Converged Analog Fiber-Wireless Point-to-Multipoint Architecture for eCPRI 5G Fronthaul Networks

G. Kalfas¹, M. Agus², A. Pagano², L. Anet Neto³, A. Mesodiakaki¹, Ch. Vagionas¹, J. Vardakas⁴, E. Datsika⁴, C. Verikoukis⁵, N. Pleros¹

¹ Dept. of Informatics, Aristotle University of Thessaloniki, Greece {gkalfas@csd.auth.gr, amesodia@csd.auth.gr, chvagion@csd.auth.gr, npleros@csd.auth.gr},
² Telecom Italia, Torino, Italy {mauro.agus@telecomitalia.it, annachiara.pagano@telecomitalia.it}
³ Orange Labs Networks, Lannion, France {luiz.anetneto@orange.com}
⁴ Iquadrat Informatica, Barcelona, Spain {jvardakas@iquadrat.com, edatsika@iquadrat.com},
⁵ Telecommunications Technological Centre of Catalonia (CTTC), Castelldefels, Spain {cveri@cttc.es}

Abstract—5G New Radio’s (NR) spectrum expansion towards higher bands, although critical towards achieving the envisioned 5G capacity requirements, creates the need for installing a very large number of Access Points (APs), which asserts tremendous capital burden on the Mobile Network Operators. Current centralization solutions such as the Cloud Radio Access Network (C-RAN) alleviate partially the costs of densification by moving the majority of radio processing functionalities from the Remote Radio Heads (RRHs) to the central Base Band Unit (BBU), but still require very high-speed Point-to-Point links between the BBU and each RRH mainly due to the digitized Common Public Radio Interface (CPRI) that is excessively inefficient for hauling broadband signals. In this article, we present a novel architecture that employs an analog converged Fiber-Wireless scheme in order to create a very spectrally efficient Point-to-Multipoint network capable of interconnecting a large number of APs, while allowing compatibility with mature Ethernet-based low-cost equipment. Preliminary simulation results show very low end-to-end Ethernet packet delay, well below eCPRI’s 100 μs mark, even for fiber lengths up to 10 km, indicating the suitability of our solution for deployment in 5G NR large-scale fronthaul networks.

Keywords—5G New Radio, evolved CPRI, analog Radio-over-Fiber, Fiber-Wireless fronthaul

I. INTRODUCTION

The mobile telecommunications networks are currently entering the critical phase where the first 5G solutions move beyond the drawing board and slowly enter commercialization phase [1]. However, many issues remain unresolved, especially considering large-scale 5G implementations, such as the choice of the optimal architecture that will be able to effectively address the costly densification problem faced today by the Mobile Network Operators (MNOs). Network densification is currently seen as the most prominent solution towards achieving the ambitious 10x 5G capacity targets, since the increment of the Access Point (AP)/Mobile Entity (ME) ratio as well as the reduced cell size can significantly enhance spatial reuse and improve network capacity [2]. Besides spatial reuse, AP densification is also enforced due to the expansion of the access networks to higher mm-wave spectrum, as has been recently standardized in the 5G New Radio (NR) specifications [3], that effectively resolves the <6 GHz bandwidth scarcity problem albeit at the cost of increased propagation and absorption losses, thus contributing further to the densification necessity.

Radio Access Network (RAN) centralization is steadily gaining momentum as a possible preferred solution for decreasing the cost of densification [4] since it provides much simpler and cheaper radio heads and offers a multitude of benefits, like load balancing, combined processing of radio signals, reduced power consumption, network extensibility, etc. The most wide-spread centralized RAN architecture is the Cloud-RAN (C-RAN) that separates the radio operations between two entities: i) the lightweight and cost-efficient Remote Radio Heads (RRHs) that perform simple radio operations and are spread-out in the mobile service coverage area and ii) the remotely located Base Band Unit (BBU) that synthesizes the radio signal and performs almost all heavy-
duty radio operations such as channel estimation, demodulation, Fourier transformations (iFFT, DFT etc.) and forward error correction. C-RANs employ Point-to-Point (PtP) fiber links for the BBU-RRH connection, but PtP wireless links have also been considered [5]. Current C-RAN implementations that are used in Long Term Evolution (LTE) mobile networks are almost exclusively based on the digitized Common Public Radio Inter-face (CPRI) protocol [6], which remains the predominant choice for commercial fronthaul solutions. However, CPRI is notoriously inefficient for supporting broadband channels [7] and imposes stringent delay requirements in the RAN, mainly due to its digital nature and its extreme centralization (only basic radio components are at the RRH) that was initially intended for very short intra-Base Station (intra-BS) communications. By combining the need for densification with the bandwidth hungry PtP nature of CPRI, MNOs would face extraordinary 5G C-RAN deployment costs, since a multitude of very high capacity links are required to interconnect the pool of BBUs with the plethora of RRH modules that are necessary for large-scale 5G implementations.

In order to mitigate densification costs, two major solutions have been proposed, each carrying its own merits and drawbacks:

1) Higher Layer functional splits (HLS): To alleviate the extraordinary CPRI requirements, a variety of higher layer functional splits have been defined in the literature [8],[9], that move radio processing functionalities from the BBU back to the RRH with the purpose of reducing the required capacity at the fronthaul. The most popular higher layer splits that have been defined are: i) option 7, often referred as intra-Physical Layer (intra-PHY) functional split, that places some radio functionalities at the RRH, such as iFFT, Cyclic Prefix addition, resource mapping and precoding functions, ii) option 6, that is often referred as the Media Access Control (MAC)-PHY split, where all RF and PHY layer operations are moved at the RRH, and iii) option 2, that is more commonly referred as the Packet Data Convergence Protocol (PDCP)/ Radio Link Control (RLC) split, where the first functionality resides in the BBU, and all the other (RLC, MAC, PHY and RF) are in the RRH. It is worth mentioning that up to Option 6, the fronthaul traffic is dependent and proportional to the user load and for the rest of the paper splits ranging from Option 1 to Option 6 are considered to comprise the Higher Layer Splits (HLS). On the other hand, Options 7 and 8, the latter being the traditional CPRI split, are constant and independent of the user load, and for the rest of this paper Options 7 and 8 are considered to comprise the Lower Layer Splits (LLS). The definition of various splits has been recently standardized in the evolved CPRI (eCPRI) specification [10] that introduced a series of similar splits entitled E, I_U, I_D, I_ID and D (Fig. 1). Splits I_U, I_D, I_ID are located within the PHY layer and therefore correspond to Option 7, split E corresponds to Option 8 and is equivalent to the traditional split used by CPRI, while split D corresponds to Option 6 and below. By employing a higher functional split the fronthaul capacity requirement is effectively reduced: for instance, split I_U halves the necessary capacity required by split E, whereas even higher splits reduce it even further [11]. However, these capacity gains come at the expense of centralization, leading to costlier RRH modules, whereas the necessity for high-speed PtP fronthaul connections remains.

2) Packetized Ethernet fronthaul: It has been widely proposed that employing Ethernet in the fronthaul
connection carries plenty of benefits, such as employment of mature and lower-cost Ethernet equipment, infrastructure sharing with already deployed fixed access networks, statistical multiplexing gains through software-defined networking, etc. [12]. However, Ethernet implementations still require PnP connections towards all the nodes of the network, even so with the employment of intermediate switches that function simply as pass-through gates, making this solution less suitable for dense urban-area deployment.

Incentivized by the above issues, this paper proposes an analog Radio-over-Fiber (RoF) optical/wireless packetized Fronthaul solution that can optimally address the above challenges while concurrently combining the advantages of the HLS and Ethernet solutions. The proposed analog architecture is capable of forming a Point-to-Multipoint (PtMP) converged Fiber-Wireless (FiWi) network that is ideal for wirelessly interconnecting multiple APs and provide coverage to dense urban areas, while on the other hand maintaining compatibility with commercial eCPRI equipment. In this paper we present the converged Fi-Wi architecture and provide initial simulation results measuring the end-to-end delay achieved in the packetized fronthaul for a series of fiber length distances, assuming a Constant Bit Rate (CBR) fronthaul load under a highly-centralized Option 7 (intra-PHY) split and for various RRH access channel bandwidths.

This rest of the paper is organized as follows: Section II presents the converged FiWi analog RoF architecture. Section III presents the end-to-end delay performance evaluation of the proposed architecture assuming Option 7 (intra-PHY) functional split. Finally, Section IV concludes the paper.

II. THE CONVERGED FIWI ANALOG ROF PtMP ARCHITECTURE

The purpose of the proposed architecture is to create a PtMP Radio Access Network that interconnects eCPRI, and therefore Ethernet, capable vendor equipment by exploiting i) the high spectral efficiency of analog RoF transmission, ii) the large spectrum of the V-band and iii) the audacity of massive MIMO antennas. This way it solves the problem of mm-wave 5G NR densification since it allows for flexible wireless last-mile placement of the RRHs in the area of service while maintaining compatibility with standardized and low-cost Ethernet equipment. The proposed architecture is versatile and supports operation as backhaul, midhaul, fronthaul depending on whether the MNO employs the analog RoF FiWi bridge to interconnect Small Cells, HLS RRHs or LLS RRHs. In this way it creates a FiWi PtMP bridge between the centralized and remote equipment, linking the multiple service APs, through a very high spectrally efficient analog RoF intermittent network that can support multiple eCPRI flows. Note that for the rest of this paper we will consider employment of the analog RoF PtMP architecture strictly as a fronthaul solution, meaning that a highly centralized functional split will be considered. The proposed PtMP solution when used in fronthaul operation is displayed in Fig. 2.

By means of Fig. 2 it can be seen that in the proposed architecture the following entities are involved:

- The Centralized BBU (C-BBU) and the RRH modules: These entities are part of the MNO’s infrastructure and are considered to be pre-existing in our proposed architecture, meaning they are not part of our proposal. The C-BBU and the RRH modules take care of the main radio access functionalities and implement the mobile protocol (i.e. LTE or 5G-NR) as well as they formulate the eCPRI packets that carry payload traffic corresponding to the chosen functional split. It is worth noting that the details of the implementation are dependent on the vendor, but as long as the eCPRI standards are maintained, the MNOs are free to choose the desired vendor and functional split.

- Centralized Analog BBU (CA-BBU): The role of the CA-BBU is to create the analog signals that will travel the FiWi network and also host all higher-level operations such as access control. The CA-BBU contains a network controller that hosts the upper-layer functionalities and can perform Ethernet packet processing, as well as a Programmable Engine (PE) module and transceivers that take care of the actual data transmission. The CA-BBU is connected through an Ethernet port (provided by the network processor) to the Centralized BBU (C-BBU).

- The analog Rooftop RRH: The analog Rooftop RRH (R-RRH) contains a mm-wave massive MIMO antenna that emits directed beams (pencil beams) towards the street-level lamppost antennas (described next).

- The secondary analog Lamppost RRH: The Lamppost RRH (L-RRH) contains the mm-wave antenna that receives the signals from the R-RRH (or transmits in the Uplink (UL) direction). This antenna module is in general simpler than the R-RRH antenna and does not need to have as many antenna elements since less directionality is demanded. It also contains a smaller, more lightweight version of the network controller and a PE that receives and decodes the signals from the CA-BBU, as well as creates the analog signals for the uplink direction. The L-RRH is connected through an Ethernet port (provided by the network controller) to the remote eCPRI RRH unit.

The connection between the CA-BBU and the L-RRHs follows the analog RoF scheme that offers inherent bandwidth efficiency that grants it a significant advantage over the digitized CPRI schemes, while demanding less complex RRH design. In this way our proposed architecture is able to support a plethora of eCPRI fronthaul flows and combine them over the air reaching multiple RRHs through employment of the vast V-band bandwidth and massive MIMO antennas.

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According to the specifications, eCPRI traffic is comprised of three main categories (Fig. 3):

- **eCPRI traffic**: the actual eCPRI traffic that contains the user data, the real-time control as well as the rest packets required for the services. The eCPRI traffic is passed to the Ethernet MAC layer through UDP and IP layers.

- **Control and management data (C&M)**: this data carries the control and management traffic that goes through to the remote unit. This data is carried through management protocols, such as SNMP, over UDP/TCP and IP layers.

- **Synchronization data (Synch)**: Data employed in order to synchronize the clocks of the remote and centralized units. It uses primarily the Precision Time Protocol (PTP) running on top of UDP and IP layers, but can be a combination of PTP with synchronous Ethernet to achieve the highest possible accuracy.

In this paper it is considered that the eCPRI traffic comprises the Data Plane (DP), whereas the C&M and synch traffic together make up the Control Plane (CP).

### A. Data Plane:

The proposed scheme employs multiple sub-bands signal, all located in the V-band spectrum, to transfer the DP traffic. A straightforward implementation could employ the ISM band (57-64 GHz) but other bands can be chosen by the infrastructure owners (such as the 70 and 80 GHz bands that together offer 10GHz) to employ in the fronthaul. The chosen band is considered to be split in sub-bands and each pair of R-RRH to L-RRH connection is assigned one sub-band pair for UL and Downlink (DL) communication. Also, the desired numerology and bandwidth of the bands can be chosen flexibly. DP is being transmitted from the R-RRH to the L-RRHs through “pencil-beams”, that are enabled by the massive MIMO antennas (Fig. 4 (a)).

### B. Control Plane:

The control plane employs out-of-band (meaning separate than the DP frequencies) channels to distribute the C&M and sync messages to/from the lamppost RRs. These channels are called the Control Plane Lamppost channels (CP-LP). In the downlink direction there is also one extra channel used for control of the rooftop antenna (the CP-RT). The CP-LP is broadcasted to the lampposts through a wide beam that covers all the served lamppost antennas (Fig. 4 (b)). In the DL direction there is no challenge since it is only the rooftop that transmits. In the UL direction however, the multiple access problem must be addressed. This problem can be solved in two ways, based on the decisions of the infrastructure owner:

1. The Frequency Division solution (FDD): In this approach, one UL CP-LP band is assigned to each lamppost. Since the traffic in the CP-LP is very low, these bands need to have only a small bandwidth. A variant could be to use an Orthogonal Frequency Division Multiplexing (OFDM) approach. In OFDM, multiple access is achieved by assigning subsets of subcarriers to individual users. This allows simultaneous low-data-rate transmission from several users.

![Fig. 4 (a) The proposed solution's Data Plane pencil beams (b) The Control Plane wide beams](image)

![Fig. 5 The simulation network (screenshot from OMNET++)](image)
Note that the rest of the paper assumes the FDD solution for the UL traffic.

2. The Code Division Multiple Access (CDMA) solution: In this approach several transmitters can send information simultaneously over a single communication channel by employing spread spectrum technology and a special coding scheme where each transmitter is assigned a code. The CDMA solution is ideal for employment in multi-user low bandwidth communications and is very mature as it has been used extensively since the Universal Mobile Telecommunications System (UMTS) 3rd generation mobile cellular system standard.

C. Flexibility in the Resource Allocation:

In the proposed architecture, flexibility in the resource allocation comes in two forms:

1) In the case of employing a single wavelength, the resource allocation method can assign the DP sub-bands to the lampposts depending on their traffic demands. For instance, considering a HLS case (lower than Option 7) where the traffic in the fronthaul fluctuates depending on the actual user traffic, one lamppost can receive more sub-bands for communicating with the rooftop antenna, whereas others receive only one or their DP can be shutdown completely in the absence of users.

2) In the scenario, where Wavelength Division Multiplexing (WDM) is employed in the optical domain, the flexibility comes from turning on or off various R-RRHs, so as to distribute the traffic coming from the lampposts to more rooftops and essentially to other wavelengths

III. PERFORMANCE EVALUATION

This section presents the performance of the proposed converged FiWi architecture in terms of end-to-end packet delay. The simulation results were derived by an event-based driven simulator created using the OMNET++ simulation framework [13]. In order to simulate the BBU and RRH components, the INET model suite was used [14], for which an extension to the OMNET++ simulator and offers off-the-shelf Ethernet components for modeling the IEEE 10GbE 802.3ae-2002 standard equipment. The simulation network setup follows a Passive Optical Network (PON) topology and comprises 4 eCPRI C-BBUs interconnected through the use of an Ethernet switch to the CA-BBU, as displayed in Fig. 5. The CA-BBU is in turn connected through a splitter (PON and/or Wavelength Division Multiplexing PON) to 4 R-RRH units, with each one wirelessly connected to 4 L-RRHs that serve through wired Ethernet connection an equivalent number of eCPRI RRHs, totaling 16 eCPRI flows to/from the RRH modules. In the above setup we consider one wavelength pair between all CA-BBU to R-RRH connections, essentially forming PtP links between the CA-BBU and all the R-RRHs, whereas using wavelength multiplexers in order to achieve co-existence with legacy deployments. The network setup follows the Option 7 UL split, meaning that it is still highly centralized but not as inefficient as the traditional Option 8 E split followed in CPRI. Option 7 split produces a Constant Bit Rate (CBR) stream of Ethernet packets between the BBU and the RRHs, and for a typical 2 × 2 MIMO RRH module the flow has a periodicity of 66.6 μs [11]. Depending on the bandwidth of the RRH channel, the fronthaul flow produces from 9000 bytes for 20 MHz access channels per period (1080 Mbit/s) up to 45000 bytes for 100 MHz 5G NR channels (5400 Mbit/s) [11]. For each case, the appropriate numerology of the analog RoF V-band spectrum is used so as to be adequate to successfully carry the 16 eCPRI flows. Table I summarizes the full specification parameters of the simulation run.

| Parameter | Value |
|-----------|-------|
| Nr. Of BBUs | 4 |
| Nr. Of R-RRHs | 4 |
| Nr. Of L-RRH per R-RRH | 4 |
| R-RRH range | 80 m |
| L-RRH range | 30 m |
| BBU/RRH Eth Rate | 10 Gbps |
| BBU/RRH buffer cap. | 50 packets |
| PON fiber length | 1-10 km |
| eCPRI flow rate (Mbps) | 1080 (20 MHz), 2160 (40 MHz), 5400 (100 MHz) |
| Nr. Of eCPRI Flows | 16 |

Fig. 6 displays the end-to-end delay results for the aforementioned network for fiber lengths ranging from 1 km and up to 10 km and for 3 different RRH channel bandwidths: 20, 40 and 100 MHz. From the results it can be seen that all derived latency values are well below the 100 μs latency target set by the eCPRI specifications for 5G NR channels [10], reaching up to 67,18 μs for 16 fronthaul flows of 100 MHz channels. The above solidifies the fact that our proposed architecture can provide an adequate solution for fronthauling networks in dense urban areas. Secondy it can be noted that the end-to-end delay increases linearly with the fiber length for all three tested RRH access channel bandwidths, meaning that the proposed scheme is suitable for urban area deployment where the average distance between the Central Office (where the BBU is placed) and the BS locations (where the R-RRH is placed) is on average 5 km [15].

IV. CONCLUSIONS

In this article, we have presented a novel architecture that employs an analog converged Fiber-Wireless scheme in order to create a very spectrally efficient Point-to-Multipoint network capable of interconnecting a large number of highly
centralized eCPRI equipment. Preliminary simulation results show very low end-to-end Ethernet packet delay, that is clearly below eCPRI’s 100 μs target that was set for 5G NR implementations, even for fiber lengths up to 10 km. Three radio access channel bandwidths where considered, ranging from 20 up to 100 MHz. Even in the worst-case tested scenario, considering 16 x 100 MHz eCPRI flows over 10 km of fiber length, the mean end-to-end Ethernet packet delay did not exceed 43.37 μs. The above results indicate the strong suitability of our solution for employment in 5G NR large-scale fronthaul networks.

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