PART III

ROUTING IN WDM NETWORKS

After introducing the need of optical networks for supporting current and future network models, in this Part the problem to be addressed is clearly presented and justified. The problem is an extension of the routing inaccuracy problem already tackled in an *IP/MPLS* scenario in previous Part of the Thesis. Therefore, this Part serves to extend the *BYPASS Based Routing* (*BBR*) solution proposed to address the routing inaccuracy problem in an *IP/MPLS* scenario so that it can be applied to *WDM* networks. In successive Chapters the proposed solution, called *BYPASS Based Optical Routing* (*BBOR*) is defined, illustrated in some network examples and finally evaluated by simulation. Depending on the wavelength-continuity constraint, different wavelength assignment algorithms are proposed, compared and evaluated.

Chapter 9

Routing and Wavelength Assignment in WDM Networks

In previous Chapters, the *BBR* mechanism has been applied to *IP/MPLS* networks to address the effects of inaccurate network state information on global network performance. In this Chapter a new mechanism extended from the *BBR* mechanism is also proposed. This mechanism, *BYPASS Based Optical Routing* (*BBOR*), copes with the routing inaccuracy problem in an optical scenario, reducing the negative effects of selecting lightpaths under inaccurate network state information. The *BBOR* mechanism is applied to networks without conversion capabilities [67] and to networks with conversion capabilities [68].

9.1 Introduction

In recent years the introduction of high capacity and reliable transport networks has become necessary in order to cover Internet traffic demands. New Internet applications increasingly request greater capacity and guarantees of traffic delivery

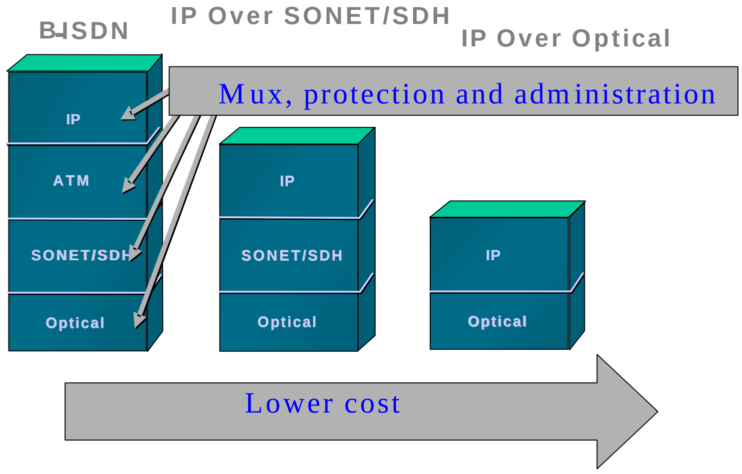

Figure 54. Network evolution

in such a way that the traffic transmission model must be modified. In fact, the network model is evolving to an *Optical Transport Network* (OTN) as shown in Figure 54.

An *OTN* consists of switching nodes (*Optical Cross-Connect*, *OXC*) interconnected by *wavelength-division multiplexed* (*WDM*) fibre-optic links that provide multiple huge bandwidth communication channels over the same fibre in parallel. A wavelength routed *WDM* network is a circuit-switched network, in which a lightpath must be established between a source-destination pair before data can be transferred. A lightpath is a unidirectional end-to-end connection between a source-destination pair, which may span multiple fibre links and use a single or multiple wavelengths. When the *OTN* includes automatic switching capabilities, it is referred to as an *Automatic Switched Optical Network* (*ASON*). Figure 55 depicts the ASON architecture. ASON must include a Control Plane, necessary to provide the network with dynamic provisioning, fast protection, restoration and *Traffic Engineering*. The *IETF* proposed *Generalized Multiprotocol Label Switching* (*GMPLS*) as a protocol to implement this Control Plane. In [69] a different solution to implement the Control Plane is discussed.

This Control Plane includes a lightpath control mechanism to efficiently set up and tear down lightpaths, which may be either centralized or distributed. In the former case, a single central controller having complete global network state

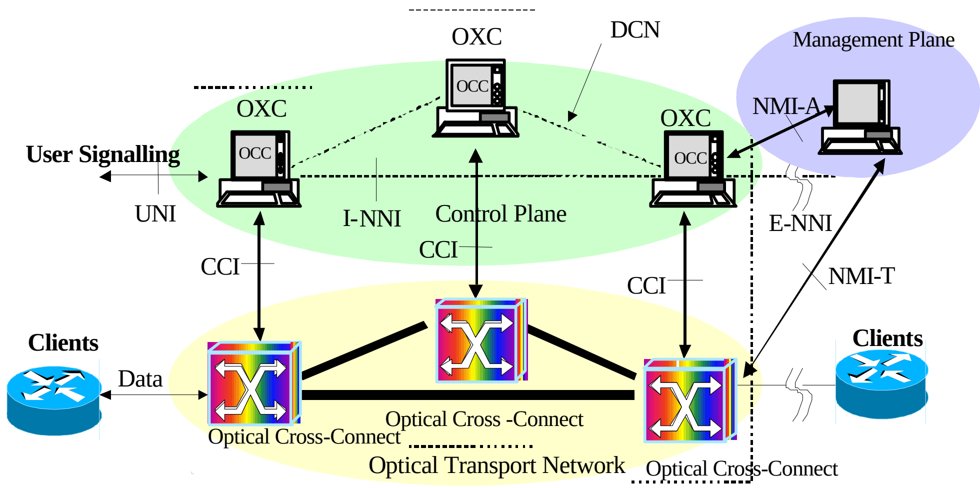

Figure 55. ASON architecture

information sequentially selects and establishes a lightpath for any incoming request. In the latter case, all incoming connection requests are simultaneously processed at different network nodes, which select the lightpaths based on either local (the nodes have not information about the whole network) or global network state information. On the one hand, if the routing decision is taken based on local information the probability that the set-up message will be rejected in any intermediate node is very large. On the other hand, using global network state information reduces the blocking probability, whenever this information represents a current picture of the network state. In spite of the fact that adaptive routing mechanisms based on global information perform better than the ones based on local information, they are only suitable for those networks where frequent network state changes are not expected.

9.2 Routing in WDM Networks

In a wavelength routing scenario, most lightpath control protocols proposed currently in the literature use a source routing mechanism which allows the source node to compute an end-to-end route for the incoming connection.

Unlike a traditional *IP/MPLS* scenario where the routing process only looks for the optimal route, in *WDM* networks the routing process, the *Routing and Wavelength Assignment* problem (*RWA*) [70], must find both the physical nodes and links that configure the lightpath (routing sub-problem), and the wavelength/s to be used on all the links along the lightpath (wavelength assignment sub-problem), in such a way that network resource utilization is optimised. Therefore, there are two steps involved in the lightpath establishment process. Firstly the network must decide a route for the connection, and secondly reserve a suitable wavelength on each link along the selected route

In general the RWA is addressed differently depending on the availability of wavelength conversion capabilities. Wavelength routed networks without wavelength conversion are known as *wavelength-selective* (*WS*) networks. In such a network, a connection can only be established if the same wavelength is available on all the links between the source and destination nodes (*wavelength-continuity constraint*). This may cause high blocking probability. Wavelength routed networks with wavelength conversion are known as *wavelength-interchangeable* (*WI*) networks. In such networks, each router is equipped with wavelength converters so that a lightpath can be set up using different wavelengths on different links along the route.

There are basically three approaches to dealing with the routing sub-problem: *fixed-routing*, *fixed-alternate routing*, and *adaptive routing*. *Fixed routing* always selects the same pre-computed route for a source-destination pair. In *fixed-alternate routing* a set of fixed pre-computed lightpaths exists for a source-destination pair, and one of them is selected according to a certain heuristic. In *adaptive routing* the lightpath is dynamically selected depending on the current network state, according to a particular heuristic, such as the *shortest path* or the *least-congested path* (*LCP*) [71]. The *LCP* selects those links with the most available wavelengths to carry the lightpath. Notice that approaches based on fixed routes reduce the complexity, but unlike adaptive routing may suffer from higher connection blocking. In general, *fixed routing* is the simplest in implementation while *adaptive routing* produced best global network performance. On the other hand, *fixed-alternate routing* offers a trade-off between computing overhead and network performance.

Once the source node selects a route for the incoming connection, a distributed reservation protocol must be used to reserve the proper wavelength on each link along the selected path. A large number of different heuristics has been proposed for the wavelength assignment sub-problem: Random, First-Fit, Least-Used, Most-Used, Min-Product, Least-Loaded, Max-Sum and Relative Capacity Loss, for example. These can each be combined with different routing mechanisms.

There are two types of wavelength reservation protocols, the *forward reservation protocol* (*FRP*) and the *backward reservation protocol* (*BRP*) [72]. Figure 56 and Figure 57 illustrate the *FRP* and *BRP* performance respectively. When using *FRP* the source node (*S_N*) sends a request packet (*REQ*) to the destination node (*D_N*) along the selected route. The *REQ* packet tries to reserve a suitable wavelength at the intermediate nodes (*I_Ns*) when available. If succeed the *REQ* packet is forwarded and the wavelength is reserved. Otherwise, a negative acknowledgment (*NAK*) packet is sent back to the source node also dropping the *REQ* packet and releasing already reserved wavelengths along the forwarded *I_Ns*. When *REQ* packet reaches the *D_N*, it sends an acknowledgment packet (*ACK*) back to the source node, configuring the *I_Ns*.

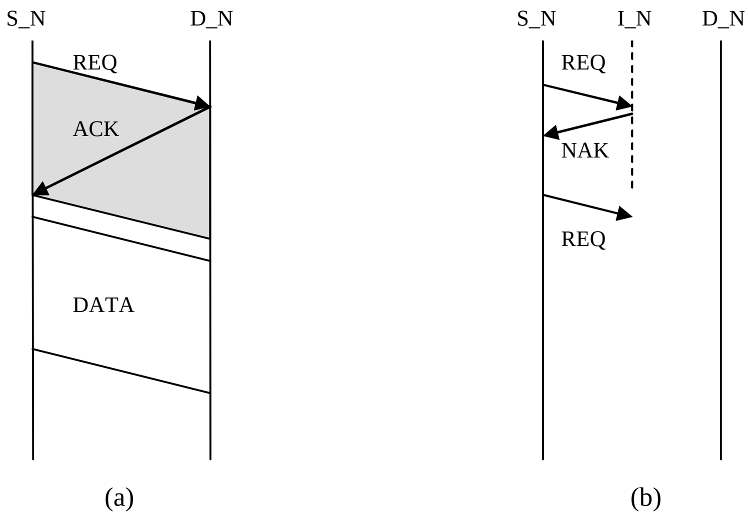

Figure 56. Forward reservation: (a) Successful; (b) Unsuccessful

The lightpath is successfully established when the *ACK* packet reaches the source node. Using this type of reservation protocol introduces a decrease in the wavelength utilization, since wavelengths are reserved on the source node. Using *BRP* improves the wavelength utilization. In fact, shaded areas in Figure 56 and Figure 57 represent the time in which wavelengths are reserved but not used. When using *BRP* a *Probe* (*PROB*) packet is sent by the source node along the selected route to the destination node. This *PROB* packet just collects information about available wavelengths on

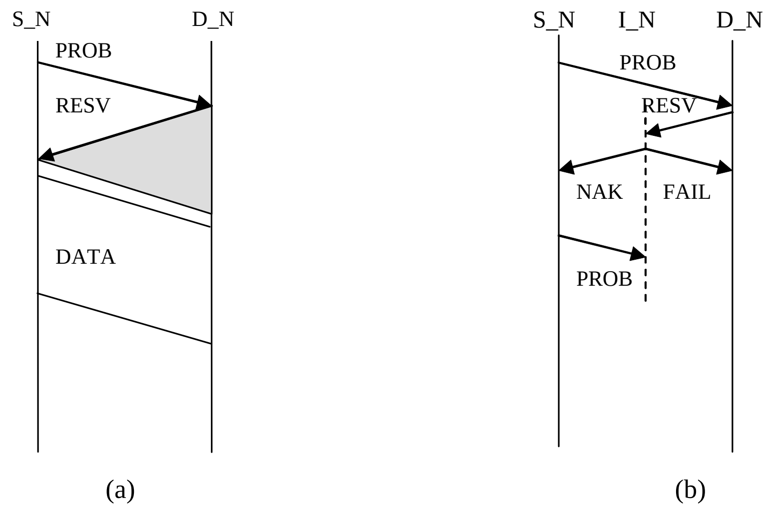

Figure 57. Backward reservation: (a) Successful; (b) Unsuccessful

each node instead of reserving wavelengths. When the *PROB* packet reaches the destination node, it selects a suitable wavelength and sends a reservation (*RESV*) packet back to the source node along the reverse path, which really performs the wavelength reservation on each intermediate node. When the reservation process does not succeed, a failure (*FAIL*) packet is sent to the destination node and a negative acknowledgment (*NAK*) is sent to the source node. While the *NAK* packet only informs the source node about the reservation failure, the *FAIL* packet must release the wavelengths already reserved by the *RESV* packet along the selected path. The lightpath is finally established when the *RESV* packet reaches the source node.

Chapter 10

The Routing Inaccuracy Problem in WDM Networks

As it has been said for an *IP/MPLS* scenario, in large dynamic networks the number of update messages generated by any update mechanism needed to keep network state information correctly updated, may overflow the network with signalling messages, causing an undesirable overhead. In this Chapter we focus on distributed lightpath control under global information, which is more appropriate and reliable for highly dynamic large networks if the network state information perfectly represents the current network state.

10.1 Problem Definition

As mentioned earlier, adaptive distributed routing mechanisms based on global network state information in a dynamic environment require a huge number of update messages to correctly update the network state databases on each node, which implies an undesirable signalling overhead. In order to overcome this signalling overhead issue, the number of update messages is limited by instituting a triggering policy. An unfortunate effect of limiting the number of update messages is that the information contained in the network state databases does not represent a current picture of the network. Indeed, the *RWA* problem under inaccurate routing information produces an increment in the connection blocking probability [73].

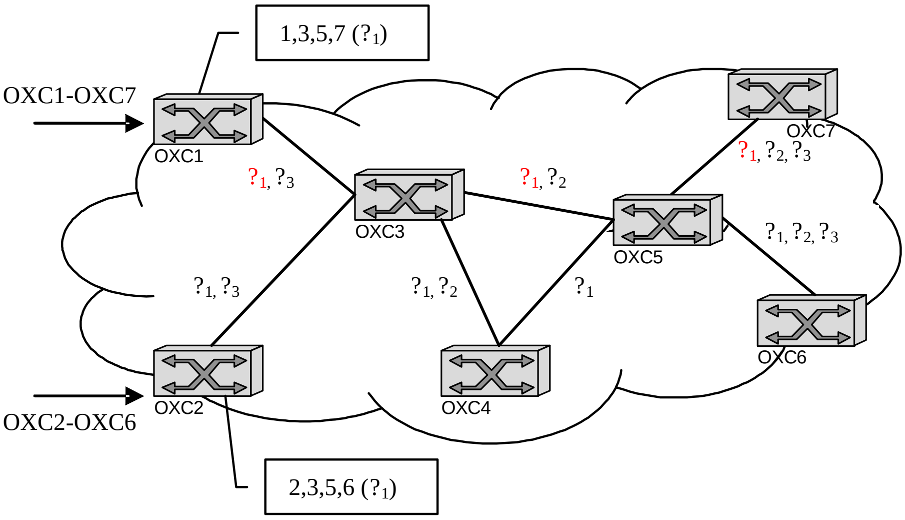

Figure 58. Routing Inaccuracy effects in WDM networks

As previously done in an *IP/MPLS* scenario, Figure 58 illustrates the routing inaccuracy problem. Metric on each link stands for the residual capacity in terms of available wavelengths. Assuming explicit routing, edge nodes computes a physical route and assigns a wavelength reacting to an connection request, so no grooming is considered. When a connection request reaches OXC1 demanding a lightpath from OXC1 to OXC7, OXC1 must select a route and assign a wavelength. This selection is performed based on the network state information contained in its database. Suppose that OXC1 selects the shortest route made up of OXC1, OXC3, OXC5, OXC7 with l_1. If update messages are not triggered, the information contained in the databases on the edge nodes is out-to-date. In red there are those wavelengths read as available on the databases although they are not really available. Suppose that a connection request demanding a lightpath from OXC2 to OXC6 reaches OXC2. OXC2 selects a lightpath based on its network state information, which now is outdated. It is perfectly reasonable a selected lightpath made of OXC2, OXC3, OXC5, OXC6 with l_1. A set-up message will be sent along the selected route to the destination to establish the lightpath. When receiving the set-up message OXC3 checks the real wavelength availability by looking at its network state database. As the selected l_1 is not available on the output link the set-up message is dropped and so the connection is rejected.

10.2 State of the Art

Regarding *WDM* networks, in [74] the effects produced in the blocking probability because of inaccurate routing information when selecting lightpaths are shown by simulation. The authors indeed verify over a fixed topology that the blocking ratio increases when routing is done under inaccurate routing information. The routing uncertainty is introduced by adding an update interval of 10 seconds. Some other simulations are performed to show the effects on the blocking ratio due to changing the number of fibres on all the links. Finally, the authors argue that new *RWA* algorithms that can tolerate imprecise global network state information must be developed for dynamic connection management in *WDM* networks.

In [75] the routing inaccuracy problem is addressed by modifying the lightpath control mechanism, and a new distributed lightpath control based on destination routing is suggested. The mechanism is based on both selecting the physical route and wavelength on the destination node, and adding rerouting capabilities to the intermediate nodes to avoid blocking a connection when the selected wavelength is no longer available at set-up time in any intermediate node along the lightpath. There are two main weaknesses of this mechanism. Firstly, since the rerouting is performed in real time in the set-up process, wavelength usage deterioration is directly proportional to the number of intermediate nodes that must reroute the traffic. Secondly, the signalling overhead is not reduced, since the *RWA* decision is based on the global network state information maintained on the destination node, which must be perfectly updated.

Another contribution on this topic can be found in [76] where authors propose a mechanism whose goal is to control the amount of signalling messages flooded throughout the network. Assuming that update messages are sent according to a hold-down timer regardless of frequency of network state changes, authors propose a dynamic distributed bucket-based Shared Path Protection scheme. (an extension of the *Shared Path Protection*, *SPP* scheme presented in [77]). Therefore, the amount of signalling overhead is limited by both fixing a constant hold-down timer which effectively limits the number of update messages flooded throughout the network and using buckets which effectively limits the amount of information stored on the source node, i.e. the amount of information to be flooded by nodes. The effects of the introduced inaccuracy are handled by computing alternative disjoint lightpaths which will act as a protection lightpaths when resources in the working path are not enough to cope with those required by the incoming connection. Authors show by simulation that inaccurate database information strongly impacts on the connection blocking. This increase in the connection blocking may be limited by properly introducing the suitable frequency of update messages. According to the authors, simulation results obtained when applying the proposed scheme along with a modified version of the *OSPF* protocol, may help network operators to determine that frequency of update messages which better maintains a trade-off between the connection blocking and the signalling overhead.

The next Chapter presents a new adaptive source routing mechanism, *BYPASS Based Optical Routing* (*BBOR*) that aims to reduce the connection blocking probability due to performing routing and wavelength assignment decisions under inaccurate routing information.

Chapter 11

BBOR: Adaptation of the BBR Mechanism to WDM Networks

BYPASS Based Optical Routing (*BBOR*) [67] is a new adaptive source routing mechanism, which dynamically computes explicit lightpaths in an *ASON* without wavelength conversion capabilities based on global network state information, aiming to reduce the connection blocking probability due to routing and wavelength assignment decisions performed under inaccurate routing information. The proposal presented in this section modifies the *BBR* structure to make it capable of addressing the effects of having the inaccurate routing information that results from applying a certain triggering policy to reduce the signalling overhead in an ASON.

Although the main concept of *BBOR* is similar to *deflection routing* [78] (studied for packet switched networks) or *alternate-link routing* [79], important differences exist between them. In *alternate-link routing* (an adaptive routing with local information approach), alternate paths are pre-computed and sorted in the routing table of each node based on local network state information and can be used depending on the resource availability at any time. Instead, based on global network state information, the *BBOR* mechanism only computes *bypass-paths* for those links that potentially might not cope with the traffic requirements, and the usage of these *bypass-paths* is decided at path set-up time depending on the resource availability.

Moreover, in spite of the fact that the *BBOR* mechanism also introduces a rerouting mechanism, unlike the mechanism suggested in [75] the alternative paths are pre-computed at the source node along with the selected lightpath. In this way connection set-up time and wavelength usage deterioration are both reduced.

11.1 BBOR Description

As mentioned above, the source of routing inaccuracy analysed in this Thesis is mainly due to the introduction of a triggering policy in order to reduce the signalling overhead produced by the update messages. Thus, the *BBOR* mechanism includes two main aspects: a triggering policy adapted to the RWA problem to reduce routing signalling, and a routing algorithm based on the dynamic bypass concept to counteract the effects of the routing inaccuracy produced by this routing signalling reduction. It is important to note that the routing algorithm includes both path selection and wavelength assignment. The triggering policy and the feasible routing algorithms inferred from the *BBOR* mechanism are now in detail described.

11.1.1 BBOR: A New Triggering Policy

Existing triggering policies are based on updating by either a periodical refresh or sending an update message whenever there is a change in the network state. In the first case, by modifying the refresh time value, the network state accuracy and the number of update messages can be adjusted. However, this scheme is not valid for large dynamic networks. In the second case, an important signalling overhead is added. In order to improve the update process, the *BBOR* mechanism introduces a new triggering policy based on a threshold value that aims to include network congestion (available network resources) in the triggering decision. In fact, a network node triggers an update message whenever a fixed number *N* of wavelengths changes their status (i.e., after a fixed number of *N* connections are established or released).

By changing the value of *N*, we can evaluate the impact of different degrees of inaccuracy on the connection blocking ratio.

11.1.2 BBOR: A New Routing Algorithm

The main characteristic of the possible routing algorithms included in the *BBOR* mechanism is that they allow several nodes along the selected path to dynamically reroute the set-up message to a different route when, due to the wavelength unavailability produced by computing the selected paths according to inaccurate routing information, this set-up message would be rejected by any one of the intermediate nodes. Two possible rerouting options exist: change the route while maintaining the wavelength, or change the wavelength while maintaining the route. In a *wavelength continuity constraint* scenario, the first one is chosen. Therefore, when an intermediate node decides to reroute the set-up message it sends this message along a different route (*bypass-path*), which bypasses the link that cannot fulfil the *wavelength continuity constraint*.

Any routing algorithm derived from the *BBOR* mechanism consists of three basic processes: (1) decide which wavelength of which link (bundle of *B* fibres) might be bypassed, (2) include these wavelengths as a parameter to be considered when selecting the lightpath, and (3) compute the *bypass-paths*.

Concerning the first process, the wavelengths that have to be bypassed are referred to as *Obstruct-Sensitive-Wavelengths (OSWs)*. The classification of a wavelength l_i as an *OSW* (l^{os}_i) on a certain link depends on the triggering policy used to update the network state information. *C* being the total number of a certain l_i on a link and *R* being the current number of available (not assigned to an already established lightpath) l_i on this link, then according to the *BBOR* triggering policy described above, this l_i is defined as l^{os}_i in this link when *R* is lower than a percentage T_p *(threshold percentage)* of *N*. Note that *N is* the number of wavelength status changes that trigger an update message. Hence, changing the T_p value can modify the granularity in the OSW definition.

Concerning the second process, the source node has to take into account the number of l_i defined as *OSW* in order to properly resolve the *RWA* problem. A new parameter OSW_i *(L, F)*, where L is the number of links where l_i has been defined as *OSW* and F is the minimum value of available wavelengths along the lightpath, has therefore been defined. Applying this parameter, two different algorithms can be inferred from the *BBOR* mechanism, *ALG1* and *ALG2*. *ALG1* lies in selecting those l_i*s* in all the links of the shortest paths (minimum number of hops) that minimize L in $OSW_i(L,F)$. If more than one wavelength is compliant with this condition, the algorithm selects the less congested by checking the F value in $OSW_i(L,F)$. *ALG2* lies in selecting the less congested l_i*s* on the shortest paths according to the F value in $OSW_i(L,F)$. If more than one wavelength is compliant with this condition, the algorithm selects that l_i which minimizes the L value in $OSW_i(L,F)$. In other words, *ALG1* prioritises minimizing the number of obstructions or bottlenecks while *ALG2* prioritises minimizing the congestion.

Concerning the third process, once the lightpath has been selected a *bypass-path* must be computed for those wavelengths defined as *OSW* in this lightpath, in such a way that the *wavelength continuity constraint* is guaranteed. Although other criteria could be used to compute the *bypass-paths* (this is left for further studies), such as minimizing the number of wavelengths defined as *OSW*, the shortest (minimum number of hops) *bypass-paths* are selected. In order to simplify the *bypass-path* computation, when a *bypass-path* exists on a link for a particular l^{os}_i, this path will also be used as the first option to bypass any other l^{os}_j on this link. Summarizing, in order to explicitly distribute the *bypass-paths* in the set-up message, source nodes must both detect those wavelengths on a link that potentially will not be available when establishing the path, and compute a *bypass-path* for each one of these wavelengths. A brief description of the *BBOR* mechanism is presented in Figure 59.

11.2 Example Illustrating How BBOR Works

The topology shown in Figure 60 is used to illustrate how *BBOR* works. Considering that every OXC includes control functions with signalling capabilities, we assume C = 10 fibres per link and 4 wavelengths per fibre. Update messages are

BYPASS BASED OPTICAL ROUTING MECHANISM

Input: An incoming connection request between a source-destination pair *(s,d)* with a *wavelength continuity constraint*

Output: An explicit route from *s* to *d* with a common available wavelength on all the links along the path and with enough *bypass-paths* to bypass the routing inaccuracy effects in the *obstruct-sensitive wavelengths*.

Algorithm:

1. Select the shortest paths
2. Mark those wavelengths that are defined as *OSW*
3. Depending on the algorithm to be used, ALG1, ALG2:

   ALG1:
   - Select that l_i on all the paths minimizing the *L* value in $OSW_i(L,F)$
   - If more than one exists the less congested is selected according to the *F* value in $OSW_i(L,F)$.

   ALG2:
   - Select the less congested wavelength on each path according to the *F* value in $OSW_i(L,F)$.
   - If more than one exists, select that l_i on all the paths minimizing the *L* value in $OSW_i(L,F)$.
4. Compute a *bypass-path* for all wavelengths defined as *OSW*.
5. Decide which *bypass-paths* must be used in accordance with real available resources in the path setup time

Figure 59. *BBOR* description

sent according to $N = 6$ and a wavelength l_i is defined as OSW_i according to T_p = 50% (i.e., when the minimum number of available wavelengths on this link is lower than or equal to 3). Incoming connection requests arrive between OXC1-OXC4.

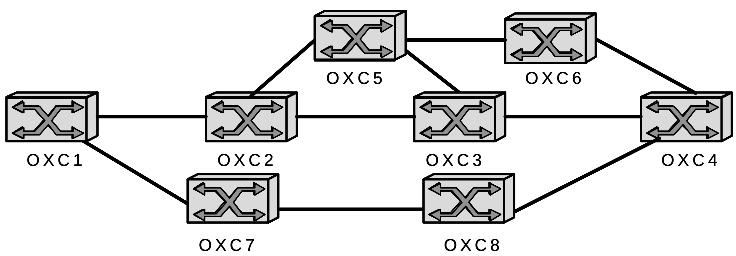

Figure 60. Network topology used in the *BBOR* illustrative example

In Table 8 the network state information existing in OXC1 is shown. It represents the number of available wavelengths for all the links. According to this information, Table 9 shows the routing table existing in OXC1, where all the feasible lightpaths between OXC1 and OXC4 are pointed out. In addition, the minimum number of available wavelengths and the OSW_i *(L,F)* parameter are shown for each lightpath.

Table 8. Network State in OXC1

Link (OXC)	l_1 l_2 l_3 l_4	*Link (OXC)*	l_1 l_2 l_3 l_4
1-2	6 3 3 6	5-6	0 7 3 3
2-3	2 3 6 0	6-4	1 1 1 1
3-4	6 3 0 2	1-7	6 3 1 6
2-5	6 2 0 1	7-8	0 3 6 1
5-3	6 6 6 6	8-4	6 6 0 6

Table 9. Routing Table in OXC1

Route (OXC)	l_1 l_2 l_3 l_4	*OSW_i (L,F)*
1-2-3-4	2 3 0 0	λ_1(1,2), λ_2(3,3)
1-2-5-3-4	6 2 0 1	λ_2(3,2), λ_4(2,1)
1-2-5-6-4	0 1 0 1	λ_2(3,1), λ_4(3,1)
1-7-8-4	0 3 0 1	λ_2(2,3), λ_4(1,1)

Finally, Table 10 shows, hop-by-hop, the process of applying the *BBOR* mechanism. As a result, a different lightpath and a different wavelength are selected to transmit the traffic depending on the algorithm in use. Thus, l_1 along the path made of OXCs 1-2-3-4 and l_2 along the path made of OXCs 1-7-8-4 are selected by *ALG1* and *ALG2* respectively. In addition, since l_1 is defined as OSW_1 on link OXC2-OXC3 a *bypass-path* through OXCs 2-5-3 is also selected.

Table 10. Illustrative Example

BBOR steps	*Algorithm 1 (ALG1)*	*Algorithm 2 (ALG2)*
1	path 1: 1-2-3-4 path 2: 1-7-8-4	path 1: 1-2-3-4 path 2: 1-7-8-4
2 (ALG1)	path 1: λ_1(**1**,2) path 2: λ_4(**1**,1)	path 1: λ_2(3,**3**) path 2: λ_2(2,**3**)
3 (ALG1)	**path 1:** λ_1(1,**2**) path 2: λ_4(1,**1**)	path 1:λ_2(**3**,3) **path 2**:λ_2(**2**,3)
4	λ_1 is *OSW* on 2-3 *bypass-path*:2-5-3	λ_2 is *OSW* on 1-7-8 No *bypass-path*

However, when using *ALG2*, path 2 and l_2 are the *RWA* result. In this case, l_2 is OSW_2 on links OXC1-OXC7-OXC8. It is not possible to find a proper *bypass-path* to directly bypass these links. In this case, *BBOR* cannot be completely applied. Further extensions must be added to the *BBOR* mechanism to cope with this problem.

11.3 Performance Evaluation

In this section the simulation scenario in which the *BBOR* mechanism has been evaluated, the parameters used to test its benefits and the obtained results are presented. However, before evaluating the proposed mechanism, the effects of applying the *BBOR* mechanism over the time needed to set-up a lightpath are analysed later on.

The time needed to set-up a lightpath is defined as the time taken from the moment an incoming connection request reaches the source node to the moment the lightpath is successfully established. This time depends on:

T_c = Time taken by the source node to compute a route
T_{c_b} = Time taken by the source node to compute a *bypass-path* route
n_s = Number of hops in the shortest path
n_{OS} = Number of wavelengths defined as *Obstruct-Sensitive* in the selected route
m = Number of wavelengths that really are not available in any intermediate node along the selected route
n_{bi} = Number of hops in the *bypass-path* i
T_d = Propagation delay on each link
T_p = Time taken by an intermediate node to process a connection request
T_r = Time taken by a node to reserve a wavelength

The set-up message sent by the source node takes a time t_d to reach the destination node. This time depends on the number of wavelengths defined as *OSW*. Thus, we define T_S as the total time needed to establish the connection, the two-way delay needed to establish a lightpath. Different cases can be analysed depending on the number of *OSW*:

1) There are no wavelengths defined as *OSW*.

$$T_s = T_c + 2 \times n_s \times T_d + (2 \times n_s + 1) \times T_p + (n_s + 1) \times T_r \quad (7)$$

2) There are n_{OS} wavelengths defined as *OSW* but none are used

$$T_s = T_c + T_{c\_b} \times n_{OS} + 2 \times n_s \times T_d + (2 \times n_s + 1) \times T_p + (n_s + 1) \times T_r \quad (8)$$

3) There are n_{OS} wavelengths defined as *OSW* and *m* are used, where

$$m \subset n_{OS} \quad \text{and} \quad m \leq n_{OS} \tag{9}$$

Now the time T_s can be represented as:

$$T_s = T_c + T_{c\_b} \text{ x } n_{OS} + 2 \text{ x} \left[(n_s - m) + \sum_{i=1}^{m} n_{bi} \right] \text{x } T_d + \left[2 \text{ x} \left[(n_s - m) + \sum_{i=1}^{m} n_{bi} \right] + 1 \right] \text{x } T_p + \quad + \left(n_s - m + 1 + \sum_{i=1}^{m} n_{bi} \right) \text{x } T_r \tag{10}$$

Although the *BBOR* mechanism requires an increment in the time needed to set up a lightpath compared to another mechanism that does not compute *bypass-paths*, this time does not substantially affect wavelength usage. This claim is next clarified by applying the above-described equations to the network topology of Figure 60. Using *ALG1*, λ_1 on OXC1-OXC2-OXC3-OXC4 represents the selected lightpath. This wavelength is defined as *OSW* in the link OXC2-OXC3. Three different cases are analysed. Firstly, we compute the time needed to establish the lightpath when no *BBOR* mechanism is applied. Therefore, $n_S = 3$, and the T_S is

$$T_s = T_c + 2 \text{ x } n_s \text{ x } T_d + (2 \text{ x } n_s + 1) \text{ x } T_p + (n_s + 1) \text{ x } T_r = T_c + 6T_d + 7T_p + 4T_r \tag{11}$$

Secondly, we compute the time needed to establish the lightpath when applying the *BBOR* mechanism but the *bypass-path* computed to bypass the link OXC2-OXC3 is not really used when the set-up message reaches OXC2. Therefore, $n_{OS} = 1$, $n_S = 3$ and T_S is

$$T_s = T_c + T_{c\_b} \text{ x } 1 + 2 \text{ x } 3 \text{ x } T_d + (2 \text{ x } 3 + 1) \text{ x } T_p + (3 + 1) \text{ x } T_r = T_c + T_{c\_b} + 6T_d + 7T_p + 4T_r \tag{12}$$

Lastly, we represent the time needed to establish the lightpath when the *bypass-path* computed to bypass the link OXC2-OXC3 is used. The final end-to-end lightpath is made of OXC1-OXC2-OXC5-OXC3-OXC4. Therefore, $n_{OS} = 1$, $n_S = 3$, $m = 1$, $n_{bi} = 2$ and T_S is

$$T_s = T_c + T_{c\_b}\text{ x }1 + 2\text{ x }\left[(3-1) + \sum_{i=1}^{1} 2\right]\text{ x }T_d + \left[2\text{ x }\left[(3-1) + \sum_{i=1}^{1} 2\right] + 1\right]\text{ x }T_p + \left(3-1+1+\sum_{i=1}^{1} 1\right)\text{ x }T_r = T_c + T_{c\_b} + 8T_d + 9T_p + 5T_r \quad (13)$$

It can be seen that the increment of time introduced due to applying the *BBOR* mechanism when no *bypass-paths* are used is just the time needed to compute these *bypass-paths*. Moreover, as the time increment does not affect the time in which a certain wavelength is reserved but not used (since it is computed before sending the set-up message), this does not produce network inefficiency. As far as comparing the first and the last situation, the increment generated in the path set-up time can be represented as

$$\Delta T_s = T_{c\_b} + 2T_d + 2T_p + T_r \quad (14)$$

It can be observed that only the time needed to propagate, process and reserve a wavelength affects the time in which a wavelength is reserved but not used. However, this increment, proportional to the number of *bypass-paths* to be computed is very low.

Once the impact of the *BBOR* mechanism on the lightpath set-up time has been analyzed, results obtained when evaluating the *BBOR* mechanism by simulation are discussed. The simulations are performed over the network topology shown in Figure 61 where the possible source-destination pairs are randomly selected. We suppose a 5-fibre topology, with 16 wavelengths on each fibre on all the bi-directional links.

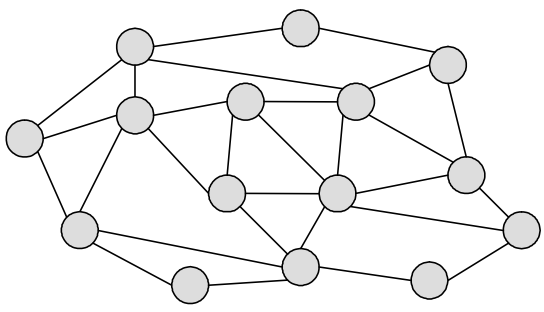

Figure 61. Topology used in simulations

Connection arrivals are modelled as a Poisson distribution with arrival rate ? and the connection holding time is assumed to be exponentially distributed with average value ($1/m$). Assuming adaptive routing and without loss of generality, routes are computed after applying the shortest path algorithm.

Three routing algorithms are evaluated by simulation: *First-Fit*, *ALG1* and *ALG2*. *First-Fit* is that wavelength assignment heuristic which selects the lowest numbered available wavelength among a set of numbered wavelengths. In the next figures the effects produced in the network performance by applying the *BBOR* mechanism are shown: the reduction in the number of update messages when the triggering policy defined in the *BBOR* mechanism is applied, and the blocking probability reduction obtained when applying the *BBOR* mechanism. Both effects are analysed as a function of both N (number of wavelength state changes that trigger an update message) and T_p (threshold percentage of N which defines when a wavelength is defined as *OSW*) values.

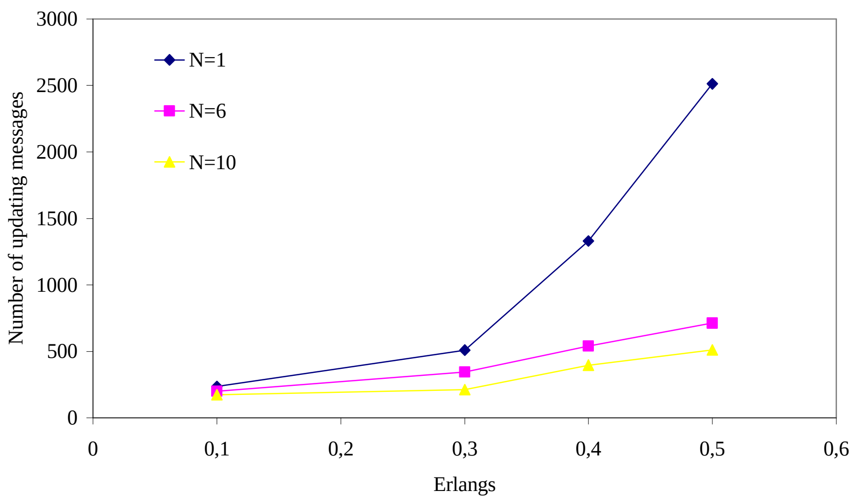

Figure 62. Number of update messages

Figure 62 shows the reduction obtained in the quantity of update messages supplied to the network when increasing the values of N. As expected, the larger the N the lower the number of update messages. Note that the case of N = 1 corresponds to a policy that triggers update messages whenever a change occurs.

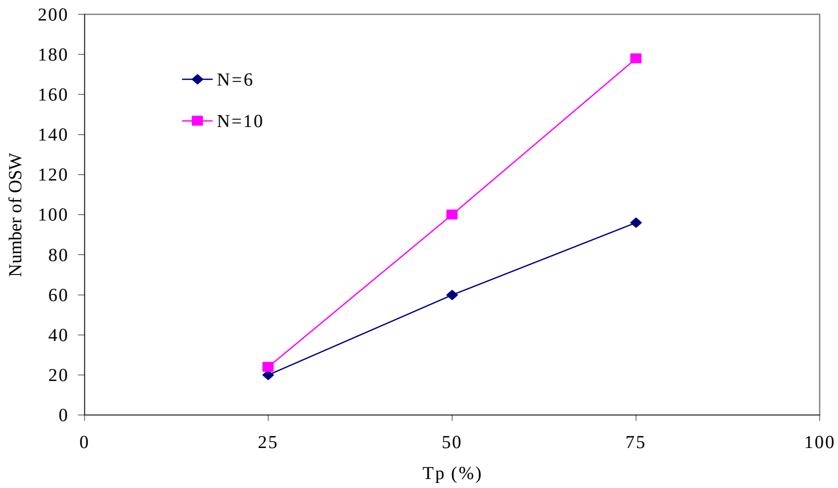

Figure 63. Number of *OSW* as a function of the threshold percentage T_p value

Figure 63 shows the number of wavelengths defined as *OSW* as a function of the T_p value. The number of defined *OSW*s grows with the T_p value, since the minimum number of available wavelengths on a certain link used to define when a wavelength is an *OSW* on this link is also directly proportional to the T_p value.

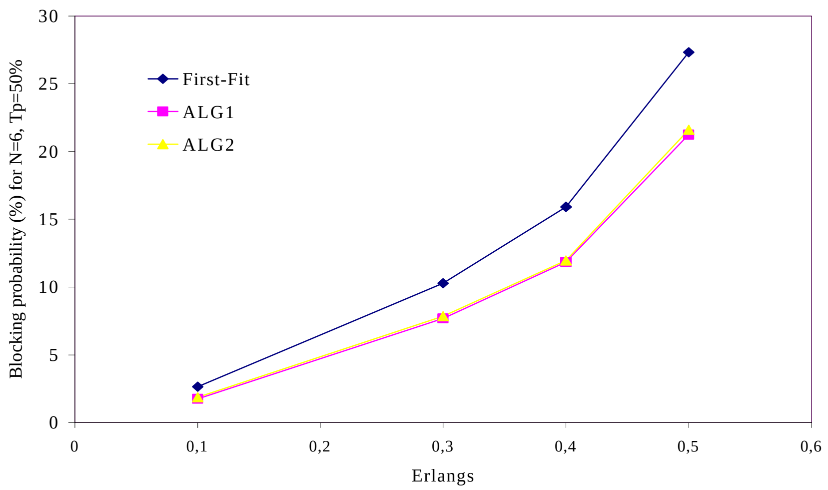

Figure 64. Blocking probability for N = 6 and T_p = 50%

According to the results obtained in Figure 63 the blocking probability is evaluated considering a value of T_p = 50%. Figure 64 compares the blocking probability obtained by the *BBOR* algorithms, and the shortest path algorithm combined with the *First-Fit* approach, considering a value of N = 6. It can be seen that in the worst case a blocking probability reduction of 6.08% is obtained when applying the *BBOR* mechanism.

It is worth to notice that the lightpath holding time does not affect on the connection blocking since update messages keep up with the frequency of network changes so regardless of any hold-down timer. Really, the lightpath holding time only leads to increment the number of update messages flooded throughout the network.

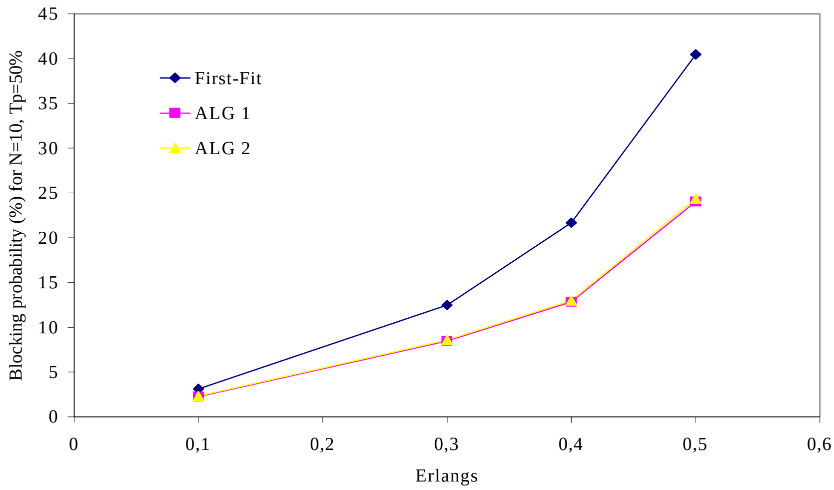

Figure 65. Blocking probability for N = 10 and T_p = 50%

Analogously, the blocking probability for N = 10 is shown in Figure 65. In this case, the blocking probability reduction achieved by the *BBOR* algorithms compared to the *First-Fit* heuristic reached 16.12%.

Analysing a fixed blocking probability value (27.32%) for the *First-Fit* heuristic shows that unlike Figure 64, where a reduction of 6.08% with N = 6 is obtained, in Figure 65 where N = 10, the reduction is about 11%. Therefore, according to the obtained simulation results, the *BBOR* mechanism obtains the largest blocking probability reduction when the N value increases, that is, when the number of update messages has been reduced as well.

As a conclusion it is possible to say that the *BBOR* mechanism reduces both signalling overhead and the negative effects produced by having inaccurate routing information.

Chapter 12

The BBOR Mechanism in a Wavelength Conversion Scenario

There are plenty of references in the literature where the need of adding conversion capabilities to the network is deeply justified. This Chapter extends the *BBOR* mechanism to be applied to networks with conversion capabilities, that is, *WI* networks [68].

12.1 Wavelength Interchangeable Networks

In *Wavelength Interchangeable Networks* (*WI*), also called *Wavelength Convertible Networks*, lightpaths may be selected without using the same wavelength in all the links along the selected lightpath. As a consequence, the global network efficiency is largely improved. If a wavelength converter provides the ability to translate any input wavelength to any output wavelength, i.e., full range conversion, and every node of the network includes a wavelength converter, the network is defined as having full wavelength-conversion capabilities. In this case, the network is equivalent to a circuit switched network, where only the routing subproblem must be considered. However, the cost associated to provide a wavelength converter at every node is currently not affordable. Therefore, other solutions based on limiting the global wavelength conversion in a network appear to design a *WI* network. There are three main issues to be considered. First, the global conversion capability may be reduced by having only a few nodes with conversion capabilities, i.e. sparse conversion, modeled by the conversion density q of the network. Second, converters may be shared among various output ports of a node. Third, the range of wavelength conversion is limited to a fixed value k, i.e., limited range wavelength conversion, defining the *degree of translation D* as

$$D = \frac{100\,k}{\Lambda - 1} (\%) \tag{15}$$

where Λ is the total number of wavelengths on a link.

In this way an input wavelength l_i may only be translated to wavelengths $l_{max(i-k,1)}$ through $l_{min(i+k,?)}$. It is show in [80] that a substantial improvement in the global blocking probability of the network when limited-range wavelength converters with as little as 25% of the full conversion range are introduced.

In this Chapter the impact on the blocking probability because of applying the *BBOR* mechanism to a network with wavelength conversion capabilities are in detail analyzed. A new routing algorithm is generated. The path selection process used in the new suggested routing algorithm is modified regarding the *ALG1* and *ALG2* already proposed in Chapter 11.

12.2 ALG3: Applying the BBOR Mechanism to WI Networks

A new algorithm inferred from the *BBOR* mechanism, named *ALG3* (as an extension of the already proposed *ALG1* and *ALG2*), is now suggested to address the routing inaccuracy problem in a wavelength conversion scenario. *ALG3* incorporates several different aspects in comparison to the *ALG1* and *ALG2*. In fact, although the main concepts are the computation of both the OSW_i *(L,F)* parameter and the *bypass-paths*, in *ALG3* both aspects are differently handled. There are three main differences between *ALG3* and the other ones:

Firstly, *ALG3* does not select only the shortest paths. Instead, the K-shortest paths of all possible disjoint paths between source and destination nodes are computed. Secondly, unlike *ALG1* and *ALG2* where the weight of each link was separately defined by the attributes *L* and *F* of the $OSW_i(L,F)$ parameter, in *ALG3*, the weight associated to each link is represented by the factor *L/F*. This factor stands for a balance between the number of potentially obstructed links and the real congestion instead of choosing one against the other. Moreover, since longer paths than the shortest ones can be selected, the length of the path is also included in the path decision. Hence, in order to avoid those paths that are either widest (in terms of wavelength availability) but too long or shortest but too narrow, the weight factor of each path is modelled by F_p according to the expression

$$F_p = n\left(\frac{L}{F}\right) \tag{16}$$

where *n* is the number of hops in the selected path.

Finally, once the path has been selected, *bypass-paths* are computed. Now, before computing the *bypass-paths* it is necessary to know whether the output link where a certain l_i is defined as $l^{os}{}_i$ belongs to a node with conversion capabilities. If it does, the bypass dynamic concept can be simply modelled by converting the wavelength. If it does not or there are not available wavelengths where limited conversion can be done, the *bypass-paths* are computed similarly to *ALG1* and *ALG2*. The box enclosed in Figure 66 shortly summarizes *ALG3*.

12.3 Performance Evaluation

To evaluate the *BBOR* mechanism in *WI* networks a set of simulations have been carried out over the network topology shown in Figure 61, where the possible source-destination pairs are randomly selected. We suppose a 5-fibre topology, with 10 wavelengths on all the fibres on all the bi-directional links. Connection arrivals are modelled by a Poisson distribution and the connection holding time is assumed to be exponentially distributed. Each arrival connection requires a full wavelength on each link it traverses.

BYPASS BASED OPTICAL ROUTING (ALG3)

***Input**: An incoming connection request between a source-destination pair (s,d)*

***Output**: An explicit route from s to d without fulfilling the wavelength continuity constraint and with enough bypass-paths to bypass the routing inaccuracy effects in the obstruct-sensitive wavelengths.*

Algorithm:

1. Select the K-shortest paths
2. Mark those wavelengths that are defined as *OSW*
3. Select that $?_i$ that minimizes the cost according to

$$F_p = n\left(\frac{L}{F}\right)$$

4. Compute the bypass-paths for all wavelengths defined as *OSW*, considering wavelength conversion when it is possible
5. Decide which *bypass-paths* must be used in accordance with real available resources in the path setup time

Figure 66. *ALG3* description

Figure 67 shows the reduction obtained in the signalling overhead when applying the triggering policy defined in the *BBOR* mechanism. As it was expected the larger the *N* the lower the number of update messages flooded throughout the network.

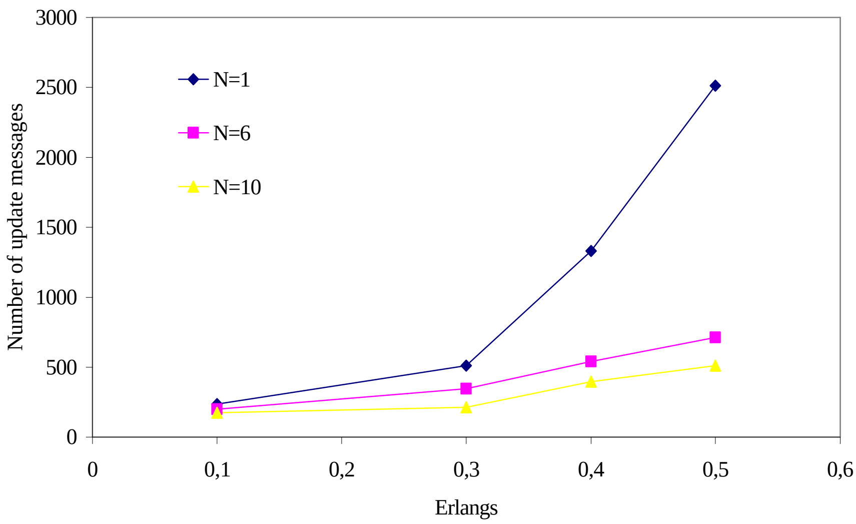

Figure 67. Number of update messages

In order to check the benefits obtained when applying *ALG3*, in Figure 68 we firstly compare *ALG1*, *ALG2*, *ALG3* and *First-Fit* algorithms behaviour in an optical network without conversion capabilities by measuring the impact in the blocking probability.

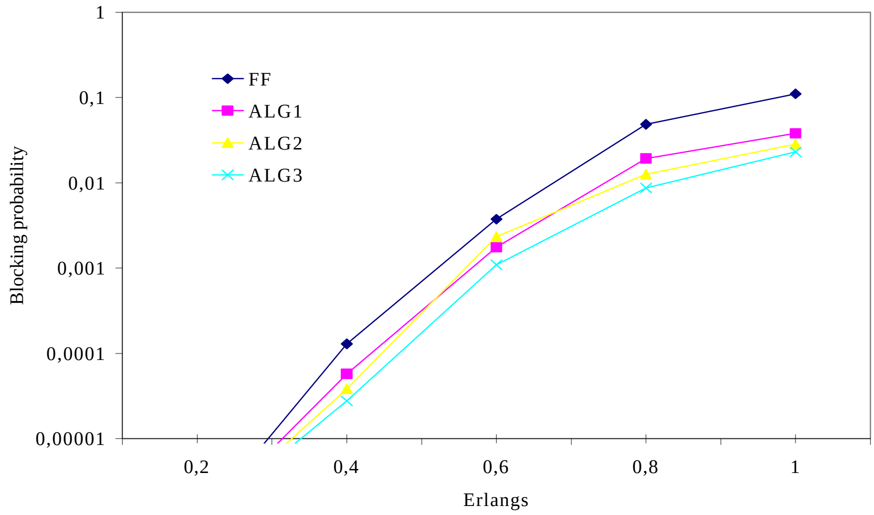

Figure 68. Blocking probability in *WS* networks

According to [4] all the simulations have been performed considering N = 6 (threshold value for triggering updating messages) and T_p = 50% (threshold percentage of N used to define *OSWs*). A light improvement in the blocking probability is obtained with *ALG3* in comparison with *ALG1* and *ALG2*. Actually, although in this scenario no conversion is allowed in the *bypass-path* computation, the weight factor modification implemented in *ALG3* leads to an even more blocking reduction.

Then, Figure 69 exhibits the *ALG3* performance when it is applied to a network with sparse and limited wavelength conversion. In our simulations we consider a fixed value of D = 25% and q in the range of 10%, 25% and 50%. A main aspect to be solved is which nodes should have conversion capabilities. We address this aspect by locating the wavelength converters in those nodes that support more traffic. These nodes are found after running *ALG3* considering there is not wavelength conversion availability in the network. *ALG3* and the *Shortest Path (SP)* algorithms are compared, combining the D and q values. We can see that going on the same trend, *ALG3* also decreases the blocking probability when incrementing the number of conversion capable nodes in the network. Moreover, we can see that when using *ALG3*, increasing the converters density q more than 25% does not imply a significant blocking probability reduction.

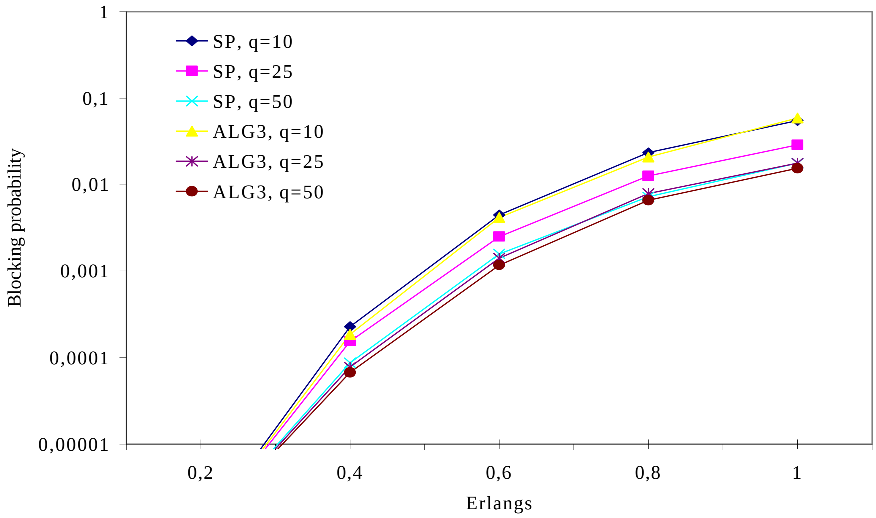

Figure 69. Blocking probability in *WI* networks

After carefully observing Figure 68 and Figure 69 we notice that *ALG3* in a non wavelength conversion scenario presents a similar behaviour than that obtained for the *SP* algorithm in a wavelength convertible scenario for q = 10% and D = 25%. So, we can say that by applying the *ALG3* a cost reduction can be achieved maintaining the same blocking probability.

Finally comparing the obtained results in *WS* and in *WI* networks, we can argue that *ALG3* can be used as an alternative solution (software solution) to reduce the blocking probability in a *WS* network to that solution based on simply adding wavelength conversion capabilities (hardware solution) to the network. Therefore, taking into account the current high prices for wavelength converters at network elements, *ALG3* is presented as a good solution to reduce the blocking probability while tempering the signalling overhead produced by the update messages

As a summary, in this Part the *BBR* mechanism has been extended to be applied to *WDM* networks. The *BBOR* mechanism addresses the negative effects on global network performance when selecting lightpaths based on inaccurate network state information. Basically, the mechanism *BBOR* lies in two main concepts, a new triggering policy based on a threshold standing for the number of changes and a new routing mechanism. *BBOR* is initially applied to *WS* networks, i.e., networks without wavelength conversion capabilities. Two routing algorithms are inferred from the

BBOR mechanism, *ALG1* and *ALG2*. Simulation results show the benefits obtained by these algorithms in terms of bandwidth blocking reduction compared to the shortest path combined with the First-Fit heuristic. Then, the *BBOR* mechanism is applied to *WI* networks, i.e., networks providing conversion capabilities. To simplify the network scenario, sparse and limited conversion is considered. This means that conversion capabilities are not allowed on each node along the network and that nodes having conversion capabilities can convert an input wavelength only to a fixed number of output wavelengths respectively. A new routing algorithm, *ALG3* is evaluated in comparison with shortest path (*SP*) algorithm. Results obtained by simulation show that *ALG3* in a *WS* network presents similar network performance than that obtained by the *SP* in a *WI* network. Therefore, the *BBOR* mechanism is an excellent option to reduce the bandwidth blocking without incrementing the unaffordable economical cost because of introducing wavelength converters.