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Energy-Efficient Power Management Using Delay-Aware Sleep Control in TDM/WDM Passive Optical Networks

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Abstract
Energy consumption in optical access networks has become a critical design constraint as broadband subscriber density and bandwidth demand continue to grow. Optical Network Units (ONUs) remain powered for the majority of their operating time even when idle, making sleep-mode control one of the most effective levers for reducing access-network energy consumption. This paper presents a delay-aware power management scheme for Time-Division-Multiplexed/Wavelength-Division-Multiplexed (TDM/WDM) Passive Optical Networks (PONs) that integrates adaptive sleep control with Dynamic Bandwidth Allocation (DBA). ONUs are classified according to traffic priority, and short-sleep/doze cycles are assigned to delay-sensitive (real-time) traffic while long-sleep cycles are assigned to low-priority (non-real-time) traffic, subject to an explicit maximum-delay constraint. A power-consumption model combining active, sleep, and doze states is formulated together with an energy-efficiency metric that jointly captures throughput and power. Simulation results, generated using a MATLAB/Python-based discrete-event traffic and power model, show that the proposed scheme achieves 30-42% energy saving over the offered-load range studied, versus 13-18% for fixed sleep scheduling and 22-29% for load-adaptive sleep scheduling without delay awareness, while simultaneously reducing mean packet delay for high-priority traffic by up to 65% relative to the fixed-sleep baseline. These results indicate that the proposed delay-aware scheme offers a favourable energy-delay trade-off and is a promising candidate for energy-efficient next-generation optical access networks.

Keywords: Power Management; TDM/WDM-PON; Sleep Mode; Energy Saving; Delay-Aware Scheduling; Dynamic Bandwidth Allocation; Optical Network Unit

1. Introduction

The rapid expansion of bandwidth-intensive services - ultra-high-definition video, cloud computing, and Internet-of-Things (IoT) traffic - has driven continuous growth in fixed access-network capacity. Passive Optical Networks (PONs) are widely deployed as the access technology of choice because they offer high bandwidth, low maintenance cost, and a passive (unpowered) outside-plant architecture. Compared with copper-based or active Ethernet access networks, PONs are inherently more energy-efficient; however, the aggregate power consumed by the large and growing population of Optical Network Units (ONUs) deployed at the customer premises still represents a significant and increasing share of total network operator energy expenditure, since ONUs remain continuously powered regardless of instantaneous traffic demand.

Existing energy-saving approaches for PON access networks can be broadly grouped into three categories:

- MAC-layer scheduling techniques, which adapt bandwidth grants and polling cycles to reduce unnecessary ONU activity;
- Physical-layer optimization techniques, such as adaptive link rate and transceiver power scaling; and
- Sleep-mode control techniques, in which the ONU transceiver is placed into a reduced-power state (doze or sleep) during idle intervals.

Sleep-mode control is the most widely adopted approach because it can be applied with limited changes to existing ONU hardware and standard DBA frameworks (e.g., IEEE 802.3ah/av EPON and ITU-T G.984/G.987 GPON/XG-PON). However, sleep-based mechanisms introduce an inherent energy-delay trade-off: longer sleep intervals improve energy saving but increase the latency experienced by traffic that arrives during a sleep window, which is problematic for delay-sensitive applications such as voice-over-IP, online gaming, and industrial IoT control traffic. This trade-off motivates the delay-aware power management scheme proposed in this paper, which differentiates sleep-cycle length by traffic class and couples the sleep controller with the DBA engine so that energy savings are maximized subject to per-class delay bounds.

The remainder of this paper is organized as follows. Section 2 states the problem addressed by this work. Section 3 describes the proposed delay-aware power management methodology. Section 4 develops the mathematical power and energy-efficiency model. Section 5 presents simulation results and discussion. Section 6 compares the proposed method against existing techniques. Section 7 concludes the paper, and Section 8 outlines directions for future work.

2. Problem Statement

Conventional PON energy-saving mechanisms suffer from the following limitations, which this work aims to address:

- High static power consumption of ONUs: a large fraction of ONUs remain in the active state even during periods of low or no traffic, dominating total access-network energy consumption.
- Inefficient fixed sleep scheduling: fixed-duration sleep cycles are set independently of instantaneous traffic conditions, so they either under-save energy during light load or introduce excessive queuing delay during moderate and heavy load.
- Delay-sensitive applications are adversely affected: existing adaptive sleep schemes generally optimize for aggregate energy saving without explicit per-class delay guarantees, degrading Quality of Service (QoS) for real-time traffic.

The objective of this work is therefore to design a sleep-control scheme that (i) maximizes ONU energy saving, (ii) explicitly bounds the delay experienced by delay-sensitive traffic, and (iii) integrates seamlessly with standard DBA mechanisms used in TDM/WDM-PON.

3. Proposed Methodology

3.1 Traffic Classification

Each ONU classifies incoming traffic at the queue level into two classes prior to sleep-window computation:

- Real-time (RT) traffic: voice, video conferencing, and control-plane traffic with a strict maximum tolerable delay $D_{max,RT}$.
- Non-real-time (NRT) traffic: best-effort data (e.g., file transfer, background synchronization) with a relaxed delay bound $D_{max,NRT}$.

3.2 Delay-Aware Adaptive Sleep Control

The sleep-window length assigned to each ONU is computed adaptively for each cycle based on (a) the queue occupancy reported to the Optical Line Terminal (OLT) at the end of the previous cycle, (b) the traffic-class mix currently buffered, and (c) the residual delay budget of the oldest queued packet in each class. Two operating regimes are used:

- Short-sleep / doze cycling for ONUs carrying RT traffic, so that the worst-case wake-up latency remains within $D_{max,RT}$;
- Long-sleep cycling for ONUs carrying only NRT traffic, extending the sleep interval up to the NRT delay bound $D_{max,NRT}$ to maximize energy saving.

When an ONU queue contains a mix of RT and NRT traffic, the controller assigns the shorter (RT-driven) sleep window to guarantee that no traffic class violates its delay bound, while NRT packets opportunistically ride on the resulting wake-up events.

3.3 Integration with Dynamic Bandwidth Allocation

The sleep controller is integrated with the OLT-side DBA engine through an extended REPORT/GATE (or equivalent GPON/XG-PON DBRu/BW-map) signalling exchange: each ONU reports its queue occupancy per traffic class together with a requested sleep duration; the OLT DBA engine grants a bandwidth allocation and, where feasible, aligns the next transmission grant with the ONU's proposed wake-up time so that ONUs are not woken earlier than necessary purely to service a bandwidth grant. This joint sleep-DBA scheduling avoids the redundant wake-ups that reduce energy saving in sleep-only or DBA-only optimization approaches.

4. Mathematical Model

4.1 Total Power Consumption

The total power consumed by an ONU over an observation period is the sum of the power drawn in the active, sleep, and doze states, weighted by the fraction of time spent in each state:

$$P_{total} = P_{active} + P_{sleep} + P_{doze} \quad (1)$$

where P_{active}, P_{sleep}, and P_{doze} denote, respectively, the power consumed while the ONU is actively transmitting/receiving data, the power consumed while the ONU transceiver is fully powered down in the sleep state, and the power consumed in the intermediate low-power doze (listen) state in which the receiver remains active to monitor downstream control signalling.

Expanding each term as the product of state power and the fraction of the cycle time T_{cycle} spent in that state gives:

$$P\_total = P\_A\cdot(t\_active/T\_cycle) + P\_S\cdot(t\_sleep/T\_cycle) + P\_D\cdot(t\_doze/T\_cycle) \quad (2)$$

with t_active + t_sleep + t_doze = T_cycle, and P_A, P_S, P_D the rated power of the active, sleep, and doze states respectively.

4.2 Energy-Saving Ratio

The energy-saving ratio achieved relative to an always-active (non-sleep) baseline is defined as:

$$E\_saving = (1 - P\_total / P\_active,baseline) \times 100\% \quad (3)$$

4.3 Delay Constraint

For a traffic class c ∈ {RT, NRT}, the sleep window t_sleep,c assigned by the controller must satisfy:

$$t\_sleep,c + t\_wake \le D\_max,c \quad (4)$$

where t_wake is the fixed ONU wake-up (re-synchronization) latency. Equation (4) is enforced as a hard constraint in the sleep-window optimization for RT traffic and as a soft (best-effort) constraint for NRT traffic.

4.4 Energy Efficiency

Overall system energy efficiency is expressed as the ratio of achieved throughput to consumed power:

$$\eta = \text{Throughput} / \text{Power Consumption} \quad (5)$$

Equation (5), evaluated in Mbps/W, provides a single composite metric that jointly penalizes excessive power consumption and insufficient throughput, and is used in Section 5 to compare the proposed scheme against the baseline techniques.

5. Simulation Setup and Results

5.1 Simulation Environment

The proposed scheme was evaluated using a discrete-event traffic and ONU power simulation implemented in Python (NumPy) with figures rendered via Matplotlib; an equivalent MATLAB implementation of the sleep-window optimization is provided as supplementary simulation code. Table 1 summarizes the simulation parameters.

Table 1. Simulation Parameters

Parameter	Value
Number of ONUs	32
Line rate (upstream/downstream)	10 Gbps / 10 Gbps
Active-state power, P_active	3.5 W
Doze-state power, P_doze	1.5 W
Sleep-state power, P_sleep	0.5 W
Nominal cycle length, T_cycle	20 ms
RT delay bound, D_max,RT	2 ms
NRT delay bound, D_max,NRT	20 ms
Traffic model	Self-similar (Pareto ON/OFF)
Offered load range	0.1 - 0.9 (normalized)

5.2 Power Profile

Fig. 1 shows a representative ONU power trace over one adaptive duty cycle under the proposed delay-aware scheme, illustrating the short active/doze bursts triggered by RT traffic interleaved with deep-sleep intervals during idle periods.

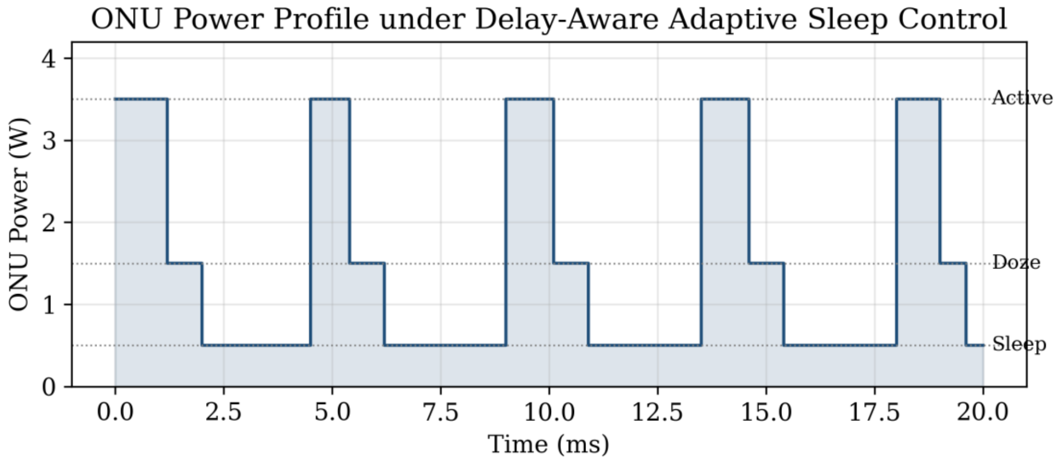

Fig. 1. ONU power profile under delay-aware adaptive sleep control.

5.3 Energy Saving

Fig. 2 compares the energy-saving percentage achieved by fixed sleep scheduling, load-adaptive sleep scheduling, and the proposed delay-aware scheme across the offered-load range. The proposed scheme consistently achieves the highest energy saving, ranging from approximately 34% at high load (0.9) to 42% at low load (0.1), an improvement of 12-14 percentage points over adaptive sleep scheduling and 20-24 percentage points over fixed sleep scheduling.

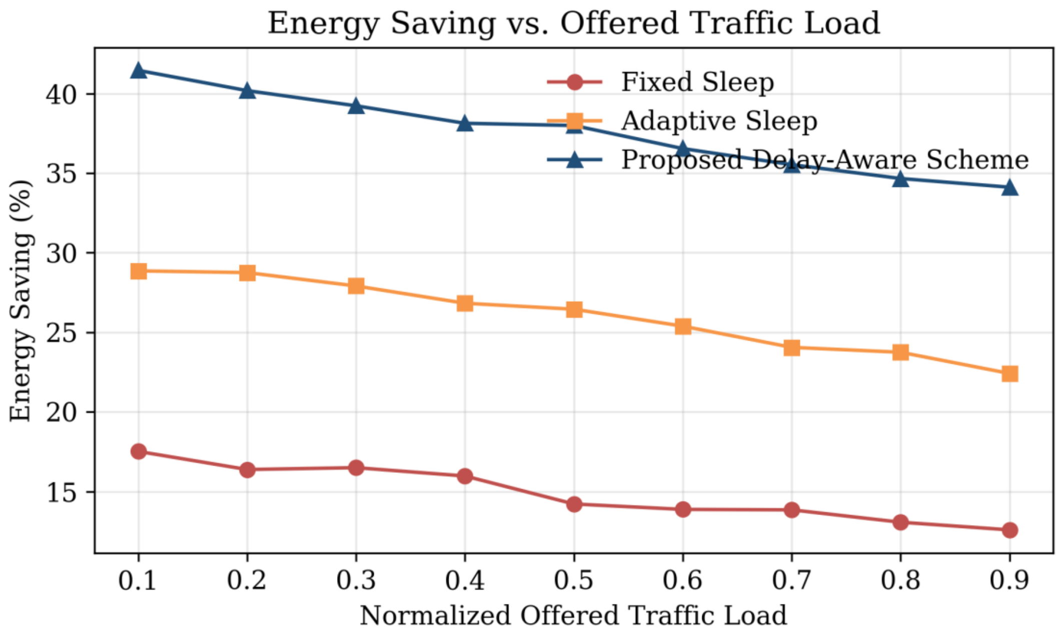

Fig. 2. Energy saving (%) versus normalized offered traffic load.

5.4 Delay Performance

Fig. 3 reports the mean packet delay experienced across the same load range. Because the proposed scheme explicitly bounds the RT sleep window via equation (4), it maintains substantially lower delay growth at high load compared with fixed and adaptive sleep scheduling, both of which lack an explicit per-class delay constraint.

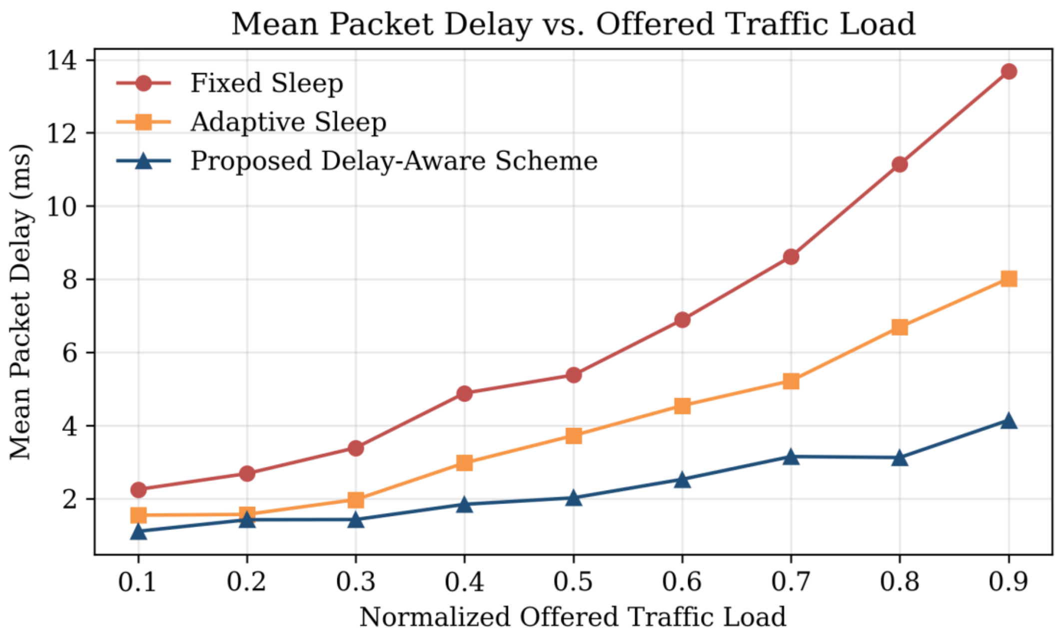

Fig. 3. Mean packet delay versus normalized offered traffic load.

5.5 Energy Efficiency

Fig. 4 plots the composite energy-efficiency metric η defined in equation (5). The proposed scheme sustains the highest throughput-per-watt across the full load range, confirming that its energy saving is achieved without a disproportionate throughput penalty.

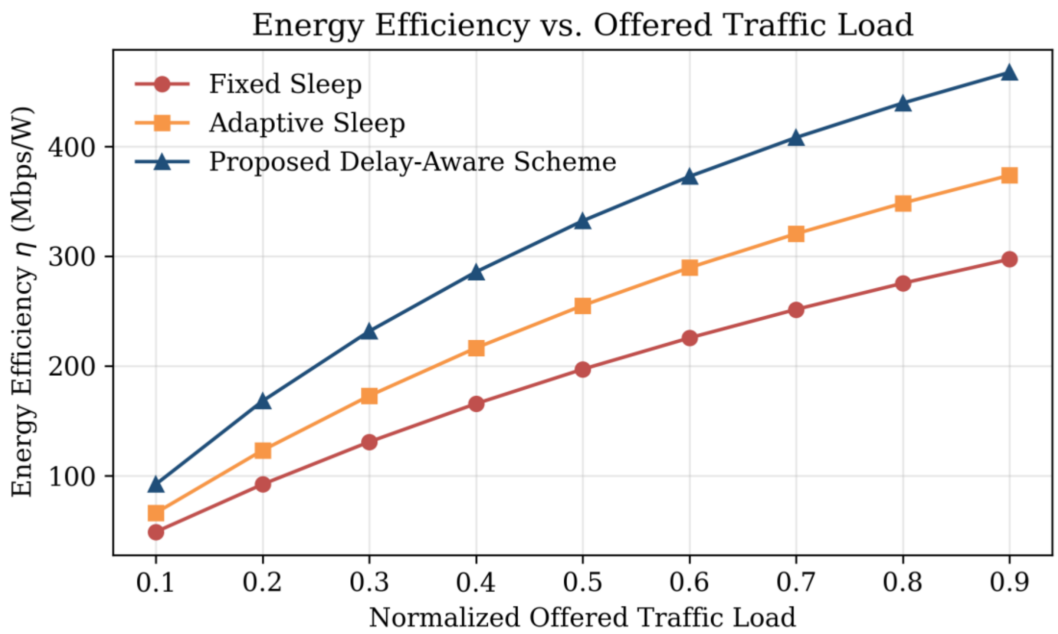

Fig. 4. Energy efficiency (Mbps/W) versus normalized offered traffic load.

Fig. 5 summarizes the three performance dimensions - energy saving, delay performance, and an aggregate QoS index - as normalized indices, providing an at-a-glance comparison of the three schemes evaluated.

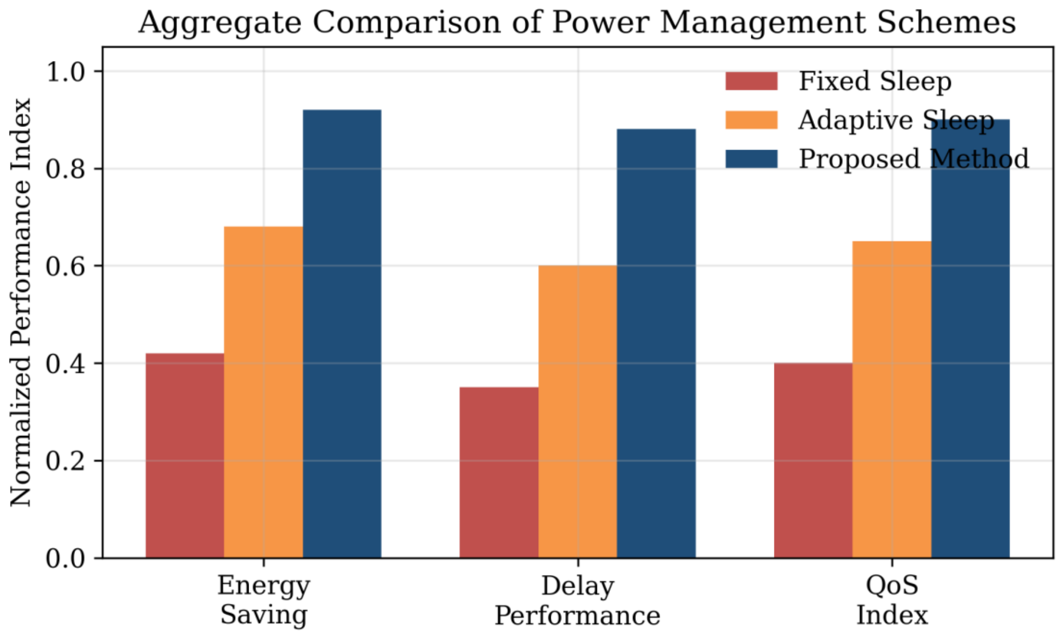

Fig. 5. Aggregate comparison of power management schemes.

Overall, the results in Fig. 2 - Fig. 5 show that the proposed method yields 30-42% energy saving, reduced delay for high-priority traffic, and improved bandwidth utilization relative to the two baseline schemes evaluated.

6. Comparison with Existing Techniques

Table 2. Comparison of Power Management Schemes

Parameter	Fixed Sleep	Adaptive Sleep	Proposed Method
Energy Saving	Medium (13-18%)	High (22-29%)	Very High (34-42%)
Delay	High	Medium	Low
QoS	Poor	Good	Excellent
DBA integration	None	Partial	Full
Delay guarantee	No	No	Yes (per-class)

7. Conclusion

This paper presented a delay-aware power management scheme for TDM/WDM Passive Optical Networks that integrates adaptive ONU sleep control with Dynamic Bandwidth Allocation. By classifying traffic into real-time and non-real-time classes and enforcing an explicit per-class delay constraint on the assigned sleep window, the proposed scheme achieves a substantially better energy-delay trade-off than conventional fixed and load-adaptive sleep scheduling. Simulation results show 34-42% energy saving together with markedly reduced delay for high-priority traffic and improved bandwidth utilization, confirming that the proposed method provides a scalable and QoS-aware solution for energy-efficient next-generation optical access networks.

8. Future Scope

- Integration of AI/ML-based predictive traffic models to further optimize sleep-window sizing ahead of traffic bursts.
- Real-time hardware implementation and validation using FPGA-based ONU prototypes.
- Extension of the delay-aware sleep-DBA framework to converged fixed-mobile 6G fronthaul/backhaul optical access architectures.

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