Gain and Cost brought in by Wavelength Conversion for the Routing and Wavelength Assignment of two Traffic Classes in WDM Networks

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This paper studies the impact of using wavelength conversion capabilities in WDM optical networks considering different traffic classes. We use two types of lightpath demands (LD) referred to as scheduled lightpath demands (SLDs) and random lightpath demands (RLDs). An SLD is a pre-planned lightpath demand with pre-determined date of arrival, life duration and capacity. Conversely, an RLD corresponds to a connection request that arrives randomly and is dealt with on the fly. The SLD model is deterministic because the demands are known in advance and is dynamic because it takes into account the evolution of the traffic load in the network over time. SLDs may for instance correspond to high priority traffic whereas RLDs represent best effort traffic.

In order to assess the gain obtained in terms of rejection ratio thanks to wavelength conversion, routing and wavelength assignment (RWA) is performed under two different assumptions. In the first case all the network nodes have wavelength conversion capabilities whereas in the second case no wavelength converter exists in the network.

We compute the RWA for the SLDs and the RLDs in two separate phases assuming a limited number of wavelengths on each fiber-link in the network. In the first phase, the characteristics of SLDs being known, we compute an optimal RWA for the SLDs (at this stage, the RLDs' characteristics are not known and hence cannot be taken into consideration). In the second phase, the RWA for the RLDs is performed over the resources not currently used by the active SLDs. The objective of both routing phases is to minimize the number of rejected LDs.

We performed simulations on various scenarios in order to evaluate to what extent the rejection ratio may be improved by conversion and at which cost this improvement may be achieved.

1. Introduction

In all-optical wavelength-division multiplexed (WDM) networks, a lightpath demand (LD) must be established along a route using a common wavelength on all the links of the considered route. This constraint called the wavelength continuity constraint (WCC) may be removed by introducing wavelength converters. A wavelength converter is a device which takes as its input a data channel modulated onto an optical carrier λ_{in}, and produces at its output the same data channel modulated onto a different optical carrier λ_{out} [1]. Wavelength converters thus improve network blocking performance allowing more efficient use of the network resources. This network performance is measured by the rejection ratio or the blocking probability which is defined as the ratio of the number of blocked LDs to the total number of LDs to be routed. However, the introduction of wavelength converters into WDM cross-connects increases the hardware cost and complexity. Thus, it is important to establish precisely what advantages wavelength converters offer WDM networks.

In order to assess the gain obtained in terms of rejection ratio thanks to wavelength conversion, we study the routing and wavelength assignment (RWA) problem under two different assumptions. In the first case, we assume that each network node has wavelength conversion capabilities. The wavelengths are hence assigned to each path on a link-by-link basis. In the second case, no wavelength converters are used and the same wavelength is assigned to a path from its source node to its destination node. In the latter case, the WCC appears to be a severe constraint and leads to higher rejection ratios. When an LD cannot be set up due to resource limitations, it is said to be rejected (blocked). This can be due to:

- The lack of free wavelengths on at least one of the paths connecting the source to the destination of the demand
- The lack of path-free wavelengths to set up the LD in the absence of wavelength converters. We call a path-free wavelength a common free wavelength on all the links of a path

The RWA problem is investigated considering two types of traffic demands referred to as Scheduled Lightpath Demands (SLD) [2] and Random Lightpath Demands (RLD) [3,4]. SLDs are pre-planned LDs with pre-determined dates of arrival, life durations and capacities. Conversely, RLDs are totally random and arrive one at a time. We propose two-phases algorithms to compute the RWA for the SLDs and the RLDs under the aforementioned assumptions. Phase 1 computes the RWA for the SLDs whereas Phase 2 computes the RWA for the RLDs. Phase 1 performs an off-line global optimization under a limited number of wavelengths per fiber. The objective is to minimize the rejection ratio. In cases when there exist several solutions with the same rejection ratio, the solution that minimizes the number of optical channels necessary to satisfy the set of SLDs is chosen. The number of optical channels is a function of the number of required cross-connects' ports. Conversely, it is only possible to enview local optimization for the RLDs. The RLDs are dealt with on the fly at their arrival dates.

The remainder of the paper is organized as follows. Section 2 details the proposed algorithms to solve the RWA problem for both sets of SLDs and RLDs in both network types (with and without wavelength converters). In Section 3 the performance of the proposed algorithms is evaluated in terms of rejection ratio as well as in terms of the number of required optical channels. Finally, Section 4 concludes the paper and presents future work.

2. The Routing and Wavelength Assignment Problem

2.1 Routing and Wavelength Assignment for Scheduled Lightpath Demands

This section is devoted to the proposed algorithm to solve the RWA problem for the SLDs. As previously introduced, an SLD is a pre-planned lightpath demand with pre-determined date of arrival, life duration and capacity.

RWA with Wavelength Conversion

When wavelength converters are supposed to be included in each cross-connect of the WDM networks, the wavelength continuity constraint is suppressed. The blocking probability is thus strongly reduced. With wavelength converters, wavelengths can be assigned on a link-by-link basis eliminating the need for the wavelength assignment algorithms and thus limiting the RWA problem to the routing problem. In this scenario, the chosen number of wavelengths is sufficient to route all the SLD requests.. Thus the efficiency of the RWA algorithm is evaluated only on the basis of the number of required ports.

The characteristics of SLD requests being known in advance, they can be routed by means of global optimization tools. The proposed algorithm determines the best routing for the SLDs that minimizes the global cost of the network while satisfying the limited number of wavelength per fiber. In general, the global cost is expressed in terms of required electrical and optical ports. This goal is achieved by means of channel reuse thanks to the knowledge of time and space correlation between the demands. In the case of SLDs, this cost depends only on the number of required optical ports. Indeed, the number of electrical ports used at the source and destination nodes of each demand remains unchanged for the various routing solutions.

The algorithm that is adopted for this task is based on Simulated Annealing (SA) [5]. The initial solution of the SA algorithm is the one that associates to each request the shortest path between its source node and its destination node. At each iteration of the SA algorithm, a new routing solution is generated by simultaneously modifying the path of a random number of requests. This path modification consists in choosing a new path from a set of K shortest path already computed for each source-destination pair.

The new routing solution is directly rejected if it doesn't satisfy the limited number of optical channels per fiber. However, the new routing solution is accepted if its cost is lower than the cost of the best current routing solution. If this new routing solution is more expensive than the best current one, it may be accepted according to a certain probability. This probability decreases step by step at each iteration. We estimate that an acceptable optimum routing solution has been reached when the routing solution with minimal cost remains unchanged for a certain number of iterations.

RWA without Wavelength Conversion

A SA algorithm is also used to solve the RWA problem when no wavelength converters are used. At each iteration of the SA algorithm, a new routing solution is generated in the same way as in the previous case. A First-Fit (FF) algorithm [6] is used to assign the wavelengths to the requested lightpaths. All wavelengths are numbered and a lower numbered wavelength is considered when searching for an available wavelength. Thus we can compute the number of rejected demands due to the lack of resources and to the limited number of wavelength per fiber-link. The aim of the SA algorithm is to minimize the number of rejected demands. If different routing solutions lead to the same number of rejected demands, we choose the one that minimizes the number of required optical channels.

2.2 Routing and Wavelength Assignment for Random Lightpath Demands

We need the following notations to explain the way we deal with the RWA for the RLDs.

Notations

- $G=(V,A,\varphi)$ is an arc-weighted symmetrical directed graph with vertex set V, arc set A and weight function $\varphi : A \to \Re^+$ representing the physical length (or any other cost function set by the network operator)
- $N=|V|$, $L=|A|$ are respectively, the number of nodes and the number of links in the network
- W denotes the number of wavelengths on each-fiber link in the network
- D denotes the total number of LDs (SLDs and RLDs) arriving at the network
- K denotes the number of alternate shortest paths (if many paths exist, otherwise we consider the available ones) computed beforehand between each possible source destination pair in the network (graph) according to [7].
- $P_{k,i}$ represents the k^th alternate shortest path in G connecting the source node to the destination node of LD number i
- ν_a denotes the number of occupied wavelengths on arc a. $\nu_a = 0$ when all the wavelengths are available on the fiber link, $\nu_a = +\infty$ if all the wavelengths are busy
- $C_{k,i,t} = \sum_{a \in P_{k,i}} \nu_a$ is the cost of path $P_{k,i}$ at time t. $C_{k,i,t} = +\infty$ if there exist at least one link a on $P_{k,i}$ whose cost is $\nu_a = +\infty$, i.e., all the available wavelengths on a are busy
- $\kappa_{k,i,t} = (\gamma_{1,k}^{i,t}, \gamma_{2,k}^{i,t}, \ldots, \gamma_{W,k}^{i,t})$ is a W-dimensional binary vector. $\gamma_{j,k}^{i,t} = 1$ if wavelength λ_j is a path-free wavelength along the k^th route, $P_{k,i}$, at time t $\gamma_{j,k}^{i,t} = 0$ otherwise
- $\sigma_{k,i,t} = \sum_{j=1}^{W} \gamma_{j,k}^{i,t}$ is the number of path-free wavelengths along $P_{k,i}$ at time t

RWA with Wavelength Conversion

Once the RWA for the SLDs have been calculated, we route the RLDs sequentially, that is demand by demand at arrival dates. When a new RLD requiring ℓ lightpaths arrives at the network at time t, the K alternate shortest paths (already computed off-line) associated to the corresponding source-destination pair are considered in turn. We compute for each shortest path its cost $C_{k,i,t}$. The path with the smallest finite cost is selected. One lightpath is set up at a time and the same process is repeated as many times as the requested number of lightpaths *ℓ*. If one or several lightpaths requested by the RLD cannot be set up, all the lightpath of the RLD are rejected. Table 1 presents the pseudo-code of the RWA algorithm for the RLDs in the presence of wavelength converters.

Table 1: RWA of RLD number *n* arriving at time *t* in the presence of wavelength converters

```
i ← 1;
setupALL ← 0;
While ((i≤ℓ) && (setupALL==0)) do
        k ← 1;
        setup ← 0;
        While ((k≤K) && (setup == 0))do
                Compute C_{k,i,t};
                If (C_{k,i,t} < +∞) then
                        setup ← 1;
                        Instantiate the lightpath and update the weight v_a of all the
                        links along the considered path:
                        If (v_a < W) then
                                v_a ← v_a + 1;
                        else
                                v_a ← +∞;
                        end if
                else
                        k ← k+1;
                end if
        end do
        If (setup==1) then
                i ← i+1;
        else
                setupALL ← 1;
        end if
end do
If (setupALL==1) then
        Increment the number of rejected RLDs ;
        Free the network resources assigned if one or several lightpaths have been
        set up by updating the arc's weight v_a;
else
        Update the number of required WDM channels;
end if
```

RWA without Wavelength Conversion

Again the RLDs are established sequentially according to the algorithm described in [3,4]. When a new RLD arrives, we look for as many path-free wavelengths along the *K* alternate shortest paths as the number of requested lightpaths. The wavelengths are assigned according to a First-Fit scheme. When no enough path-free wavelengths are left in the network to set up the RLD, the RLD is rejected. Table 2 shows the pseudo-code used to compute the RWA for the RLDs when the network nodes have no wavelength conversion capabilities.

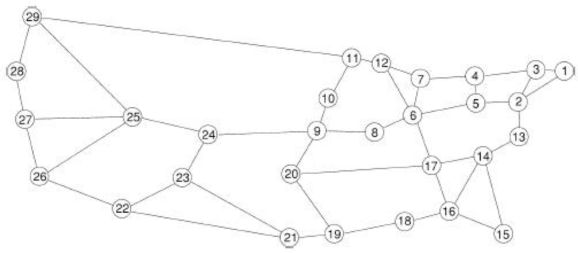
Table 2: RWA of RLD number *n* starting at time *t* in the absence of wavelength converters

For k = 1 to K do
    Compute $\kappa_{k,i,t} = (\gamma_{1,k}^{i,t}, \gamma_{2,k}^{i,t}, \ldots, \gamma_{W,k}^{i,t})$;
    Compute $\sigma_{k,i,t} = \sum_{j=1}^{W} \gamma_{j,k}^{i,t}$;
end for
If ($\sum_{k=1}^{K} \sigma_{k,i,t} \geq \ell$) then
    Instantiate the lightpaths;
    Update $\gamma_{j,k}^{i,t}$ values;
    Update the number of required WDM channels;
else
    Increment the number of rejected RLDs;
end if

3. Experimental results

In this section we experimentally evaluate the algorithms proposed in the previous sections. We used the NSFnet US backbone network of 29 nodes and 44 links shown in Figure 1. The source/destination nodes of both SLDs and RLDs are drawn according to a random uniform distribution in the interval [1,29]. We also used uniform random distributions over the interval [1,1440] for the set-up/tear-down dates of the SLDs. We assume observation periods of about a day (1440 is the number of minutes in a day). Random connection requests (RLDs) arrive according to a Poisson process with an arrival rate $1/\upsilon = 1$ and if accepted, will hold the circuit for exponentially distributed times with mean $1/\mu = 30$ much larger than the cumulated round-trip time and the connection set-up delay. The number of lightpaths required by an LD (be it an SLD or an RLD) is drawn from a random uniform distribution in the interval [1,5]. We call a scenario the set of demands scheduled or random that occur from the beginning to the end of a day. We assume that we compute *K*=4 alternate shortest paths between each source/destination pair in the network.

The performance of the two algorithms has been measured for different traffic loads. For a given traffic load, we generated 25 test scenarios, ran the two algorithms on them and computed the average rejection ratio for each algorithm. As the arrival rate of RLDs is of one request per minute, we have in average 1440 RLDs per day. On the other hand, the number of SLDs has been chosen in the set {125, 187, 250, 312, 375, 437, 500}.



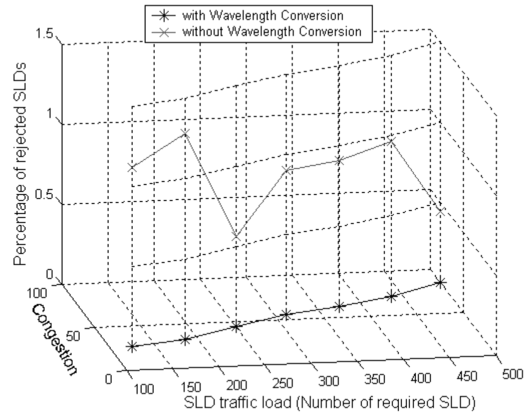
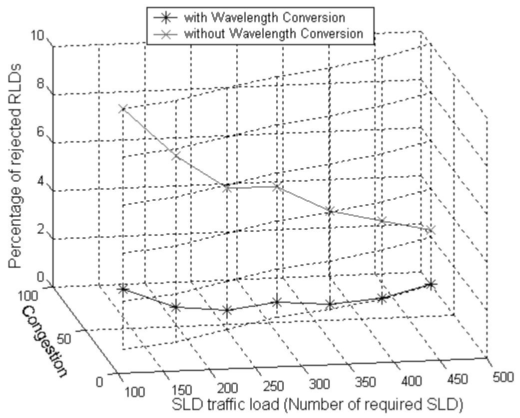


Figure 1 – NSFnet network

Figure 2 – Rejection ratio of SLDs



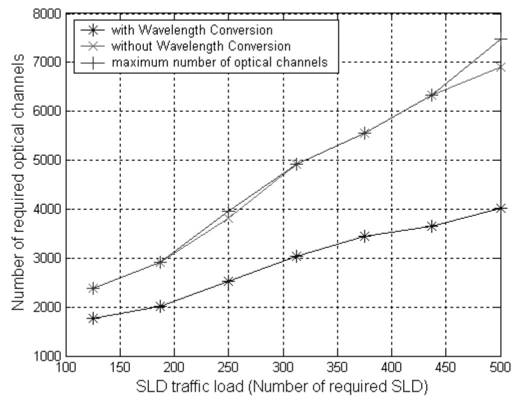


Figure 3 – Rejection ratio of RLDs

Figure 4 – Number of required optical channels

Figure 2 plots the rejection ratio of the SLDs respectively for a network with and without wavelength conversion capabilities. This rejection ratio has been computed for different SLD traffic loads and with a limited number *W* of wavelengths per fiber. The value assigned to *W* has been chosen so that when the network has wavelength conversion capabilities, all the SLDs are accommodated. Once the SLDs are routed, we reserve the resource occupied by these demands. Then, without changing the value assigned to *W*, we try to route additional RLD requests. These sets of RLDs are composed of about 1440 RLDs. Figure 3 shows the rejection ratio of the RLDs which is computed over these sets. One notices that the rejection ratio decreases for large values of *W*. This is due to the fact that the SLDs leave more unoccupied wavelengths which are used to carry out more RLD requests. Finally, Figure 4 shows the number of required optical channels to carry out the SLDs and the RLDs in both cases when the network has wavelength conversion capabilities or not. Figure 4 shows also the maximum number of optical channels given the values assigned to *W*. From Figures 3 and 4, one notices the reduction in the rejection ratio, as well as the reduction in the number of required optical channels when the network is able to perform wavelength conversion. In average over all the traffic loads, one notices that the use of wavelength converters reduces the rejection ratio of the RLDs by an average of 5%. In addition, the use of wavelength converters reduces the number of required optical channel by an average of 35%.

4. Conclusion

In this paper we studied the effect of using wavelength converters in WDM optical networks on the rejection ratio for different simulation scenarios. We considered two types of Lightpath Demands called Scheduled Lightpath Demands and Random Lightpath Demands. We proposed a two phases routing algorithm to compute the RWA for the considered lightpath demands. The objective is minimizing the number of rejected LDs given a limited number of wavelengths per fiber-link. We concluded that the wavelength continuity constraint imposed in the case when no wavelength converters exist in the network, leads to poor rejection ratios. Fewer optical channels are required and an average rejection ratio gain of about 5% is obtained when wavelength converters are used at the price of a higher network cost. Wavelength converters represent about 75% of the network cost.

Future work will focus on how optimally placing a given number of wavelength converters in the network to improve the rejection ratio whilst improving the network cost design.

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