Passive Optical Networking for 5G and Beyond 5G Low-Latency Mobile Fronthauling Services

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Abstract—Passive optical network (PON) technology offers an attractive cost-efficient alternative to support 5G and Beyond 5G mobile network fronthauling (MFH). However, MFH for such networks is challenging given its high bandwidth and strict latency requirements. To reduce these requirements, radio access network (RAN) functional splitting has been introduced in 5G networks; this provides more flexibility in resource allocation since the protocol stack is distributed between the centralized and the distributed units. In contrast to the conventional MFH requirement of the RF-PHY splitting, the MFH traffic produced by higher-layer splittings becomes more dependent on the actual user traffic load. By capitalizing on the new characteristics of the MFH traffic with RAN functional splitting, this article introduces a resource allocation mechanism to improve the performance of PONs serving MFH.

Index Terms—Low-latency, Mobile network fronthauling, Passive optical networks, Time-wavelength division multiplexing, 5G.

I. INTRODUCTION

The Cloud Radio Access Network (CRAN) technology has recently been proposed to deal with the high demands imposed by the need to provide services with stringent delay and high throughput requirements for the Fifth Generation Mobile Networks (5G) and Beyond 5G (B5G). The employment of CRAN saves energy by gathering shared resources into cloud-based facilities, such as the Baseband Unit (BBU), which is responsible for processing signals sent by the Remote Radio Head (RRH) located in the cell site. On the other hand, the physical separation of BBUs and RRHs imposes a strong dependence on Mobile Fronthauling (MFH) capabilities.

The Common Public Radio Interface (CPRI) is the most prominent interface and protocol adopted for MFH in 4G networks. However, depending on the base station (RRH) configuration, the use of CPRI requires the availability of a huge fixed bandwidth capacity in the MFH. The required MFH capacity can range from 614 Mbps to 24.3 Gbps, with the delay and jitter required to synchronize the RRH with the BBU being 250 μs and 65 ns, respectively. Such stringent requirements make impractical the adoption of CRAN for 5G and B5G networks, since these can require MFH data rates as high as hundreds of gigabits per second due to the use of technologies such as massive multiple-input multiple output (mMIMO), mmWave and terahertz communications.

To decrease the burden on the MFH, the 3rd Generation Partnership Project (3GPP) has proposed the radio access network (RAN) functional splitting in Figure 1. It splits the functionality of BBUs by locating more RAN functions on the remote site and fewer on the centralized site than does the conventional BBU-RRH splitting of previous generations. This allows various possible split options, which provides flexibility and reduces the required bandwidth and delay in the fronthaul, although at the price of decreasing RAN centralization. Lower-layer splittings generate constant bit rates, whereas higher-layer splittings imply MFH links with variable bit rates, which are dependent on the load of the user data plane.

There is no imposition on the type of technology implemented in MFH, this can range from wireless to optical technologies. Due to its vast transmission capacity and current availability, the latter are preferable. Passive Optical Networks (PONs) are attractive for MFH due to their point-to-multipoint topology, which is quite suitable for fine granularity transport services. Moreover, recent efforts in PON standardization have resulted in a new architecture specified in the 50G-EPON (IEEE 802.3ca-2020), which employs the Time and Wavelength Division Multiple Access (TWDMA) technique for upstream transmissions between Optical Network Units (ONUs) and optical line terminal (OLT). It supports up to two 25 Gbps wavelength channels with non-tunable transceivers, increasing adequacy of the PON to support MFH traffic.

Dynamic Wavelength and Bandwidth Allocation (DWBA) algorithms for resource allocation in PONs are typically based on on-demand schemes for granting bandwidth. In these schemes, clients request bandwidth in a scheduling cycle for transmission in the next cycle. This, however, adds queuing delays in the transmission of packets, which can be detrimental for the traffic of overloaded base stations. Resource allocation algorithms for the support of fronthauling traffic over PONs that deal with load prediction, cooperation among 5G and PON devices, and PON sharing have all recently been proposed (Table 1). However, it is imperative that these DWBA algorithms consider the tidal nature of mobile network traffic and capitalize on that spatiotemporal imbalance to improve overall network performance and decrease MFH costs.

This article addresses the employment of Ethernet PON (EPON) for mobile fronthauling in 5G and B5G networks and proposes a DWBA algorithm that capitalizes on the opportunities emerging from the tidal nature of fronthaul traffic, as well as on the existence of customers leasing (owning) several ONUs from a single Infrastructure Service provider (multi-ONU customers), as in the case of the Mobile Network Operators (MNOs). The proposed algorithm increases network
II. RAN Functional Splitting and its Implication to the Mobile Fronthauling Requirements

Industry cooperation has recently taken place to decrease the MFH data rate and delay requirements through RAN functional splitting, as illustrated in Fig. [1]. The CPRI protocol was also extended, resulting in a packetized protocol called eCPRI (enhanced CPRI), which supports these new split options. The functional splits range from the simplest Distributed Unit (DU) (option 8) to the most complex DU (option 1).

The conventional CPRI protocol used in 4G networks supports the PHY-RF option. In these networks, baseband processing is centralized in the CU, and the DU performs radio frequency (RF) functionality such as transmit and receive functions, filtering, amplification, analog-to-digital or digital-to-analog conversion, up/down conversion, and cyclic prefix (CP) removal/addition. This centralization of the RAN functions saves money by reducing the complexity of the remote units, the number of equipment, and energy consumption for running the network. It also allows the sharing of the processing resources and facilitates cross-cell cooperation. Advanced Coordinated Multipoint (CoMP) and soft handover schemes may be implemented at the CU to handle inter-cell interference and multi-cell transmissions. However, this split option requires a large amount of MFH capacity to transport in-phase and quadrature (I/Q) signal components between the remote and centralized locations.

The intra-PHY option has three variants. In option 7.1, the Fast Fourier Transform (FFT) and inverse FFT (iFFT) also reside in the DU, while the rest of the physical and link layer functions reside in the CU. Option 7.2 also adds the pre-filtering/precoding and resource mapping/demapping to the DU. With option 7.3 (downlink only), the encoder also resides at the CU. The fronthaul interface transport subcarriers, subframe symbols, and codewords when the options 7-1, 7-2, and 7-3 are employed, respectively.

The MAC-PHY option locates the Media Access Control (MAC) and upper-layer functionality at the CU, while the PHY and RF functions are located at the DU. Thus, the MAC scheduler is centralized, and physical processing is performed locally in the DU. The transport blocks containing control and user data are transported through the MFH interface with this split option.

The intra-MAC option locates the real-time MAC functions (e.g., Hybrid Automatic Repeat Request (HARQ) and random access control) at the DU, whereas the less restrictive MAC functions such as resource scheduling, inter-cell interference coordination, and multiplexing functions are located at the CU. By locating the time-critical functions in the DU, the delay requirements on the fronthaul interface are relaxed compared to the previous split options.

Centralized scheduling options (i.e., Options 5, 6, 7, and 8) support CoMP functionality. Option 7-2 and lower-layer options fully support CoMP functions without performance degradation, while options 7-3, 6, and 5 restrict CoMP functionalities due to latency issues (e.g., uplink joint reception).

With the RLC-MAC option, the Radio Link Control RLC, Packet Data Convergence Protocol (PDCP), and Radio Resource Control (RRC) functions are located in the CU, while MAC and lower-layer functions reside at the DU. The tight coupling between RLC and MAC functions imposed the most stringent latency requirements, especially for short subframes in 5G, requiring more frequent scheduler decisions.

The intra-RLC option splits the RLC layer into high-RLC and low-RLC located, respectively, at the CU and DU. The segmentation process is performed in the low-RLC, while the Automatic Repeat Request (ARQ) and other RLC functions reside in the high-LRC. It is robust in non-ideal channel scenarios and scenarios with high mobility.

In the PDCP-RLC option, the RRC and PDCP are located in
the CU, while RLC, MAC, physical, and RF functions reside in the DU. This split option improves the traffic load control and traffic aggregation between the New Radio and Evolved Universal Terrestrial Radio Access transmission points. Since the real-time MAC and RLC functions are performed locally in the DU, these last two options relax even more the MFH latency requirements.

In the RRC-PDCP option, the CU handles the RRC function, while the rest of the RAN functions are located in the DU. It separates the user-plane from the CU and improves traffic management in cases in which the user data needs to be placed near the transmission point (e.g., edge computing and caching applications).

The low-layer related split options (7-1, 7-2, and 8) may generate very high constant bit rates in the MFH links, which depend on the cell bandwidth and the number of antennas, and options 7-3 to 1 produce a variable bit rate MFH traffic which is more dependent on the actual user data plane traffic.

III. ISSUES AND APPROACHES FOR SUPPORTING MOBILE FRONTHAULING OVER EPON NETWORKS

Typically, Infrastructure Providers (InPs) attempt to maximize network utilization and revenue by furnishing various services over the same PON infrastructure to their customers, including MNOs and conventional customers such as residential users, enterprises and Virtual Network Operators. Nevertheless, the unique requirements of MFH make Quality of Service (QoS) provisioning a challenging task, especially in scenarios with coexisting MFH and conventional PON services.

Various Resource Allocation (RA) algorithms for EPON networks have been proposed for providing guaranteed bandwidth and low latency in MFH (See Table I). In the following, the main issues of RA algorithms and their approaches used to support of MFH in PONs are reviewed.

The RA algorithms can be classified into those for Static Bandwidth Allocation (SBA) and those for Dynamic Bandwidth Allocation (DBA). The former allocate a fixed transmission window for each ONU, independent of the ONU load, which guarantees deterministic delays, although bandwidth can be wasted, increasing costs, especially when dealing with splittings with variable rates. The latter allocate transmission windows on a per-cycle-basis depending on the offered load, delay requirement, and available bandwidth; they increase statistical multiplexing gain in scenarios with unbalanced loads but introduce challenges for the management of the available bandwidth in scenarios with low-latency requirements.

A. Problem of Bandwidth Requests

One of the most important issues in RA is the Problem of Bandwidth Requests (Fig. 2a). DBA schemes use Gate and Report messages to coordinate upstream transmissions between the ONUs and the OLT. Bandwidth is requested in Report messages sent from the ONUs to the OLT to request bandwidth, whereas information on the bandwidth allocated in Gate message sent from the OLT to the ONU. Hence, the OLT must wait for a request message before granting bandwidth, which implies that the upstream delay will be at least one scheduling cycle in duration. This delay can be as long as a millisecond, yet this is much longer than the required delay for split option 6 and above.

An approach to this problem involves estimations of accurate upcoming MFH traffic estimation to avoid the need to wait for a report message, thus reducing latency to acceptable levels. This approach use MFH traffic information (Wireless Scheduling Information (WSI) or traffic prediction based on report messages) to forecast traffic arrivals in the near future and to allocate bandwidth without the need of OLT to receive a request, as shown in Fig. 2b.

Cooperation between the CU/DU and the OLT was first proposed in [1], and has been widely adopted ever since as a key technique for low-latency MFH ([2], [4], [7]–[9]). This cooperation allows the OLT to obtain accurate information about upcoming traffic by exploiting the WSI, which is used to inform mobile users about resource allocation 4ms before the actual uplink transmission.

B. Problem of Maximum Cycle Length

On the one hand, the upstream delay depends on the cycle duration because each ONU usually transmits only once per cycle. If, for example, mobile traffic arrives at the ONU just after a transmission, these frames remain in the ONU queue at least until the next transmission cycle, as shown in Figure 2b. Even with MFH traffic estimation, this delay can be as long as the maximum cycle length when the network is overloaded. On the other hand, the polling overhead (or bandwidth wasted) mainly depends on the number of guard periods per cycle and the number of cycles per second. This means that the larger the maximum cycle length is, the lower the overhead. Thus, there is a trade-off between overhead and delay, which needs to be carefully addressed. As can be seen in Table I, the importance of the maximum cycle length has not received the attention deserved in previous investigations (e.g., [1], [3]–[5], [7], [11]).

C. Problem of Grant Sizing

As seen in Table I various resource allocation schemes for supporting MFH over PONs employ a Gated policy in which the OLT allocates a transmission window equal to the requested/forecast one (e.g., [1], [4], [7], [9], [12]). However, this policy does not allow QoS provisioning (e.g., guaranteed bandwidth and delay) to diverse types of services coexisting on the same PON infrastructure, as occurs with current shared PONs. This problem occurs because a customer may overuse the total available bandwidth, thus increasing the cycle duration if no traffic shaping is undertaken.

InPs usually employ a limited type of policy to guarantee bandwidth for PON customers according to a pre-defined Service Level Agreements (SLAs). In this policy, the OLT grants a transmission window equal to the minimum between the requested window and the maximum allowed transmission window (Fig. 2c). However, customers who have offered load greater than their guaranteed bandwidth in a scheduling cycle (overloaded customers) require various scheduling cycles to
TABLE I: Literature review on resource allocation for mobile fronthauling over PONs. G: Gated; L: Limited; F: Fixed; V: Variable; U: Unlimited; S: Simulation; A: Analytical; E: Experimentation; Y: Yes; N: No; NS: Not Specified; NA: Not Applicable

| Feature                                      | This | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] | [10] | [11] | [12] |
|----------------------------------------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Standard family**                          |      |     |     |     |     |     |     |     |     |     |     |     |     |
| IEEE (EPON)                                  | X    | X   | -   | NS  | NS  | NS  | -   | X   | X   | -   | X   | NS  | -   |
| ITU (GPON)                                   | -    | -   | X   | NS  | NS  | NS  | -   | X   | -   | X   | NS  | -   | X   |
| Multi. access tech.                          |      |     |     |     |     |     |     |     |     |     |     |     |     |
| TDMA-PON                                     | X    | X   | X   | X   | X   | -   | X   | X   | X   | X   | -   | -   | -   |
| TWDMA-PON                                    | X    | -   | -   | X   | X   | -   | -   | X   | X   | X   | -   | -   | -   |
| Rate per wavelength                          |      |     |     |     |     |     |     |     |     |     |     |     |     |
| 10 Gbps                                      | -    | X   | X   | X   | X   | X   | X   | X   | X   | X   | -   | -   | -   |
| 25 Gbps                                      | X    | -   | -   | -   | -   | -   | -   | -   | -   | -   | X   | X   | -   |
| Wavelengths (\(\lambda\)) per OLT           |      |     |     |     |     |     |     |     |     |     |     |     |     |
| 2                                            | 2    | 1   | 1   | 1   | 1   | 1   | 4   | U   | 1   | 1   | 1   | 16  | 2   |
| Simultaneous TX (\(\lambda\)) per ONU       |      |     |     |     |     |     |     |     |     |     |     |     |     |
| 1                                            | 1    | 1   | 1   | 1   | 1   | 2   | U   | 1   | 1   | 1   | 1   | 1   | 1   |
| Splitting option                             |      |     |     |     |     |     |     |     |     |     |     |     |     |
| 6                                            | 8    | NS  | 7.2 | 6   | 7.3 | 6   | 8   | 6   | 6   | 8   | 7.1 | -   | -   |
| Traffic prediction                           |      |     |     |     |     |     |     |     |     |     |     |     |     |
| BS-OLT coop.                                 | X    | X   | X   | N   | N   | X   | -   | N   | X   | X   | X   | X   | N   |
| Grant-Report                                 | -    | -   | -   | X   | X   | -   | X   | -   | X   | X   | N   | N   | N   |
| Maximum cycle length [ms]                    | 0.25 | 0.5 | NA  | NS  | V   | 1   | NA  | NS  | 0.2 | NA  | 0.25| NA  | NA  |
| SLA support                                  | Y    | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   |
| Conventional customers                       | Y    | N   | N   | N   | N   | N   | N   | N   | N   | N   | Y   | N   | Y   |
| Grant sizing policy for MFH ONUs             |      |     |     |     |     |     |     |     |     |     |     |     |     |
| L                                            | G    | F   | F   | G   | L   | F   | G   | F   | G   | F   | NS  | G   | G   |
| Bandwidth Sharing                            | Y    | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   |
| Perf. eval. based on real deployment.        | Y    | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | Y   |
| 3GPP TR-38.816 traffic modeling              | Y    | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | N   | Y   |
| Publication year (20YY)                      | 21   | 14  | 20  | 18  | 16  | 18  | 19  | 19  | 20  | 21  | 17  | 17  | 21  |

fully send their packets in the ONU queue. The uplink data queuing delay of these overloaded customers will depend on the number of cycles required for the OLT to provide the required bandwidth. A bandwidth sharing mechanism has been proposed in [13] to address the bandwidth starvation problem of overloaded ONUs in 4G backhauling scenarios with multi-ONU customers. This mechanism guarantees that the bandwidth of ONUs belonging to the same customer can be shared, so that unused bandwidth from underloaded ONUs can be assigned to overloaded ones on a per-cycle basis, thus reducing the number of scheduling cycles needed to serve an overloaded customer. However, the calculation of the total unused bandwidth of an underloaded ONU requires that the OLT wait for the arrival of all the Report messages from the ONUs belonging to that same customer before sending Gate messages to the overloaded ONUs. This introduces latency.

In summary, even though MFH traffic prediction can reduce the latency introduced by the bandwidth request problem, the grant sizing policy problem and maximum cycle length problem may still generate delays longer than those required by the MFH service.

IV. DWBA Algorithm for EPON-based Mobile Fronthauling

To address the issues raised in the previous section, we introduce a novel DWBA algorithm to provide high-throughput and low-latency for 5G and B5G mobile fronthauling services, while meeting the requirements of the SLAs of all the PON customers.

The proposed mechanism adopts the widely-used cooperative approach proposed in [1] to tackle the problem of bandwidth requests. To ameliorate the problem of grant sizing and exploit spatio-temporal characteristics of MFH traffic, a bandwidth sharing mechanism is also employed. The waiting time associated with bandwidth sharing techniques is avoided by employing an excess bandwidth compensation approach. The idea behind our proposal is to allow the use of the excess bandwidth of the previous and current cycles to serve the upcoming traffic of the overloaded ONUs of a multi-ONU customer in an online fashion. Moreover, the maximum cycle length is chosen so that it does not exceed the latency requirement, thus addressing the maximum cycle length problem. To the best of our knowledge, this is first solution to address QoS provisioning for 5G and B5G MFH in shared PONs.

Figure 3 summarizes the proposed scheme, which resides in the OLT. When a Report message arrives from a conventional ONU, the OLT calculates the transmission window according to the limited policy (Block 1). If the Report message comes from a multi-ONU customer, the OLT updates the requested window by utilizing the optical-wireless cooperation procedure (Block 2). If the maximum window is greater than the requested windows, the ONU is fully served by the legacy transmission window and the unused bandwidth value is stored (Block 3). Otherwise, the OLT grants additional bandwidth to the overloaded ONUs by utilizing the excess bandwidth from the previous and current cycles (Block 4). Moreover, when the scheduling cycle ends for the multi-ONU customer, the OLT saves the remaining excess bandwidth value of the current cycle and discards the excess bandwidth of the previous one (Block 5). After this procedure, the OLT allocates the upstream wavelength channel according to the First-Fit policy and calculates the next start time. The Gate message is then sent to the ONU.
V. Performance Evaluation

The performance of the proposed DWBA scheme was evaluated using an EPON simulator (EPON-Sim), previously validated in [13]. EPON-Sim was extended to support TDWMA-PON and MFH service. We compare the performance of our proposal to that of First-Fit and MOS-IPACT [13] schemes both with and without the MFH traffic prediction technique.

A. Mobile Traffic Modelling

A large dataset containing data of two MNO cellular network deployments in Ireland [14] was used to capture the impact of relevant aspects such as topology, spatial traffic demands, and demographic and MNO information on the MFH performance. This dataset provides base station location, operator, base station to user clusters association, area type of user clusters, and the cumulative distribution function (CDF) of the demands of users served at the peak hour for each type of area.

Each BS was classified as commercial, residential, or rural, on the basis of its most representative type of user served. Its peak offered traffic load was generated by using Monte Carlo simulations. First, we simulate the peak traffic load for each user served by employing the CDF of data demand for the corresponding type of area and aggregated the user cluster traffic demands corresponding to each base station.

An InP with an EPON system with a 5 km radius coverage to the North of Dublin was assumed. In that region, one of the MNOs owns 44 BSs, out of which 40% serve residential areas; the rest serve commercial areas. Moreover, about 15% of the base stations (six) was assumed to be employing that PON as their MFH. The BS traffic distribution was assumed to vary depending on BS location and time period following [15] so that the tidal effect can be fully captured and exploited in the performance evaluation. Thus, three commercial and three residential base stations within the region were selected (shown in Fig. 4) such that the Jain fairness index of offered load in peak hours was maximized in the selected region. The BSs shared their guaranteed bandwidths when bandwidth sharing based schemes were employed.

In this way, the BS offered loads for each scenario were obtained, as well as the distances between the OLT and the MFH ONUs used in the simulations. The obtained load values were scaled with a factor \( c = 3 \) to cope with 5G demands. The scaled offered loads obtained were (25.51; 30.09; 21.46) Mbps and (27.45; 23.36; 30.00) Mbps for the residential and commercial BSs, respectively.

B. Simulation Model and Setup

A 50G TWDMA-EPON network with a tree topology and an OLT that handles a set of 32 ONUs was simulated. Each ONU can transmit on a single 25G wavelength that is allocated dynamically. There is a MNO employing the MFH service of an InP to serve six BSs, as described in Section V-A. Each MFH ONU is connected to its corresponding DU through a local 100Gbps Ethernet interface.

We assumed the split option 6 for all the BSs because it is the most demanding one with the largest bandwidth and lowest latency requirements among the upstream variable-rate split options (see Fig. 1). The BS peak loads obtained in Section V-A and the same assumptions proposed in 3GPP TR 38.801v14 were used to generate the peak average offered load of the 4th ONU/DU \( (P_k) \). The obtained \( P_k \) values were (4170, 4445 and, 3927) Mbps and (4287, 4041, and 4440) Mbps, respectively, for the residential and commercial ONU/DUs.

The guaranteed bandwidth \( B_k \) of the MFH ONUs was varied from \( 0.8 \cdot P_k \) to \( 1.2 \cdot P_k \). For the sake of clearness, herein after, \( P_k \) has been omitted from the \( B_k \) values. To test a coexisting scenario with support for different PON services,
the rest of the ONUs in the PON were conventional ones. Each conventional ONU had a guaranteed bandwidth equal to the remaining available bandwidth in the PON divided by the number of conventional ONUs. Moreover, to simulate a highly loaded network condition, the mean offered load of the conventional ONUs was 85% of their guaranteed bandwidth. It was pointed out by a Brazilian InP that, in practice, additional network resources are allocated to the system when it achieves around 85% of its capacity.

The load generated by the ONU/DU follows a Poisson distribution with a mean value equal to the offered load for the corresponding scenario, while that for the traffic of conventional ONUs follows the implementation in [13]. Moreover, DU was assumed to generate bursts of Ethernet frames (MFH data) every 250 \(\mu s\). The maximum cycle length was set to 250 \(\mu s\), the propagation delay in fiber was considered to be 5 \(\mu s/km\), and the guard time period between transmissions from different ONUs in the PON was 0.624 \(\mu s\). Each simulation scenario lasted 60 s and was replicated 10 times.

Two different time period scenarios were considered, namely 18h and 24h, as these account for the peak of the offered traffic loads for commercial and residential BSs, respectively. The offered load for residential BSs on 18h and commercial BSs on 24h were, respectively, 38.1% and 8.1% of that during the peak hour. Since MFH ONUs serving BSs in off-peak traffic hours experience lower delay values than do those serving BSs in peak traffic hours, the analysis in the next section focuses on MFH ONUs in the peak traffic hour for each time scenario.

**C. Simulation Results and Discussions**

The proposed scheme achieved the required delay value (<250\(\mu s\)) for both scenarios with guaranteed bandwidth per ONU/DU greater than or equal to 105% of its peak hour average load value (Fig. 5). Note that the MFH ONUs in the 18h scenario require 10% more guaranteed bandwidth than do those in the 24h scenario because of the differences in the BS

**Fig. 3: Flow chart of the proposed resource allocation algorithm**
off-peak traffic loads of the two scenarios. Since the bandwidth leased has to satisfy the worst-case scenario, the MNO needs 1.05 guaranteed bandwidth per ONU/DU. The other schemes fail to produce satisfactory MFH delay values for the splitting option considered for the guaranteed bandwidth values tested.

These results show not only that the MFH delay requirements can be met by our proposal but also that it significantly reduces the required guaranteed bandwidth per ONU/DU when compared to the other schemes, thus leading to an increase in bandwidth utilization and a reduction in costs for MNOs renting bandwidth from the InP.

The schemes employing MFH traffic prediction reduce the percentiles of delay values when compared to their version with no prediction scheme. Moreover, bandwidth sharing based schemes give 99.999th percentile delay values lower than those without this technique. Furthermore, online-based with traffic prediction schemes (i.e., First-Fit-prediction, and our proposal) generate 99th percentile delay values lower than those using offline policies. Our proposal combines all these features to meet the stringent MFH requirements of a network which provides QoS guarantees for all supported services.

The evaluated schemes do not decrease the 99.999th percentile of the delay value after a particular increase in the contracted bandwidth. There is a fundamental limit in the performance of resource allocation mechanisms that cannot be surpassed by simply increasing the bandwidth. Even with accurate MFH traffic forecasting and appropriate maximum cycle length settings, the grant sizing problem must be properly addressed to meet MFH low latency requirements.

VI. FUTURE RESEARCH DIRECTIONS

This section presents some future research directions for the application of PON technology in fronthauling 5G and B5G networks.

A. MFH Traffic Forecasting

Most of the current approaches for forecasting MFH traffic employ information from the cooperation interface between the BS and the OLT. However, for splitting 5 and below, the direct cooperation between the OLT and the 5G MAC layer is not feasible since the required information is available only at the ONU/DU side. Alternatively, the ONU/DU and the OLT could communicate to provide the information needed for traffic forecasting. However, such communication requires additional bandwidth and introduces latency, which can only be afforded by Enhanced Mobile Broadband (eMBB) and massive machine-type communications (mMTC) services.

Another option is to perform forecasting at the ONU either with or without ONU-DU cooperation and include the predicted value in conventional report messages. There is a trade-off between latency overhead and prediction accuracy. Such trade-off is especially relevant when involving Ultra-Reliable and Low-Latency Communications (URLLC) since it may require a one-way access delay as low as 100 μs. Machine learning algorithms can be employed for traffic prediction with high accuracy and in acceptable time frames to cope with this trade-off.

B. MFH-Aware PON Dimensioning and Planning

The designs of PONs have not considered the requirements of MFH traffic. Principles in PON design need to be defined to maximize network utilization yet minimizing the guaranteed bandwidth of a group of ONUs and supporting the demands under various delay constraints. For instance, groups of ONU/DUs could be employed to optimally exploit the bandwidth sharing concept. Another potential approach is the design of an MFH network to reduce the number of wavelengths and OLT equipment required.

C. MFH Traffic Management

Traffic management at the ONU plays a key role in supporting low-latency MFH traffic over PONs, especially for variable-rate splitting options under dynamic resource allocation schemes that employ the Gated bandwidth allocation policy. Traffic management mechanisms are essential to guarantee deterministic delay bounds. For instance, the value of the parameters of traffic shaping mechanisms should be optimal for the delay requirement of each splitting option. Such tuning needs to be well understood to achieve compliance with the definition of splitting options.

VII. CONCLUSION

This paper has introduced a novel resource allocation (RA) mechanism for supporting 5G and B5G mobile network fronthauling (MFH) in EPONs. The main RA issues and approaches for supporting low-latency MFH in these networks
are discussed. Our proposal includes bandwidth sharing for multi-ONU customer, MFH traffic prediction and maximum cycle length tailored to MFH traffic requirements. Simulation results show that our proposal provides lower delay values than do existing schemes under realistic traffic scenarios. The proposal increases network utilization and statistical multiplexing gain for an MNO employing PON-based MFH services. This leads to lower MFH costs than those of existing approaches. Moreover, with our proposal, InPs can offer attractive business models for MFH services.

ACKNOWLEDGMENT

The authors would like to thank CNPq and the Sao Paulo Research Foundation (FAPESP) for grant 2015/24494-8.

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