End-to-end Delay Performance of Analog Fiber Wireless architecture for 5G NR fronthaul

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ABSTRACT

The convergence of fiber and wireless systems based on millimiter-wave (mmWave) bands seems to be a promising fronthaul solution for the fifth generation (5G) centralized radio access network (C-RAN) deployments. The 5G fronthaul allows the flexible splitting of functionalities between centralized and remote units but requires high data rates. These can be achieved by combining the traits of analog radio-over-fiber (RoF) communication, the wide mmWave spectrum and the availability of different functional splits. To that end, we focus on a novel RoF fronthaul architecture and evaluate its performance in terms of end-to-end packet delay under different network setups. Our simulation results show that the experienced delay is affected by the fronthaul load but remains below 100 μs in most cases.

Keywords: Fiber-wireless fronthaul, analog radio-over-fiber, functional split, C-RAN, 5G networks.

1. INTRODUCTION

In the last few years, the centralized radio access network (C-RAN) design has become a prevalent fronthaul solution that connects centralized and remote network components using the common public radio interface (CPRI) over Ethernet (ETH) [1]. However, as the fifth generation new radio (5G NR) network deployments become denser, high-capacity fronthaul infrastructure is required to support their operation. The high centralization of C-RAN and the use of CPRI require very high fronthaul data rates and impose strict delay demands (e.g., target delay lower than 100 μs in CPRI for 5G). Lately, converged fiber-wireless technology has been introduced in C-RAN to support fast broadband connectivity, relying on analog radio-over-fiber (RoF) transmissions and exploiting the spectral efficiency of millimiter-wave (mmWave) frequency bands [2].

The analog RoF fronthaul enables the multiplexing of several signals over the same optical carrier and the functional splitting between baseband units (BBUs) and remote radio heads (RRHs), e.g., split inside the physical layer (Intra-PHY) or between the medium access control and physical layer (MAC-PHY) that can be managed by the mobile network operator (MNO). Various splits have been described in the evolved CPRI (eCPRI) specification. The functional split type affects the fronthaul load levels, as it determines the amount of data exchanged between centralized and remote units and the fronthaul data rate and delay constraints [3].

Motivated by the capabilities of fiber-wireless convergence, in this paper, we assess the suitability of a novel analog RoF architecture for 5G fronthaul by extensively evaluating the end-to-end packet delay. In our simulations, we vary the fronthaul parameters (i.e., RoF channel conditions, ETH data rates and packet size) and parameters related to the 5G network supported by the fronthaul architecture (i.e., functional split type and channel bandwidth of remote units).

The rest of the paper is organized as follows. In Section 2, the considered fronthaul architecture and the system model are described. The performance results are discussed in Section 3 and conclusions are drawn in Section 4.

2. FRONTHAUL ARCHITECTURE AND SYSTEM MODEL

We consider the architecture depicted in *Figure 1*, where a rooftop RRH serves a number of K lamppost RRHs via mmWave links in the 57-66 GHz band. The lampposts can serve a number of end users that generate fronthaul traffic managed by the MNO, i.e., the centralized base band unit (C-BBU) and the remote units (RUs). The network intelligence is located at the centralized analog base band unit (CA-BBU) that communicates via an ETH port with C-BBU. The RRH is connected with the CA-BBU via a dedicated fiber link and emits directed beams to the lampposts. Each lamppost is connected with an RU using ETH links. The lampposts in the range of the RRH are user traffic aggregators that gather the traffic related to the end users. The traffic related to each lamppost may be either uplink or downlink and the load per lamppost may vary. The mmWave spectrum is split in half and is allocated separately to lampposts with uplink or downlink traffic. Furthermore, two functional splits are employed between different fronthaul nodes. The functional split between CA-BBU and RRH is performed inside the physical layer (intra-PHY split, Option 7 [3]), placing some of the radio functionalities at the RRH. A similar functional split is performed between the C-BBU and the RUs. However, the MNO may choose a higher layer split in order to reduce the generated fronthaul load, e.g., MAC-PHY split (Option 6).

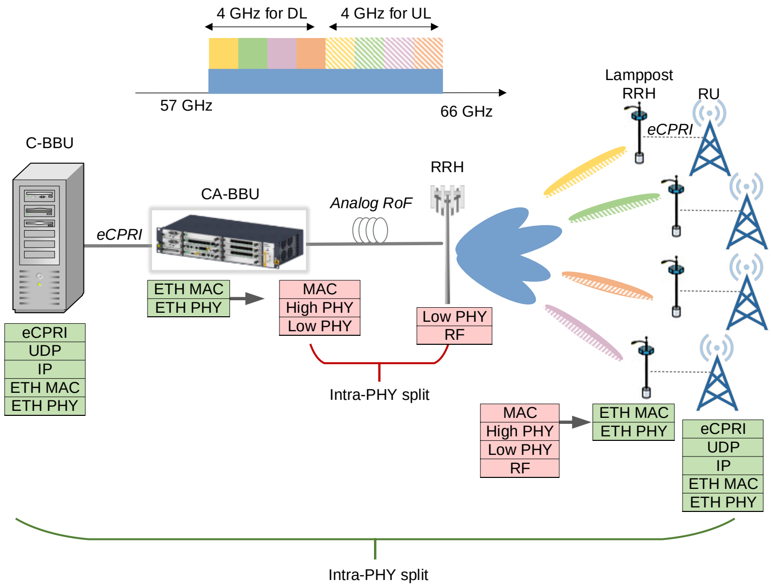

Figure 1. Converged fiber-wireless analog RoF fronthaul architecture.

The packets generated by the C-BBU are transmitted to the CA-BBU, which forwards each packet to the corresponding RU via the RoF channels that are dedicated to the lamppost connected to the RU. Thus, the end-to-end delay experienced by a packet destined to a lamppost k is estimated as:

$$D_k = D_Q + D_{Prop}^{C-BBU\ to\ CA-BBU} + D_{Tx}^{C-BBU\ to\ CA-BBU} + D_{prop}^{CA-BBU\ to\ RRH} + D_{prop}^{RRH\ to\ k} + D_{Tx}^{CA-BBU\ to\ k}, \quad (1)$$

where D_Q is the waiting time at the queue of C-BBU, $D_{Prop}^{C-BBU\ to\ CA-BBU}$ and $D_{Tx}^{C-BBU\ to\ CA-BBU}$ are the propagation and transmission delays in the C-BBU to CA-BBU link, respectively, $D_{prop}^{CA-BBU\ to\ RRH}$ and $D_{prop}^{RRH\ to\ k}$ are the propagation delays in the optical medium (CA-BBU to RRH) and the wireless medium (RRH to lamppost k), respectively, and $D_{Tx}^{CA-BBU\ to\ k}$ is the transmission delay in the RoF channel between the CA-BBU and the lamppost k that depends on the RoF data rate achieved for lamppost k.

Each lamppost k located in a distance d_k from the RRH can use a portion W_k of the available bandwidth for DL transmissions. It can be served with a RoF data rate R_k that is equal to:

$$R_k^N = W_k log_2(1 + SNR_k), \quad (2)$$

where SNR_k is the signal-to-noise ratio (SNR). Denoting as P_{Tx} the transmission power, $PL(d_k)$ the average path loss related to the lamppost k and as N_k the average noise power, the SNR of each lamppost is calculated as $SNR_k = P_{Tx} - PL(d_k) - N_k$. For the estimation of SNR, it is assumed that the mmWave path loss is affected by both line-of-sight (LOS) and no-line-of-sight (NLOS) components that occur with probability $P_{LOS}(d_k)$ and $P_{NLOS}(d_k)$, respectively. Thus, it holds that $PL(d_k)$ (dB) is equal to [4]:

$$PL(d_k) = P_{LOS}(d_k)L_{LOS}(d_k) + P_{NLOS}(d_k)L_{NLOS}(d_k), \quad (3)$$

where $P_{NLOS}(d_k)$= $\left(1 - P_{LOS}(d_k)\right)$ and $P_{LOS}(d_k) = \frac{18}{d_k}\left(1 - e^{\left(-\frac{d_k}{63}\right)}\right) + e^{\left(-\frac{d_k}{63}\right)}$. The values L_{LOS} and L_{NLOS} reflect the path loss values in cases LOS and NLOS, respectively, and are estimated as $L(d_k) = P_0 + 10nlog_{10}(d_k) + \gamma_k\ (dB) + \delta_k(dB)$, where P_0 is the path loss at the reference distance d_0 and n is the path loss exponent [5]. The values γ_k and δ_k represent the shadowing and the small-scale fading, respectively.

3. DELAY PERFORMANCE EVALUATION

We assess the fronthaul performance in terms of end-to-end packet delay under the impact of different parameters, i.e., SNR levels in the RRH-lamppost wireless link, ETH packet size and functional split type, considering varied fronthaul load per lamppost in a downlink scenario. The simulation parameters are provided in *Table 1*.

Table 1. Simulation parameters

Parameter	***Value***
***W* (downlink) (GHz)**	4 (10 channels, 400 MHz/channel)
Data rate per wavelength (Gb/s)	10
Fiber length (km)	5
RRH P_{tx} (dBm)	20
Modulation schemes	16QAM, 64QAM, 256 QAM

Path loss model parameters	LOS, NLOS
$\boldsymbol{P_0}$	63.4, 65.3
$\boldsymbol{n}$	1.72, 1.94
$\boldsymbol{\gamma}$ (shadowing)	(1.18, 1.15), (4.48, 0.27)
$\boldsymbol{\delta}$ (small-scale fading)	Rician (s=0.93, σ=0.31, K_R=3), Nakagami-m (m=4.68, Ω=1.03)

3.1 Varied SNR and number of RoF channels

We first study the packet delay performance when one lamppost is active and experiences different SNR values according to its distance from the RRH, i.e., for distances equal to {50, 60, 70, 80} m the average SNR is {20, 15, 10, 5} dB, respectively. We vary the number of channels that are allocated to the lamppost, i.e., $w = [1,4]$. The ETH rate is 10 Gb/s, the packet size is 1500 B and the fronthaul load related to the lamppost is 5.4 Gb/s, assuming a 100 MHz 5G NR channel with 2x2 MIMO and 15 KHz subcarrier spacing for the corresponding RU [6].

In *Figure 2*, we observe that that the packet delay experienced by the lamppost is affected by both the SNR and the number of used channels. These parameters affect the achieved data rate levels in the RoF channel between the CA-BBU and the lamppost. More specifically, when one channel is allocated to the lamppost, SNR value equal to 20 dB leads to 22% lower delay comparing to the case where SNR is 5 dB. However, this effect diminishes when more channels are used. For the same SNR value, the allocation of more channels reduces the delay by up to 20% when two channels are used instead of one (SNR equal to 5 dB). The lowest observed packet delay is 32.6 μs and it can be achieved with the use of four channels and 256 QAM for SNR equal to 20 dB.

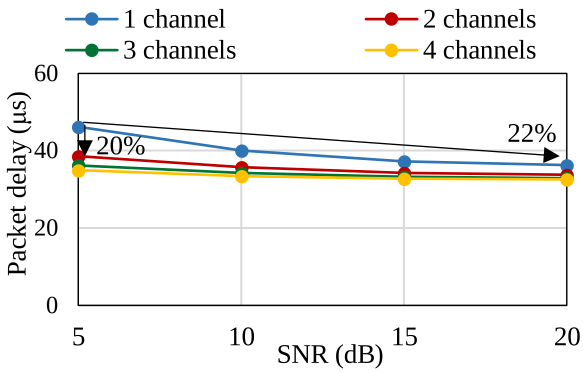

Figure 2. Delay vs SNR of RRH-lamppost link.

3.2 Varied ETH data rates

We next study the scenario of three active lampposts using different ETH data rates. In case A, the ETH rate is 10 Gb/s and in case B, the ETH rate is 40 Gb/s. We consider four 5G NR channel bandwidths, i.e., 10, 20, 40 and 100 MHz, which result in 0.54, 1.08 and 2.16 Gb/s fronthaul load per lamppost. Each lamppost uses one RoF channel that offers average data rate equal to 2.4 Gb/s.

Figure 3 illustrates the packet delay for both cases. The use of higher data rates in the link between C-BBU and CA-BBU is able to reduce the resulting delay by up to 32 %. In case of 100 MHz, the setup of case A is not able to support the load levels, as the ETH data rate is insufficient and increases the delay to values that exceed 100 μs.

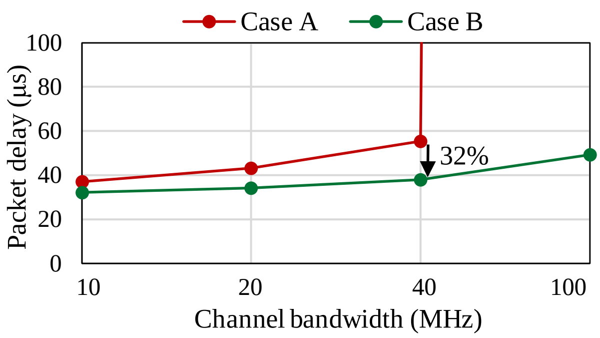

Figure 3. Packet delay for different ETH data rates.

3.3 Varied functional split types

We evaluate the delay performance comparing two types of functional split between the C-BBU and four RUs, i.e., the Option 6 (MAC-PHY) split and the Option 7 (Intra-PHY split), considering three 5G NR channel bandwidths, i.e., 10, 20 and 40 MHz (with 2x2 MIMO and 256 QAM), as shown in *Table 2*. For the Option 6 split type, we assume that the bandwidth of each RU is fully utilized, producing different downlink data rates [7] and required fronthaul data rate levels [8]. In our simulations, the ETH rate is 10 Gb/s and the ETH packet size is 1522 B for Option 6 and 1490 B for Option 7. For Option 6, each packet also contains the 5G NR headers, equal to 32 B [9]. Each lamppost uses one RoF channel (400 MHz) that offers RoF data rate equal to 0.82 Gb/s.

Table 2. Fronthaul load per functional split type

5G NR channel bandwidth (MHz)	Option 6 DL data rate (Mb/s)	**Option 6 load per lamppost** (Gb/s)	**Option 7 load per lamppost** (Gb/s)
10	111	0.154	0.54
20	227	0.618	1.08
40	462	1.245	2.16

As shown in *Figure 4*, in all cases, the resulting packet delay is much lower than the delay threshold imposed by each functional split type, i.e., 250μs for Option 6 and 100 μs for Option 7. It is also worth noting that the packet delay is lower when the Option 6 split is used, reaching a reduction of 29 % for 40 MHz. This effect occurs due to the lower fronthaul load produced comparing with the Option 7 split.

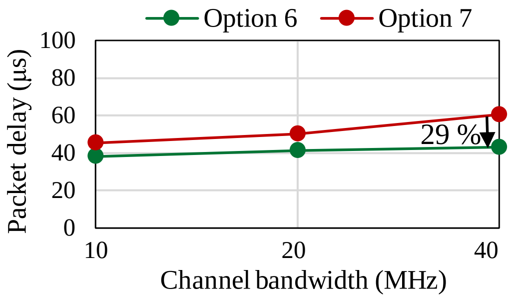

Figure 4. Packet delay for different functional split types.

4. CONCLUSIONS

Our study has shown that the end-to-end packet delay is affected by various parameters of the fronthaul architecture (i.e., ETH data rate, packet size, RoF data rate). More specifically, the ETH data rate affects the waiting time of the packets in the queue of C-BBU, which in turn determines the packet generation rate at the CA-BBU. Furthermore, the RoF data rate that depends on number of allocated channels and experienced SNR in the RRH-lamppost wireless link can also influence the delay. We have also observed that the functional split type between the C-BBU and the RUs affects the packet delay. In particular, the MAC-PHY split results in lower load levels than the Intra-PHY split, leading to lower packet delay.

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