Optimizing multicast services in Flexible-Rate Passive Optical Networks

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ABSTRACT

Flexible-rate passive optical networks (PON) allow optical network units (ONU) to be grouped according to their channel conditions, thereby enhancing the system throughput. In this paper, we show that in the case of multicast services, scheduling downstream with the peak-rate ONU grouping scheme might result in data redundancy, which would degrade effective throughput. The opportunities to enhance the effective throughput by optimizing the ONU grouping scheme are highlighted.

Keywords: Flexible-rate passive optical network, Multicast services, ONU grouping

1. INTRODUCTION

The rapid growth of high bandwidth video applications, such as live streaming and ultra-high-definition video-on-demand services, has posed significant challenges to the capacity of optical access networks [1,2]. To meet this rising demand, flexible-rate passive optical networks (PON) have emerged as a promising approach for increasing system capacity [3].

In a flexible-rate PON, optical network units (ONU) with similar channel conditions can be grouped to share the same transmission parameters, e.g., modulation formats and forward error correction (FEC) coding, enabling them to operate at a specific peak data rate. These parameters can be tuned within the power budget to adapt the data rate as needed [3-5]. In the downstream direction, since ONUs may employ different transmission parameters, the traditional broadcast-based downstream scheduling protocol in the fixed-rate PON becomes ineffective. To address this, the downstream PHY frame is divided into multiple subframes, each occupying multiple specific time slots [6]. The subframe differs in modulation and coding parameters, which are assigned to a group of ONUs with similar channel conditions and data rate requirements. Different from fixed-rate PONs, where ONUs need to process the whole downstream frame, ONUs in flexible-rate PON only receive and process their own downstream subframe to reduce computing complexity and energy consumption [6]. While this approach addresses the scheduling issue caused by ONU grouping, it also introduces redundancy for multicast services.

In this paper, we compare the downstream scheduling protocols used in fixed-rate and flexible-rate PONs for multicast services. Building on this, we evaluate effective throughput under various ONU grouping schemes to reveal how grouping decisions influence system performance.

2. FLEXIBLE-RATE PASSIVE OPTICAL NETWORK

In this section, we introduce the concept of flexible-rate PON. Fig. 1 illustrates the high-level architecture of a flexible-rate PON, which consists of an OLT and multiple ONUs. The ONUs adopt different transmission parameters, e.g., modulation format, according to their OPL, which is influenced by factors such as physical fiber distance and the number of optical splitters along the ODN. For example, ONU1 in Fig. 1, is connected to the OLT via a single optical splitter, thus experiencing a low OPL, which enables utilizing the 4-level pulse amplitude modulation (PAM4) format to achieve higher data rates. In contrast, ONU2 and ONU3 are connected via two optical splitters, hence experiencing a higher OPL. Therefore, they employ the non-return-to-zero (NRZ) modulation format to maintain reliable performance under more challenging channel conditions. Based on their OPL, these ONUs are grouped into two groups: ONU1 belongs to Group 1, while ONU2 and ONU3 belong to Group 2. To support this, digital signal processing (DSP) modules are introduced in both the OLT and the ONUs, enabling modulation format adaptation during transmission and reception. The operation of the DSP modules is managed by the PON transmission convergence (TC) layer, which consists of the service adaptation sublayer, framing sublayer, and PHY adaptation sublayer. These sublayers handle framing, scheduling, and group management, among others.

In the downstream transmission, the OLT divides the frame into multiple codewords customized for different ONU groups. For instance, codewords modulated with PAM4 are designated for Group 1, while those modulated with NRZ are directed to Group 2. Upon receiving the downstream frame, each ONU identifies the codewords corresponding to its modulation format and reconstructs its assigned subframe. For example, Group 1 only processes the PAM4-modulated codewords (yellow blocks), while Group 2 processes the NRZ-modulated

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The research leading to these results has received funding from the European Commission MSCA-DN NESTOR (G.A.101119983) and the Horizon Europe SEASON (G.A. 101096120); and from the ICREA Institution.

codewords (green blocks). This ensures that each ONU group handles only its designated data, thereby reducing DSP complexity. The flexible-rate PON architecture determines a special downstream scheduling scheme that is distinct from that of conventional fixed-rate PONs. Downstream scheduling protocol plays a critical role in implementing dynamic ONU grouping, especially in multicast scenarios.

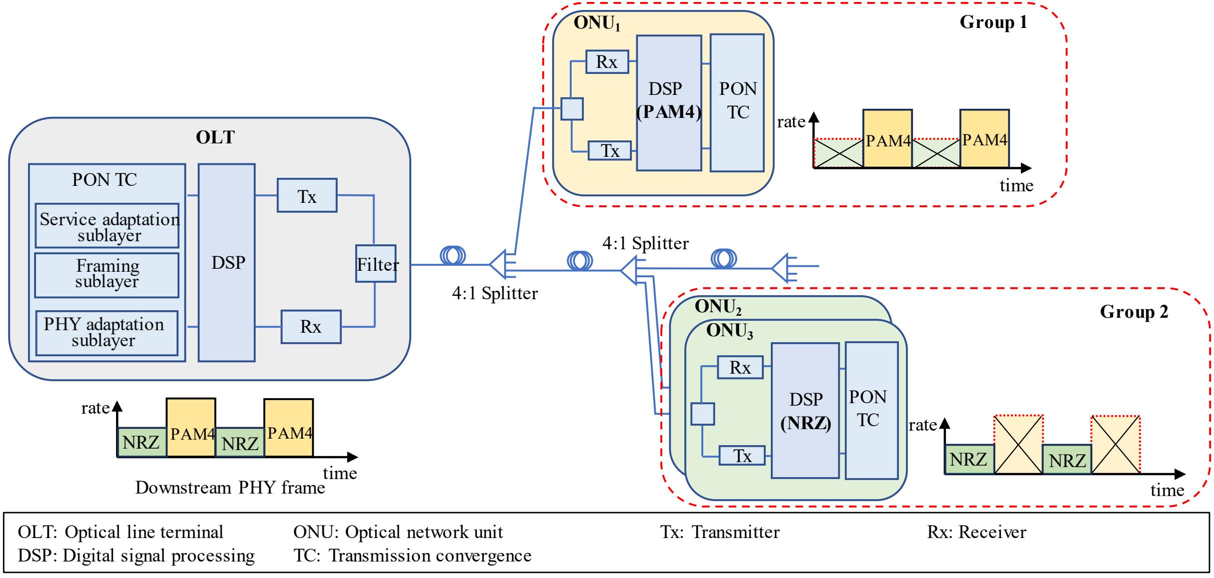


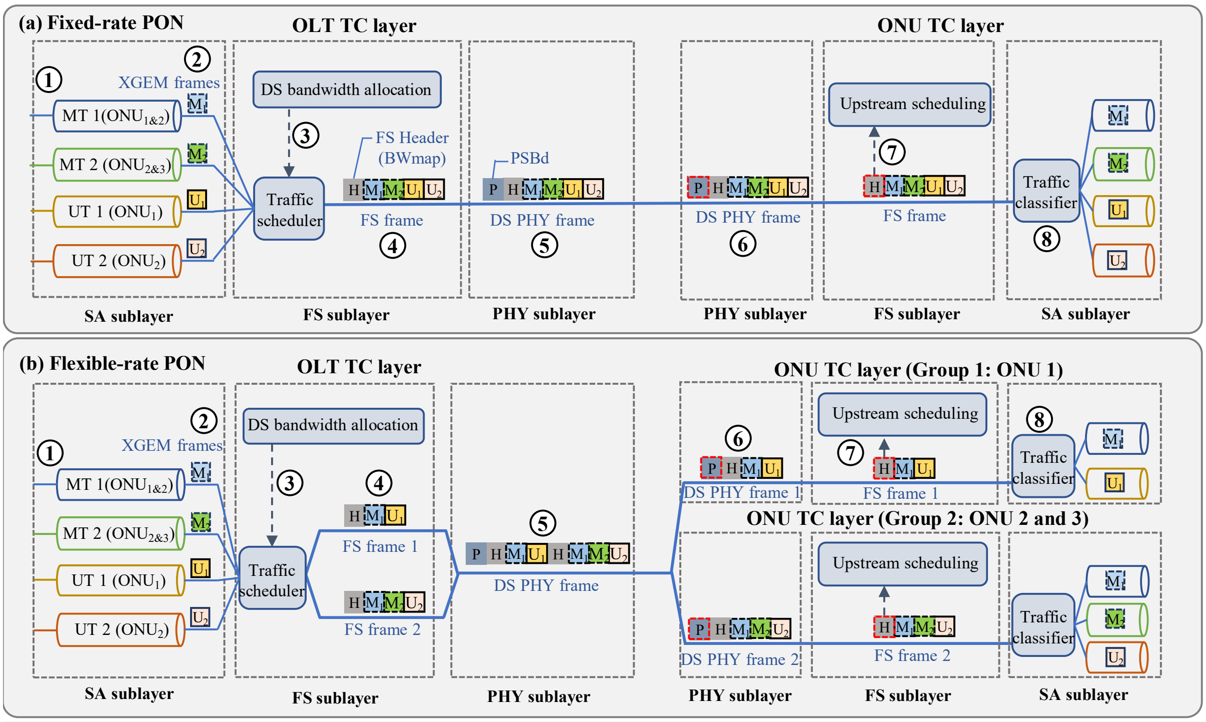
Fig. 1 High-level architecture of flexible-rate PON.

3. DOWNSTREAM SCHEDULING PROTOCOL

In this section, we compare the downstream scheduling protocols of fixed-rate and flexible-rate PONs, with a focus on multicast scheduling. Fig. 2(a) illustrates the downstream scheduling protocol based on the ITU-T 50G-PON Common TC layer specification [7]. In the OLT, service data units (SDU), such as Ethernet frames, are first classified and added to different queues based on their service types (step 1). Then, in the service adaptation sublayer, SDUs are encapsulated into XGEM frames using an XG-PON encapsulation method and assigned a Port-ID, which is included in the header (step 2). The XGEM Port-ID identifies its corresponding service type and broadcast mode. The XGEM Port-ID of a unicast XGEM frame corresponds to a single ONU, whereas the XGEM Port-ID of a multicast XGEM frame can be recognized by multiple ONUs. For illustrative purposes, Fig. 2(a) shows two multicast (M_1 and M_2) and two unicast (U_1 and U_2) traffic flows belonging to different services. Multicast XGEM frames are marked with dashed-line blocks, while the unicast XGEM frames are represented by solid-line blocks. As a result, all multicast XGEM frames need to be transmitted only once, and therefore, each service requires one single dedicated time slot.

In the framing sublayer, a bandwidth allocation module allocates downstream bandwidth to each traffic, determining the XGEM frames that need to be scheduled (step 3). As per the bandwidth allocation information, the traffic scheduler aggregates these XGEM frames and encapsulates them into an FS frame by adding an FS header (step 4). The FS header contains the upstream bandwidth allocation information for ONUs (i.e., the BWmap field). Since a multicast XGEM frame can be recognized by multiple ONUs, each multicast traffic (M_1 and M_2) is allocated one single dedicated time slot in an FS frame. Subsequently, in the PHY adaptation sublayer, this FS frame is further encapsulated into a 125-μs downstream PHY frame after FEC encoding, scrambling, and bit interleaving (step 5). After adding a downstream physical synchronization block (PSBd), the downstream PHY frame is broadcast to all ONUs in the network. Upon receiving the PHY frame, each ONU synchronizes with the PSBd field and extracts the FS frame (step 6). The FS frame is then further de-encapsulated into XGEM frames at the framing sublayer, where the BWmap field is extracted from the FS header and utilized by the ONU for upstream scheduling (step 7). A traffic classifier then categorizes the data frames and selects its corresponding XGEM frames based on the XGEM Port-IDs, restoring them into SDUs in the service adaptation sublayer (step 8). Notably, in this protocol, every ONU must receive and process the entire downstream PHY frame.

In flexible-rate PONs, data for different ONU groups must be independently encapsulated due to varying transmission parameters among the groups. To achieve this, after processing in the service adaptation sublayer, XGEM frames belonging to the same ONU group are aggregated and encapsulated into an independent FS frame. For multicast traffic, if all its ONU members belong to the same group, the corresponding FS frame can directly carry its multicast XGEM frames without duplication. Otherwise, the XGEM frames must be duplicated and encapsulated into n FS frames, where n represents the number of ONU groups spanned by the multicast service.



OLT: Optical line terminal
ONU: Optical network unit
TC: Transmission convergence
MT: Multicast traffic
UT: Unicast traffic
SA: Service adaptation
FS: Framing
PHY: Physical interface adaptation
DS: Downstream
BWmap: Bandwidth map
PSBd: Physical synchronization block downstream
PLOAMd: Physical layer operation, administration and maintenance downstream

Fig. 2 Comparison of downstream scheduling protocols: (a) fixed-rate PON and (b) flexible-rate PON.

This implies that a multicast service will be assigned a different time slot in multiple distinct FS frames. Fig. 2(b) illustrates the downstream scheduling protocol of flexible-rate PONs that incorporates ONU grouping [6]. Assume that ONU1 belongs to Group 1, ONU2, and ONU3 belong to another group. The multicast XGEM frame M_1 of multicast traffic 1 is intended for ONU1 and ONU2. Therefore, M_1 is duplicated and encapsulated into both FS Frame 1 and FS Frame 2 (step 4). In contrast, multicast traffic 2 has ONU members ONU2 and ONU3 in the same group, and thus M_2 is only encapsulated into FS Frame 2. Noted that the duplication of XGEM frames occurs only during the encapsulation into FS frames. Additionally, each FS frame includes the transmission parameter information within the downstream physical layer operation, administration, and maintenance (PLOAMd) field for the ONUs of the group. This information is generated by a bandwidth allocation module and copied to all FS frame headers by the traffic scheduler (step 3). The FS frames from different groups are subsequently aggregated in the PHY adaptation sublayer and encapsulated into a complete downstream PHY frame (step 5). During this process, a codeword interleaving method between FS frames can be performed to reduce DSP complexity [6]. Upon receiving the downstream PHY frame, the ONU reconstructs the FS frame for its group (step 6). Subsequently, the FS frame is de-encapsulated at the framing sublayer (step 7). The extracted XGEM frames are then processed at the service adaptation sublayer (step 8), where the traffic classifier determines whether the frames are intended for the receiving ONU.

Compared with the fixed-rate PON, the flexible-rate protocol exhibits a potential drawback. When a multicast service spans multiple ONU groups, the scheduler replicates the same multicast XGEM frame into every group's FS frame (step 4). This replication produces redundant traffic in the downstream PHY frame, which can degrade multicast efficiency and indicates that the bottleneck resides in the present ONU-grouping method.

4. EFFECTIVE THROUGHPUT EVALUATION

To investigate the potential impact of ONU grouping on multicast efficiency, we further evaluate the downstream effective throughput under three scenarios: a) a fixed-rate PON without ONU grouping; b) a flexible-rate PON with peak-rate ONU grouping; and c) a flexible-rate PON with optimized ONU grouping.

Fig. 3(a) illustrates an example of a downstream PHY frame in a fixed-rate PON without ONU grouping. For simplicity, the overhead is omitted. The colored blocks represent the bandwidth allocated to different services, which is determined by a fixed data rate r_0 and frame duration t_0. U_j^i and M_j^i indicate the j^{th} unicast and multicast service targeting ONU i, respectively. Suppose that there are six ONUs and five traffic flows (from four unicast services and one multicast service) that require transmission. Since both unicast and multicast data are transmitted

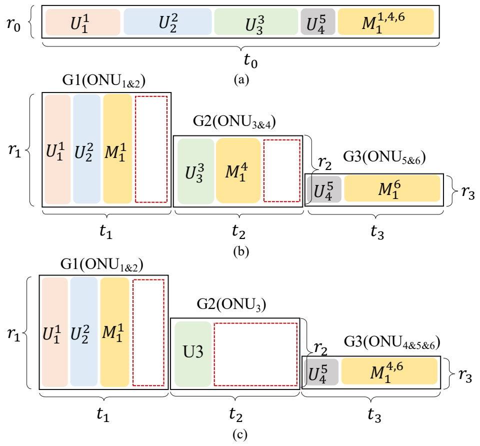


Fig. 3 Examples of a downstream PHY frame in (a) a fixed-rate PON, (b) a flexible-rate PON, and (c) a flexible-rate PON with ONU grouping optimization.

only once, no redundancy is generated. In this scenario, the downstream effective throughput equals the sum of bandwidth allocated to each service.

Fig. 3(b) presents an example of a downstream PHY frame in a flexible-rate PON with a fixed ONU grouping method. In this case, the system achieves its maximum system capacity. Six ONUs are divided into three groups: Group 1, Group 2, and Group 3. ONU1 and ONU2 in Group 1 achieve the highest data rate r_1 due to favorable channel conditions, while ONU3 and ONU4 in Group 2 operate at a lower peak data rate r_2. The ONU5 and ONU6 in Group 3 experience the poorest channel conditions and operate at the lowest peak data rate $r_3=r_0$. Assuming the FS frame of each group is allocated an equal time slot duration (i.e., $t_1=t_2=t_3$), the flexible-rate PON can transmit the same data in less time (indicated by the red dashed blocks), thereby increasing the maximum system throughput. However, the multicast data M_1 directed to ONUs in three different groups (i.e., ONU1, ONU4, and ONU6) must be transmitted separately for each group, occupying up to three time slots (M_1^1, M_1^4, and M_1^6), which introduces unnecessary redundancy and significantly reduces the effective throughput.

Fig. 3(c) shows an example after optimizing the grouping by moving ONU4 from Group 2 to Group 3 (i.e., lowering its data rate to r_3), so the redundant transmission M_1^4 can be eliminated. Compared to the solution in Fig. 3(b), this adjustment further improves the effective throughput. However, moving ONU1 to Group 3 to further reduce redundancy is not advisable, as lowering its data rate would increase the time slot required for the unicast service U_1^1, thus decreasing the overall effective throughput. Therefore, optimizing ONU grouping involves a trade-off between minimizing redundancy and maintaining high ONU data rates.

5. CONCLUSION

To optimize multicast services in flexible-rate PONs, we compared the downstream scheduling protocols of fixed-rate and flexible-rate PONs and found that the peak-rate ONU grouping scheme in flexible-rate PONs causes notable multicast inefficiency. Using illustrative examples, we compared the effective throughput of different ONU grouping schemes and highlighted the main factors that influence effective throughput. These findings lay a foundation for future work on downstream ONU grouping and bandwidth allocation schemes.

REFERENCES

[1] H. Li *et al.*, "Broadcasting and 6G converged network architecture," IEEE Trans. Broadcast 70, 971-979 (2024), doi: 10.1109/TBC.2024.3407482.
[2] "Performance metrics for end-to-end IPTV video quality," ITU-T Technical Paper GSTP-IPTV-QoS (2020).
[3] R. Borkowski *et al.*, "FLCS-PON – a 100 Gbit/s flexible passive optical network: concepts and field trial," J. Lightwave Technol. 39, 5314-5324 (2021), doi: 10.1109/JLT.2021.3102383.
[4] V. Houtsma *et al.*, "Investigation of modulation schemes for flexible line-rate high-speed TDM-PON," J. Lightwave Technol. 38, 3261-3267 (2020), doi: 10.1109/JLT.2020.2976959.
[5] J. Zhou *et al.*, "100G fine-granularity flexible-rate passive optical networks based on discrete multi-tone with PAPR optimization," J. Opt. Commun. Netw. 14, 944-950 (2022), doi: 10.1364/JOCN.463671.
[6] W. van Hoof *et al.*, "G.hsp: reducing ONU complexity through FEC codeword interleaving," in Proc. ITU-TQ2/15, contribution SG15-C1914, Geneva, 2020.
[7] "Higher speed passive optical networks – common transmission convergence layer specification," ITU-T Recommendation G.9804.2 (2021).