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A Loading-Aware TDMA Sleep Scheme to Improve Power Consumption Performance on Medium to High Traffic for NG-EPON Networks

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Abstract: The inter-cycle sleep design previously proposed as a power-saving scheme for next-generation Ethernet passive optical networks (NG-EPONs) is able to effectively decrease the power consumption of heavy-load traffic. However, with a medium to high traffic load, these networks may still suffer from a high level of power consumption if no enhanced mechanisms are used. It was noted that the optical line terminal (OLT) often fully opens all communication channels at a medium to heavy load. Moreover, the number of opened channels was changed cyclically according to the traffic loading status. Accordingly, optical network units (ONUs) may be frequently allocated to different channels with changing loads. This may lead to inefficient operation and result in significant channel tuning delays. We thus propose a loading-aware time-division multiple access (TDMA) mechanism that allows the OLT to reserve a maximum bandwidth for each ONU when the network experiences heavy-load traffic. The performance results of our simulations reveal that the proposed scheme is able to reduce power consumption for targeted medium to high loads since ONUs under such loads can extend their sleep time because the cycle length is maximized. Moreover, the total delay is maintained at a relatively low level after applying the proposed scheme since the tuning delay is reduced significantly; however, the transmission delay is slightly increased due to the increased cycle length.

Keywords: TDMA; sleep mode; traffic load; power consumption; NG-EPON

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1. Introduction

An NG-EPON is an optical telecommunication technology that delivers packets between optical network units (ONUs) and an optical line terminal (OLT). The OLT consists of one-to-many optical subscriber units (OSUs) and connects to a core switch at a central office. It transmits packets and coordinates ONUs whose traffic is multiplexed for the shared upstream channel. The multi-point control protocol (MPCP) contains many handshaking messages for the transmission mechanism between the OLT and the ONUs to allow for efficient data transmission in the upstream channel via GATE and REPORT messages that grant and request bandwidth.

In recent years, various schemes [1–5] have been proposed to improve the network performance of NG-EPONs. The research in [6] tried to analyze the cost of ONUs and the transmission performance of a wavelength scheme in NG-EPONs. The applications [7–11] of 5G technology and beyond in NG-EPONs have grown rapidly, as NG-EPONs have huge bandwidth requirements. On the other hand, many research projects have tried to reduce the power consumption of the active components in passive optical networks while providing high-speed transmission and a huge amount of bandwidth. The main active components that consume the major share of power are the ONUs and the optical subscriber units (OSUs) located at the OLT. Therefore, a reduction in total power consumption should include both types of components.

Chen et al. [4] proposed a deep reinforcement learning-based policy for power-efficient dynamic subcarrier assignment in orthogonal frequency division multiple access (OFDMA) PONs by jointly considering both delay and transmission power. Latif et al. [12] studied the quality of service and energy-saving performance in a network combining a PON and a wireless network, i.e., a fiber-wireless (FiWi) access network, with sleep-mode-enabled ONUs. Alharthi et al. [13] used a software-defined networking (SDN) controller for routing and resource assignment on two-tier cascaded arrayed waveguide grating routers (AWGRs) to connect groups of racks, i.e., cells, within a data center. Their approach improved routing and load balancing between any two cells and significantly reduced power consumption compared with a fat-tree data center architecture.

Mohammed et al. [14] investigated the influence of gratuitous grants that periodically scheduled sleep for ONUs, thus switching them to another energy mode. They developed a method for setting both the gratuitous grant interval and the size at levels that decreased the total upstream grant time and improved power efficiency in time-division multiplexing (TDM) PONs. Alqahtani et al. [15] utilized the connectivity of a PON to connect multiple distributed fog units for the purpose of cooperative computing. In their work, they adopted mixed-integer linear programming (MILP) to optimize virtual machine placement in order to meet intensive demand and reduce power consumption. Alenazi et al. [16] presented a framework of an energy-efficient neural network service for smart homes that was embedded in Internet of Things (IoT) devices over PONs. They utilized MILP to formulate the embedding problem that minimized the total power consumption of both networking and processing. Zhu et al. [17] presented a solution for dynamic subcarrier allocation based on deep reinforcement learning in OFDMA PONs. The scheme designed a reward function and considered the allocated time slot, subcarriers, and modulation formats so that the ONUs could significantly reduce transmission power via a lower-order modulation format while still meeting delay requirements.

Thus, the goal of reducing power consumption still needs to be addressed while providing high-speed transmission in PONs. A previous cycle-based energy-saving scheme [18] utilized the idle time between cycles to allow ONUs to sleep in order to reduce power consumption. However, that method, inter-cycle sleep, imposes a rigid restriction rule for ONUs entering inter-cycle sleep mode: it requires an ONU's request size to exceed a certain level. Therefore, it has been observed that for many scenarios, ONUs cannot enter the inter-cycle sleep mode to save power.

It was noted that our previous study, which utilized the maximum transmission window (MTW) [19] rule in an MPCP with OLT scheduling to allow ONUs to enter inter-cycle sleep mode, was only suitable for high-load traffic. The power consumption of medium to high traffic still hovers at a higher level because the design of such a scheme can only be triggered during high-load traffic. Moreover, the previous study did not consider the efficiency of OSU channel usage; as a result, the OLT might open a channel to transmit only a few packets, resulting in inefficiency and wasted OSU power.

In this study, we propose a loading-aware time-division multiple access (TDMA) power-saving scheme that extends the sleep duration for ONUs under medium to high traffic loads and reduces the number of activated OSUs for inefficient channels. We aimed to improve the power-saving performance of medium- to high-load traffic compared with our previous scheme. In addition, in order to simultaneously reduce the power consumption of OSUs, this study considers the balance of channel usage to reduce the idle channel issue. The proposed scheme can reduce ONU and OSU power consumption. The main contribution of this work is that it keeps packet delays at a low level for high-priority packets while saving power.

A power-saving framework was adopted in this study, and the article is organized as follows. Related works on reducing unnecessary power consumption, particularly under high-load traffic, are described in Section 2. In Section 3, the proposed TDMA-based scheme is introduced. In Section 4, the simulation results of applying the proposed scheme for different downstream traffic patterns are evaluated. Finally, the study is concluded in Section 5.

2. Related Works

A tri-mode energy-saving scheme [20] was adopted in this work to save energy. It switches modes among active, doze, and sleep modes inside the ONU according to the transmission needs. In active mode, the ONU will turn on both the transmitter and receiver for upstream and downstream transmission. When only downstream traffic exists, the ONU turns on its receiver and goes into doze mode. ONU switches to sleep mode if it does not have any transmission either upstream or downstream. When any high-priority packets arrive during sleep mode, the ONU will trigger an early wake-up scheme. Therefore, all high-priority packets can be delivered soon, even with sleeping ONUs.

Hu et al. proposed a hybrid energy-saving scheme [21] by utilizing an idle slot in each scheduling cycle to perform an intra-cycle sleep under heavy-load traffic without delaying data transmission. In light-load traffic, ONUs perform a long sleep for several scheduling cycles. However, since the design did not consider the requirements of high-priority packets, the delay of such packets will be large under a light load. Moreover, only two energy modes, active and sleep, were taken into account in the design, which is different from the previous tri-mode scheme.

Based on the tri-mode energy-saving scheme, another cycle-based energy-saving scheme [18] explored the idle duration under heavy-load traffic to save energy. Due to the nature of the polling-based EPON network, the OLT has to serve the ONUs one by one. The ONUs currently not being served will be in the idle state. The scheme commands those ONUs in the idle period to go into intra-cycle sleep mode and sleep until the end of each scheduling cycle if its request size is less than 2 MTWs.

Furthermore, the scheme acknowledges that ONUs under heavy-load traffic usually request a large bandwidth. If the request size reaches double the MTWs, the OLT will reserve a corresponding bandwidth size of one MTW per cycle on next two consecutive cycles. The OLT then transfers the MTW limitation to certainty scheduling. That is, OLT knows the time slot location for each heavy-load ONU from the current cycle to the next cycle. Therefore, the idle ONUs can execute the action of an inter-cycle sleep for saving more power.

Another scheme [22] reduces the threshold of ONUs for entering inter-cycle sleep. It allows the system operators to define an inter-cycle sleep threshold as less than 2 MTWs but greater than 1 MTW (denoted herein as 1.x MTW mode). This approach provides ONUs with more opportunities to enter inter-cycle sleep mode. Therefore, the number of ONUs switching to inter-cycle sleep mode is increased because ONUs requiring only a smaller request size switch into this mode. In this work, an ONU request size of greater than 1 MTW is enough. Therefore, more ONUs are allowed to switch to inter-cycle sleep mode to save power. However, this improvement in inter-cycle sleep is not enough and the system still suffers from high power consumption under medium- to high-load traffic.

With the multiple channels in NG-EPON networks, the packets of ONUs are assigned and transmitted to different channels frequently for medium to high traffic. The packets are switched from one channel to another, which could involve many tuning delays in such a network. Moreover, it is not easy to save power for ONU transmissions under medium to high loading. Therefore, it is a challenge to design a scheme to suppress tunning delays and save power at the same time.

3. Proposed Scheme

We aimed to improve power savings in both ONUs and OLT devices while maintaining satisfactory delay performance. This study consists of the following aspects: Part A: Advanced activation of TDMA mode under heavy-load traffic; Part B: Reducing the number of inefficient opened OSUs.

3.1. Activating TDMA Mode under Heavy-Load Traffic

One observed phenomenon that occurs under heavy-load traffic is that all channels need to be opened simultaneously. Moreover, ONUs have a higher probability of requesting a near-maximum request size, i.e., MTW, even though the requested size may be different. Moreover, in a multi-channel network, an ONU could be assigned to a different channel and switch from one channel to another, which involves many tuning delays. In addition, under heavy-load traffic, there is no chance to save OSU power, since all channels are opened.

Therefore, it is possible to simplify the request/grant process and reduce tuning delays in such a heavy-load network if the OLT allocates each ONU a fixed size of MTW in terms of the time-division multiple access (TDMA) allocation mechanism. Moreover, turning the network via the TDMA mode extends the ONU power saving effect because the cycle length becomes the maximum size that allows an ONU to sleep longer after the ONU finishes its transmission.

To accomplish this, whenever the traffic load goes beyond a certain threshold, the OLT allocates each ONU a time period equal to the size of MTW, no matter what size ONU actually requests. For instance, in Channel 1 of a NG-EPON four-channel network, the request sizes of ONU2 and ONU3 are 0.7 and 0.9 MTW, respectively. The OLT will grant both ONU2 and ONU3 the size of 1 MTW if the threshold of the advance TDMA mode for ONUs is set at 0.7 MTW. All time slots, in units of MTW, are then arranged in a specified sequence, for example, in accordance with the ONU's ID sequence, after scheduling the channel assignment phase, as shown in Figure 1.

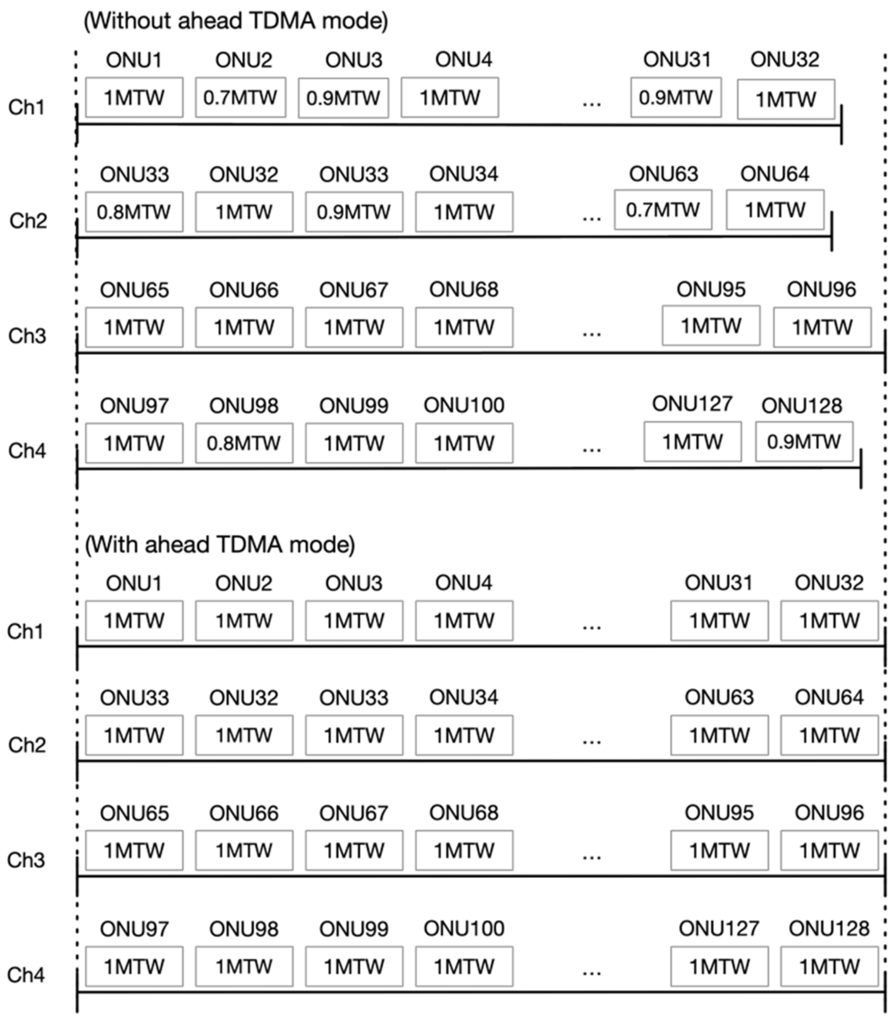

Figure 1. All ONUs are granted the size of 1 MTW in advance and afterwards.

Note that in the scenario without advance TDMA mode, the ONU with the largest request size will be allocated first to the front of each channel for easily saving channel space and scheduling an inter-cycle sleep so that the ONU can sleep from the current cycle to next cycle, as in [18]. Therefore, the channel allocated to each ONU could be changed from cycle to cycle according to its request size.

The turning delay in terms of delay performance can be reduced because the number of switching channels is reduced since each ONU will be allocated a fixed time slot for each fixed channel in the proposed scheme. Moreover, the sleep length of the ONUs can be increased because the total cycle length is also extended to the maximum length. However, the idle time will be slightly increased by giving an extra bandwidth for a few cases under heavy-load traffic.

Usually, the OLT grants the size according to ONU's request size but with an upper limitation on the size of MTW. On the contrary, in this proposed work, when the traffic load reaches a certain high level but the request size of each ONU is less than the size of MTW, the OLT automatically grants each ONU the full size of MTW. Under medium- to high-load traffic, granting a fixed MTW size for each ONU results in allocating ONUs a fixed time slot in channel assignment phase; if the ID sequence of the ONUs is adopted for assignment, this reduces the tuning delay of the ONUs. In addition, giving the full MTW size for each ONUs also extends the cycle time for the system. Therefore, ONUs in an idle period within a long cycle period can sleep longer to save power.

3.2. Saving Inefficient Channels

Since the total power consumption includes ONUs and OSUs in an EPON system, any newly opened channel powered by the OSUs at the OLT will also increase the total power consumption. Moreover, opening a new channel for only a few packets is inefficient.

To avoid such inefficiency, the first step is to calculate the total number of channels needed and measure the rate of channel usage. The channel usage rate is measured per cycle and per channel. Moreover, in this work, for the channel assignment phase, a new channel is considered to be opened for incoming requests of ONUs whenever no channel is opened or if all opened channels are full. For the second step, if the usage rate for a channel is lower than a defined value, the OLT rejects opening a new channel for requests from ONUs. These requests will be distributed evenly among all already open channel(s).

For instance, in a network with two open channels, if the system sets the threshold of channel usage rate to be 50%, the system can open a third channel until the total request bandwidth in bps is greater than or equal to that threshold for the new channel. Otherwise, all requests will be scheduled and allocated evenly after the end of the originally opened two channel(s). For example, if the measured usage rate of opening a new channel is 20% according to ONU's request size for channel Ch3, this is less than the threshold setting of 50%. These requests are then allocated as evenly as possible to the end of channels Ch1 and Ch2, each with a size of 10%, as shown in Figure 2. It is possible that the request size cannot be divided evenly if the number of packets or the packet size is an odd number.

The packets not scheduled for a new channel will be scheduled at the end of the previously opened channel(s), i.e., Ch1 and Ch2. Therefore, the total length of the previously opened channel(s) will be longer. This implies that the average packet delay for ONUs could be slightly increased.

Usually, the OLT will open a new channel to deliver any number of packets whenever no channel is open or if all the existing channels are full. By considering the power consumption of OSUs on the OLT side, we set the open-channel threshold so that an OSU would not be activated for only a small number of packets to reduce the issue of inefficient channel usage.

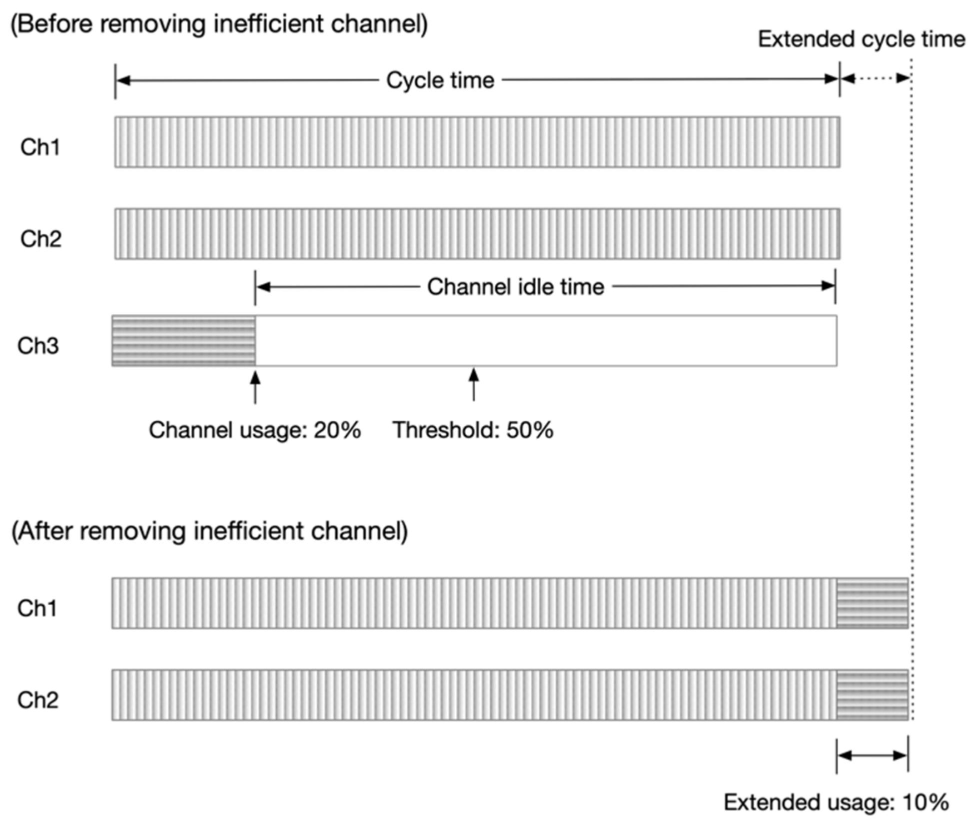

Figure 2. Cases of idle channels.

4. Simulation Results

The simulation was conducted by the Objective Modular Network Testbed in C++ (OMNet++). There were four channels in the simulation network. Each channel had a capacity of 25 Gbps in both the upstream and downstream directions and was equipped with one OSU located at the OLT for serving ONUs in the respective channel. The upstream loading was fixed at 12.8 Gbps and the downstream loading varied from 16 to 96 Gbps.

Total power consumption considered in this measurement included consumption by both ONUs and the OLT. The measurements of power consumption for ONUs in active, doze, and sleep modes are described in earlier studies [23–25]. Since each study has its own circuit design, the power consumption even in the same modes is different. However, the consumption values of the different modes, ranked from low to high, are in the order sleep, doze, and active. We adopted relative consumption proportions of 30% for doze to active and 10% for sleep to active rather than absolute consumed power in watts.

According to another study [26], the transceiver of the OLT and an active ONU consumes 11 and 3.98 W, respectively. If the power consumption of one ONU in active mode is normalized as 100%, the relative power consumption of one OLT transceiver is then calculated as 276%. Moreover, the total power consumption, P_{total}, jointly considering the OLT and ONUs, can be expressed as follows:

$$P_{total} = \frac{T_aP_a + T_dP_d + T_sP_s + T_1P_1 + T_2P_2 + T_3P_3 + T_4P_4}{(T_a + T_d + T_s)P_a + (T_1 + T_2 + T_3 + T_4)P_4}$$

where T_a, T_d, and T_s denote the total time length in the active, doze, and sleep modes, respectively; P_a, P_d, and P_s denote the power consumption ratio for ONUs in active, doze, and sleep modes, respectively. In a four-channel network for T_i, i = 1, 2, 3 and 4, i denotes the number of opened channels and T_i denotes the total time length of i channel(s). For P_i, i = 1, 2, 3 and 4, i indicates that the OLT opens i channel(s) and P_i indicates the power consumption ratio of the OLT for opening i channel(s).

Aside from power consumption, the total delay parameters considered in this work include switching delays, tuning delays, and transmission delays. The time required for an ONU to wake up is the switching delay. The tuning time required for an ONU to switch from one channel to another is 10 µs, and the switching overhead for an ONU waking up from sleep to active or doze mode is 125 µs. All the relevant parameters are listed in Table 1.

Table 1. Simulation parameters.

Parameters	Value
Number of ONUs	128
Total number of channels	4
Downstream capacity of a channel	25 Gbps
Upstream capacity of a channel	25 Gbps
OLT-to-ONU distances	20 km
Traffic pattern	Self-similar
Frame size	64 bytes~1518 bytes
Maximum ONU queue size	100 Mbytes
Time length of a transmission cycle	2 ms
Maximum transmission window (MTW)	195,000 bytes
Simulation time	10 s
Bandwidth allocation	IPACT Limited Service
Timer for ONU sleeping time	20 ms
Tuning time	10 µs
Sleep mode switching overhead	125 µs
High priority ratio	20%
Max loading per ONU	1 Gbps

The power consumption and delay performance evaluated in this section include Scheme 1: Advance activation of TDMA mode; Scheme 2: Saving channels; and Scheme 3: Combined advance activation of TDMA mode and saving channels. The study of [22] was set as our benchmark scheme in the simulation.

4.1. Impact of Advance Activation of TDMA Mode

In this subsection, the threshold of inter-cycle sleep mode in [22] was set as a size of 1.1 MTW. The trigger condition for ONUs entering TDMA mode was whenever the total traffic measured at each cycle needed to open the last (fourth) channel. Since the average bandwidth requirement for ONUs under such circumstances could be at a higher level, this scheme allowed the OLT to turn on TDMA mode in advance, which would open all four channels, allocating each ONU a bandwidth with a size of MTW no matter what size each ONU requests. In contrast, the no-TDMA mode means that the OLT allocates only the bandwidth size that ONU requests and no extra bandwidth will be allocated for the ONUs.

Figure 3 shows a comparison of the ONUs' power consumption for OLTs with and without activation of TDMA mode. The consumption falls at a downstream loading 64 of Gbps because such a load could require three to four channels to deliver all the packets, thus activating TDMA mode in this scenario. The power consumption reduced since all ONUs in this mode could sleep longer because the cycle time had been maximized.

As shown in Figure 4, enabling TDMA mode reduces downstream high-priority packet delay because each ONU is given a time slot with the maximum size, i.e., 1 MTW, which results in the number of required channels changing from being three or four at random to being fixed at four, especially under a loading of 64 Gbps. This makes the ONUs transmit packets in fixed channels, which reduces the amount of tuning channel delay. Figure 5 shows that downstream low-priority packet delay increases with increased downstream loading when all channels are full.

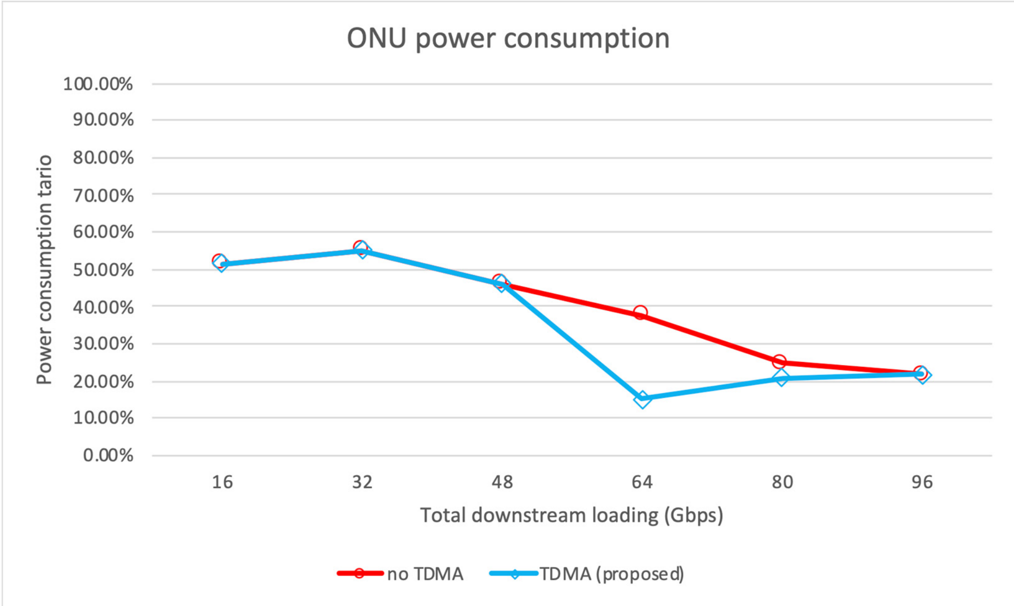

Figure 3. Comparison of ONU power consumption for OLTs with/without TDMA mode under a fixed upstream load.

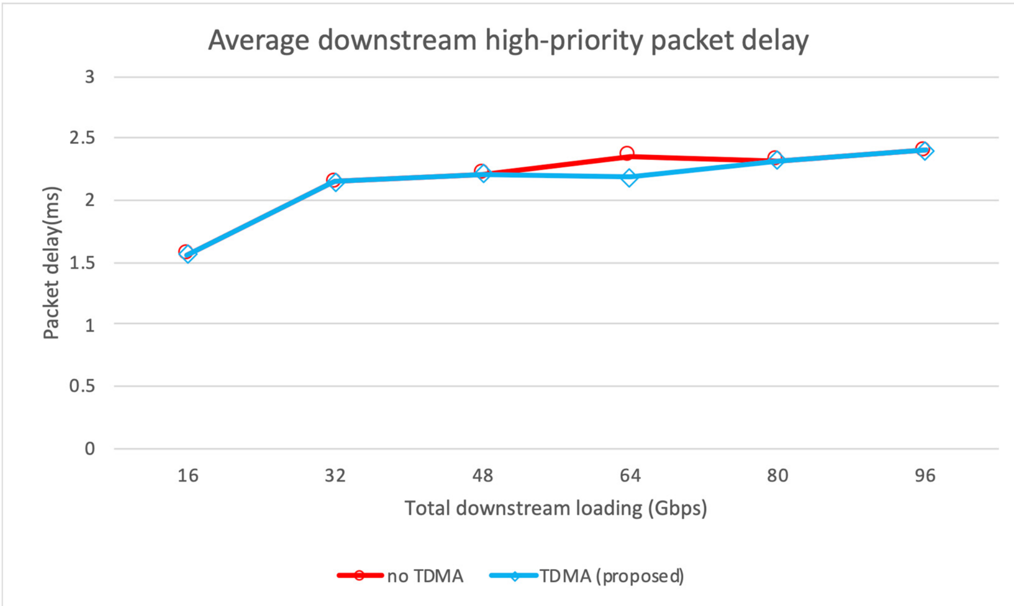

Figure 4. Comparison of average downstream high-priority packet delay with/without TDMA mode under a fixed upstream load.

For both high- and low-priority upstream packets, the packet delays had a reasonably low value due to the fixed small upstream traffic. Moreover, this delay in TDMA mode was lower, since all ONUs could keep the same specific channels with a fixed channel assignment algorithm, as shown in Figures 6 and 7. No tuning delay was involved.

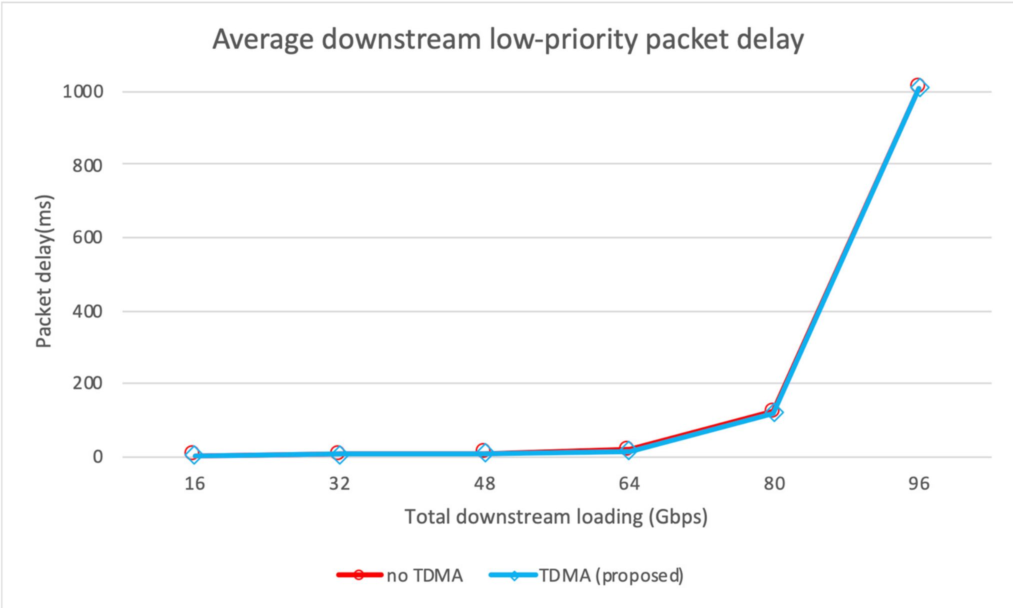

Figure 5. Comparison of average downstream low-priority packet delay with/without TDMA mode under a fixed upstream load.

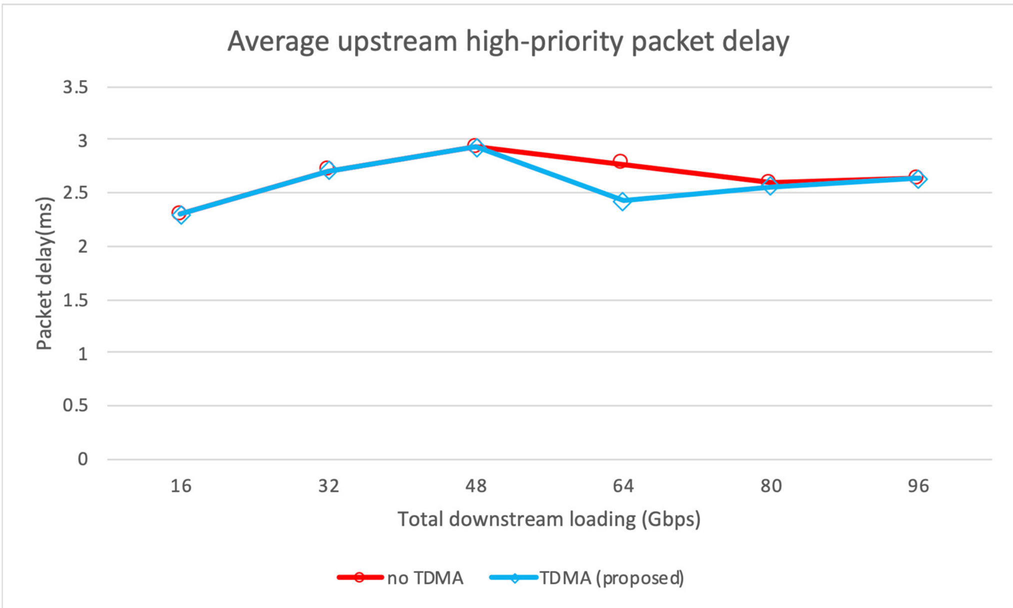

Figure 6. Comparison of average upstream high-priority packet delay with/without TDMA mode under a fixed upstream load.

4.2. Impact of Saving Channels

Opening a channel for only a few of packets is inefficient in terms of transmission and wastes the power of OSU(s). In this subsection, the total power consumption of both OSUs and ONUs are evaluated, adopting the proposed method of saving inefficient opened OSU(s).

The total power consumption ratio can be reduced significantly by increasing the threshold for opening a new channel, as shown in Figure 8. This is because the calculation of total power consumption includes the consumption of both the OLT and the ONUs. Moreover, the consumption of OSUs located at the OLT makes up the largest proportion of the total.

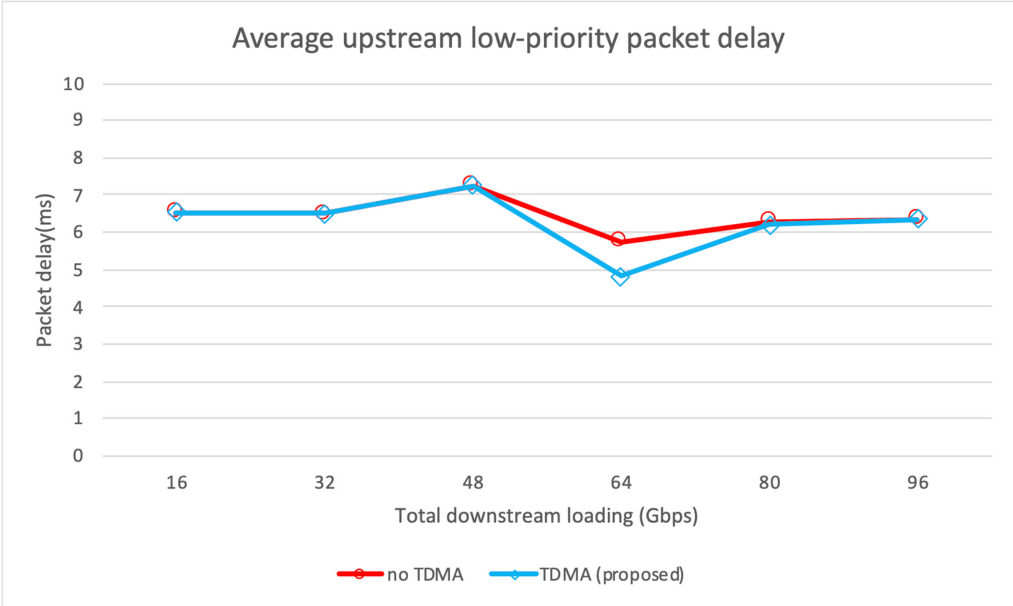

Figure 7. Comparison of average upstream low-priority packet delay with/without TDMA mode under a fixed upstream load.

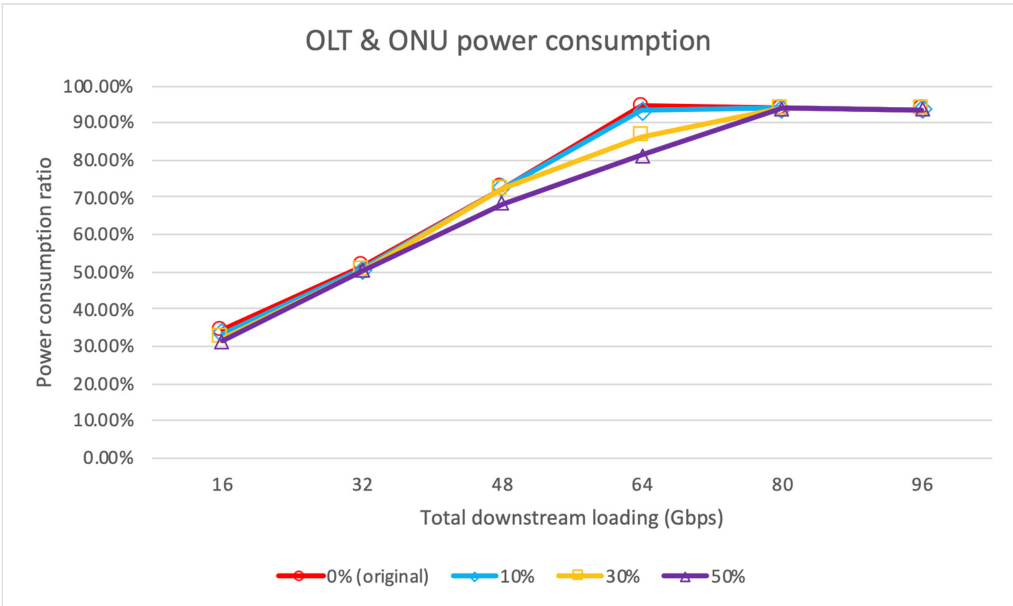

Figure 8. Comparison of the total power consumption for different thresholds of opening a new channel under a fixed upstream load.

The high-priority packet delay in the downstream channel for various thresholds was maintained at a fairly low level, as shown in Figure 9. This means that the proposed method of saving channel usage will not involve too much delay while saving power. The delay with the saving channel threshold set at 50% while the downstream loading was at 16 Gbps had a higher value compared with other, lower thresholds. Moreover, the difference in the delay under this loading will be larger, since the number of service channels reduces from two channels to one under low downstream loading. The packets are originally assigned to two channels that will be added back to the end of the one remaining channel. Thus, it is more obvious that the total cycle time will be longer than the others, which is reflected in the delay performance.

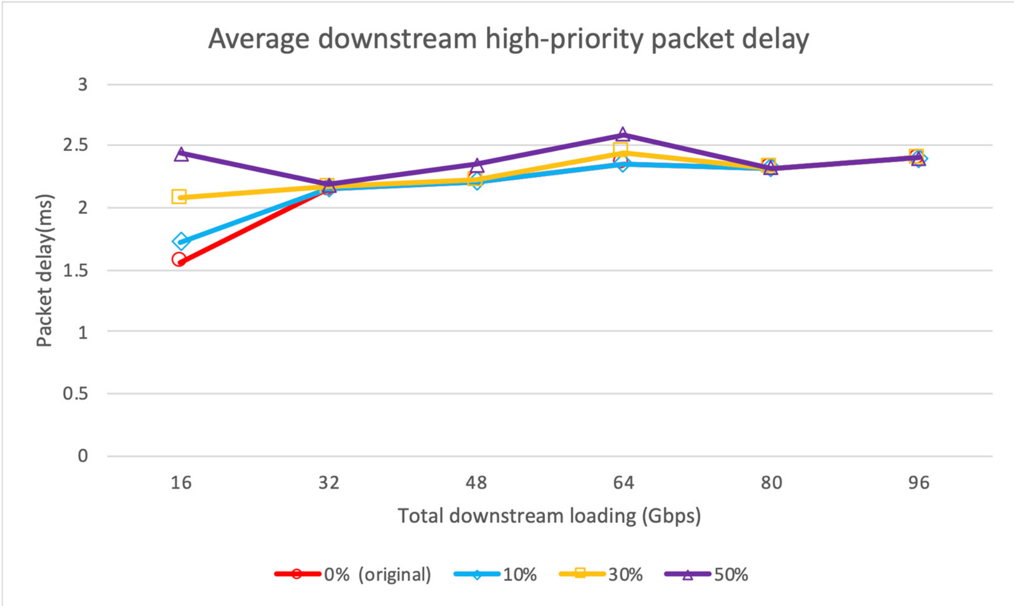

Figure 9. Comparison of the average downstream high-priority packet delay for different thresholds of opening a new channel under a fixed upstream load.

There is no great difference in low-priority packet delay in downstream channels under different channel-saving thresholds, i.e., 0% (original), 30%, and 50%. All delays increased with an increase in the downstream load. This increasing trend is the same as shown in Figure 5.

All the upstream high-priority packet delays for all thresholds remained at a relatively low level. However, at a downstream loading of 16 Gbps, only one channel needed to be opened, with a capacity of 25 Gbps for that channel. A setting with a higher channel threshold has to accumulate more packets to open the first channel for delivering the packets. Therefore, the highest channel threshold has the highest delay, as shown in Figure 10.

Figure 11 shows a comparison of the upstream low-priority packet delay for different thresholds of opening a new channel. In contrast to high-priority packet delay, the low-priority packets have a greater delay, but it is still relatively small because the upstream channel is not full. The reason why the highest channel threshold has the highest delay is the same as in the case shown in Figure 10.

4.3. Impact of Mixing Channel-Saving and Advance Activation of TDMA Mode

In this subsection, the effects on delay and power consumption are evaluated for a combination of saving channels and advance activation of TDMA mode. The activation of TDMA mode will be triggered when the traffic load is large enough and requires the fourth channel to be opened for processing the traffic. In this mode, all ONUs are given the maximum bandwidth MTW for delivering packets, no matter what size they request. In this comparison, saving channels means that the OLT opens a new channel when the traffic size reaches at least half of a channel. The label ch50 represents this condition. The label ch50+TDMA represents the mixed method with both ch50 and TDMA.

The ch50 method is used to reduce the number of open channels in each cycle to save the power of the OSU. This is different from the TDMA method of extending the sleep length of ONUs. Therefore, as shown in Figure 12, all methods, including advance activation of TDMA mode, can save more power in ONUs, especially under medium to high loads.

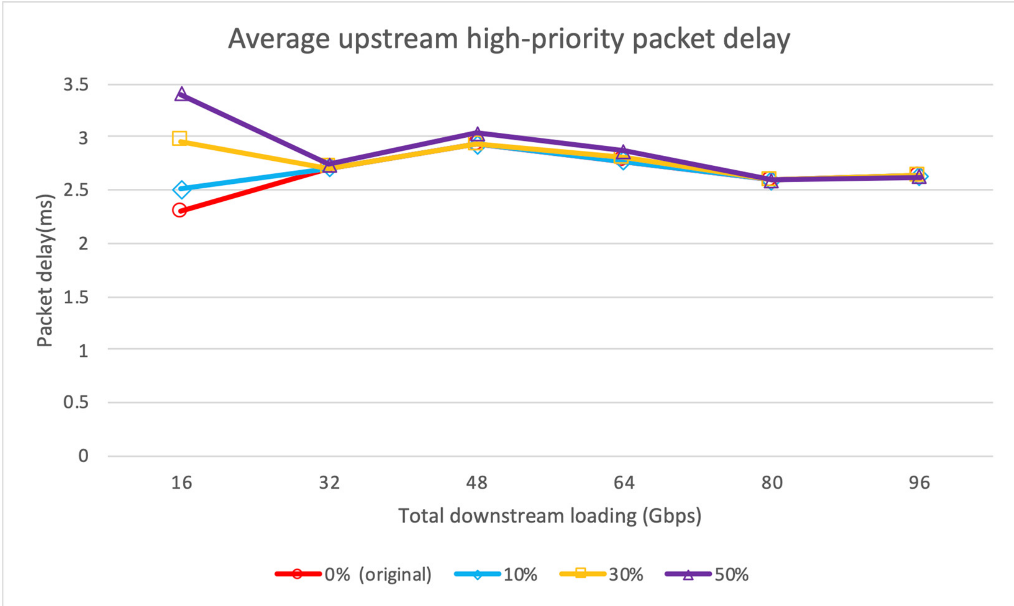

Figure 10. Comparison of the average upstream high-priority packet delay for different thresholds of opening a new channel under a fixed upstream load.

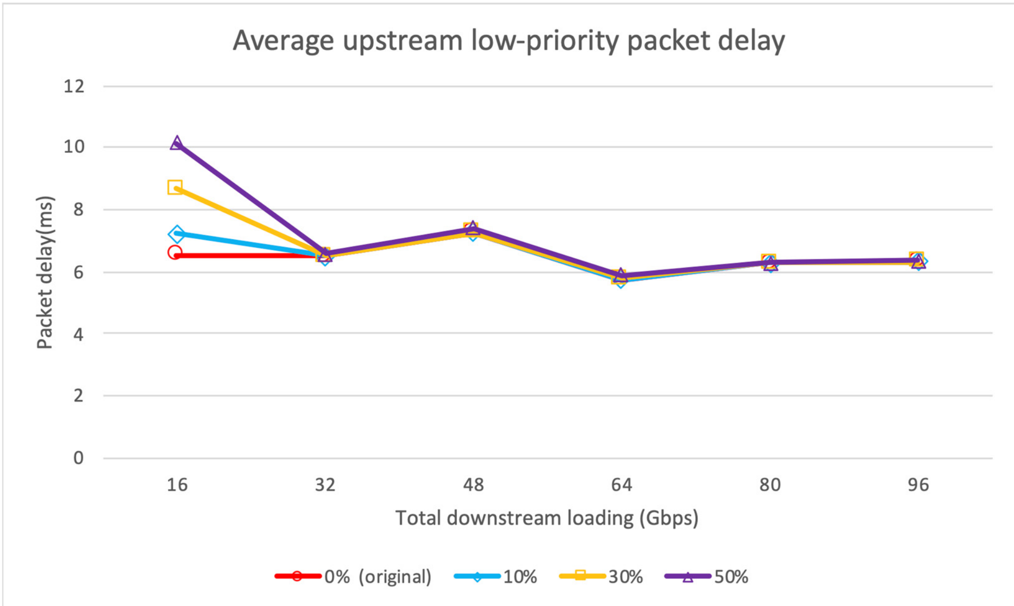

Figure 11. Comparison of the average upstream low-priority packet delay for different thresholds of opening a new channel under a fixed upstream load.

In comparison with the TDMA method, the mixed method, i.e., ch50+TDMA, achieved lower total power consumption under a low to medium load due to the effects of decreasing the number of opened channels, which saves the power of the OSUs, as shown in Figure 13. However, under a medium to high load, e.g., 64 Gbps to 96 Gbps, the TDMA part of the mixed method drives all ONUs go into TDMA mode. In this mode, all OSU channels will be opened, since the OLT grants each ONU the maximum bandwidth size. In addition, OSUs consume more power than ONUs in such networks. Therefore, total consumption will increase and create more bias toward the TDMA method.

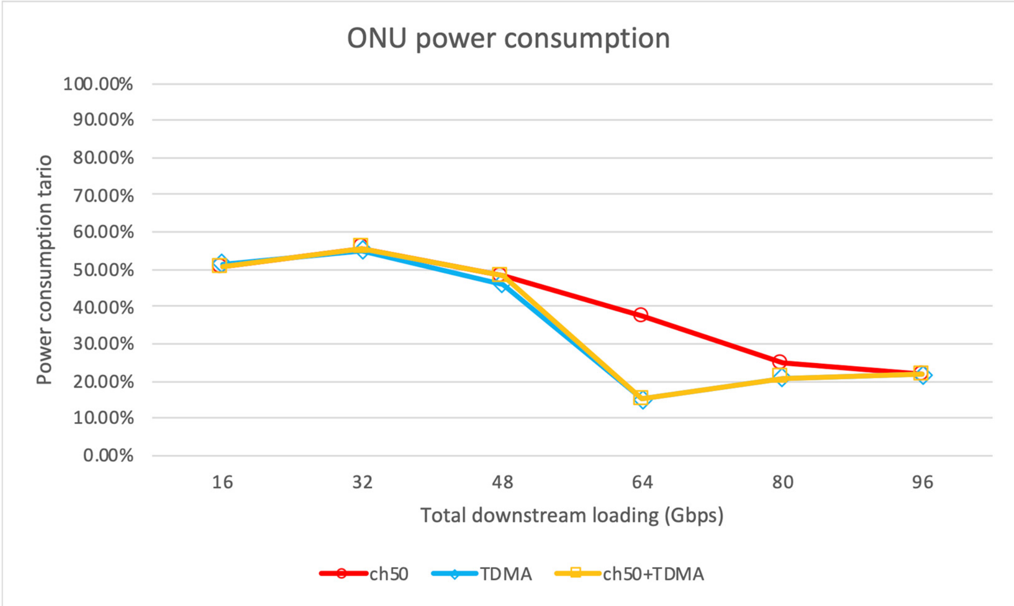

Figure 12. Comparison of ONU power consumption for mixed and individual methods under a fixed upstream load.

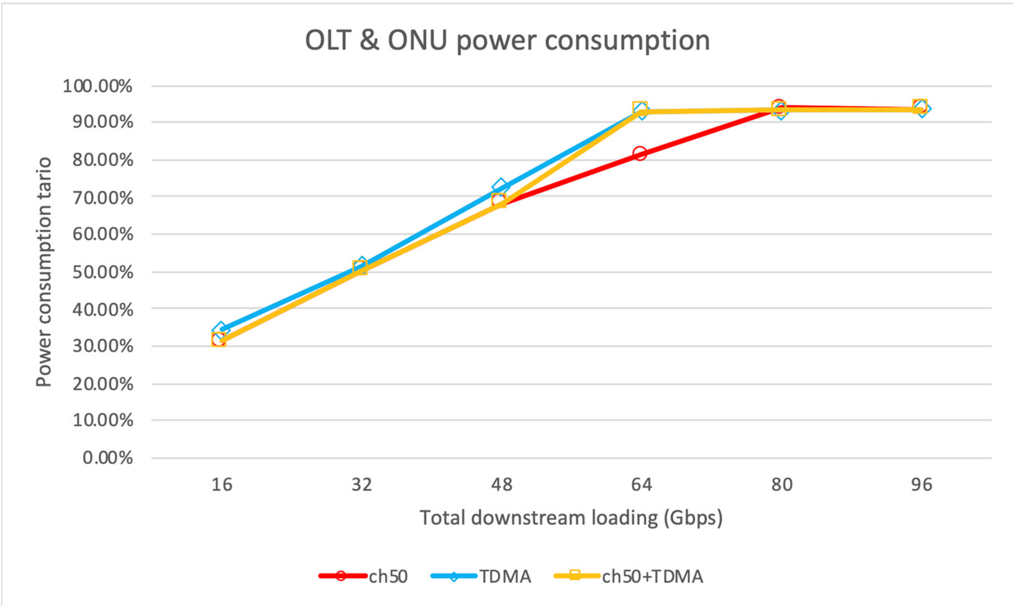

Figure 13. Comparison of the total power consumption for mixed and individual methods under a fixed upstream load.

In Figure 14, the delay of mixed methods remained at a low level between the values of the ch50 and TDMA methods. In under a low to medium load, the mixed method was better than the ch50 method, since the traffic loading was still low. Under such conditions, part of the traffic is deferred at the buffer, which increases delay. Under a medium to high load, the TDMA methods had less delay, since the traffic can be transmitted on all open channels and the tuning delay that decreases total delay was eliminated.

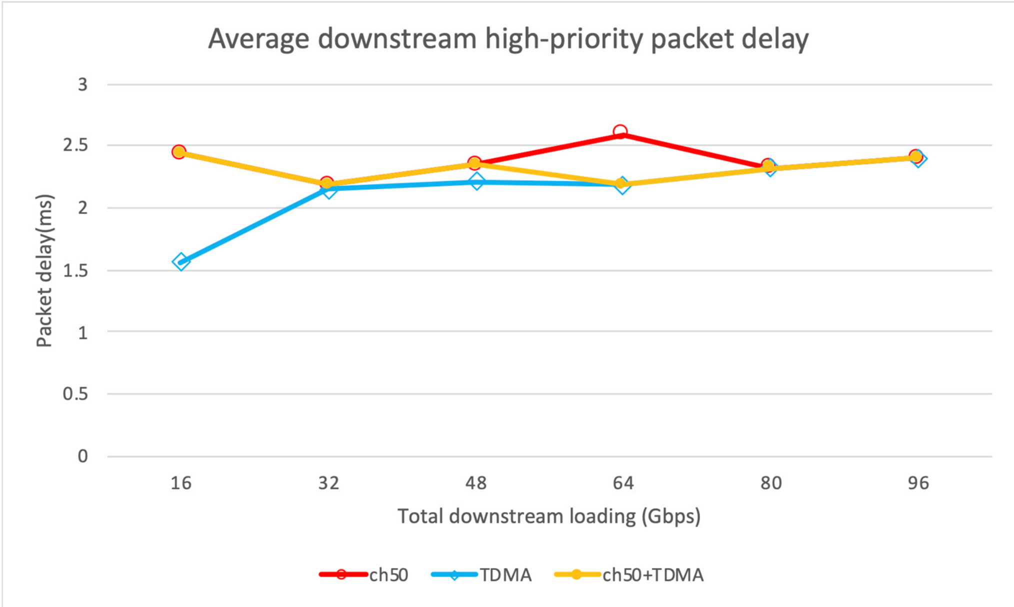

Figure 14. Comparison of average downstream high-priority packet delay for mixed and individual methods under a fixed upstream load.

The low-priority packet delay in the downstream channel of all methods, i.e., ch5, TDMA, and ch50+TDMA, was quite close and increased with an increase in the downstream load, which is the same trend as shown in Figure 5.

Figures 15 and 16 show that the high- and low-priority packet delay for all methods was maintained at a fairly low level. The delay of the mixed method under a light load has a higher value, since the effect of ch50 in the mixed method defers transmission until the total request size of all ONUs reaches 50% for opening a new channel. When the downstream load rises to a higher level, the TDMA part of the mixed method takes effect and all channels are opened for transmission so that the delay decreases.

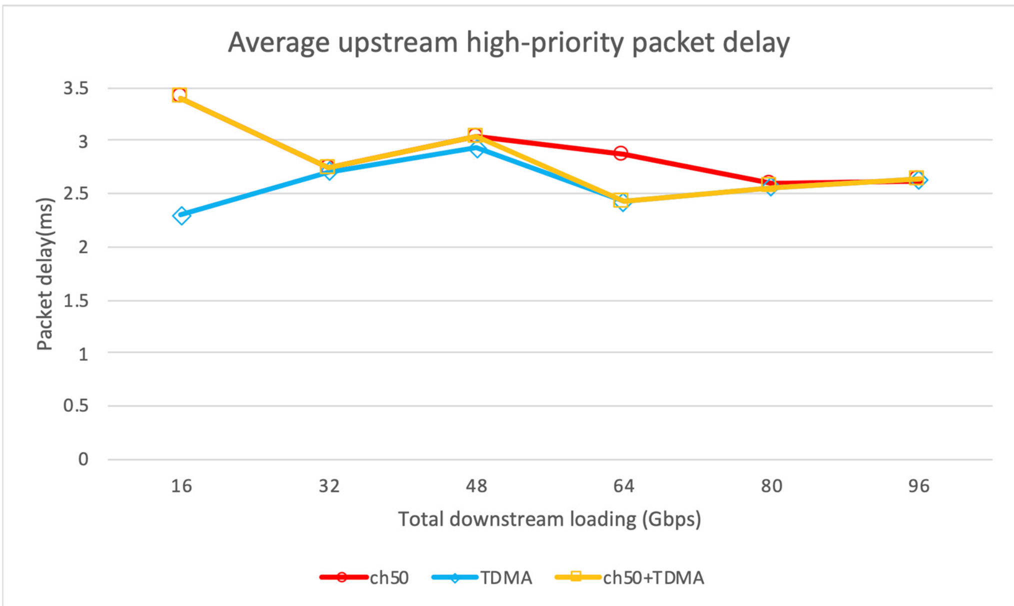

Figure 15. Comparison of average upstream high-priority packet delay for mixed and individual methods under a fixed upstream load.

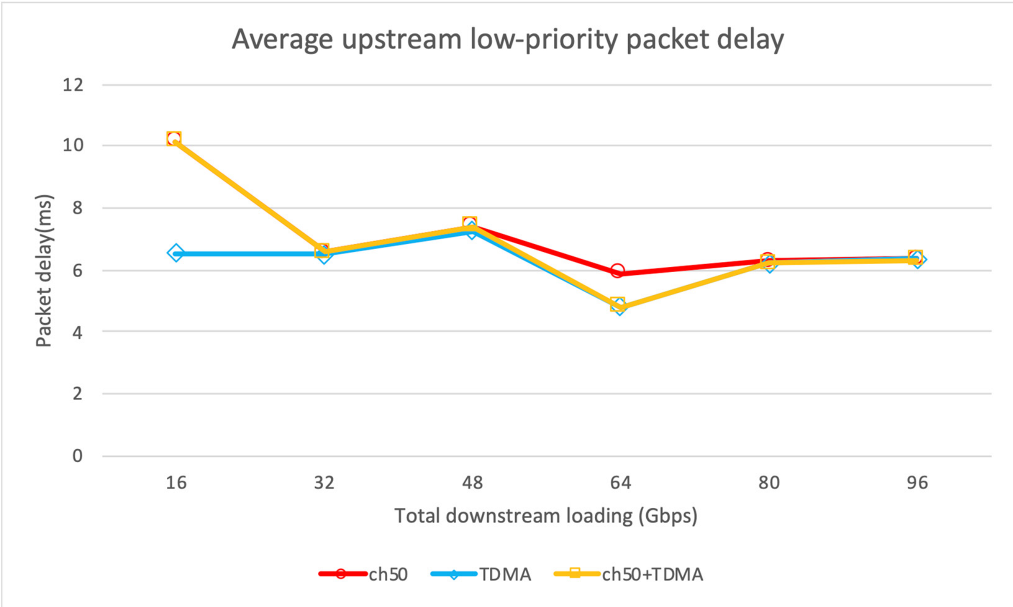

Figure 16. Comparison of average upstream low-priority packet delay for mixed and individual methods under a fixed upstream load.

5. Conclusions

In general, the OLT grants ONUs the size they request under the limit of MTW. However, our proposed scheme grants a MTW size in advance for ONUs if the ONUs' request size is close to size of the MTW, which decreases ONUs' power consumption and removes the tuning delay under medium to high traffic in such a network. Moreover, setting a threshold for opening a new channel in a multi-channels network can reduce the number of inefficient channel(s). For the scheme with advance activation of TDMA mode, ONUs can extend their sleep time and save power under medium- to high-load traffic. Moreover, the total delays under the targeted load can be further reduced, in contrast to the scheme without TDMA mode, since the channel tuning delay is minimized. When applying the channel-saving scheme, the total power consumption can be reduced without sacrificing packet delay in both the upstream and downstream channels, as shown in the simulation results. With a combination of advance activation of TDMA mode and saving channels, the saving channel scheme has lower total power consumption, since this scheme limits the opening of a new OSU and its power consumption dominates the ratio of total consumption. Moreover, the channel-saving scheme only increased the delay slightly under a medium to high load. To sum up, the results of the simulation show that the proposed schemes can save ONU and/or OSU power consumption and keep the delays at a lower level for high-priority packets.

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