Design and Analysis of a WDM EPON for Supporting Private Networking and Differentiated Services

Hui-Tang Lin, Chia-Lin Lai, Wang-Rong Chang, and Sheng-Jhe Hong

Abstract—Although EPONs have been proposed as a means of overcoming the bandwidth bottleneck problem in local access networks, they may not be able to meet the ever-growing bandwidth demand from users in the near future. Accordingly, this study presents what we believe to be a novel wavelength-division-multiplexing (WDM) Ethernet passive optical network (EPON) system based on an arrayed-waveguide-grating (AWG) module to meet the rapidly increasing bandwidth demand anticipated in the future. The use of the AWG enables the proposed WDM EPON architecture to achieve wavelength spatial reuse and to provide an intercommunication capability between optical network units (ONUs). As a result, the architecture not only allows upstream access to the central office, but also facilitates a truly shared LAN capability among the end users. Furthermore, the proposed WDM EPON scheme takes account of the requirement for backward compatibility with the IEEE 802.3ah multipoint control protocol and incorporates a dynamic bandwidth allocation scheme and a quality-of-service provisioning mechanism to arbitrate the access of the individual ONUs over the WDM layer. An analytical framework is developed for evaluating the mean packet delay and mean queue length of the proposed WDM EPON system. The analytical results derived using this framework are found to be in good agreement with those obtained from computer simulations.

Index Terms—EPONs; Private networking; QoS; WDM; Wavelength spatial reuse.

I. INTRODUCTION

Ethernet passive optical networks (EPONs) [1,2] have emerged as a promising solution for resolving the bandwidth bottleneck between end users and backbone networks in recent years, and they have attracted significant attention due to their inherent simplicity, longevity, low operational costs, and huge bandwidth. However, with the rapidly increasing number of end users and the proliferation of emerging applications, the volume of network traffic carried by access networks is increasing rapidly, and thus current single-channel EPON architectures are no longer adequate. Therefore, an urgent requirement exists to upgrade the capabilities of EPONs such that they can accommodate the huge volume of traffic demands anticipated in the future. One of the most promising solutions for doing so is the wavelength-division-multiplexing (WDM) EPON scheme [3–10], which utilizes WDM techniques to increase the transmission capacity of conventional EPON access networks.

To support the requirement for a private networking capability within an autonomous access environment, e.g., for end users based on a university campus or working within a large-scale private corporation housed in several buildings within close physical proximity, there is a need for the deployment of point-to-point customer communication links to emulate a shared local area network (LAN) within a single PON infrastructure. Many PON systems have been proposed to meet this requirement in recent years. For example, in [11], a fiber Bragg grating (FBG) was installed in the trunk fiber to reflect a predefined wavelength in order to facilitate intercommunication between optical network units (ONUs). Meanwhile, in [12], the authors proposed a system in which each ONU was connected to a star coupler (SC) via two fibers, one of which was used to deliver redirected frames back to the ONU. However, these solutions incurred a high splitting loss since the redirected signals passed through the SC once or twice and thus the maximum permissible number of ONUs within the PON was limited. In an attempt to resolve this prob-
Section IV introduces the proposed QoS provisioning DBA algorithm, and the buffer scheduling scheme. (MAC) protocol, namely, the WDM MPCP protocol, the components of the proposed media access control EPON network, while Section III describes the major mechanism. Section V derives an analytical framework, the authors in [10].

The current study presents what we believe to be a novel WDM EPON system based on an arrayed-waveguide-grating (AWG) module [14–16] to support the requirements of high-speed access networks and to provide private networking capability. The proposed WDM EPON architecture has a full-duplex tree topology, in which a dual-fiber is employed to facilitate simultaneous transmissions in the downstream and upstream directions, respectively. Significantly, the cyclic AWG not only enables the ONUs to access the upstream bandwidth, but also allows them to communicate directly with one another. As a result, the proposed architecture provides an efficient solution for end users seeking a private networking capability. The AWG permits each wavelength in the network to be spatially reused and therefore yields a considerable improvement in the bandwidth utilization. A DBA scheme and a quality-of-service (QoS) provisioning mechanism are proposed to arbitrate the access of the individual ONU to the available upstream wavelengths. Furthermore, an analytical framework is derived for evaluating the packet queuing delay and the mean queue length in the WDM EPON network. The validity of the analytical framework is verified by comparing the results with those obtained from simulations.

The remainder of this paper is organized as follows. Section II introduces the proposed AWG-based WDM EPON network, while Section III describes the major components of the proposed media access control (MAC) protocol, namely, the WDM MPCP protocol, the DBA algorithm, and the buffer scheduling scheme. Section IV introduces the proposed QoS provisioning mechanism. Section V derives an analytical framework to analyze the packet queuing delay and the mean queue length within the WDM EPON system. Section VI compares the analytical and simulation results and investigates the performance of the proposed WDM EPON protocols under a variety of network loads and traffic patterns. Finally, Section VII presents some brief concluding remarks.

II. AWG-BASED WDM EPON ARCHITECTURE

This section commences by providing an overview of the WDM EPON architecture proposed previously by the current authors in [10].

A. Proposed WDM EPON System

The WDM EPON proposed in this study is based on the bidirectional tree topology shown in Fig. 1. The overall network consists of an optical line terminal (OLT), an AWG module, and N ONUs. The OLT is connected to the AWG module through a dual fiber and resides in a central office (CO), where it connects the access network to a metropolitan area network (MAN) or a wide area network (WAN). Each ONU in the network uses an upstream fiber for transmission purposes and a downstream fiber for reception. Basically, an AWG module with degree of \( D \) has \( D \) input ports and output ports. All wavelengths of each input port are routed cyclically to all the \( D \) output ports simultaneously without causing channel collision. Due to the length constrains, please refer to [15,16] for the detailed description of the AWG basic properties.

The AWG module enables the OLT to broadcast its data to all of the ONUs in the downstream direction. In contrast to traditional EPON architectures, ONUs in the WDM EPON system presented in this study can not only send data to the OLT, but can also communicate directly with one another through the AWG module. Therefore, the traffic generated by each ONU can be classified as either private or public. In the former case, the packets are destined for other ONUs attached to the same access network and are served by allowing the ONUs to communicate with one another directly, i.e., through the AWG module rather than through the central OLT. However, in the case of public traffic, the data packets are destined for remote end users attached to a different access network and are therefore routed through a MAN (or a WAN) via the OLT.

Using the AWG module to enable direct ONU–ONU communications has a number of advantages. First, the burden on the border router is substantially reduced since it only needs to forward public traffic to a MAN (or a WAN). Second, the need for an additional Ethernet bridge at the OLT can be avoided if the data frames are redirected by a layer-two bridge rather than a layer-three router and thus the OLT architecture is simplified. Third, the bandwidth waste and the end-to-end delay increase of private traffic forwarding for the meaningless loopback in question is significantly avoided compared with the case of a conventional EPON.
B. Network Hardware Architecture

Figure 2 illustrates the hardware architecture of the proposed WDM EPON system. In this illustrative example, the architecture has a 1:4 OLT:ONU ratio. The bandwidth in each direction is subdivided into four wavelengths \( \{\lambda_0, \lambda_1, \lambda_2, \lambda_3\} \). Wavelengths \( \lambda_0 \) and \( \lambda_1 \) in the upstream fiber are used by the ONUs to transmit data to the OLT or to other ONUs attached to the same access network, while wavelengths \( \lambda_2 \) and \( \lambda_3 \) are used by the OLT to broadcast data to the ONUs via the downstream fiber. Although this network allows the OLT to forward data to the ONUs on multiple wavelengths, in practice, it is reasonable to dedicate a single wavelength, \( \lambda_d \) (i.e., \( \lambda_2 \) in the current example) for the transmission of both control messages and data frames from the OLT to the ONUs.

As illustrated in Fig. 2, the proposed network architecture comprises three major elements, namely, the transmission part, the receiving part, and the AWG module. In the transmitting and receiving parts, each ONU is fitted with a tunable transmitter for data transmission purposes and is equipped with a fixed-tuned receiver array to enable data reception on multiple wavelengths. Therefore, in the downstream fiber, each ONU can simultaneously receive both the data sent from other ONUs on wavelengths \( \lambda_0 \) and \( \lambda_1 \) and the data and control messages sent from the OLT on wavelengths \( \lambda_2 \) and \( \lambda_3 \). In addition, the OLT is fitted with an array of fixed-tuned transmitters (receivers), with each transmitter (receiver) dedicated to one particular wavelength in order to simultaneously deliver (receive) data frames on multiple wavelengths.

The AWG module shown in Fig. 2 is based on a 2 \( \times \) 2 cyclic AWG. The module is connected to the OLT via a splitter, S2, and a combiner, C2, in the downstream and upstream directions, respectively. The 1 \( \times \) 3 splitters S0 and S1 distribute the incoming wavelengths to the two groups of ONUs within the network and to a single 2 \( \times \) 1 combiner, C2. Similarly, two 3 \( \times \) 1 combiners, C0 and C1, integrate the incoming wavelengths from the ONUs and a 1 \( \times \) 2 splitter, S2. The network, thus consists of two 3 \( \times \) 1 optical combiners (i.e., C0 and C1) attached to the AWG input ports and two 1 \( \times \) 3 optical splitters (i.e., S0 and S1) connected to the AWG output ports. A 1 \( \times \) 3 optical splitter (or a 3 \( \times \) 1 combiner) is implemented by cascading two 1 \( \times \) 2 splitters (or 2 \( \times \) 1 combiners). In a typical WDM EPON, the number of ONUs (\( N \)) is greater than the degree of the AWG, i.e., \( N > D \), and is generally an integer multiple of \( D \). Therefore, for a given number of ONUs and a single OLT, a particular network can be constructed in more than one way simply by varying the degree of the AWG. For instance, the network shown in Fig. 2 can also be formed by connecting 16 ONUs to a 4 \( \times \) 4 AWG using four 5 \( \times \) 1 combiners and four 1 \( \times \) 5 splitters and connecting the OLT to the AWG module using a single 4 \( \times \) 1 combiner and one 1 \( \times \) 4 splitter. Note that in the case of maintaining a high number of ONUs within the WDM EPON, the issues related to network scaling (i.e., the splitting losses of the optical splitters and the associated losses of the equipped AWG) may need to be addressed. However, it is beyond the scope of this study.

In the proposed WDM EPON network, it is assumed that the ONUs attached to the same splitter/combiner form a single private group (PG). In other words, given the degree of the AWG device considered in the current example (i.e., \( D = 2 \)), the ONUs can be subdivided into two PGs, with each PG containing two ONUs. (Note that in general, the number of PGs is always identical to the degree of the AWG, \( D \).) To support the simultaneous transmission of public and private traffic, each ONU maintains dedicated buffering spaces for the two different types of traffic, i.e., a single buffering space of public queue for traffic destined for the OLT and \( D \) separate buffering spaces of private queues (one queue per destination PG).

In contrast to the directional properties of the optical splitters/combiners used in conventional EPONs, the cyclic AWG used in the proposed scheme functions as a wavelength-routing device. When transmitting private traffic, the individual data frames on a fiber are routed to different splitters by sending them on different wavelengths. Once the data frames arrive at the appropriate splitter, the private packets are extracted by the ONUs specified in their respective MAC addresses. To facilitate wavelength spatial reuse within the WDM EPON, the AWG permits different data frames to be transmitted on the same data wavelength at the same time but via different AWG input ports. Thus, each data frame on the same data wavelength is routed to a different AWG output port, and hence a considerable improvement in the bandwidth utilization is achieved. If an ONU wishes to commu-

---

Fig. 2. (Color online) Hardware architecture of a WDM EPON.
nicate with an ONU in another PG, it must first determine the particular wavelength that exits the AWG and passes to the splitter associated with that PG. For example, consider the case where ONU 0 in Fig. 2 wishes to send private data to an ONU in PG 1. To achieve this, it must send the data on wavelength $\lambda_1$ to ensure that the transmitted data exits the AWG through output port $O_1$ and therefore passes to splitter $S_1$, which is connected to PG 1.

To enable the OLT to broadcast data frames and control messages to all the ONUs in the downstream direction, it is connected to splitter $S_2$, which spreads all the wavelengths to the two combiners $C_0$ and $C_1$ attached to the AWG input ports. Similarly, combiner $C_2$, which combines all the incoming wavelengths from the two splitters $S_0$ and $S_1$ attached to the AWG output ports, enables each ONU to send upstream traffic on $\lambda_0$ or $\lambda_1$ to the OLT. To avoid the downstream signals sent from the OLT on wavelengths $\lambda_2$ and $\lambda_3$ looping back to the OLT, an optical filter is installed at the output port of combiner $C_2$, which allows only upstream traffic from the ONUs to enter the upstream trunk fiber connected to the OLT.

III. WDM EPON Protocol Design

This section commences by introducing the proposed WDM-MPCP (extended from the original MPCP standardized by IEEE 802.3ah [1]). The WDM DBA algorithm is then introduced. Finally, the proposed private queue scheduling scheme is described.

A. MPCP Extended for WDM EPON

To ensure the compliance of the signaling protocol used in the proposed WDM EPON scheme with the specifications in IEEE 802.3ah, this study extends the conventional MPCP to a WDM-MPCP in order to facilitate the proposed DBA algorithm and private queue scheduling scheme.

In the normal MPCP operation mode, the OLT transmits a GATE message to a particular ONU. A GATE message typically contains a grant start time, a grant length, and a 4 byte timestamp. However, in the proposed WDM EPON scheme, the OLT is required to assign a specific data wavelength for the upstream transmission of private and public traffic from a given ONU, and thus two additional information fields must be added to the reserved fields of the conventional MPCP data unit (MPCPDU), i.e.,

- **Grant Traffic Type** (1 bit): This bit is set to 0 (or 1) to indicate that the corresponding ONU is granted permission to transmit public (or private) traffic.
- **Grant Wavelength** (1 byte): This 8 bit wavelength identifier is used to indicate the assigned wavelength of the transmission grant.

Once the ONU receives the GATE message, it updates its local clock to the time indicated by the timestamp specified by the OLT in order to achieve global synchronization with the OLT. At the grant start time, the ONU starts to transmit its backlogged data and continues transmission until the transmission window expires.

To ensure backward compatibility, WDM-MPCP is specifically designed to enable non-WDM ONUs [i.e., ONUs in conventional time-division-multiplexing (TDM) single-channel EPONs] [4] to coexist alongside WDM ONUs within the WDM EPON. To achieve this, the traffic generated from non-WDM ONUs and the traffic generated from WDM ONUs destined to non-WDM ONUs are both classified as public traffic. In this way, the transmissions to and from non-WDM ONUs can be processed using the public traffic rules defined in WDM-MPCP and WDM interleaved polling with adaptive cycle time (IPACT), as described below.

B. Dynamic Bandwidth Allocation

In conventional EPONs, the well-known IPACT algorithm [17] is one of many possible candidate DBA algorithms proposed to allocate upstream bandwidth for ONUs by enabling the OLT to poll the ONUs individually and to issue transmission grants to each ONU in a round-robin (RR) fashion. However, IPACT cannot support private traffic transmissions among ONUs that share multiple data wavelengths. Therefore, the current study presents a new DBA algorithm, designated as WDM-IPACT, to schedule the transmissions of private and public traffic on different upstream wavelengths.

In WDM-IPACT, an ONU is prevented from immediately sending the REPORT message as soon as the ONU transmits private data for up to the granted window size. In other words, the REPORT message is only permitted to piggyback by the transmission window of public traffic from an ONU. Consequently, the bandwidth demand within the REPORT message generated by an ONU reflects the instantaneous queue lengths of both the public and the private traffic at that ONU.

As shown in Fig. 3, in WDM-IPACT, each polling cycle consists of a public subcycle and a private subcycle. In the public subcycle, the OLT allocates the public bandwidth by sending GATE messages to all of the ONUs within the network. As stated above, the REPORT (RPT) messages sent by the ONUs in this subcycle include a consolidated bandwidth request for both the public and the private traffic in the queues at the ONU. The polling behavior of this subcycle is similar to that of traditional EPON schemes. That is, in the event that an ONU empties its public buffer, it re-
ports this event to the OLT, which responds by granting the ONU zero bytes in the following public subcycle; i.e., the ONU can send a new bandwidth request, but no public data. Regarding the private subcycle, the polling protocol employs an on-demand bandwidth allocation approach. Thus, if an ONU presents a bandwidth request of zero bytes for its private queue in its REPORT message transmitted during the public subcycle, the OLT skips this particular ONU and polls only the other ONUs in the subsequent private subcycle. In other words, the OLT polls only those ONU(s) that has (have) backlogged private packets waiting for a transmission opportunity.

As in IPACT, in each polling cycle of WDM-IPACT, the OLT is allowed to issue a GATE message to the next ONU scheduled for transmission on a data wavelength before the ONU currently using that wavelength has terminated its own transmission. However, unlike IPACT, the OLT does not start the next polling cycle until it has received REPORTs from all of the ONUs in the public subcycle. In other words, the OLT employs the IPACT with a stop policy concept [18]. As shown in Fig. 3, a computation time is introduced between successive scheduling polling cycles in order to make its scheduling decisions based on global knowledge of the current bandwidth requirements. This computation time inevitably incurs a small channel utilization cost since the upstream channel is not utilized for the interval between the moment at which the transmission of the last polled ONU in the previous cycle completes and that at which the transmission of the first polled ONU in the next cycle starts.

1) Polling Policy in Private Subcycle: In the private subcycle, the problem of receiver collisions is prevented since each ONU is equipped with an array of fixed-tuned receivers. However, data channel collisions may occur if multiple granted transmissions on the same data wavelength reach the same combiner from different fibers (i.e., different ONUs) at the same time.

To resolve this problem, the OLT not only evaluates the round-trip time (RTT) associated with each ONU in the network, but also estimates the propagation delay between each ONU and the AWG module. As shown in Fig. 1, the propagation delay of the trunk fiber is denoted as $PROP_T$, while the propagation delay associated with branch fiber $n$, i.e., the propagation delay between the AWG module and ONU $n$ ($n \in \{0, 2, \ldots, N-1\}$), is denoted as $PROP_B^H_n$. Finally, the delay of the AWG module itself is denoted as $PROP_{AWG}$. As a result, the propagation delay from ONU $n$ to the AWG module is given by

$$PROP_B^H_n = \frac{1}{2} \frac{RTT^H_n - PROP_T - PROP_{AWG}}{2}, \quad (1)$$

where $RTT^H_n$ is the time required for a bit to travel from the OLT to ONU $n$ and then back to the OLT. Using $RTT^H_n$ and the propagation delay information computed from Eq. (1), the OLT overcomes the data channel collision problem by applying the simple policy described in the following.

Consider the network architecture shown in Fig. 2 and assume that ONUs 0 and 1 both have private data destined for PG 1. Since the OLT knows the propagation delay between itself and ONU 0, i.e., $1/2 RTT^H_0$, according to the AWG routing rule, it can notify ONU 0 to start transmission on the granted wave-

![Fig. 3. (Color online) Typical polling cycle in proposed WDM IPACT algorithm.](image-url)
length $\lambda_1$ at a certain time index, $T$, by sending a GATE message at time $T-1/2 \ RTT^{[0]}$. Once ONU 0 receives this GATE message, it immediately commences transmission and continues to transmit until the assigned transmission window expires. Furthermore, from Eq. (1), the OLT also knows that the last bit of the transmission from ONU 0 will arrive at the attached combiner C0 (i.e., the AWG module) at an interval of $\text{PROPB}^{[0]}+\ WTT$ after the transmission commences, where $\ WTT$ is the window transmission time. Thus, the OLT can prevent the data channel collision problem simply by scheduling the first bit of ONU 1’s granted transmission on wavelength $\lambda_1$ in such a way that it reaches combiner C0 no sooner than time $T +\text{PROPB}^{[0]}+\ WTT$.

The left part of Fig. 3 illustrates a transmission scenario during the private subcycle of a WDM EPON network with the system structure shown in Fig. 2. Note that an assumption is made here that at the beginning of the private subcycle of polling cycle $P$, the OLT knows (via the REPORT messages received in the public subcycle of polling cycle $P-1$) that ONUs 0, 1, 2, and 3 have made bandwidth requests for private queues 0, 1, 0, and 1, respectively. Due to the spatial-reuse feature of the $2\times2$ AWG, the OLT grants the private traffic transmissions of ONUs 0 and 3 (ONUs 1 and 2) on data wavelength $\lambda_0(\lambda_1)$ to enable the ONUs to transmit their private data simultaneously to PGs 0 and 1 (PGs 1 and 0), respectively. As a result, the available wavelengths within the network are spatially reused when transmitting the private traffic of the various ONUs connected to different combiners. Note that private data collisions would occur at the OLT in this scenario since the transmissions of ONUs 0 and 3 (ONUs 1 and 2) are overlapped in time on data wavelength $\lambda_0(\lambda_1)$ and are routed to the OLT through the combiner, C2. However, since the proposed WDM EPON permits the ONUs to exchange private traffic directly among themselves through the AWG, the issue of private traffic collisions at the OLT is not essential to be concerned with. On the other hand, the private data might arrive at the OLT without collision. The OLT must drop all the received private data in this subcycle; otherwise, these data frames would be forwarded to the attached router or the Ethernet bridge. Consequently, these data frames would come back to the OLT and then be sent to their destination ONUs, causing duplicate private data receptions at ONUs.

2) Polling Policy in Public Subcycle: In the public subcycle, the polling policy employs an efficient bandwidth allocation approach, designated as the first available-wavelength prioritized algorithm (FAPA), to schedule the upstream transmissions of each ONU on the first of the various wavelengths in the upstream fiber to become available [3,5]. (Note that when more than one wavelength can be used to route a granted transmission in the private subcycle, FAPA is also used by the OLT to schedule the earliest idle wavelength to the ONU seeking a transmission opportunity.)

The right part of Fig. 3 illustrates the polling policy executed during the public subcycle in polling cycle $P$. As shown, through the use of an interleaved polling strategy and the FAPA, the public subcycle is established before the private subcycle terminates by permitting the OLT to send a GATE message to grant a 3840 byte public transmission from ONU 0 at a time equivalent to the guard time interval after the preceding 1500 byte private transmission from ONU 3. It can also be seen that after the 3840 byte public transmission is granted permission to transmit, the 640 byte, 2560 byte, and 1280 byte public data transmissions from ONUs 1, 2, and 3, respectively, are scheduled on the earliest idle data wavelength, $\lambda_1$, with a timing such that each transmission is separated from the preceding transmission by a guard time interval.

Since an on-demand polling policy is enforced in the private subcycle, if all the REPORT messages received by the OLT in the public subcycle of polling cycle $P$ indicate a 0 byte private bandwidth requirement, polling cycle $P+1$ involves only a public subcycle. As a consequence, the polling overhead incurred by the private traffic within each polling cycle is eliminated.

3) Maximum Transmission Window Assignment: To prevent the upstream channel from being monopolized by a single ONU with a high volume of transmission data, WDM-IPACT adopts a limited service scheme [17], in which the size of the transmission window granted by the OLT to each ONU in a polling cycle is limited to a maximum value of $W_{\text{MAX}}$ (bits). Since the network traffic includes both public traffic and private traffic, $W_{\text{MAX}}$ comprises two components: the maximum public window size ($W_{\text{MAX, PUB}}$) granted in the public subcycle and the maximum private window size ($W_{\text{MAX, PRI}}$) granted in the private subcycle, i.e., $W_{\text{MAX}}=W_{\text{MAX, PUB}}+W_{\text{MAX, PRI}}$. As discussed above, in the WDM-IPACT algorithm, the REPORT messages issued by the ONUs in the public subcycles request bandwidth for both the public traffic and the private traffic. Therefore, the OLT can determine appropriate values of $W_{\text{MAX, PUB}}$ and $W_{\text{MAX, PRI}}$ for a given ONU on a dynamic basis by observing the ratio of public traffic to private traffic at that particular ONU. Consequently, the values of $W_{\text{MAX, PUB}}$ and $W_{\text{MAX, PRI}}$ assigned to each ONU in the public and private subcycles, respectively, are given by

$$W_{\text{MAX, PUB}} = \frac{\delta_{\text{PUB}}}{\delta} \times W_{\text{MAX}},$$

(2)
$W_{\text{MAX,PRI}} = \frac{\delta_{\text{PRI}}}{\delta} \times W_{\text{MAX}}, \quad (3)$

where $\delta_{\text{PUB}}(\delta_{\text{PRI}})$ is the public (private) traffic load at the ONU and $\delta$ (bits/s) is the total traffic load of the ONU (i.e., $\delta = \delta_{\text{PUB}} + \delta_{\text{PRI}}$). Thus, in the limited service scheme, each ONU receives not one but two GATE messages from the OLT in each polling cycle, namely, one message for the public traffic in the public subcycle and one message for the private traffic in the private subcycle. In both cases, the GATE messages grant the ONU as many bytes as requested in the corresponding REPORT message, but no more than the limits prescribed by $W_{\text{MAX,PUB}}$ and $W_{\text{MAX,PRI}}$, respectively.

### C. Private Queue Scheduling

In general, private queue scheduling mechanisms are responsible for interposing the transmissions of the different private queues at each ONU. This section proposes a simple two-phase RR scheduling scheme to ensure fair access for each private queue and to achieve a full wavelength spatial-reuse capability, i.e., each wavelength is spatially reused $D$ times in every private subcycle. As described in the following, the two-phase RR scheduling scheme comprises two phases, namely, the ONU setup phase and the RR steady-state phase.

1) **ONU Setup Phase:** The ONU setup phase takes place during the initialization of the WDM EPON network. The goal of this setup phase is to initially schedule (assign) a reported private queue for each ONU in the first public subcycle (counted from the moment at which the network first becomes active) in order to achieve full bandwidth spatial reuse in the subsequent private subcycle.

In the following discussions, the connection between input port $x$ (I$_x$) and output port $y$ (O$_y$) of the AWG on wavelength $\lambda_w$ is defined as an AWG routing path $P(x,y,\lambda_w)$, where $x, y \in \{0, 1, \ldots, D-1\}$, $w \in \{0, 1, \ldots, M-1\}$, and $M$ is the number of wavelengths used by the ONUs in the upstream fiber. Since in an AWG with a degree of $D$, each wavelength can be spatially reused $D$ times, the total number of AWG routing paths is equivalent to $A_{\text{ROUTE}} = M \times D$. \quad (4)

To achieve full wavelength spatial reuse, the private transmission grants must be evenly distributed among all the AWG routing paths, i.e., the number of private transmission grants carried by each AWG routing path is given by

$$G_{\text{PRI}} = \frac{N}{A_{\text{ROUTE}}}. \quad (5)$$

To ensure a fair distribution of the private transmission grants across all the available AWG routing paths, the reported private queue ID of each ONU $n$ is hashed to a number in the interval $[0, D-1]$ using the following function:

$$h(n) = n \bmod D. \quad (6)$$

Consider the simple case shown in Fig. 2, in which the ONUs share $M=2$ wavelengths $\{\lambda_0, \lambda_1\}$ in the upstream fiber. The WDM EPON has $N=4$ ONUs, an AWG with degree $D=2$, and $A_{\text{ROUTE}}=4$ AWG routing paths $\{P(0,0,\lambda_0), P(0,1,\lambda_1), P(1,0,\lambda_1), P(1,1,\lambda_0)\}$. From Eq. (5), full wavelength spatial reuse can be achieved by letting each AWG routing path route exactly one private transmission window in each private subcycle. Assume that by applying the hash function given in Eq. (6) in the first public subcycle, ONUs 0, 1, 2, and 3 schedule private queues 0, 1, 0, and 1, respectively, when reporting their initial private bandwidth demands. According to the AWG routing rule, the private queue scheduling strategy results in the OLT assigning a single granted transmission on each AWG routing path, and hence full wavelength spatial reuse is achieved in the subsequent private subcycle.

2) **RR Steady-State Phase:** The RR steady-state phase takes place in all subsequent public subcycles. Starting from the private queue initially scheduled by each ONU in the ONU setup phase, each ONU selects a queue from among all its private queues in accordance with a simple RR technique. This approach ensures that the available bandwidth is fully reused in every private subcycle (assuming that the private queues selected by all the ONUs are nonempty) and is evenly distributed among all the private queues. Therefore, the two-phase RR scheduling scheme not only enhances the bandwidth utilization within the network, but also ensures that all the private queues at the ONUs receive fair access to the network bandwidth resources.

### IV. QoS Provisioning Mechanism

This study adopts the DiffServ framework developed by the Internet Engineering Task Force (IETF) by classifying network traffic into three different priorities, namely, expedited forwarding (EF), assured forwarding (AF), or best effort (BE). In general, existing QoS provisioning mechanisms intended for deployment at the individual ONUs in a TDM EPON are implemented using a strict priority scheduling strategy (defined in IEEE 802.1D, clause 7.7.4) [18,21,22]. In accordance with this strategy, a lower-priority...
queue is scheduled for transmission if, and only if, all of the queues with a higher priority are empty. However, this approach may starve low-priority traffic of the network resources and may therefore cause high packet losses. In [23], the authors simulated the problem of providing differentiated services to EF, AF, and BE traffic, respectively, for the case in which a strict priority scheduling policy was enforced at the ONUs. The results revealed the presence of a so-called light-load penalty phenomenon, i.e., the queuing delay experienced by traffic with a lower priority increased as the network load decreased. The authors proposed two mechanisms for resolving this problem, namely, a two-stage buffer method and a constant-bit-rate credit scheme.

Although the two-stage buffer and constant-bit-rate credit mechanisms provide an effective means of supporting differentiated services in TDM EPONs, they cannot satisfy the QoS requirements of the private and public traffic carried in the proposed WDM EPON. To resolve this problem, the present study extends the two-stage buffer concept presented in [22,23] and implements a two-stage buffering module within each ONU in the network.

A. Stage-I Buffering Space

As shown in Fig. 4, in Stage-I, each ONU is equipped with a buffering space containing three separate priority queues, i.e., one queue for each of the three different classes of traffic. Upon receipt at the ONU, the packets transmitted from the end users are classified by checking the type of service (ToS) field in the IP packets encapsulated in the Ethernet frames and are then buffered in the appropriate priority queue. If a high-priority packet arrives at the ONU, but the corresponding buffer is full, the packet simply displaces a lower-priority packet. Conversely, if a low-priority packet arrives at the ONU and the buffer is full, the arriving packet is dropped [22]. As a result, low-priority traffic may experience excessive delays, increased packet losses, and even resource starvation. This issue can be addressed by implementing the traffic policing scheme at each ONU [19] in order to monitor each type of traffic for conformity with the corresponding maximum arrival rate, as specified in accordance with user-defined criteria.

B. Stage-II Buffering Space

To support differentiated QoS for public and private traffic, in Stage-II, each ONU maintains buffering spaces of one public queue and \( D = 2 \) private queues and each buffering space is shared by three separate traffic priorities that correspond to EF, AF, and BE traffic classes. As a result, the second-stage buffering spaces of one public queue and two private queues all comprise three priority subqueues, i.e., EF, AF, and BE subqueues (see Fig. 4). Packets within each priority queue in Stage-I are delivered via a dedicated packet scheduler and are then buffered into the corresponding priority subqueue at the target buffering space in Stage-II depending on the MAC address observed by the MAC address check module. Since in each ONU, each buffering space at Stage-II consists of three priority subqueues, each ONU in every public subcycle reports the total three priority subqueue occupancies of the public queue and the selected private queue (i.e., the total public queue length and the total selected private queue length) when sending REPORT messages. Hence, in each public (or private) subcycle, data packets are extracted from all of the priority subqueues in the buffering space of the public queue (or in the buffering space of the scheduled private queue) and are then transmitted to the OLT (or ONUs). The buffering spaces vacated by these packets are then occupied by data packets sent from Stage-I in accordance with the service rate, \( \mu_C (C \in \{AF,BF,BE\}) \), given by the packet scheduler to each Stage-I priority queue.

V. Analytical Framework

Although the literature contains various analytical models for analyzing the performance of TDM EPONs [24–26], these models all consider the case of a single-channel EPON environment. By contrast, this section presents an analytical framework for analyzing the performance of the dual-fiber WDM EPON shown in Fig. 1, in which the upstream bandwidth is allocated using the WDM-IPACT algorithm (described in Subsection III.B) and the various QoS requirements of the different traffic classes are satisfied using the two-stage buffering approach (introduced in Section IV).

The analysis presented in this section considers the WDM EPON to consist of a single OLT, \( N \) ONUs, \( M \) available wavelengths used by the ONUs in the upstream fiber, and an AWG module based on an AWG with degree \( D \). In performing the analysis, an assumption is made that the packets from the end users
arrive at each ONU in accordance with a Poisson distribution with a rate $d$ (bits/s) and have a constant size (bits). Furthermore, it is assumed that the network traffic is evenly distributed over all the ONUs and the ONUs are all situated at the same distance from the OLT.

### A. Analysis of Maximum Polling Cycle Time, $T_{\text{MAX}}$

Figure 5 illustrates the various components of the maximum polling cycle time calculation for the case of a WDM EPON with the structure shown in Fig. 2 under a heavy traffic load (i.e., an overloaded condition). Since the OLT employs the proposed two-phase RR private queue scheduling scheme to evenly distribute the granted transmissions over all the AWG routing paths, the number of transmission grants routed by each AWG routing path in the private subcycle is equivalent to $G_{\text{PRI}}=1$ [from Eq. (5)]. Starting from the beginning of the private subcycle, the OLT issues $A_{\text{ROUTE}}=4$ consecutive GATE messages to grant the four ONUs their $W_{\text{MAX,PRI}}$ transmissions on AWG routing paths $P(0,0,\lambda_0)$, $P(0,1,\lambda_1)$, $P(1,0,\lambda_1)$, $P(1,1,\lambda_0)$, respectively. An assumption is made that any of two consecutive GATE messages are separated by a guard time interval, $T_{\text{GUARD}}$. As a result, the maximum private subcycle time, $T_{\text{MAX,PRI}}$, is equivalent to the sum of the transmission times of the four GATE messages, the guard times between these GATEs, the transmission time of a single $W_{\text{MAX,PRI}}$ frame on the last scheduled AWG routing path [i.e., $P(1,0,\lambda_1)$ in the current example] in the private subcycle, the zero guard time of this granted transmission, and the RTT. $T_{\text{MAX,PRI}}$ can therefore be expressed in the following normalized form:

$$T_{\text{MAX,PRI}} = A_{\text{ROUTE}} \frac{S_{\text{GATE}}}{R} + (A_{\text{ROUTE}} - 1)T_{\text{GUARD}} + \frac{G_{\text{PRI}}W_{\text{MAX,PRI}}}{R} + (G_{\text{PRI}} - 1)T_{\text{GUARD}} + \text{RTT},$$  

where $S_{\text{GATE}}$ is the size of the GATE message, and $R$ is the upstream line rate (bits/s) of each wavelength. Since an interleaved polling scheme and the FAPA are applied in each polling cycle, the maximum private subcycle time, $T_{\text{MAX,PRI}}$, and the maximum public subcycle time, $T_{\text{MAX,PUB}}$, are permitted to overlap partially for the time interval between the moment at which the first bit of the first GATE message for the public traffic is issued by the OLT and the moment at which the last bit of the last transmitted $W_{\text{MAX,PRI}}$ frame in the private subcycle arrives at the OLT on wavelength $\lambda_1$ (see Fig. 5). Assuming that the duration of this overlap period is denoted as $T_{\text{OVERLAP}}$, the maximum polling cycle time, $T_{\text{MAX}}$, can be formulated as

$$T_{\text{MAX}} = T_{\text{MAX,PRI}} + (T_{\text{MAX,PUB}} - T_{\text{OVERLAP}}) + T_{\text{COMPU}},$$

where $T_{\text{COMPU}}$ is the computation time duration. Since the OLT simply schedules the granted transmissions to the upstream wavelength that it estimates will become idle earliest, under heavy traffic load conditions, each wavelength shown in Fig. 5 is only permitted to deliver $G_{\text{PUB}}=2W_{\text{MAX,PUB}}$ grants on average, where $G_{\text{PUB}}=N/M$. Therefore, the time $T_{\text{MAX,PUB}} - T_{\text{OVERLAP}}$ is equivalent to the transmission time of the two $W_{\text{MAX,PUB}}$ frames on the last scheduled wavelength $\lambda_1$ in a cycle plus two guard time intervals, and can be formally expressed as

$$T_{\text{MAX,PUB}} - T_{\text{OVERLAP}} = \frac{G_{\text{PUB}}W_{\text{MAX,PUB}}}{R} + G_{\text{PUB}}T_{\text{GUARD}}.$$

Substituting Eqs. (7) and (9) into Eq. (8), the maximum polling cycle time, $T_{\text{MAX}}$, can be formulated in the following normalized form:

$$T_{\text{MAX}} = A_{\text{ROUTE}} \frac{S_{\text{GATE}}}{R} + (A_{\text{ROUTE}} - 1)T_{\text{GUARD}} + \text{RTT} + \frac{G_{\text{PRI}}W_{\text{MAX,PRI}}}{R} + (G_{\text{PRI}} - 1)T_{\text{GUARD}} + \frac{G_{\text{PUB}}W_{\text{MAX,PUB}}}{R} + G_{\text{PUB}}T_{\text{GUARD}} + T_{\text{COMPU}}.$$

### B. Analysis of Stage-I Queues

Obviously, each ONU has the guaranteed ability to send a minimum of $W_{\text{MAX}}$ bits in time $T_{\text{MAX}}$. Thus, the minimum guaranteed bandwidth of each ONU is given by

$$\lambda_{\text{MIN}} = \frac{W_{\text{MAX}}}{T_{\text{MAX}}},$$

However, the bandwidth available to an ONU is only limited to this guaranteed bandwidth if all the other ONUs in the system are currently using all of their available guaranteed bandwidths. If at least one ONU does not consume all its guaranteed bandwidth, it is assigned a shorter transmission window, thus reducing the overall polling cycle time. Therefore, a greater amount of bandwidth is made available to the other ONUs in the network. In other words, the poll-
ing cycle time is not static, but varies dynamically in accordance with changes in the instantaneous network load.

As shown in Fig. 4, packets in the Stage-I priority queues are advanced to the Stage-II public/private queues in accordance with the service rates assigned by the packet scheduler to each of the three traffic classes. In the scheduling strategy, each priority queue is assigned a service share value \( f_C \). To distribute the allocated bandwidth fairly among the different traffic classes, the service share of each traffic class is assigned in accordance with the corresponding traffic load, i.e.,

\[
\frac{\delta_C}{d} = \frac{1}{H_9272} \frac{C}{H_9254/H_9268} C \frac{H_20849}{H_20850},
\]

where \( d_C \) is the traffic load of traffic class \( C \) (\( C \in \{AF, EF, BE\} \)), \( d \) is the total ONU traffic load (i.e., \( \delta = \Sigma C \delta_C \)), and \( \sigma_C \) is a weighting factor assigned to traffic class \( C \) based on its priority (\( \Sigma C \sigma_C = 1 \)). To ensure a fair service to each of the different traffic classes, the service rate provided to each class is determined in accordance with its service share, \( f_C \), i.e.,

\[
\mu_C = \frac{\varphi_C}{\sum C \varphi_C} \Lambda_{MIN}.
\]

(Note that various schemes for assigning an appropriate priority weight to each traffic class, such as bandwidth-based algorithm, jitter-based algorithm, etc., have been studied extensively in [27]. As long as the weights are determined, they can be readily plugged in the proposed model for performance analysis. Therefore, the current study does not prescribe a specific priority weight assignment approach.)

In the present analysis, it is assumed that new packets arrive at the ONUs in accordance with a Poisson process with a rate \( d_C \) and have an exponential service time distribution with a mean \( 1/\mu_C \). The analytical model developed in this study focuses principally on the average packet delay at the ONUs rather than the level of packet losses throughout the network, and thus the priority buffers are assumed to be of an infinite size. As a result, the three priority queues in the Stage-I buffering space are all modeled as \( M/M/1 \) queues. In developing an analytical model for the queuing delay at the Stage-I queues, it is assumed that (1) the Stage-I buffer contains only monoserver stations that operate under a first in first out (FIFO) discipline, (2) the service time is exponentially distributed with a mean \( 1/\mu_C \), and (3) the end user packets arrive at the ONUs in accordance with a Poisson process with a rate \( d_C \). Under these assumptions, the Stage-I queues can be modeled as a mono-class open queuing network, i.e., a Jackson’s network. As a result, the state probability can be expressed as follows:

\[
P(n_{EF}, n_{AF}, n_{BE}) = \prod C P_C(n_C),
\]

where \( p_C(n_C) \) is the marginal probability associated with the priority queue of traffic class \( C \).

As stated above, the present analysis focuses specifically on modeling the average packet delay at the ONUs. Let \( E[D_C] \) denote the average packet delay associated with class \( C \) traffic. To formulate an analytical expression for \( E[D_C] \), it is first necessary to deter-
mine the expected number of packets of this particular type, i.e., \( E[P_C] \), where \( P_C \) is a random variable associated with the number of packets buffered at the priority queue dedicated to traffic class \( C \). In evaluating \( E[P_C] \), it is assumed that the system stability factor, \( \rho_C \), is equal to \( \delta_C/\mu_C \) and the system stability condition is defined as

\[
\rho_C < 1. \tag{15}
\]

Note that all the parameters presented in the current analysis are computed at equilibrium with regard to this queuing network stability condition. Since each priority queue in the Stage-I buffer is treated as an \( M/M/1 \) queue, the expected number of packets buffered in each queue at any moment in time can be estimated as follows:

\[
E[P_C] = \frac{\rho_C}{1-\rho_C} = \frac{\delta_C}{\delta_C - \delta_C}. \tag{16}
\]

The average packet delay associated with traffic class \( C \) can then be computed by applying Little’s formula (i.e., \( L=\lambda W_T \), where \( L \) is the queue length and \( W_T \) is the packet waiting time), i.e.,

\[
E[D_C] = \frac{E[P_C]}{\delta_C} = \frac{1}{\mu_C - \delta_C}. \tag{17}
\]

C. Analysis of Stage-II Queues

This Subsection commences by constructing a recursive model to obtain approximate estimates of the polling cycle time, \( T_{CYCLE} \), for a limited service under an ONU offered load, \( \delta \). The estimated results are then used to compute the packet delay at the Stage-II buffers in the ONU. In estimating the polling cycle time in the limited service discipline, the model explicitly recognizes the fact that successive polling cycle times influence one another [28].

As discussed in the previous section, new packets are assumed to arrive at the priority queues in the Stage-I buffering space in accordance with a Poisson process with a rate \( \delta_C \). To model each \( M/M/1 \) priority queue under equilibrium conditions, the average packet departure rate must be equal to the average packet arrival rate. In other words, the total packet departure rate from the Stage-I priority queues (equivalent to the total packet arrival rate at the Stage-II queues) also conforms to a Poisson process with a rate \( \delta_C \).

It is assumed that the OLT polls the ONUs with the same polling sequence in every polling cycle. Note that in the following analysis, the cycle time is computed from the perspective of the last polled ONU. In the WDM-IPACT scheduling algorithm, the ONUs are unable to transmit a REPORT until they receive a GATE message because they can only request bandwidth when polled by the OLT. The duration of the first polling cycle in the network, i.e., polling cycle 1, therefore comprises a half of the RTT between the OLT and the ONUs, the time required to transmit \( N \) GATE messages, the time required to transmit the REPORT from the last polled ONU, and the sum of the guard time intervals separating these GATE messages. The total duration of polling cycle 1 is therefore given by

\[
T_1 = \frac{S_{GATE}}{R} + (N-1)T_{GUARD} + \frac{1}{2}RTT + \frac{S_{REPORT}}{R}, \tag{18}
\]

where \( S_{REPORT} \) is the size of the REPORT message. The average granted window size for each ONU in polling cycle 2 (i.e., \( W_2 \)) is equivalent to the amount of traffic accumulated during \( T_1 \) (i.e., \( A_1 \)), and can be estimated as

\[
W_2 = W^{PRI}_2 + W^{PUB}_2 = A_1 = (\delta^{PRI} + \delta^{PUB})T_1, \tag{19}
\]

where \( W^{PRI}_2 \) and \( W^{PUB}_2 \) are the private and public transmission windows granted to each ONU in polling cycle 2, respectively. In the successive polling cycles, the duration of any arbitrary polling cycle \( P \) (where \( P>2 \)) can be easily obtained [from Eq. (10)] as

\[
T_P = A_{ROUTE} - \frac{S_{GATE}}{R} + (A_{ROUTE} - 1)T_{GUARD} + RTT + \frac{G^{PRI}_P W^{PRI}_P}{R} + (G^{PRI}_P - 1)T_{GUARD} + \frac{G^{PUB}_P W^{PUB}_P}{R} + G^{PUB}_P T_{GUARD} + T_{COMPU}, \tag{20}
\]

where

\[
W^{PRI}_P + W^{PUB}_P = W_P = A_{P-1} = (\delta^{PRI} + \delta^{PUB})T_{P-1}. \tag{21}
\]

As a result, the following recursive model for calculating the polling cycle time of cycle \( P \) [i.e., \( T(P) \)] can be established:
\[
T(P) = \begin{cases} 
\frac{S_{GATE}}{R} + (N - 1)T_{GUARD} + \frac{1}{2}RTT + \frac{S_{REPORT}}{R}, & \text{if } P = 1, \\
A_{ROUTE} \frac{S_{GATE}}{R} + (A_{ROUTE} - 1)T_{GUARD} + RTT \\
+ \frac{G_{PRI}\delta_{PRI}T(P - 1)}{R} + (G_{PRI} - 1)T_{GUARD} \\
+ \frac{G_{PUB}\delta_{PUB}T(P - 1)}{R} + G_{PUB}T_{GUARD} + T_{COMPU}, & \text{if } P \geq 2 
\end{cases}
\]

(22)

If the total window size assigned to an ONU is insufficient for that ONU’s needs, i.e., the achievable transmission rate is less than the packet arrival rate at the ONU, the duration of the following cycle increases accordingly. As a result, the polling cycle time, \(T_{CYCLE}\), can be estimated by continuously calculating the polling cycle times of successive cycles [i.e., calculating \(T(2), T(3), \ldots\), and so forth] and approximates to \(T(P)\) if the transmission rate is equal or approximate to the arrival rate, i.e.,

\[
W_p = W_p^{PRI} + W_p^{PUB} \equiv (\delta_{PRI} + \delta_{PUB})T_p.
\]

(23)

Assuming that the condition given in Eq. (23) holds, the estimated polling cycle time [i.e., \(T_{CYCLE} = T(P)\)] can be used to calculate the packet delay in the Stage-II queue using the method described below.

In analyzing the packet delay at the public queue (comprising three priority subqueues) in Stage-II of each ONU, it is important to recall that a packet arriving at the Stage-II buffering space of the public queue is not transmitted in the first transmission window granted to that ONU (counted from its arrival), but is buffered in the public queue. In practice, before transmitting packets, the ONU must first send a REPORT message to the OLT requesting bandwidth for the packets that were buffered in all priority subqueues of its public queue during the previous \(T_{CYCLE}\). Having done so, the ONU must then wait for the corresponding GATE to arrive. Since the packets arrive at the Stage-II buffers in accordance with a Poisson distribution, a packet arrives at each of three priority subqueues on average halfway through each polling cycle. Hence on average, the time for which a packet is buffered in each priority subqueue of the public queue is equal to one and a half times the polling cycle time. In other words, the mean packet delay in the Stage-II public queue is equal to that of each priority subqueue and therefore can be approximated as follows:

\[
E[D_{PUB}] = T_{CYCLE} + \frac{1}{2}T_{CYCLE} + \frac{3}{2}T_{CYCLE}.
\]

(24)

Regarding the private packet delay, the transmissions from the private queues are managed using the two-phase RR scheme described in Subsection III.C, and thus each private queue is selected for transmission once every \(D\) polling cycles. Given the Poisson distribution of the packet arrivals at the Stage-II buffers, a private packet arrives at any arbitrary priority subqueue of the selected private queue on average halfway through the \(D\) polling cycles. Since an ONU has to wait until the next public subcycle to send a REPORT indicating the backlogged private packets that arrived during the previous \(D\) polling cycles, and must then wait further to receive the corresponding GATE in the next private subcycle, the average mean queuing delay of private traffic at Stage-II comprises the computation time, the private subcycle time, \(T_{CYCLE, PRI}\), and half of the time required to execute the \(D\) polling cycles. As a result, the mean packet delay at each Stage-II private queue can be approximated as

\[
E[D_{PRI}] = T_{COMPU} + T_{CYCLE, PRI} + \frac{D}{2}T_{CYCLE}.
\]

(25)

From Eq. (7), the private subcycle time can be easily obtained as

\[
T_{CYCLE, PRI} = A_{ROUTE} \frac{S_{GATE}}{R} + (A_{ROUTE} - 1)T_{GUARD} + RTT + \frac{G_{PRI}W_{P}^{PRI}}{R} + (G_{PRI} - 1)T_{GUARD},
\]

(26)

where \(W_p^{PRI} = \delta_{PRI}T(P - 1)\). Substituting Eq. (26) into Eq. (25), the mean packet delay of each Stage-II private queue can be formulated in the following normalized form:

\[
E[D_{PRI}] = T_{COMPU} + A_{ROUTE} \frac{S_{GATE}}{R} + (A_{ROUTE} - 1)T_{GUARD} + RTT + \frac{G_{PRI}W_{P}^{PRI}}{R} + (G_{PRI} - 1)T_{GUARD} + \frac{D}{2}T_{CYCLE}.
\]

(27)

VI. COMPARISON RESULTS AND PERFORMANCE EVALUATION

This section commences by verifying the analytical model presented in the previous section by comparing
the analytical results obtained for the mean queuing delay and mean queue length under various network conditions with the results obtained from a series of computer simulations. The performances of the various WDM EPON protocols proposed in this study, namely, the WDM-IPACT scheme, the two-phase RR scheduling strategy, and the QoS provisioning mechanism are then systematically examined and discussed. In performing the numerical calculations and simulations, the network parameters were assigned as shown in Table I.

The capacity of each priority queue, one public queue, and each private queue maintained at each ONU was assumed to be 10 Mbytes. In simulating the private traffic, the destination was generated in accordance with a uniform destination distribution at each ONU.

A. Comparison of Analytical and Simulation Results

The validity of the analytical framework presented in Section V was verified by performing a series of simulations of the WDM EPON under various network conditions. In performing the comparative trials, the Ethernet frame size was assigned a constant size of 12,000 bits (1500 bytes) and the WDM EPON was assumed to be equipped with a 4-degree AWG device. Furthermore, the traffic of each ONU was modeled in accordance with a Poisson process at a rate of $\lambda$, and the ratio of private traffic to public traffic was assumed to be 30:70. Finally, the weighting factors, $\sigma$, of the EF, AF, and BE traffic loads were specified as 0.6, 0.3, and 0.1, respectively. The performance of the WDM EPON was evaluated in terms of the mean queuing delay and the mean queue length. The mean queuing delay was defined as the elapsed time between the arrival of a data packet at the ONU and the moment at which the packet was extracted from the queue. Since the public queue and each private queue are serviced once every polling cycle and once every $D$ polling cycles, respectively, in the WDM-IPACT scheme the mean queue lengths of the public queue and the $D$ private queues were defined as the average amount of traffic accumulated during each cycle and the average amount of traffic accumulated during every $D$ polling cycles, respectively.

Figures 6 and 7 illustrate the mean queuing delay and mean queue length of the Stage-I and Stage-II buffers as the network offered load is increased. Note that the EF, AF, and BE traffic loads were specified as 20%, 30%, and 50% of the network offered load, respectively. Note also that the maximum network offered load was deliberately restricted to a value of 1.64 Gbps in order to ensure the stability of the BE queue in the Stage-I buffer. In Fig. 6(a), it is observed that for an offered load of 1.64 Gbps, the average delay in the BE queue increases to almost 0.1 s, which indicates that the arrival rate of the BE traffic has reached its service rate (i.e., $\rho_{BE} \approx 1$). Figure 6(b) shows that the private traffic consistently yields a higher delay than the public traffic. Intuitively, this finding is reasonable since under the RR scheduling policy, each private queue is arbitrated for transmission just once every $D=4$ polling cycles, and hence the average queuing time is inevitably increased.

Figure 7(a) plots the mean queue length in each of the three priority queues in the Stage-I buffer. Comparing the three traffic classes, it can be seen that the BE traffic has the longest queue length followed by the AF traffic and the EF traffic, respectively. As in Fig. 6(a), it can be seen that the BE traffic reaches its

---

**TABLE I**

**SIMULATION PARAMETERS FOR WDM EPON**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Number of ONUs</td>
<td>64</td>
</tr>
<tr>
<td>$M$</td>
<td>Number of upstream wavelengths used by ONUs</td>
<td>4</td>
</tr>
<tr>
<td>$D$</td>
<td>Degree of AWG</td>
<td>[2, 4]</td>
</tr>
<tr>
<td>$R$</td>
<td>Bandwidth capacity of each wavelength</td>
<td>1 Gbps</td>
</tr>
<tr>
<td>$RTT$</td>
<td>Round-trip delay on WDM EPON</td>
<td>200 $\mu$s</td>
</tr>
<tr>
<td>$T_{COMPU}$</td>
<td>Computation time</td>
<td>35 $\mu$s</td>
</tr>
<tr>
<td>$T_{GUARD}$</td>
<td>Guard time between ONU transmissions</td>
<td>1.5 $\mu$s</td>
</tr>
<tr>
<td>$SGATE$</td>
<td>Size of GATE message</td>
<td>64 bytes</td>
</tr>
<tr>
<td>$SREPORT$</td>
<td>Size of REPORT message</td>
<td>64 bytes</td>
</tr>
<tr>
<td>$W_{MAX}$</td>
<td>Maximum transmission window</td>
<td>15,000 bytes</td>
</tr>
</tbody>
</table>

---

![Fig. 6. (Color online) Mean queuing delay of WDM EPON with a 4×4 AWG. (a) Stage-I queues, (b) stage-II queues.](image-url)
stability limit at a network offered load of 1.64 Gbps, whereas the AF and EF traffic remain in a stable condition. Figure 7(b) presents the variation of the mean queue lengths of the public and private traffic in Stage-II as the network offered load is progressively increased. Since, in performing the simulations, the public traffic was assumed to account for 70% of the total network traffic load, it is observed that the public queue has a longer mean queue length than any of the private queues under all values of the network load.

It can be seen that in all figures shown in this subsection, a good agreement exists between the analytical results and the simulation results.

B. Numerical Results of WDM-IPACT Algorithm and Two-Phase RR Scheduling Protocol

For simplicity, in investigating the effectiveness of the WDM-IPACT and two-phase RR schemes, this subsection considers the network to carry only BE traffic. In the following simulations, each ONU consists of one public queue and D private queues and no two-stage buffering approach is employed. For the traffic model considered here, an extensive study shows that most network traffic [i.e., http, ftp, variable bit rate (VBR), video applications, and so forth] are characterized by self-similarity and long-range dependence (LRD) [28]. Hence, this model is used in the present analysis to generate highly bursty BE traffic with a packet size uniformly distributed in the range of 64–1518 bytes.

Figure 8 shows the variation in the mean queuing delay of the proposed WDM EPON scheme and a conventional WDM EPON system (e.g. [5,6,9],) under various network traffic loads. Note that in the conventional WDM EPON, all of the packets (i.e., both public and private) are processed through the OLT, whereas in the proposed WDM EPON, the private packets are routed directly through the AWG. In performing the simulation, the network traffic is assumed to be evenly split between public traffic and private traffic. Due to the wavelength spatial-reuse feature of the AWG, the network capacity is greater than 4 Gbps in the WDM EPON system with four upstream data wavelengths. Therefore, the results clearly show that queue overflows (due to the use of finite size queues) occur at much higher traffic loads in the proposed WDM EPONs than in the conventional WDM EPON. Furthermore, when comparing the results obtained using AWGs with different degrees, it is observed that the WDM EPON with a 4x4 AWG can accommodate around 5 Gbps of network traffic before queue overflows occur, whereas that with a 2x2 AWG can support a network traffic load of 4.4 Gbps. The performance improvement obtained by increasing the degree of the AWG arises since a higher degree increases the number of times that each data wavelength can be reused, and therefore improves the bandwidth utilization.
To verify the effectiveness of the proposed RR scheduling scheme, Fig. 9 compares the variation in the queuing delay for various private to public traffic ratios in WDM EPONs implemented using the proposed two-phase RR scheme and a random (RND) scheduling scheme, respectively. In the RND scheme, when two or more nonempty private queues at an ONU are waiting for a transmission opportunity, the ONU simply selects a queue at random when reporting its bandwidth requirement for private traffic to the OLT. Comparing the results obtained from the two schemes, it can be seen that when the network operates under a heavy traffic load (i.e., $d = 4$ Gbps), the two-phase RR scheme consistently achieves a better delay performance than the RND method. In other words, the full wavelength spatial-reuse capability achieved by the two-phase scheduling scheme yields a significant reduction in the queuing delay as a result of the improved bandwidth utilization throughout the network. However, under a light traffic load (i.e., $d = 2$ Gbps), the private traffic delay of the two-phase RR scheme is slightly higher than that of the RND method. Intuitively, this finding is reasonable since under light traffic load conditions, the RR scheme may cause an ONU to select an empty private queue when reporting its bandwidth requirements, and hence the average queuing delay of the private traffic is increased.

C. Numerical Results of Stage-I Priority Queues for QoS Support

Figures 10 and 11 present the simulation results obtained for a network providing differentiated services, i.e., adopting the proposed two-stage buffering approach. Note that in performing the simulations for high-priority traffic (e.g., voice application), the EF traffic was modeled using a Poisson distribution with a constant packet size of 70 bytes [20]. Furthermore, to reflect the self-similarity nature of Ethernet traffic, the AF and BE traffic classes were generated using the same self-similar traffic model as that used in Subsection VI.B. In both cases, the packet size was randomly generated from a uniform distribution of U[64 bytes, 1518 bytes].

Figures 10 and 11 illustrate the variations of the mean queuing delay and the mean queue length, respectively, for the EF, AF, and BE traffic classes under various network traffic loads. Note that in the simulations, the private traffic to public traffic ratio was specified as 30:70 and the EF, AF, and BE traffic loads were set to 20%, 30%, and 50% of the network offered load, respectively. Furthermore, the WDM EPON network was assumed to be equipped with either a 2-degree or a 4-degree AWG. In Fig. 10, it can be seen that the EF traffic obtains the best delay performance followed by the AF traffic and the BE traffic, respectively, irrespective of the network load or the degree of the AWG device. This result confirms the ability of the packet scheduler to provide a high QoS guarantee for high-priority traffic. Comparing the results obtained for the WDM EPONs equipped with different AWGs, it is observed that the saturation limits of all three traffic classes are increased in the network fitted with a $4 \times 4$ AWG. As described in the previous section, this performance improvement arises since an AWG with a higher degree permits an improved wavelength spatial reuse and thus allows the packet scheduler to allocate more bandwidth to each of the three traffic classes. In Fig. 11, it is observed that irrespective of the degree of the AWG, the EF traffic queue saturates at the maximum queue length of 10 Mbytes under a higher value of the network offered load than either the AF queue or the BE queue. This result demonstrates that the EF queue is allocated a higher service rate and thus transmits frames more rapidly than either the AF or the BE queue. Furthermore, since a $4 \times 4$ AWG makes a greater amount of bandwidth available to the packet scheduler than a $2 \times 2$ AWG, Fig. 11 shows that the queues of all three traffic classes are saturated at a higher total network load when the WDM EPON is fitted with a $4 \times 4$ AWG.
VII. CONCLUSIONS

This study has proposed a novel WDM EPON architecture to facilitate Ethernet transmissions in high-speed access networks. In the proposed network, a cyclic AWG device is employed to interconnect the ONUs and the OLT. The AWG enables the WDM EPON architecture to support both direct ONU–OLT communications and upstream access to the OLT. A WDM-IPACT bandwidth allocation algorithm and a RR private queue scheduling scheme have been developed to arbitrate between private and public transmissions and to achieve a full wavelength spatial-reuse capability over the WDM layer. Furthermore, a two-stage buffering approach has been presented to support the different QoS requirements of different traffic classes. The simulation results have demonstrated that the wavelength spatial-reuse capability of the proposed WDM EPON architecture yields a significant improvement in the bandwidth utilization of the access network and therefore reduces the queuing delay at the ONUs.

An analytical framework comprising an $M/M/1$ queue model and a recursive formulation for the polling cycle time has been developed to derive the mean packet delay and mean queue length at each buffering stage of the ONU. It has been shown that the results obtained via computer simulations are in close agreement with those obtained using this analytical framework. To the best of the current authors’ knowledge, this study represents the first reported attempt to analyze the performance of WDM EPONs with QoS support and private networking capability. Therefore, the analytical framework presented in this paper provides a convenient means of establishing suitable performance evaluation guidelines for any application using an EPON-based access network with a two-stage buffer QoS provisioning mechanism.

ACKNOWLEDGMENT

This work was supported by the National Science Council of Taiwan under grant NSC 97-2221-E-006-175-MY3.

REFERENCES


