A 5G C-RAN Architecture for Hot-Spots: OFDM based Analog IFoF PHY and MAC Layer Design

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Abstract— Centralized Radio Access Network (C-RAN) comprises one of the high technologies for high capacity and low latency fronthauling in 5G networks. In this paper, we propose and evaluate an optical fronthaul 5G C-RAN architecture that targets to meet the bandwidth, latency and energy requirements of high traffic hot-spot areas. The proposed architecture employs Intermediate-Frequency-over-Fiber (IFoF) signal generation by Photonic Integrated Circuit (PIC) Wavelength Division Multiplexing (WDM) optical transmitters at the Base-Band Unit (BBU), while a novel design of Reconfigurable Optical Add-Drop Multiplexers (ROADMs) is used at the Remote Radio Head (RRH) site. An aggregate capacity up to 96 Gb/s has been reported by employing two WDM links with 4-band Orthogonal Frequency Division Multiplexing (OFDM) 64-QAM 0.5 Gbaud signals, showing error vector magnitude performance within the acceptable 8% limit. The physical layer evaluation of the proposed fronthaul is also extended with the evaluation of the network throughput and mean packet delay latency, using a Medium Transparent-Medium Access Control (MT-MAC) protocol, which employs gated service indicating latencies below 10ms.

Keywords — 5G, Intermediate Frequency over Fiber, MAC, OFDM, Optical Fronthaul, Photonic Integration.

I. INTRODUCTION

Future Radio Access Networks (RANs) are expected to bring a 1000x increase in mobile traffic, setting a diverse set of requirements beyond the capabilities of 4G networks [1]. Towards satisfying user experience, 5G broadband access has been defined by expert alliances through Key Performance Indicators (KPIs) that foresee user rates of 1 Gb/s and peak rates up to 10 Gb/s at latencies less than 10 ms [1]. To meet these requirements, research efforts have been directed towards upgrading the underlying key technologies, which appear to converge to some widely accepted directions:

i) Centralized (C)-RAN technology [2] promoted by the operators as a means to alleviate the densification costs and reduce complexity of the fronthaul networks. C-RAN schemes shift the most demanding operations to the Central Office (CO), simplifying the Access Points (APs), while concurrently enabling improved radio coordination.

ii) High-bandwidth optical links between the Base-Band Unit (BBU) and the Remote Radio Head (RRH) for efficient fronthauling. Analog Radio over Fiber has emerged as an appealing transport scheme, since data signals are modulated on Intermediate Frequencies over Fiber (IFoF) using cost-effective Externally Modulated Lasers (EMLs) achieving CPRI equivalent rates up to 1 Tb/s, mainly evaluated for the fiber part of the network [3]-[4]. On the contrary, Fiber Wireless (FiWi) fronthaul links have been studied either for high capacity single carrier QPSK, QAM-16 with up to 1 GHz channel bandwidths [5] or OFDM channels with a bandwidth up to 150MHz [6].

iii) OFDM-based waveforms benefiting from their simple wireless channel estimation and efficient hardware implementation, have shaped the success of 4G LTE networks [7]. This has inspired also some first steps towards multi-user OFDM-based 5G optical fronthaul studies, which apart from small channel bandwidth, typically rely also on costly, bulky Mach Zehnder Modulators (MZMs) [6].

iv) Photonic Integrated Circuits (PICs) with proven credentials in optical communications, can bring equal cost-and energy-savings to the 5G networks. This involves cost-and energy-efficient transceivers with peak data rates beyond the 10 Gb/s and high optical output powers [5], as well as the use of Reconfigurable Add/Drop Optical Multiplexers (ROADMs) [8], integrated on a low-loss silicon photonics platform. However, both PICs have been investigated only for metro-rings and PONs.

v) Medium Access Mechanisms and Dynamic Bandwidth Allocation protocols to handle the burst mode access schemes of the FiWi medium, while simultaneously ensuring the low latency constraints. Recently, we presented the preliminary results of the employment of a Medium-Transparent resource allocation scheme in a hotspot FiWi network [9], however without investigating the actual physical (PHY) - layer topology requirements.

On the race to make 5G a reality till 2020, predominant research efforts have indeed achieved significant advances in each of the above distinct technologies, yet it remains a prevailing ambiguity on what will be the optimum network platform that will manage to synergize all innovation aspects and simultaneously meet the stringent KPIs. Drawing from these recent distinct achievements, we extend our previous MAC-layer study [9] by providing a PHY - layer study of the proposed analog IFoF 5G fronthaul architecture. In this analysis, we deployed OFDM-based IFoF links with 500 MHz channel bandwidths using...
integrated photonic InP transceivers and WDM-ROADMs to synthesize a hot-spot FiWi network for stadiums with up to 96 Gb/s capacity. Our analysis relies on experimentally verified simulation models of the optical transceivers as well as the impairments of the fiber-propagation, while WDM functionalities are leveraged by a novel ROADM design.

Finally, an updated scalability analysis of the network coverage is presented, aligned with the PHY-layer topology requirements resulted by the PHY-layer study. In this analysis we applied a MT-MAC protocol for evaluating the overall network performance in terms of aggregate throughput and latency, achieving mean packet delay latencies below 10 ms even for 80% network loads and meeting in this way the 5G KPIs metrics. To the authors’ knowledge, this work is the first to investigate the overall PHY-layer architecture of a 5G network of an actual stadium, relying on OFDM-based IFoF links and completing the analysis by incorporating the PHY-layer specifications into a 5G Hot-Spot MT-MAC mechanism.

This paper is organized as follows: Section II describes the 5G hot-spot architecture, Section III the PHY-layer evaluation of the optical link, Section IV the MAC-layer performance evaluation and Section V the conclusions.

II. 5G FRONTHAUL ARCHITECTURE FOR HOT-SPOTS

The conceptual representation of the proposed optical fronthaul network architecture of the sport-stadium is depicted in Fig. 1. Our scheme consists of a BBU at a centralized location of a converged FiWi architecture, being optically interconnected with multiple RRHs dispersed around the stadium and equipped with mmWave antennas. The RRHs are cascaded in an optical bus, with each node comprising a ROADM before the antenna, while the communication between the BBU and the RRH relies on dedicated WDM transceivers for each optical bus, based on integrated photonic EMLs equal to the number of WDM channels available in the bus. Each ROADM is capable of either dropping any of the available wavelengths to the connected RRH or forwarding them to the next node of the bus, allocating in this way the available optical capacity to the different regions of the hot-spot area. Finally, the RRH comprises a number of antennas operating at the mmWave band and each of these antennas converts the data signal carried by a specific wavelength from the optical to electrical form and up-converted it to the mmWave band for wireless transmission to the users. At this point, it is also worth mentioning that frequency aggregation on a per wavelength basis allows loading several user channels on different Intermediate Frequency (IF) bands for optical transmission.

Towards designing the overall architecture, it is critical to identify what is the optimum set of resources in terms of fiber-lengths, optical losses, inter-antenna distances, number of wavelengths, modulation format, throughput etc., targeting to meet the 5G KPIs, while simultaneously complying with the PHY-layer performance metrics of the underlying hardware and maintaining a low cost and power consumption envelope, as presented in the next sections.

III. OPTICAL FRONTHAUL PHY-LAYER EVALUATION

Towards evaluating the PHY-layer performance of the optical fronthaul, we performed simulations carried out by means of VPI software. Initially, we created an
experimentally verified simulation model of the end-to-end optical transmission used as a reference single wavelength communication link. In this setup, the employed optical transmitter was matched with the respective experimental characterization results obtained for a high-power linear EML monolithically integrated on an InP platform [5], while the signal degradation induced by the fiber was matched to a Standard Single Mode Fiber (SMF). We then proceed to the simulated response of a novel MZI-based ROADM design on the TriPleX platform [10], and simulate the multi-channel OFDM-based transmission through the overall optical bus architecture to compare the additional degradation induced by the WDM transmission and the four ROADMs with respect to the reference single-λ link.

### A. Reference Link Simulated Setup

To evaluate the reference link, we employed the simulation setup shown in Fig. 2 (a). An EML-based transmitter [5] is modulated by IFs carrying the analog radio signals, imprinting them on a wavelength in the 1536.9-1539.25 nm window. As the EML has been characterized in terms of Power-Voltage, S21 response and modulation of FiWi links [5], the simulated response was matched with the measurements of the actual PIC device. Four OFDM-waveforms were electrically generated and loaded on different IF bands centered at 4.4 GHz, 5 GHz, 5.6 GHz and 6.2 GHz, before driving the modulator of the EML. Each individual OFDM-waveform consists of 256 Sub-Carriers (SCs), each carrying a 64-QAM format and a baud rate of 1.953 Mbps, resulting in a channel bandwidth of 500 MHz with a data-rate of 3 Gb/s. The 4 OFDM waveforms are separated by a guard band of 100 MHz, while the aggregate data rate of the 4 channels loaded on the EML output is equal to 12 Gb/s. The generated optical signal is transmitted through a SMF, received by a 10 GHz Photodiode (PD) for o/e-conversion, and amplified by a low-noise Trans-Impedance Amplifier (TIA) with 20 dB gain before being down-converted and evaluated at an Oscilloscope (OSC). A Variable Optical Attenuator (VOA) was used to vary the optical power entering the PD for the EVM testing.

### B. Hot-Spot Link Simulated Setup

The proposed fronthaul architecture consists of two identical optical buses extending around the stadium, each one consists of a cascade of 4 ROADMs. Without loss of generality, we here focus our study on one of the two identical buses in the downlink communication, as depicted in Fig. 2 (b), yet equal optical performance is also expected for the second bus or the uplink communication. The WDM transmitter of the BBU comprises 4 EMLs operating in the C-band, to modulate the respective CWs at 1536.9 nm, 1537.67 nm, 1538.46 nm and 1539.25 nm with 100 GHz channel spacing. Each EML is driven by a multi-band electrical signal with 4 frequency-aggregated OFDM signals towards a fronthaul capacity of 12 Gb/s per λ, exactly as the one used in the reference link of Fig. 2 (a) and equivalent to the experimental demonstration of the EML based FiWi link [5]. The outputs of the four EMLs are then multiplexed by a 4:1 optical Multiplexer (MUX) into a 4-λ-WDM stream for fiber propagation from the BBU towards the cascade of 4 ROADMs of the RRHs across half of the stadium periphery, as shown in Fig. 1. The data rate of the WDM signal serving half of the stadium is then equal to 48 Gb/s, resulting in a total network throughput of 96 Gb/s for 2 optical buses.

The 4 ROADMs used for adding/dropping of the 4 λs, are placed at equidistant locations around the periphery of the stadium [9]. The neighboring ROADMs are placed at a distance of 80 m in a bus topology. In order to investigate the worst case scenario for the longest reach ROADM of the bus, we have evaluated the performance of a WDM signal that crosses through the first three ROADMs and is being dropped only by the last ROADM. The filtering response of the ROADMs was based on the transfer function derived by the PHY-layer designs, presented in the next subsection. After the optical signals are dropped by the last ROADM, they are inserted in an array of 4 photo-receivers (PD+TIA), before being down-converted and sent to the EVM tester.

### C. ROADM Design and Implementation

Towards obtaining low-loss insertion losses by the ROADM device, a novel MZI-based configuration was designed on SiN/SiO2 TriPleX platform with losses as low as 0.1 dB [10], capable to add/drop four wavelengths in the C-band with a channel spacing of 100 GHz. Fig. 3 (a) depicts the ROADM circuit-layer design which is based on a cascaded configuration of MZI-channel interleavers. The four wavelengths (λ1, λ2, λ3, λ4) are fed into the input port of the first (green) cascade of MZIs, with a Free Spectral Range (FSR) of 200 GHz in order to split the 200 GHz spaced λ1 and λ2, λ3 wavelengths to its output port 1 and output port 2, respectively. Each WDM output signal is inserted into the brown cascade of MZIs which has an FSR equal to 400 GHz. Focusing on the upper arm of the ROADM, the first brown block of MZIs drops λ1 while the second cascade of MZIs drops λ2. Similarly, λ3 and λ4 are exiting the output port 1 of the first and second cascade of MZIs at the lower arm.

Fig. 3 (b) illustrates the building block of the MZls, with two of them being connected to each other via tunable couplers (TCs). In this way, it is possible to control the coupling coefficients of the device, and thus, obtain the desired transfer functions. The first MZI has an arm difference of 2dL while the arm difference of the second one is equal to dL. Due to the dispersion, it is crucial that the 2dL and dL are not in the same path, but on the opposite parts of the waveguides. Phase Shifters (PSs) are placed in each MZI to adjust the maximum and minimum power spectral positions of the filter of the MZIs for dropping or passing the proper λ. Fig. 4 (a) illustrates the transfer functions for the output ports 1 and 2 of the green block of MZIs having an FSR equal to 200 GHz. Fig. 4 (b) shows the respective transfer function of the brown cascade of MZIs that has an FSR equal to 400 GHz. In both cases flat-top filter shape was obtained by properly adjusting the coupling coefficients of the TCs. The required arm difference for the block of MZIs with FSR=200 GHz is equal to dL=1=872.1 μm while the respective difference for the block of MZIs with FSR=400 GHz is equal to 436 μm. The maximum expected losses of the ROADMs are estimated to 4.2 dB. The designed ROADM is currently being fabricated and the experimental characterization is expected within the next months.

### D. Simulation Results

Initially, we evaluated the performance of the single-λ transmission of the OFDM-based IF channels through the reference link without any ROADM. The SMF length was considered 500 m, based on the typical stadium periphery specifications, resulting in a Received Optical Power (ROP) of -13 dBm for each of the IF bands. The results obtained
for the EVM values per SC for all IF bands shown in Fig. 5, where it is clear that all IF bands exhibit similar performance and nearly equal EVM values at an average of 4.6%. It is worth noting that all SCs exhibit performance within the EVM threshold of 8%, as defined by 3GPP [11].

Having evaluated the single-λ reference transmission, we proceeded to the investigation of the additional degradation inserted by the 4-λ WDM optical transmission and the interleaved ROADM devices for the longest reach antenna of the hotspot fronthaul network, i.e. when the optical data stream has to cross through three cascaded ROADMs and be dropped at the 4th ROADM. The results obtained are presented in Fig. 6. The length of the SMF was again considered to be equal to 500 m and the minimum ROP corresponded to IF1 due to unequal power losses inserted by the ROADM channels, was also set to be equal to -13 dBm for comparison purposes against the reference link. Fig. 6 (a) shows the EVM measurements per SC for all IF bands of the first WDM channel (λ1=1536.9 nm). The first IF band at 4.4 GHz exhibited the worse performance with EVM values of the SCs ranging between 5.2% - 6.9% and the last IF at 6.2 GHz revealing slightly better performance with EVMs between 4.4% - 5.6%. The constellation diagrams for the worst performing SCs of the first and fourth IF are shown in Fig. 6 (b), (c). This non-equal performance of the four IFs is attributed to the filtering effect experienced by the aggregated-IF signal, as it crosses through the first 3 ROADMs and is being dropped by the 4th ROADM, resulting in uneven losses and not ideally flat channel response. Despite the slight deviations, all IFs achieved EVM performance within the accepted threshold of 8% [11].

Towards evaluating the longest reach to place the BBU from the hotspot area and the maximum optical losses of the transport network, we performed a power budget analysis with the main criteria being the EVM value after the 4th ROADM to be within the acceptable limit. We considered the same topology for the hotspot network, with the distance between the BBU and the 1st ROADM of the hotspot extended up to few kms. Fig. 7 shows the ROP versus the length of the SMF connecting the BBU with the 1st ROADM. The red line corresponds to the actual ROP reaching the PIDs calculated by taking into account the output power of the EML (5.8 dBm), the losses of the MUX and each ROADM of 1.5 dB and 1.7 dB, respectively, and a standard SMF propagation losses of 0.25 dB/km. The other 4 curves show the ROP required by the worst-performing SC at the PDs employed after the last ROADM to achieve EVM of 8%. As it is shown, the EVM degrades for all channels as the SMF length increases due to the chromatic dispersion, resulting in a slightly higher ROP required for the WDM channel of the higher wavelength (1539.25 nm). Furthermore, by comparing the actual and required ROP, it is obvious that these curves cross at a length of 3.2 km, where the required ROP is higher than the available power budget that would severely degrade the EVM. This reveals that the longest distance between the BBU and the hotspot can be 3.2 km.

**Fig. 5. Single-λ link without ROADM: EVM per SC for all IF bands.**

**Fig. 6. Hot-spot WDM Link with ROADM: a) EVM per SC for all IF bands b) constellation diagram for the first IF band and c) last IF band.**

**Fig. 7. Received Optical Power (ROP) versus the length of the fiber connecting the BBU with the first ROADM. Curve of the actual ROP deriving from the power budget of the hot-spot link and curves of the ROP required to achieve EVM = 8% for all WDM channels.**

IV. **Fiber-Wireless MAC Layer Performance Evaluation**

In this section, we evaluate the performance of the proposed optical fronthaul architecture in a hotspot scenario, where end-point wireless users communicate with the BBU through the Fiber Wireless mmWave links and access to the FiWi medium is controlled by a Medium Transparent-MAC (MT-MAC) protocol [9].

We consider a typical stadium area, matching Thessaloniki’s Toumba stadium specifications [12], as depicted in Fig. 9 (a). Based on the mmWave antenna coverage analysis and parameters provided in [9], the maximum coverage of a single RRH is equal to 38 m. Therefore, we assume 32 mmWave antennas located at 8 discrete points, i.e. RRH locations, arranged in the two identical optical buses interconnecting the RRHs to the BBU (four RRHs per bus), to cover the area of the stadium. Before each RRH, there is a ROADM, i.e. four ROADMs per bus. Furthermore, each RRH consists of four antennas, with each one of them having a dedicated wavelength, as shown in Fig. 8 (b), which can be dropped or not by the ROADM. For instance, focusing on one of the optical buses, λ1 could be dropped to the 1st, the 5th, the 9th or the 13th antenna at a specific instant, λ2, to the 2nd, the 6th, the 10th or the 14th and so on. This dynamic allocation is decided by the MAC protocol.

For our analysis, we adopted the results derived from the above PHY - layer analysis in terms of optical data streams up to 12 Gb/s per λ and fronthaul distances up to 3 km, in
equipped with 4 mmWave antennas and a ROADM.

Fig. 8. (a) Simulated scenario of Toumba Stadium, (b) Each RRH is equipped with 4 mmWave antennas and a ROADM.

<table>
<thead>
<tr>
<th>Fiber Prop. Delay</th>
<th>s (Slots in RRF)</th>
<th>Air Prop. Delay</th>
<th>Normalized Load</th>
<th>ACK Size</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µs / 200 m</td>
<td>250</td>
<td>0.2 µs</td>
<td>Normalized Load</td>
<td>16 bytes</td>
<td></td>
</tr>
<tr>
<td>Data Size</td>
<td>9 KB</td>
<td>ID, POLL Size</td>
<td>72 bytes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Bit rate per λ</td>
<td>12 Gbps</td>
<td>Buffer Size</td>
<td>250 packets</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9. (a) Normalized throughput and (b) mean packet delay versus the normalized load in the system.

TABLE I. MT-MAC SIMULATION PARAMETERS

order to adapt the Java network simulator used in the MT-MAC analysis of [9], considering gated service for maximum performance gains. As a result, the superframes have no longer fixed size, given that each user is authorized to send the number of bytes it requested. Regarding the user distribution, according to NGMN [1], the connection density in hot-spots is 150000/km² assuming an activity factor of 30 %. As a result, for the Toumba stadium (0.016 km²), this leads to 8000 connections on average, and 2400 active connections for the same activity factor of 30 %. We also assume a uniform distribution of users in the 32 antennas, i.e., 250 users per antenna. The traffic follows the Poisson distribution, while all users are equipped with buffers (able to hold 250 packets) to accommodate the packets. The rest of the MT-MAC parameters are summarized in Table I.

V. CONCLUSION

We presented an analog optical 5G fronthaul architecture exploiting spectrally efficient OFDM-based IFoF links and photonic integrated technologies to meet the high-bandwidth and low-latency demands of hot-spot areas in a cost effective and energy efficient manner. The fronthaul utilizes WDM PIC-based optical transmitters and RRHs arranged on a bus topology using cascaded low-loss TriPleX ROADM. By exploiting 4-band OFDM, each carrying 0.5 Gbaud 64-QAM, and 4-λ WDM, an almost close to 100 Gb/s aggregate capacity is achieved, while the power budget analysis reveals the feasibility of placing the BBU in a distance up to 3.2 km from the hotspot. The network performance is evaluated by means of a MT-MAC protocol, verifying latency values below 10 ms, showcasing a candidate network solution to serve the stringent demands of 5G hot-spots.

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