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High-Capacity 5G Fronthaul Networks Based on Optical Space Division Multiplexing

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Abstract—The introduction of 5G mobile networks, bringing multi-Gbit/s user data rates and reduced latency, opens new opportunities for media generation, transport and distribution as well as for new immersive media applications. The expected use of millimeter-wave carriers and the strong network densification resulting from a much reduced cell size – which enable the expected performance of 5G – pose major challenges to the fronthaul network. Space division multiplexing in the optical domain has been suggested for ultra-high capacity fronthaul networks that naturally support different classes of fronthaul traffic and further enable the use of analog radio-over-fiber and advanced technologies such as optical beamforming. This work discusses the introduction of space division multiplexing with multi-core fibers in the fronthaul network as suggested by the blueSPACE project, regarding both digitized and analog radio-over-fiber fronthaul transport as well as the introduction of optical beamforming for high-capacity millimeter-wave radio access. Analog and digitized radio-over-fiber are discussed in a scenario featuring parallel fronthaul for different radio access technologies, showcasing their differences and potential when combined with space division multiplexing.

Index Terms—5G mobile communications, fronthaul networks, radio-over-fiber, space division multiplexing, microwave photonics.

I. INTRODUCTION

MOBILE communications and the ready availability of data connectivity have re-shaped many aspects of daily life, including the way we communicate and interact, the way we access information and form opinions and the way media is generated, distributed and consumed [1], [2]. The introduction of 5G, i.e., the fifth generation of mobile networks, is set to drastically expand the range of applications and use cases

for mobile communications and to fundamentally re-shape many of the traditional use cases. As networks become ever faster and coverage reaches unprecedented levels of density, the potential for the use of mobile communication networks for media generation, transport and distribution are ever more promising, including the development of fully immersive media experiences with real-time bidirectional interaction [3]–[6].

The burden placed by such applications on the underlying radio access network (RAN) in terms of required data rates, quality of service and acceptable latency requires major transformations in the network and the introduction of new strategies and technologies [7], [8]. In the radio frequency (RF) access segment the required multi-Gbit/s user data rates necessitate the utilization of extended spectrum ranges, namely the introduction of millimeter wave (mm-wave) carriers, a reduction in cell size, as well as the use of multiple-input multiple-output (MIMO) signalling or beamforming to increase the signal to noise ratio (SNR) or received powers [8], [9].

The use of larger bandwidths on mm-wave carriers at the same time challenges the fronthaul segment, where current digitized fronthaul schemes, e.g., common public radio interface (CPRI), do not scale well to larger RF bandwidths and higher frequency carriers as the required data rates quickly become prohibitive, especially when considering a more dense deployment with smaller cells [8], [10]. Multiple directions are available to solve the capacity shortage in the fronthaul segment, including a (partial) step backwards from a centralized radio access network (C-RAN) architecture to an architecture were some functionality and processing is moved back to the remote sites while maintaining digitized radio-over-fiber (DRoF) fronthaul. In this sense, the recent enhanced common public radio interface (eCPRI) specifications and the next generation fronthaul interface (NGFI) concept (described in section III) introduce further flexibility, allowing to efficiently communicate the different locations where the functionality and processing are executed. On the other hand, a more scalable alternative is to move to analog radio-over-fiber (ARoF) fronthaul where an analog RF or intermediate frequency (IF) signal is transported over the fiber and all processing remains centralized.

To further extend the capacity of the fronthaul network and add an additional degree of freedom for multiplexing, slicing or routing, optical space division multiplexing (SDM) has been suggested and directly combines with both DRoF and ARoF fronthaul transport [11]–[15]. The introduction of SDM for 5G fronthaul networks is one of the key concepts of the

5G-PPP 2nd phase project blueSPACE [16] to establish high-capacity fronthaul with added flexibility. Combining SDM with ARoF transport, blueSPACE envisions a fronthaul network ideally suited to support large RF bandwidths and mm-wave carriers. The optical technologies introduced by blueSPACE are compatible with the developments in other 5G-PPP 2nd phase projects focused on optical front- and backhaul, such as 5G-PHOS [17] and Metro-Haul [18], and with their added capacity and flexibility may benefit the solutions developed by those concerned with media and broadcasting, such as 5G-MEDIA [19] and 5G-Xcast [20].

This work briefly discusses the blueSPACE concept and introduces a multi-application scenario in a stadium or concert venue, featuring fronthaul for different radio access technologies (RATs) over a shared SDM network. Supporting RF distribution at traditional RF frequencies below 6 GHz, as well as mm-wave transmission for both high-speed end-user connectivity and ultra-high capacity point-to-point links for media production, the suggested scenario uses SDM to support the different RATs and relies on ARoF fronthaul with optical heterodyning for large bandwidth mm-wave signals. Optical beamforming is used to concentrate the transmitted energy to a small area to improve SNR and to allow frequency reuse for ultra-high bandwidth point-to-point links for media production. Both analog and digitized radio-over-fiber (RoF) fronthaul are discussed, highlighting the increased flexibility gained from SDM and expanding on previous experimental results [14], [21], [22].

The remainder of this article is structured as follows: section II briefly outlines the concept of blueSPACE (section II-A) and introduces the multi-RAT scenario (section II-B). Section III discusses digitized fronthaul over a hybrid SDM and wavelength division multiplexing (WDM) based network, before section IV introduces ARoF fronthaul for mm-wave 5G NR signals and showcases initial experimental results. Finally, section V summarizes and concludes the article.

II. SPACE DIVISION MULTIPLEXING FOR 5G FRONTHAUL

A. The blueSPACE fronthaul concept

The 5G-PPP 2nd phase project blueSPACE [11], [16] focuses on the introduction of two key technologies for future fronthaul, first the use of optical SDM to solve capacity issues in the fronthaul network and, second, the use of ARoF fronthaul with optical beamforming for mm-wave radio access at ultra-high data rates.

The blueSPACE optical distribution network (ODN) introduces the benefits of SDM in networking and for the support of new fronthaul technologies, while building upon existing infrastructures such as passive optical networks (PONs) and bundles of single-mode fibers (SMFs), as transition paths to an ODN based on multi-core fiber (MCF). The proposed ODN allows massive fronthaul capacities and by introducing an additional independent degree of freedom, i.e., the spatial dimension, directly supports multi-operator and multi-service scenarios as well as increased flexibility and splitting ratios in the distribution network.

Since nowadays fiber optic-based RANs are deployed with DRoF fronthaul, a smooth migration is expected. To this end,
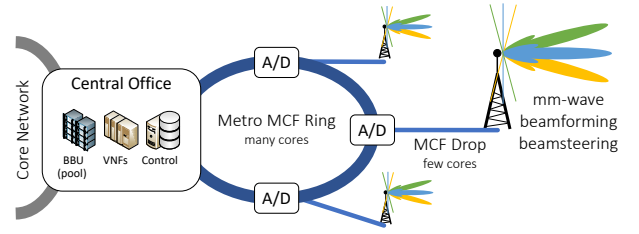

Fig. 1. Overview of the blueSPACE RAN architecture, based on ARoF fronthaul, SDM using MCF and optical beamforming for mm-wave. BBU: baseband unit, VNF: virtual network function, MCF: multi-core fiber, A/D: add/drop multiplexer.

an adaptation of existing DRoF technologies to the blueSPACE ODN infrastructure is sought, in order to scale up the network capacity while introducing ARoF.

The introduction of ARoF fronthaul over the SDM based ODN further increases the amount of radio traffic that can be supported in the RAN, as ARoF avoids all overhead resulting from digitization of the RF signal and hence minimizes bandwidth usage. By transporting 5G NR conform orthogonal frequency-division multiplexing (OFDM) signals in an intermediate frequency-over-fiber (IFoF) configuration and relying on photonic upconversion for mm-wave generation, blueSPACE establishes a transparent fronthaul link and directly enables analog beamforming in the optical domain. By implementing full matrix-type beamforming networks [9], [23] blueSPACE achieves true multi-beaming from a single antenna array.

Through the combination of SDM and ARoF with optical beamforming, as shown in Fig. 1, blueSPACE is capable of supporting massive and dense deployments of small cells, while maintaining fully centralized processing and control and thus maximizing the potential gain from virtualization in the access segment. To this end blueSPACE develops a software-defined networking (SDN) and network function virtualization (NFV) framework adapted to the introduction of SDM and supporting both digitized and analog RoF transmission as well as optical beamforming.

B. Multi-application fronthaul network based on SDM

Live sharing via social media platforms and interaction between the members of the audience as well as with the outside world has become an essential part of the entertainment derived from any sporting or cultural event. Such interaction and concurrent live content streaming from a large number of users in a highly concentrated area creates large demands for mobile/wireless traffic of different requirements. This set of requirements includes high-bandwidth latency sensitive traffic from live video interaction, less latency sensitive traffic for one-wave streaming, as well as smaller bandwidth non latency sensitive traffic for text/messaging interaction or sharing of photographs.

In addition, the traffic and demand generated by the audience, the production of the event itself as well as potential media coverage will require ultra-high capacity, low latency and highly reliable communications to both fixed locations and mobile recording, video and production equipment. While
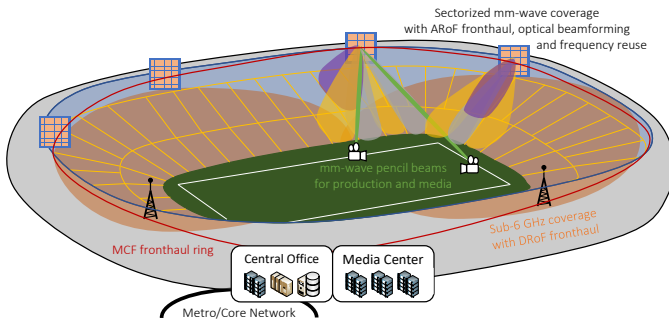
Fig. 2. Multi-service scenario with converged SDM optical fronthaul network, supporting DRoF and ARoF transport as well as optical beamforming.

such links traditionally were established through dedicated connectivity, a unification of technologies and network equipment is highly sought after.

Supporting the large and varied mobile/wireless traffic demands in a very dense and active environment such as a stadium or concert venue is a major challenge both in terms of capacity and in terms of requirements for different users and applications involved. Unified support for the different traffic types and requirements through a single fronthaul network poses a major challenge to network flexibility and management – here the introduction of SDM offers a clear path towards a unified fronthaul network with shared fiber infrastructure for multiple applications with entirely different requirements. SDM in the optical domain, combined with WDM where needed for capacity, provides a single, highly flexible infrastructure that can concurrently support multiple heterogeneous streams of DRoF and ARoF fronthaul as well as optical beamforming and thus is ideally suited for scenarios in which traffic of heterogeneous nature must be served in a coordinated fashion through a converged infrastructure.

Fig. 2 shows a schematic of an event venue with multiple, overlaying radio access networks, serving different applications at the same time and supported through the same fronthaul network. Therein, a sub-6 GHz network served by DRoF fronthaul forms the basis, providing user registration and authentication as well as low volume transport, a second layer of mm-wave networks is served via ARoF fronthaul, making use of optical beamforming for multi-beam transmission. The mm-wave network serves high-volume applications in the audience via multiple beams covering sectors in a regular grid, as well as the production of the event and the media coverage via dedicated, narrow and highly focused pencil beams. The use of beamforming in the mm-wave network allows significant capacity increases for audience coverage, as the reduced spatial area per beam results in a smaller number of users as well as a higher SNR and allows denser frequency reuse. Similarly, ultra-high capacity can be achieved through dedicated pencil beams for the production and media equipment as the strong focus significantly increases the received power and allows the use of larger bandwidths as beams are overlap free and interference is avoided.

III. SDM/WDM FRONTHAUL USING SDN-ENABLED DROF TRANSMISSION

DRoF has been pursued and developed since 2011 for the support of C-RAN and in order to cope with high capacity demands in mobile data traffic for densely populated areas [24]. Following this approach, a pool of baseband units (BBUs) is kept in a central office (CO) while several remote radio units (RRUs) are scattered along the optical network. The BBUs implement all radio signal modulation/demodulation and further digitization, while the RRUs are simple units that basically reconstruct the wireless waveforms from a digital stream and perform the signal conditioning towards the antennas. Therefore, this digital fronthaul has very strict requirements in terms of high bandwidth and low delay because it is required to directly transport complex, digitally sampled radio waveforms between CO and RRUs. Further, no dynamic management of the capacity in the network is possible, as the associated traffic requires a high, constant bit rate independent of the cell loads.

In order to relax these requirements, several radio functions can be decentralized and returned to the remote sites. This is envisioned in the so-called NGFI [25], which proposes to split the different radio functions and implement them in three logical entities: the central unit (CU), the distributed unit (DU) and remote unit (RU). In fact, when approaching NGFI, a flexible functional split is envisioned between CUs and DUs, so that part of the wireless waveforms are generated at the CU and another part at the DUs. In turn, the RAN is split into two different segments. First, the pure fronthaul, which is the segment between the DUs and RUs. Second, the so-called midhaul, which covers the segment between CUs and DUs. This approach enables the use of statistical packet multiplexing while reducing the latency and capacity constraints.

A. Network concept

Fig. 3 shows a generic scheme for the SDM/WDM fronthaul based on DRoF. There, a CO is attached to an optical metro/core network in order to provide connectivity to the network edge. At the CO, a pool of BBUs delivers the traffic to the corresponding bandwidth/bitrate variable transceivers (BVTs). Also a pool of CUs is envisioned to be connected to the corresponding packet switch whose outputs are connected to the the BVTs. The BVTs can be remotely configured by the control plane, for an optimal management of the network resources [26]. In addition to the bitrate variability that can cope with a dynamic traffic variation (e.g., daily traffic variation), the BVTs also feature other benefits such as the capability to maximize their capacity for a given connection [26]. The inputs/outputs of each BVT are connected to an optical switch in order perform the appropriate connections to each of the wavelength selective switches (WSSs), which perform the wavelength division multiplexing/demultiplexing of M different signals into arbitrary portions of the spectrum according to the control plane indications. The main outputs of the WSSs are connected to the multi-core multiplexers (MCMs), which are the fan-in/out devices for SDM on N different fiber cores.
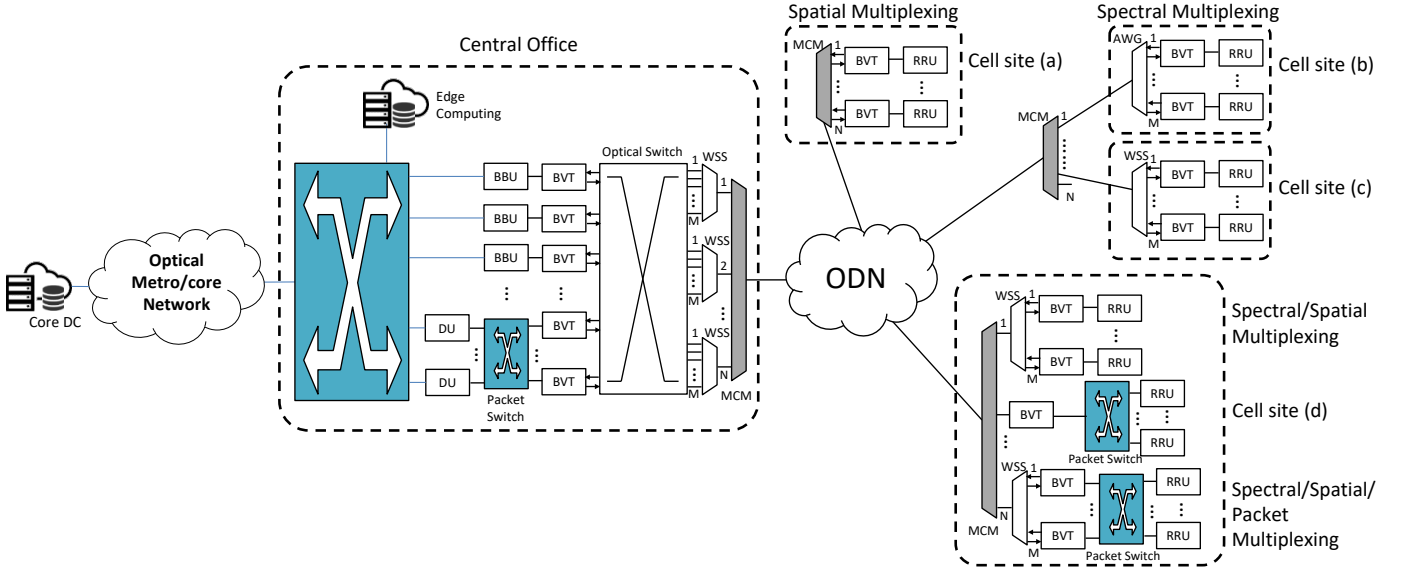
Fig. 3. General scheme for the SDM/WDM DRoF fronthaul with different multiplexing and demultiplexing options at the cell site: (a) pure spatial multiplexing, (b)-(c) spectral multiplexing based on fixed channels (b) or variable channels (c), (d) combined spatial and spectral multiplexing with optional packet multiplexing. AWG: arrayed waveguide grating; BBU: baseband unit; BVT: bandwidth/bitrate variable transceiver; CU: central unit; DU: distributed unit; MCM: multi-core multiplexer (fan-in/-out); RRU: remote radio unit; RU: remote unit; WSS: wavelength selective switch.

Thus, space and spectrum resources can be managed by a centralized SDN controller in order to provision the different services, possibly including residential access and/or some other service that could require a direct interface with the metro/aggregation segment. All the systems and subsystems belonging to the central office and, especially, the BVTs can be programmed by means of the corresponding SDN agents, allowing an automated channel establishment between the central office and the cell sites in a 2D space (WDM+SDM).

The CO delivers its data signals to the optical distribution network in order to give connectivity to the different cell sites. This optical distribution network is expected to be mainly passive, featuring low operating expenses (OpEx) and limited capital expenditure (CapEx) [27]. Different options are envisioned for the cell sites, as shown in Fig. 3 (a) to (d). A first cell site option (a) is a purely spatially multiplexed site. There, the BVTs are tuned to use the very same wavelength while using different cores either for scaling up the capacity or for implementing a dual-core duplex. Therefore, a simplification of the BVTs can be foreseen, as some wavelength dependent parts can be shared, depending on the specific BVT design. For instance, in case external modulation is used, a laser source can be shared between several BVTs in order to keep the solution at low cost.

The cell site options (b) and (c) correspond to a spectrally multiplexed site. In that case, a single core is used while the multiplexing is exclusively performed in terms of wavelength. Therefore, a straightforward approach can be to employ passive devices – for example an arrayed waveguide grating (AWG) as in cell site (b) – to perform the wavelength multiplexing in order to keep the solution at low cost. Also active devices such as WSSs can be employed, trading cost against flexibility as in cell site (c). It should be noted that a dual wavelength duplex is envisioned in these cases.

Finally, a generic cell site option is depicted in (d). There either spatial and/or wavelength multiplexing is used in order to use all the available network resources. This case further shows the possible interconnection between BVTs and BBUs for an NGFI-like solution, which is generic for all aforementioned cases.

It is worth mentioning that the optical switch at the CO can be removed in case the BVTs are directly attached to the WSSs, trading flexibility against hardware complexity.

Interestingly, this approach can be easily adapted for the fronthaul over packet solutions in order to leverage the statistical multiplexing gains offered by packet switching, while efficiently integrating fronthaul with data centers that might execute the BBU processes. Therefore, a pool of CUs is envisioned to be connected to the corresponding packet switch whose outputs are connected to either the DUs or the BVTs, including the corresponding framing/de-framing. Hence, the traffic served over the network corresponds to either the NGFI-I or NGFI-II subnetworks, depending on the specific configuration of the CO and the cell sites.

For NGFI-II traffic delivery over the network, the packet switch after the CUs directly feeds the BVTs at the CO. Thus, each BVT can serve different cell sites where DUs and RUs are located, properly interfaced by the suitable packet switches after the BVTs. For the case of NGFI-I traffic, the DUs are also present at the CO. Hence, several BVTs can be attached to a single DU (conveniently interfaced by a packet switch), but the simplest case is for a 1 to 1 pairing. In this case, the cell sites only contain the RUs, together with the appropriate packet switches (when needed) and the corresponding BVTs.

One of the main benefits of the proposed architecture is that it features high configurability and flexibility. The CO and the different cell sites are expected to host their corresponding SDN control agent in order to configure the main parameters

Case	Max. capacity per flow	
	Upstream [Gbit/s]	Downstream [Gbit/s]
(i) back to back	33.02	58.17
(ii) single SSMF bidirectional	33.11	56.90
(iii) MCF central core bidirectional	31.78	55.17
(iii) MCF outer core bidirectional	31.57	58.95
(iv) MCF dual core bidirectional	34.39	57.70

Fig. 4. Transport SDN control architecture.

of their network components for the efficient control of the fronthaul traffic over the ODN. In turn, each SDN control agent interacts with the control plane infrastructure, which is in charge of the overall network management. Therefore, the programmability of the different elements composing the CO and the cell sites is of key importance.

The main optical modules that may have programmable features are: the optical switching matrix of the CO; the WSSs (at the CO and/or the cell sites); and the different BVTs, as described in [14]. Among them, the most interesting optical element to control is the BVT. The BVTs can be remotely configured for an optimal management of the network resources [28], [29]. The parameters to be configured include forward error correction (FEC) code, emission wavelength, bandwidth occupancy and/or bit rate [14], [30].

A set of preliminary experiments has been devised and carried out within blueSPACE in order to demonstrate the feasibility of the concept for an urban or dense area, covering distances of up to 6 km, in line with the scenario proposed in section II-B. The full experimental setup and the complete set of results are reported in [14]. There, two different direct detection (DD)-OFDM spectral flows were generated (at 1550.12 nm and 1550.92 nm) and launched into the WDM/SDM ODN. The performance was evaluated in terms of maximum capacity for covering a power budget of 25 dB. Different cases were analyzed: i) back-to-back; ii) bidirectional transmission over 6 km of standard single-mode fiber (SSMF); iii) single-core bidirectional transmission over 5 km of MCF plus 1 km of SSMF; and iv) dual-core bidirectional transmission over 5 km of MCF plus 1 km of SSMF.

Results reported in [14] are summarized in Table I, where the maximum capacity per flow is averaged between the wavelengths tested. Furthermore, the data rates reported are optimized for coping with a target bit error ratio (BER) of $4.62 \cdot 10^{-3}$, assuming a standard FEC with 7 % overhead [31, p. 22], i.e., a super-FEC of a Reed-Solomon and a product code. Results show that all obtained performance measurements are well aligned for the different cases. In fact the BVTs are able to successfully transmit maximum capacities in the range between 55.17 Gbit/s and 58.95 Gbit/s for downstream and in the range between 31.57 Gbit/s and 34.39 Gbit/s for upstream, and are thus easily able to accommodate functional split options up to 7a [32, p. 82, Table A-1], i.e., a functional split where RF and parts of the physical layer are located at the cell site, while the remaining physical layer and all higher layers are located at the CO.
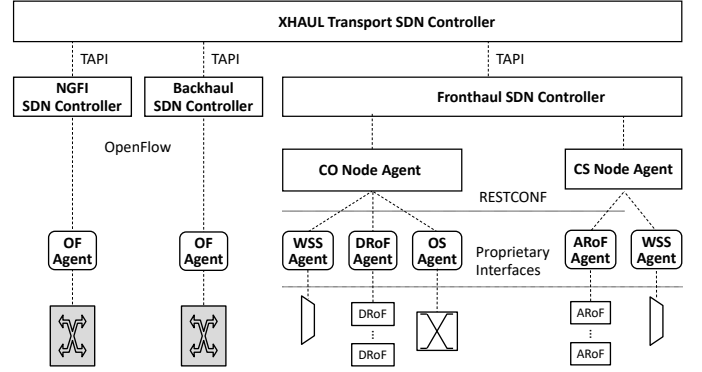
B. Control aspects

A single SDN controller comprising the multiple and diverse technologies of the SDM/WDM/packet-based fronthaul and backhaul is not realistic. We rely on a hierarchical transport SDN control approach with different levels of hierarchy (parent/child architecture). In particular, we propose to use child SDN controllers for the SDM/WDM fronthaul, NGFI and backhaul segments, and a parent SDN controller on top acting as the xhaul transport network orchestrator, as shown in Fig. 4. The open networking foundation (ONF) transport application programming interface (TAPI) [33] is used as the northbound interface (NBI) of the child SDN controller and as southbound interface (SBI) of a parent SDN controller. This allows abstracting a set of common SDN control plane functions (e.g., topology and connectivity service) and defines a common data model and protocol based on YANG/RESTconf. However, TAPI does not support SDM networks, since only extensions for OTSi (WDM), ODU, and Ethernet are included in official releases. TAPI has a flexible modularity and allows extension of all of its data models, and we have proposed a novel hybrid SDM/OTSi data model (tapi-sdm.yang) in [34]; the extended TAPI YANG models are publicly available [35]. Additionally, the parent SDN controller also uses the TAPI as NBI. It is worth to highlight the considered architecture can be applied recursively enabling the cascading of the different SDN controllers.

The SDN controllers for the packet-based backhaul and NGFI-I network segments are based on the OpenFlow protocol as SBI to configure the packet switches. On the fronthaul segment side, the proposed solution is to deploy node SDN agents at the cell sites and the central office. The SDN node agents can configure and monitor the blueSPACE nodes' hardware through SDN agents. The SDN hardware agent's purpose is to map high-level operations coming from the node SDN agent into low-level, hardware-dependent operations using the proprietary protocols. This involves defining a data model for the DRoF transceivers, the optical SDM/WDM aggregation elements, and agreeing on a protocol, with the corresponding message formats and encodings.

We consider protocols standardized by the IETF for network control and management for the interface between the SDN controller, SDN node agents and SDN agents. In particular, the interface between the SDN controller and the node SDN agents

is based on NETCONF, and the interface between the SDN node controllers and the SDN agents is based on RESTconf. Both rely on YANG as modeling language, used for defining the configurable parameters and state information in XML format. However, RESTconf describes how to map a YANG specification to a RESTful interface. The REST-like application programming interface (API) is intended to provide an additional simplified interface that follows REST-like principles and is compatible with a resource-oriented device abstraction.

We propose a YANG model for retrieving the topology of the nodes (CO and cell sites), and for configuring a connection between ports. The topology YANG model (node-topology.yang) encompasses a list of ports with their parameters (e.g., available/occupied frequency slots, available cores, transceiver type, supported modulation formats, bandwidth, central frequency, FEC and equalization, etc.). The connection YANG model (node-connectivity.yang) is composed of identifiers for connection, input and output port, and the SDM/WDM transceiver yang model previously defined. The defined YANG models are publicly available [35].

IV. 5G FRONTHAUL BASED ON AROF

AROF based fronthaul is an attractive solution and has gained a lot of attention recently over DROF, mainly due to two reasons. The first is associated to the use of bandwidth resources, AROF systems minimize the use of bandwidth while DROF systems based on low level functional splits usually require two or three orders of magnitude more bandwidth. The reason for this lies in the fact that in order to reconstruct the radio signal with sufficient quality it is discretized with a high number of bits, therefore the resulting digital bit rate has a poor scalability with the bandwidth of the radio signal. The second reason for the attractiveness of AROF is related to the cost of the fronthaul network. In the case of using AROF the remote site (RS) is very much simplified (ideally a photodiode and an amplifier), this enables a substantial reduction on deployment and operational costs. Furthermore, keeping all functionalities in a central office allows an efficient use of resources. The first 5G technical specifications appeared recently in 3GPP release 15. Two different frequency ranges are specified for the radio access, frequency range 1 (FR1) covers from 0.45 GHz to 6 GHz whereas frequency range 2 (FR2) covers from 24.25 GHz to 52.6 GHz [36]. Several operating bands are defined within FR1 and FR2, particularly interesting is the band *n258* (24.25 GHz to 27.5 GHz) that has been selected for use in Europe and is the focus of blueSPACE. Transmitting and generating the 5G NR signals in the aforementioned operating band is the objective of the designed AROF based fronthaul.

A. ARoF fronthaul network concept

The fronthaul network concept for AROF fronthaul largely follows the same outlines as the network concept for DROF fronthaul as discussed in section III and illustrated in Fig. 3, though with a few key differences which shall be briefly discussed in the following. First and foremost, the major difference lies in the centralization of all processing functions at the CO, and thus in the implementation and capabilities of the BBU, the transceivers at both ends and the simplified RU.

An AROF BBU includes all processing functions required also for DROF, but rather than providing an output of digitized complex in-phase and quadrature (I/Q) samples, it includes a digital to analog converter (DAC) and IF modulation stage to produce an analog IF output signal. In the receiving direction, they include the inverse chain, i.e., an IF demodulation stage and analog to digital converter (ADC) for recovery and digitization of the baseband signals. A pool of AROF BBUs will drive a pool of AROF transceivers, potentially interfaced by an analog IF switch to take advantage of statistical multiplexing in case of varying traffic loads. The output of the transceivers are optical two-tone signals carrying analog IF waveforms on one tone, while the second tone is continuous wave (CW). Hence they may be multiplexed in the wavelength and spatial domain similar to the DROF case, provided both tones are always treated as a single signal. Contrary to the DROF case, due to the analog nature of the modulation signal, statistical packet switching is not an option and optical switching – if required – must be performed in a circuit switching fashion. Apart from the restriction of applicable switching methods, the SDM based ODN follows the same principles as in the DROF case, allowing a shared ODN for both AROF and DROF fronthaul as well as a multi-service ODN where optical fronthaul and other services coexist.

Finally, the AROF fronthaul network features an RU of much reduced complexity, where the minimum configuration consists of only a photodiode for optical heterodyne upconversion to mm-wave using the unmodulated tone of the two-tone signal and RF amplification stages for signal conditioning to the antenna. In a spatially and spectrally multiplexed network, the four options for demultiplexing illustrated in Fig. 3 (a) to (d) remain valid also in the AROF case.

The introduction of optical beamforming instead of electrical beamforming, may further impact the fronhaul network and give advantages to AROF based fronthaul. Optical beamforming naturally supports multi-beam transmission through implementation of a Blass matrix or similar in the optical beamforming network (OBFN) [23], simplifying the RU design and potentially reducing the number of required antenna elements compared to electrical beamforming based on banks of phase shifters. While optical beamforming may be combined with DROF fronthaul, it ideally combines with AROF fronthaul, as all functions in the OBFN may be performed on the optical signal carrying the IF signal and will be transferred to the RF signal in the heterodyning process.

In the case of demanding installations with reduced distances between CO and RUs, such as the multi-application scenario described in section II-B, the combination of AROF and optical beamforming may further allow complete centralization also of the beamforming process by placement of the OBFN at the CO. Such centralization comes at the cost of tight synchronization demands on the ODN, as the relative delays between signals must be maintained through the ODN to preserve beam shape. The use of the spatial domain in an SDM based ODN, offers a suitable base for such advanced centralization, as the differential delays between cores in
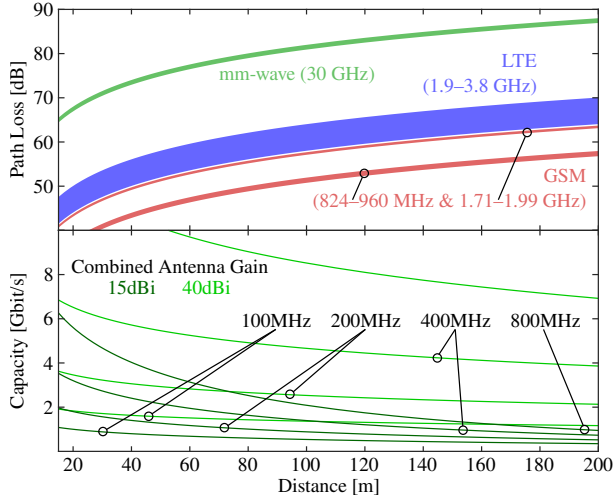
Fig. 5. (a) Comparison of path loss between the traditional RF bands and the mm-wave band; (b) achievable capacity at mm-wave frequencies for different bandwidths and antenna gains.
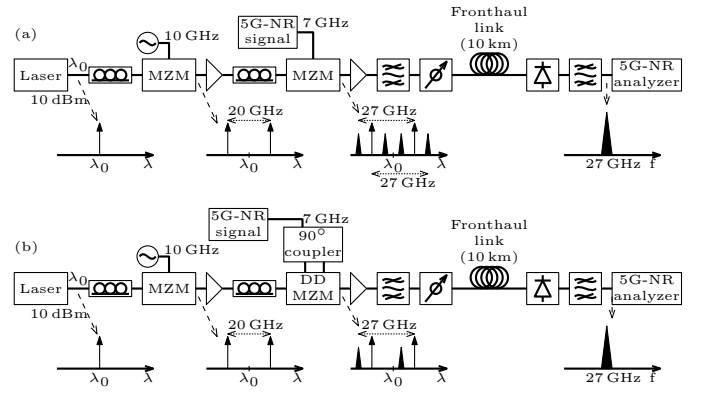

Fig. 6. Experimental setups for the optical generation of 5G NR signals in FR2: (a) setup based on DSB modulation and (b) setup based on SSB modulation.

an MCF are expected to be significantly smaller than those between separate fibers or different fibers in a bundle.

With its reduced bandwidth requirements on the opto-electronic components, optimized usage of optical spectrum, direct tie-in with optical beamforming and simplified RU thanks to photonic heterodyne upconversion, AROF fronthaul is considered a key candidate for large bandwidth mm-wave signal transport and generation for 5G and beyond.

B. Ultra-high capacity ARoF point to point links

The main strategy to overcome the increased path losses at mm-wave is the focus of the radiated energy onto a small physical area, by means of high-gain, highly directive antennas or through the use of beamforming with antenna arrays. The contrast in path loss between the traditional sub-6 GHz mobile bands and the mm-wave band around *n258* is shown in Fig. 5, which also shows the achievable capacity within limited bandwidths and for different antenna gains [22], [37]. Using high gain antennas which can almost entirely offset the increased path loss at mm-wave, such links have been demonstrated with capacities well beyond 100 Gbit/s over a few metres or with multiple Gbit/s over a few km [38]–[41].

The use of optical beamforming with AROF fronthaul, opens the door for such links to not be based on highly directive antennas, but on highly concentrated beams with pencil shape, featuring similar levels of effective gain from antenna and beamforming. As optical beamforming naturally allows the generation of multiple beams with different shape, coverage area, frequency and contained information, a single antenna array may be used to both serve a set of dedicated, mobile, high-capacity clients – such as media production cameras or facilities – and a grid of areas with multiple users at lower per-user capacity – such as spectators in the audience. The use of a joint infrastructure based on AROF fronthaul over an SDM ODN, offers the chance for significant saving and increased flexibility, while allowing multi-Gbit/s connectivity

with guaranteed quality of service, especially for the dedicated point-to-point links.

C. Experimental validation of intermediate frequency ARoF fronthaul with 5G NR signals

Normally, three different options arise in the implementation of AROF systems, differing in whether the signal is transmitted through the fiber in baseband-over-fiber (BBOF), IFOF or radio frequency-over-fiber (RFOF). On the one hand, the BBOF and IFOF schemes have the drawback that they require a frequency upconversion stage before being radiated, in this sense RFOF is usually the preferred approach. However, on the other hand, RFOF imposes high bandwidth requirements on the optoelectronic components. In order to relax bandwidth constraints an RFOF scheme with two electro-optic modulation stages can be employed, this was originally proposed in [42], [43]. Based on that work we propose two new approaches to generate signals at *n258* operating band in the FR2, precisely we target the generation of the 5G NR signals at 27 GHz.

The experimental setups for the generation of 5G NR signals at 27 GHz are sketched in Fig. 6 (a) and (b), including the theoretical spectra of the relevant signals. Both setups are based on a first stage of optical carrier suppression (OCS) based modulation, followed by second modulation stage where the 5G NR signal is introduced by means of either double side band (DSB) modulation (Fig. 6 (a)) or single side band (SSB) modulation (Fig. 6 (b)). First, a single drive LiNbO$_3$ Mach-Zehnder modulator (MZM) biased at the null point is used to implement the OCS based modulation. A 10 dBm power laser source is used as a carrier input signal to the modulator, whereas an RF tone at 10 GHz is used as modulating signal. The theoretical spectrum of the optical output signal (sketched in Fig. 6) comprises two tones separated by 20 GHz. Due to the reduced power level typical from OCS based modulation, the output signal of the first modulation stage is amplified before the second modulation stage. The two tone signal is then used as a carrier signal in the second modulation stage.

A Rohde & Schwarz SMW200A is used to generate the 5G NR signals centered at 7 GHz that serve as modulating signals for the second modulating stage. The equipment modulation bandwidth was limited to 100 MHz, therefore the 5G NR

OFDM signals generated comprised 66 resource blocks (RBs) with a subcarrier spacing (SCS) of 120 kHz. The modulation scheme employed on the user data subcarriers was 64-QAM. This signal was used to modulate the signal coming from the first modulating stage, as mentioned we used DSB modulation in one case and SSB modulation in the other case. DSB modulation was implemented by means of a single electrode LiNbO$_3$ MZM biased at the quadrature point. The theoretical optical spectrum of the output signal is represented in Fig. 6 (a), it comprises six spectral contributions. The second modulation stage adds the 5G NR signal spectra, separated 7 GHz, to each side of the two tones originated in the first modulation stage. Therefore, the beating of each tone with the furthest 5G NR signal contribution will generate the desired 27 GHz signal, it is important to remember that the highest frequency employed is 10 GHz meaning that bandwidth constraints are reduced. In the case of a second modulation stage based on SSB modulation (Fig. 6), the 5G NR signal is first coupled to a 90° coupler and then the outputs of the coupler drive a dual drive Mach-Zehnder modulator (DDMZM) biased in the quadrature point. The theoretical output spectrum for this case is represented in Fig. 6 (b), four spectral contributions can be observed, the two tones from the first modulating stage and on one side of each tone the 5G NR signal separated 7 GHz. In this case the desired 27 GHz signal is generated by the beating of the two most separated spectral contributions.

After the second modulation stage the signal is amplified again and passed through an optical bandpass filter in order to reduce the amplified spontaneous emission coming from the amplifiers. Then a variable optical attenuator (VOA) is used to control the received optical power. A 10 km span of SSMF experimentally models the fronthaul link. On the remote site a high-speed photodiode receives the signal coming from the fiber and then an RF bandpass filter selects the contribution around 27 GHz. The output of the filter models the interface with the radiating elements where signal quality assessment is specified [36], therefore the filter output signal is fed to the 5G NR signal analyzer.

The experiments performed consisted mainly of the assessment of the performance of both schemes in the case of back-to back configuration (without fiber) and in the case of the 10 km fiber link. 3GPP specifies a maximum error vector magnitude (EVM) at that interface of 8 % for a 64-QAM subcarrier modulation scheme. In each of the four cases received optical power and RF output power of the signal generator were selected to optimize the EVM of the received signal. Then the received optical power was swept within the margins where the analyzer was able to synchronize with the received signal. The EVM of the received signal was recorded for each of those points and results are shown in Fig. 7. It can be seen that in all cases the EVM is below 8 %, indicating that both configurations fulfill 3GPP specifications.

Optimum received optical powers where found in a range of 2 dBm to 5 dBm, whereas optimum RF output power varied from 4 dBm to 8 dBm. Specifically, optimized RF output power was 4 dBm for the DSB case in back-to-back and 6 dBm in the DSB case with 10 km of fiber. For the SSB it was 6 dBm in the back-to-back case and 8 dBm with the 10 km link. Taking a
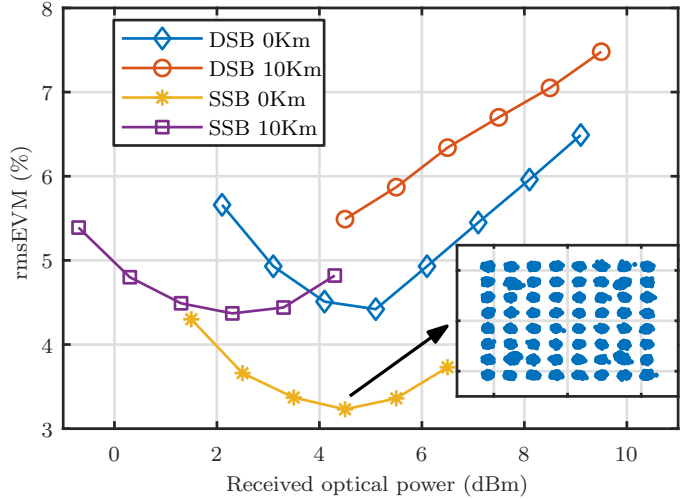

Fig. 7. Experimental results on both setups, EVM as a function of received optical power.

closer look to Fig. 7 it can be seen that the approach based on SSB modulation outperforms the one based on DSB, reporting around 1 % less EVM. The curves exhibit a valley around the optimized received optical power, outside that value the measured EVM worsen significantly. It can also be seen that the propagation through the 10 km long fiber has an impact on the EVM performance of around 1 %. This is due to two effects, the first one is the actual propagation loss of the fiber that worsens the SNR, the second one is the dispersion of the fiber that also worsen the quality of the signal. The best achieved EVM value was 3.3 %, it was obtained using the SSB approach in back to back configuration, the received optical power for that case was 4.5 dBm and the received 64-QAM constellation diagram is represented in the inset of Fig. 7.

The presented experimental demonstration of IFoF fronthaul with optical heterodyning for upconversion to mm-wave showcases the feasibility of IF ARoF fronthaul for 5G NR signals and with a significant EVM margin remaining suggests significantly longer fiber transmission or more complex optical setups to be feasible. As such, the presented results are the first step towards a full ARoF based fronthaul implementation with optical beamforming and mm-wave wireless transmission.

V. CONCLUSIONS

The use of high-bandwidth millimeter wave (mm-wave) signals in 5G networks puts significant loads on fronthaul networks, making changes to current radio access network (RAN) architectures and fronthaul strategies mandatory. The introduction of optical space division multiplexing (SDM) in the fronthaul network, allows significant upgrades to fronthaul network capacity, offers an additional degree of flexibility for multiplexing and signal distribution, while maintaining compatibility with current digitized radio-over-fiber (DRoF) fronthaul methods and software-defined networking (SDN) and network function virtualization (NFV) paradigms. It further combines seamlessly with analog radio-over-fiber (ARoF) fronthaul for reduced bandwidth usage and optimized fronthaul ca-

pacity especially for signals utilizing the large RF bandwidths available in the mm-wave spectrum assigned for 5G.

This article introduced the use of SDM in the fronthaul network, discussing first the concepts of the 5G-PPP project blueSPACE, before introducing a multi-service scenario in a stadium or concert venue, where an SDM based fronthaul network is employed to serve sub-6 GHz mobile signals with DRoF fronthaul and mm-wave signals for both end users and media production equipment and facilities through ARoF fronthaul with optical beamforming. The impact and added flexibility of introducing SDM to the fronthaul network was discussed for DRoF fronthaul, addressing also related challenges and opportunities for SDN and NFV in the fronthaul network. ARoF fronthaul for mm-wave signal transport and generation was discussed, highlighting the impact of ARoF fronthaul over SDM and the opportunities afforded by optical beamforming. The latter allows generation of both highly focused pencil beams for media production connectivity and larger beams serving a grid of sectors with spectators. First experimental results are discussed for DRoF fronthaul over multi-core fiber (MCF), as well as for ARoF fronthaul with 5G NR compliant signals.

The presented concepts and initial results show the potential of introducing SDM to the optical distribution network (ODN) employed for 5G fronthaul in general, while specifically highlighting a scenario in which concurrent transport of multiple flavours of fronthaul signals over a shared infrastructure is of significant interest. The added flexibility of SDM in the fronthaul, as well as the possibility to not only support multiple flavours of fronthaul transport, but also different applications and services over the same infrastructure, makes it a key step in the evolution of optical distribution networks to the much larger capacities required for densely deployed 5G small cells.

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