An Absolute And Fair QoS Differentiation Scheme
For DWDM OBS Networks

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Abstract— Optical Burst Switching (OBS) is a promising switching technology for the next generation all-optical networks. An OBS network without wavelength converters and fiber delay lines can be implemented simply and cost-effectively using the existing technology. However, this kind of networks suffers from a relatively high burst loss probability at the OBS core nodes. To overcome this issue and consolidate OBS networks with QoS provisioning capabilities, we propose an absolute QoS differentiation scheme, called Absolute Fair Quality of service Differentiation (AFQD), which is based on a wavelength partitioning scheme, called Optimization Topology-aware Wavelength Partitioning scheme (OTWP). AFQD is the first absolute QoS provisioning scheme that guarantees loss-free transmission for high priority traffic inside the OBS network. Simulation results show that AFQD not only guarantees loss-free transmission for high priority traffic but also substantially decreases the loss probability of best effort traffic to a remarkable level compared to the existing schemes.

Keywords: Optical Burst Switching (OBS); Quality of Service (QoS); Admission Control; Linear Programming; Tabu Search; Fairness; Dense Wavelength Division Multiplexing (DWDM).

I. INTRODUCTION

Optical Burst Switching [1] is a promising switching technology for the next generation all-optical networks. It is considered as a tradeoff between Optical Circuit Switching (OCS) and Optical Packet Switching (OPS). Indeed, theoretical research on OBS networks has reached the stage of prototypes in research laboratories [2, 3] and even commercial products (e.g., EtherBurst optical switch [4]). Hence, OBS networks could play an important role in metropolitan, access and local area optical networks.

Wavelength contention is the main cause of burst losses in OBS networks. A wavelength contention occurs when two or more bursts intend to take the same output fiber, on the same wavelength, at the same time. Hence, any Quality of Service (QoS) scheme for OBS networks has to consider how to deal with wavelength contentsions for each class of traffic. In fact, reducing loss probability for the OBS network is performed by reducing the level of wavelength contentsions in the network. Moreover, in the context of multi-class traffic, reducing the loss probability of a given class of traffic can be performed by privileging this class in the case of contentsions. It is worth noting that the store-and-forward based QoS schemes developed for electronic networks cannot be applied for OBS networks because of the lack of Random Access Memories (RAM) for optical networks.

In [5-9], absolute QoS differentiation schemes are proposed. In [5], the proposed QoS differentiation scheme is based on a dynamic wavelength assignment approach where wavelengths are shared (dynamically) among different classes of traffic. The authors in [6] propose two schemes for absolute QoS provisioning: Early Dropping (ED) and Wavelength Grouping (WG). Early Dropping drops intentionally and probabilistically low priority bursts in order to maintain the level of loss probability of guaranteed bursts. Wavelength Grouping provisions wavelengths for the guaranteed traffic and schedules bursts based on this provisioning mechanism. The authors in [7] propose a mechanism that guarantees a maximum loss probability for each guaranteed class of traffic. To do so, each core OBS node has to maintain traffic statistics for each class of traffic; a guaranteed burst can preempt a non-guaranteed burst (i.e., cancel its reservation) proactively according to a given preemption probability. The authors in [8] propose Reserve-and-Preempt Scheme (RPS) to improve the bandwidth provisioning of best effort traffic. The same authors in [9] propose several schemes which integrate RPS and wavelength grouping schemes in order to ensure that the highest priority guaranteed classes can be provided with their respective guaranteed loss rates. We can see that all of the above absolute QoS schemes consider a target value or a threshold for loss probability of high priority traffic. Also, to the best of our knowledge, fairness has never been considered for OBS networks in the context of QoS differentiation.

In this paper, we consider absolute QoS differentiation for OBS networks. We propose Absolute Fair Quality of service Differentiation scheme (AFQD) which guarantees, for the first time, loss-free transmission for high priority bursts whatever the kind of the OBS network topology. AFQD is based on a wavelength partitioning scheme, called Optimization Topology-aware Wavelength Partitioning scheme (OTWP) which uses Integer Linear Programming (ILP) to partition data wavelengths among the nodes in the network. Also, AFQD is the first QoS differentiation scheme to provide fairness among the users (nodes) of the network. Moreover, we propose a wavelength assignment scheme, called Best Effort Traffic Wavelength Assignment scheme (BETWA), which uses OTWP to improve the performance of Best-Effort traffic.

We consider an OBS network without wavelength converters and without FDLs. This assumption is relevant since: (a) currently, wavelength conversion devices are complex, expensive, and not technologically mature; (b) FDLs suffer from the lack of flexibility. Thus, the network under study can be implemented simply and cost-effectively using the
existing optical networks technology. Furthermore, this assumption allows measuring the performance improvement brought exclusively by our proposed schemes. Besides, we adopt Just Enough Time (JET) [1] protocol for resource reservation.

The remainder of this paper is organized as follows: Section II presents a description of the proposed wavelength partitioning scheme (OTWP), the exact ILP formulation of the wavelength partitioning problem and the tabu search algorithm to resolve it efficiently. Section III presents the proposed absolute QoS differentiation scheme (AFQD). In Section IV, we present simulation results that show the performance of AFQD. Finally, Section V concludes the paper.

II. TOPOLOGY-AWARE WAVELENGTH PARTITIONING SCHEME

In this Section, we present our wavelength partitioning scheme, called Optimization-based Topology-aware Wavelength Partitioning scheme (OTWP). First, we present a description of OTWP. Then, we present an exact formulation of wavelength partitioning in OTWP as an Integer Linear Programming (ILP) model. Finally, we present a tabu search algorithm to resolve efficiently the proposed ILP model.

A. OTWP description

The idea of OTWP is to allocate a number of wavelengths (one or more) to each OBS edge node in the network by considering the network topology. To this end, we model the OBS network as a graph \( G(V,E) \) where \( V \) is the set of nodes (\( |V| = N \)) and \( E \) is the set of links (\( |E| = M \)). We suppose that each DWDM fiber link operates with \( W \) wavelengths where \( W \) is supposed to be bigger than \( N \). Hence, OTWP allocates a wavelength interval (i.e., a number of wavelengths) of size \( W/N \) to each node in the OBS network based on topological constraints, i.e., the closer two nodes to each other (i.e., the smaller the distance between the nodes), the more distant their allocated wavelength intervals from each other (i.e., the larger the distance between the intervals).

For a given node \( i \in \{0,...,N-1\} \), its allocated wavelength interval is denoted by \( i^\prime \in \{0,...,N-1\} \). The first wavelength in the wavelength interval \( i^\prime \) is computed as follows:

\[
St(i^\prime) = \begin{cases} 
\left\lfloor \frac{i^\prime \cdot (W/N)}{1} \right\rfloor; & \text{if } \left\lfloor i^\prime \cdot (W/N) \right\rfloor - \left\lfloor i^\prime \cdot (W/N) \right\rfloor < 0.5 \\
\left\lfloor i^\prime \cdot (W/N) \right\rfloor; & \text{otherwise}
\end{cases}
\]  

(1)

Thus, even if the size of wavelength intervals \( W/N \) is not always an integer value, we use floor and ceil functions to determine the start wavelength of each wavelength interval.

The distance between two wavelength intervals \( i^\prime \) and \( j^\prime \), denoted by \( D(i^\prime,j^\prime) \), is calculated as follows:

\[
D(i^\prime,j^\prime) = |i^\prime - j^\prime|
\]  

(2)

The distance between two nodes \( i \) and \( j \) in the network, denoted \( d(i,j) \), is equal to the number of hops of the shortest path between nodes \( i \) and \( j \).

![Figure 1. An example of wavelength partitioning using OTWP scheme.](image)

Fig. 1 shows an example of OTWP scheme using a linear topology of 4 nodes and 3 fiber links with 12 wavelengths on each link. In the optimal solution presented here (obtained by the resolution of the model in subsection B using CPLEX 10.11 solver [10]), wavelength intervals \( 0 = [0, 2], 1 = [3, 5], 2 = [6, 8] \) and \( 3 = [9, 11] \) are allocated to nodes 1, 3, 0 and 2, respectively. The distance between the wavelength interval of node 1 and the wavelength interval of its neighbor, node 2, is \( D(0,3) = 3 \). Similarly, for nodes 0 and 1 we have \( D(2,0) = 2 \) and for nodes 2 and 3 \( D(3,1) = 2 \). These distances could be calculated for each pair of nodes in the network. Due to these distances, we can expect that wavelength contentions could be significantly reduced (see Section III).

B. Exact Formulation

We formulate the above wavelength partitioning problem as a combinatorial optimization problem; in the following we present the model formulation.

Given:

\[ D[D_{ij}] \] Matrix of distances between wavelength intervals where \( D_{ij} \) is calculated using Eq. 2.

\[ d[d_{ij}] \] Matrix of distances between nodes in the network where \( d_{ij} \) is the number of hops of the shortest path between node \( i \) and node \( j \).

\( N \) The number of nodes in the network and the number of wavelength intervals (each one of size \( W/N \)); we have one wavelength interval per node.

Variables:

\( x_{ij}^{i\prime} \) A binary variable which takes the value 1 if wavelength interval \( i^\prime \) is allocated to node \( i \); 0 otherwise.

Objective:

Maximize \( C = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \sum_{i^\prime=0}^{N-1} \sum_{j^\prime=0}^{N-1} \frac{D_{ij}^{ij}}{d_{ij}} x_{ij}^{i\prime} x_{ij}^{j^\prime} \)  

(3)

Subject to:

\[
\sum_{i=0}^{N-1} x_{ij}^{i\prime} = 1 \quad i^\prime = 0,...,N-1
\]  

(4)

\[
\sum_{j=0}^{N-1} x_{ij}^{i\prime} = 1 \quad i = 0,...,N-1
\]  

(5)

Bounds:

\( x_{ij}^{i\prime} = 0, 1 \quad i = 0,...,N-1 \quad i^\prime = 0,...,N-1 \)
The objective function (3) maximizes the sum of ratios \( \frac{D_{ij}}{d_{ij}} \) (for each pair of nodes \( i \) and \( j \) where \( i < j \) and their allocated wavelength intervals \( i' \) and \( j' \), respectively) is that we have a maximization problem where we aim to increase the distance \( D_{ij} \) whenever the distance \( d_{ij} \) is small. For example, let us consider again the topology shown in Fig. 1, the metric \( C = R_{12} + R_{23} + R_{13} + R_{23} \) is equal to \( \frac{2}{1} + \frac{1}{2} + \frac{1}{3} + \frac{1}{2} + \frac{2}{1} \) in the optimal solution. We can see clearly that closer nodes have been allocated distant wavelength intervals and vice-versa, which is our aim. Furthermore, any other solution that does not respect this property will not be optimal.

Constraint (4) states that each wavelength interval \( i' \) is allocated to exactly one node \( i \) in the network. Constraint (5) states that each node \( j \) in the network has exactly one allocated wavelength interval \( j' \).

This model is similar to the Quadratic Assignment Problem (QAP) [11] with the exception that we maximize the metric \( C \) instead of minimizing a cost in a typical QAP. In fact, a standard formulation of QAP is given by:

\[
\text{Minimize } \sum_{i,j=1}^{n} a_{\pi(i)\pi(j)}b_{ij}
\]

where \( \pi \) is the set of permutations of \( \{1,2,...,n\} \) and each individual product \( a_{\pi(i)\pi(j)}b_{ij} \) is the cost caused by assigning facility \( \pi(i) \) to location \( i \) and facility \( \pi(j) \) to location \( j \).

Since the quadratic form in the objective function (3) makes the task of finding efficient resolution methods difficult, we formulate the problem as an Integer Linear Programming (ILP) model to benefit from its efficient resolution methods; thus, we define new variables \( y_{ij}^{ij} \) and a constraint (7) with new bounds:

\[
y_{ij}^{ij} \leq x_{i'} + x_{j'}
\]

\( i=0,...,N-1 \) \( j=0,...,N-1 \) \( i'=0,...,N-1 \) \( j'=0,...,N-1 \) \( x_{i'} + x_{j'} \) with bounds:

\[
y_{ij}^{ij} = 0, i=0,...,N-1 j=0,...,N-1 \]

Constraint (7) constrains variables \( y_{ij}^{ij} \) to take the value 1 if both variables \( x_{i'} \) and \( x_{j'} \) take the value 1; this is always true because the coefficient of \( y_{ij}^{ij} \), in the new objective function (8), is strictly positive in a maximization problem; otherwise, \( y_{ij}^{ij} \) takes the value 0.

The new objective function becomes:

\[
\text{Maximize } C = \sum_{i,j=1}^{n} \sum_{j'=1}^{n} \sum_{i'=1}^{n} \sum_{d_{ij}} \frac{D_{ij}}{d_{ij}} y_{ij}^{ij}
\]

C. Complexity analysis

Even formulated as an ILP, our model remains a Quadratic Assignment Problem (QAP). It is known that QAPs are not only NP-hard but also remain among the hardest combinatorial optimization problems. In fact, the authors in [12] proved that QAP is NP-hard. This difficulty to resolve QAPs can be seen in their computational complexity. In our case, we can see that the set of feasible solutions is the set of all possible permutations of \( \{0,...,N-1\} \) which is \( n! \).

Indeed, to have a good idea of the computational complexity of our ILP, we tried to resolve it using CPLEX 10.11 solver. Whereas the resolution time is reasonable for small instances, such as the network shown in Fig. 1, it takes several days before returning the optimal solution for medium and large instances, such as 14-nodes NSFNET topology (Fig. 2). Hence, a meta-heuristic approach that returns good solutions (rather than the optimal solution) in a reasonable time is clearly mandatory in this case.

D. Tabu search algorithm

The proposed tabu search algorithm aims to find, efficiently, a good solution to the wavelength partitioning problem in a reasonable time. Tabu search has been proposed by Glover in 1986 [13]. This meta-heuristic searches the best feasible solution starting from the neighbourhood of an initial solution. The process is repeated until a maximum number of iterations is reached. Tabu search avoids cycles by forbidding moves that take the current solution to a solution previously visited. These moves are stored in a list called tabu list.

Let us define \( L \) as the function that returns the wavelength interval allocated to a given node. For instance, if wavelength interval \( i' \) is allocated to node \( i \), then \( L(i) = i' \). Also, let us note a solution to the wavelength partitioning problem as a permutation \( P \) and the cost of this solution, defined in (8), as \( C(P) \).

In our tabu search algorithm, a move represents an exchange of the assigned wavelength intervals between two nodes \( i \) and \( j \), which means that if the current solution is a
and 1
are the matrices of distances between 

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Here because of the space limitation.

The proof of the equivalence of (9) and (10) is not presented

complexity of formula (9) is clearly O(n²). For efficiency

wavelength intervals for solutions 1

algorithm is O(n²).

A.

Algorithm I shows the pseudo code of the proposed tabu

search algorithm. The algorithm begins by the initialization

step where an initial feasible solution has to be found. This can

be performed by generating a random feasible solution which

can be a very bad solution. Hence, to improve the efficiency of

the proposed tabu search algorithm, we propose to use a simple

heuristic algorithm, called Construction Method (CM). CM

uses a loop of N iterations (the number of nodes and

wavelength intervals) where, at each iteration, a new node is

assigned a wavelength interval that maximizes the metric:

\[
C^* = \sum_{k \in S} \frac{D_{ij}(k)}{d_{ij}}
\]  

(11)

where S is the set of nodes which have already been assigned

a wavelength interval. After that, in step1, at each iteration k

between 0 and Max_Iterations, the tabu search algorithm finds the best solution \( P_{k+1} \) in the neighborhood of the current solution \( P_k \) using a non tabu pair exchange; if the cost of solution \( P_{k+1} \) is better that the best cost found until now (denoted best_cost), best_cost will take the value of the cost of \( P_{k+1} \). The computational complexity of the loop in this algorithm is O(n²).

To measure the quality of the proposed tabu search

algorithm solutions, we performed experiments that compare its solutions to: (a) the initial solution given by the heuristic algorithm (CM) which is a good solution; and (b) the solution obtained when stopping CPLEX after long running time (several days). We observe that, overall, our tabu search algorithm improves the solutions in (a) and (b) by around 1%

to 5 % for instances of sizes 10 to 100 nodes (related numerical results are not presented here because of space limitation).

ALGORITHM I. The tabu search algorithm.

Begin

Step 0: Initialisation

Compute an initial feasible solution, noted \( P_0 \), using a construction method heuristic.

best_cost = \( C(P_0) \)

int k = 0

Step 1: loop

while ( k < Max_Iterations)

Find in the set of neighbours of the current solution \( P_k \) \{ \( P_m \) obtained using a non tabu pair exchange on \( P_k \) \} the best solution \( P_{k+1} \) such that:

\[
\Delta(P_k, P_{k+1}) = \text{Max} \Delta(P_k, P_m)
\]

add the pair exchanged, to move from \( P_k \) to \( P_{k+1} \), to the tabu list.

If (\( C(P_{k+1}) > \text{best_cost} \)) then

\[ \text{best_cost} = C(P_{k+1}) \]

k = k+1

End while

End

III. ABSOLUTE FAIR QOS DIFFERENTIATION SCHEME

In this Section, we present the proposed Absolute Fair Quality of service Differentiation scheme (AFQD). First, we describe the operation of AFQD. Then, we present a solution for the starvation problem of low priority traffic. Finally, we discuss the fairness aspect of AFQD.

A. The operation of AFQD

AFQD uses the wavelength partitioning scheme OTWP, presented in Section II, to provide absolute quality of service differentiation. We assume that each wavelength interval assigned by OTWP to each node contains at least one wavelength. This assumption is very reasonable since DWDM fiber links operate with tens to hundreds wavelengths. Without loss of generality, we suppose that we have two classes of traffic: (a) Loss Sensitive (LS) traffic (e.g., mission critical applications traffic); and (b) Best-Effort (BE) traffic. For simplicity, a burst belonging to LS traffic is called LS burst and a burst belonging to BE traffic is called BE burst. LS bursts have higher priority compared to BE bursts. We suppose that each OBS edge node has a burst assembly buffer for each destination OBS node and each class of traffic (i.e., LS or BE). Hence, an incoming packet from the client network (e.g., an IP network) is classified as LS or BE and forwarded to the
appropriate assembly buffer according to: (1) its destination; and (2) its QoS requirements.

After the burst assembly phase, each LS burst is transmitted using one of the wavelengths of its source node’s wavelength interval (we call these wavelengths: local wavelengths) along the OBS network with loss-free transmission guarantee. Thus, LS bursts from a given source node will never contend with LS bursts of the other nodes, and naturally, will never contend among themselves since they are transmitted from the same source of traffic. Consequently, there will be no wavelength contentions, and hence, no LS burst losses inside the network. Moreover, any classical wavelength assignment policy can be used to assign a local wavelength to a LS burst in the source node (e.g., First-Fit or Random). Differently from LS bursts, BE bursts can use any wavelength at the OBS source node; consequently, BE bursts can contend with LS bursts and BE bursts of the other nodes in the network. Let us notice that wavelength assignment at the OBS source node is decisive because of the absence of wavelength converters at the OBS core nodes. Thus, bursts (LS and BE) will use the same wavelength up to their OBS destination nodes. When two BE bursts are involved in a wavelength contention, one of the two bursts is dropped randomly; when a LS burst and a BE burst are involved in a wavelength contention, the LS burst is privileged to maintain the loss-free transmission guarantee; hence, even if a BE burst has already performed wavelength reservation, a LS burst can cancel this reservation and preempt the BE burst. If a LS burst cannot reserve a wavelength (in its OBS source node) even by preempting a BE burst, this will mean that the local wavelengths of this node are fully used by LS bursts; in this case, the LS burst can be stored (in the electronic domain) until a local wavelength becomes available, or it can be simply dropped. This can be seen as an admission control mechanism for LS traffic; a LS burst will never contend with another LS burst once it reserves a wavelength at its OBS source node. Fig. 3 shows the operation of AFQD to schedule a LS burst at OBS source node. The test of LS traffic local wavelengths bandwidth utilization (threshold U) is related to the starvation problem which is discussed in subsection III.B.

So far, we have explained how to guarantee loss-free transmission for LS bursts, thus, the remaining challenge is to improve the performance of BE traffic as much as possible. For that, we propose a novel wavelength assignment scheme for BE bursts at the OBS source node. We call this scheme Best Effort Traffic Wavelength Assignment scheme (BETWA). BETWA uses OTWP wavelength partitioning solution to find an available wavelength to transmit BE bursts. Indeed, given a solution to the wavelength partitioning problem returned by OTWP, a node $i$ searches an available wavelength to transmit a BE burst starting from the start wavelength $St(i')$ of its wavelength interval $i'$ defined in (1); since the closer the nodes to node $i$ (e.g., one hop neighbors) the distant their start wavelengths to $St(i')$, wavelength contentions (and hence burst losses) among BE bursts will be considerably decreased. It is worth noting that a source node can assign any available wavelength (from the set of all wavelengths) to a BE burst; however, the order in which this available wavelength is searched is specific. Indeed, a source node with wavelength interval $i'$ searches an available wavelength starting from wavelength $St(i')$ (defined in (1)) to wavelength $(W-1)$, then from wavelength $(St(i')-1)$ to wavelength 0 (in the reverse direction). This order is used to benefit from the concept of distance between intervals. We conclude that OTWP maximizes (implicitly) the traffic isolation between the different nodes in the network. For example, in Fig. 1, if BETWA is not used and a classical wavelength assignment is used instead (e.g., First Fit), BE bursts originating from nodes 1 and 2 with destination 0 are more likely to contend on the link from node 1 to node 0. Fig. 4 shows the operation of AFQD to schedule a BE burst at OBS source node.

We can see that AFQD is fair since each OBS node has the same amount of bandwidth on each outgoing link (the bandwidth of its local wavelengths) to transmit its LS bursts with loss-free transmission guarantee.

![Figure 3. The operation of AFQD to schedule a LS burst at source node.](image)

**B. Starvation problem for BE traffic**

Since LS bursts have the ability to preempt BE bursts, the BE bursts could suffer from the starvation problem when LS
bursts use all of the available bandwidth in the network (i.e., each node uses fully its local wavelengths for LS traffic). Allowing preemption of BE bursts makes it impossible to solve the problem of starvation. Hence, we propose to disable the preemption of BE bursts at an outgoing fiber link of a source node when the bandwidth utilization of LS traffic exceeds a predefined threshold, denoted by $U$, of the local wavelengths bandwidth of this node on this outgoing link (e.g., 80%). Thus, each OBS edge node has to monitor the bandwidth utilization of LS traffic at each one of its outgoing fiber links; whenever this bandwidth utilization exceeds the threshold $U$ on a given outgoing fiber link, LS bursts cannot preempt BE bursts that have already reserved resources on this link. In this case, LS bursts are stored (in the electronic domain) until until resources become available or simply dropped at the source node (admission control); this still preserves the loss-free transmission guarantee for LS traffic inside the OBS network. This scheme is simple since it operates only in the OBS edge nodes. Also, it allows LS traffic to use the whole capacity of the node’s local wavelengths on a link when no (or negligible) BE traffic uses this link.

IV. SIMULATION RESULTS

In this Section, we present simulation results that show the performance of AFQD. We use ns-2 simulator [14] and modules that implement OBS in ns-2 [15]. We present only the results of NSFNET topology (Fig. 2) since the results of the other kinds of topologies (regular and ring) are similar and because of the space limitation. We assume that each single fiber link is bidirectional and all links have the same number of wavelengths. Each node in the network can generate, route and receive traffic. Sources and destinations of traffic connections are generated randomly between any two nodes in the network (i.e., dynamic traffic). The traffic load is expressed as the percentage of the total load that can be carried by the network (i.e., Traffic Load = (Offered Load) / (Σ Link capacities)) where Offered Load is the amount of traffic injected, per second, in the network. The capacity of a link is the sum of the capacities of all the wavelengths in this link. We use Min Burst length Max Assembly Period (MBMAP) algorithm for burst assembly [16], with maximum burst size fixed to 10 KB (Kilo Bytes). We use exponential ON/OFF traffic and shortest path for routing. We fix the value of the threshold $U$ to 0.8, i.e., preemption is disabled when the bandwidth utilization of LS traffic reaches 80% of the bandwidth capacity of the local wavelengths of a node on an outgoing link. We set the proportion of LS traffic to 50% of the overall traffic unless stated otherwise.

The goal of these simulations is to measure the performance of AFQD. We present: (a) $AFQD$: the overall loss probability for all of the bursts (i.e., blocking probability for LS bursts and loss probability for BE bursts); (b) $LS$: the blocking probability for LS traffic at the access of the OBS network (admission control blocking probability) since the loss probability of LS traffic is equal to zero inside the OBS network; and (c) $BE$: the loss probability for BE traffic. Also, we compare AFQD to Last Available Unscheduled Channel with Void Filling (LAUC-VF) [17] which is a good wavelength assignment algorithm that outperforms largely the classical wavelength assignment policies (e.g., First-Fit and Random).

All the following results have a confidence level of 95%.

Fig. 5 shows the performance of AFQD compared to LAUC-VF. We can see that AFQD reduces effectively the loss probability of the OBS network. Indeed, whereas the mean loss probability of LAUC-VF (over all of the loads) is about $10^{-4}$, the mean loss probability of AFQD is about $5x10^{-5}$. In addition, whereas at load 100% the loss probability of LAUC-VF is $1.4x10^{-4}$, it is as low as $2x10^{-4}$ for AFQD. This proves that AFQD is not only able to provide absolute QoS differentiation for the OBS network, but also it can reduce its loss probability to a very remarkable level for the network under study (i.e., without wavelength converters and FDLs). The same behavior is observed for regular and ring topologies (related figures are not presented here).

![Figure 5: Loss probability vs. load for AFQD and LAUC-VF on NSFNET with 64 wavelengths.](image)

Fig. 6 shows the loss probability for BE traffic when varying its proportion (of the overall traffic). We can see clearly that the proposed wavelength assignment scheme for BE traffic (BETWA) is efficient in reducing loss probability of BE traffic regardless of its proportion. Indeed, we can see that even at load 100%, the loss probability for BE traffic is in the order of $10^{-4}$. Also, we can see that BE loss probability increases when the proportion of BE traffic decreases (i.e., the proportion of LS traffic increases) which was expected.

![Figure 6: BE traffic loss probability vs. load on NSFNET with 64 wavelengths.](image)

Fig. 7 shows the blocking probability of LS traffic at the source OBS edge nodes. This blocking could happen when the LS traffic bandwidth utilization of the local wavelengths of a node on an outgoing link exceeds the threshold $U$ (80% in these simulations). We can see that this blocking probability is at most in the order of $10^{-4}$ which is very low compared to the high priority traffic loss target in other QoS schemes (e.g., $10^{-2}$ in [7] and $2x10^{-2}$ in [8]). Also, we can see that this blocking
probability increases when the proportion of LS traffic increases, which is obvious.

Figure 7. LS traffic blocking probability on NSFNET with 64 wavelengths

Fig. 8 plots together the loss probability of AFQD and BE traffic (50%) and the blocking probability of LS traffic (50%). We observe that the blocking probability of LS traffic is significantly lower than the loss probability of BE traffic, especially when traffic load exceeds 40%. This proves that AFQD successfully provides QoS differentiation among LS traffic and BE traffic.

Figure 8. Loss probability of AFQD and BE (50%) and blocking probability of LS (50%) on NSFNET with 64 wavelengths.

Fig. 9 shows AFQD loss probability, BE (50%) loss probability and LS (50%) blocking probability when fixing the traffic load to 60% and varying the number of wavelengths from 32 to 128 on NSFNET topology. We can see that the number of wavelengths has a significant impact on the performance of AFQD. Indeed, the loss probability of AFQD is in the order of $10^4$ with 32 wavelengths and it is in the order of $10^5$ with 64 wavelengths. This behavior was expected since the size of each wavelength interval (the number of local wavelengths) in OTWP becomes larger when the number of wavelengths increases; this increases the capability of traffic isolation amongst the nodes in the OBS network. Also, this proves that AFQD is more efficient when using DWDM technology where each fiber link operates with a large number of wavelengths. Moreover, even with 32 wavelengths, we can observe the QoS differentiation capability of AFQD: the loss probability of BE traffic is about seven times the blocking probability of LS traffic.

V. CONCLUDING REMARKS

In this paper, we have proposed an absolute QoS differentiation scheme for OBS networks (AFQD). AFQD is based on a wavelength partitioning scheme (OTWP) which models the wavelength partitioning problem as an Integer Linear Programming (ILP) model and uses a tabu search algorithm to resolve efficiently this model. AFQD guarantees loss-free transmission inside the OBS network for high priority traffic (Loss Sensitive (LS) traffic) whatever the kind of the OBS network topology. In addition, AFQD uses a novel wavelength assignment scheme (BETWA) to improve the performance of Best Effort (BE) traffic in terms of loss probability. Simulation results show that AFQD decreases significantly loss probability of the OBS network to a remarkable level. Also, simulation results show the effectiveness of AFQD to provide absolute QoS differentiation.

REFERENCES