dimensioning in ODN*

3.2.1. *ODN granularity levels for capacity allocation*

The realization of agile spatial multiplexing for the formation of an NGPON in the context of the 5G fronthaul exhibits its full potential when combined with wavelength and time multiplexing. This concept relies on the identification of different granularity levels along the ODN. In more detail, the coarsest granularity is found at the fiber duct and regards the space dimension. It represents the highest capacity granularity level which allows linear capacity increase by providing housing options. At the following level, the use of MCF links with SMF or FMF cores provides unbundling capabilities and increases the overall capacity. Next, the different SDM-based modes allow per user bandwidth increments. The wavelength dimension is found at the following granularity level and provides further multiplexing capabilities for supporting separation of different data streams as well as duplexing. The finest granularity is found when breaking down each wavelength in multiple time slots, under the condition of course that the supported transmissions digital. As it becomes evident, the finer the granularity gets, the more detailed bandwidth allocation can become to match specific service demand. The aforementioned granularity levels are graphically depicted in Figure 8.

3.2.2. *Space and spectrum dimensions in ODN*

The combination of spatial and spectral dimensions provides several possibilities in network design given the multiple options in allocating resources. An overall goal (and a key objective for the blueSPACE project) is the provision of resource allocation agility in network planning according to the deployment area and the specific usage scenario.

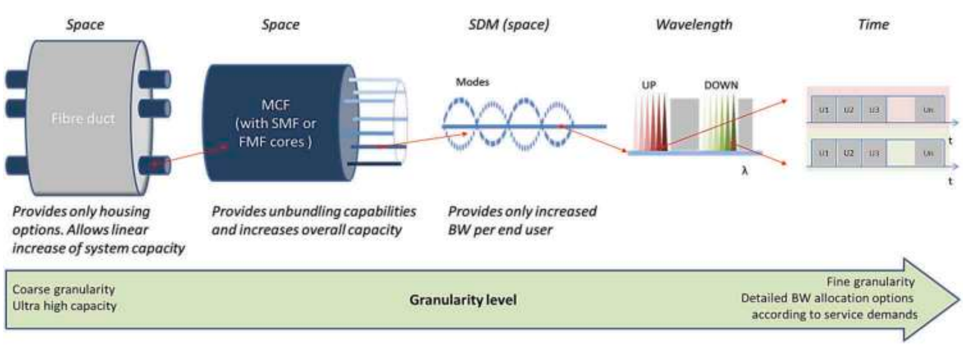

Figure 8. Granularity levels along SDM-based ODN.

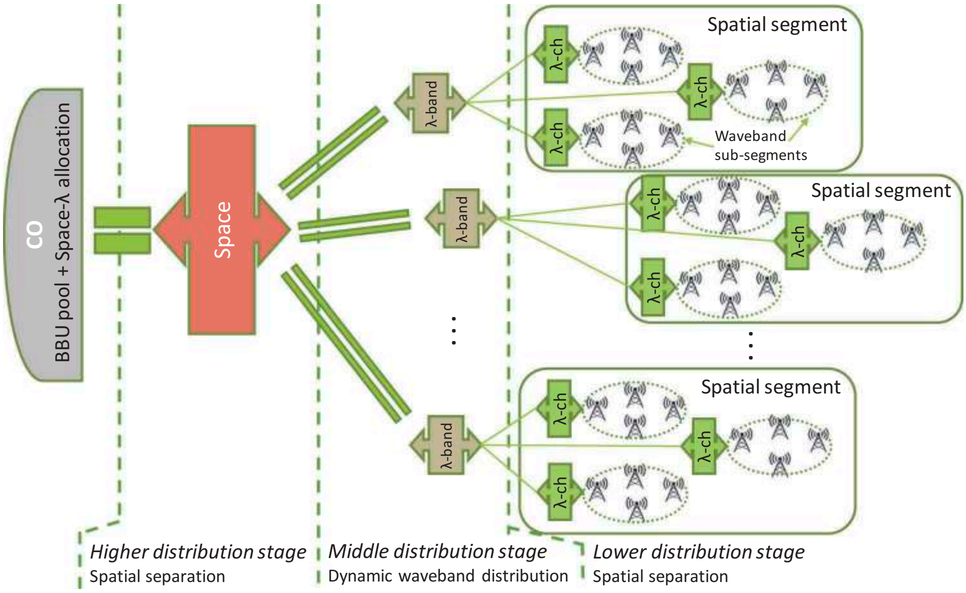

Figure 9. Overview of distribution stages in ODN with spectral and spatial dimensions.

A representation of the considered distribution stages is depicted in Figure 9. As it is illustrated, micro-cells are initially grouped into sub-segments which are allocated different wavelengths, hence, they are spectrally separated. The segments are then spatially separated. The overall planning concept relies on the adoption of higher, middle, and lower distribution stages. The highest of the stages exploits spatial dimensioning, since it is characterized by coarser granularity. The following stage performs dynamic waveband distribution, which is in line with the Wavelength Division Multiplexing (WDM) scheme; hence, it is characterized by the spectral dimension. Generally, there can be many alternatives and various options in the way the spatial and spectral dimensioning can take place in the next generation PONs of the 5G ODNs. The exact scheme depends on the specific switching capabilities of the involved optical elements, the types of fibers, the available number of cores, the number of OBFN ports, the devices' power budget, the supported distances. However, it is now evident that advanced network resource allocation capabilities are becoming available, which enable optimized adaptation to different service demands and network infrastructures.

4. Fronthaul resource allocation process

This section presents and details the fronthaul model considered by the ODN resource allocation scheme devised in the context of the blueSPACE project.

4.1. *Resource modeling*

The optical network domain of the blueSPACE resource allocation model includes all the elements of the ODN, starting from the BBUs and finishing at the RRHs, covering all intermediate optical switching elements. The optical resource allocator is responsible for assigning complete lightpaths (corresponding to optical routes) between each pair of BBU-beam. The model is designed to be compatible with any (Spectrally Spatially Flexible Optical Networks (SS-FON)) architecture, allowing all possible combinations of flexible spectral/spatial switching, depending on the capabilities of the individual optical switching elements (a) full spectral/spatial switching, (b) only spectral switching, (c) only spatial switching, (d) only core switching, (e) only port switching. SS-FONs are able to combine SDM with Elastic Optical Network (EON) technologies. This can increase transmission capacity and extend flexibility in resource management, due to the introduction of the spatial domain.

The optical resource allocator receives as input the radio allocations to identify the active RRHs, which are paired with BBUs. Each such pair constitutes an optical demand which requires a full lightpath within the ODN. All optical elements are modeled as "nodes" which have a number of input/output ports and specific switching capabilities. Each port is connected with a neighboring port of an adjacent node over a fiber link which is characterized by its number of cores and number of wavelengths supported by each core. The optical resource allocation decides which nodes/ports/cores/wavelengths constitute the lightpath for each optical demand. It is assumed that the bandwidth available by a single wavelength is higher than the bandwidth available by a single radio beam, which is in line with the specifications of NR numerologies.

The infrastructure requirements and technology solutions on the reference architecture for the SDM approach have been studied in detail in the blueSPACE project [7]. Considering that the reference use cases obey the tech limitations set, there is no impact on our SDM-based approach. Indicatively, however, it is noted that state-of-the-art techniques allows distances of about 5 km at the fronthaul with satisfactory power budget (without requiring optical amplification), which is sufficient for the type of use cases that consider urban deployment and small cells.

4.2. *Optical domain optimization*

The allocation of optical networking resources ensures the creation of end-to-end lightpaths between BBUs and beams of RRHs. The optimization process aims at identifying the shortest optical routes while utilizing the least possible optical elements. The goal is to minimize the consumed power and the utilized physical resources by aggregating the lightpaths in common switching nodes/ports/cores. This approach allows the deactivation of unused switching elements through the SDN controller, so energy can be conserved. The optimization process is modeled as an Integer Linear Programming (ILP) problem, which can rapidly identify optimal paths, dynamically adapting to traffic demands and available optical networking resources. The input requests are in the form of routing demands which are created after the assignment of radio resources. Hence, the first step of the respective algorithm is the serial allocation of BBUs to active RRHs' beams. The formulation of the ILP problem is presented in the rest of this subsection.

4.2.1. *Variables*

The decision variables are formulated as an array of binary elements (x), which are finally mapped to the "alloc_optic_slots" output. It is noted that an allocated optical slot is the minimum resource element that can be allocated to a traffic demand. In detail, the slot corresponds to a specific optical channel (wavelength) of an optical core that is part of a fiber link connected to one of the ports of a network node (such as an optical switch). The optimization process decides whether a specific element (net_node/port/core/wavelength) is allocated to a specific traffic demand (i.e. BBU-beam lightpath) or not.

4.2.2. *1st Constraint (Equation (1))*

Preoccupied allocation slots are reserved, so that they are not allocated by the current process. Also serving the constraint: one optical demand is allowed per specific optical resource. It is pointed out that each pair of an active beam of an RRH and the associated BBU at the CO constitutes an optical demand, which requires a full lightpath within the ODN. The parameter "num_optical_demands" represents the total number of optical demands in the current allocation cycle, while the parameter "num_prev_optical_demands" represents the total number of optical demands in the previous allocation cycle.

for each node j, for each port k, for each core l, for each wavelength m

$$\sum_{i=1}^{num\_optical\_demands} x(i,j,k,l,m) + \sum_{\hat{i}=1}^{num\_prev\_optical\_demands} occupied\_slots\left(\hat{i},j,k,l,m\right) \leq 1 \tag{1}$$

4.2.3. *2nd Constraint*

Creation of routes (lightpaths) from initial sources (BBUs) to final destinations (RRHs) depends on the switching capabilities of each node.

(i) Full Spectral-Spatial Switching Nodes (Equation (2))

for each demand 'i', for each node 'j':
sum of ingress allocations – sum of egress allocations = u(i,j)
(1: 'j' is the initial source of 'i', −1: 'j' is the final destination of 'i', 0: otherwise)

$$\sum_{k=1}^{net\_node(j).total\_ports} \left(\sum_{l=1}^{net\_node(j).port(k).total\_cores} \left(\sum_{m=1}^{net\_node(j).port(k).core(l).total\_wavelengths} x(i,j,k,l,m) \times net\_node(j).port(k).in\_out \right) \right) = u(i,j) \begin{cases} 1 \\ 0 \\ -1 \end{cases} \tag{2}$$

(ii) Only Spectral Switching (no spatial) Nodes – the ingress core matches the egress core (Equation (3))

for each demand 'i', for each node 'j', for each core 'l':
sum of ingress allocations – sum of egress allocations = u(i,j)
(1: 'j' is the initial source of 'i', −1: 'j' is the final destination of 'i', 0: otherwise)

$$\sum_{k=1}^{net\_node(j).total\_ports}\left(\sum_{m=1}^{net\_node(j).port(k).core(l).total\_wavelengths} x(i,j,k,l,m)\times net\_node(j).port(k).in\_out\right) = u(i,j)\begin{cases}1\\0\\-1\end{cases} \tag{3}$$

(iii) Only Spatial Switching (no spectral) Nodes – the ingress wavelength matches the egress wavelength (Equation (4))

for each demand 'i', for each node 'j', for each wavelength 'm':
sum of ingress allocations – sum of egress allocations = u(i,j)
(1: 'j' is the initial source of 'i', −1: 'j' is the final destination of 'i', 0: otherwise)

$$\sum_{k=1}^{net\_node(j).total\_ports}\left(\sum_{l=1}^{net\_node(j).port(k).total\_cores} x(i,j,k,l,m)\times net\_node(j).port(k).in\_out\right) = u(i,j)\begin{cases}1\\0\\-1\end{cases} \tag{4}$$

(iv) Only Port Switching (no spectral – no spatial) Nodes – the ingress core/wavelength matches the egress core/wavelength (Equation (5))

for each demand 'i', for each node 'j', for each core 'l', for each wavelength 'm':
sum of ingress allocations – sum of egress allocations = u(i,j)
(1: 'j' is the initial source of 'i', −1: 'j' is the final destination of 'i', 0: otherwise)

$$\sum_{k=1}^{net\_node(j).total\_ports}(x(i,j,k,l,m)\times net\_node(j).port(k).in\_out) = u(i,j)\begin{cases}1\\0\\-1\end{cases} \tag{5}$$

4.2.4. *3rd Constraint (Equation (6))*

The allocations to the two end-points of each link (neighboring ports of neighboring nodes) should have the exact same characteristics.

for each demand i, for each node j, for each port k, for each core l, for each wavelength m

$$x(i,j,k,l,m) - x(i, net\_node(j).port(k).neighbour\_nodeID\_index, net\_node(j).port(k).neighbour\_portIndex, l, m) = 0 \tag{6}$$

4.2.5. *Objective (Equation (7))*

The objective of the optical allocation process is to assign the requested optical resources given the constraints, while minimizing energy consumption. In order to achieve this objective, the optimization goal is to use as few as possible (in the following order):

- Optical nodes (i.e. optical switches)
- Optical ports
- Optical cores

To avoid scattering allocations among nodes/ports/cores of the same characteristics, we also consider the corresponding index for differentiation.

$$\sum_{i=1}^{num\_optic\_demands}\left(\sum_{j=1}^{total\_nodes}\left(\sum_{k=1}^{net\_node(j).total\_ports}\left(\sum_{l=1}^{net\_node(j).port(k).total\_cores}\left(\sum_{m=1}^{net\_node(j).port(k).core(l).total\_wavelengths} x(i,j,k,l,m)\times\frac{1+\frac{1+\frac{1+\frac{j+\frac{k+\frac{l}{net\_node(j).port(k).total\_cores}}{net\_node(j).total\_ports}}{total\_nodes}}{net\_node(j).port(k).core(l).total\_wavelengths}}{net\_node(j).port(k).total\_cores}}{net\_node(j).total\_ports}\right)\right)\right)\right)\right) \tag{7}$$

5. Evaluation of resource allocation

The evaluation of the ODN resource allocation algorithms is conducted through suitable simulation scenarios in MATLAB. It concerns a 5G deployment for the coverage of a city park. All simulations were conducted on Intel i7-920@2.67GHz with 15GB DDR3 RAM.

5.1. *Simulation scenario*

The specific scenario is fictional and represents a city park of 64 areas forming a symmetric grid and 5G coverage provided by 49 RRHs (with 4 beams each) deployed in the internal intersection of the areas, as shown in Figure 10. Each area is covered by a beam from each adjacent RRH.

The ODN for the considered scenario includes one BBU for every possible beam and full spectral/spatial capabilities for every intermediate optical switching node. In more detail, the specific ODN is structured in four layers, including a ring topology: (1) BBUs, (2) Central Switch, (3) End Switches, (4) RRHs. It is clarified that the Central Switch and the End Switches are just optical switches that can be found in the ODN and are named in that manner to be distinguished within the specific scenario. The optical network domain simulation parameters and their values are presented in Table 2, while an overview of the ODN is depicted in Figure 11. It can be seen that the optical network forms a ring topology the last end-switch being connected back to the central switch. Such a topology is common in ODNs and is completely in-line with the considered SDM-based architecture as it is depicted in Figure 9. Specifically, the distribution stages of ODN enable the formation of any kind of PON, given that it allows the division of optical resources in all required dimensions, spectrally and spatially.

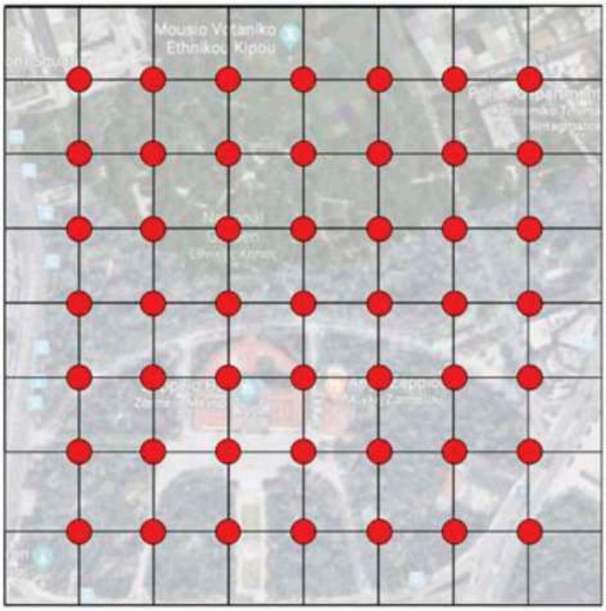

Figure 10. Illustration of the RRH deployment in the “City Park” simulation scenario.

Table 2. ODN simulation parameters and values for the “City Park” scenario.

Simulation parameter	Value
Number of BBUs	196 ● Each with 1 port to Central Switch/1 core/1 wavelength
Number of optical switches	1 Central Switch (full spectral/spatial switching) ● 196 ports to BBUs/1 core/1 wavelength ● 4 ports (total 8) to the first and last End-switches/8 cores/ ● 4 wavelengths 49 End Switches (full spectral/spatial switching) ● 1 port to RRH/4 cores/1 wavelength ● First (1st) and last (49th) switch ○ 4 ports to Central Switch/8 cores/4 wavelengths ○ 2 ports to adjacent End-switch/8 cores/16 wavelengths ● Intermediate End-switches (2nd–48th) ○ 4 ports to adjacent End-switch/8 cores/16 wavelengths
Number of RRHs	49 (each one supporting four beams) ● Each with 1 port to one End Switch/4 cores/1 wavelength

5.2. *Simulation results*

Figure 12 shows the number of allocated optical elements (nodes, ports, cores) versus the number of optical demands (i.e. requested BBU-to-RRH lightpaths). The optical demands are generated in the form of BBU-beam pairs uniformly in bulks and in a sequential manner, starting with 1 such demand requesting optical resources and ending the discrete simulations with 60 simultaneous resource requesting demands per simulation cycle time. In order to fairly evaluate the introduced resource allocation scheme, we compare it against a reference

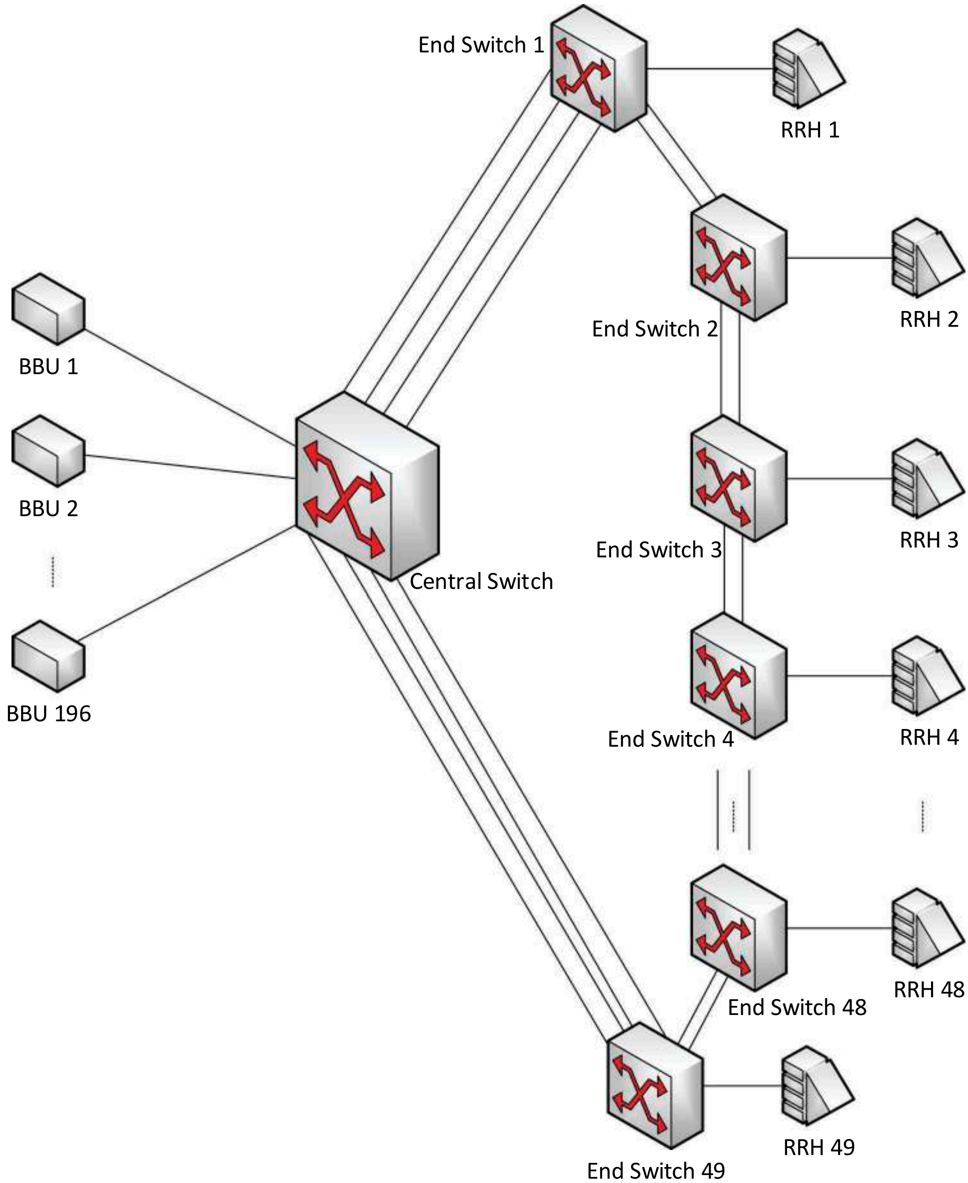

Figure 11. Illustration of the ODN topology/architecture of the "City Park" simulation scenario.

scheme with the same optimization procedure and constraints as detailed in Section 4, but without the coefficient (i.e., weight) introduced in the last part of the objective function. Hence, this reference "unweighted" scheme allocates resources to the optical demands without averting resource allocation scattering. Consequently, evaluation can be focused on the efficiency of the proposed "weighted" scheme that allows optical resource conservation through physical aggregation. It is evident that the introduced weighted optimization allows conserving significant amount of resources which total up to 9% fewer optical ports and 16% fewer optical cores. Regarding the activated optical switches, the distribution of routing

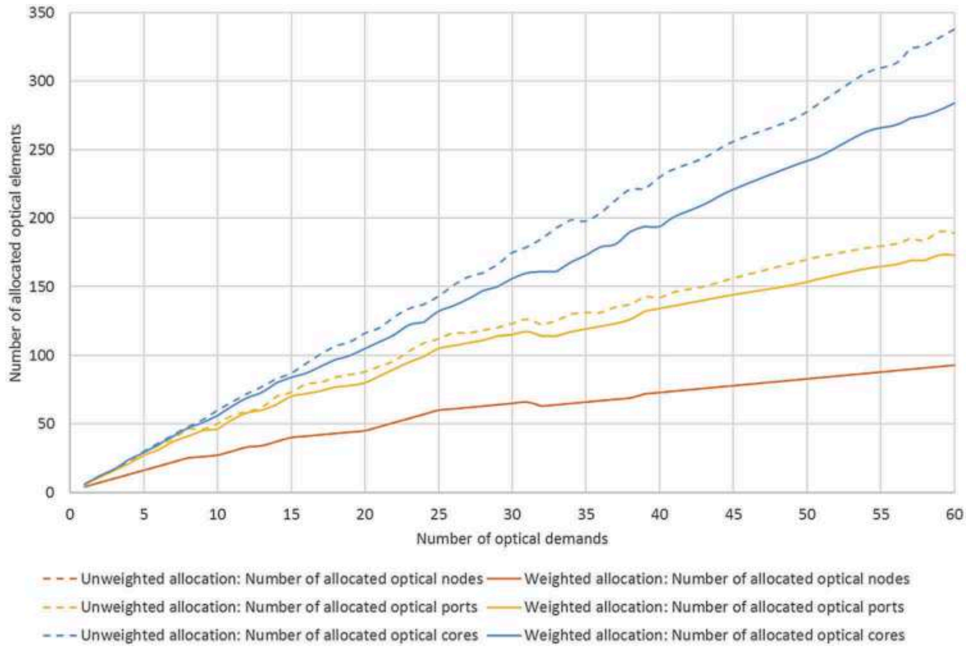

Figure 12. The resulted number of allocated optical nodes/ports/cores in the "City Park" simulation scenario.

demands and the considered topology necessitate the use of all switches in all cases. As far as the number of used optical channels (i.e. wavelengths) is concerned, it is reminded that it depends solely on the number of optical demands, so there are no differences between the optimization approaches (given that a single channel carries the information of a single beam). It is noted that the curves that represent optical nodes are overlapping, since the specific scenario does not really allow the conservation of whole optical nodes.

6. Conclusions

In this paper, we have presented the most promising approaches for the realization of the 5G fronthaul based on cutting-edge NGPON technologies by utilizing the advanced capabilities offered by SDM. We emphasized on the key solutions provided by the blueSPACE project, including ARoF for latency minimization and power saving, OBFN for targeted bandwidth provision and area coverage, MCF optical links for mitigating phase variations, and spatial/spectral dimensioning for capacity increase and adaptive allocation of network resources. Focusing on efficient resource allocation in the ODN space and spectrum, we have introduced an optimization scheme for the aggregation of allocated physical resources and reduction of consumed energy. Following the mathematical analysis of the presented ILP, a "City Park" scenario was designed to evaluate the proposed scheme. The simulation results are considered quite positive, showing up to 9% reduction of the utilized optical ports, while the conservation of optical cores reached 16%. The next steps of our related research include focusing on the radio and computing domains of the 5G infrastructure, as well as considering additional optimization factors, such as techno-economical ones.

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