Abstract—Analog optical fronthaul for 5G network architectures is currently being promoted as a bandwidth- and energy-efficient technology that can sustain the data-rate, latency and energy requirements of the emerging 5G era. This paper presents 5G-PHOS project approach, which relies on a new optical fronthaul architecture that can effectively synergize optical transceiver, optical add/drop multiplexer and optical beamforming integrated photonics towards a DSP-assisted analog fronthaul, administered by means of a Medium Transparent Dynamic Bandwidth Allocation (MT-DBA) protocol for seamless and medium-transparent 5G small-cell networks.

Keywords—5G networks, analog optical fronthauling, mmWave massive MIMO, Medium-Transparent MAC protocols, optical beamforming technology

I. INTRODUCTION

At the dawning of the 5G era for mobile communications, the telecommunications industry today races towards realizing broadband services in urban and highly dense areas, while the vastly growing use of emerging applications, e.g. 4K High Definition video, augmented/virtual reality, immersive video conference etc. have been stimulating an insatiable demand for ubiquitous high bandwidth connectivity and enhanced Mobile Broadband (eMBB) services [1]. The first 5G trials and commercial deployments are expected to be validated in hot-spot and overcrowded areas, such as stadiums, malls, train stations, open air festivals etc. where the presence of multiple users may result in financially more feasible deployments with reduced cost per Gb/s [2], while the first 5G roll outs are foreseen to be deployed in the next two years. More specifically for the European region, EURO 2020 is currently considered as a possible 5G “launching event” at stadiums and fan zones [3], with augmented and virtual reality services providing immersive experiences to entertain fans before, during and after the game, or even around the stadium, e.g. when a large number of fans are concurrently leaving a public event with low nomadic mobility, providing broadband services to users and connection to automated transportation.

Despite the simultaneous connectivity of large numbers of subscribers, users would still expect guaranteed bandwidth to experience high-quality services, with expert alliances such as International Telecommunications Union [4] and Next Generation Mobile Networks [5] currently defining certain Key Performance Indicators (KPIs). Indicatively, broadband access in 5G KPIs is expected to reach end-user downlink data rates spanning from 1 Gb/s for a few indoor devices up to 30,000 subscribers in a stadium area with 25 Mb/s. Such high user rates and high-density networks certainly scale well beyond what is currently supported by 4G Long-Term Evolution (LTE) and LTE-Advanced (LTE-A) systems, and are translated into a 1000x capacity increase that has to be achieved with reasonable cost- and energy-expenses [2]. In addition, 5G guidelines have set stricter delay constraints for ultra-low latency applications with delay down to 1 ms [5].
Towards addressing these 5G goals, intense research and industrial efforts have promoted further technology advances mainly in two directions, i.e. higher capacity New Radio (NR) wireless systems and more efficient mobile Fronthaul (FH). On the one hand, NR wireless systems may facilitate higher-capacities deliver over smaller-cells [6], i.e. short-range Base Stations (BSs) that are densely deployed using highly directional massive Multiple Input Multiple Output (MIMO) antennas [7], precisely focused antenna pencil-beams to end users and enhancing the spectral efficiency and frequency reuse factors of the network. NR systems will utilize the immense unused spectrum at the millimeter-wave (mmWave) frequency bands around the 28 GHz or 60 GHz bands; the first deployments of 28 GHz are promoted for outdoor backhauling for fixed wireless access and moving hotspots in Pyeong Chang winter Olympic Games in 2018 [8] and 60GHz access system for ultra-high speed content delivery with low-latency at the Tokyo-Narita airport [9]. On the other hand, Analog-Radio over Fiber (A-RoF) techniques are currently being investigated as efficient fronthauling schemes, aiming to replace the widely deployed inefficient Common Public Radio Interface (CPRI) standard between the Baseband Unit (BBU) and the Remote Radio Head (RRH). As CPRI necessitates dense sampling of the In-phase (I) and Quadrature-phase (Q) wireless signal constituents with 16 bits/sample resolution in order to digitally transport the signals using On/Off Keying format, resulting in roughly two orders of magnitude bandwidth penalties compared to actual data [10]. For instance, a single 100MHz LTE signal with 16 bits/sample resolution and 30% compression, transmitted by 2 antennas would consume approximately 20.6 Gb/s CPRI capacity [11], while scaling to higher number of users or MIMO antennas (e.g. 64x64) would make the costs prohibitive large.

All the above indicate that multi-user Gbit-class wireless traffic cannot be served or backhauled by traditional Base-Station architectures, necessitating the synergy of both fiber and wireless solutions that combined can support ultra-high bandwidth, dense coverage and long-distance signal transmission with alternative schemes for efficient aggregation and RoF signal transportation. In addition, ultra-dense high-bandwidth RRH deployments cannot rely exclusively on fiber connections reaching every BBU, but instead must be based on both wireless and fiber-based fronthauling to avoid. In this article, motivated by the majority of efforts that suggest mmWave massive MIMO communications [12], efficient functional split between BBU and RRHs [13] and transition to Ethernet-based fronthaul transport [14][15], we present “5G-PHOS” (H2020 5GPPP Phase II project) approach that exploits optical technologies towards a Digital Signal Processing (DSP) -assisted analog fronthaul for seamless and medium-transparent V-band (57-64GHz) 5G small-cell networks.

II. THE 5G-PHOS APPROACH

The proposed approach relies on the synergy of integrated optical technologies and medium transparent resource allocation protocols towards enhancing Fiber-Wireless (FiWi) convergence and realizing cost-effective energy-efficient 5G network solutions for high density networks. More specifically, the proposed solutions include the development of 5G broadband fronthaul architectures for Urban (Dense/Ultra-Dense) and Hot-Spot areas, leveraging optical mmWave signal generation, DSP-assisted optical transmission, ROADM and optical beamforming functionalities in conjunction with mmWave massive MIMO capabilities. Thus, the exploitation of a 5G cross-layer technology portfolio, spanning from FiWi Cloud-Radio Access Network (C-RAN) centralized unit and MIMO antennae up to DSP-assisted analog FiWi fronthaul and Software Defined Networking (SDN) control plane, allows for the migration from CPRI-based to integrated FiWi packetized C-RAN fronthaul supporting mmWave massive MIMO communications.

Following the aforementioned approach, we have identified three different use cases scenarios with different operation needs and characteristics, translating also to varying needs in network-cell densification, aggregate traffic capacities and connection densities, as illustrated in Fig. 1: a Dense area, an Ultra Dense area and a Hot-spot area. All three scenarios consider a centralized architecture with the BBUs placed at a centralized box, which is here termed as FlexBox, fiber interconnected to the RRH units, which are equipped with mMIMO mmWave antennas.

A. Dense Area

For typical dense areas, a 25 Gb/s wireless peak data rate operating on top of Passive Optical Networks (PONs) is envisioned, as illustrated in Fig. 1(i) delivering a packetized integrated FiWi fronthaul network for dense area coverage, while mmWave connections at the RRH provide street level antennas, which in turn are responsible for providing access to end users through a second wireless network interface, effectively replacing fiber links and circumventing the need for cost-expensive brown field fiber installation.

B. Ultra-Dense Area

In case of increasing number of subscribers in Ultra-Dense environments such as in metropolitan city centers, e.g. in enterprise building, university campuses, shopping malls, etc. with significantly increased capacities, spatially multiplexing
of multiple parallel FH links over a bundle of 16 fibers can deliver 400 Gb/s wireless peak data rate, as shown in Fig. 1(ii). Here, adopting optical Spatial-Division-Multiplexing (SDM) techniques are considered for several dedicated point-to-point 25 Gb/s converged FiWi links.

C. Hotspot Area

Finally, for hotspot areas with thousands of subscribers tightly located in a small geographical region, as e.g. in stadiums, open events, etc. mmWave frequencies can be directly utilized at the access part of the network to facilitate direct high speed data links to the subscribers, with peak aggregate data rates of 100 Gb/s per wavelength, as shown in Fig. 1(iii). In this case, a large number of RRH antennas can be scattered around the stadium to cover the whole area, e.g. when users are temporarily located at certain spots/stadium gates, at dedicated fan-zones or around the stadium when leaving the public event, and the number of RRH units can potentially exceed the number of available wavelengths of the network, requiring dynamic allocation of the wavelength resources. This scenario would showcase the benefits of introducing Wavelength Division Multiplexing (WDM) technology and ROADMs to the RRH units, so as to facilitate wavelength selectivity and wavelength re-configurability, necessitating a suitable Medium Transparent MAC protocol to manage the shared network resources, i.e. wavelength, frequency and time.

In order to achieve the above capacities and transport them across the mobile FH, while maintaining the cost- and energy-expenses and investments at a reasonable level, it is being evident that significant advances are required. In this direction, 3GPP has started investigating a re-definition of the possible functional split between the BBU and the RRH [16]. The possible functional splits are illustrated in Fig. 2. Higher layer function include Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC), followed by the MAC layer, the higher physical sublayer featuring wireless coding/decoding and the lower layer including coding, equalization and MIMO processing. CPRI forms the most widely deployed standard, implementing a low layer split, while the possible higher layer split at order of increasing layer are referred as Split PHY, Split MAC and PDCP-RLC. The figure also shows the impact that each split has on the FH capacity requirements for transportation of 151 Mbps actual user data stream, as found in [17]. As it can be clearly seen, the transmission capacity required for the CPRI scheme is 2500 Mb/s, resulting in two order of bandwidth penalty compared to the actual 150Mb/s, while shifting to the higher layer splits achieves drastic reduction of the capacity requirements down to 1075 Mb/s, 151Mb/s and 151Mb/s respectively. Although higher layer splits seem appealing in terms of efficient fronthauling of radio signals, they require more sophisticated functionalities and advanced processing placed to the RRH unit, turning the RRH into costly equipment, dispensing the benefits and advantaged of the C-RAN architecture, which centralizes all the intelligence at the BBU.

On the contrary, the 5H-PHOS project envisions a different low-layer analog PHY split, based on A-RoF transport schemes that will facilitate native wireless signals to be load on Intermediate Frequencies (IF) and flow over the Fiber (IFoF) through the converged FiWi architecture with bandwidth requirements less than 200 MHz, depending on the modulation format employed, while also utilizing a common pool of hardware for all the above three use-case scenarios.

The functional block-diagram of the proposed DSP-assisted RoF FH is illustrated in Fig. 3(ii). In particular, the centralized units (BBUs) host the majority of cross-layer technologies and functions, such as the PHY layer analog electro-optic (EO) transceivers for EO/EO signal conversion in DL/UL mode, the PHY layer functions offered by the DSP engine (i.e. channel (de)mapping, channel (de)coding and multi-carrier (de)modulation) and the Medium Access Control (MAC) layer for moving packets between end-hosts and the centralized units in order to dynamically allocate both the optical and wireless capacity resources among the different RRH sites. On the other hand, the RRHs contain only the necessary PHY layer optics for phase shifting and optical switching operations, OE/EO conversions as well as the required RF electronics for transmitted/receiving the incoming wireless signals. This architecture centralizes all the main processing operation, such as DSP and MAC functionalities, at the FlexBox, alongside with analog-to-digital converters and analog-linear transceivers, while the RRF features only the required PHY hardware for A-RoF transportation, as well as transmitting/receiving the wireless signals. This layout eliminates the need for complex DSP at the antenna site that comes from the use of RF-beamformers at the RRH, and instead utilizes an Optical Beamforming Network (OBFN), pushing photonic components and o-e converters further inside the RRH to effectively replace the costly- and power-consuming electronics.

III. OPTICAL TECHNOLOGIES FOR 5G A-ROF FRONTHAUL

The 5G-PHOS project relies on already developed Photonic Integrated Chip (PIC) technologies towards enabling a SDN
Fig. 5 Technology pool of Photonic Integrated Chips of the 5G-PHOS project, including microscope images of actual fabricated devices (left side) and principle of operation (right side), including: i) cost-effective linear analog optical transceivers employing an Externally Modulated Laser and a Photodiode [18], ii) 1x8 Optical Beamforming Network implemented on Triplex platform [21],[22] and iii) a 2x2 Ring resonator part of Silicon Reconfigurable Optical Add Drop Multiplexer [23].

programmable architecture, which mainly include i) linear analog optical transceivers capable to handle spectrally efficient advanced modulation formats on optical IF carriers, ii) low-loss integrated OBFN to facilitate scalable mmWave massive MIMO antennas and iii) ROADM supporting wavelength selectivity and reconfigurability in the optical FH network. Fig. 4 shows the basic optical technologies to be employed within the 5G-PHOS project, including some indicative microscope images on the left side of fabricated devices and the proof-of-principle operation on the right side.

A. Analog Optical Transceivers

The linearity of the analog optical transceiver plays a critical role in the performance of microwave photonic links. As optical modulators typically rely on Mach-Zehnder Modulators (MZM), they exhibit a cos²-shaped transfer function that typically induce some frequency chirp. On the other hand, such a microwave IF link between the FlexBox and the RRH can be implemented by a low bandwidth Externally Modulated Laser (EML), featuring a DFB laser followed by an Electro-Absorption Modulator (EAM) exploiting the linearity region of the transfer function of the EAM, as schematically illustrated at the right inset of Fig. 4(i), which can be monolithically integrated on a common InP substrate to facilitate a cost-effective solution. Although high optical powers together with linear performance are required for long fiber reach, typically EAM performance degrades at high optical powers as, owing to saturation effects of photogenerated carriers, non-linearly distorting the signals or limiting the optical power budget. On the contrary, here we employ a high-power linear EML with high optical output power and linear response, develop initially for PON and access networks, as described in [18]. By utilizing low cost optics with bandwidth up to 10GHz, native wireless signals of up to 1Gbaud can be loaded on IF carriers at around 5GHz using A-RoF techniques to be transported over the fiber in a cost-effective way, featuring advanced modulation format (QPSK, QAM, OFDM) to achieve higher bitrates, while DSP techniques can facilitate frequency-channel aggregation. Such mobile optical FH links have been recently demonstrated both for the fiber transport part [10] and for a converged 28GHz Fiber Wireless link with aggregate speeds up to 4.56Gb/s [17], while one of our early exhaustive experimental studies of the mmWave/IFoF Fiber Wireless link reveals the potential of the 57-64GHz towards aggregate capacities beyond 10Gb/s [20] over a V-band wireless link transmitted at 5m, using an off-the-shelf antenna with 10° beamwidth and 23dBi antenna gain.

B. Optical Beamforming Network

5G-PHOS will deploy the Triplex waveguide platform to implement a ring-based binary tree structure of an OBFN network, to benefit from the ultra-low loss down to 0.1dB/cm and CMOS-compatibility features [21],[22], aiming to achieve a scalable feeding network architecture for massive MIMO antenna systems up to 64x64 with low-cost, low-footprint and low-power consumption requirements. A typical 1x8 OBFN and its proof-of-principle operation are illustrated at Fig. 4(ii), adopting a tree-based splitting/combining architecture, i.e. the incoming signal is split by a three-stage cascade of 1x2 splitters, where optical True-Time Delay units are interleaved between the sequential stages, adding each time some extra propagation time-delay along the path to the 8 signal constituents. The 8x signals in turn feature such a differential phase shift so that they can constructively interfere only at certain angles, bring additional flexibility and steering capabilities to the mMIMO antenna. Triplex based OBFNs can easily support the 7GHz bandwidth of the 57-64GHz spectrum, while also supporting large tunable delays above 1ns for squint-free beamsteering with near instantaneous response. Furthermore, OBFNs can be integrated and controlled by a microcontroller, to utilize SDN programmability of the FH.
C. Add/Drop Multiplexers

In cases of Ultra high densities such as stadiums and open air events, etc. connections densities may reach 150,000 / km² or 30,000 users in a stadium, which translated to traffic densities can reach Downlink and Uplink values of 3.75Tb/s and 7.5Tb/s respectively [5][4]. Such high traffic demand can certainly not be transported by a single wavelength or a few IF-carriers neither can be statically allocated to tightly confined region, but instead it has to support dynamic allocation and reconfigurability in order to be steered towards mobile users with some mobility within or around the stadium [3]. Triplex platform will also be employed here towards developing ring-resonator based ROADM s [22], to be fabricated and installed in-front of the OBFN networks, i.e. before the fiber connection of the MIMO antenna, acting as an optical front-end. Optical Add/Drop Rings and ROADM devices, as illustrated in Fig. 4(iii), are capable of switching wavelength channels, and allocating different traffic capacities to the RRH. The WDM architecture envisioned and illustrated in Fig. 5 will employ multi-wavelength transmitters using 4x arrays of EMLs and equal number of wavelengths. In this configuration, a multi-wavelength optical downstream will be transmitted around the stadium, with sequential ROADM-equipped RRHs being arranged in a bus topology. The ROADM will either Drop the wavelength to the first RRH unit, in case the traffic is allocated to this specific antenna, or switch it to the next RRH2 of the bus and so on.

IV. MEDIUM-TRANSPARENT PACKET-BASED FRONTHAULING

In this section we present the main operation characteristics of the MT-MAC protocol while a complete presentation can be found in [25]. According to the MT-MAC specifications, the BBU is connected through an PON architecture or optical bus topology to a number of RRHs that serve the wireless clients through the mmWave medium. The optical wavelengths are transmitted from the BBU and are injected into the optical fiber in pairs for serving both the downlink (BBU to RRH) and uplink (RRH to BBU) traffic. A dedicated wavelength pair is utilized for control purposes, i.e. for identifying the active RRHs and for carrying out the wavelength allocation to the active RRHs in order realize the data transmission between the wireless clients and the BBU. The MT-MAC protocol incorporates two contention periods for managing the dual-medium allocation to the wireless clients: (a) the First Contention Period (FCP) is responsible for identifying the RRHs with clients requesting data transmission and (b) the Second Contention Period (SCP) is responsible for allocating both the optical and wireless resources to the end clients.

According to the FCP, every active RRH is being controlled by the BBU in order to tune its photodiodes to the specific wavelengths that will be used for the data transmission. In cases that the number of active RRHs exceeds the number of the available wavelengths, the BBU employs a Time Division Multiplexing (TDM) scheme in order to serve all the active RRHs. The MT-MAC protocol currently supports two TDM mechanisms where (a) the first is based on the Round Robin algorithm where each RRH is being served for equal amount of time and (b) the second is based on the number of active clients residing in the different RRHs where RRHs with more clients are proportionally served for higher amount of times [25]. Data transmission is carried out in form of Superframes (SFs) where each SF is comprised of (a) the Resource Requesting Frames (RRFs) and (b) Data Frames (DFs). The RRFs are responsible for carrying out the configuration procedures of the SCP while DFs are responsible for the carrying out the actual data transmission.

During the SCP contention resolution each wireless client proceeds to a random number selection and as long as all nodes choose distinct numbers, all terminals will be successfully identified and, consequently, the SCP will conclude. The RRFs are divided into s slots, with each slot being long enough to support the transmission of a series of POLL, ID and ACK packets. At the beginning of the RRF, each UE chooses a random number between 1 and s. This number signifies the number of POLL frames that the UE must receive prior to transmitting its ID frame. If the BBU receives and decodes the ID frame successfully it will reply with an ACK, notifying the UE that is has been correctly identified. However, if two or more UEs choose the same number γ, they will transmit at the same time, and a collision will occur. In turn, the BBU will be unable to correctly decode the ID packets and will keep on transmitting RRFs until no collisions are detected. Eventually, the BBU will ensure that every node has been correctly identified and will then proceed with the transmission of the data packets based on the newly formed polling sequence.

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