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Multi-Stage Resource Allocation in Hybrid 25G-EPON and LTE-Advanced Pro FiWi Networks for 5G Systems

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Abstract: The 5G vision is not restricted solely to the wireless domain and its challenging requirements cannot be fulfilled without the efficient integration of cutting-edge technologies in all portions of the telecommunications infrastructure. The promoted architectures for next generation telecommunications systems involve high capacity network domains, which operate flexibly and seamlessly to offer full Quality of Experience to all types of subscribers. The proliferation of highly demanding multimedia services and the advanced features of modern communication devices necessitate the development of end-to-end schemes which can efficiently distribute large amount of network resources anywhere and whenever needed. The paper introduces a new resource allocation scheme for cutting-edge Fiber-Wireless networks is introduced that can be applied in the fronthaul portion of 5G-enabled architectures. The adopted technologies are the forthcoming 25G-EPON for the optical domain and the 5G-ready LTE-Advanced Pro for the wireless domain. The proposed scheme performs allocation decisions based on the outcome of an adjustable multi-stage optimization problem. The optimization factors are directly related to the major considerations in bandwidth distribution, namely priority-based traffic differentiation, power awareness, and fairness provision. The conducted evaluations prove that this approach is able to ensure high efficiency in network operations.

1 Introduction

With the proliferation of advanced network services and especially the modern demanding multimedia applications offered to mobile users, the need for highly efficient access networks has emerged. The primary aim is to provide subscribers with advanced Quality of Experience (QoE) and the ability to take full advantage of their state-of-the-art smart devices (e.g., high resolution big screen smartphones) in order to consume and generate large volumes of traffic with extensive energy autonomy anywhere at anytime. On the telecommunications provider side, it is evident that there is a clear shift towards multimedia services, content delivery networks, and resource tenancy. Hence, it becomes apparent that the high capacity core infrastructure at the backhaul network needs to be seamlessly, flexibly, and efficiently interconnected with the fronthaul and the radio access networks. The ultimate objective is to enable end-to-end management of the network resources, which can be effectively assigned to subscribers (focusing on mobile users) ensuring high performance, power efficiency, and fairness.

The 5G-PPP (5th Generation Public Private Partnership), composed of industrial and academic partners as well as emerging communities, aims at integrating the wireless and optical communications, while providing pervasive network access to all subscribers. The combination of the high capacity of the most promising optical technologies, namely Passive Optical Networks (PONs), with the mobility and flexibility of state-of-the-art cell network technologies, such as LTE (Long Term Evolution) and WiMAX (Worldwide Interoperability for Microwave Access), enables the formation of efficient hybrid FiWi (Fiber-Wireless) networks. Possible solutions for the optical domain involve versions of PONs standardized by ITU (International Telecommunication Union) and IEEE (Institute of Electrical and Electronics Engineers). In more detail, the ITU has standardized XG-PON [1], which supports 10 Gbit/s at the downstream and 2.5 Gbit/s at the upstream, and recently developed NG-PON2 [2], supporting symmetrical 10 Gbit/s both at the downstream and the upstream. The standardization endeavours by IEEE have led to 10G-EPON [3], supporting symmetrical 10 Gbit/s, and currently develops the most promising 25G-EPON standard and the subsequent versions with multi-channel support 50G-EPON and 100G-EPON [4]. At the wireless domain, state-of-the-art solutions for mobile networking come from IEEE and 3GPP (3rd Generation Partnership Project). The former has developed WiMAX, with latest version being WiMAX Release 2, which corresponds to the 802.16m standard [5] and supports data rate up to 100 Mbit/s for mobile users, fulfilling the IMT-Advanced (International Mobile Telecommunications-Advanced) 4G requirements set by ITU. The latter has developed LTE, with the latest version being LTE-Advanced Pro, which was introduced in 3GPP Release-13 [6] and is currently enhanced in Release-15 [7]. In fact, LTE-Advanced Pro, which is able of supporting data rates in the range of 1 Gbit/s, is now considered 5G-ready technology.

A crucial challenge in the formation of next generation FiWi networks, as part of the overall 5G vision, is the efficient integration of cutting-edge optical and wireless technologies. The created interdependencies in enabling high performance, fair, and power aware allocation of resources across the heterogeneous domains affect the overall network performance and lead to highly dynamic tradeoffs in bandwidth assignments among multiple user devices (UE - User Equipment). Thus, it is necessary that the adopted Dynamic Bandwidth Allocation (DBA) scheme is highly flexible, adaptable, effective in terms of channel utilization, and considers all major factors (performance, power efficiency, fairness). Failing to take into account these factors leads to low Quality of Service (QoS), unfair treatment of subscribers, and rapid depletion of mobile device batteries.

This work contributes to the related state-of-the-art by introducing an efficient multi-stage resource allocation technique, which can be applied in cutting-edge FiWi networks that couple the two most promising latest optical-wireless technologies for the 5G fronthaul, namely 25G-EPON and LTE-Advanced Pro. The proposed solution adaptably combines and optimizes the key bandwidth distribution factors by formulating a multi-stage optimization problem. It enables maximum utilization of the available optical and wireless capacity, effectively differentiates traffic by applying a compatible prioritization scheme across the heterogeneous domains, boosts the overall power efficiency by favouring UEs with low power consumption, and ensures fairness by uniformly distributing the available bandwidth subjected of course to any constraints. Given the specific network requirements, the resource allocation scheme can be adjusted to take into account all or some of the optimization factors.

The rest of the paper is structured as follows. Section 2 presents an overview of the considered hybrid architecture and the related entities and technologies. Existing endeavours towards combination of optical-wireless technologies and allocation of resources in such networks are discussed in Section 3. Section 4 provides an analytical presentation of the proposed scheme. The simulation results are provided and discussed in Section 5. Finally, the paper is concluded in Section 6.

2 Background

Among wireless and optical 5G-ready technologies, LTE-Advanced Pro and 25G-EPON are considered promising solutions for integrating the wireless and optical domains. Combining LTE-Advanced Pro and 25G-EPON networks in a hybrid system is an efficient approach, because it involves two cutting-edge telecommunication technologies which can be compatible in resource allocation and QoS provision. In this section, the adopted FiWi system architecture is presented. Furthermore, we provide details regarding the considered QoS mapping approach between 25G-EPON and LTE-Advanced Pro traffic classes.

Exploiting the obvious benefits of the latest optical telecommunication technologies and particularly the reliable support of very high data rates at long distances, optical networks have evolved as the best candidate for the fronthaul of hybrid telecommunication architectures [8]. At the access part, state-of-the-art wireless standards provide advanced mobility along with notably increasing capacity. The adopted FiWi system architecture involves a 25G-EPON network as the fronthaul portion and a number of LTE-Advanced Pro cells for radio access, as depicted in Fig. 1. It constitutes a C-RAN (Cloud Radio Access Network) architecture, in which the 25G-EPON realizes the interconnection between the Remote Radio Heads (RRHs) mounted on LTE-Advanced Pro base stations (eNodeBs or eNBs) and the centralized BaseBand Units (BBUs) at the edge of the cellular network. In the 25G-EPON, an Optical Line Terminator (OLT) which is placed in the operator's central office, uses a passive splitter/combiner to connect to several Optical Network Units (ONUs) that are deployed in the coverage area. The use of passive optical equipment boosts flexibility in fibre deployment and maintenance at reduced costs. Every ONU device is integrated with an LTE-Advanced Pro eNB, forming a hybrid ONU/eNB. The benefits of such an integration are obvious: the optical domain is a highly efficient gateway for the wireless domain, the signal attenuation/noise due to optical-electrical conversion is minimized, the wireless base stations can be kept simple and easy to deploy and maintain, while the radio controllers can be placed remotely and managed centrally, providing the ability to perform high-level control including efficient resource allocation.

A crucial mechanism for the optical-wireless integration and the provision of advanced end-to-end QoS support is the traffic priority mapping scheme. Since the resource allocation takes place centrally and is performed by the OLT, the priority levels supported by LTE-Advanced Pro uplink are mapped to the corresponding ones of the EPON standard. According to its technical specifications [9], LTE-Advanced Pro associates the Service Data Flows (SDF) with a QoS Class Identifier (QCI). Flows of the same QCI can be treated as an aggregated stream. A number of QoS characteristics are specified for each QCI. The 3GPP Release-15 specifies 15 QCI classes, each one associated with a priority level, ranging from 0.5 (Mission Critical delay sensitive signalling) to 9 (TCP-based services). The lowest priority level value corresponds to the highest priority. The purpose of the priority levels is to differentiate individual and aggregated flows, so that the scheduler meets the transmission requirements of the lower valued priority levels and then the requirements of the higher valued levels. On the other hand, 25G-EPON supports the three traffic classes that were originally defined for EPONs in [10]: the high priority Expedited Forwarding (EF) class, the medium priority Assured Forwarding (AF) class, and the low priority Best Effort (BE) class, which originate from the DiffServ scheme provided by the Internet Engineering Task Force (IETF).

In the 25G-EPON domain, the Multi-Point Control Protocol (MPCP) is employed for bandwidth allocation by the OLT to ONU/eNBs. This protocol utilizes two types of control messages to perform the allocation process: the GATE and the REPORT messages. The former typically uses in-band signalling to assign transmission opportunities to the ONU/eNBs through allocated transmission windows. The latter is used by the ONU/eNBs to communicate their buffers' sizes and transmission requests to the OLT through the upstream channel.

In the LTE-Advanced Pro domain, at the initialization phase, the UE sends to the eNB a Scheduling Request (SR), in order to inform it about the data awaiting transmission. The eNB replies with an uplink grant assigned to the UE. Through uplink data transmissions, the UE is able to notify the eNB about its updated transmission requirements using a Buffer Status Report (BSR) control message, which carries information about the amount of queued data that wait to be transmitted. This information is used by the scheduler to decide how many Resource Blocks (RBs) to allocate.

In this context, the introduced resource allocation technique adopts a straightforward QoS mapping process between the 25G-EPON and the LTE-Advanced Pro networks, which fulfills the traffic differentiation purposes of both and provides end-to-end compatibility. Specifically, the LTE priority levels are evenly divided into three ranks; the first rank levels (from 0.5 to 2) are mapped to the EF service class, the second rank levels (from 2.5 to 5.5) are mapped to the AF service class, and the third rank levels (from 6 to 9) are mapped to the BE service class. In that manner, the hybrid FiWi system eventually considers three traffic priorities (low priority 1, medium priority 2, high priority 3) for performing resource allocation at the OLT side.

Furthermore, the allocation scheme considers the power consumed by UEs for data transmission. This information is made available through the LTE power control mechanism [11] on the Physical Uplink Shared Channel (PUSCH) and specifically by exploiting the closed loop component. Taking into account the transmission power and the current UE uplink data rate, the power per transmitted bit is estimated. It is noted that the data rate derives from the current Modulation and Coding Scheme (MCS) and the number of used Resource Elements (REs).

3 Related Work

In this section, we review state-of-the-art FiWi architectures which are expected to enable the 5G vision, along with the latest approaches for resource allocation in such hybrid networks.

3.1 FiWi Architectures

FiWi networks constitute a mix of optical and wireless technologies. In the literature, there can be mainly found two classes of FiWi networks: a) Radio over Fiber (RoF) performing integration at the physical layer and b) Radio and Fiber (R&F) bridging the optical and wireless components in the context of a hybrid network. A key challenge which is currently addressed is related to the seamless and cost-effective modulation and transmission of Radio-Frequency (RF) and BaseBand (BB) signals over a single wavelength of an optical fiber with satisfactory performance [12, 13]. The most promising 5G-enabling approach for efficient RoF solutions is C-RAN, which is supported by numerous major vendors and operators [14] and is capable of centrally collecting and controlling all network resources associated with the base stations. The RF signals are transmitted through the optical equipment, which composes the network fronthaul portion. The main benefits of such an integrated approach are evident: the capital and operating expenditures (CAPEX and OPEX) for deploying and maintaining the network infrastructure are significantly reduced, while enabling cutting-edge and highly demanding network services in an agile manner.

One of the terms that have been used to characterize hybrid FiWi systems for network access is WOBAN (Wireless-Optical Broadband-Access Network). Such a network consists of a number of wireless routers connected to ONUs through gateways and eventually through the OLT to the core network and the Internet [15]. A key difference between the WOBAN and the C-RAN architectures is the involved number of routing hops, since the former creates a multi-hop network, while the latter creates a single-hop connection between the optical and the wireless domain.

A promising approach for the integration of optical and wireless technologies into a hybrid network has been the combination of EPON with WiMAX, which has been shown to allow cost-effective access to network subscribers [16]. The concept of sub-OLTs between the ONUs and the OLT was introduced in [17], with the aim to extend the coverage of the network. Another integration approach involves the LTE, which is considered the most promising starting point for 5G networks, along with the EPON standards. It has been proposed in [18] and it was shown to combine the highly mobility of LTE with high capacity of EPON in a cost-effective manner. The ability to converge LTE with WDM-PON (Wavelength Division Multiplexing - Passive Optical Network) was demonstrated in [19]. Each ONU is combined with an eNB and is arranged on an optical ring, with the OLT connected to the Evolved Packet Core (EPC). In this architecture, thousands of LTE users can have high performance network access.

A thorough comparison of different FiWi architectures is provided in [20]. The specific survey considers several comparison criteria, namely the cost of equipment, the implementation complexity, the coverage of the network, the application protocols, the scalability and sustainability. Regarding the optical domain of the hybrid architectures, WDM technologies seem quite immature, yet. The PON solutions provided by IEEE and ITU which offer capacities of 10 Gbit/s and beyond are eventually expected to dominate the telecommunications market in the near-future. Lately, the idea of employing multiple apertures for transmission and reception was examined in [21]. The innovative and very promising concept of orthogonal space-time coding for transmission over optical links was adopted and successfully analyzed. At the wireless domain, it becomes evident that the LTE standards by 3GPP constitute the primary choice for FiWi networks, compared to the competitive WiMAX standards by IEEE.

3.2 *Resource Allocation Approaches for Hybrid Networks*

Effectively combining fairness and high performance in allocation of resources in latest access networks has attracted much interest from the telecommunications industry and the related research community. The approach of static allocation is now considered obsolete, due to significant flaws, such us overall throughput decline. Hence, DBA has become the dominant solution for assigning network resources. A detailed related survey is provided in [22] that reviews the recent developments in the subfields of reliability, QoS support, and power conservation in hybrid FiWi networks, which incorporate novel bandwidth assigning protocols.

The issue of balancing fairness with performance has been examined n DBA schemes for optical or wireless networks. Starting with the optical networks, authors in [23] proposed a fair-weighted bandwidth allocation method for EPONs, which favours high-priority requests while trying to maintain bandwidth distribution fairness. Fair DBA schemes for NG-PONs (Next Generation PONs) were presented in [24] and [25], providing a trade-off between fair resource allocation and network efficiency. The evaluation results have proved the feasibility of such schemes, however, they are destined solely for optical networks.

Regarding DBA approaches for wireless access networks, there are several efforts to provide fair distribution of the wireless network capacity to mobile users. A related allocation algorithm, which is based on game theory principles, was introduced in [26]. It groups mobile stations in order to improve total throughput by reducing the overall network overhead. A scheduling scheme was introduced in [27] for multi-rate multi-channel wireless networking, which employs a proportionally fair utility function. A similar technique

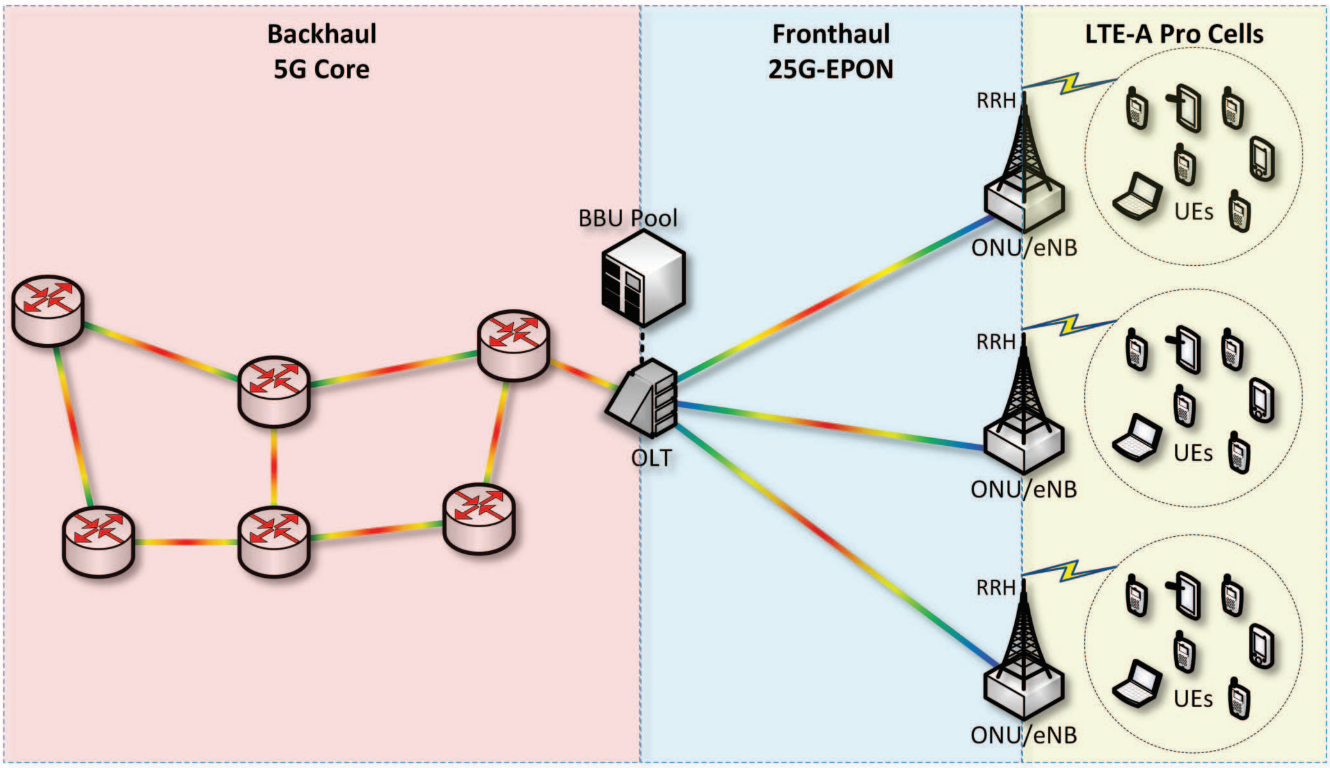

Fig. 1: Hybrid 25G-EPON and LTE-Advanced Pro FiWi Architecture

for OFDMA (Orthogonal Frequency Devision Multiple Access) networks was proposed in [28], exhibiting a good trade-off between fairness and network throughput.

Hybrid optical-wireless networks present unique characteristics, which require specially tailored solutions for efficient bandwidth allocation. Specifically, FiWis need resource assigning processes which are fully compatible across the optical and wireless domains. This means that the grants from the OLT to the ONU need to be converted to individual UE grants in the cell. Hence, the necessity for FiWi-specific efficient resource allocation schemes arises. A QoS-supportive DBA scheme for FiWi systems was presented in [29], which allocates bandwidth according to users' requests and priority buffer weights. The evaluation showed that network delay and drop rate are decreased, however, fairness and energy efficiency are neglected. The DBA algorithm proposed in [30] increases performance by reducing signaling overhead via the synchronization of the allocation slots. Again, fairness and power consumption are ignored. The DBA scheme introduced in [31] guarantees a minimum amount of bandwidth, while the rest is distributed among the wireless subscribers, however, allocation fairness and power efficiency are not considered. The DBA scheme introduced in [32], called WE-DBA (WiMAX EPON DBA), guarantees QoS in a seamless manner across the optical and the wireless domains. The respective bandwidth distribution technique involves sharing of the excess bandwidth, but not in an ensured fair way; power saving is again not taken into account. The resource allocation scheme provided in [33] for hybrid 10G-EPON-WiMAX networks is capable of offering bandwidth distribution fairness, however, power efficiency is not considered.

Hence, it becomes evident that the need for efficient agile resource allocation schemes for cutting-edge hybrid FiWi networks arises, which can take into consideration performance, fairness, as well as energy consumption.

4 Multi-Stage Optimization for Resource Allocation

The key objective and the main contribution of this work is the provision of an efficient resource allocation scheme, which can function over cutting-edge FiWi hybrid systems. The primary requirements of this scheme include: i) seamless application on both optical and wireless domains, ii) high utilization of the overall available optical and wireless capacity, iii) bandwidth distribution based on traffic priorities, power efficiency, fairness, and iv) tunable functionality according to communication demands.

The proposed allocation scheme fulfills these requirements in a straightforward manner. The core idea is that the OLT allocates resources to ONUs/eNBs and subsequently to UEs in a frame-by-frame basis, while optimizing priority-based traffic differentiation, transmission energy, and distribution of resources among UEs. Such an optimization process takes into consideration bandwidth requests and capacity constraints. The notations used in the presented analysis are listed in Table 1.

On this ground, the introduced resource allocation scheme is formulated as a multi-stage optimization problem, which is solved for each frame and outputs the exact bandwidth grant for each requesting UE. In each stage, a different objective function is set, associated with the optimization of different factors: prioritization, transmission power, and fairness. The optimal solution found in each stage is used as a constraint in the following stage. The reason is our purpose to clearly prioritize the optimization factors, hence, the optimization problem is not really formulated as multi-objective, since the goal is not to optimize all factors simultaneously, but to find each time the optimal solution within the optimal solution already identified in the previous stage. Apparently, this concept is based on the fact that most of the times there are multiple possible optimal solutions within each stage.

It is evident that in such an approach, the earlier stages have higher chances to achieve better solutions, since the corresponding problems are restricted by less constraints set by previous stages. In the first optimization stage, the goal is to maximize allocations to the highest priority (q = 3) traffic streams requesting for bandwidth, while favouring the UEs with low transmission power. The respective problem is formulated as follows.

Stage 1:

$$\underset{G}{\text{maximize}} \sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^3G_i^j \times {}^3B_i^j}{p_i^j} \tag{1}$$

s.t.

$$CO \geq \sum_{i=1}^{m} \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{2}$$

$$CW_i \geq \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{3}$$

$${}^qB_i^j \geq {}^qG_i^j \tag{4}$$

The previous optimization stage assigns maximum possible bandwidth grants to the highest priority requests, favouring those belonging to UEs of low transmission power, given the constraints. In more detail, the goal of the objective function (1) is to maximize the bandwidth grants, while minimizing transmission power consumption for the highest priority traffic. It should be further noted that the objective function also favours larger bandwidth requests (B), in order to provide more transmission opportunities to requests with higher requirements for resources. Morevoer, it needs to be clarified that according to the LTE specifications, UEs inform the eNB about the traffic size queued in their buffers through the BSR control messages. These values are mapped by our scheme to bandwidth requests. In that context, by favouring requests with more buffered traffic, it is ensured that these larger buffers will be given higher chance to be eventually adequately served. The constraint defined in (2) ensures that the total grants to all UEs is not higher than the available optical capacity. The aggregated grants to all UEs of the same cell are constrained by the capacity of the respective eNB in (3). The last constraint (4) ensures that each traffic stream receives a grant which does not exceed its requested bandwidth.

The next optimization stage considers the next lower priority requests (q = 2). The concept remains the same as well as the

Table 1 Notations

Symbol	Explanation
n	Number of UEs
m	Number of ONUs/eNBs
k_i	Number of UEs belonging to ONU/eNB i
${}^qB_i^j$	Bandwidth request of UE j, which belongs to ONU/eNB i, having priority q (bits per frame)
p_i^j	Power per transmitted bit of UE j, which belongs to ONU/eNB i (pW)
CO	Optical domain capacity (bits per frame)
CW_i	Wireless domain capacity of ONU/eNB i (bits per frame)
${}^qG_i^j$	Grant to request of UE j, which belongs to ONU/eNB i, having priority q (bits per frame)
OFV_s	Objective function value derived by optimization stage s

constraints, with an extra constraint (6) which derives from the previous optimization stage. Thus, the stage 2 optimization problem is formulated as follows.
Stage 2:

$$\underset{G}{\text{maximize}} \sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^2G_i^j \times {}^2B_i^j}{p_i^j} \tag{5}$$

s.t.

$$CO \geq \sum_{i=1}^{m} \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{2}$$

$$CW_i \geq \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{3}$$

$${}^qB_i^j \geq {}^qG_i^j \tag{4}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^3G_i^j \times {}^3B_i^j}{p_i^j} = OFV_1 \tag{6}$$

The following optimization stage covers the lowest priority requests (q = 1). It is noted that the approach is generic enough to be applied for any number of traffic priorities. The number of stages equals the number of priorities. This optimization stage is formulated as follows.
Stage 3:

$$\underset{G}{\text{maximize}} \sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^1G_i^j \times {}^1B_i^j}{p_i^j} \tag{7}$$

s.t.

$$CO \geq \sum_{i=1}^{m} \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{2}$$

$$CW_i \geq \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{3}$$

$${}^qB_i^j \geq {}^qG_i^j \tag{4}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^3G_i^j \times {}^3B_i^j}{p_i^j} = OFV_1 \tag{6}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^2G_i^j \times {}^2B_i^j}{p_i^j} = OFV_2 \tag{8}$$

The last part of the multi-stage optimization problem concerns the fair distribution of bandwidth grants to requests, given the existing constraints. The objective is to minimize the variance of allocated grants (9), without violating the already achieved optimization according to traffic priorities and transmission power (constraints (6), (8), and (10)). The respective problem of the last optimization stage is formulated as follows.
Stage 4:

$$\underset{G}{\text{minimize}} \frac{\sum_{i=1}^{m} \sum_{j=1}^{k_i} \sum_{q=1}^{3} \left({}^qG_i^j - \frac{\sum_{\hat{i}=1}^{m} \sum_{\hat{j}=1}^{k_{\hat{i}}} \sum_{\hat{q}=1}^{3} {}^{\hat{q}}G_{\hat{i}}^{\hat{j}}}{n} \right)^2}{n} \tag{9}$$

s.t.

$$CO \geq \sum_{i=1}^{m} \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{2}$$

$$CW_i \geq \sum_{j=1}^{k_i} \sum_{q=1}^{3} {}^qG_i^j \tag{3}$$

$${}^qB_i^j \geq {}^qG_i^j \tag{4}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^3G_i^j \times {}^3B_i^j}{p_i^j} = OFV_1 \tag{6}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^2G_i^j \times {}^2B_i^j}{p_i^j} = OFV_2 \tag{8}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k_i} \frac{{}^1G_i^j \times {}^1B_i^j}{p_i^j} = OFV_3 \tag{10}$$

The resource allocation is formed by the bandwidth grants (G) calculated as a result of the final optimization stage. This multi-stage optimization problem is solved by the OLT for each frame and is communicated to the ONUs/eNBs via the optical downstream. Then, UEs are informed of the final grants via the wireless downlink.

The introduced scheme also allows for varying tuning of optimization stages depending on the factors that need to be optimized according to the network configuration requirements. Specifically, in case power awareness is not required, p_i^j can be set to 1, resulting in ignoring UE transmission power per bit. In a similar manner, traffic priorities can be ignored by merging all optimization stages but the last one, so that grants are calculated to all requests regardless their priorities. Under the same concept, the last optimization stage can be also omitted, if fairness optimization is not an issue. Apparently, it is also possible to optimize combinations of different factors.

Regarding the optimization computational complexity, which is of course correlated with processing requirements, it is highlighted that all optimization stages, except from the last one, are classified as constrained Linear Programming (LP) problems, which are known to be solvable in P. Hence, the only possible issue regarding the required processing time concerns the last optimization stage, which is a linearly constrained Quadratic Programming (QP) problem. However, the specific objective function shown in (9) yields a Hessian matrix which is positive definite, resulting in an optimization problem that is solvable in P. In addition, the rapid developments in cloud and parallel computing enable vast processing power for almost instantaneous solving of demanding problems, a capability which could be of course exploited by the OLT and is in line with the C-RAN architecture of 5G systems. Conclusively, in terms of computational complexity, it is perfectly feasible for the proposed allocation scheme to provide on time calculation of bandwidth grants on a per frame basis.

5 Evaluation Results

The introduced resource allocation scheme for FiWi systems is evaluated through MATLAB simulations. The considered hybrid architecture is composed of the optical domain and the wireless domain; the former is realized as an 25G-EPON network, whereas the latter is realized as LTE-Advanced Pro cells. The adopted simulation parameters are presented in Table 2.

The conducted simulation scenarios consider a network topology of an OLT device connected to 125 ONUs forming a 25G-EPON network, which is operating in a symmetric manner with upstream and downstream line rates equal to 25 Gbit/s. Each ONU is integrated with an eNB supporting the LTE-Advanced Pro standard. There are 15 active UEs connected to each eNB, which support the 18^{th} uplink category of the 3GPP Release-15 and are capable of transmitting at 211 Mbit/s. Within a single cell, five UEs consume 50 pW per transmitted bit, another five UEs consume 100 pW per transmitted bit, and the rest 5 UEs consume 200 pW per transmitted bit. Each UE incorporates three buffers of 10 Mbits capacity, associated with three traffic streams of different priority levels. The lowest priority stream is associated with priority 1 of the hybrid FiWi system, the medium priority stream is associated with priority 2, and the highest priority stream is associated with priority 3. We perform simulations of varying traffic load, starting with data generation rate per traffic stream equal to 1 Mbit/s and eventually reaching a rate of 10 Mbit/s per stream with a 250 Kbit/s step. The simulation scripts were developed and executed in MATLAB, making also use of its Optimization Toolbox^{TM}.

The adopted evaluation criteria are classified into the categories of network performance, energy efficiency, and allocation fairness. Five network metrics are calculated and plotted against traffic load: throughput, latency, drop rate, power consumption, and Jain's Fairness Index [34]. The considered independent variable is the load per traffic stream. It should be noted that the network becomes saturated at a load of about 4.7 Mbit/s per stream, which yields almost 211 Mbit/s total load rate per cell, reaching the wireless domain capacity.

In order to assess the effectiveness of the prioritization aspect of the introduced resource allocation scheme, in Fig. 2 we plot the average throughput of each different priority traffic stream, along with the respective values that result when priorities are ignored. In practice, ignoring priorities means that all optimization stages which correspond to different priorities are merged into one stage addressing all the requests. The chart clearly shows that the complete allocation scheme ensures that as long as there are available resources the highest priority requests always receive the required bandwidth. Under network saturation conditions, this behaviour takes place in expense of the priority 1 grants and later of the priority 2 grants. On the contrary, it is obvious that ignoring priorities leads to identical treatment of all requests, failing in that manner to differentiate traffic.

The ability to guarantee the transmission requirements of high demanding traffic is also evident in Fig. 3, where average latency is depicted, which corresponds to buffer queuing delay. It can be seen that the higher priority traffic (Pr3) is not delayed by other streams, regardless the overall load. On the other hand, the lowest priority traffic experiences high increase in latency as soon as the saturation point is reached, while medium priority traffic (Pr2) starts being significantly delayed over 7 Mbit/s of load per traffic stream. It is noticed that there is a cap limit of maximum possible latency, due to the simulation duration and the finite buffer capacity. This limit is actually reached as soon as a traffic class stops being served, which takes place at $\sim$7 Mbit/s of load per stream for Pr1 traffic. Without considering priorities, the respective curves show that requests are not differentiated in terms of latency, which starts increasing for all traffic right after the saturation point.

The evaluation of the priority-based differentiation feature of the introduced scheme continues with the drop rate metric. As it is already explained, each traffic stream is associated with a buffer and sends bandwidth requests by informing the connected eNB about the

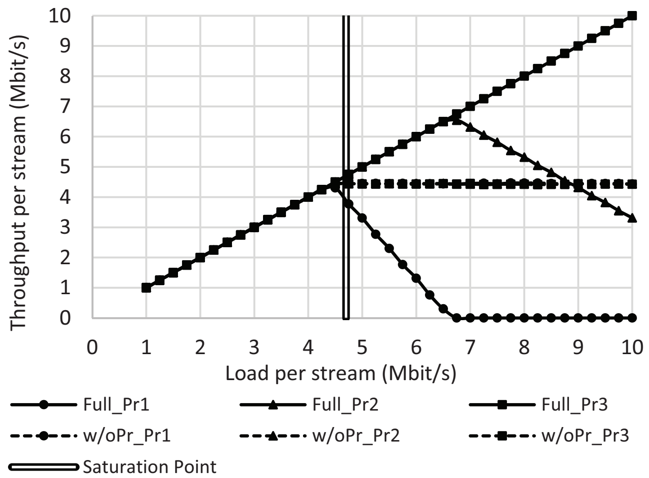

Fig. 2: Throughput versus load per stream considering full optimization (Full) and without prioritization (w/oPr) allocation for different traffic priorities

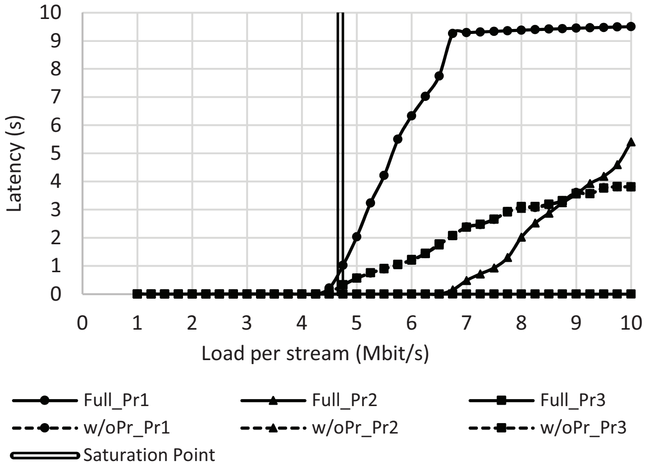

Fig. 3: Latency versus load per stream considering full optimization (Full) and without prioritization (w/oPr) allocation for different traffic priorities

Table 2 Simulation Parameters

Parameter	Value
25G-EPON upstream line rate	25 Gbit/s
25G-EPON downstream line rate	25 Gbit/s
LTE-Advanced Pro UE uplink rate	211 Mbit/s
LTE-Advanced Pro frame length	10 ms
UE buffer size per traffic stream	10 Mbits
Simulation time	10 s
Number of ONUs/eNBs (i)	125
Number of UEs per ONU/eNB (k_i)	15
Number of traffic priorities per UE	3
Data generation rate per traffic stream	1-10 Mbit/s
Wireless transmission power per bit	50, 100, 200 pW

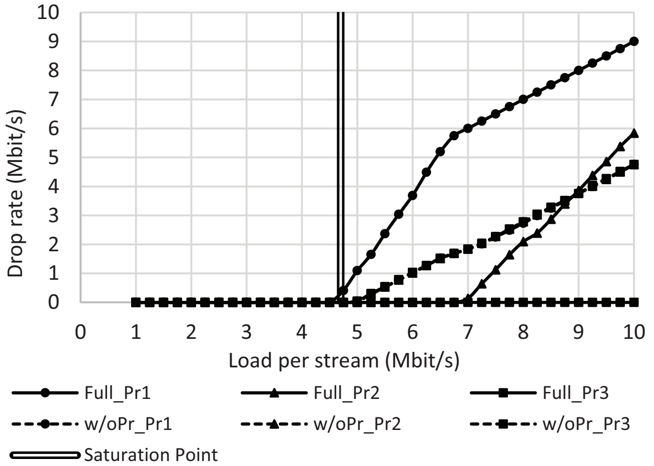

Fig. 4: Drop rate versus load per stream considering full optimization (Full) and without prioritization (w/oPr) allocation for different traffic priorities

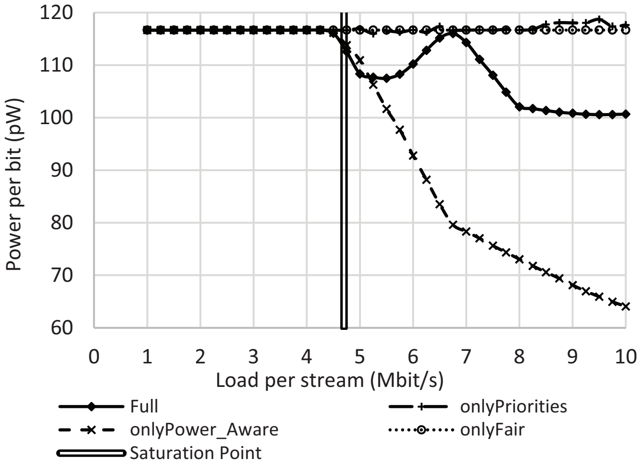

Fig. 5: Consumed power per transmitted bit versus load per stream considering full optimization (Full), only priorities (onlyPriorities), only power efficiency (onlyPower_Aware), and only fairness (onlyFair) allocation

current buffer size. The modelled buffers are of finite capacity (10 Mbits each), hence, at overflowing conditions the generated traffic is dropped. In Fig. 4, we have plotted the drop rate of the different priority traffic streams. In case the full multi-stage optimization scheme is applied, the highest priority traffic enjoys zero drops, whereas the two lower priority streams exhibit increasing drops under saturated conditions. On the other hand, the lack of priority-based traffic differentiation leads all buffers to a rising drop rate, when surpassing the saturation point. It should be noticed that even the medium priority Pr2 traffic outperforms the priority-ignorant scheme for load rate per stream up to 9 Mbit/s. In overall, the evaluation of the network performance metrics has revealed that the priority support of the proposed scheme allows guaranteeing full QoS support to time-sensitive delay-intolerant network traffic.

Proceeding with the evaluation of the power efficiency capabilities of the introduced resource allocation scheme, we have plotted in Fig. 5 the average power consumed per transmitted bit. It is obvious that higher energy conservation is achieved when the only considered optimization factor is power efficiency, as illustrated by the corresponding curve. In case allocation is based solely on traffic priorities or fairness, the consumed power is actually ignored and remains constantly at high levels. In general, when the load increases over the saturation point, the power-aware scheme allocates more of the available resources to low power consuming UEs, resulting in extensive energy savings. However, if priority-based optimization takes place, as in the case of the full resource allocation scheme, higher priority requests are served first, while the power consumption of the hosting UEs are considered second. For instance, regarding the full scheme at 7 Mbit/s of load per stream, all 30 traffic streams of priority 2 and 3 within a single cell get fully served ($\sim$210 Mbit/s aggregate throughput), leaving almost no bandwidth available for low priority grants. Hence, there is not really room for power-based differentiation in such a case.

The final evaluation criterion which is considered in this work is fairness. It is associated with the ability to distribute resources in a uniform manner. However, it is evident that traffic differentiation, which involves favouring requests over others, and fairness are to some extent contradictory. Thus, it is challenging to find the required equilibrium point. We adopt the well-known Jain's Index as representative fairness metric; the formula is provided in (11).

$$Jain's\ Fairness\ Index = \frac{\left(\sum_{i=1}^{m}\sum_{j=1}^{k_i}\sum_{q=1}^{3}{}^{q}G_i^j\right)^2}{n\sum_{i=1}^{m}\sum_{j=1}^{k_i}\left(\sum_{q=1}^{3}{}^{q}G_i^j\right)^2} \tag{11}$$

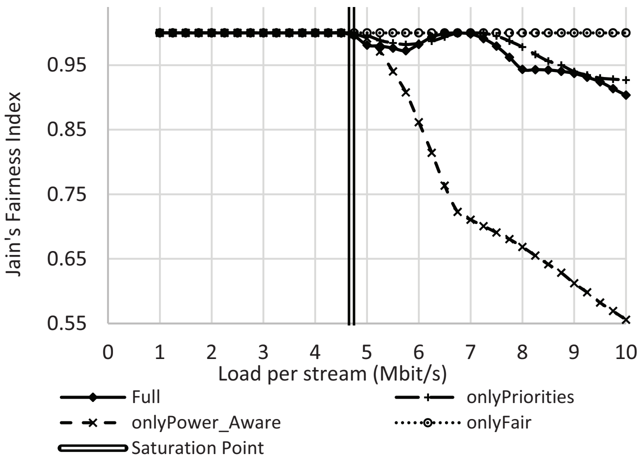

Fig. 6: Jain's fairness index versus load per stream considering full optimization (Full), only priorities (onlyPriorities), only power efficiency (onlyPower_Aware), and only fairness (onlyFair) allocation

The respective results are plotted in Fig. 6. As expected, highest fairness is achieved when the only optimization factor is fairness. On the other end, only optimizing power efficiency causes maximum fairness degradation. The reason is related to the metric definition, which considers the distribution of bandwidth among UEs. Since different UEs consume different amounts of energy, considering only power consumption results in assigning most of the bandwidth grants to requests of low-power UEs, which decreases Jain's Index. On the other hand, in the specific simulation scenario optimizing prioritization results in uniform sharing of resources among UEs, hence, in fairness increment. The reason is the symmetry in the considered network of the different priority traffic requests, since they are evenly deployed among all UEs. The respective curve shows that the full allocation scheme manages to maintain high fairness, while being power-aware. It is also noticed that until the saturation point all UEs receive all the bandwidth they request. Given that according to the simulation scenario all UEs have the same requests, the fairness index is at the maximum value of 1. Similarly to the case of power efficiency, there seems to be a behaviour that requires further explanation at load rate per stream close to 7 Mbit/s. Specifically, for the exact same reason which was clarified in the context of Fig. 5, all traffic streams of priority 2 and 3, which are evenly deployed in all UEs, get fully served, hence, fairness index is close to 1.

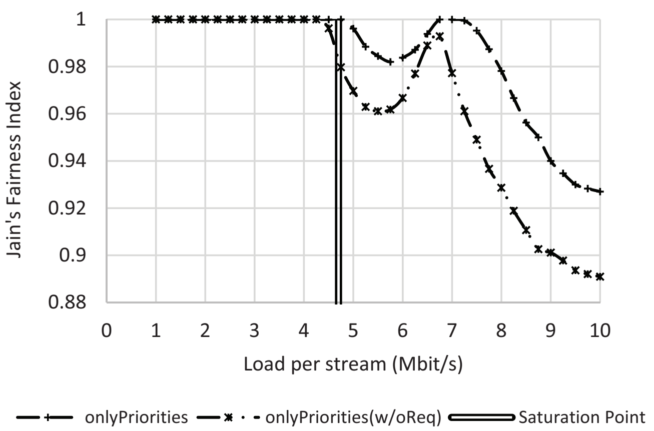

Fig. 7: Jain's fairness index versus load per stream considering only priorities including requests (onlyPriorities), and only priorities without considering requests (onlyPriorities(w/oReq)) allocation

An extra factor which is also worth to examine in this evaluation is the bandwidth request, which is included in the objective function of all optimization stages, except from the last one. As already explained, the request reveals the current number of buffered bits of the corresponding request, so considering it in optimization provides higher transmission chances to requests that have a lot of queued data. One of the effects of this approach is that it enhances fairness. In Fig. 7, we have plotted the fairness index when the objective functions only consider priorities including requests, along with the fairness index when the objective functions only consider priorities without requests. This means that for the latter version of the allocation scheme, the B factor is omitted from formulas (1), (5), and (7). It becomes obvious that omitting the bandwidth factor from the objective function causes lower fairness. Conclusively, the high levels of fairness achieved when the optimization stages only consider priorities, as shown in Fig. 6, is also attributed to the impact of the bandwidth request factor.

In summary, the evaluation procedure has demonstrated not only the effectiveness of the introduced scheme in optimizing allocation prioritization, power efficiency, and fairness, but also its flexibility in allowing to select different combinations of these optimization factors, in the context of a hybrid FiWi system.

6 Conclusion

An efficient, fair, and power-aware resource allocation scheme for cutting-edge FiWi networks was proposed in this paper. An adjustable multi-stage optimization technique was introduced for prioritizing traffic and effectively distributing bandwidth considering UEs' energy consumption. According to the adopted architecture, the OLT solves the corresponding optimization problem to assign resources to end-users through ONUs/eNBs. The scheme was evaluated via a simulated 25G-EPON and LTE-Advanced Pro hybrid network scenario. The results have shown that it can achieve high channel utilization, guarantee service for high priority streams, fairly assign resources, and favour low power transmissions. It was also demonstrated that by considering/ignoring specific optimization factors it is possible to dynamically tune network behaviour. Regarding the solution process of the optimization problem, technical feasibility has been justified on the grounds that the problem is broken down to low complexity linear and quadratic programming sub-problems. The overall adopted concept is in line with the C-RAN architecture for the fronthaul of 5G hybrid networks.

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