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Study on the Solutions to Heterogeneous ONU Propagation Delays for Energy-Efficient and Low-Latency EPONs

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ABSTRACT The scattered Optical Network Units (ONUs) in an optical access network have different propagation delays. In an Ethernet passive optical network (EPON) adopting the traditional Interleaved Polling with Adaptive Cycle Time (IPACT) scheme, such ONU propagation delay difference will waste network resources and will degrade both network delay performance and network energy efficiency in delivering low-latency services. In this article, to deal with the heterogeneous ONU propagation delays problem, two solutions are proposed and investigated. The first solution, namely the Upstream Postponing with ONU Dozing (UP-OD) scheme, is to properly postpone the upstream transmissions of those ONUs having relatively short propagation delays to improve channel utilization efficiency, and ONU doze mode is incorporated to enhance network energy efficiency. The second solution, namely the Identical Fiber Length with ONU Sleeping (IFL-OS) scheme, is to adopt an identical distribution fiber length for ONUs to enhance channel utilization, and ONU sleep mode is incorporated for energy consumption reduction. Simulation results show that both the UP-OD scheme and the IFL-OS scheme reduce network delay and improve network energy efficiency in delivering low-latency ($<$1 ms) data, and the IFL-OS scheme shows lower energy consumption in transmitting per bit of low-latency ($<$1 ms) data compared with the UP-OD scheme. Further practical value discussion shows that for the case of serving services requiring 1 ms delay, the UP-OD scheme is suitable for applying in the 1G-EPONs, whereas the IFL-OS scheme is considerable for the 10G-EPONs.

INDEX TERMS Propagation delay, energy efficiency, low-latency, EPON, optical access network, fiber length.

I. INTRODUCTION

In recent years, increasing demands from network users and advanced applications have prompted access networks undergone a rapid development [1]. More and more users are able to be supported in an access network and increasing numbers of access networks are being established. However, the exploding scale and numbers of access networks also make the network energy consumption a crucial problem. As telecommunication networks are estimated responsible for over 20% of global energy consumption in 2030 and considering the fact that 70% of the energy consumption from telecommunication networks is contributed by access networks [2], [3], building energy-efficient access networks becomes a key part of reducing carbon footprint for future environmental-friendly society. Passive Optical Network (PON) is the most popular access network technology due to its well-known advantages of low cost and high reliability [4]. Therefore, reducing the energy consumption of PONs, especially the most widely deployed Ethernet PONs (EPONs), has attracted intensive interest [5]. In an EPON, Optical Network Units (ONUs) use time division

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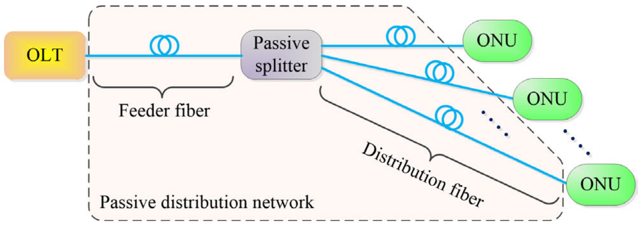


FIGURE 1. EPON structure.

multiplexing technique to exchange data with the Optical Line Terminal (OLT). Hence, turning off the transceiver or the transmitter of an ONU to let it operating under a low power consumption mode (i.e. sleep mode or doze mode) during transmission intervals is a main way to improve the energy efficiency of an EPON [6], [7]. Without any doubt, the longer the sleep/doze time, the better the energy saving performance. However, as sleep/doze mode disables (or partially disables) data transmission, better energy saving is achieved at the cost of worse delay performance [8], [9]. With the entering of the 5G era, there are increasing delay-sensitive applications being delivered over EPONs, and some of the applications such as e-health, backhauling, and VR/AR prefer a delay requirement as low as ∼1 ms [10], [11]. As this stringent delay requirement will decrease the energy efficiency of EPONs due to reduced sleep/doze time, how to achieve the best energy saving while delivering the services requiring 1 ms delay becomes an important study for future EPONs.

To save energy while providing low-latency service, channel utilization efficiency must be improved first. In an EPON, ONUs communicate with the OLT via a passive optical distribution network consisting of a feeder fiber (connecting the OLT and the passive splitter), a passive splitter, and numbers of distribution fibers (connecting each ONU to the passive splitter), as shown in Fig. 1. All data packets are framed according to the Ethernet standard. To avoid collision, GATE and REPORT messages are used to allocate bandwidth among ONUs. Usually, ONUs are scattered over a large area, and different ONUs have different distances to the passive splitter. Hence, the lengths of distribution fibers of the ONUs are different, resulting in different propagation delays for ONUs. To improve the channel utilization efficiency of an EPON, masking ONU propagation delays is necessary. Fig. 2 provides a simple example showing the importance of ONU propagation delays masking. For illustration, here the data transmission time of each ONU is fixed to T_D, and GATE and REPORT transmission times are set to zero. The ONU propagation delays are set as: $\text{ONU}_1 = \tau$, $\text{ONU}_2 = 2\tau$, and $\text{ONU}_3 = 3\tau$. Clearly, the time length needed for the OLT to serve an ONU once is the sum of the data transmission time and two times of the ONU propagation delay (e.g. $T_D + 2\tau$ when serving ONU_1). As shown in Fig. 2(a), if ONU propagation delays are not masked, the time length for the OLT to serve all ONUs once is $3T_D + 12\tau$, which is just the accumulation of the time lengths of serving each ONU once. Also,

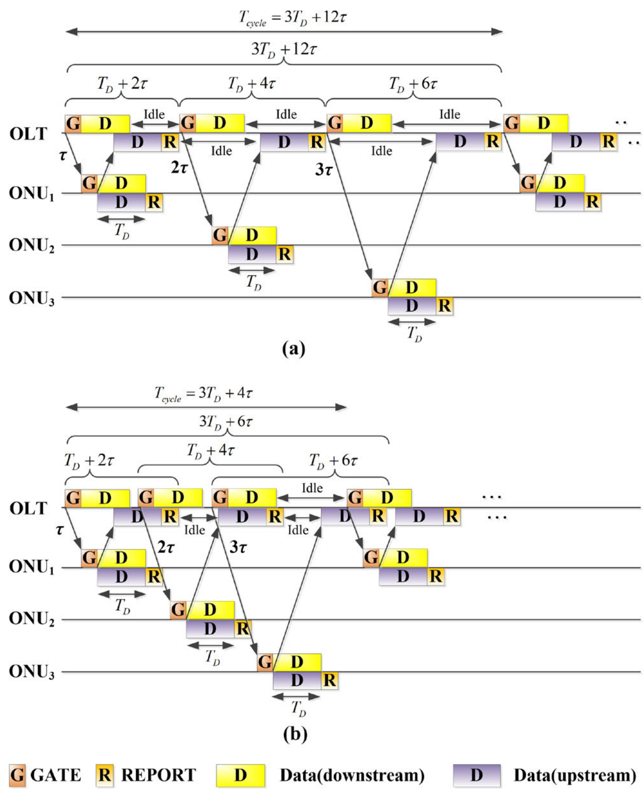


FIGURE 2. ONU propagation delays masking: (a) before masking; (b) after masking (adopting the shortest propagation delay first scheduling scheme). (For illustration, here the data transmission time of each ONU is fixed to T_D, and GATE and REPORT transmission times are set to zero. The ONU propagation delays are: $\text{ONU}_1 = \tau$, $\text{ONU}_2 = 2\tau$, and $\text{ONU}_3 = 3\tau$.)

the polling cycle time is $3T_D + 12\tau$, indicating that the ONU propagation delays create an overall idle length of 12τ in each direction of the channel within a polling cycle time. However, if ONU propagation delays are masked as shown in Fig. 2(b), the time periods for serving successive ONUs can partially overlap. Therefore, the time length for the OLT to serve all ONUs once is reduced to $3T_D + 6\tau$, and the polling cycle time is reduced to $3T_D + 4\tau$. This means that the overall idle length created by the ONU propagation delays is reduced to 4τ in each direction of the channel within a polling cycle time. Hence, ONU propagation delays masking reduces polling cycle time and improves channel utilization, and packet delay performance can be benefited as short polling cycle time means short queueing delay. So far, the most well-known way to mask ONU propagation delays is the Interleaved Polling with Adaptive Cycle Time (IPACT) scheme [12]. However, as in practice ONUs can have different propagation delays, the masking performance of the interleaved polling of long-propagation-delay ONUs and short-propagation-delay ONUs is not satisfactory. To solve this problem, the shortest propagation delay (SPD) first scheduling scheme is proposed [13]. By polling the ONUs following the ascending sequence of ONU propagation delays, the masking performance can be improved, and the channel utilization efficiency of the SPD scheme is enhanced compared with the original IPACT scheme. Nevertheless, as shown in Fig. 2(b), as long as the ONU propagation delay difference exists, ONU propagation delays still contribute to the polling cycle time, and therefore ONU propagation delays cannot be completely masked and channel cannot be fully utilized. There are two methods to solve the problem. One is to postpone the upstream transmissions of those ONUs having short propagation delays, while the other is to eliminate ONU propagation delay difference by adopting an identical distribution fiber length for ONUs. In this article, in order to evaluate the two methods and also to find an energy-efficient scheme to deliver services requiring 1 ms delay, the Upstream Postponing with ONU Dozing (UP-OD) scheme and the Identical Fiber Length with ONU Sleeping (IFL-OS) scheme are proposed and studied. In the UP-OD scheme, the OLT sets ONUs having relatively short propagation delays to postpone their upstream transmissions to mask the propagation delays, whereas in the IFL-OS scheme, ONUs are deployed with the identical length of distribution fibers to mask the propagation delays. The UP-OD scheme adopts ONU doze mode to improve energy efficiency, whereas the IFL-OS scheme adopts ONU sleep mode to improve energy efficiency. The two schemes are compared in terms of polling cycle time, packet delay, and energy efficiency in transmitting low-latency data, and their practical values are discussed by envisioning the cost-saving tradeoff.

The main contributions of the paper are as follows. Firstly, to the best of our knowledge, this is the first paper investigating the ways to completely mask the heterogeneous ONU propagation delays while considering both energy efficiency and <1 ms delay for EPONs. Secondly, this is the first study investigating the method of adopting an identical distribution fiber length for ONUs to deal with the heterogeneous ONU propagation delays problem for energy-efficient and low-latency EPONs. Thirdly, the UP-OD scheme and the IFL-OS scheme are proposed and compared to facilitate the energy-efficient delivery of low-latency services over the EPONs having heterogeneous ONU propagation delays, and their practical values are envisioned.

The rest of the paper is organized as follows. Section II reviews the related works. Section III introduces and analyzes the UP-OD scheme and the IFL-OS scheme. Simulations and results discussions are presented in Section IV. Section V gives a brief conclusion of the paper.

II. RELATED WORKS

A. ENERGY SAVING IN EPON BY ONU SLEEP/DOZE MODE

As previously mentioned, an EPON adopts time division multiplexing to share bandwidth among ONUs, and therefore, an ONU can enter a low power mode (i.e. sleep mode or doze mode) during transmission intervals to save energy. In sleep mode, an ONU turns off its transceiver and leaves its background circuit operating. In doze mode, an ONU only turns off its transmitter, while keeps its receiver and background circuit running. Clearly, sleep mode can save more power than doze mode. However, entering sleep mode causes an ONU to lose synchronization with the OLT, and thus the ONU needs a longer time to recover from sleep mode (turn on transceiver and synchronize) than to recover from doze mode (turn on transmitter). Therefore, the two low power modes have their own edges. Focusing on these two low power modes, various energy saving studies have been reported to improve the energy efficiency of EPONs.

Based on dynamic bandwidth allocation, Nikoukar *et al.* proposed an adaptive ONU doze scheme for energy-efficient EPONs [14]. By extending ONU doze time according to queue status, the scheme reduces the energy consumption of ONUs and maintains service quality. Dutta *et al.* proposed an ONU-assisted protocol for EPONs adopting cyclic sleep mechanism. They enhanced the energy saving performance by allowing ONUs to enter doze mode during active cycles [15]. Van *et al.* investigated an energy-efficient framework for EPONs and studied the impact of message transmission order on the energy consumption of the networks [16]. They revealed that initiating transmission from GATE is more energy-efficient than from REPORT. They also found that triggering ONU sleep by downstream traffic saves more energy than by upstream traffic [17]. Shi *et al.* proposed a service layer agreement based ONU sleep scheduling scheme for energy-efficient EPONs [18]. Through dynamically adjusting sleep time and postponing the entering of sleep mode, ONU energy consumption is reduced and the delay requirement of high priority data is ensured. Dias *et al.* presented an energy-efficient dynamic bandwidth allocation scheme based on Bayesian estimation [19]. By predicting packet arrivals and allocating bandwidth and ONU sleep/doze time accordingly, the scheme saves substantial energy and maintains the capability to deliver delay-sensitive services.

Besides the studies mentioned above, Dhaini *et al.* proposed an ONU sleep time sizing and shifting mechanism and proved that by sorting ONUs based on their transmission start times and simultaneously shifting their sleep times, ONU energy consumption can be reduced and service quality can be ensured [20]. Hwang *et al.* studied an ONU-initiated energy saving scheme and revealed that the ONU-initiated scheme has lower delay than the OLT-initiated scheme [21]. In our previous works, we investigated how polling sequence and polling cycle length affect the energy efficiency of ONUs and proposed a dynamic polling sequence arrangement scheme as well as a polling cycle compressing scheme for energy-efficient EPONs [22], [23].

All these studies have contributed to the advance of energy-efficient EPONs. However, while achieving energy saving, the majority of these works have not put their target on serving services requiring 1 ms delay as conventional delay-sensitive services such as voice only require 10 ms delay [24], and they also miss the field of dealing with the heterogeneous ONU propagation delays problem to benefit network efficiency. In this article, we focus on serving the services requiring 1 ms delay while saving energy, and we investigate the methods to deal with the heterogeneous ONU propagation delays problem.

B. MASKING ONU PROPAGATION DELAYS

The necessity of masking ONU propagation delays in an EPON has been illustrated in Fig. 2. It reduces polling cycle time, improves channel utilization, and thus decreases network delay and increases network throughput. It also benefits network energy efficiency as more data can be transmitted under a same energy cost. The first study of ONU propagation delays masking is known as the IPACT scheme [12]. By following the REPORT-GATE-data interaction cycle and sending GATE to the next ONU before finishing data receiving from the previous ONU, ONU propagation delays can be masked. Based on the IPACT scheme, McGarry *et al.* studied ONU scheduling order and proposed the SPD scheme to enhance ONU propagation delays masking for EPONs with heterogeneous ONU propagation delays [13]. Further, another ONU scheduling scheme that jointly considers processing time and ONU propagation delay is proposed by Shuai *et al.*, and ONU polling cycle time and packet delay are effectively reduced [25]. In addition, Shi *et al.* investigated the variance of ONU propagation delays and found that the SPD scheme performs better under large variance scenarios [26]. To further mask ONU propagation delays between consecutive polling cycles, the multi-thread polling mechanism is proposed and investigated [27], [28]. By allowing an ONU to send the next request before receiving the respond to the previous request, polling cycle time, channel utilization efficiency, packet delay, and network throughput are all optimized, especially under long-reach network scenarios.

The above studies have significantly improved the channel utilization efficiency and benefited network delay performance. However, for an EPON with heterogeneous ONU propagation delays, these schemes have not discussed the way to completely mask the ONU propagation delays, and have never combined ONU power saving into consideration. In this article, two methods are studied to completely mask the ONU propagation delays for an EPON with heterogeneous ONU propagation delays, i.e. (a) postponing the upstream transmissions of those ONUs having short propagation delays and (b) adopting an identical distribution fiber length for ONUs. Based on the two methods, two schemes that adopt ONU low power mode, namely the UP-OD scheme and the IFL-OS scheme, are proposed and investigated to find an energy-efficient way to deliver services requiring 1 ms delay over EPONs.

III. PROPOSALS AND THEORETICAL ANALYSIS

A. THE UP-OD SCHEME

The UP-OD scheme is investigated first. Since postponing the upstream transmission of an ONU will force the ONU to remain active for a longer time and thus significantly decreases the available sleep time of the ONU, ONU doze mode is adopted. It should be mentioned that in this article,

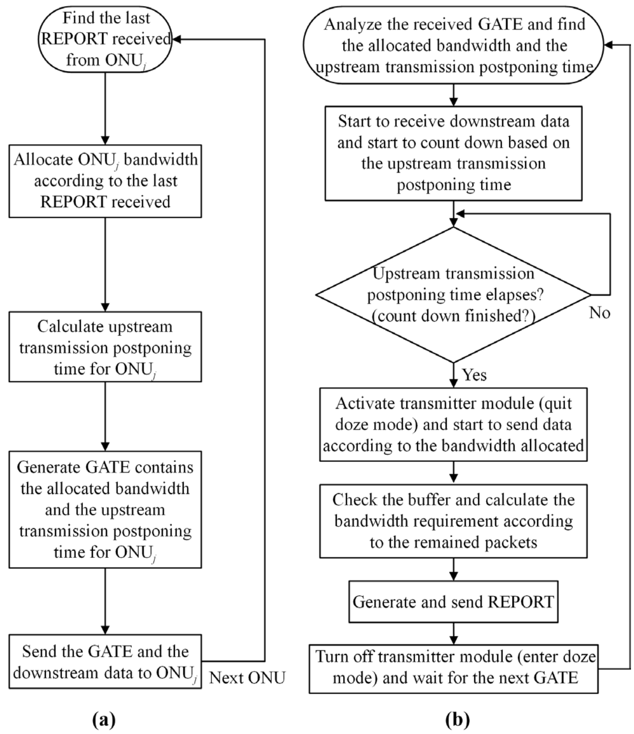


FIGURE 3. The UP-OD scheme executing at: (a) OLT; (b) ONU.

as we consider symmetric link rate networks, we set bandwidth allocations for a pair of upstream transmission and downstream transmission to be identical (i.e. identical data transmission time for a pair of upstream transmission and downstream transmission) for simplicity and clear statement. In the UP-OD scheme, in each polling cycle, the OLT will poll the ONUs following the ascending sequence of ONU propagation delays, and when polling an ONU, the OLT will set the ONU to start upstream transmission $T_{postpone}$ after receiving the GATE message. The postponing time $T_{postpone_i}$ of ONU$_i$ is calculated by (1):

$$T_{postpone_i} = 2(T_{propagation\_longest} - T_{propagation\_ONU_i}), \quad (1)$$

where $T_{propagation\_longest}$ is the longest propagation delay among all ONUs and $T_{propagation\_ONU_i}$ is the propagation delay of ONU$_i$.

Fig. 3 illustrates how the UP-OD scheme executes at the OLT and ONUs. At the OLT side, after finishing the downstream transmission of the previous ONU, the OLT first finds the last REPORT received from the ONU which will be polled next. Then, the OLT plans to allocate this ONU the same bandwidth as indicated in the last REPORT, and calculates the upstream transmission postponing time $T_{postpone}$ for this ONU according to (1). After that, the OLT will generate a GATE message containing the allocated bandwidth and the upstream transmission postponing time $T_{postpone}$ for the ONU, and will send the GATE and corresponding downstream data to the ONU. At ONU side, after an ONU receives its GATE, the ONU first analyzes the GATE and finds the

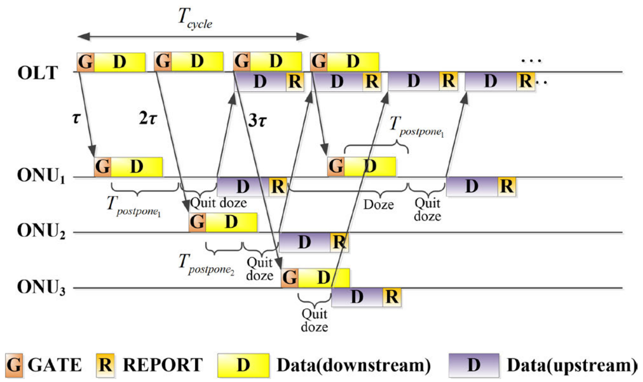


FIGURE 4. Traffic flow schematic of the UP-OD scheme. (For illustration, here the ONU propagation delays are: $ONU_1 = \tau$, $ONU_2 = 2\tau$, and $ONU_3 = 3\tau$.)

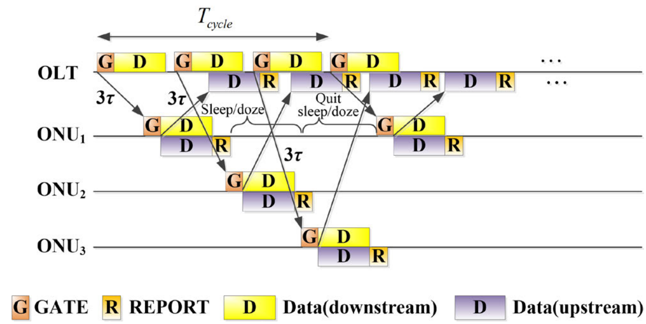


FIGURE 5. Traffic flow schematic of the IFL-OS scheme. (As an example, here although the ONU_1 and ONU_2 are closing to the passive splitter, their distribution fiber lengths are the same as that of ONU_3. Therefore, the ONU propagation delays are: $ONU_1 = 3\tau$, $ONU_2 = 3\tau$, and $ONU_3 = 3\tau$.)

allocated bandwidth and the upstream transmission postponing time $T_{postpone}$. Then, the ONU starts to receive its downstream data and simultaneously starts to count down based on the $T_{postpone}$. When the $T_{postpone}$ elapses, the ONU activates its transmitter (quit doze mode) and then starts to send upstream data according to the bandwidth allocated. After finishing the upstream data transmission, the ONU checks its buffer and calculates the bandwidth required for the remaining packets, and then generates and sends a REPORT containing the bandwidth requirement information. As soon as the REPORT is sent, the ONU turns off its transmitter (enter doze mode) and starts to wait for the next GATE. The traffic flow schematic of the UP-OD scheme is shown in Fig. 4. Clearly, the polling cycle time is completely decided by data volume, and ONU propagation delays do not create any idle in the channel, indicating that ONU propagation delays have been completely masked. Note that the time interval between sending a REPORT and receiving the corresponding GATE allocating the requiring bandwidth may cross several polling cycles due to propagation delays.

As the UP-OD scheme only needs to adjust the upstream transmissions of ONUs, it is totally software-based and thus is easy to apply. However, as ONUs can only enter doze mode during transmission intervals, the energy saving performance of the scheme is limited.

B. THE IFL-OS SCHEME

Based on the upstream transmission postponing time calculation of the UP-OD scheme, it is easy to understand that if all ONUs have the same propagation delay, each ONU will work the shortest time during each pair of upstream and downstream transmissions. As entering sleep mode is more energy-efficient than entering doze mode, and considering the fact that adopting an identical distribution fiber length could ensure all ONUs have the same propagation delay, the IFL-OS scheme is proposed. The traffic flow schematic of the IFL-OS scheme is shown in Fig. 5. It is clear that ONU propagation delays are completely masked as they do not create any idle in the channel. As in the IFL-OS scheme an ONU in sleep mode totally loses connection to the OLT and thus cannot quit sleep mode based on the receiving of GATE message like that in the UP-OD scheme, the polling cycle time needs to be set beforehand so that the available sleep time of an ONU can be calculated. Here we calculate the polling cycle time by using an offline process that the OLT measures the average network data packet arrival rate and the average data packet transmission time during a period of time (e.g. 1 s) and calculates the polling cycle time by (2) (details are explained in Appendix I):

$$T_{cycle} = N\left(\left(\frac{T_{REPORT} R_{packet\_occur} \overline{T_{packet}}}{1 - R_{packet\_occur} \overline{T_{packet}}} + BW_{add}\right) + T_{REPORT}\right), \tag{2}$$

where N, T_{REPORT}, $\overline{T_{packet}}$, R_{packet_occur} refer to the number of ONUs, the REPORT transmission time (including a gap time), the average data packet transmission time (including a gap time), and the average network data packet arrival rate, respectively. BW_{add} is an additional bandwidth (in time unit) assigned to each ONU in each transmission. A maximum allowable bandwidth (in time unit) corresponding to the polling cycle time is set as well, which is expressed as (3):

$$BW_{\max} = \left(\frac{T_{REPORT} R_{packet\_occur} \overline{T_{packet}}}{1 - R_{packet\_occur} \overline{T_{packet}}} + BW_{add}\right). \tag{3}$$

The polling cycle time calculation process does not need to be triggered frequently and therefore here we consider it as a sub-process of network initialization. The details of the execution of the IFL-OS scheme at the OLT and ONUs are shown in Fig. 6. At the OLT side, the polling cycle time is calculated at first. In each polling cycle, when the OLT starts to poll an ONU, it first finds the last REPORT received from this ONU. Then, the OLT compares the required bandwidth of this ONU with the maximum allowable bandwidth. If the required bandwidth exceeds the maximum allowable bandwidth, the maximum allowable bandwidth is allocated to the ONU. Otherwise, the required bandwidth is allocated to the ONU. Once the allocated bandwidth is confirmed, the available idle time of the ONU can be calculated by (4):

$$T_{idle} = T_{cycle} - T_{ONU} - T_{GATE}, \quad (4)$$

where T_{ONU} and T_{GATE} refer to the ONU upstream transmission time and the GATE transmission time (including a gap time), respectively. Noting that ONU sleep-to-active mode transition time is longer than ONU doze-to-active mode transition time, it may be more energy-efficient for an ONU to turn into doze mode than to turn into sleep mode when the available idle time is short. Therefore, to achieve the best energy saving in the IFL-OS scheme, the available idle time is compared with a threshold time which is calculated by (5):

$$Threshold = \frac{P_{active}T_{DA} - P_{doze}T_{DA} - P_{active}T_{SA} + P_{sleep}T_{SA}}{P_{sleep} - P_{doze}}, \quad (5)$$

where P_{active}, P_{doze}, and P_{sleep} refer to the ONU power consumption in active mode, doze mode, and sleep mode, respectively. T_{DA} and T_{SA} denote the ONU doze-to-active mode transition time and the ONU sleep-to-active mode transition time, respectively. If the available idle time is larger than the threshold, the OLT assigns a sleep time of $T_{idle} - T_{SA}$ to the ONU. Otherwise, the OLT assigns a doze time of $T_{idle} - T_{DA}$ to the ONU. After calculating the available sleep (or doze) time, the OLT generates a GATE containing the allocated bandwidth and the available sleep (or doze) time, and sends the GATE and corresponding downstream data to the ONU. At ONU side, when an ONU receives its GATE, it first finds the allocated bandwidth and the available sleep (or doze) time. Then, the ONU starts to receive its downstream data and simultaneously starts to send upstream data. After sending out the last allowed packet, the ONU checks its buffer and calculates the bandwidth required for the remaining packets. Based on the bandwidth requirement, a REPORT is generated and is sent to the OLT. As soon as the REPORT is sent, the ONU enters sleep (or doze) mode as indicated in the received GATE. The ONU will quit sleep (or doze) mode and starts to wait for the next GATE when the indicated sleep (or doze) time elapses.

In practice, the polling cycle time calculation process can be set to be triggered automatically or manually when load level changing or after a pre-set period of time, but corresponding details are not discussed in this article. Also, it should be mentioned that during the last polling cycle before adopting a new polling cycle time, ONUs will not be allowed to turn into low power mode for the reason of preventing data loss.

Overall, as ONU sleep mode is incorporated and ONU sleep time is ensured due to minimized ONU operating time during each pair of upstream and downstream transmissions, the IFL-OS scheme is more energy-efficient than the UP-OD scheme. However, as polling cycle time needs to be set beforehand, its adaptability to traffic fluctuation is limited, and therefore its channel utilization efficiency and network delay performance would be degraded. In addition, as extra fibers are introduced, additional propagation delays are induced for those ONUs closing to the passive splitter, and capital cost is increased as well. Nevertheless, the extra capital cost would not be high, because the additional fibers can be placed indoor and therefore can be cheap.

IV. SIMULATIONS AND RESULTS DISCUSSIONS

In this section, the performances of the UP-OD scheme and the IFL-OS scheme are evaluated and compared. Two conventional schemes, namely the IPACT with ONU dozing (IPACT-OD) scheme and the IPACT with ONU sleeping (IPACT-OS) scheme, are introduced for comparison. In the IPACT-OD scheme, ONUs are set to doze during transmission intervals, whereas in the IPACT-OS scheme, ONUs are set to sleep during transmission intervals. Both the IPACT-OD scheme and the IPACT-OS scheme follow the SPD polling rule. As adopting ONU sleep mode needs to set polling cycle time beforehand (as explained in part B of section III), the IPACT-OS scheme also uses an offline process to calculate the polling cycle time. In the offline process, the OLT measures the network average data packet arrival rate and the average data packet transmission time during a period of time, and calculates the polling cycle time and the corresponding maximum allowable bandwidth by (6) and (7), respectively (details are explained in Appendix II). Here N, T_{REPORT}, R_{packet_occur}, $\overline{T_{packet}}$, BW_{add}, $T_{propagation\_longest}$, $T_{propagation\_shortest}$ refer to the number of ONUs, the REPORT transmission time (including a gap time), the average network packet arrival rate, the average data packet transmission time (including a gap time), the additional allocated bandwidth, the longest propagation delay among all ONUs, and the shortest propagation delay among all ONUs, respectively. The execution of the IPACT-OS scheme at the OLT and ONUs is the same as that of the IFL-OS scheme. Both 1G-EPON and 10G-EPON environments are considered. For the 1G-EPON case, distributed-feedback laser based ONU with fast clock recovery function is considered, and related network parameters are listed in Table 1. For the 10G-EPON case, vertical-cavity surface-emitting laser based ONU with fast clock recovery function is considered, and related network parameters are listed in Table 2. Due to the lack of relevant data, the power consumption of the fast clock recovery module in the 10G-EPON ONU is assumed to be identical with that of the fast clock recovery module in the 1G-EPON ONU. Therefore, the power consumption of a 10G-EPON ONU in sleep mode is set to 1.08 W [29], [30]. In both the 1G-EPON case and the 10G-EPON case, the ONU mode transition time from doze to active is the laser turn-on time (i.e. 0.76 μs for a 1G-EPON ONU and 0.33 μs for a 10G-EPON ONU), and the ONU mode transition time from sleep to active is the laser turn-on time plus 0.01 μs clock recovery time [29], [30]. The length of feeder fiber is 10 km, and the original lengths of ONU distribution fibers are evenly distributed in the 0-10 km range. That is, the original propagation delays of the ONUs are evenly distributed in the 50-100 μs range. Source traffic

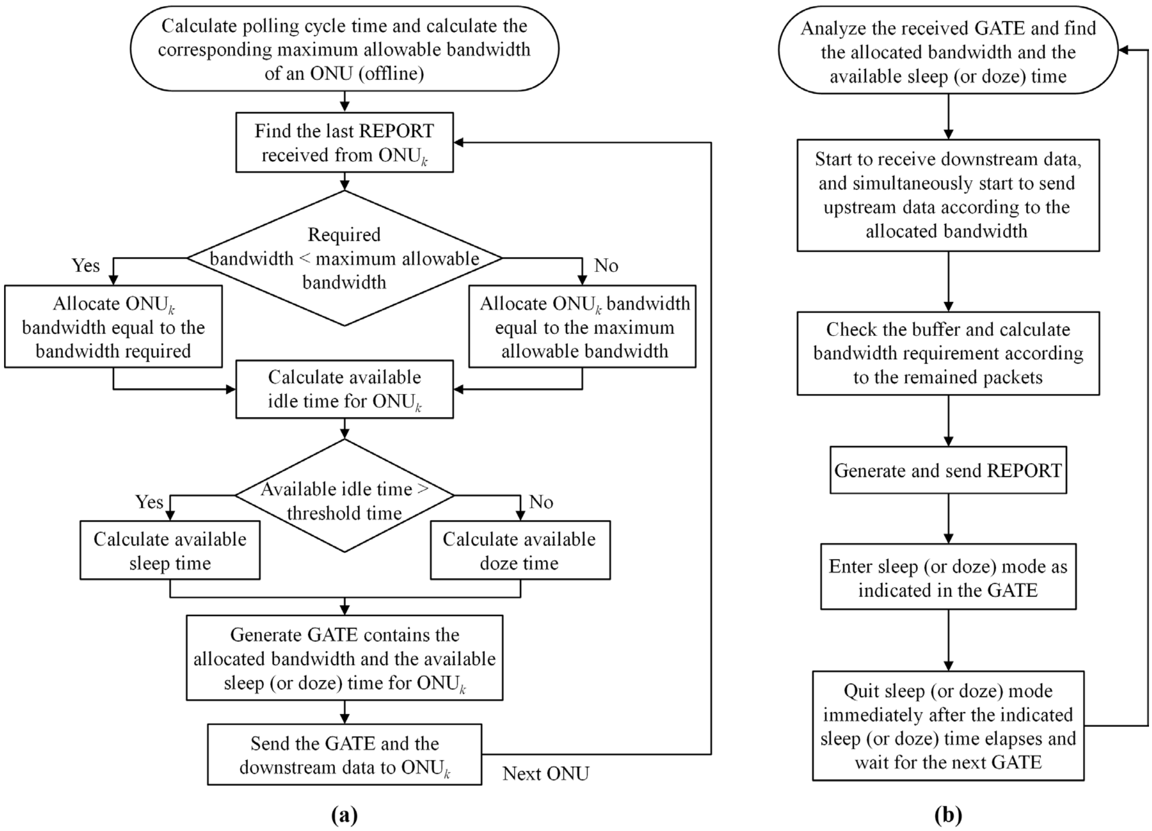


FIGURE 6. The execution of the IFL-OS scheme at: (a) OLT; (b) ONU.

follows Pareto distribution, and the shape parameters for ON and OFF intervals are set to 2.8 and 2.4, respectively [31]. Link rate is identical in both directions. In our simulations, we consider delay-sensitive traffic (e.g. tactile internet traffic) and therefore set the payload size fixed to 512 bit [32]. Also, since a 512 bit payload needs 816 bit (512 bit payload+208 bit header+96 bit gap) of bandwidth for transmission, the normalized traffic load (data rate/link rate) is set to vary from 0.05 to 0.62. For the IFL-OS scheme and the IPACT-OS scheme, BW_{add} is set equivalent to 5 packets, and the maximum polling cycle time is set to 10 ms. Therefore, if the calculated polling cycle time T_{cycle} exceeds 10 ms, T_{cycle} will be set to 10 ms, and $BW_{\max}$ will be modified as described in Appendix I and Appendix II. We compare the four schemes in terms of average polling cycle time, average packet delay, delay value satisfied by 95% of packets, and energy consumption to transmit per bit of data satisfying the 1 ms delay. Also, the practical values of the UP-OD scheme and the IFL-OS scheme are discussed.

A. AVERAGE POLLING CYCLE TIME

1) 1G-EPON CASE

Fig. 7(a) shows the average polling cycle time performances of the four schemes in the 1G-EPON. Clearly, with the growth of traffic load, all schemes show a growing trend in average

$$\begin{aligned} T_{cycle} = N(&\frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1-R_{packet\_occur}\overline{T_{packet}}} + BW_{add} + T_{REPORT} \\ &+ \frac{2(T_{propagation\_longest} - T_{propagation\_shortest})R_{packet\_occur}\overline{T_{packet}}}{(1-R_{packet\_occur}\overline{T_{packet}})N}) \\ &+ 2(T_{propagation\_longest} - T_{propagation\_shortest}), \end{aligned} \tag{6}$$

$$\begin{aligned} BW_{\max} = &\frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1-R_{packet\_occur}\overline{T_{packet}}} + BW_{add} \\ &+ \frac{2(T_{propagation\_longest} - T_{propagation\_shortest})R_{packet\_occur}\overline{T_{packet}}}{(1-R_{packet\_occur}\overline{T_{packet}})N}. \end{aligned} \tag{7}$$

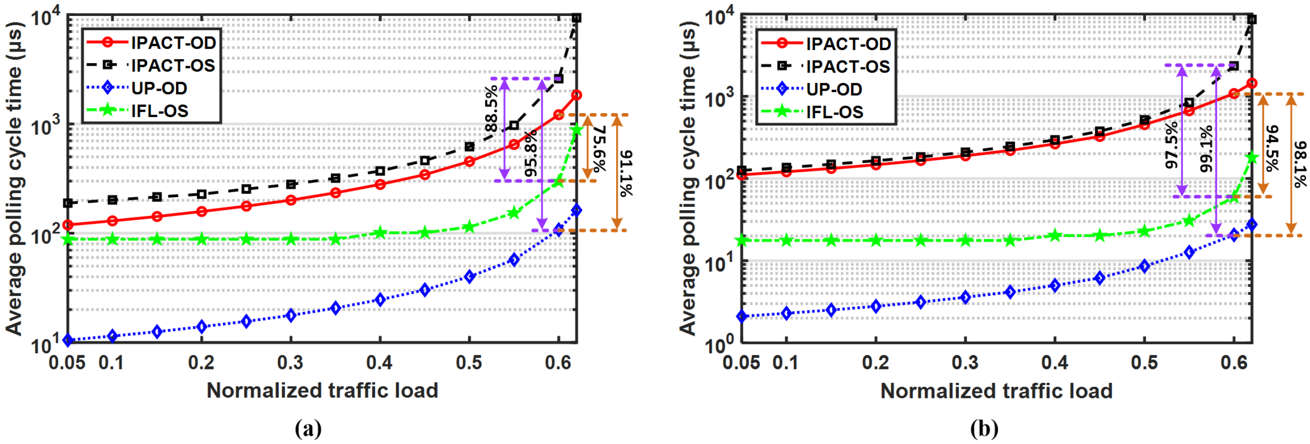


FIGURE 7. Average polling cycle time comparison in: (a) 1G-EPON; (b) 10G-EPON.

TABLE 1. Network parameters for 1G-EPON.

Parameter	Value
Link rate	1 Gbps
ONU number	16
Payload size	512 bit [32]
Load (normalized)	0.05-0.62
Simulation time	5 s
ONU power consumption	3.85 W (active) [30]
	1.7 W (doze) [30]
	1.08 W (sleep) [30]
OLT power consumption	20 W [20]
GATE/REPORT	512 bit [21]
Packet header	208 bit [33]
Inter packet gap	96 bit [33]
ONU mode transition time	0.76 μs (doze-to-active) [29]
	0.77 μs (sleep-to-active) [29], [30]

TABLE 2. Network parameters for 10G-EPON.

Parameter	Value
Link rate	10 Gbps
ONU number	32
Payload size	512 bit [32]
Load (normalized)	0.05-0.62
Simulation time	5 s
ONU power consumption	3.984 W (active) [29]
	3.85 W (doze) [29]
	1.08 W (sleep) [29], [30]
OLT power consumption	75 W [34]
GATE/REPORT	512 bit [21]
Packet header	208 bit [33]
Inter packet gap	96 bit [33]
ONU mode transition time	0.33 μs (doze-to-active) [29]
	0.34 μs (sleep-to-active) [29], [30]

polling cycle time as the bandwidth requirement of each ONU is increased under heavy load. Among all the schemes, the IPACT-OD scheme and the IPACT-OS scheme have relatively longer average polling cycle times because their ONU propagation delays have not been completely masked. The IPACT-OS scheme shows a longer average polling cycle time than the IPACT-OD scheme as its polling cycle time cannot be adjusted dynamically between polling cycles and thus results in inefficiency in channel utilization. On the contrary, as the IFL-OS scheme completely masks the ONU propagation delays by adopting an identical distribution fiber length, the IFL-OS scheme shows a shorter average polling cycle time than the IPACT-OS scheme and the IPACT-OD scheme. However, since the IFL-OS scheme is still inefficient in channel utilization due to the reason that polling cycle time cannot be adjusted dynamically between polling cycles, the average polling cycle time of the IFL-OS scheme is longer than that of the UP-OD scheme. The UP-OD scheme shows the shortest average polling cycle time among the four schemes, because it can completely mask the ONU propagation delays and can dynamically adjust bandwidth allocation and polling cycle time to further avoid channel idle. It is shown that under the load of 0.6, the UP-OD scheme and the IFL-OS scheme can reduce the average polling cycle time by 95.8% (91.1%) and 88.5% (75.6%) compared with the IPACT-OS (IPACT-OD) scheme, respectively.

2) 10G-EPON CASE

The average polling cycle time performances of the four schemes in the 10G-EPON are depicted in Fig. 7(b). Similar to the performances in the 1G-EPON, all the four schemes show an upward trend in average polling cycle time when the traffic load increases. However, compared to the results shown in Fig. 7(a), it can be observed that the average polling cycle times of the four schemes decrease when the network environment is changed from 1G-EPON to 10G-EPON. This is because less time is needed to transmit the same amount of data as the link rate increases. In addition, as the UP-OD scheme and the IFL-OS scheme can completely mask the ONU propagation delays and therefore their polling cycle times are completely decided by data volume, their average polling cycle times are decreased effectively by the link rate increasing. Under the load of 0.6, the UP-OD scheme and the IFL-OS scheme are shown to reduce the average polling cycle time by 99.1% (98.1%) and 97.5% (94.5%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. Clearly, compared to the results in the 1G-EPON case, the average polling cycle time reductions of the two proposed schemes are improved in the 10G-EPON case. This means that it is important to completely mask ONU propagation delays in high speed EPONs as polling cycle time directly affects packet delay performance.

B. AVERAGE PACKET DELAY

1) 1G-EPON CASE

Fig. 8(a) shows the average packet delay performances of the four schemes in the 1G-EPON. For the IPACT-OD scheme and the IPACT-OS scheme, their average packet delays grow gradually with the increasing of the traffic load, and the IPACT-OS scheme has a higher average packet delay than the IPACT-OD scheme because its average polling cycle time is longer than that of the IPACT-OD scheme as shown in Fig. 7(a). Since the IFL-OS scheme has a shorter average polling cycle time than the IPACT-OD scheme due to complete ONU propagation delays masking, the average packet delay of the IFL-OS scheme is lower than that of the IPACT-OD scheme under most load cases. Its average packet delay is around 290 μs under the load range of 0.05-0.4, and then grows to 1614 μs under the load of 0.62. However, when the traffic load is very low, i.e. 0.05-0.1, the IFL-OS scheme shows a higher average packet delay than the IPACT-OD scheme due to the increased propagation delays for those ONUs closing to the passive splitter and the low channel utilization efficiency caused by inadaptable polling cycle time and the additional allocated bandwidth. For the UP-OD scheme, it has the lowest average packet delay among all the four schemes. This is because the UP-OD scheme has short and adaptable polling cycle time and does not induce additional propagation delay for those ONUs closing to the passive splitter. The average packet delay of the UP-OD scheme is around 180 μs under the load range of 0.05-0.3 and grows to 525 μs under the load of 0.62. It is shown that under the load of 0.6, the UP-OD scheme and the IFL-OS scheme can reduce the average packet delay by 90.4% (80.3%) and 83.4% (65.7%) compared with the IPACT-OS (IPACT-OD) scheme, respectively.

2) 10G-EPON CASE

The average packet delay performances of the four schemes in the 10G-EPON are shown in Fig. 8(b). Compared to the results obtained in the 1G-EPON, as average polling cycle time is decreased and packet transmission delay is reduced, all the four schemes have lower average packet delays in the 10G-EPON. Also, it can be observed that the low delay advantage of the two proposed schemes (the UP-OD scheme and the IFL-OS scheme) over the two conventional schemes (the IPACT-OD scheme and the IPACT-OS scheme) is increased in the 10G-EPON, because the polling cycle times of the two proposed schemes are strongly benefited from link rate increasing due to their complete data volume decided polling cycle time feature (as explained in the 10G-EPON case part of the average polling cycle time comparison). Under the load of 0.6, the UP-OD scheme and the IFL-OS scheme are shown to reduce the average packet delay by 94.3% (88.1%) and 93.5% (86.3%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. These results indicate that with link rate growing, completely masking ONU propagation delays becomes increasingly effective in reducing network delay.

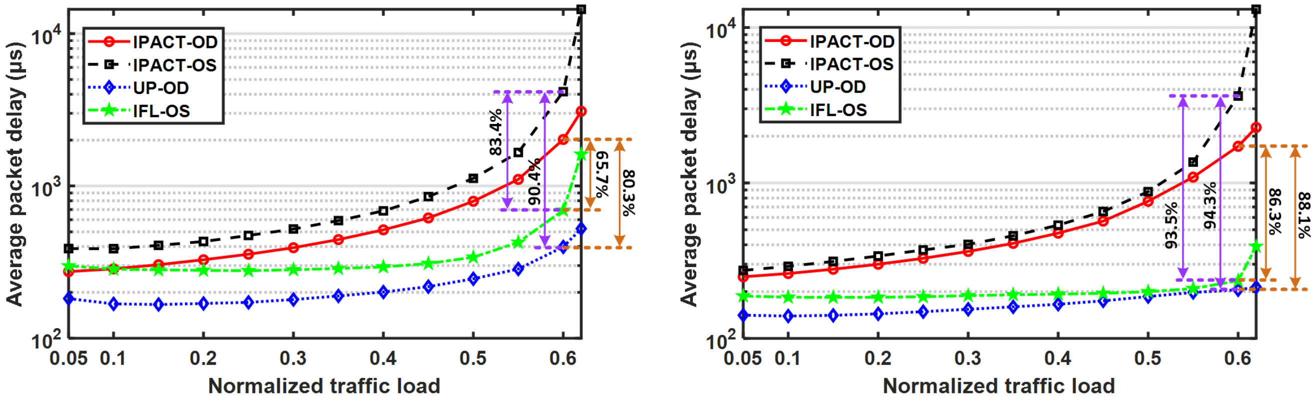
C. DELAY VALUE SATISFIED BY 95% OF PACKETS

1) 1G-EPON CASE

Considering the fact that for delay-sensitive services, where the network delay bound is more important than the average network delay value, the delay value satisfied by 95% of packets (note as D_{95}) is measured. Corresponding results obtained in the 1G-EPON are shown in Fig. 9(a). Since this article focuses on delivering services requiring 1 ms delay, a pink dashed line at 1 ms is plotted as well for reference. It is shown that in general, the D_{95} performances of the four schemes match the average packet delay performances (i.e. the IPACT-OS scheme > the IPACT-OD scheme > the IFL-OS scheme > the UP-OD scheme). Under the load of 0.6, the UP-OD scheme and the IFL-OS scheme are observed to reduce the D_{95} by 86.5% (76.4%) and 79.3% (63.9%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. Also, it can be seen that the D_{95} values of the two proposed schemes reach the 1 ms line under much higher loads (under the load of 0.59 for the IFL-OS scheme and under the load of 0.62 for the UP-OD scheme) than those of the IPACT-OS scheme (under the load of 0.42) and the IPACT-OD scheme (under the load of 0.48), which means that completely masking ONU propagation delays can significantly improve network throughput in delivering low-latency services.

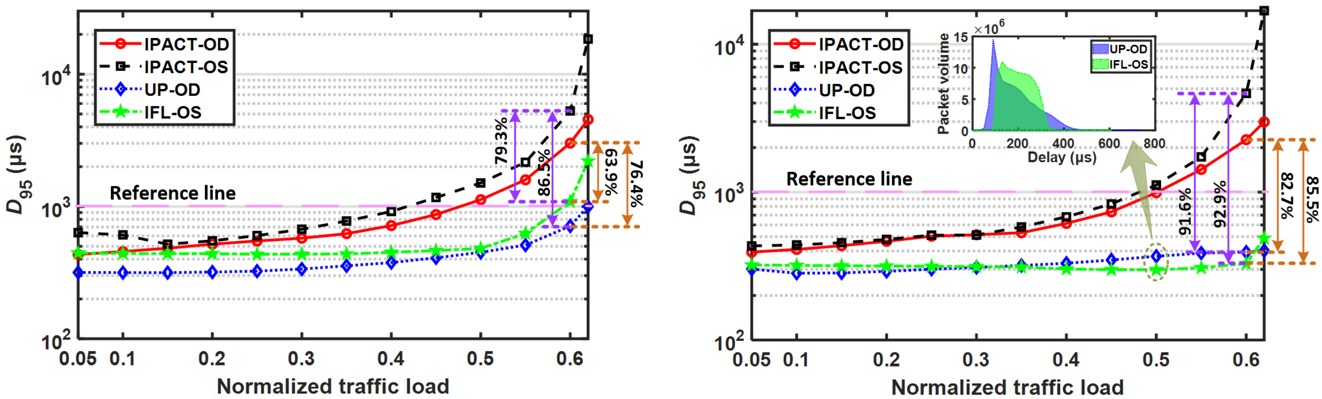
2) 10G-EPON CASE

Fig. 9(b) shows the D_{95} performances of the four schemes in the 10G-EPON. Compared to the results obtained in the 1G-EPON, it is easy to understand that the D_{95} values of the four schemes drop as the link rate increases. As complete ONU propagation delays masking strongly benefits packet delay reduction when link rate is high, the advantage of the UP-OD scheme and the IFL-OS scheme over the IPACT-OD scheme and the IPACT-OS scheme in term of D_{95} is significant in the 10G-EPON. Under the load of 0.6, the UP-OD scheme and the IFL-OS scheme are shown to reduce the D_{95} by 91.6% (82.7%) and 92.9% (85.5%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. It is worth noting that unlike the performances in the 1G-EPON, the IFL-OS scheme in the 10G-EPON is observed to lead the board with the lowest D_{95} under the load range of 0.35-0.6. This is because the packet delay distribution of the IFL-OS scheme is



(a) (b)

FIGURE 8. Average packet delay comparison in: (a) 1G-EPON; (b) 10G-EPON.



(a) (b)

FIGURE 9. Delay value satisfied by 95% of packets in: (a) 1G-EPON; (b) 10G-EPON.

more centralized than that of the UP-OD scheme, as shown in the inset of Fig. 9(b). As the average packet delay difference between the UP-OD scheme and the IFL-OS scheme reduces with the link rate increasing and the difference is relatively small in the 10G-EPON under the load range of 0.35-0.6, the IFL-OS scheme shows a lower D_{95} than the UP-OD scheme. From Fig. 9(b), it can be seen that the IPACT-OS scheme, the IPACT-OD scheme, the UP-OD scheme, and the IFL-OS scheme can ensure 95% of their packets below the 1 ms delay constraint as long as the traffic load does not exceed 0.48, 0.50, 0.62, and 0.62, respectively.

D. ENERGY CONSUMPTION PER BIT OF DATA SATISFYING 1 ms DELAY CONSTRAINT

1) 1G-EPON CASE

The energy efficiency performances of the four schemes are evaluated by comparing the energy consumption to transmit per bit of data satisfying the 1 ms delay constraint (note as $ECPBD_1$). As shown in Fig. 10(a), in the 1G-EPON, with the traffic load increasing, all the four schemes show a downward trend at first and then go up. This is mainly because under low traffic load, almost all packets satisfy the 1 ms delay constraint and therefore the increment on traffic load means increasing number of packets being transmitted, and hence the $ECPBD_1$ decreases. However, with the further growth of traffic load, as packet delay increases and the number of packets satisfying the 1 ms delay constraint drops, the $ECPBD_1$ rises. Under low traffic load, as ONU in sleep mode consumes less power than in doze mode, the schemes adopting ONU sleep mode (i.e. the IPACT-OS scheme and the IFL-OS scheme) show a lower $ECPBD_1$ than the schemes adopting ONU doze mode (i.e. the IPACT-OD scheme and the UP-OD scheme). Also, under low traffic load, the IPACT-OS scheme and the IPACT-OD scheme are observed to have a slightly lower $ECPBD_1$ than their counterpart scheme that adopting the same ONU low power mode for the reason that their ONUs can stay in low power mode for relatively longer periods due to their relatively longer polling cycle times. However, with the traffic load increasing, as the IPACT-OS

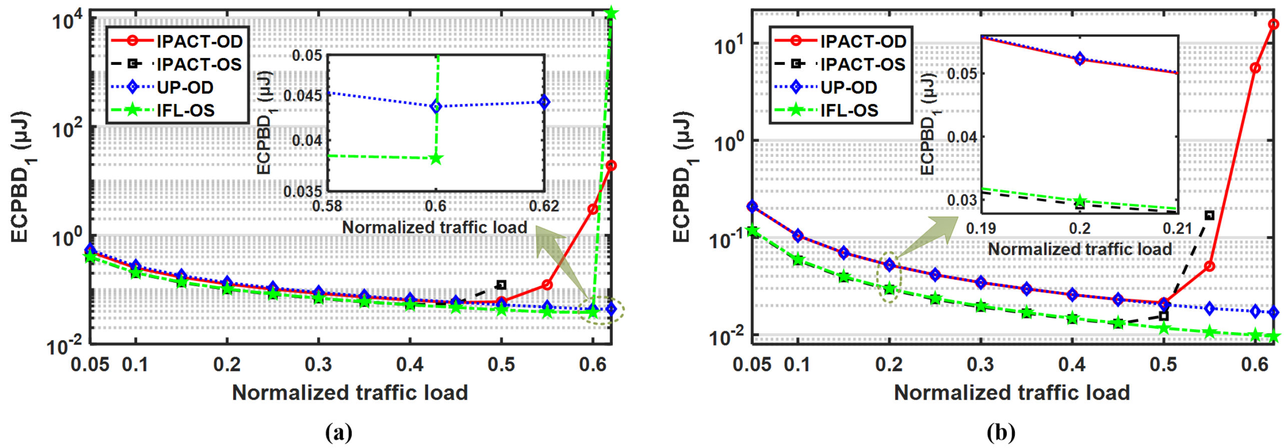
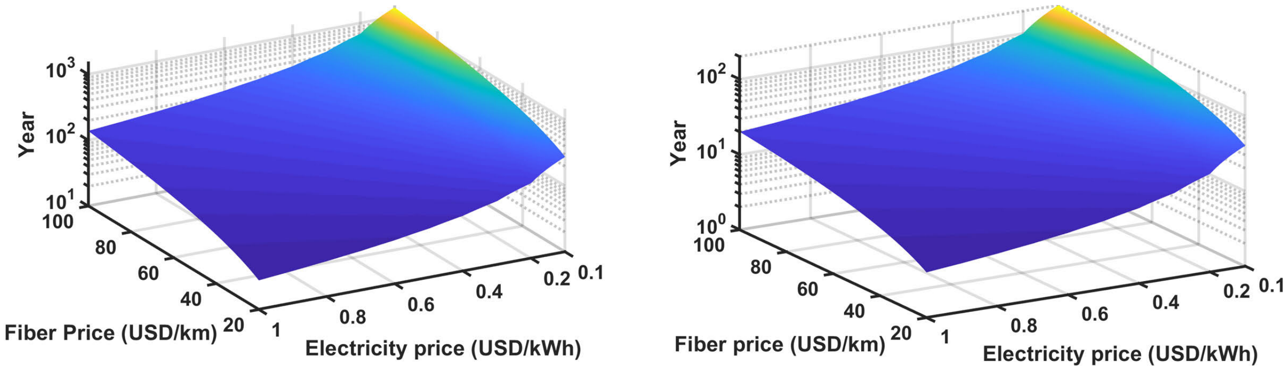


FIGURE 10. Energy consumption to transmit per bit of data satisfying the 1 ms delay constraint comparison in: (a) 1G-EPON; (b) 10G-EPON.

scheme and the IPACT-OD scheme have relatively higher average packet delays, their numbers of packets satisfying the 1 ms delay constraint fall quickly, and the IPACT-OS scheme and the IPACT-OD scheme show an upward trend in $ECPBD_1$ after the load exceeds 0.4 and 0.45, respectively, which are lower than their counterpart scheme that adopting the same ONU low power mode (i.e. load of 0.6 for both the UP-OD scheme and the IFL-OS scheme). Therefore, the IFL-OS scheme becomes the most energy-efficient scheme in term of $ECPBD_1$ after the load reaches 0.4, and the IPACT-OS scheme becomes the most energy-inefficient scheme in term of $ECPBD_1$ after the load reaches 0.5. It needs to be mentioned that the figure for the IPACT-OS scheme ends at the load of 0.5 because when the traffic load is above 0.5, the number of packets satisfying the 1 ms delay constraint is almost zero in the IPACT-OS scheme, and hence the data are neglected. When the traffic load increases to 0.62, the $ECPBD_1$ of the IFL-OS scheme rockets up since the number of packets satisfying the 1 ms delay constraint drops extremely quick. As a consequence, the UP-OD scheme shows a lower $ECPBD_1$ than the IFL-OS scheme under the load of 0.62 as it can adapt its polling cycle time dynamically and therefore can still keep a considerable proportion of its packets satisfying the 1 ms delay constraint. From Fig. 10(a), it can be observed that the lowest $ECPBD_1$ achieved by each scheme is: 0.0578 μJ for the IPACT-OD scheme under the load of 0.45, 0.0530 μJ for the IPACT-OS scheme under the load of 0.4, 0.0437 μJ for the UP-OD scheme under the load of 0.6, and 0.0382 μJ for the IFL-OS scheme under the load of 0.6, respectively. That is, the UP-OD scheme and the IFL-OS scheme can decrease the lowest $ECPBD_1$ value by 17.5% (24.4%) and 27.9% (33.9%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. These results intuitively prove the energy saving advantage of the UP-OD scheme and the IFL-OS scheme in delivering low-latency services over EPONs, and also indicate that the IFL-OS scheme is the most energy-efficient scheme in delivering data with the 1 ms delay constraint as it can achieve the lowest $ECPBD_1$ among the four schemes.

2) 10G-EPON CASE

Fig. 10(b) shows the $ECPBD_1$ performances of the four schemes in the 10G-EPON. Under low traffic load, similar to the trend in the 1G-EPON, the $ECPBD_1$ performances of the four schemes drop with the increasing of the traffic load, and the IPACT-OS scheme and the IFL-OS scheme show a lower $ECPBD_1$ than the IPACT-OD scheme and UP-OD scheme because almost all packets satisfy the 1 ms delay constraint and an ONU could save more energy in sleep mode than in doze mode. Also, under low traffic load, the IPACT-OS scheme and the IPACT-OD scheme are having a slightly lower $ECPBD_1$ than their counterpart scheme that adopting the same ONU low power mode, because their ONUs can stay in low power mode for relatively longer periods due to their relatively longer polling cycle times. However, when the traffic load grows, as packet delay increases and few packets are able to meet the 1 ms delay constraint, the $ECPBD_1$ performances of the IPACT-OD scheme and the IPACT-OS scheme start to rise after the load reaches 0.45 and 0.5, respectively. Nevertheless, for the UP-OD scheme and the IFL-OS scheme, their $ECPBD_1$ performances keep dropping in the whole load range as most of their packets still satisfy the 1 ms delay constraint as shown in Fig. 9(b). From Fig. 10(b), it can be observed that the IPACT-OS scheme reaches its lowest $ECPBD_1$ value of 0.0130 μJ under the load of 0.45, the IPACT-OD scheme reaches its lowest $ECPBD_1$ value of 0.0213 μJ under the load of 0.5, the UP-OD scheme reaches its lowest $ECPBD_1$ value of 0.0170 μJ under the load of 0.62, and the IFL-OS scheme reaches its lowest $ECPBD_1$ value of 0.0096 μJ under the load of 0.62, respectively. That is, the UP-OD scheme and the IFL-OS scheme can decrease the lowest $ECPBD_1$ value by -30.8% (20.2%) and 26.2% (54.9%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. Clearly, the IFL-OS scheme is still the most



(a) (b)

FIGURE 11. Capital cost recovery time evaluation for: (a) 1G-EPON; (b) 10G-EPON.

TABLE 3. Performance promotions summary.

Scheme	Reduction in average polling cycle time (traffic load: 0.6)	Reduction in average packet delay (traffic load: 0.6)	Reduction in D_{95} (traffic load: 0.6)	Reduction in lowest $ECPBD_1$ value
UP-OD	1G-EPON: 95.8% reduction compared with the IPACT-OS scheme; 91.1% reduction compared with the IPACT-OD scheme.	1G-EPON: 90.4% reduction compared with the IPACT-OS scheme; 80.3% reduction compared with the IPACT-OD scheme.	1G-EPON: 86.5% reduction compared with the IPACT-OS scheme; 76.4% reduction compared with the IPACT-OD scheme.	1G-EPON: 17.5% reduction compared with the IPACT-OS scheme; 24.4% reduction compared with the IPACT-OD scheme.
	10G-EPON: 99.1% reduction compared with the IPACT-OS scheme; 98.1% reduction compared with the IPACT-OD scheme.	10G-EPON: 94.3% reduction compared with the IPACT-OS scheme; 88.1% reduction compared with the IPACT-OD scheme.	10G-EPON: 91.6% reduction compared with the IPACT-OS scheme; 82.7% reduction compared with the IPACT-OD scheme.	10G-EPON: 30.8% increment compared with the IPACT-OS scheme; 20.2% reduction compared with the IPACT-OD scheme.
IFL-OS	1G-EPON: 88.5% reduction compared with the IPACT-OS scheme; 75.6% reduction compared with the IPACT-OD scheme.	1G-EPON: 83.4% reduction compared with the IPACT-OS scheme; 65.7% reduction compared with the IPACT-OD scheme.	1G-EPON: 79.3% reduction compared with the IPACT-OS scheme; 63.9% reduction compared with the IPACT-OD scheme.	1G-EPON: 27.9% reduction compared with the IPACT-OS scheme; 33.9% reduction compared with the IPACT-OD scheme.
	10G-EPON: 97.5% reduction compared with the IPACT-OS scheme; 94.5% reduction compared with the IPACT-OD scheme.	10G-EPON: 93.5% reduction compared with the IPACT-OS scheme; 86.3% reduction compared with the IPACT-OD scheme.	10G-EPON: 92.9% reduction compared with the IPACT-OS scheme; 85.5% reduction compared with the IPACT-OD scheme.	10G-EPON: 26.2% reduction compared with the IPACT-OS scheme; 54.9% reduction compared with the IPACT-OD scheme.

energy-efficient scheme in delivering data with the 1 ms delay constraint. However, opposite to the result in the 1G-EPON, the UP-OD scheme underperforms the IPACT-OS scheme in term of the lowest achievable $ECPBD_1$ in the 10G-EPON because for 10G-EPON ONU, sleep mode consumes much less power than doze mode.

E. PRACTICAL VALUE DISCUSSION

The above evaluations have shown that the IFL-OS scheme is the most energy-efficient scheme for delivering services requiring 1 ms delay over an EPON. However, noting that for the IFL-OS scheme, the energy saving performance is achieved at the cost of deploying additional fibers, the capital cost and energy saving tradeoff needs to be evaluated to discuss the practical value of the scheme.

1) 1G-EPON CASE

The evaluation is firstly conducted for the 1G-EPON case. The UP-OD scheme is selected as the counterpart since it is a completely software-based scheme and can achieve lower $ECPBD_1$ than the conventional schemes. Considering the load level where the IFL-OS scheme and the UP-OD scheme achieve their lowest $ECPBD_1$ values, 0.6 is set as the traffic load. Fig. 11(a) shows the capital cost recovery time versus fiber price and electricity price for the 1G-EPON case. It is indicated that with fiber price dropping and electricity price rising, the capital cost recovery time decreases, and with a low fiber price and a high electricity price, e.g. 20 USD/km for fiber (available from the product in [35]) and 0.36 USD/kWh for electricity (available in Germany [36]), the capital cost can be returned after 76.87 years. Obviously, this time is far beyond the typical 20 year lifetime of an access network [37], and therefore the UP-OD scheme would be a proper choice for energy-efficient delivery of services requiring 1 ms delay over a 1G-EPON.

2) 10G-EPON CASE

For the 10G-EPON case, according to the best $ECPBD_1$ achieved by the IFL-OS scheme, 0.62 is set as the traffic load. It should be mentioned here that although the IPACT-OS scheme can achieve lower $ECPBD_1$ than the UP-OD scheme, it cannot afford any <1 ms delay packet under the load of 0.62, and therefore, the UP-OD scheme is still considered as the counterpart. Fig. 11(b) shows the capital cost recovery time versus fiber price and electricity price for the 10G-EPON case. When the fiber price drops and the electricity price rises, the overall trend of the capital cost recovery time is the same as that in the 1G-EPON case. However, as the relative energy saving in term of $ECPBD_1$ is significant in the 10G-EPON, it is shown that with the fiber price at 20 USD/km and the electricity price at 0.36 USD/kWh, the capital cost can be returned after 11.11 years. Therefore, for a 10G-EPON, the IFL-OS scheme is a promising option for delivering services requiring 1 ms delay. Besides, as the IFL-OS scheme brings other benefits such as reducing receiving power fluctuation at OLT without tuning ONU transmitting power, and considering the fact that the actual energy-harvesting time of the IFL-OS scheme is much longer than the lifetime of a network as fibers can still be used after network upgrade, the real profit of applying the IFL-OS scheme is believed more than the above evaluation. Therefore, in practice, the IFL-OS scheme should be a considerable solution to realize energy-efficient delivery of services requiring 1 ms delay over a 10G-EPON.

V. CONCLUSION

In this article, two schemes, namely the UP-OD scheme and the IFL-OS scheme, are proposed and studied to deal with the heterogeneous ONU propagation delays problem for future energy-efficient and low-latency EPON. The UP-OD scheme properly postpones the upstream transmissions of ONUs and incorporates ONU doze mode during transmission intervals to achieve network delay reduction and energy saving, whereas the IFL-OS scheme adopts an identical distribution fiber length for ONUs and incorporates ONU sleep mode during transmission intervals to realize network delay reduction and energy saving. The two schemes are evaluated and compared with two conventional IPACT based schemes under both 1G-EPON and 10G-EPON environments in terms of average polling cycle time, average packet delay, D_{95}, and $ECPBD_1$. Table 3 summarizes the performance promotions of the two proposed schemes. It is shown that under the normalized load of 0.6, the UP-OD scheme can:

(a) in the 1G-EPON, reduce the average polling cycle time by 95.8% (91.1%) compared with the IPACT-OS (IPACT-OD) scheme;
(b) in the 10G-EPON, reduce the average polling cycle time by 99.1% (98.1%) compared with the IPACT-OS (IPACT-OD) scheme;
(c) in the 1G-EPON, reduce the average packet delay by 90.4% (80.3%) compared with the IPACT-OS (IPACT-OD) scheme;
(d) in the 10G-EPON, reduce the average packet delay by 94.3% (88.1%) compared with the IPACT-OS (IPACT-OD) scheme;
(e) in the 1G-EPON, reduce the D_{95} by 86.5% (76.4%) compared with the IPACT-OS (IPACT-OD) scheme;
(f) in the 10G-EPON, reduce the D_{95} by 91.6% (82.7%) compared with the IPACT-OS (IPACT-OD) scheme.

In the 1G-EPON and the 10G-EPON, the UP-OD scheme can also reduce the lowest $ECPBD_1$ value by 17.5% (24.4%) and −30.8% (20.2%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. For the IFL-OS scheme, under the same network load of 0.6, it can:

(a) in the 1G-EPON, reduce the average polling cycle time by 88.5% (75.6%) compared with the IPACT-OS (IPACT-OD) scheme;
(b) in the 10G-EPON, reduce the average polling cycle time by 97.5% (94.5%) compared with the IPACT-OS (IPACT-OD) scheme;
(c) in the 1G-EPON, reduce the average packet delay by 83.4% (65.7%) compared with the IPACT-OS (IPACT-OD) scheme;
(d) in the 10G-EPON, reduce the average packet delay by 93.5% (86.3%) compared with the IPACT-OS (IPACT-OD) scheme;
(e) in the 1G-EPON, reduce the D_{95} by 79.3% (63.9%) compared with the IPACT-OS (IPACT-OD) scheme;
(f) in the 10G-EPON, reduce the D_{95} by 92.9% (85.5%) compared with the IPACT-OS (IPACT-OD) scheme.

In the 1G-EPON and the 10G-EPON, the IFL-OS scheme is also able to reduce the lowest $ECPBD_1$ value by 27.9% (33.9%) and 26.2% (54.9%) compared with the IPACT-OS (IPACT-OD) scheme, respectively. These results clearly show that the two proposed schemes decrease network delay effectively compared with the two conventional schemes, especially in the 10G-EPON case, and the IFL-OS scheme is more energy-efficient than the UP-OD scheme in delivering services with the 1 ms delay constraint. The practical values of the two proposed schemes are discussed as well, and it is found that the UP-OD scheme is fit for 1G-EPONs to deliver services requiring 1 ms delay, whereas the IFL-OS scheme is competitive for 10G-EPONs to deliver services requiring 1 ms delay.

The limitation of this study is that it sets bandwidth allocations for a pair of upstream transmission and downstream transmission to be identical, and therefore it ignores the fact that in a practical network with various traffics and services the bandwidth requirements of an ONU in upstream direction and downstream direction may not be the same at one moment. In future, we will take traffic types and service types into consideration and will investigate how to allocate asymmetric bandwidth to ONUs to achieve the best delay and energy saving performance in an EPON with heterogeneous ONU propagation delays.

APPENDIX I

The polling cycle time of the IFL-OS scheme is calculated as follows.

We consider that traffic is evenly distributed to each ONU and we analyze upstream transmissions. For an ONU in the IFL-OS scheme, its data delivery time in an upstream transmission is:

$$T_{ONU} = T_{REPORT} + \overline{N_{packet}}\,\overline{T_{packet}}, \quad (8)$$

where T_{REPORT}, $\overline{N_{packet}}$, and $\overline{T_{packet}}$ are the REPORT transmission time (including a gap time), the average number of packets to deliver in a transmission, and the average data packet transmission time (including a gap time), respectively. Then, the polling cycle time can be expressed as:

$$T_{cycle} = NT_{ONU}, \quad (9)$$

where N is the number of ONUs. Clearly, for each ONU, the volume of data occurred in a polling cycle should be equal to the volume of data transmitted in a transmission. Therefore, we can have:

$$\overline{N_{packet}} = T_{cycle}R_{packet\_occur}/N. \quad (10)$$

Here, R_{packet_occur} represents the average network data packet arrival rate. Substituting $\overline{N_{packet}}$ of (10) based on (8) and (9), we have:

$$T_{cycle} = N(T_{REPORT} + T_{cycle}R_{packet\_occur}\overline{T_{packet}}/N), \quad (11)$$

which means:

$$T_{cycle} = \frac{NT_{REPORT}}{1 - R_{packet\_occur}\overline{T_{packet}}}. \quad (12)$$

Then, in this case, the average bandwidth (in time unit) needed for a transmission of an ONU is:

$$BW = \frac{T_{cycle}R_{packet\_occur}\overline{T_{packet}}}{N} = \frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1 - R_{packet\_occur}\overline{T_{packet}}}. \quad (13)$$

As traffic will fluctuate between polling cycles, an additional bandwidth BW_{add} should be available. Hence, the maximum allowable bandwidth is set to:

$$BW_{\max} = \frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1 - R_{packet\_occur}\overline{T_{packet}}} + BW_{add}, \quad (14)$$

and the polling cycle time is calculated as:

$$T_{cycle} = N\left(\frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1 - R_{packet\_occur}\overline{T_{packet}}} + BW_{add} + T_{REPORT}\right). \quad (15)$$

Note: If maximum polling cycle time is set and T_{cycle} calculated from (15) exceeds the maximum polling cycle time, then T_{cycle} will be set equal to the maximum polling cycle time, and the maximum allowable bandwidth is set to:

$$BW_{\max} = \frac{T_{cycle}}{N} - T_{REPORT}. \quad (16)$$

APPENDIX II

The polling cycle time of the IPACT-OS scheme is calculated as follows.

Similarly, we analyze upstream transmissions and consider that traffic is evenly distributed to each ONU. Using the same notations as in Appendix I, for an ONU in the IPACT-OS scheme, its data delivery time in a transmission is:

$$T_{ONU} = T_{REPORT} + \overline{N_{packet}}\,\overline{T_{packet}}. \quad (17)$$

Then, the polling cycle time is:

$$T_{cycle} = NT_{ONU} + 2(T_{propagation\_longest} - T_{propagation\_shortest}), \quad (18)$$

where $T_{propagation\_longest}$ and $T_{propagation\_shortest}$ refer to the longest propagation delay and the shortest propagation delay among the ONUs, respectively. Considering that for each ONU, the volume of data occurred in a polling cycle should be equal to the volume of data transmitted in a transmission, we can have:

$$\overline{N_{packet}} = T_{cycle}R_{packet\_occur}/N. \quad (19)$$

Substituting $\overline{N_{packet}}$ of (19) based on (17) and (18), we have:

$$T_{cycle} = \frac{NT_{REPORT} + 2(T_{propagation\_longest} - T_{propagation\_shortest})}{(1 - R_{packet\_occur}\overline{T_{packet}})}. \quad (20)$$

With this polling cycle time, the average bandwidth (in time unit) needed for a transmission of an ONU is:

$$BW = \frac{T_{cycle}R_{packet\_occur}\overline{T_{packet}}}{N} = \frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1 - R_{packet\_occur}\overline{T_{packet}}} + \frac{2(T_{propagation\_longest} - T_{propagation\_shortest})R_{packet\_occur}\overline{T_{packet}}}{(1 - R_{packet\_occur}\overline{T_{packet}})N}. \quad (21)$$

Adding an additional bandwidth BW_{add}, the maximum allowable bandwidth in the IPACT-OS scheme is:

$$BW_{\max} = \frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1 - R_{packet\_occur}\overline{T_{packet}}} + BW_{add} + \frac{2(T_{propagation\_longest} - T_{propagation\_shortest})R_{packet\_occur}\overline{T_{packet}}}{(1 - R_{packet\_occur}\overline{T_{packet}})N}, \quad (22)$$

Therefore, the polling cycle time of the IPACT-OS scheme is calculated as:

$$T_{cycle} = N\left(\frac{T_{REPORT}R_{packet\_occur}\overline{T_{packet}}}{1 - R_{packet\_occur}\overline{T_{packet}}} + BW_{add} + T_{REPORT} + \frac{2(T_{propagation\_longest} - T_{propagation\_shortest})R_{packet\_occur}\overline{T_{packet}}}{(1 - R_{packet\_occur}\overline{T_{packet}})N}\right)$$

$$+2(T_{propagation\_longest}-T_{propagation\_shortest}). \quad (23)$$

Note: If maximum polling cycle time is set and T_{cycle} calculated from (23) exceeds the maximum polling cycle time, then T_{cycle} will be set equal to the maximum polling cycle time, and the maximum allowable bandwidth is set to:

$$BW_{\max}=\frac{T_{cycle}-2(T_{propagation\_longest}-T_{propagation\_shortest})}{N}-T_{REPORT}. \quad (24)$$

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