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Efficient Resource Allocation in Tactile-Capable Ethernet Passive Optical Healthcare LANs

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ABSTRACT Communication networks for healthcare environments support various application types and should be capable of providing them with the required Quality of Service (QoS) in terms of reliable data delivery, considerable data rate and low latency. The introduction of Tactile Internet (TI) healthcare applications is expected to upgrade the level of provided services to patients. The requirements of these applications are very stringent and a major requirement is that the existing network infrastructure must support them. Passive Optical Networks (PONs) have been proposed as an ideal candidate to support such demanding environments. One of the major challenges of such networks, which significantly affects the provided QoS, is the effective resource allocation in both the time and the wavelength domains. The existing resource allocation algorithms for PONs were designed without considering the stringent requirements of TI applications thus making PON support for TI inefficient. In this paper, a new double per priority queue dynamic wavelength and bandwidth allocation algorithm is presented. This algorithm allocates the network resources efficiently and fairly using several techniques, in order to meet the QoS demands of Tactile and other types of healthcare applications. Extensive simulation results indicate the effectiveness of the proposed algorithm to provide the required QoS for medical applications under various simulation scenarios whereas other well-known schemes are shown to lack such support.

INDEX TERMS Healthcare applications, passive optical networks, quality of service, tactile Internet.

I. INTRODUCTION

The Tactile Internet (TI) is considered to be the evolution of the Internet of Things (IoT) assisted by the 5G vision. TI will enable the remote control of IoT devices in real time, with its main target to add a new dimension of human-to-machine interaction by allowing tactile and haptic sensations. To sufficiently support TI applications, the most important design goals for the network infrastructure are an ultra-low end-to-end latency of less than 1 msec, a high reliability with a guaranteed availability of 99.999% and an elevated level of security [1]. Barriers to achieving these TI latency constraints are the distance between the tactile control/steering server and the tactile edge due to the signal propagation delay. Possible solutions to this problem include the adoption a decentralized service architecture which is based on cloudlets, the use of mobile edge computing, and the implementation of the TI applications in Local Area Networks (LANs), where the dimensions of the area are bounded [2].

Passive Optical Networks (PONs) provide a good solution to bandwidth limitation of the last mile bottleneck problem in access networks. The Institute of Electrical and Electronics Engineers (IEEE) and the International Telecommunication Union (ITU) are continuously evolving the technology standards for such networks, with time and wavelength division multiplexed PONs (TWDM-PON) to be selected as the best candidate for the next generation PONs (NG-PON2), due to several factors including technology maturity, system performance, power consumption, cost effectiveness and backward compatibility [3]. The PON technology has also

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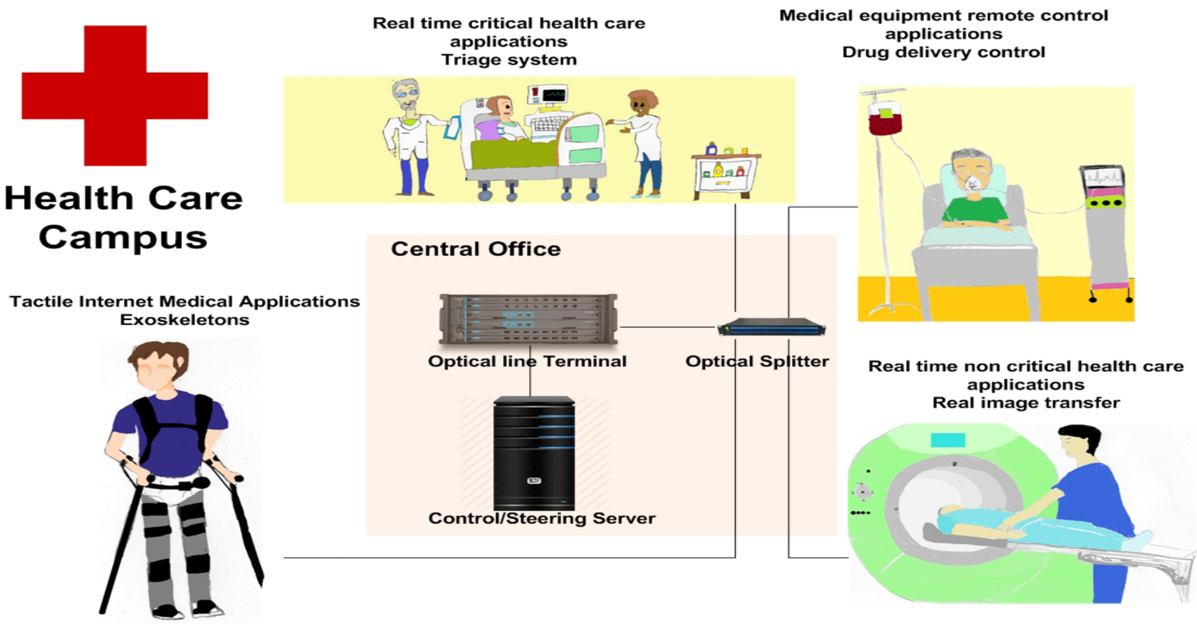

FIGURE 1. A modern health care campus equipped with a passive optical local area network capable of serving various medical applications with different QoS requirements.

spread into the LAN domain, since it can provide an improved overall efficiency combined with significant cost savings and an upgrade of the provided services to large businesses and organizations [4]. Passive Optical LAN (POL) solutions are implementations of the PON technology adapted to enterprise LAN environments. The main reasons behind the quickly gaining traction of POLs in the communication industry are the offered scalability and reliability, the ease of use and administration, the energy efficiency and environmental sustainability, the optimized bandwidth connectivity, the advanced security and the reduced cost of ownership.

One of the best environment candidates, where TI applications are expected to be employed, is the healthcare sector. Such applications include tele-diagnosis, tele-surgery and tele-rehabilitation [5]. In a modern healthcare campus as shown in Figure 1, various type of health care applications will upgrade the level of the provided services to the patients. These applications include haptic devices for exoskeletons, health information technology, real-time health-monitoring and high definition medical image transfer, each one with its own individual constraints in terms of quality of service (QoS). The deployed network infrastructure should be able not only to preserve the stringent QoS demands of the TI applications, but also other class of service (CoS) crucial non-TI applications demands.

The PONs implement a point-to-multipoint architecture. In the downstream direction, an optical line terminal (OLT) broadcasts data to every connected optical network unit (ONU) at the user end. In the upstream direction, transmissions of different ONUs could collide since the optical distribution network is shared; hence upstream transmissions of the ONUs should be scheduled. The Multi-Point Control Protocol (MPCP) has been introduced for Ethernet PONs (EPONs) to facilitate the dynamic bandwidth and wavelength allocation scheduling process. MPCP does not specify or require any particular dynamic wavelength and bandwidth allocation (DWBA) algorithm. A proper DWBA algorithm needs to satisfy the QoS parameters of each CoS served by the PON including packet delay (latency), packet delay variation (jitter) and packet loss ratio.

Due to the high demands on the QoS of the TI applications, various significant challenges arise for the existing DWBA algorithms. The first one is that they are designed without considering the very high QoS requirements that these applications have, and as a result the techniques they use are inadequate for the efficient management of the optical network resources. A second problem that arises is that the preservation of the provided services to the demanding TI applications should not monopolize the allocation of network resources to these particular application, a fact which will certainly lead to the QoS degradation of the other applications served by the optical network. For these reasons especially in healthcare environments where the running applications are life-crucial, it is absolutely necessary to design new DWBA algorithms, which will be able to effectively address the above problems.

In this paper, we present a double per priority queue (DPPQ) DWBA algorithm which is capable to preserve the stringent QoS demands of TI applications without degrading the other non-TI applications served by the same optical network. The preservation of the QoS of healthcare applications in the MAC layer, can be the base of a new generation of MAC protocols for healthcare networks which are capable of providing high quality communication services in a healthcare environment. The proposed algorithm uses several techniques to satisfy the aforementioned QoS goals. The main among the used techniques, which enables the fair resource allocation, is the implementation of two different queues, the high priority (HP) and the low priority (LP) one, for each CoS on every ONU. In terms of transmission priority, by utilizing this technique the packets of lower CoS priority can overcome the packets of higher CoS priority under specific conditions applied by the algorithm. In order to evaluate the efficiency of the proposed DWBA algorithm and to compare it to other already proposed algorithms, we consider a use case of a modern hospital campus equipped with an Ethernet POL infrastructure which can serve TI among other healthcare applications.

In health environments equipped with a POL, each ONU represents a small set of user end devices with a very bursty traffic, due to the small number of existing bursty sources, in contrast to Metropolitan or Wide Area Networks where the bandwidth requirements are quite smooth due to the aggregation of many traffic sources [6]. For this reason and in order to be more realistic in our simulation scenarios, the injected traffic follows the Pareto distribution. A gap in the literature exists and for this reason we test the proposed DWBA algorithm under various traffic scenarios including one that takes into account the network-wide synchronized traffic - a situation where bursts of data from different flows tend to synchronize in time. Thus, we are able to test the robustness of DWBA algorithms under an extremely bursty traffic [7]. Moreover, the proposed algorithm implements a double per CoS queue technique, provides concurrent QoS preservation of TI and non-TI applications and guarantees the maximum packet delay.

The rest of the paper is organized as follows. Section II overviews the related work concerning DWBA algorithms for EPONs. The proposed DPPQ-DWBA algorithm is presented in section III. The system model and the simulation setup which are used to evaluate the performance of the proposed algorithm are described in Section IV. In Section V the evaluation of the algorithm via simulation is presented, whereas conclusions and plans for future work are presented in Section VI.

II. RELATED WORK

The research for EPON DWBA algorithms has received a considerable interest over the last two decades. Many algorithms have been presented during these years. These algorithms can be differentiated by three major design dimensions [8]. The first one is the grant scheduling framework, which determines the OLT decision time for grant transmissions to the ONU. According to the grant scheduling choice a DWBA algorithm can be Online, Offline, ONU load status or Double Phase Polling. In the Online approach, the grant scheduling is individual for each ONU and it is triggered by any ONU, in contrast with the Offline case where all the ONUs are scheduled at the same time after the reception of all the ONUs to OLT REPORT messages [9]. The ONU load status is a hybrid approach where the grant scheduling is triggered by the receipt of REPORT messages by individual ONUs, if the request bandwidth is less than a guaranteed minimum. Otherwise, the grant will be scheduled when reports from all the ONUs will be received from the OLT [10]. Finally, on Double Phase Polling, ONUs are partitioned into independent groups where each group is scheduled separately [11].

The second DWBA design dimension is the grant sizing policy, which is responsible for the size of the grant transmission window of each ONU. There exist two scheduling types in EPONs, the inter-ONU scheduling, where the grant size of each ONU is scheduled, and the intra-ONU scheduling, where the individual queues of the Ethernet frames at the ONU are scheduled, within the grant transmission slot granted from inter-ONU scheduling. The major techniques for the inter-ONU grant sizing policy are the fixed, the limited, the gated, the credit and the limited with excess distributions. In the fixed scheme, the grant size is fixed for every ONU in each cycle and it is independent from the ONUs buffer occupancy. The grant ONU size is set to the reported grant request up to a maximum grant size in the limited scheme [12], while the grant ONU size is equal to the reported grant request in the gated one [13]. The credit approach adds an extra bandwidth to the requested window size, using queue size prediction mechanisms, in order to reduce the average delay [14]. In the limited with excess distribution scheme, the ONUs are partitioned in two individual groups, the overload and under load [15]. The under load ONUs grant size is equal to the reported grant request, while the overload ONUs share the excess or unused from the under load ONUs bandwidth. The intra ONU scheduling uses two major classes, the strict priority where the packets are transmitted according to their CoS and the weighted fair scheduling where all the CoS have a minimum guaranteed bandwidth [16].

The scheduling policy, which is the third DWBA design dimension, determines the order of the ONU transmission window within the grant cycle. The shorter grant first [17] orders the ONUs according to the grant size; the larger frame first [18] orders the ONUs according to the frame size; and the shortest propagation delay first [19] orders the ONUs in an ascending order of the round trip propagation delay.

A plethora of DWBA algorithms have been presented in the literature during the last two decades. The design of these DWBA algorithms followed closely not only the PONs standard technology evolution but also the evolution of research in the general area of communication networks as well as the user applications. In this context, the trade-off between fairness and efficiency in PONs is addressed in [20], to this purpose a resource allocation algorithm based on learning automata is employed. The proposed algorithm called IFAISTOS succeeds to improve fairness index and average packet delay. The most recent research work in the literature includes a DBWA scheme [21] which can meet the QoS demands for TI and non-TI applications in a cloud distribution network. The proposed DWBA scheme employs the

Water-Filling technique and an advanced intra-ONU scheduling discipline but it requires the ONUs capability to transmit over multiple wavelengths simultaneously, using a bank of fixed transceivers or tunable lasers, a fact which raises the overall cost dramatically. A first-fit DBWA algorithm providing a low average packet delay and catering the frame resequensing problem for NG-PONs is presented in [22]. The proposed solution improves the bandwidth utilization by reducing the excessive use of guard time as compared with other schemes but it also suffers from the high cost demand of the ONU multichannel transmission capability. In [23], a DWBA scheme which employs Bayesian and maximum likelihood sequence estimation (MLSE) introduces prediction mechanisms to estimate the total expected traffic in order to cope with the stringent end-to-end TI delays. Simulation results reveal promising results for a Poisson distributed traffic in contrast with the Pareto distributed traffic where the proposed algorithm fails to preserve the stringent QoS demands of TI applications. Also, a major drawback for the proposed scheme is the advance knowledge requirement of the traffic type distribution. In our previous work [24], a DWBA scheme which combines Bayesian estimation techniques with a Knapsacking based dynamic programming algorithm for efficient resource allocation according to traffic volume for a Poisson traffic distribution was presented. A set of simulations proved the efficiency of our framework; the tactile traffic was successfully delivered with a mean packet delay below the time constraint of 500μs for a large number of network loads. The metrics used in [23], [24] compared to our present work, include only the mean packet delay and the wavelength usage, but no other crucial metrics for the evaluation of a DWBA algorithm such as the maximum packet delay, the packet loss rate and the jitter. Also in the mentioned manuscripts the system model they used includes only two classes of healthcare service traffic.

III. THE DOUBLE PER PRIORITY QUEUE DYNAMIC BANDWIDTH AND WAVELENGTH ALLOCATION ALGORITHM

The choice of the design parameters of the DPPQ algorithm focuses on satisfying the TI applications' stringent requirements, without degrading the performance of the other types of applications which have their individual demands in terms of QoS. These design parameters include the implementation of a double buffering queue for each CoS, the calculation of both the duration and of the number of active wavelengths for each polling cycle, as well as of a grant scheduling framework, a grant sizing policy and a grant scheduling policy. For the reader's convenience, the notations used in this section are summarized in Table 1.

A. THE DOUBLE PER PRIORITY QUEUE TECHNIQUE

The DPPQ algorithm implements two priority queues for each CoS, i.e. the HP and the LP. The transmission priority of a packet is determined by two factors; the first and most important one is the type of queue where a packet is buffered (high, low) and the second one is the CoS of a packet, since the CoS are classified according to their importance. For example, a packet of a lower priority CoS which is buffered in a HP queue will be offloaded first, during the next polling cycle, compared to a packet of a higher priority CoS which is buffered in a LP queue.

TABLE 1. Summary of notations.

Notation	Description
Ind_i	Value of index for the LP queue *i*
Thr_i	Threshold value for the LP queue *i*
T_{poll}	Duration of a poll cycle (sec)
L_{max}	Maximum acceptable delay (sec)
T_{proc}	Processing time of OLT (sec)
L_{cons}	Latency constraint for a CoS (sec)
T_{rtt}	Round trip time of the furthest ONU from OLT (sec)
RN_{BW}	Total requested from ONUs bandwidth (bytes)
$RO_{i,j}$	Requested bandwidth of ONU *i* for queue *j* (bytes)
G_{WL}	Granted number of wavelengths for a poll cycle
N_{WL}	Number of available wavelengths
WL_{BW}	Capacity of a single wavelength (bytes)
T_{Idle}	Idle time for upstream wavelength (sec)
Rtt_{FP}	Propagation delay of the first polled ONU to OLT (sec)
Rtt_{LP}	Propagation delay of the last polled ONU to OLT (sec)
G_{min}	Minimum transmission timeslot for ONU (sec)
NUM_ONU	Number of ONUs
ONU_{FWL}	Number of ONUs assigned to the first G_{WL}-1 wavelengths
ONU_{LWL}	Number of ONUs assigned to the last granted wavelength
ONU_{WLi}	Number of ONUs assigned to the wavelength *i*
R_{HPi}	Requested bandwidth from the ONU *i* for all HP queues and TI LP queue (bytes)
R_{LPi}	Requested bandwidth from the ONU *i* for all LP queues except TI LP queue (bytes)
R_{BWi}	Remaining bandwidth of the wavelength *i* (bytes)
P_i	Portion of R_{BW} granted to the ONU *i*
G_{BWi}	Grant size bandwidth of the ONU *i* (bytes)

Every packet arriving at the ONU is placed on the LP queue of its CoS. In each LP queue, the ONU assigns an index to the last packet arrived during the current polling cycle, which defines the number of polling cycles that the packet is buffered in the queue; initially this index is set to 1. After the transmission window has been assigned by the OLT in every polling cycle, each ONU checks the indexes of the buffered packets in each LP queue and transfers them to the HP of their CoS if the following condition is true:

$$Ind_i = Thr_i, \tag{1}$$

where Ind_i is the value of the index for LP queue *i* and Thr_i is a predefined threshold value for LP queue *i*, which determines the transfer time of a packet from an LP to a HP queue. This threshold value is adjusted according to latency constraints of each CoS in order to preserve the QoS requirements. The Ind_1, which corresponds to TI, is set to 1 while the other indexes are calculated as follows for the rest of the CoS:

$$Ind_i = floor\left(0.9L_{cons}/T_{poll}\right), \tag{2}$$

where L_{cons} is the latency constraint for CoS *i*, T_{poll} is the fixed duration of the polling cycle and 0.9 is a factor which reduces the period of packet buffering in the LP queues, since it is not guaranteed that a packet will be offloaded straight after its arrival at the HP queue. After the packet transfer procedure, each ONU increments by one the mentioned index in the LP queues, for the packets which it couldn't offload. In this way, packets of lower CoS priority can overcome packets of higher CoS priority in terms of transmission priority. Using this technique the proposed DWBA algorithm simplifies the intra-ONU scheduling and also is more agile and capable of serving all CoS fairly, without monopolizing the allocation of network resources to the most demanding traffic type.

The function of the mentioned technique, which serves two CoS for simplicity, is analyzed in a four-stage diagram during a Poll cycle in Figure 2. In the first stage, the GATE message to the ONU which contains the amount of bandwidth allocated by the OLT for the next transmission cycle corresponding to 180000 bytes is shown. Also, in this stage the amount of data buffered in the LP and HP queues of both CoS is shown, as well as the value of the indexes in the LP queues. In the second stage, the packets are offloaded during the granted by the OLT transmission timeslot. The third stage shows the transfer of packets from the LP queues to the HP queues for packets that their index value matches the threshold value corresponding to the CoS they belong to. Finally, the fourth stage shows the buffering of the newly arrived packets in the corresponding to their CoS LP queues and the initialization of their index to 1.

B. DURATION AND ACTIVE WAVELENGTHS OF POLLING CYCLE

The proper function of DPPQ requires a fixed duration of the polling cycle T_{poll}, since the timing of the packet transfer from the LP to the HP queues is determined by the value of Thr_i(eqns. 1 and 2). The T_{poll} value is calculated by the algorithm using to the value of the latency constraint L_{cons}, of the most demanding CoS application, which in our case is the TI. By setting the threshold of Thr_1 to 1 and assuming that the PON is capable of offloading all the TI packets which are buffered in HP in a single polling cycle, the maximum queuing delay of a TI packet is three polling cycles. The resulting total maximum queuing delay is analyzed as follows: during the first poll cycle, a newly arrived TI packet is buffered at the ONU's LP queue, at the second one it is transferred to the HP queue and, finally, at the third one it is offloaded. The total maximum end-to-end latency L_{max} for a TI packet is:

$$L_{max} = 3(T_{poll} + T_{proc}) + T_{rtt}, \tag{3}$$

where T_{proc} is the processing time of OLT and T_{rtt} is the round-trip time of the furthest ONU from the OLT. When preserving the QoS of a TI packet the following condition must always be true:

$$L_{max} \leq L_{cons}, \tag{4}$$

where L_{cons} is the latency constraint of a TI packet. The fixed duration of the polling cycle is equal to the maximum

Algorithm 1 DPPQ Algorithm

Inputs: $\boldsymbol{WL_{BW}}$, $\boldsymbol{RO_{ij}}$, $\boldsymbol{N\_ONU}$, $\boldsymbol{L_{cons}}$, $\boldsymbol{T_{rtt}}$, $\boldsymbol{T_{proc}}$, $\boldsymbol{N_{WL}}$

Outputs: Scheduling timetable per wavelength

Stage 1 //Duration of Poll cycle $\boldsymbol{T_{poll}}$

1. $T_{poll} = (L_{cons} - 3T_{proc} - T_{rtt})/3$

Stage 2 // Number of active wavelengths for the next poll cycle $\boldsymbol{G_{WL}}$

1. $\mathrm{RN}_{BW} = \sum_{i=1}^{NumONU} \sum_{j=1}^{NumQueues} RO_{ij}$
2. $\mathrm{G_{WL}} = \min(\mathrm{N_{WL}}, \mathrm{ceil}(RN_{BW}/\mathrm{WL_{BW}})$

Stage 3 //Number of ONUs per wavelength $\boldsymbol{ONU_{WL}}$

if $G_{WL} > 1$

1. for $i = 1{:}\ G_{WL} - 1$
2. $ONU_{WL}(i) = \mathrm{floor}(N\_ONU/\ G_{WL})$
3. end
4. $ONU_{WL}(G_{WL}) = N\_ONU$ -sum(ONU_{WL})
5. else
6. $ONU_{WL}(1) = N\_ONU$
7. end

Stage 4 //ONU assignment to wavelength $\boldsymbol{WL_{ONU}}$

1. $R_{HP_i} = \sum_{j=1}^{Num\_HP\_Queues+1} RO_{ij}$

   $R_{LP_i} = \sum_{j=Num\_HP\_Queues+2}^{Num\_Queues} RO_{ij}$
2. sort(R_{HP})
3. Assign ONUs to each wavelength, until ONU_{WL} is reached, according to $\mathrm{R_{HP}}$, choosing in turn the most overloaded and the least under loaded HP ONUs

Stage 5 //Grant size calculation for ONUs $\boldsymbol{G_{BW}}$

1. $G_{min} = T_{proc} + T_{rtt}$
2. if $\sum_{j=1}^{Num\_WL\_ONU} R_{HP_j} == 0$

   $P_i = \frac{R_{HP_i}}{\sum_{j=1}^{Num\_WL\_ONU} R_{HP_j}}$
3. else
4. $P_i = \frac{R_{LP_i}}{\sum_{j=1}^{Num\_WL\_ONU} R_{LP_j}}$
5. end
6. $R_{BW} = WL_{BW} - (\ ONU_{WL}(G_{min} + Guard))$
7. $G_{BWi} = G_{min} + P_{i*}R_{BW}$

Stage 6 //Grant scheduling

1. for $i = 1{:}\ G_{WL}$
2. Schedule first the most overloaded ONUs according to R_{HP}
3. end
4. **Return** Scheduling timetable per wavelength

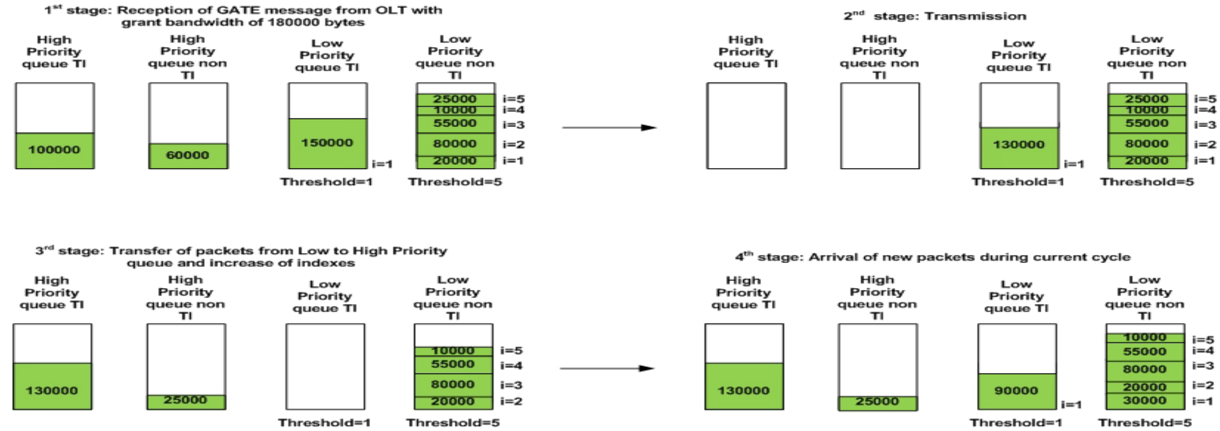

FIGURE 2. Function of the double per priority queue technique during a poll cycle with two classes of service.

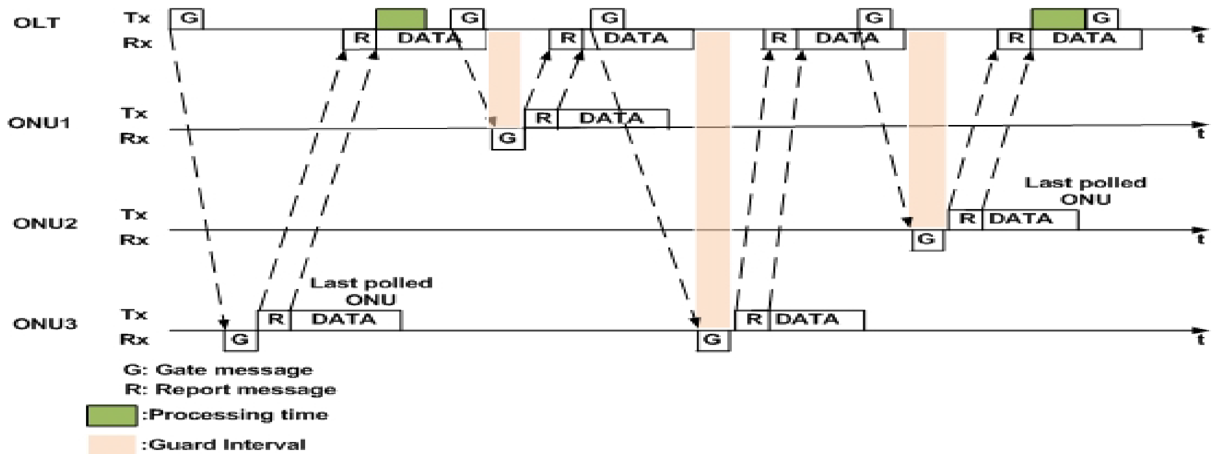

FIGURE 3. Timing diagram of the double per priority queue dynamic wavelength and bandwidth allocation algorithm.

duration of a polling cycle T_{poll}, which can be calculated using equations 3 and 4 as follows:

$$T_{poll} \leq \frac{L_{cons} - 3T_{proc} - T_{rtt}}{3}. \quad (5)$$

Depending on the load conditions, the proposed algorithm reduces the number of active wavelengths during a cycle. The REPORT message from each ONU to OLT has the following structure , $(RO_{i1}\ , RO_{i2}, \ldots, RO_{ij})$, where RO_{ij} is the requested bandwidth for the priority queue j of the ONU i according to queue j occupancy. The total request bandwidth RN_{BW} of the optical network is

$$\mathrm{RN}_{BW} = \sum_{1}^{i=NumONU} \sum_{1}^{j=NumQueues} RO_{ij}. \quad (6)$$

The granted number of active wavelengths, G_{WL}, for a poll cycle is calculated as:

$$G_{WL} = min\left(N_{WL}, ceil\left(RN_{BW}/WL_{BW}\right)\right), \quad (7)$$

where N_{WL} is the number of available wavelengths and WL_{BW} is the offered bandwidth of a single wavelength.

C. GRANT SCHEDULING FRAMEWORK

The grant scheduling of DWBA algorithms determines the OLT timing decisions for the grant transmissions to the ONU. The proposed algorithm follows the Offline approach, where all the ONUs are scheduled at the same time by OLT. The Offline approach is chosen because the design parameters of the DPPQ algorithm require that all the REPORT messages be received by the OLT before making DWBA decisions. Following this approach, the OLT has all the information it needs in order to provide a fair, dynamic and effective distribution of the network resources to the ONUs. The timing sequence of the algorithm events (Figure 3) begins with the arrival of all the REPORT messages from the ONUs to the OLT. Using the grant sizing and scheduling policy, the OLT processes the bandwidth request contained in the REPORT message and schedules a timetable for each wavelength. The timetable contains the time of the GATE message transmission to each ONU.

At the arrival of the GATE message, each ONU responds immediately with the REPORT message, and afterwards offloads the buffered packets, during the time window assigned by the OLT. The ONU responds using the same wavelength with the one that the GATE message received from the OLT. The REPORT message contains the requested bandwidth for each queue, according to its buffer occupancy, without considering the number of packets which will be offloaded during the transmission window of the current cycle. This way the credit grant sizing policy approach is used in order to reduce the average delay, since an extra bandwidth is requested by each ONU for the next polling cycle in comparison with the real buffer occupancy after the transmission timeslot.

The proposed algorithm is performed Offline, as mentioned before, and uses the interleaved polling with the stop technique, in which the OLT stops and waits between granting cycles for all the ONU REPORT messages to be received, before making grant decisions. Thus, the bandwidth utilization is decreased by forcing an idle period T_{Idle} for the uplink wavelengths [6] which is equal to:

$$T_{Idle} = (1/2Rtt_{LP}) + T_{proc} + (1/2Rtt_{FP}), \tag{8}$$

where Rtt_{LP} is the one way-propagation delay from the last polled ONU, T_{proc} is the processing time of OLT and Rtt_{FP} is the one way-propagation delay of the first polled ONU. In order to deal with the reduced bandwidth utilization caused by the Offline grant schedule approach the REPORT message precedes the transmission window and the algorithm defines a minimum transmission timeslot period G_{min} for each ONU which must satisfy the following condition:

$$G_{\min} \geq \max(T_{Idle}). \tag{9}$$

From equations 8 and 9, we get that G_{min} is given by:

$$G_{\min} = T_{proc} + T_{rtt}, \tag{10}$$

where T_{rtt} is the round-trip time of the furthest ONU from the OLT. Thus, a sufficient time is available for the OLT both to schedule the next interleaved polling cycle and to fully utilize the uplink wavelength bandwidth.

D. GRANT SIZING POLICY

The proposed algorithm calculates the grant sizing for each ONU in four stages. In the first stage, after receiving the REPORT messages from all ONUs, the OLT calculates the number of the uplink active wavelengths which will be used for the next cycle as previously described. The number of the active wavelengths, G_{WL}, is a function of the total bandwidth demand contained in the REPORT message.

In the second stage, the algorithm calculates the number of ONUs, ONU_{WL}, which will be assigned to each active wavelength for the next cycle. If G_{WL} is the number of active uplink wavelengths and $G_{WL} > 1$, the number of ONUs, ONU_{FWL}, which will be assigned to the first G_{WL}-1 wavelengths is:

$$ONU_{FWL} = floor(Num\_ONU / G_{WL}), \tag{11}$$

where Num_ONU is the number of ONUs. The number of assigned ONUs to the last wavelength, ONU_{LWL}, is:

$$ONU_{LWL} = Num\_ONU - (ONU_{FWL}(G_{WL} - 1)). \tag{12}$$

During the third stage each ONU is assigned to a specific wavelength. Firstly the OLT calculates, using the REPORT message, the requested bandwidth for HP queues plus the TI LP queue, R_{HP}, for each ONU

$$R_{HP_i} = \sum_{j=1}^{Num\_HP\_Queues+1} RO_{ij}, \tag{13}$$

and then the OLT sorts the ONUs according to their R_{HP}.

After R_{HP} calculation the OLT calculates the requested bandwidth for LP queues minus the TI LP queue, R_{LP}, for each ONU

$$R_{LP_i} = \sum_{j=Num\_HP\_Queues+2}^{Num\_Queues} RO_{ij}. \tag{14}$$

Finally, during this stage the OLT assigns, to each active wavelength, in turn the most overloaded and the least underloaded ONUs according to R_{HP}, until the ONU_{FWL} is reached for the first G_{WL}-1 wavelengths. The remaining ONUs are assigned to the last active wavelength. For example, if we have 10 sorted ONUs, according to their R_{HP}, $ONU_{FWL} = 3$ and $G_{WL} = 3$ for the next polling cycle, ONUs 1,10 and 2 will be assigned to the first wavelength, ONUs 8, 3 and 9 will be assigned to the second wavelength and the remaining ONUs (4, 5, 6, 7) will be assigned to the third wavelength. Using the above procedure, each set of ONUs, assigned to a wavelength, consists both of overloaded and underloaded ONUs.

Taking advantage of the ONUs per wavelength set composition, the proposed algorithm can flexibly calculate the grant size G_{BW}, for each ONU for the next polling cycle, during the fourth stage. The G_{BW} for each ONU is the sum of two factors. The first one is the minimum transmission timeslot period G_{min}, and the second one is a portion of the wavelengths remaining bandwidth which is shared between ONUs according to R_{HP} or R_{LP}. Specifically, the remaining bandwidth R_{BW} for each wavelength is:

$$R_{BW} = WL_{BW} - (ONU_{WL} (G_{min} + Guard)), \tag{15}$$

where $Guard$ is the guard interval between the ONUs' transmission timeslot. First, in this stage the OLT checks if the following condition is true for each ONU belonging in the same wavelength set

$$R_{HP} > 0. \tag{16}$$

When (16) is true it means that the HP queues and the TI LP queue for all the ONUs are not empty and the portion P_i, of R_{BW} which will be assigned to ONU i is calculated as:

$$P_i = \frac{R_{HP_i}}{\sum_{j=1}^{Num\_WL\_ONU} R_{HP_j}}. \tag{17}$$

TABLE 2. Medical applications requirements [25].

	Requirements		
Healthcare CoS	**Delay**	**Packet loss rate**	**Applications**
Tactile Internet medical	<1 msec	$<10^{-5}$	Tele-diagnosis, Tele-surgery, Tele-rehabilitation, Exoskeletons
Medical equipment remote control	<3 sec	~0	Control of medical devices (infusion pumps, drug delivery, ventilators)
Real time critical health care	<300 msec	$\sim10^{-6}$	Remote monitoring of patients, Triage medical systems
Real time non critical health care	<10 msec	$<10^{-4}$	Medical image transfer, Teleconference and Teleconsultation for medical issues, Voice over IP
Office medical IT	<1 sec	$<10^{-2}$	Email, Web browsing, File transfer of patient records.

When (16) is false it means that the HP queues and the TI LP queue for all the ONUs are empty and the portion P_i, of R_{BW} which will be assigned to i ONU is calculated as:

$$P_i = \frac{R_{LP_i}}{\sum_{j=1}^{Num\_WL\_ONU} R_{LP_j}}. \quad (18)$$

Finally, the grant size G_{BWi} of ONU i for the next poll cycle is:

$$G_{BWi} = G_{min} + P_i \cdot R_{BW}. \quad (19)$$

Thus, the OLT can efficiently allocate more bandwidth to overloaded ONUs, and manage to cope with the burstiness of the traffic and reduce the overall packet delay.

E. GRANT SCHEDULING POLICY

The scheduling policy, which determines the order of the ONU transmission window within the grant cycle, follows the longer grant first approach. According to this approach, the ONUs are sorted according to their HP queue occupancy, and the more overloaded ones are scheduled first for the next cycle transmission. With this type of scheduling, the algorithm prioritizes, in terms of transmission, the more loaded ONUs, in order to reduce the queue packet delay, since these ONUs are more prone to experience an increased overall packet delay.

F. ALGORITHM COMPLEXITY

Low complexity is a key design for intra-ONU schedulers so that the cost of the ONUs is kept to a minimum [6]. Using the double per priority queue technique the proposed algorithm simplifies the intra-ONU scheduling, since it only requires a matching process between the index and the threshold values for each LP queue. The time complexity of the proposed inter-ONU scheduling algorithm is dominated by the ONU load sorting procedure in step 2 of stage 4 of the algorithm, which is:

$$O(Num\_ONUs^2), \quad (20)$$

and, thus, very fast, so as to be able to can easily run in every polling cycle within the available processing time, as the number of ONUs is small and remains constant.

IV. SYSTEM MODEL AND SIMULATION SETUP

The evaluation of the proposed algorithm was carried out by a PON simulator which we built using MATLAB. The system model includes a healthcare campus which consists of various departments like, emergency, surgical, diagnostic, rehabilitation, physician, logistics and security. The campus is equipped with a POL to serve the generated by the various departments traffic.

The POL infrastructure includes a single mode fiber which connects the OLT with the ONU through splitters. A Central Office is built in the campus which houses the OLT and the control/steering server for the TI applications. The ONUs are interfaced with wired or wireless access points and serve as a gateway to/from tactile edges comprising sensors and actuators, or other campus equipment. The CO serves as a gateway to/from the wide area network. The POL has the capability to support a maximum of 40 Gbps symmetrical bandwidth by multiplexing up to four 10 Gbps downstream and upstream wavelength channels. In order to be cost-efficient, the system model used allows the ONUs to transmit over a single wavelength at a time by using a single tunable laser.

The generated traffic from healthcare campus departments are classified in five CoS according to their importance [25]. Each one of them has its own QoS requirements which the network infrastructure must be able to support. In order of importance the five CoS include TI medical applications (TIM), medical equipment remote control applications (MERC), real time critical healthcare applications (RTCH), real time non-critical health care applications (RTNH) and office/medical IT applications (OMIT) (Table 2).

TIM applications include tele-diagnosis, tele-surgery and tele-rehabilitation among others. These kinds of applications cannot tolerate data loss since they require a less than 10^{-5} packet error rate (PER). Also, they require a less than 1 msec end-to-end latency from the tactile edge to the control/steering server. If the mentioned constraints cannot be fulfilled, a 'cyber sickness' phenomenon occurs – this phenomenon is similar to the motion sickness. The maximum acceptable delay for the TIM applications for all the simulation scenarios is set to 500μsec, since the end to-end latency can be divided into three distinct latency budgets attributed to (a) the user interface (~300 μs), (b) the radio interface (~200 μs), and (c) and the end-to-end latency between the ONU and the control/steering server (~500 μs) [5].

The MERC applications support the vital functions of the medical devices, such as infusion pumps which control drug delivery and ventilators that control physiological functions. These applications on the one hand require a low bandwidth and delays but on the other hand they require a very high reliability with zero PER.

TABLE 3. Simulation parameters.

Parameter	Value
Number of ONUs	64
Number of priority classes	5
Line rate of user-to-ONU	1 Gbps
Number of wavelengths	4
Upstream bandwidth per wavelength	10 Gbps
Downstream bandwidth per wavelength	10 Gbps
Buffer size in ONU	10 Mbytes
TI packet size	64 bytes
Non-TI packet size distribution	64-1518 bytes
Interframe gap	12 bytes
Frame preamble	8 bytes
Maximum distance between OLT and ONU	600 m
Guard time between adjacent slots	1 μsec
Traffic distribution	Pareto
Traffic packets	10^8

The RTCH applications include the remote monitoring of the patients' physiological functions, as well as the support of Triage medical systems [26], which is a prioritization set of methods for patient classification according to the severity of their status. Typically, these applications are highly sensitive to PER and delay since they are life-critical.

Real-time medical image transfer, teleconferencing and teleconsultation for medical issues and voice over IP are some of the RTNH applications. These applications are tolerable to some data loss but they are highly sensitive to delay and jitter.

The OMIT applications are the less demanding ones in terms of QoS since they can tolerate moderate delays and packet loss. They are office-oriented applications and include email, web browsing and file transfers of patient records.

In order to evaluate the effectiveness of the proposed DWBA algorithm, we compare its performance with other existing schemes from the literature. These schemes are the MLSE [23] and two versions of the state-of-the-art wavelength division multiplexing interleaved polling with adaptive cycle time with a single table (WDM-IPACT-ST) [27]. The first version of WDM-IPACT-ST employs strict priority (IPACT-SP) and the second one employs the weighted fair queuing (IPACT-WFQ) for the intra-ONU scheduling. IPACT-SP and IPACT-WFQ employs the limited grant sizing policy since it is the most effective one in order to cope with the stringent latency constraints.

The deployed POL consists of 64 ONUs, which are spread across the campus, with the minimum and maximum distance from the OLT to be 10 and 600 meters respectively. The ONUs are equipped with a 10 Mbyte buffer which is shared by ten priority traffic queues for the DPPQ, since there are two priority queues for each CoS. For the other DWBA schemes the buffer is shared by five priority queues, one for each CoS. When a buffer is fully occupied and a packet with higher priority arrives, the lowest priority queue will drop one or more packets in order to buffer the new packet. The offered load is the ratio of the upstream traffic generated by all the ONUs per second on all the wavelengths to the total capacity of the network, which is 40 Gbps. The offered load is equally distributed between the deployed ONUs. The generated traffic in all the simulation scenarios is either TI or non-TI. The portion of non-TI traffic consists of 20% MERC, 20% RTCH, 30% RTNH and 30% OMIT applications. The TIM applications traffic consist of control/steering and sensor packets with a size of 64 bytes according to the control packet size defined by IEEE 802.3av 10 Gigabit Ethernet Passive Optical Network [28]. The packet size is normally distributed between 64 and 1518 bytes for the non-TI CoS applications.

Recent studies in [29], [30] found that the packet arrival processes in TI applications are very bursty. Moreover, an extensive study in [31] shows that the most network traffic flows can be characterized by self-similarity and long-range dependence. For these reasons all the CoS generated traffic in the simulation scenarios is characterized by the bursty self-similar Pareto distribution. For the generation of bursty traffic we used the method described in [32]. According to this approach the resulting traffic is an aggregation of multiple streams each consisting of alternating Pareto-distributed ON/OFF periods. The Pareto distribution probability function is:

$$f(x) = \frac{ab^2}{x^{a+1}}, \tag{21}$$

where α is the shape parameter and b is the location parameter. The Hurst parameter H for the Pareto distribution is estimated to 0.8 for a moderate traffic by measurements on actual Ethernet traffic performed in [33]. The relation between the shape parameter α and the Hurst parameter H is:

$$H = \frac{(3-a)}{2}, \tag{22}$$

which results to $\alpha = 1.4$ given that $H = 0.8$. For the ON period the shape parameter α_{ON} is set to 1.4 according to (22) and the location parameter b_{ON}, which adjusts the lower limit of a burst is set to 1 since the smallest burst contains only 1 packet. For the OFF periods, we follow the approach described in [7], i.e. we use a heavier tail for the Pareto distribution for the OFF periods. The shape parameter in this case, α_{OFF}, is set to 1.2 while the location parameter b_{OFF} is:

$$b_{OFF} \simeq 0.597\left(\frac{1}{l} - 1\right), \tag{23}$$

The b_{OFF} value is chosen so as to obtain a desired load l_i from the given substream i:

$$l_i = \frac{E[on_i]}{E[on_i] + E[off_i]}. \tag{24}$$

In our implementation the traffic is generated by aggregating 64 substreams for each ONU.

V. EVALUATION OF ALGORITHMS

A. SIMULATION SCENARIOS

The evaluation of the DWBA algorithms is performed using three simulation scenarios. The first scenario considers metrics as the mean and the maximum packet delay and the

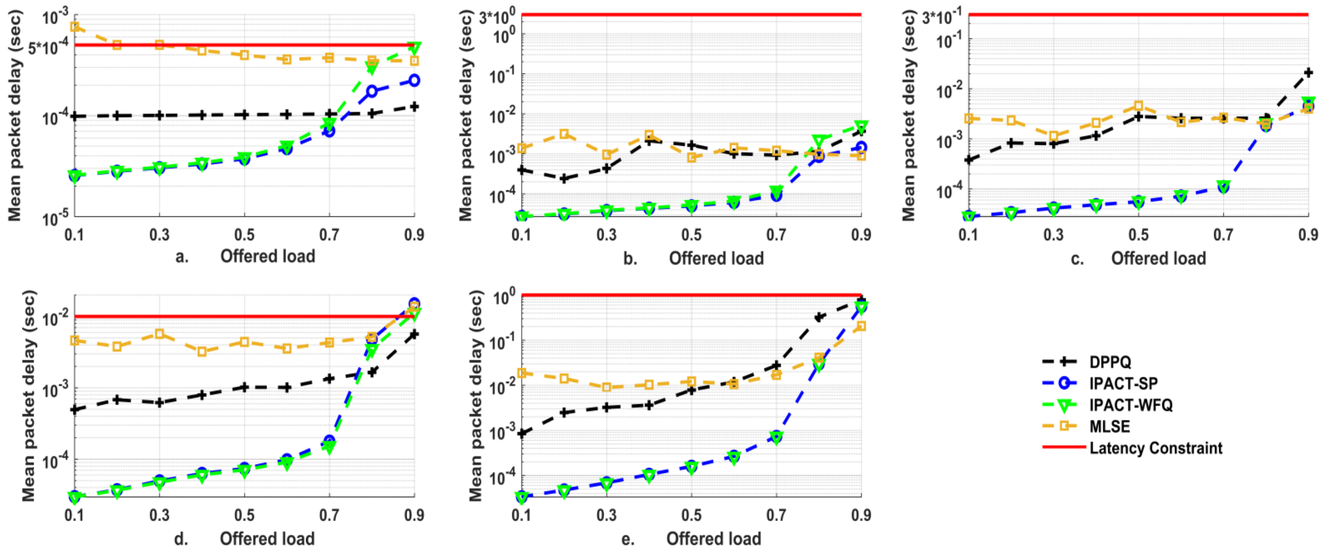

FIGURE 4. Mean packet delay of (a) TIM,(b) MERC, (c) RTCH, (d) RTNH and (e) OMIT applications under variable offered load.

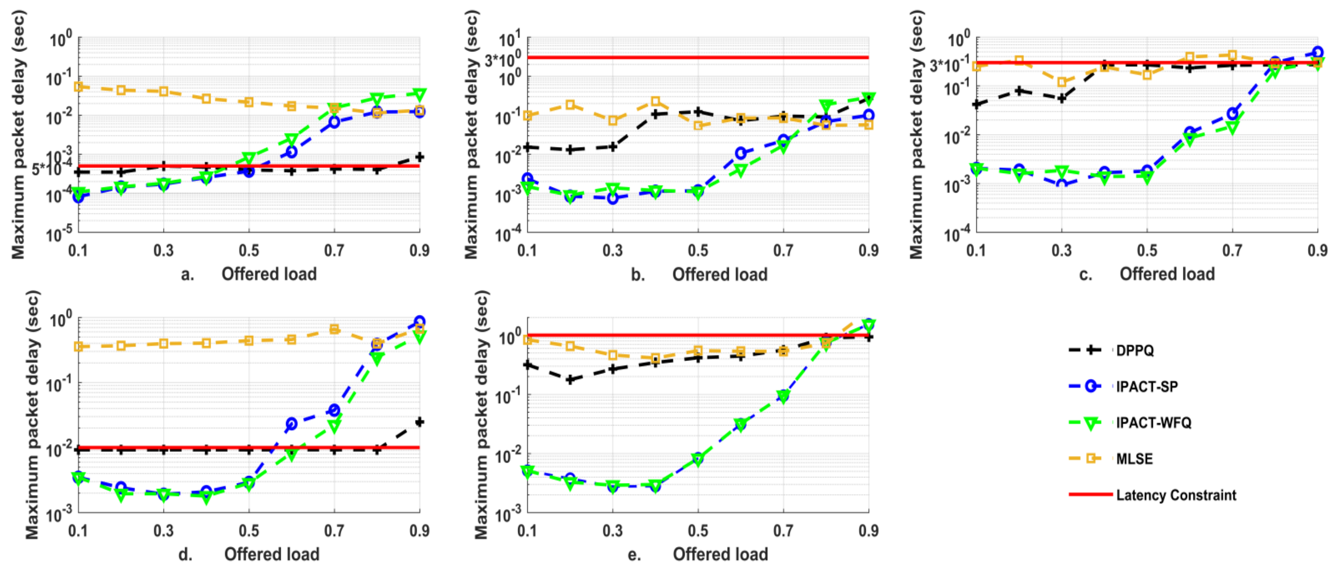

FIGURE 5. Maximum packet delay of (a) TIM,(b) MERC, (c) RTCH, (d) RTNH and (e) OMIT applications under variable offered load.

packet loss and delay rate (PLDR) for all the five CoS. It also includes the jitter performance for the real time applications as well as the degree of wavelength usage by the optical network. All the results, for the aforementioned first scenario metrics, are a function of a variable normalized offered load which consists of 40% TI traffic and 60% of non-TI traffic. The other two scenarios consider two CoS, the TIM CoS and the non-TIM CoS consists of the remaining four medical CoS presented in the system model section and examines the performance of the evaluated DWBA algorithms for the PLDR metric. The second scenario uses a fixed offered load of 0.8 and a variable percentage of TI traffic. Finally, the third scenario uses a fixed offered load of 0.7, a fixed percentage of 40% TI traffic and 60% of non-TI traffic and a variable percentage of data burst generation synchronized ONUs.

B. SIMULATION METRICS

The metrics used for the evaluation of the DWBA algorithms include the mean packet delay, the maximum packet delay, the jitter, the wavelength usage and the PLDR. The mean packet delay is a metric which shows a generic performance of the algorithms in terms of latency since it cannot show the deviation of the packet delay as well as the amount of packets which cannot fulfill the latency constraint demands of their CoS. The maximum packet delay metric shows the capability of the algorithms to keep the latency of all the packets under a certain level. The jitter metric shows the deviation of packets latency over the mean packet delay value and is crucial for the real time applications. Concluding, only the combined results of the three mentioned metrics can lead to safe conclusions about the DWBA algorithms' performance as far as latency is concerned. The wavelength usage metric is used to show

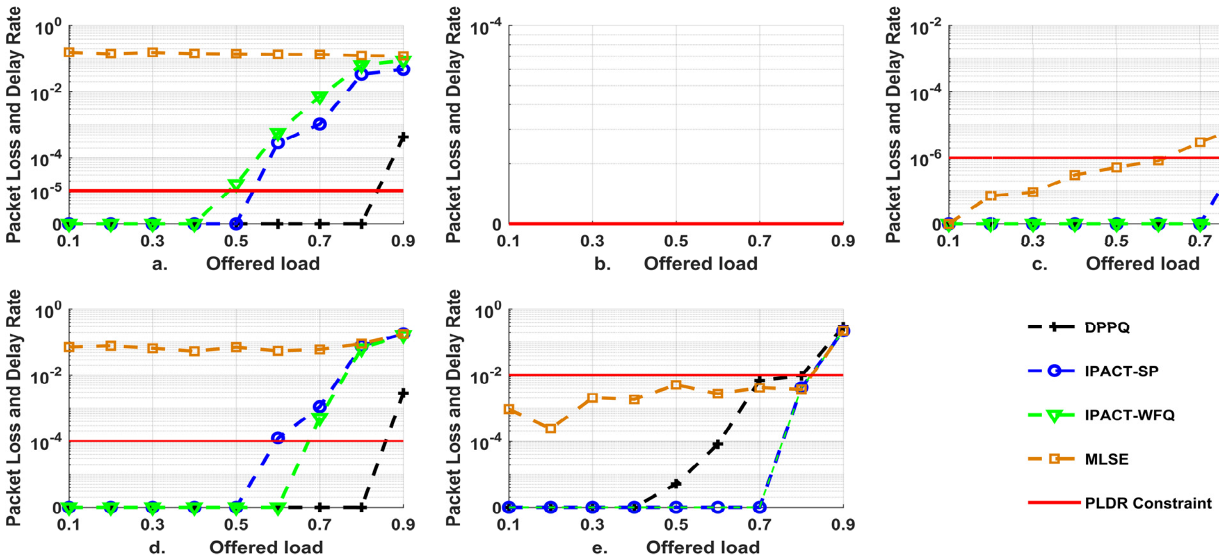

FIGURE 6. Packet loss and delay rate of (a) TIM,(b) MERC, (c) RTCH, (d) RTNH and (e) OMIT applications under variable offered load.

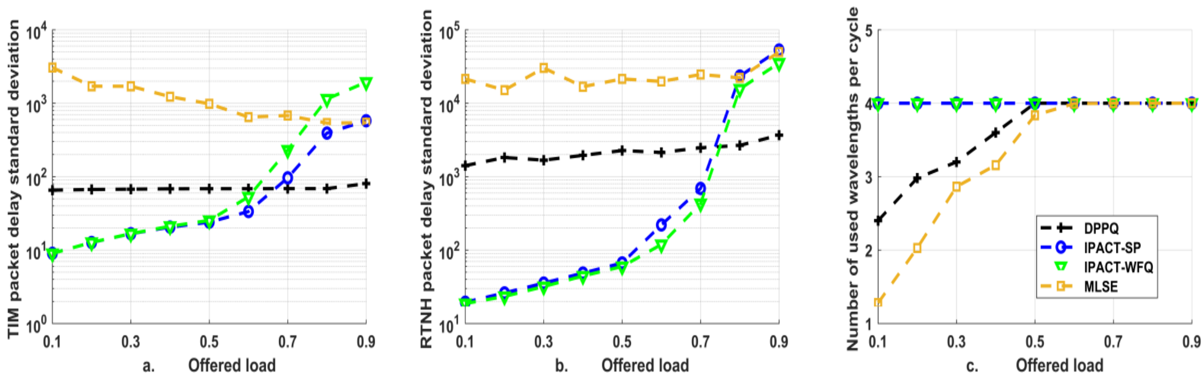

FIGURE 7. Performance of DWBA algorithms for (a) jitter of TIM applications, (b) jitter of RTNH applications and (c) per poll cycle wavelength usage.

the ability of the algorithms to be energy-efficient, since in light-load conditions they can reduce the usage of network resources, without degrading the overall efficiency of the network to properly serve all the running applications. Finally, PLDR is a metric which shows the ability of the algorithms to meet the packet loss rate demands of their CoS. PLDR is the summation of the packets lost due to buffer occupancy and of the delayed packets which cannot fulfill the latency constraint demands of their CoS.

C. SIMULATION RESULTS

The mean packet delay for all the five CoS of the first simulation scenario is depicted in Figure 4. In most of the cases, even in the heavy load one, all the algorithms can successfully maintain the average packet delay under the latency constraint of each CoS. The only exceptions are observed under light load conditions for the TIM applications of MLSE, and under heavy load for the RTNH applications for all the algorithms except DPPQ. For the MLSE, this observation can be explained by the inefficient reduction of the wavelength usage that the algorithm employs. We can also see that the DPPQ and MLSE curves are smooth all over the offered load range, in contrast with IPACT-SP and IPACT-WFQ, where the mean packet delay increases in proportion with the offered load increase. This fact can be explained by the fixed polling cycle that DPPQ and MLSE employ while IPACT-SP and IPACT-WFQ employ a variable polling cycle.

In Figure 5, the maximum packet delay for the five CoS is illustrated. In this metric, MLSE shows the worst performance since its predictive mechanism cannot handle the traffic burstiness and fails to achieve the latency constraint requirements for the entire range of the offered load scenarios of the TIM and RTNH applications. IPACT-SP and IPACT-WFQ can handle the traffic burstiness and preserve the latency constraint requirements up to medium traffic loads for the TIM and RTNH applications. DPPQ shows the best performance since for almost all the traffic load scenarios it guarantees the latency constraint requirements. The only exception for DPPQ is for the TIM and RTNH applications under very heavy load conditions. Moreover, all the algorithms, except from DPPQ, show an over the latency constraint maximum packet delay for the RTCH and OMIT applications under very heavy load conditions.

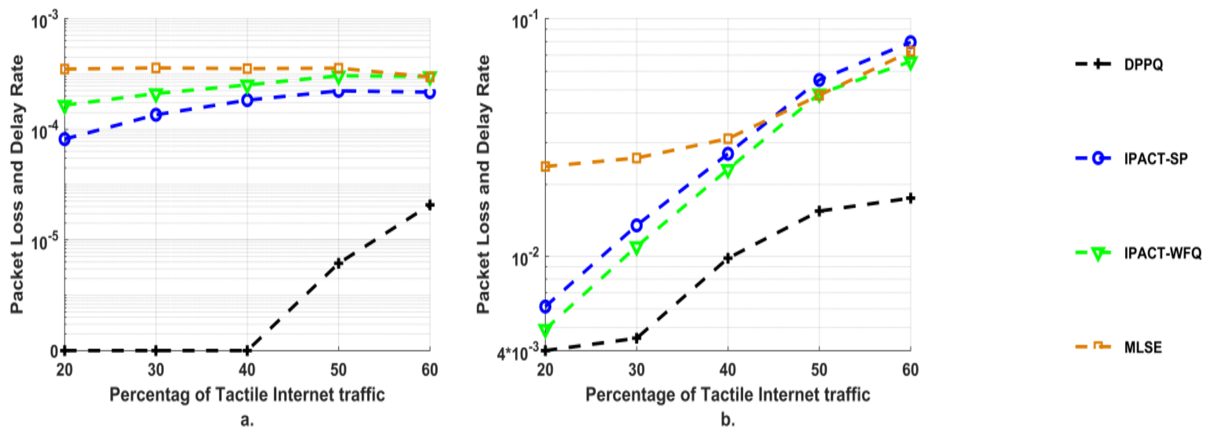

FIGURE 8. Packet loss and delay rate of (a) TIM, (b) non-TIM applications under variable percentage of TI traffic.

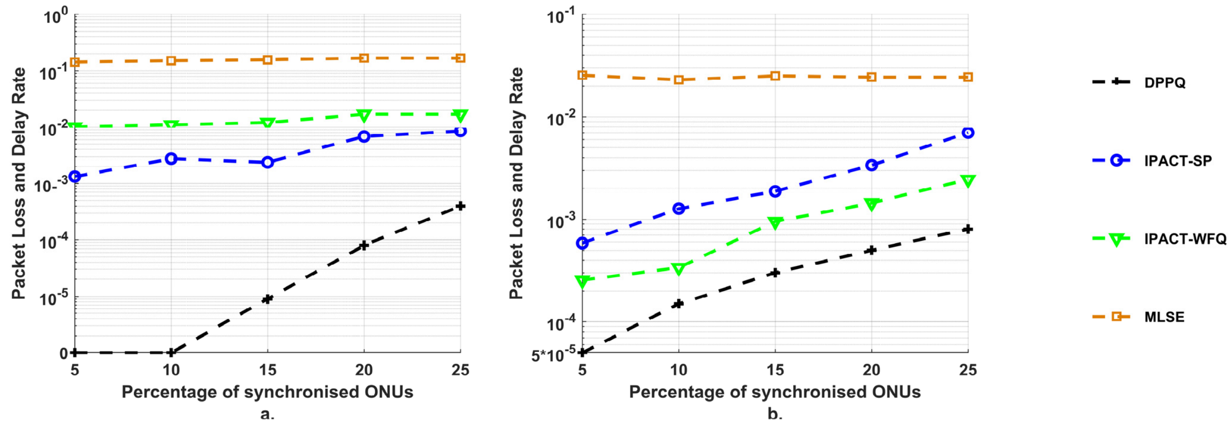

FIGURE 9. Packet loss and delay rate of (a) TIM, (b) non-TIM applications under variable network-wide synchronized traffic.

The next metric for the first simulation scenario is PLDR, which shows the rate of both delayed and dropped due to buffer occupancy packets. The results in Figure 6 show almost the same performance as shown in the maximum packet delay metric, confirming the superiority of DPPQ. The only difference is that DPPQ fails to satisfy the OMIT application PLDR constraint under very heavy load conditions. This fact is explained by the increased, compared to the other algorithms, packet drop rate of DPPQ due to the wasted bandwidth, since it uses a fixed poll cycle and, thus, a shorter one than the other algorithms under heavy load conditions.

The jitter performance of the DWBA algorithms is depicted in Figure 7a for the TIM applications and in Figure 7b for the RTNH applications. The results reveal that DPPQ in both cases achieves a balanced performance all over the offered load range. Low values of jitter, in light and medium load conditions, which increase dramatically when the load becomes heavier, are observed for IPACT-SP and IPACT-WFQ. Finally, MLSE shows again the worst performance since high jitter values are spread all over the offered load range. The smooth jitter performance of DPPQ is due to the low maximum packet delay that the algorithm achieves as shown previously.

The last metric of the first simulation scenario is the wavelength usage from the evaluated DWBA algorithms. IPACT-SP and IPACT-WFQ are designed to use the entire available spectrum in all the cases. MLSE, as shown in Figure 7c, is more energy-efficient than DPPQ, but as previously shown this fact affects its efficiency since in very light load conditions MLSE shows an overall poor performance.

The results in Figures 5, 6 and 7, show that DPPQ and MLSE perform worse than the IPACT-based algorithms in terms of mean and maximum delay and jitter under light-to-medium network loads. The first reason for this fact is that the IPACT algorithms use all the network resources regardless of the network load in contrast with the DPPQ and MLSE algorithms which reduce the usage of network resources in light loads. The second reason is the usage of the variable time polling cycle by the IPACT algorithms which allows the implementation of a small polling cycle in light and medium load conditions in contrast with DPPQ and MLSE which use a fixed polling cycle. The mentioned observation does not affect the DPPQ efficiency and the provided QoS as long as this latency is under the value of the latency constraint of the corresponding CoS. The key outcome from Figures 5,6 and 7 is that DPPQ manages to guarantee the latency constraints for all the CoS in more cases compared to the other algorithms

The results of the second simulation scenario are shown in Figure 8. DPPQ clearly outperforms the other DWBA algorithms since it achieves a null PLDR for TIM applications for up to 40% of TI traffic. Moreover, it shows a lower PLDR for the non-TI applications for all the traffic scenarios. Finally, in the third simulation scenario (Figure 9) DPPQ shows its robustness under a network-wide synchronized traffic since it achieves a null PLDR for up to 10% of synchronized ONUs. For the same scenario, the results reveal the DPPQ superiority since it shows a lower PLDR for the non-TI applications.

VI. CONCLUSION

The use of TIM applications is expected to upgrade the quality of the healthcare services provided to patients. The requirements of these applications are very demanding. The existing networking infrastructures cannot support these demands. POLs are presented as the ideal solution for these high-demand environments. An important role in the effectiveness of these networks is the management of their available resources. The existing optical network resource management algorithms are designed without taking into account the requirements of TIM applications. Designing new algorithms that will be able to cope with the new requirements is absolutely necessary, especially in environments such as healthcare where the applications' constraints are vital. The support of the QoS for the CoS of a healthcare network traffic in the MAC layer can be the base of a new generation of MAC protocols for healthcare networks which are capable of providing high quality communication services to the healthcare environment. In this paper, we presented a DPPQ algorithm which is capable to preserve the stringent QoS demands of the TIM applications, without at the same time degrading other crucial healthcare CoS served by the same network. The proposed algorithm employs a combination of techniques that enable the efficient and fair management of the available network resources. The most important aspect of these techniques is the implementation of double per CoS queues, which at the same time both simplifies and maximizes the efficiency of an important design parameter of the DWBA algorithms that is the intra-ONU scheduling. The simulation results revealed the superiority of the proposed algorithm to preserve the QoS of healthcare applications under several scenarios compared to other well-known schemes. Also the simulation results showed that the algorithm is both robust to extreme bursty traffic scenarios and scalable, since it can be adapted to any possible QoS individual demands. As future work, we plan to work on the implementation of the DPPQ algorithm in a Radio and Fiber MAC protocol which can successfully serve the end-to-end QoS requirements of TIM and other applications.

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