The Minimum Coincidence Routing Approach in Wavelength-Routed Optical WDM Networks

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Abstract— **Management is a critical issue in optical networks. Highly impacting in management, routing in optical networks, is often decoupled into both the path selection and the wavelength assignment problems. In the former, shortest path based approaches are often applied to compute paths. Although such approaches offer advantages in terms of network loading, they are restricted by the fact, that routes are selected without taking into account parameters pertaining to any explicit and desired service guarantees. Thus, the wavelength assignment process may assign a non-optimal wavelength with respect to incoming traffic requirements and any associated quality of service specifications. This paper addresses the lightpath selection problem by proposing a novel route selection scheme where routes are determined based upon the twin criteria of minimizing the number of hops and balancing the network load, resulting in a reduction in both network congestion and blocking probability.**

Keywords- Optical networks, routing and wavelength assignment, adaptive routing, routing inaccuracy

I. Introduction and Motivation

Optical Transport Networks (OTN) appear as a solution to support new network requirements arising from broader network expectations produced by a combination of both an unforeseen and rapid increment of network users coupled with the emergence of new and more sophisticated Internet applications. An OTN consists of switching nodes (Optical Cross-Connect, OXC) interconnected by wavelength-division multiplexed (WDM) fibre-optic links that provide multiple parallel high-capacity communication channels over a common fibre. When the OTN includes automatic switching capabilities, it is referred to as an Automatically Switched Optical Network (ASON) [1].

A key component of an ASON is its Control Plane. The Control Plane is necessary to provide the network with dynamic provisioning, fast protection, restoration and Traffic Engineering. The IETF proposed Generalized Multi-Protocol Label Switching (GMPLS) as a protocol to implement this Control Plane. This Control Plane includes a centralised or distributed lightpath control mechanism to efficiently set-up and tear-down lightpaths. In the centralised case, a single central controller, having complete global network-state information, sequentially selects and establishes a lightpath for any incoming request. In the distributed case (shown in Fig. 1), different network nodes simultaneously process the incoming connection requests..

It is also important to recognise that, in optical networks, path determination is highly affected by the network wavelength-conversion capabilities. Wavelength routed networks without wavelength conversion are known as wavelength-selective (WS) networks, e.g. the example presented in Fig. 1. In such a network, a connection can only be established if the same wavelength is available on all links in the path between source and destination nodes; known as the wavelength-continuity constraint. Such a constraint may result in higher blocking probabilities at higher loads. On the other hand, wavelength routed networks with wavelength conversion are known as wavelength-interchangeable (WI) networks. In these networks, several (or all) network nodes are equipped with wavelength converters so that a lightpath can be set-up using different wavelengths on different links along the route. However, the cost associated in providing a wavelength converter at every node is currently considered to be prohibitive. Thus, solutions that attempt to limit the extent of wavelength conversion required within a WI network are sought.

In optical networks, the traditional routing concept can be decoupled into both the path selection and the wavelength assignment sub-problems (referred as the Routing and Wavelength Assignment problem, RWA [2]). Assuming source routing as an ASON recommendation [1], the source node A (in Fig. 1) calculates the route usually applying Shortest Paths based algorithms (step 2a) and assigns the wavelength (step 2b) to the connection AE. Then, the source node starts the signalling process required to set up the connection. Under this constraint, end-to-end routes are computed at the source nodes according to the network state information contained in their network-state databases. This assumption introduces a potential problem often referred to as the routing inaccuracy problem. The routing inaccuracy problem, or the selection of routes based on outdated

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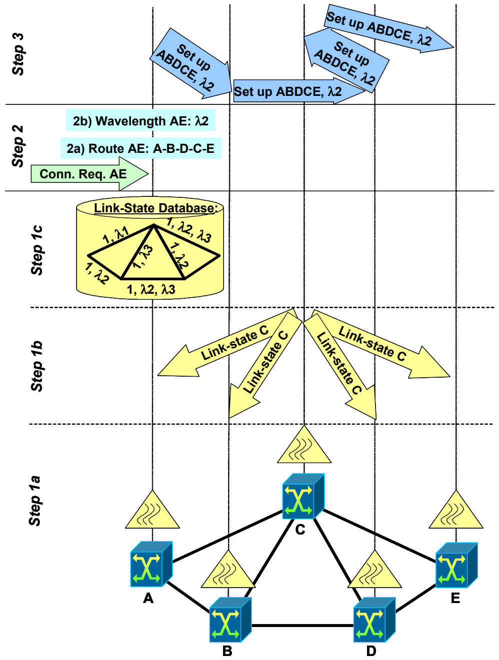

Figure 1. Principle of source-based link-state routing: 1a) each node filters link-state updates; 1b) flood link-state packets; 1c) each node constructs LSDB; 2) RWA; 3) Signal the set-up of the connection

network state information, may significantly affect global network performance [3]. Regardless of any potential impact on the selected routes based on inaccurate network state information, a key point is how these routes are computed, i.e. which algorithm is used to select the physical path. In fact, in this source routing approach, the physical route and the wavelength assignment processes are independent. This means that the computed route might not have sufficient capacity (i.e. available wavelengths) to transport the desired traffic thus blocking the incoming connection. In this paper, the authors present a new routing approach aiming at optimizing the path selection process in WS networks. Here, routes are determined by combining, in a novel manner, a shortest path approach with an attempt to balance network load. Adopting a simulation-based methodology, the performance of the proposed mechanism is investigated and then contrasted with alternative RWA mechanisms. The ability of the proposed mechanism to mitigate the effects of the routing inaccuracy problem is deeply investigated along with its impact on the network performance.

The remainder of this paper is organized as follows. In Section II authors review key RWA mechanisms and explicitly define the objectives of the paper. Then, Section III describes the proposed solution which is extensively evaluated in Section IV. Finally, Section V concludes the paper.

II. Handling the RWA Problem

Unlike traditional IP/MPLS scenarios where the routing process only looks for the optimal route, the Routing and Wavelength Assignment problem (RWA) in WDM networks must find both the physical nodes and links that configure the lightpath (routing sub-problem: i.e. step 2a in Fig. 1), and the wavelengths to be used on all the links along the lightpath (wavelength assignment sub-problem: i.e. step 2b in Fig. 1). This must be done in such a way that the network resources are optimally utilised. Many different strategies can be found in the literature addressing the routing subproblem (static routing, fixed-alternate routing and adaptive routing) and the wavelength assignment subproblem (Random, First-Fit, Least-Used, Most-Used, Min-Product, Least-Loaded, Max-Sum, Relative Capacity Loss, Protecting Threshold, etc) as read in [2].

Focusing on the routing sub-problem (i.e. step 2a in Fig. 1), existing routing algorithms can be classified into two classes: static and adaptive (also called dynamic). Static routing considers that a route connecting a source node to a destination node is selected off-line. However, in the adaptive approach, a route from a source node to a destination node is selected dynamically, explicitly reacting to an incoming connection request, and responding with a route that is a function of the current network state. Two routing approaches have been proposed for static routing: fixed routing and fixed-alternate routing. Fixed routing; the simplest approach, always considers the same route for each source-destination node pair. Shortest-path (SP) routing fits such a scenario as any connection between a particular source-destination node pair always uses the same off-line predetermined path. Such an approach can lead to high blocking probabilities since shortest path links may be congested while longer path links would be under-utilised. Such a drawback can be reduced by deploying fixed-alternate routing [4]. In fixed-alternate routing, multiple routes appropriate for setting up a connection between any source-destination node pair are exploited. Each node in the network maintains a routing table that contains an ordered list of a pre-determined number of fixed routes to each destination node. When a connection request arrives at the source node, this node tries, in sequence, to establish the connection on each of the ordered routes allocated in its routing table. This process finishes when a route with a valid wavelength is found. The connection is blocked when there is not any available wavelength. Generally speaking, the main drawback of static routing is that routing decisions are taken without considering the current network state. This weakness is addressed by adaptive routing allowing routes to be dynamically selected based on the network state information.

In an adaptive routing scheme, the route from the source to the destination nodes is computed dynamically according to the network state information allocated in the network-state databases. Maintenance of such network-state information in the network nodes is achieved by the application of the so-called updating mechanisms. In general, adaptive routing algorithms significantly enhance network performance in terms of connection blocking. There are numerous adaptive routing schemes. Most of them (such as the Least-Congested Path (LCP) routing [5] and the Least-Loaded Routing (LLR) [6]) select paths based on wavelength availability, usually selecting the route with the largest number of free wavelengths from among a set of pre-computed routes. Improvements are obtained when the LCP is applied over the set of shortest routes (SP-LCP) [7]. An alternative to LCP and LLR approaches is Fixed-Path Least-Congestion routing (FPLC) which selects paths based on path and neighbourhood congestion [7].

Summarising; schemes based on fixed routes reduce the complexity but, unlike adaptive routing approaches, may suffer from higher connection blocking and, thus, degraded global network performance. On the other hand, because of the extensive support from the signalling mechanism required by adaptive routing to keep the network state databases on the network nodes perfectly updated, fixed-alternate routing offers a trade-off between computing overhead and network performance. Hence, assuming adaptive routing as the most suitable approach the two following issues must be considered. The former, traditional adaptive routing algorithms (such as those mentioned above) usually select their routes based on maximizing the number of free wavelengths and do not explicitly consider the hop length. While this is not good for wavelength conversion networks ([8], [9] present new adaptive routing algorithms for full wavelength conversion networks), it usually can lead to better results than static approaches in WS networks. In fact, without wavelength conversion, the route with more free wavelengths also usually has shorter hop length; the probability that a longer route has more free wavelengths is much smaller by comparison with shorter routes [10]. Fewer contributions address jointly the issues of wavelength availability and the hop length. As an example, WLCR-FF [11] is an adaptive routing algorithm that considers the distribution of free wavelengths and the hop length to compute the route and then assign the wavelength; the FF heuristic is used because of its simplicity and performance benefits [12].

The latter, adaptive routing algorithms allow network nodes to take routing decisions based on the network-state information stored in their databases. Unfortunately, there are many factors such as the aggregation schemes, the delay on flooding and processing the update messages and the update procedure implemented to decide when an update message must be flooded throughout the network, all introducing inaccuracy in the state-information. The introduced inaccuracy can result in a significant increase in the blocking probability [3]. There are some contributions already addressing the routing inaccuracy problem for optical networks. Most of them deal with mono-fibre wavelength switched WS networks; few are concerned with WI networks. An overview of the most relevant contributions may be found in [13].

In this paper, the authors propose a new routing approach, termed the Minimum Coincidence Routing (MCR) algorithm, that selects physical paths on a WS network by attempting to maximise the free wavelengths or/and minimise the hop length, while simultaneously balancing network load. The scheme has two prime motivations. First, despite the fact that, as stated above, computing routes based only on maximizing the number of free wavelengths might not significantly affect the performance in WS networks, this elemental routing approach must be improved in order to optimize the network behaviour. Secondly, a path computation algorithm is proposed to be applied along with any wavelength assignment heuristic where the lightpath is computed from a set of pre-computed routes. Such versatility adds further value to the proposed scheme.

III. MCR: A NEW PROPOSAL FOR SELECTING ROUTES

The proposed Minimum Coincidence Routing (MCR) algorithm tackles the problems motivated by selecting lightpaths based on either the hop length or the wavelength availability. Enhancing the route selection process, the MCR scheme exploits the concept of minimum coincidence between paths to balance the traffic load, hence reducing the network congestion. The MCR computes the end-to-end paths by considering the routes that have fewest shared links and minimum hops. In order to maintain a trade-off between the number of hops and the number of shared links, the routing algorithm obtains the k-paths with the minimum number of shared links among them. Once the k-paths are pre-computed, any wavelength assignment heuristic may be applied to select the wavelength. The MCR scheme comprises three basic steps, described next:

Firstly, MCR chooses the shortest path from the list of feasible paths between the source-destination node pair, already pre-computed and ordered by the SP algorithm. Secondly, it associates a metric to the shortest routes left. This metric is named Minimum Shared Link (MSL) and is computed according to the following expression

$$MSL = N_H * S_L \quad (1)$$

where N_H is the number of hops of the particular path and S_L is the number of links shared between the particular path and the path previously selected in the first step. According to this expression, computed routes attempt to minimise the network congestion as well as improving scalability. Afterwards, MCR selects the path with the minimum MSL as the second path. Finally, in the third step, this process is repeated to obtain an ordered list of k- paths.

In order to clarify the mechanism an example to illustrate the MCR performance in a simple topology is presented next.

A. MCR example

MCR performance is illustrated by considering the topology shown in Fig.2. Assume that an incoming connection reaches node 1 demanding a lightpath to node 7. The MCR should compute the k-paths with minimum coincidences. Finally, in this example k = 3 is considered. As stated in this section there are three basic steps in the MCR detailed below.

1st. step: Shortest route selection.

As described previously, the first MCR step is to select the shortest route. This is achieved by choosing the shortest one among the set of shortest routes between node 1 and node 7 computed by the SP algorithm (in this example, the number of

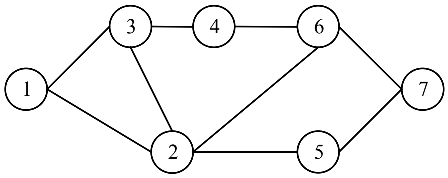

Figure 2. Network topology used in the illustrative example

computed shortest routes is limited to 5). Table I lists the routes selected by the SP as well as the one finally selected.

2nd. step: Computing MSL and selecting the second route.

Then, the MCR computes the MSL parameter according to the expression in (1). Hence, S_L is computed between the first selected route and the routes remaining. MSL is obtained by multiplying the S_L value with the hop length. The second selected route will be the route minimizing the MSL parameter. This process is shown in Table II.

3rd. step: Selecting up to k-routes

Finally, the process is repeated in order to choose the next path. It is important to note that from the third route on (this one included), the SL value is computed by adding the S_L values obtained by the previously computed paths. This process is clearly shown in Table III. After these three steps, the MCR algorithm ends up providing k-routes (Table III). The lightpath will be then selected among these routes according to the wavelength assignment heuristic in use.

Having presented the MCR scheme and its basic operation, the next section provides performance evaluation of the proposed scheme based on a series of simulation-based experiments.

IV. Performance Evaluation

Two sets of experiments were conducted in order to evaluate the MCR performance. The first are used to demonstrate how MCR improves network performance: achieved by modelling and evaluating the MCR-FF, the SP-FF and the SP-LCP-FF algorithms. The second set demonstrates how MCR reduces the effects of the routing inaccuracy problem in the network performance. Algorithms proposed in [14] are modified to include the MCR as the path selection mechanism. A set of simulations have been carried out using the 14-node NSFNET topology, where the possible source-destination node pairs are randomly selected, assuming an arbitrary 5-fibre topology, with 10 wavelengths per fibre on each bi-directional links. Connection arrivals are Poisson modeled and the connection holding time is also assumed to be exponentially distributed. Each arrival connection requires a full wavelength on each link traversed.

TABLE I. MCR: Step 1

k-Shortest paths	*Selected paths*
1-2-5-7	**1-2-5-7 *(path1)***
1-2-6-7	
1-3-2-5-7	
1-3-2-6-7	
1-3-4-6-7	

TABLE II. MCR: Step 2

path 1	S_L	*MSL*	*Selected paths*
1-2-6-7	1	3 * 1 = 3	**1-2-5-7 *(path 1)***
1-3-2-5-7	2	4 * 2 = 8	**1-3-2-6-7 *(path 2)***
1-3-2-6-7	0	4 * 0 = 0	
1-3-4-6-7	0	4 * 0 = 0	

TABLE III. MCR: Step 3

path 1/path 2	S_{Lpath1}	$S_{Lpath\ 2}$	*MSL*	*Selected paths*
1-2-6-7	1	2	3 * 3 = 9	**1-2-5-7**
1-3-2-5-7	2	2	4 * 4 = 16	**1-3-2-6-7**
1-3-4-6-7	0	2	2 * 4 = 8	**1-3-4-6-7**

A. Case 1

In case 1 the behavior of the SP-FF, SP-LCP-FF and MCR-FF algorithms (being FF the wavelength assignment heuristic) is investigated. We assume the network state information to be perfectly updated so that wavelength availability information is considered exact. Fig.3 compares results obtained by the three algorithms when k=3. It is shown that the MCR-FF always outperforms the SP-FF and the SP-LCP-FF in terms of blocking performance. Also of interest is the impact of the number of selected routes on the blocking probability, i.e. variation of k. Fig.4 shows how blocking probability reacts to variations from k = 2 to k = 4 by the MCR-FF and the SP-LCP-FF algorithms (termed as MCR-FF_k and SP-LCP-FF_k). As expected large values of k (k = 4 is the critical value where the blocking trend changes) do not reduce but rather increase the blocking in the SP-LCP-FF case. However, because of the shared link value the MCR-FF behaves even better when k=4.

B. Case 2

Since MCR is simply a route selection mechanism, it can be applied along with any existing wavelength heuristic (the first experiments presented applied the MCR only with FF). Hence, having observed the advantages of using the MCR algorithm to select paths, this algorithm is applied to a routing mechanism tackling a previously well-known issue, namely the routing inaccuracy problem. As stated in Section II, this problem arises when selecting lightpaths under inaccurate network state information; such an issue is relevant when an adaptive routing approach is in use. In this set of results the inaccuracy is introduced by the updating procedure used to maintain network state databases. In general, the updating procedure is implemented by triggering policies which are based on either a

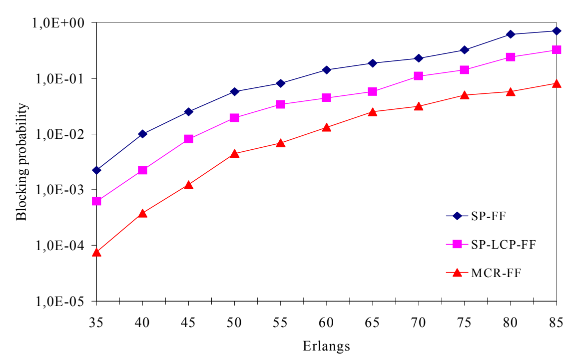

Figure 3. Blocking probability

threshold value (an update message is triggered after a fixed number of changes occur in the network) or a hold-down timer (update messages are triggered periodically). Using these triggering policies is essential otherwise the signaling overhead associated with update messages issued in a highly dynamic network would be significant and possible insupportable. In this paper, a threshold-based triggering policy defined in [14] is implemented.

In order to see the additional benefits on the network performance attained by including the MCR as the route selection mechanism, ALG1 and ALG2 algorithms, both proposed in [14], with/without using the MCR are compared. ALG1 and ALG2 select lightpaths based on including a new parameter (accounting for the network inaccuracy) in the route selection process. This parameter is applied to select the route from a pre-computed set of k-routes which are computed by SP. In this set of simulations the effects on the network performance when MCR is used to select the physical route (ALG1_MCR and ALG2_MCR) are examined. Results in Fig.5 show that MCR can be perfectly implemented along with ALG1 and ALG2 turning out a better response in terms of blocking probability.

V. CONCLUSIONS

This paper deals with routing in optical networking as a critical part of management activities. The authors propose a new routing algorithm named Minimum Coincidence Routing (MCR) to counteract the negative effect of selecting paths based only on either the number of hops or the number of available wavelengths. Instead, MCR computes paths in an attempt to balance the traffic load, therefore reducing the network congestion and enhancing the global network performance. Results show that the MCR depicts promising behaviour in terms of the network blocking probability when compared with other well-known algorithms such as the shortest path or the LCP. A further key advantage of the proposed scheme is its versatility. Such versatility is illustrated by incorporating MCR in a previously presented routing mechanism that addresses the routing inaccuracy problem. Again, results show that better network performance is obtained when replacing the SP algorithm by the MCR.

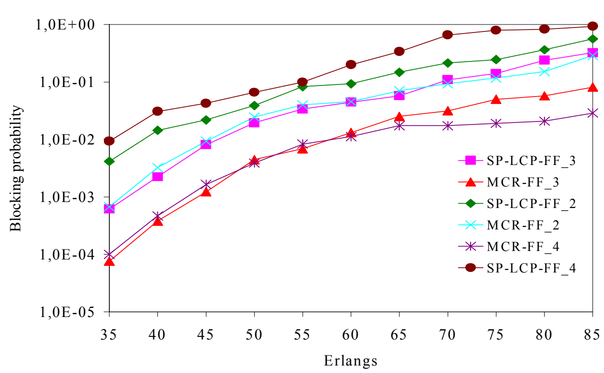

Figure 4. Blocking probability as a function of the k value

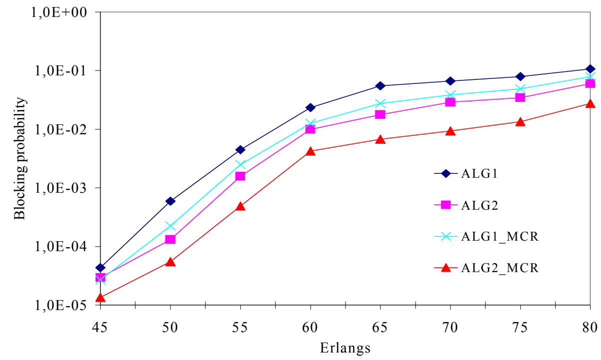

Figure 5. Effects of the MCR on the blocking probability when applied to ALG1 and ALG2

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