Future Evolutions of Fronthauling Architectures over Passive Optical Networks

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ABSTRACT We overview the expected evolution of 5G and 6G functional split (FS)-based fronthauling architectures over Passive Optical Networks (PON), with a specific focus on physical layer considerations. We start by analyzing the expected bit rate, latency, and bit error rate requirements for different advanced fronthauling architectures. Then, we prosecute by showing that these requirements will likely need a technological jump in PON from current direct detection to coherent detection that can lead to several enhancements and performance increments. In turn, this will require new digital twin models for the PON transmission physical layer, which will be reviewed in the last part of the paper. **Keywords:** Fronthauling, 5G, 6G PON.

1. INTRODUCTION

In this Paper, we present the evolution of fronthauling (FH) requirements for advanced 5G and future 6G networks and discuss how they can be implemented on an architecture that uses today's ubiquitous Passive Optical Networks (PON), in a new scenario in which PONs are not only used for FTTH residential access but also to connect remote units for mobile applications. In Sect. 2 we give a review of the latency and bit rate proposed by 3GPP, and we elaborate on the consequences for FH in the following Sect. 3, which discusses how PON physical layer technology should likely evolve to coherent transmission. We then show in Sect. 4 that proper modeling tools for coherent PON must be available, particularly if and when network planning tools are needed for end-to-end optimization of converged metro and PON networks for ultra-high bit rate FH.

2. REVIEW OF THE EVOLUTION OF FRONTHAULING REQUIREMENTS TOWARDS 6G

This section presents an overview on the existing literature on FH forecasted evolution along the trends expected for the transition from 5G to 6G mobile networks, with specific focus on several proposed functional-split (FS) trends. In particular, we summarize here the expected requirements in terms of bit rate and latency. In modern mobile networks, it is fundamental to achieve seamless communication between the network wireless part and the supporting fiber access network through FH, which involves connecting two key network components: the centralized baseband units (BBU) and the remote radio heads (RRHs) located at remote sites, typically closer to the end-users or antennas. This link ensures that processed signals from the BBU can be efficiently transmitted to the RRHs for wireless transmission and reception [1]. FH plays a crucial role in both 5G and 6G networks. A key advancement in 6G networks compared to 5G, will be a significant reduction in latency. This improvement is crucial for various applications, including advanced real-time communication as required by self-driving cars and virtual reality [2]. Many published papers, such as [3], focus on optimizing the functional split selection and resource allocation in a Radio Access Network (RAN) using the new concept of Elastic Optical FH (EOF), i.e., a dynamically optimized FH scenario. In particular, [3] proposed a novel scheme that uses an SDN controller to dynamically select FS for each RU, which impacts the traffic load on the EOF. The FH rates are determined based on the selected functional split and the working bandwidth of the baseband virtualization terminal (BVT). Additionally, the work also mentions the frequency slots assigned to each BVT for transmission and the modulation format related to bandwidth utilization efficiency. Anyway, latency requirement is crucial for ensuring the time to deliver data from the remote units (RUs) to the central unit (CU). Thus, meeting the latency requirements as part of the FH specification is essential. The one-way latency of each functional split should be maintained below a specific value over its path to the CU. Much research on delay requirements focuses on the EOF instead of fixed optical FH to achieve delays below 250 μs. 3GPP standards defined eight possible functional split options, but in Fig. 1 we considered the most relevant ones, focusing specifically on the uplink. The following Table I reports the latency requirements set by 3GPP (assuming that macro-base station options for the RUs). It is also crucial today to consider bit rate requirements associated with different functional splits, which vary depending on the specific functions that are centralized or distributed between the CU and distributed units (DU) in the network architecture. Table II provides specific bit rate values for each FS in the FH for the downlink and uplink directions, respectively [4].

In [5], the impact of choosing the proper FS depending on the FH capacity was described. Consequently, it is generally agreed that the FH requirements are changeable based on different functional splits. A description for the FH network was introduced, where gNBs split into a CU and a DU. CU is centralized in the data center/central office, and DU is located remotely near RU. This centralized system depends on the selected functional split, thus requiring different FH requirements, such as the capacity of the FH. The choice of these

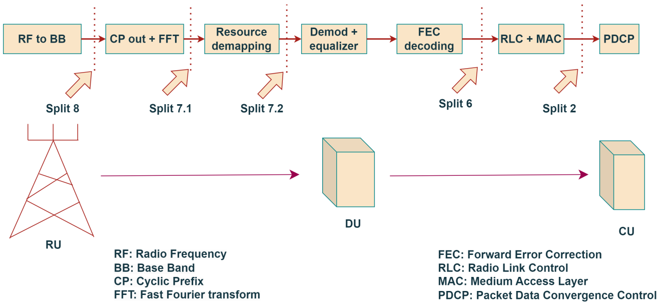

Figure 1: Functional split options in 3GPP for the uplink direction [3].

i	3GPP functional split number	Fronthaul latency (μs)
1	2	1500 – 10000
2	6	250
3	7.2	250
4	7.1	250
5	8	250

TABLE I: Functional splits latency values [3].

TABLE II: Functional splits with their downlink and uplink bit rate requirements

Bandwidth [MHz]	Modulation [bit/symbol]	MIMO layers number	Antennas number	Downlink bit rate [Gbps]			Uplink bit rate [Gbps]		
				FS 6	FS 7.2	FS 7.1	FS 6	FS 7.2	FS 7.1
100	8	8	32	51.216	528.634	139.096	5.640	21.624	86.096
200	8	8	32	102.432	1057.267	278.193	9.926	28.544	278.193
400	8	8	32	204.864	2114.534	556.385	19.853	57.087	556.385

centralization levels is studied in this work to determine the FH requirements, i.e., (with higher centralization levels demanding higher FH capacity). Moreover, the authors highlight the importance of enabling different levels of centralization and the importance of the FH network in supporting it. However, they mention the constraints of the FH for the selection of the functional split to optimize both cost and performance. In the RAN architecture, the functions can be divided between different elements and this is what is called a functional split where some functions can be implemented at the CU or the DU. Known that each gNB at any given time operates at a certain centralization level or functional split that can be chosen by the network operators, Fig. 2 shows four centralization levels (PDCP-RLC, RLC-MAC, MAC-PHY, and C-RAN), corresponding to splits between five different functions. The choice of centralization level depends on two main factors. Low centralization levels require less FH capacity which makes them easier to implement without congesting the FH network. On the other hand, high centralization levels require more FH capacity but it is faster for communication between the functions of gNB. A dynamic adaptation to FH requirements by changing the selection of the functional splits based on the current demands by considering the FH limitation was studied in [6]. In this context, a FS selection problem (FSSP) was formulated in the system model defined in Fig. 2. This visualization helps in understanding how the choice of centralization level impacts network performance and resource utilization. To support high centralization levels, the FH must meet the latency requirements between the CU and DU in the order of 10s ms in the case of the high-level splits and sub-ms in the case of low-level splits. A summary of the maximum one-way latency requirements for the different functional splits can be found in Table III.

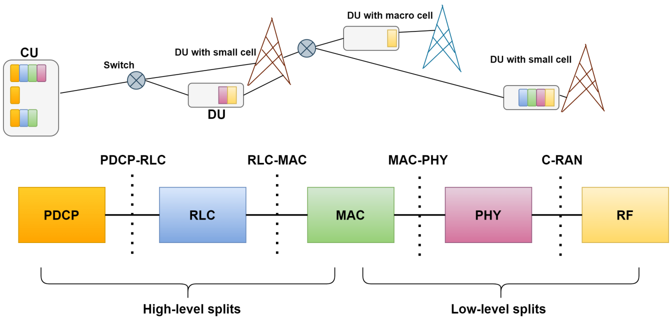

Figure 2: Functional splits scheme [6].

Functional split	Maximum latency requirements
PDCP-RLC	10 ms
MAC-PHY	250 μs
MAC-PHY	250 μs
C-RAN	250 μs

TABLE III: Latency requirements for different centralization levels [6].

3. EVOLUTIONS TOWARDS COHERENT PON

PON for FTTH are today ubiquitous in urban areas, and it would thus be extremely interesting for telco operators to use the same access fiber network also as a support for FH. Anyway, in the previous section

Tables II, we pointed out that when the target RF Bandwidth is 100 MHz or above, the resulting bit rates become extremely high so today PON standards may not be able to support them. In fact, the most advanced ITU-T standard for PON (ITU-T G.9804 50-GPON) can deliver 50Gbps, which would satisfy only some of the cases reported in the aforementioned two tables. There is thus a growing interest in coherent transmission technologies over PON (C-PON), which were experimentally demonstrated to allow much higher bit rates, up to 400 Gbps. This is a bit rate that, coupled with an adaptive selection of the best functional split option, may cover most of the situations presented in the previous section. Moreover, coherent technologies may also allow to extend the reach of access networks, enabling a potential all-optical convergence between the access and metro segments. Anyway, coherent transmission technologies are today commercially available only for the long-haul optical networking segments, while still significant research and development activity is needed to make them suitable for the PON access segment. On one side, the cost of coherent transceivers must significantly decrease before they are suitable for access. It is anyway expected that in the next 4-5 years (which is also the timeframe when 6G will be introduced), these CAPEX prices should decrease thanks to the introduction of coherent technologies and also in the inter-data center interconnections (Inter-DCI) ecosystem. At the same time, C-PON would also have physical layer technical requirements that are different from the current long-haul ones, in particular for the upstream direction, that should likely be completely re-engineered to support an efficient multiplexing approach on all the Optical Network Units (ONU) that support FH connectivity on a given PON optical tree.

4. SOFTWARE MODELLING TOOLS FOR COHERENT PON

In previous sections, we showed two recent research trends: elastic optical FH and ultra-high bit rate over PON using coherent transmission. If this scenario is implemented, it will require completely new simulation models: in particular, accurate, reliable, and efficient models, which can digitally mirror the optical physical layer for future network design, dimensioning, and management through digital twins, whether they are physical- or hybrid physics- and data-based [8]. Moreover, these models are especially important for future C-PON FH, given its expected requirements like ultra-high speed and extended reach, alongside challenges such as bandwidth limitations and imperfections in optoelectronics. We thus developed an analytical frequency-resolved physical-based model that predicts the signal-to-noise ratio (SNR) for which we can then estimate the resulting pre-FEC BER at the output of coherent receiver DSP adaptive equalizer, based on the physical-layer parameters of the optical channel and the receiver optoelectronics. This model and consequently the resulting simulator is an updated version of the model presented in [11], where we include the coherent receiver physical impairments [9] on the basis of the widely linear representation described in [10]. The model can serve as the basis for planning tools, scalability assessments, and future digital twins.

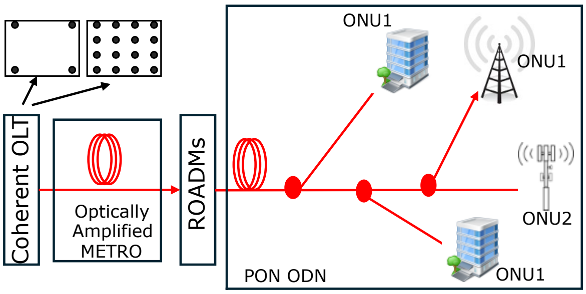

Figure 3: Downlink coherent transmission over metro+PON converged optical network.

	ONU1	ONU2
PD Electrical BW (GHz)	0.6 Rs	0.35 Rs
TIA current density ($pA/\sqrt{Hz}$)	20	32
IQ phase imb. (deg)	0	20

TABLE IV: The two ONUs physical parameters used in the simulated application example.

Figure 3 presents an example of a future C-PON configuration that considers an all-optical converged metro+PON; i.e. the metro segment is linked to the access distribution segment using reconfigurable add-drop multiplexers (ROADMs). It is expected that this setup incorporates various ONU types with different physical attributes, data-rate requirements, and reach. Therefore, we considered two types of ONUs as an illustration of the potential future flexible C-PON deployment [12]. As a future application example, we consider the following scenario, 50 Gbaud transmitted symbols are carried by a dual-polarization (DP) quadrature phase shift keying (QPSK) or 16-quadrature amplitude modulation (16-QAM) signal with an average transmitted power of 11 dBm shaped by a square-root raised cosine filter with 0.2 roll-off factor. The signal then passes through the metro segment represented by the concatenation of 5 ROADMs, each with 2 wavelength selective switches with a super-Gaussian profile of a 75 GHz bandwidth. The channel also incorporates a random unitary Jones matrix before adding colored optical noise. At the receiver side, the considered ONUs are varied by their photodiode (PD) electrical bandwidth, equivalent trans-impedance amplifier (TIA) input-referred noise current density and consequently its added thermal noise, in-phase quadrature (IQ) phase imbalance as detailed in Table IV. In addition to the aforementioned imperfections, both shot and relative intensity noises are considered at the coherent receiver of both ONUs. The developed frequency-based simulator is deployed to analyze the optical distribution network (ODN) loss that is allowed for each ONU to achieve an almost error-free transmission using hard-decision (HD) and soft-decision (SD) FEC, and consequently a pre-FEC BER of 10^{-2} and 2.10^{-2}, respectively. Figure 2 (a) and (b) illustrate the ODN loss with respect to optical signal-to-noise ratio (OSNR) for ONU1 and ONU2, respectively, considering two modulation orders, that is QPSK and 16QAM, i.e. a bit rate of 200 and 400 Gbps. Moreover, the frequency-based simulator is validated with respect to time-domain extensive simulations as described in [11]. As seen, there is an excellent accuracy between the frequency- and time-based simulation results with a great reduction in time and CPU resources attained by the frequency simulator in comparison to its counterpart time simulator. As shown in Fig. 4 (a), at an OSNR of the value 20 dB and an ONU with no IQ imbalance or electric bandwidth limitation such as ONU1, 400 Gbps can be supported for up to 37 dB ODN loss whereas 200 Gbps for up to 45 dB loss. Moreover, deploying SD FEC can allow for around 1 dB extra loss. On the other hand, an ONU with higher thermal noise value, IQ imbalance of 20 deg and a narrower electrical bandwidth such as ONU2, requires a loss of less than 32 dB to achieve a bit rate of 400 and less than 40 dB for a 200 Gbps at an OSNR of the value 20 dB, as demonstrated in Fig. 4(b).

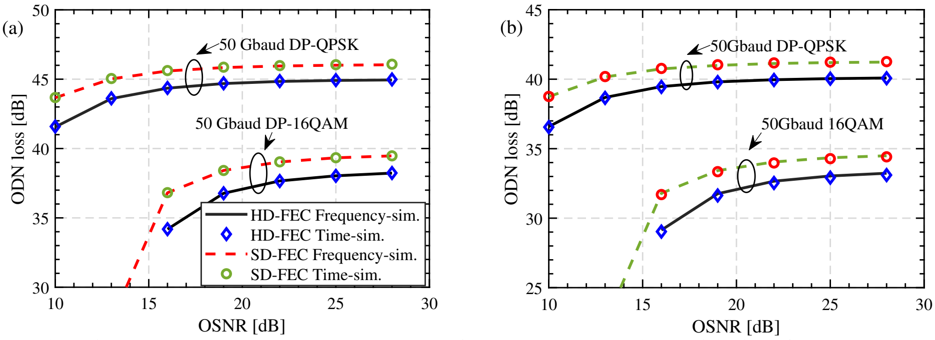

Figure 4: ODN loss in a metro+PON setup corresponding to OSNR and considering frequency- and time-domain simulators for (a) ONU1 and (b) ONU2. Legend of (a) applies to (b).

5. CONCLUSIONS

We present an overview on future 6G FH requirements and their potential application over PON networks. Moreover, we briefly present some numerical tools that we developed for physical layer analysis.

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