Al-Farouk journal of sciences
Volume (2), Issue (3) (JUNE, 2026)
ISSN: 3135-2359

مجلة الفاروق للعلوم
المجلد (2) العدد 3 يونيو 2026
ردمد: 3135-2359

Adaptive Mini-Slot Selection for Low-Overhead ACP-2D Scheduling in Multi-OLT Multi-Lane PON-Based 5G Fronthaul

Marai M.Abousetta
m.abousetta@academy.edu.ly
Mohammed Said Almjrab
Libyan Academy For Postgraduate Studies
Email: almjrab706@gmail.com

تاريخ الاستلام: 2026/04/21 تاريخ المراجعة 2026 /05/23 تاريخ القبول:2026/06/07- تاريخ النشر: 2026 /06/30

Abstract

Multi-optical-line-terminal (multi-OLT) multi-lane passive optical networks (PONs) are promising candidates for converged optical and wireless access, especially when fifth-generation (5G) fronthaul traffic must coexist with Internet of Things (IoT), fiber-to-the-home (FTTH), and wireless sensor network (WSN) services. The access class priority-based two-dimensional scheduling (ACP-2D) algorithm has shown that 5G fronthaul traffic can be transported over a 100 Gb/s next-generation Ethernet PON (NG-EPON) while satisfying the 250 µs 3GPP fronthaul delay requirement. However, a fixed mini-slot duration creates a direct tradeoff: shorter mini-slots reduce delay but increase overhead, whereas longer mini-slots reduce the overhead-to-data ratio (ODR) but may violate the latency bound. This paper proposes Adaptive ACP-2D, a lightweight extension that selects the largest feasible mini-slot duration before running ACP-2D. The proposed selector uses a delay constraint and the optical network unit (ONU) distance to choose between 125 µs and 71 µs mini-slots while preserving a 36 µs fallback mode. Numerical evaluation based on the published ACP-2D parameters shows that the proposed method maintains 5G delay within 250 µs over a 20 km reach and reduces the average 5G ODR by 56.83% compared with fixed 36 µs operation. The approach requires no physical-layer modification and adds only constant-size decision overhead to the existing ACP-2D scheduler.

Index Terms—5G fronthaul, ACP-2D, dynamic bandwidth allocation, mini-slot selection, multi-OLT PON, NG-EPON, O-RAN, passive optical network.

I. INTRODUCTION

Optical and wireless access convergence is becoming essential as mobile traffic, fixed broadband traffic, and machine-type communication increasingly share the same access infrastructure. Passive optical networks (PONs) are attractive in this context because they are widely deployed for FTTH and can be extended to support mobile fronthaul and midhaul traffic. In 5G centralized radio access network (C-RAN) and open radio access network (O-RAN) scenarios, fronthaul between the distributed unit and the radio unit has stricter latency requirements than conventional fixed access services.

Recent work proposed a multi-OLT multi-lane PON architecture for 5G fronthaul and differential services using access class priority-based two-dimensional scheduling (ACP-2D) [1]. The architecture follows a 100 Gb/s NG-EPON design with four 25 Gb/s wavelength lanes, four OLTs, and service-class-aware ONUs. In that system, 5G traffic is assigned to high-priority P-class ONUs that can use dynamic channel bonding over multiple lanes. The published results show that ACP-2D can transmit the target 5G load of 0.798 while satisfying the 250 µs delay limit and maintaining approximately 99.9% upstream bandwidth utilization [1].

A remaining operational issue is the selection of the mini-slot duration. ACP-2D was evaluated for 36, 71, 125, and 250 µs mini-slots. Short mini-slots provide low latency but increase control overhead, while long mini-slots reduce ODR but may violate the fronthaul delay bound. For example, the 36 µs and 71 µs cases remain feasible up to 20 km, whereas the 125 µs case reaches the 250 µs delay threshold at approximately 7 km [1]. This motivates an adaptive policy that selects the largest mini-slot that remains feasible for the current operating condition.

This paper makes the following contributions:

- It proposes a lightweight mini-slot selection layer that can be placed before ACP-2D without changing the original channel bonding logic.
- It formulates mini-slot selection as a constrained decision problem that maximizes the mini-slot duration subject to the 5G delay requirement.
- It provides numerical results showing that Adaptive ACP-2D preserves the 250 µs 5G delay constraint over a 20 km reach while reducing average 5G ODR compared with fixed short-mini-slot operation.

II. RELATED WORK

PON-based 5G fronthaul has been studied using time-division multiplexing PONs, time-and-wavelength-division multiplexing PONs, and NG-EPON systems. Early mobile dynamic bandwidth allocation (DBA) mechanisms relied on cooperation with mobile scheduling information, whereas later approaches introduced traffic monitoring, slicing, wavelength assignment, and channel bonding to satisfy fronthaul latency constraints [3], [5], [6]. NG-EPON is especially relevant because it supports multiple wavelength lanes and channel bonding, which allows high-rate ONUs to aggregate capacity when their service demand exceeds a single lane [2], [4].

Dynamic wavelength and bandwidth allocation (DWBA) in NG-EPON must address load balancing, guard-time overhead, frame resequencing delay, and the non-fragmentable nature of Ethernet frames. Water-filling approaches favor load balancing but can increase overhead, while first-fit and single-channel-as-possible strategies reduce reordering but can be less adaptive under high load. The ACP-2D scheme was designed for a multi-OLT open-access PON and combines service-class prioritization with dynamic channel bonding for 5G P-class ONUs [1]. Unlike those works, this paper does not replace the DWBA algorithm. Instead, it adds a mini-slot selection policy that reduces overhead when the latency budget permits.

III. SYSTEM MODEL AND BASELINE ACP-2D

The considered system follows the multi-OLT multi-lane PON configuration of [1]. The network capacity is 100 Gb/s, divided into four wavelength lanes of 25 Gb/s. Four OLTs represent four service providers: IoT, FTTH, WSN, and 5G. The subscriber side contains 16 ONUs grouped into S-, G-, and P-class devices. The P-class ONUs represent 5G fronthaul subscribers and can use dynamic channel bonding over multiple lanes.

TABLE I. Evaluation Parameters

Parameter	Value
Network capacity	100 Gb/s
Number of wavelength lanes	4
Capacity per lane	25 Gb/s
Number of OLTs	4
Number of ONUs	16
Services	IoT, FTTH, WSN, 5G
5G traffic load	0.798
Mini-slot set	36, 71, 125, 250 µs
5G delay bound	250 µs
Maximum reach	20 km
Guard time	0.01 µs
Control message size	64 bytes

ACP-2D has two dimensions. In the first dimension, each service class receives bandwidth on its predefined wavelength lane. In the second dimension, high-priority P-class ONUs use dynamic channel bonding to consume excess bandwidth from other lanes when the reserved 5G lanes are insufficient. This is necessary because the P-class traffic load is 0.798, while the two reserved 5G lanes provide only 0.50 of normalized network capacity. Channel bonding is therefore required to obtain the remaining 0.298 normalized load from other lanes.

The key delay and ODR observations from the baseline ACP-2D study are as follows. A 36 µs mini-slot gives a maximum 5G delay of 161.362 µs up to 20 km; a 71 µs mini-slot gives a maximum 5G delay of 220.332 µs up to 20 km; a 125 µs mini-slot reaches the 250 µs threshold at approximately 7 km; and a 250 µs mini-slot is unsuitable for the considered open-access 5G fronthaul scenario [1]. The published ODR values for 5G traffic on the third and fourth lanes are also lower for larger mini-slots, which confirms the delay-overhead tradeoff.

IV. PROPOSED ADAPTIVE ACP-2D

A. Design Objective

The objective is to select the largest mini-slot duration that satisfies the 5G fronthaul delay bound. The proposed selection is executed before the standard ACP-2D bandwidth allocation and channel bonding procedures. Therefore, the proposal modifies the scheduling cycle length but does not alter the resource allocation equations or the bonding mechanism.

Let T be the candidate set of mini-slot durations:

$$T = \{36, 71, 125\}\ \mu s \qquad (1)$$

The 250 µs mini-slot is excluded from normal 5G operation because it is not feasible for the considered open-access fronthaul case. For a given ONU distance d and traffic condition ρ, the selected mini-slot is

$$T^* = \arg\max_{T \in T} T \qquad (2)$$

subject to

$$\hat{D}5G(T, d, \rho) \leq Dmax, \quad Dmax = 250\ \mu s \qquad (3)$$

Here, $\hat{D}5G$ is the predicted 5G upstream delay. In an implementation, this value can be obtained from online monitoring, lookup tables, or a lightweight delay model. In this paper, a calibrated numerical model is used only for evaluation.

B. Distance-Aware Selection Rule

Based on the feasibility results reported for ACP-2D, the proposed rule is:

$$T^*(d) = 125\ \mu s \text{ if } d \leq 7 \text{ km};\ 71\ \mu s \text{ if } 7 < d \leq 20 \text{ km};\ 36\ \mu s \text{ as fallback.} \qquad (4)$$

The 125 µs mode is used only when the reach is short enough to remain within the 250 µs constraint. The 71 µs mode is used for longer ONUs because it remains feasible up to 20 km while offering lower ODR than 36 µs operation. The 36 µs mode is preserved as a conservative fallback when measured delay approaches the limit or traffic conditions differ substantially from the expected profile.

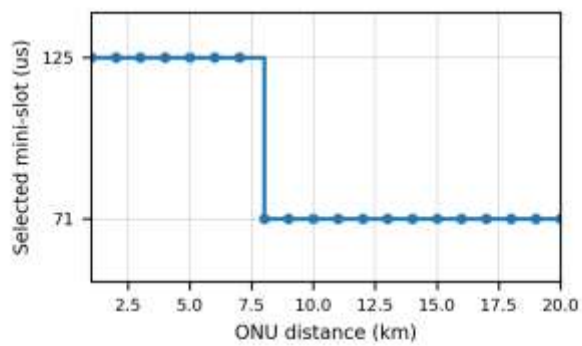

Fig. 1. Adaptive mini-slot decision as a function of ONU distance.

C. Complexity

The additional complexity is limited to checking a fixed candidate set of mini-slot durations for the P-class ONUs. If |P| is the number of P-class ONUs and |T| = 3, the extra complexity is O(|P||T|), which reduces to O(|P|) because the number of candidate mini-slots is constant. Thus, Adaptive ACP-2D preserves the practical scalability of ACP-2D.

V. NUMERICAL EVALUATION

A. Methodology

The evaluation uses the baseline network parameters listed in Table I. Since the full MATLAB simulator from [1] is not available, this paper performs a numerical evaluation calibrated to the published ACP-2D anchor points. The delay model is

$$\hat{D}5G(T, d) = 1.6849T + 4.7165d + 6.3775 \qquad (5)$$

where T is in µs and d is in km. Equation (5) is calibrated so that it reproduces the reported points D(36,20)=161.362 µs, D(71,20)=220.332 µs, and D(125,7)=250 µs. It is used as an interpolation model rather than as a replacement for full packet-level simulation.

The 5G ODR values are taken from the baseline 5G lanes. Averaging the third and fourth lane values gives 8.17×10^{-7} for 36 µs, 4.155×10^{-7} for 71 µs, and 2.36×10^{-7} for 125 µs operation. For Adaptive ACP-2D, the average ODR is computed over a 20 km reach by using 125 µs for the first 7 km and 71 µs for the remaining 13 km:

$$ODR_{adp} = (7/20)(2.36\times10^{-7}) + (13/20)(4.155\times10^{-7}) \quad (6)$$

$$ODR_{adp} = 3.52675\times10^{-7} \quad (7)$$

B. Delay Performance

Fig. 2 compares fixed and adaptive mini-slot policies. Fixed 36 µs and fixed 71 µs remain below the 250 µs delay bound over the 20 km reach. Fixed 125 µs provides lower ODR but violates the 250 µs requirement beyond approximately 7 km. Adaptive ACP-2D follows the 125 µs mode at short distances and switches to 71 µs for longer distances, thereby maintaining feasibility over the full 20 km reach.

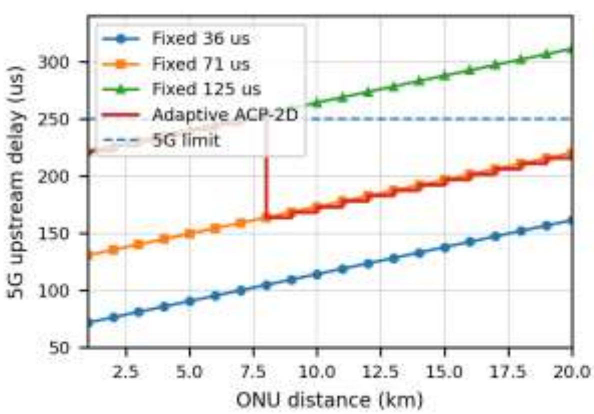

Fig. 2. Numerical 5G upstream delay versus ONU distance.

The maximum modeled adaptive delay is 250 µs at the switching boundary. In practical deployments, a small guard margin may be introduced so that the policy switches from 125 µs to 71 µs slightly before the analytical boundary. This would slightly increase ODR but improve robustness against measurement uncertainty and short-term traffic bursts.

C. ODR Performance

Fig. 3 shows the ODR comparison. Fixed 36 µs operation is the most conservative latency choice but has the highest ODR. Fixed 125 µs gives the lowest ODR among the feasible candidates but cannot satisfy the full 20 km reach. Adaptive ACP-2D obtains an average ODR of 3.53×10^{-7} while remaining feasible over 20 km.

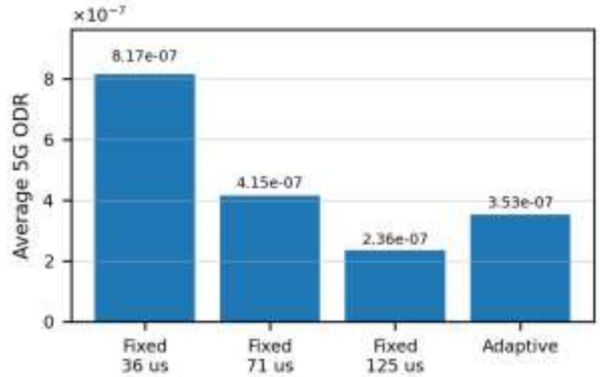

Fig. 3. Average 5G ODR comparison.

The ODR reduction relative to fixed 36 µs is

$$((8.17\times10^{-7} - 3.52675\times10^{-7}) / 8.17\times10^{-7}) \times 100 = 56.83\% \quad (8)$$

Relative to fixed 71 µs, the reduction is 15.12%. Therefore, the proposed policy improves overhead efficiency even against the strongest fixed mini-slot that remains feasible over 20 km.

TABLE II. Summary of Numerical Results

Policy	Full 20 km feasible	Max. delay (µs)	Avg. ODR	ODR saving vs. 36 µs
Fixed 36 µs	Yes	161.36	8.17×10−7	0%
Fixed 71 µs	Yes	220.33	4.16×10−7	49.14%
Fixed 125 µs	No	311.31	2.36×10−7	71.11%
Adaptive	Yes	250.00	3.53×10−7	56.83%

D. Throughput and Bandwidth Utilization

Adaptive ACP-2D does not change the ACP-2D bandwidth allocation or dynamic channel bonding operations. Therefore, when the total offered load remains within the 100 Gb/s network capacity, the proposed extension preserves the baseline ability to deliver the normalized 5G throughput of 0.798 and approximately 99.9% upstream bandwidth utilization. The primary gain is not additional throughput; it is reduced overhead under the same 5G latency constraint.

VI. DISCUSSION

The proposed method is intentionally simple. It does not require changes in the ONU optical hardware, the OLT architecture, or the ACP-2D bonding equations. This makes it suitable as a scheduler-level improvement for multi-OLT open-access PONs. The main practical requirement is delay awareness. A network controller can obtain the required information from ONU registration distance, ranging information, historical delay measurements, or online delay monitoring.

The numerical results also show that the mini-slot value should not be treated as a universal static parameter. A fixed 36 µs mini-slot is safe but unnecessarily overhead-intensive. A fixed 125 µs mini-slot is efficient but unsafe for longer reach. Adaptive selection exploits the middle ground by using a longer cycle where the delay budget allows it and a shorter cycle where the reach is longer.

The main limitation of this study is that the evaluation is calibrated from published ACP-2D results rather than produced from an independent packet-level simulator. Future work should implement Adaptive ACP-2D in a full discrete-event NG-EPON simulator, include bursty traffic, use non-uniform ONU distances, and test guard-margin policies under load variation, OLT failure, and service restoration scenarios.

VII. CONCLUSION

This paper proposed Adaptive ACP-2D, a lightweight mini-slot selection extension for ACP-2D scheduling in multi-OLT multi-lane PON-based 5G fronthaul. The method selects the largest feasible mini-slot while satisfying the 250 µs 5G delay requirement. Numerical evaluation using published ACP-2D parameters shows that Adaptive ACP-2D maintains 5G latency feasibility over a 20 km reach and reduces average 5G ODR by 56.83% compared with fixed 36 µs operation. Since the method does not alter the physical architecture or the underlying channel bonding mechanism, it is a practical candidate for improving overhead efficiency in open-access NG-EPON fronthaul systems.

REFERENCES

[1] F. Rawshan, M. Hossen, and M. R. Islam, “Multi-OLT multi-lane PON for 5G fronthaul and differential services through access class priority-based 2D scheduling,” IEEE Open Journal of the Communications Society, vol. 5, pp. 6593–6610, 2024, doi: 10.1109/OJCOMS.2024.3479241.

[2] IEEE Standard for Ethernet Amendment 9: Physical Layer Specifications and Management Parameters for 25 Gb/s and 50 Gb/s Passive Optical Networks, IEEE Std 802.3ca-2020, 2020.

[3] J. Zhang, X. Liu, M. Liang, H. Yu, and Y. Ji, “Low latency DWBA scheme for mini-slot based 5G new radio in a fixed and mobile converged TWDM-PON,” Journal of Lightwave Technology, vol. 40, no. 1, pp. 3–13, Jan. 2022.

[4] A. Zaouga, A. De Sousa, M. Najjar, and P. P. Monteiro, “Dynamic bandwidth allocation for NG-PONs with channel bonding,” IEEE Communications Letters, vol. 26, no. 2, pp. 374–378, Feb. 2022.

[5] H. Uzawa et al., “Dynamic bandwidth allocation scheme for network-slicing-based TDM-PON toward the beyond-5G era,” Journal of Optical Communications and Networking, vol. 12, no. 2, pp. A135–A143, Feb. 2020.

[6] T. Tashiro et al., “A novel DBA scheme for TDM-PON based mobile fronthaul,” in Proc. Optical Fiber Communication Conference (OFC), San Francisco, CA, USA, 2014, pp. 1–3.

[7] BenHusein, A. H., Shakrum, F. M., & Elgdiri, E. M. (2026). A Comprehensive Performance Evaluation of a Wi-Fi-Based Wireless Sensor Network Using Raspberry Pi and ESP8266 Under Multi-Rate Traffic Conditions. Al-Farooq Journal of Sciences, 2(3), 816-818.

[8] Elwalwa, H. M., Zarig, F. H. A., Murad, M. K. H., & Nashnush, A. N. E. (2026). The role of innovation technology in developing solar energy technologies: challenges and future trends towards sustainable development (literature review). *Al-Farooq Journal of Sciences*, *2*(3), 585-594.