Quality of Service Provisioning in High-Capacity 5G Fronthaul/Backhaul Networks

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Abstract— Passive Optical Networks (PONs) are an efficient high-performance optical access solution that is able to provide huge bandwidth in a resourceful way through the incorporation of inexpensive passive elements. PONs have been widely used for the provision of high-demand services to a number of wired end-users. However, the PON configuration may be also used for the support of wireless end-users through the integration of the PON with a wireless access system. This converged network can therefore take advantage of the mobility features of the wireless network and the high-bandwidth benefits of the PON. In this article, we highlight the basic features of the existing optical-wireless access systems. Moreover, we discuss the challenges in the medium access control layer of the converged network and viable solutions for the efficient Quality of Service management support.

Keywords—5G networks, passive optical networks, fiber-wireless networks, medium access control

1   Introduction

The strong demand for delivering broadband telecommunication services to residential users suggests the utilization of high-capacity technologies in the access domain. To meet these demands, Passive Optical Network (PONs) are introduced as the basic technology for the implementation of Fiber-To-The-Home (FTTH) solutions [1]. PONs provide fiber connections directly to end-users, low operational costs, and tremendously larger bandwidth compared to the traditional copper twisted pair. The installation of a PON also allows the service provider to deliver any current or

foreseeable set of broadband services that creates the footing to the migration to 5G systems.

PONs come in different flavours depending on the multiple access scheme that they apply in order to provide service to a high number of users. Current PON configurations are based on the cost-effective Time Division Multiplexing (TDM) technology, while Optical Code Division Multiple Access (OCDMA) [2] and Orthogonal Frequency Division Multiple Access (OFMDA) [3] have been also considered as viable solutions to support current and future bandwidth demands. In addition, more advanced PON-based techniques that are based on the Wavelength Division Multiplexing (WDM) technology are currently being developed and standardized. Recent advances in photonic technology allow the realization of the Ultra-Dense WDM (UDWDM), which is the key technology for the Wavelength-To-The-User (WTTU) concept [4].

PONs are also the key player in the converged optical-wireless access network, where they act as the optical backhaul of a wireless access network front-end, thus forcing all possible FiWi solutions to ensure PON compatibility. Various technologies have been proposed for the wireless fronthaul/backhaul; these solutions include Wireless Fidelity (WiFi), Worldwide interoperability for Microwave Access (WiMAX) and Long-Term Evolution (LTE). Nevertheless, the 5G operational framework is targeted to be the key technology that will enable the roll-out of very dense wireless networks interconnecting over 7 trillion devices and 7 billion people. 5G networks envision to significantly increase the network capacity, mainly through the utilization of the mmWave advantages, such as the small wavelength that allows the application of Multiple-Input Multiple-Output (MIMO) communication schemes that further enhance the efficient exploitation of the spectrum [5]. However, the utilization of the mmWave frequencies may outcome a number of transmission deficiencies, such as blocking-coverage holes (as a result of weaker non-line-of-sight paths), higher path losses (due to the high frequencies) and reduced diversity (as a result of less significant scattering). However, the incorporation of effective mechanisms in the MAC layer can further improve the network capacity, especially when medium transparent schemes are applied that provide support to wireless signals over the optical transport.

In this article, we discuss the challenges that arise from the utilization of PONs as the backhaul solution for 5G networks and study the applicability of Quality of Service (QoS) mechanisms. Specifically, we initially present the technology changes that are necessary to support the high data rates envisioned in 5G through an integrated optical wireless network. Next we present the solutions that should be incorporated both in the physical and network domains, in order to implement a fully converged PON-based 5G network that is able to realize the ambitious targets of 5G networks, even in ultra-dense deployments, and provide QoS differentiation through the application of a packet priority-based mechanism. The proposed method targets to differentiate the network services, by considering different queues for each one of the supported QoS classes, and determines the mean queuing delay in the uplink direction of the network. The results show that the proposed approach is able to reduce the end-to-end delay for delay-sensitive, high-priority QoS classes.

2   5G integrated PON-based network challenges and solutions

Mobile network operators are facing significant challenges in order to cope with the ever increasing demands for bandwidth both in the uplink and downlink. Current 4G technology deployments are able to provide uplink and downlink rates that are far from the 5G targets of 50 Mbps and 300 Mbps per user, respectively. Furthermore, current solutions may provide latency up to 10 ms; however, specific low-latency 5G applications require latency values below 1 ms. In addition, the new network must also target to achieve the 1000x capacity increase compared to the current LTE technology, as well as the significant power consumption reduction by a 10x factor. It therefore evident that these ambitious targets cannot be realized by just upgrading or extending the current 4G solutions, since: i) current frequency bands cannot support the envisioned data rates; ii) the high cell densification that may increase the total capacity will lead to significantly higher interference levels; iii) in ultra-dense deployments the connection of every antenna with the backhaul exclusively through fiber will significantly increase the installation cost.

To address the aforementioned challenges, significant research challenges have been considered that are based on newly proposed deployment paradigms like Network Function Virtualization (NFV) [6], and network slicing [7]. The main conclusions of these efforts are the promotion of mmWave bands and massive MIMO antennas, as well as an eventual transition to Ethernet-based fronthaul transport. Still, these solutions may provide inefficient results when applied to high-density urban area environments.

In such a challenging environment, PONs are expected to play a vital role as part of a fiber-wireless network, mainly by utilizing advantages of other technologies both in the physical and network domain, in order to become an efficient 5G network solution. In the physical domain, cost-effective and high-speed transceivers are required, in order to support the emerging 25 Gb/s and 100 Gb/s PON access. In addition, the optical beamforming technology is an attractive solution for offering beamforming to high-bandwidth and ultra-fast massive (e.g. 64x64) MIMO antennas in a cost- and energy efficient way. Furthermore, in order to fully exploit the huge optical bandwidth offered by the WDM technology, Reconfigurable Optical Add Drop Multiplexers (ROADMs) with reduced insertion loss are necessary for the dynamic switching of the wavelengths in and out of the Remote Radio Head (RRH) of the wireless network, over a given time span.

The aforementioned technology in the optical domain should be combined with high-capacity and efficient equipment in the wireless domain. To this end, massive MIMO antennas are essential in order to provide multi-Gbps fronthaul, especially in densely populated areas [8]. The development of such technology requires to dynamically allocating different wireless frequency bands within the mmWave available spectrum to multiple MIMO boards at sub-μsec-scale tunability speeds. These configurations can therefore be combined with the WDM technology in order to simplify high-capacity setups and reduce their energy consumption. However, for such high-capacity MIMO setups, a Digital Signal Processing engine is required for carrying out the channel coding/mapping and MIMO processing tasks.

In Layer 2 new approaches are necessary in order to allocate both optical and wireless bandwidth to the RRHs and end-users. Such solutions should be therefore medium-transparent [9], so as to allow the direct traffic negotiation between the PON's central office and the wireless end-users. This can be implemented through a centralized polling-based synchronization and resource allocation scheme, in order to resolve the current challenges of synchronization and packet delay variation in Ethernet-based fronthaul, and achieve very-high-throughput performance with very low latency values.

In the network domain, a Software Defined Network (SDN) plane can be considered as an effective solution for orchestrating the entire optical-wireless converged network. Such a solution can provide the means for the design, deployment, customization, and optimization of the different network slices and resources of both the optical and the wireless domain. This configuration will therefore allow an advanced and efficient network configuration and management providing the necessary credentials for a holistic network reconfiguration and orchestration over all the available resources across the complete optical-wireless network.

3   System Model

We consider the network architecture of Fig. 1 that supports N rooftop antennas. Each one of the rooftop antennas are connected to the Optical Line Terminal (OLT) in the uplink direction and to a number of small-cell antennas in the downlink direction. Specifically, we consider that in rooftop n ($n = 1,…, N$) a number of B_n small-cell antennas are connected that provide service to $U_{n,bn}$ users ($bn = 1,…, B_n$). Each one of these users has a number of K queues, one for each one of the K QoS classes. Specifically, packets that belong to QoS-class k ($k = 1,…, K$) are stored in the corresponding queue until they are transmitted to the corresponding rooftop antenna.

Each rooftop antenna is able to transmit groups of packets to the OLT, called superframes (see Fig. 1). In order to avoid collisions, each rooftop antenna is able to transmit its superframe during a specific time-interval in each transmission window; we consider that this time-interval has a fixed duration of T_{sp} sec. During T_{sp}, each rooftop transmits the packets of all K QoS-classes, as well as the control packets that are necessary for the coordination of the bandwidth allocation mechanism. In order to support QoS differentiation, we assume that each QoS class allocates a dissimilar percentage of the superframe in such a way so that more packets that belong to higher QoS classes are transmitted compared to the lower QoS classes. Specifically, we assume that QoS-class k transmits up to m_k packets in each transmission window, with $m_1>m_2>…>m_K$. Therefore, the total number of packets that are transmitted from each small-cell antenna to the rooftop is:

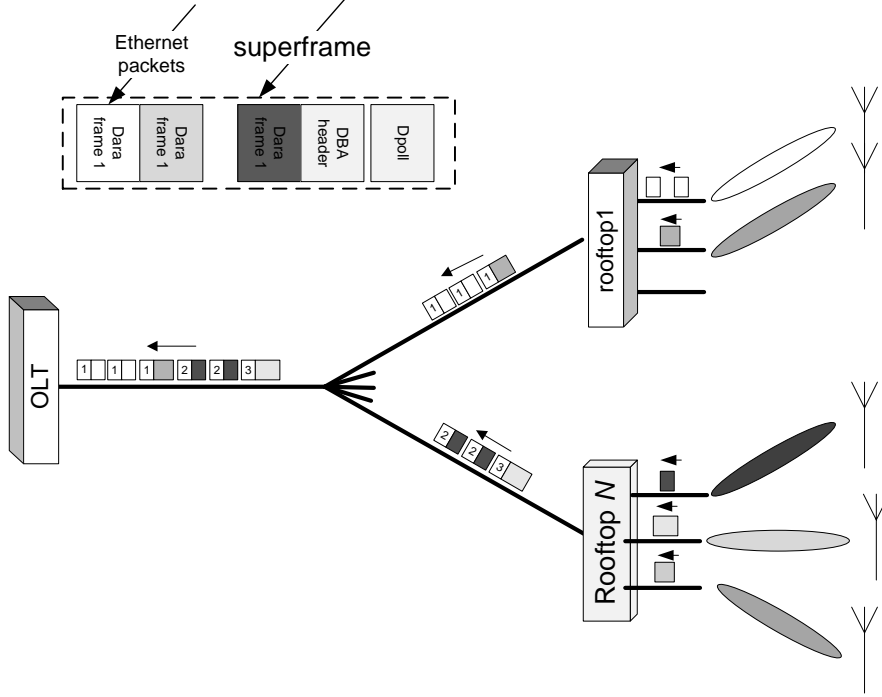$$T_{packets} = \sum_{k=1}^{K} m_k \tag{1}$$

Fig. 1. The converged optical-wireless network.

The values of m_k are selected based on the mean packet arrival rates of the corresponding QoS class and are assumed to be constant for each transmission window. By considering that each packet is transmitted during a time-slot of duration σ, and that the network applies a safety time interval δ between two consecutive superframes, the transmission window can be calculated by the following equation:

$$T_{TW} = \sum_{n=1}^{N} \sum_{b_n=1}^{B_n} T_{sp} \sigma + (N-1)\delta \tag{2}$$

where $T_{sp}=T_{data}+T_{ctr}$, and T_{ctr} refers to the transmission of the control packets. The transmission window T_W can be considered as the service-time of each one of the queues that are installed in each rooftop antenna, which is constant over time. On the other hand, we assume that the packet arrival rate of each QoS-class for small-cell antenna b_n of rooftop antenna n is Poisson with mean value of $\lambda_{bn,k}$; the total arrival rate of QoS-class packets to the rooftop antenna n is therefore equal to $\lambda_{n,k} = \sum_{b_n=1}^{B_n} \lambda_{b_n,k}$. By considering this value, the packet arrival rate of the group of packets of QoS-class k is

$$\lambda_{n,k}^{group} = \frac{\lambda_{n,k}}{m_k} \tag{3}$$

while the corresponding equivalent offered traffic load is

$$A_{n,k}^{group} = \lambda_{n,k}^{group} \cdot T_{TW} \cdot \sigma \tag{4}$$

By considering these groups of packets as individual entities, we may assume that they can be modeled by an M/D/1 queueing system, since the arrival rate of the group also follows a Poisson process (Eq. (3)), the service time is constant (and equal to T_W) and there is only one server, since one superframe is transmitted in each transmission window. Therefore, the mean waiting time of the group of packets that belong to QoS-class k is:

$$W_{n,k}^{group} = \frac{T_{TW} \cdot \sigma}{2 \cdot (1 - A_{n,k}^{group})} \tag{5}$$

The mean queue length of this M/D/1 system can be calculated by applying Little's theorem:

$$L_{n,k}^{group} = \lambda_{n,k}^{group} \cdot W_{n,k}^{group} \tag{6}$$

As the main target of the presented analysis is the calculation of mean queueing delay for the individual packets, we use the approximation proposed in [10] in order to firstly determine the mean queue length of the individual packets:

$$L_{n,k} \approx m_k \cdot L_{n,k}^{group} + P_{n,k}^w \frac{m_k - 1}{2} + (1 - P_{n,k}^w) \cdot \frac{w_k - 1}{2} \tag{7}$$

where w_k is the minimum number of QoS-class k packets that are transmitted in each transmission window, and $P_{n,k}^w$ is is the probability of waiting in the corresponding M/D/m_k queuing system. Finally, the mean queueing delay for the individual packets can be calculated by applying Little's law:

$$W_{n,k} = \frac{L_{n,k}}{\lambda_{n,k}} \tag{8}$$

4   Evaluation

In this section we provide numerical results from the proposed analysis for the mean queueing delay by considering a network of $N = 10$ rooftop, each one providing service to 3 small-cell antennas. The network supports $K=5$ QoS-classes, which transmit their packets during a superframe duration of 50 time-slots, which are

distributed to the 5 QoS classes by considering that $(m_1, m_2, m_3, m_4, m_5)=(14, 12, 10, 8, 6)$. The time-slot duration is assumed to be equal to 25 μsec. In Fig. 2 we present analytical results for the queueing delay. In order to prove that the proposed approach results in lower queueing delay values for the high-QoS-classes, we assume that the packet arrival rate of all classes is the same and equal to the values of the x-axis of Fig. 2. As the results of Fig. 2 reveal, low QoS-class packets experience higher delay values, since a smaller number of packets are serviced in each transmission window compared to the higher classes.
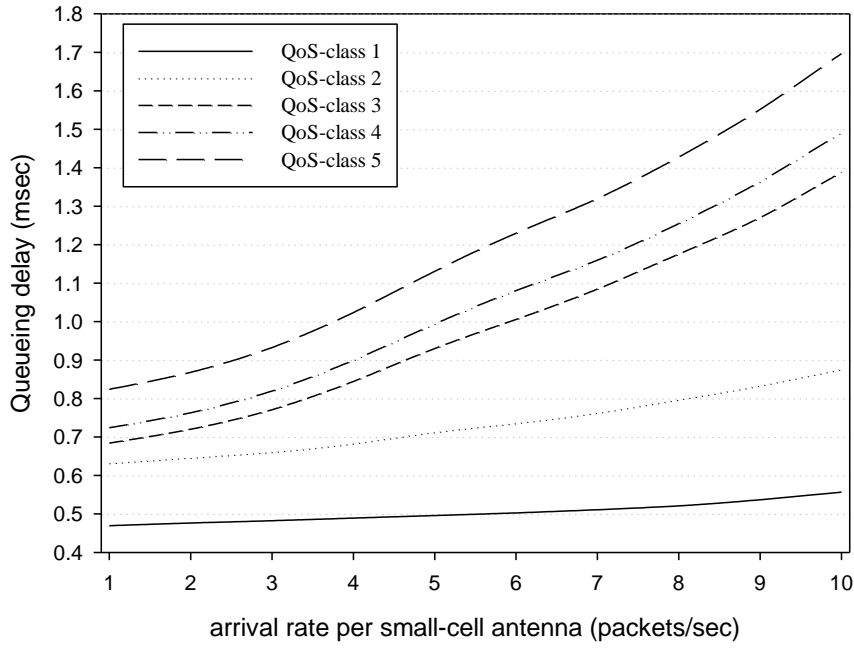

Fig. 2. Numerical results of the queueing delay of each one of the 5 QoS classes.

5 Conclusions

In conclusion, several challenges arise for the full exploitation of an integrated optical and wireless network in order to provide 5G network solutions. These challenges should be addressed by utilizing advances in the area of photonics as well as of network management, in order to architect 5G network that are capable of providing cost-effective and energy efficient solutions, especially in high density urban areas. To this end, we presented an approach for the provision of QoS differentiation in 5G networks and a corresponding analytical model for the determination of the queueing delay. The results showed that the prioritization of the QoS-classes can favor the high-priority classes in terms of queueing delay.

6   Acknowledgment

7   References

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