QoS-aware resource management for converged Fiber Wireless 5G Fronthaul networks

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***Abstract*—The upcoming generation of mobile networks is expected to serve numerous mobile users with high quality-of-service (QoS) demands, requiring high-capacity fronthaul. As the provision of fiber connections directly to the end users is not cost-efficient, the integrated fiber wireless (FiWi) fronthaul design based on wireless networking and passive optical networks (PONs) has been proposed. The FiWi design involves modern networking technologies that can accommodate the need for data rates in the Gb/s scale and low delay, such as the wavelength division multiplexing (WDM) in the optical domain and the multiple input multiple output (MIMO) communication over millimeter wave (mmWave) spectrum in the wireless domain. The co-existence of two network types requires resource management in a medium transparent manner, i.e., the sharing of the bandwidth in the wireless domain should allow the organization of the data packets in optical frames. As the traffic circulating in the FiWi fronthaul involves packets of different priorities, i.e., different QoS classes, the resource management scheme should support QoS differentiation. To this end, we propose a resource management scheme for FiWi fronthaul and we extensively study its performance in terms of experienced delay and throughput. Our simulation results demonstrate that the proposed scheme significantly reduces the delay of the high priority class.**

Keywords*—Fiber-wireless networks, C-RAN, Fronthaul resource management, QoS differentiation, 5G networks.

I. Introduction

As the users' quality-of-service (QoS) demands escalate and various delay-sensitive and bandwidth-hungry applications (e.g., online gaming, video streaming, etc.) appear, the need for high-capacity in fronthaul emerges. The fronthaul based on passive optical networks (PONs) can support fast broadband connections in the upcoming fifth generation (5G) wireless networks. The high cost of fiber connections close to end users, i.e., fiber-to-the-home, has further motivated the deployment of integrated fiber wireless (FiWi) fronthaul solutions. The FiWi fronthaul combines the reliability and high capacity of PONs with the flexibility of wireless networking [1].

In FiWi networks, a central unit, i.e, the optical line terminal (OLT), manages the network resources, allocating bandwidth to remote optical network units (ONUs) connected to the OLT via fiber links. The optical resource allocation to users can be arranged according to various schemes, e.g., time division multiplexing (TDM), orthogonal frequency division multiplexing (OFDM) and wavelength division multiplexing (WDM) [2]. In the wireless domain of a FiWi network, each ONU can connect to multiple access points (APs), which serve the end users, via wireless links controlled by the OLT. The wireless connections between ONUs-APs and APs-users may rely on various technologies, e.g., long term evolution (LTE). In view of the requirement for data rates of multiple Gb/s, the 60 GHz frequency band that has high unlicensed spectrum availability can be used, enabling the millimeter wave (mmWave) wireless connectivity [3]. The mmWave connections may suffer from high propagation losses due to the use of small wavelengths, an effect that can be alleviated by beamforming methods and the use of multiple antennas in the transmitters and/or receivers, i.e., multiple input multiple output (MIMO) design [4].

The different network elements can be coordinated in a centralized manner, as performed by the paradigm of cloud radio access network (C-RAN), where the baseband functionality of the radio units is managed by a central cloud computing-based unit [5]. The communication between the remote radio heads (RRHs) and the baseband units (BBUs) is based on fronthaul transmission protocols, e.g., common public radio interface (CPRI). As MIMO enabled RRHs operating at mmWave bands are expected to be used in 5G fronthaul, CPRI will require extremely high fronthaul data rates. The required fronthaul capacity can be reduced by the deployment of analog FiWi fronthaul that enables the multiplexing of several signals over the same optical carrier and is also affected by the type of functional splitting between BBUs and RRHs, e.g., split inside the physical or medium access control (MAC) layer [6].

In order to leverage the capabilities for high data rates and low delay of FiWi networks, efficient resource management mechanisms for the hybrid optical-wireless end-to-end links are required [7]. The FiWi network can be orchestrated by the OLT using network virtualization tools that enable the centralized network management, such as the software-defined-networking (SDN) framework [8]. Nevertheless, the design of an efficient FiWi resource management scheme can be quite complex. On one hand, different types of resources should be allocated in a medium-transparent manner, i.e., the sharing of bandwidth among APs in the wireless domain should allow the organization of packets in optical frames by RRHs [9]. This functionality can be implemented by enabling the direct negotiation over the resources between APs and OLT, without the intervention of RRHs. However, the wireless capabilities of RRHs should be considered in the resource allocation, as the existence of MIMO-enabled RRHs determines the achieved data rates in the mmWave wireless links, affecting the performance of the resource allocation scheme. On the other hand, the resource management method should take into account the co-existence of different QoS requirements of APs, which serve end-users that may generate traffic of different QoS priority [10]. As the traffic of APs may belong to different QoS classes, the coordination of packet transmissions in optical and wireless domain should enable QoS prioritization when the optical frames are created.

Several methods that efficiently allocate the resources in FiWi networks have been proposed. In [11], the authors present a dynamic optical resource allocation scheme that reduces the power consumption at ONUs, allocating bandwidth to each ONU according to the traffic levels and allowing ONUs with low traffic intensity to enter sleep mode. The work in [12] proposes a TDMA based bandwidth allocation scheme, where the APs exchange information for their queue status, negotiating directly with each other without the intervention of OLT. However, these works do not consider the interaction between optical and wireless domain when the resources are allocated, thus, the wireless APs are not able to negotiate over the resources of both types with OLT. This functionality is provided by the medium-transparent polling-based scheme presented in [13], which allocates optical and wireless resources to ONUs and their wireless users. Despite their benefits, the aforementioned schemes assume that all packet flows are of equal importance and do not perform QoS prioritization. The resource management scheme presented in [14] supports QoS differentiation for video delivery over FiWi networks by prioritizing the transmission of high priority packets in each transmission period, however, it does not provide a medium-transparent solution, as required by the FiWi fronthaul. The work in [15] allocates time slots to different ONUs considering different services in a converged PON/WiMax network. Nevertheless, the bandwidth requests sent by each AP to OLT increase the signaling overhead occupying significant portion of the bandwidth. Additionally, the existing FiWi resource management schemes have not been studied considering the capabilities of modern FiWi networks, e.g., the MIMO capability of ONUs, which affect the FiWi network performance.

Motivated by the aforementioned issues, in this paper, we present a medium-transparent resource management scheme that provides QoS differentiation in FiWi fronthaul, where a set of APs generate flows of packets belonging to different QoS classes. The proposed scheme is applicable in FiWi networks with WDM capability in the optical domain and MIMO capability of the ONUs in the wireless domain. The contribution of our work is summarized in the following points:

(i) We propose a QoS-aware medium transparent (QMT) resource management scheme that allows the sharing of the optical and wireless bandwidth among different APs. It enables the dynamic configuration of the allocated time slots per QoS class according to the QoS performance requirements each class in terms of delay and throughput.

(ii) We demonstrate the capabilities of the QMT scheme studying its performance in terms of experienced delay per QoS class and achieved throughput. For the performance evaluation, varied traffic levels per QoS class and different FiWi network setups, i.e., different number of APs and time slot allocation, are considered.

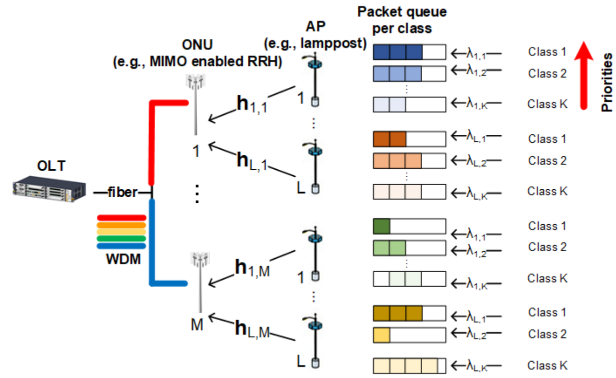


Fig. 1: Considered FiWi network

The rest of the paper is organized as follows. The considered system model is described in Section II. In Section III, the propose scheme is presented. The simulation results are discussed in Section IV and conclusions are drawn in Section V.

II. System model

We consider a network with a FiWi fronthaul, where a set of APs (small cell lampposts), communicate via wireless links with M ONUs (RRHs) connected via fiber links with OLT. Each MIMO-enabled RRH uses N antennas to communicate with L single-antenna lampposts using the available bandwidth W in V-band. The network intelligence is located at OLT that manages part of the MAC layer of the fronthaul. The lampposts manage the rest of the MAC functionalities, coordinating the channel access of the end users. Thus, functional split inside the MAC layer is applied [16][1]. We focus on the uplink (UL) fronthaul traffic, however, the system operates in a similar manner for downlink (DL). Each lamppost serves users that generate UL traffic of K different QoS classes. The UL traffic of each QoS class per lamppost follows a Poisson distribution with $\lambda_{l,k}$, where $l = 1, \dots, L$ and $k = 1, \dots, K$.

In the optical domain of the FiWi network, wavelengths are allocated to the RRHs by the OLT according to the WDM technique. More specifically, a wavelength is allocated to each RRH m, which is served with a fiber link data rate r_m^F in UL and DL direction [17]. The RRHs transmit groups of packets of different lampposts, i.e, superframes (SFs), to the OLT in a round robin manner during the transmission window duration. A lamppost can transmit its packets during an SF, i.e., a time interval T_{SF} of fixed duration that is set by the OLT[2]. During the T_{SF}, a lamppost establishes a directional mmWave link with the corresponding RRH and transmits packets of all QoS classes, whereas the control packets required for the resource scheduling by the OLT are also exchanged. For the support of QoS differentiation, different portion of each SF can be allocated to each class, depending on its QoS requirements.

In the wireless domain of the considered network, the transmissions of each lamppost to the OLT utilize the whole spectrum in each time slot, offering the maximum possible UL data rate that can be achieved considering the signal-to-noise ratio (SNR) in the RRH-lamppost channel. It is assumed that

[1]Other types of functional split could be also considered.

[2]SFs of variable duration can be also supported.

perfect channel state information (CSI) is available to the OLT. We denote as $r_{l,m}$ the achievable UL data rate for lamppost l that is connected to RRH m. Given the channel matrix $\mathbf{h}_{l,m}$ that describes the channel between lamppost l and RRH m in each time slot, the value $r_{l,m}$ can be estimated as [18]:

$$r_{l,m} = W \log(1 + \overline{\gamma}_{l,m} \mathbf{h}_{l,m}^{\dagger} \mathbf{h}_{l,m}) \quad (1)$$

where $\overline{\gamma}_{l,m}$ is the average SNR at lamppost l that transmits to RRH m and $\mathbf{h}_{l,m}^{\dagger}$ is the conjugate transpose of $\mathbf{h}_{l,m}$. The channel matrix $\mathbf{h}_{l,m}$ is given by [19]:

$$\mathbf{h}_{l,m} = \sqrt{\beta_{l,m}} \mathbf{w}_{l,m}, \quad (2)$$

where $\beta_{l,m}$ is the large scale channel fading coefficient that is equal to $1/d_{l,m}$, assuming a distance $d_{l,m}$ between lamppost l and RRH m, and $\mathbf{w}_{l,m}$ is the channel gain vector estimated according to the channel fading model. The DL rate is at least equal to the UL rate and is estimated in a similar manner [20].

For the channel fading model, we consider that each lamppost steers its main lobe towards the RRH that serves it, establishing a line-of-sight (LOS) link. In order to model the LOS signal propagation and the scattered non-LOS (NLOS) signal propagation, we assume Rician fading channels between RRHs and lampposts. The channel gain vector $\mathbf{w}_{l,m}$ when channels are memoryless is given by [21]:

$$\mathbf{w}_{l,m} = \sqrt{\frac{\kappa_{l,m}}{1+\kappa_{l,m}}} \mathbf{w}_{l,m}^{LOS} + \sqrt{\frac{1}{1+\kappa_{l,m}}} \mathbf{w}_{l,m}^{NLOS}, \quad (3)$$

where the vector $\mathbf{w}_{l,m}^{LOS} \in \mathbb{C}_N$ is deterministic, whereas the vector $\mathbf{w}_{l,m}^{NLOS} \in \mathbb{C}_N$ represents a random component and contains independent and identically distributed values that follow a Gaussian distribution with zero mean and unit variance. The value $\kappa_{l,m}$ is the Rician factor defined as the ratio of the signal power of the LOS (deterministic) component over the signal power of the NLOS (random) component.

III. The QoS-aware Medium Transparent Resource Management Scheme

In this section, we describe the operation of the QMT scheme that enables the direct negotiation for resources between lampposts and OLT, without the intervention of the RRHs. The communication takes place with the use of SFs transmitted by each lamppost in a specific time interval. Each SF comprises of a fixed number of time slots, of fixed duration σ, that are dedicated for the transmission of the control packets required for the coordination of the bandwidth allocation mechanism and the data packets of the different QoS classes.

As depicted in Fig. 2, the lampposts transmit SFs in a round robin manner and a lamppost is removed from the polling sequence if it remains silent for a number of SFs. Before the transmission of data packets of a lamppost during an SF, a resource requesting (RR) time period that occupies a portion of the first time slot in each SF is used for the transmission of the necessary information by the lamppost. In the RR period, the OLT broadcasts a POLL packet to all lampposts and the lamppost served in the current SF responds with an INFO packet that contains the lamppost ID, the number of packets per QoS class that will be sent in the current SF and the CSI of the UL channel between the lamppost and the RRH that serves it. Upon correct INFO packet reception, the OLT sends an ACK packet, acknowledging the correct identification of the lamppost. The RR period may have a different duration in each SF, depending on the data rates of the OLT-lamppost link.

The rest of the time slots in the SF are used for DATA packet transmissions. The time slots are allocated in a way that the packets of a QoS class with higher priority are sent using more time slots comparing to a class of lower priority, whereas the transmissions of the higher priority packets precede the transmissions of lower priority packets. In each time slot of the DATA transmission period in the SF (Data Tx slot), the lamppost sends a number of DATA packets of the current QoS class. After the correct reception of each DATA packet, the OLT responds with an ACK packet. Hence, in each Data Tx slot, several packets of the same class may be delivered, according to the achievable data rates of the OLT-lamppost link. Once the current SF ends, the OLT notifies the next lamppost in the polling sequence by broadcasting a POLL packet.

IV. Performance Evaluation

In this section, we assess the performance of the proposed scheme in scenarios with varied UL traffic load, number of lampposts per RRH and time slot allocation per QoS class, using the settings described in Section IV-A. We evaluate the QMT scheme in terms of average delay and throughput and compare its performance with a baseline scheme that transmits packets in a first-in-first-out (FIFO) manner and does not take into account the QoS classes of the packets. We use an event-driven C++ simulator for the implementation of QMT and FIFO schemes. The simulation results are discussed in Section IV-B.

A. Simulation setup

We consider the FiWi network of Fig. 1 with $M = 2$ RRHs and L lampposts per RRH, which serve users that generate UL traffic of $K = 3$ different QoS classes. The simulation parameters are summarized in Table I.

B. Simulation results

We next evaluate the QMT scheme in different scenarios, studying the effect of the UL traffic load $\lambda_{l,k}$ of each QoS class per lamppost (Section IV-B1) and the number L of the lampposts per RRH and the time slot allocation per class (Section IV-B2) on the performance of the scheme.

1) Effect of different UL traffic load levels: In the considered network, each RRH serves $L = 2$ lampposts. The UL traffic load per QoS class per lamppost varies from 40 to 420 Mb/s. Each SF comprises of 20 slots, distributed to the classes according to their priority. The class with $k = 1$ has the most stringent QoS requirements and the highest priority. We study an example where 55% of the time slots are allocated to the high priority class, whereas 30% and 15% are allocated to the other classes (11, 6 and 3 slots, respectively).

Figure 3a shows the average delay per QoS class achieved by the QMT scheme and the FIFO scheme. It can be observed that the proposed scheme is able to perform QoS differentiation, providing the lowest achievable delay to the high priority class ($k = 1$) for all load levels. More specifically, the delay of the high priority class is at least 26% and 56% (load equal to 40 Mb/s) lower than the delay experienced by the QoS class with $k = 2$ and $k = 3$, respectively. This result is attributed to the unequal allocation of time slots to each QoS class in each SF. As more time slots are allocated to the high priority class, more packets belonging to this class are delivered in each SF. In

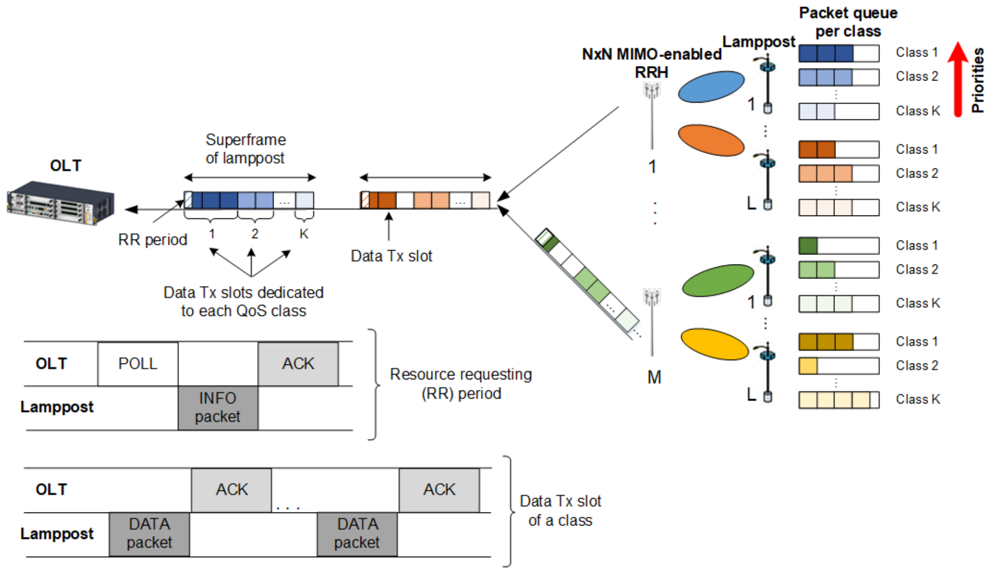
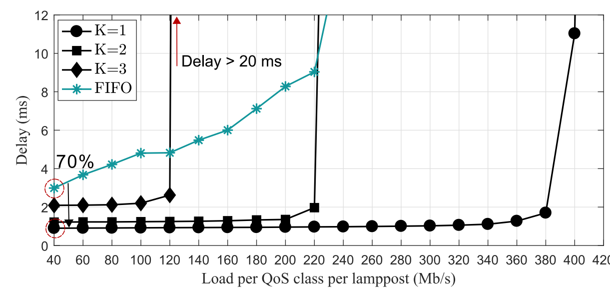


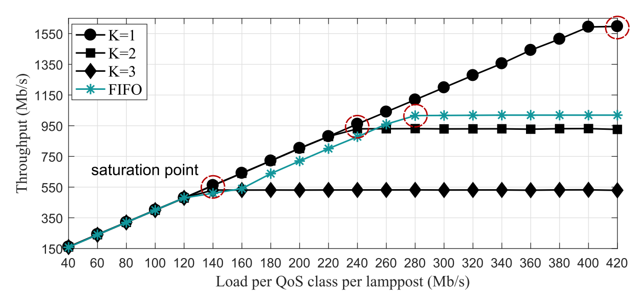
Fig. 2: Operation example of the QMT scheme

TABLE I: Simulation parameters

Parameter	Value
M	2 RRHs
Time slot duration σ	25 μs
Fiber link rate r_m^F	10 Gb/s
POLL size	64 B
INFO size	128 B
DATA size	1500 B
ACK size	8 B
Functional split overhead	9 B [16]
N	64 antennas/RRH
W	1 GHz
$\beta_{l,m}$	0.003
$\overline{\gamma}_{l,m}$	10 dB
$\kappa_{l,m}$	5



(a) Delay per QoS class



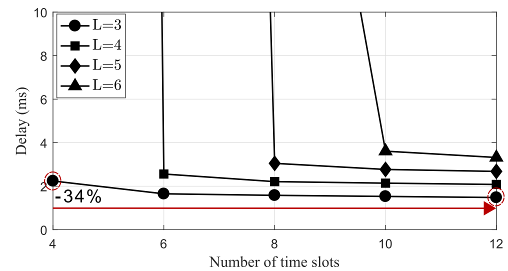
(b) Throughput per QoS class

Fig. 3: Performance for different load values

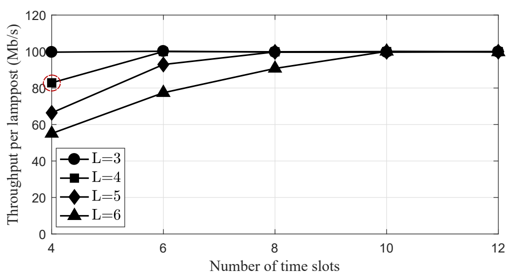
contrast, the FIFO scheme demonstrates similar delay levels for all classes as in each time slot, packets from the three packet queues are transmitted by ascending packet generation time, regardless of their priority. The proposed scheme outperforms the FIFO scheme, achieving at least 70% lower delay for the high priority class (load equal to 40 Mb/s).

In Fig. 3b that depicts the average throughput per QoS class achieved by the two schemes, we may see that, with QMT, the throughput levels are different per QoS class in high loads, close to the saturation points of each class. As the number of time slots allocated to each class is different, the saturation point per class is also different, i.e., for $k = 1$, saturation occurs at load equal to 420 Mb/s, whereas for $k = 2$ and $k = 3$, saturation point is reached much earlier, at load equal to 240 Mb/s and 140 Mb/s, respectively. It should be noted that beyond the saturation point of each class, the delay levels are much higher than 20 ms. However, for the high priority class, the proposed scheme offers delay values lower than 12 ms for load values in the range $[40 - 400]$. We can also observe that the FIFO scheme demonstrates delay values higher than 12 ms for the high priority class for load equal to 240 Mb/s and higher, before reaching the saturation point (load equal to 280 Mb/s).

2) Effect of different number of lampposts and allocated time slots: We evaluate the QMT scheme in terms of average delay and throughput per lamppost for a specific QoS class.



(a) Delay for different L values



(b) Throughput per lamppost for different L values

Fig. 4: Performance for different number of allocated time slots

Each RRH is connected to $L = \{3, 4, 5, 6\}$ lampposts, each generating UL traffic load equal to 100 Mb/s per class. The number of time slots allocated to the class under study increases from 4 to 12, whereas a number of 20 time slots is assumed.

The allocation of higher number of time slots reduces the average delay of the QoS class, as more packets belonging to this class are delivered per SF (Fig. 4a). Considering the case where $L = 3$ lampposts are used, the increase of the number of time slots from 4 to 12 leads to a reduction of 34%. We also observe that the use of more lampposts increases the delay, as each lamppost waits for a longer time period until it can transmit packets. Moreover, when fewer time slots are allocated, the saturation point is reached for the specific class even when few lampposts are used. As shown in Fig. 4b, for $L = 4$, 6 or more time slots are required for the accommodation of the traffic, as 4 time slots offer throughput equal to 82 Mb/s per lamppost for the specific QoS class and are not sufficient.

V. Conclusions

In this paper, a new resource management scheme for FiWi fronthaul that offers QoS differentiation in a medium-transparent manner has been presented and evaluated in scenarios with different load per QoS class and number of lampposts. The simulation results have shown that the proposed scheme favors the high priority class, achieving lower delay in all cases. Moreover, the delay of a specific class is improved when higher portion of the optical frame is allocated for the packet transmissions of this class. As future work, we plan to study the effect of different types of traffic load and analytically describe the performance of the proposed scheme.

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