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Protection in Optical Networks with Limited Wavelength Conversion Capabilities

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Abstract This paper addresses shared-path protection with 100% recovery against single-link failures in dynamic wavelength-routed WDM networks. Wavelength converters can improve network performance, but are also costly. Therefore, sparse-partial networks, which have a small number of converters placed at a few nodes, are considered. Routing and Wavelength Assignment is proposed by applying dynamic Shortest Path Routing in a multi-layer Wavelength Graph (SPR-WG) for primary as well as backup paths. The algorithm uses resource costs that can be adjusted to achieve efficient utilization of the limited available converters. The NSFNET topology is used to simulate several sparse-partial configurations with different numbers of converters at four selected nodes. It is found that if the number of converters at these nodes is only 25 % of the number required for a complete set, no significant performance degradation occurs.

Key words All-Optical Networks, Wavelength Division Multiplexing, Wavelength Conversion, Network Survivability, Routing and Wavelength Assignment.

1 Introduction

The demand for transmission capacity by telecommunication services, such as the world wide web, multimedia conferencing, and video-on-demand, is ever increasing, while user locations cover the entire globe. Moreover, more and more organizations rely on public networks for their mission critical applications, leading to stringent Quality of Service (QoS) demands. The development of survivable high-capacity transport networks based on optical fiber is presently seen as the solution to satisfy these requirements [1].

Wavelength Division Multiplexing (WDM) provides a practical way to exploit the vast bandwidth of optical fiber. WDM partitions the optical bandwidth into independent channels, each at a different wavelength, operating at transmission rates compatible with electronic speeds, to support transmission at an aggregate bandwidth beyond any single-channel system. Currently, the most practical approach for optical transport networks with mesh-based topologies is wavelength routing [2]. In this WDM-based approach, node pairs can establish point-to-point paths of light (or lightpaths) for information exchange. Lightpaths consist of wavelength channels in a sequence of optical links, interconnected at the transit nodes by means of optical routing. In the absence of wavelength conversion, a lightpath must use the same wavelength on all the links of its route (the wavelength continuity constraint). Wavelengths can be reused by different lightpaths in the network, as long as they do not share a fiber link.

When nodes are equipped with wavelength converters, a lightpath can be assigned different wavelengths on different links along its route. Consequently, the wavelength continuity constraint is relaxed, thereby increasing the number of lightpaths that can simultaneously exist in the network. Wavelength converters are costly and may cause signal quality degradation, but research has shown that with only a small number of converters placed in strategic locations, a significant performance improvement can be achieved [3], [4]. The converter configuration of a network is referred to as *full* if all nodes have wavelength converters and *sparse* if only part of the nodes have wavelength converters. The converter configuration of a node is called *complete* if a wavelength converter is provided for each wavelength channel on all output links, and *partial* if a smaller number of wavelength converters is available.

A single optical fiber can carry data rates in excess of one Terabit per second. A fiber cut (or a node failure) may interrupt a tremendous number of ongoing communications. Hence, the optical transport network will need some form of survivability to recover the interrupted communications. Recovery is normally accomplished by establishing a backup lightpath when the primary (or working) lightpath fails. Survivable network architectures are based on protection or on restoration [5]. In protection, backup resources are computed and reserved at the time of lightpath setup, while in restoration, backup resources are discovered and allocated after a failure occurs. Compared to restoration, protection can reestablish failed lightpaths faster and can offer 100 % guarantee of recovery, but it requires more backup resources. The utilization of backup resources can be improved by a technique called shared protection (also known as backup multiplexing). Multiple backup paths can reserve the same resource, as long as their corresponding primary paths are link disjoint. This requirement guarantees that these backup paths are not activated simultaneously under the assumption of single link failures. Survivability schemes can also be classified into link and path recovery [5]. In link recovery, all the lightpaths that traverse the failed link are rerouted around that link. In path recovery, a backup path is established between the source and destination node of the failed lightpath. When path protection is applied, the reserved backup path has to be link disjoint from the primary path to enable recovery from the failure of any link of the primary path. Compared to link recovery, path recovery has a higher recovery time, but requires fewer network resources.

In this paper, we consider survivable mesh-based optical networks that employ shared-path protection. Much work published on survivable optical networks assumes the full-complete converter configuration.[注1] Our focus is, however, on sparse-partial converter configurations, since these are expected to offer the best price-performance ratio. The required number of wavelength converters and their placement has been discussed for non-survivable networks in several papers (e.g., [3], [4]). To provide survivability, however, a backup path has to be reserved in conjunction with each primary path. Moreover, backup paths may share converters. Hence, it is not obvious that approaches for wavelength converter placement in non-survivable networks will work just as well in survivable networks. For that reason, we study the performance of sparse-partial converter configurations in this paper. We assume dynamic traffic conditions, whereby lightpath setup requests arrive based on a stochastic process. For the Routing and Wavelength Assignment (RWA) of both primary and backup path, we propose a dynamic algorithm that performs Shortest Path Routing in a multi-layer Wavelength Graph (SPR-WG). The algorithm uses two routing cost values, i.e., one for wavelength channels and one for converters, which can be independently set for primary and backup path routing. By adjusting the ratio of these cost values, the algorithm's inclination to incorporate wavelength converters in a path can be controlled in order to achieve an efficient utilization of the limited available converters. The NSFNET topology is used to simulate several sparse-partial configurations with different numbers of converters at four selected nodes. It is found that if the number of converters at these nodes is only 25 % of the number required for a complete set, no significant performance degradation occurs.

The remainder of this paper is organized as follows. Section 2 describes related work. Next, our network model is presented in Section 3. Then, the routing and wavelength assignment algorithm is described in Section 4. Section 5 reports the simulation results whereby the NSFNET topology is used to study the performance of sparse-partial converter configurations. Finally, conclusions and directions for future research are presented in Section 6.

2 Related work

Most of the work published to date on survivable mesh-based optical networks with limited wavelength conversion capabilities considers static traffic, whereby the demands are fixed and predetermined. Based on the demand set, lightpaths are determined and permanently setup in the network. Typically, Integer Linear Programming (ILP) approaches are used to solve the lightpath RWA. In this category, Belotti and Stidsen [7] consider a survivable network based on dedicated path protection with sparse-complete converter configurations.[注2] They present an ILP for obtaining the minimum number of converter nodes and their locations to satisfy a given demand set. Due to the computational complexity, only small networks and demand sizes are investigated (up to 12 nodes and 7 demands). Zang et al. [8] consider a survivable network based on shared-path protection with sparse-complete converter configurations.[2] The authors present an ILP that given a demand set and the maximum number of converter nodes, solves for the set of converter nodes that minimizes the number of wavelength-links[注3] used. To circumvent the computational complexity of the ILP, four heuristics are proposed for converter placement. No results are presented, however. Fumagalli et al. [9] consider shared-link protection based on self-healing rings. An ILP formulation is presented that solves for the ring cover of the network topology, the routing of the primary paths, and the provisioning of spare wavelengths, assuming full-complete wavelength conversion. The ILP is made computational tractable by pruning the solution space. Two heuristic approaches are proposed to reduce the number of wavelength converters required in the solution. Li and Wang [10] consider shared-path protection (with and without converter sharing) and full-partial converter configurations. They present an ILP that minimizes the total cost of wavelength-links and converters used. The ILP is used to benchmark a heuristic RWA algorithm that performs shortest-widest path first (SWPF) routing in a multi-layer wavelength graph. The performance of the SWPF algorithm turns out to be near optimum. The demand sizes used in the experiments present, however, a very low load for the network sizes considered. In another work, Li and Wang [11] apply a shared-link protection approach in networks with full-partial conversion. Backup resources form so-called p-cycles that can share converters. ILPs are formulated for determining p-cycles and number of wavelength converters under the objective to minimize the total cost of used wavelength-links and wavelength converters. Yang et al. [12] consider shared-path protection in networks with sparse-partial conversion.[注4] Apart from sharing of wavelength channels and wavelength converters among backup paths, they introduce the sharing of wavelength converters between backup path and primary paths. After failure of a primary path, its wavelength converters are available for use by its backup path. An ILP and two heuristic approaches are presented that minimize the number of wavelength-links and wavelength converters for a given demand set.

Contrary to static traffic, in the case of dynamic traffic, connection setup requests arrive at random time intervals and have a finite holding time. In this category, Gowda and Sivalingam [13] consider both dedicated and shared-path protection in a network that has a full-partial converter configuration. The authors show that backup paths can share wavelength converters in the same way as wavelength channels can be shared. A shortest path routing algorithm is proposed that produces conversion free primary paths without wavelength conversion, as far as possible. To improve performance, two backup path relocation mechanisms are proposed that migrate existing backup paths when needed. Finally, So [14] inves-

（1）：See, for example, the article by Ou et al. [6] and references therein.

（2）：Actually, digital cross-connects (DXCs) are used as converter nodes.

（3）：A wavelength-link is defined as a wavelength channel on some link.

（4）：Optical-electrical-optical (OEO) modules are used as wavelength converters.

tigates survivable networks with a sparse-complete converter configuration. An algorithm for converter placement is proposed that starting from the full-complete configuration removes converters one-by-one from nodes where they are the least utilized. The converter utilization at each node is obtained by means of simulation. A modest performance improvement was found with respect to a converter placement algorithm that does not take network survivability into account.

3 Network model

We consider a WDM network with limited wavelength conversion capabilities. Such a network consists of nodes that are interconnected by means of unidirectional optical links into an arbitrary topology. Each link is composed of one or more optical fibers, and each fiber carries the same number of wavelength channels. Nodes are capable of switching lightpaths arriving on any incoming fiber to any outgoing fiber, and, if necessary, changing its wavelength channel. The set of wavelength converters at a node is organized into a single converter bank for use on any output link (share-per-node architecture) [3]. The number of wavelength converters in the bank can be different for each node. As long as unused wavelength converters are available, a new lightpath transiting the node can be allocated a converter to change its wavelength. Full-range converters are employed that can convert any incoming wavelength to any outgoing wavelength.

Network survivability is implemented by shared-path protection. Without loss of generality, only link faults are considered in this study. A link fault is assumed to result in the loss of all fibers of that link. Links are joined into a Shared Risk Group (SRG) if they are affected by the same fault. For example, links that make use of the same fiber duct form an SRG. In order to guarantee 100 % survivability against *single* link faults, the primary path and the backup path of a connection shall be SRG-disjoint. The fault scenario comprising link faults only allows a backup path to transit intermediate nodes of its primary path. Backup paths are allowed to share network resources (wavelength channels and wavelength converters), as long as their primary paths are SRG-disjoint.

Dynamic traffic is considered whereby connection requests arrive based on a stochastic process. Each connection request is assumed to require the unidirectional transmission capacity of an entire wavelength channel. For simplicity of this description, a central control facility is assumed that maintains the network state and handles all connection requests.[注5] Upon receipt of a connection request, the control facility performs routing and wavelength assignment as described in Section 4. If no blocking occurs, it commands the nodes in the network to configure switching fabric and tune wavelength converters. Blocking occurs if there are no free wavelengths-links and/or wavelength converters available to establish both the primary and the backup lightpath.

4 Routing and Wavelength Assignment

Routing and wavelength assignment for both the primary path and backup path of a lightpath request is achieved by routing in the so-called Wavelength Graph (WG) [10], [15]. Links in the WG represent network resources, i.e., wavelength channels and wavelength converters, and costs are assigned for traversing a link. Routing in the WG is performed by finding the shortest path between source and destination (if it exists) in terms of total resource cost, using a modified Dijkstra's algorithm. The RWA algorithm performs routing and wavelength assignment in an integrated fashion, as apposed to approaches that separate routing and wavelength assignment into two steps. The advantage is that a path will be found if it exists, resulting in high performance.

The wavelength graph is constructed as follows [8], [10], [15]. A *directed* graph representing the network is replicated K times, with K the number of wavelength channels; each replication forms a wavelength layer in the WG, and each link in a layer of the WG represents a wavelength-link. If wavelength converters are available at a network node, then all the replications of that node in the WG are connected in a full-mesh manner to allow wavelength conversion between any pair of wavelength channels.[注6] A pseudo source node and a pseudo destination node are added for each network node, together with links from a pseudo source node to all its replications, and links from all the replications of a node to their pseudo destination node. The pseudo nodes are the starting and terminating points for routing.

Appropriate cost assignment to the links of the WG is important for achieving efficient utilization of the limited available converters in the network. The cost assignment procedure uses two basic cost values, i.e., the cost C of a wavelength-link and the cost W of a wavelength converter.[注7] Cost assignment is performed twice; once for primary path routing and once for backup path routing. The cost assignment for backup path routing differs from cost assignment for primary path routing in two ways. First, backup paths are not allowed to have common risks with their primary path. This is guaranteed by setting the cost of all wavelength-links that share a risk with the primary path to infinity. Second, backup paths may share network resources, as long as they are not activated simultaneously. If a previously reserved resource can be shared with the backup path to be set up, then that resource comes essentially at no cost.

First, consider the cost assignment for primary path routing. The wavelength-link cost $C^p(e,w)$ for wavelength channel w on link e receives the value C if there are free channels available. Otherwise, its cost is set to infinity. More formally:

$$C^p(e,w) = \begin{cases} C & \text{if } p_c(e,w) + b_c(e,w) < f(e), \\ \infty & \text{otherwise.} \end{cases} \qquad (1)$$

Herein is $f(e)$ the number of fibers on link e, i.e., the number of channels available on link e for each wavelength. $p_c(e,w)$ is the number of primary channels currently using wavelength w on link

（5）：Distributed control would also be possible, but it incurs a protocol overhead for disseminating state information. In addition, measures are required to handle possible contention in resource allocation and to deal with differences between the network state maintained by each node.

（6）：In case of limited-range converters, nodes in the WG are only connected if conversion between their respective wavelength channels is supported.

（7）：The application of constant costs C and W essentially minimizes resource usage. Other approaches are also possible, whereby the values of C and W can be dependent on link and node, respectively. For example, C and W can be set to actual implementation costs.

e, and $b_c(e, w)$ is the number of reserved backup channels for wavelength w on link e.(注8) The assignment of wavelength converter costs is performed in an analogous fashion. The cost $W^p(n)$ for wavelength conversion at node n for primary path routing is given by:

$$W^p(n) = \begin{cases} W & \text{if } p_w(n) + b_w(n) < c(n), \\ \infty & \text{otherwise.} \end{cases} \tag{2}$$

Herein is $c(n)$ the total number of converters available at node n. $p_w(n)$ is the number of converters in use at node n by primary paths, and $b_w(n)$ is the number of converters reserved at node n for backup paths. A lightpath can start and terminate at any wavelength. Therefore, the costs of the links in the WG connecting the pseudo source nodes and the pseudo destination nodes are set to zero.

Next, consider the cost assignment for backup path routing. The wavelength-link cost $C^b(e, w)$ for wavelength channel w on link e is given by:

$$C^b(e, w) = \begin{cases} \infty & \text{if } e \text{ shares a risk with primary path,} \\ \epsilon & \text{else if } u_c(e, w, r) < b_c(e, w) \ \forall \text{ risks } r \\ & \quad \text{of primary path,} \\ C & \text{else if } p_c(e, w) + b_c(e, w) < f(e), \\ \infty & \text{otherwise.} \end{cases} \tag{3}$$

Herein is $u_c(e, w, r)$ the number of backup channels currently reserved for wavelength w on link e to protect against a failure of risk r. Notice that a small cost value ϵ is assigned in case of a shareable wavelength-link. This enables the RWA algorithm to select the backup path with the smallest number of no-cost resources in case of otherwise equal cost paths. The cost $W^b(n)$ for wavelength conversion at node n for backup path routing is given by:

$$W^b(n) = \begin{cases} \delta & \text{if } u_w(n, r) < b_w(n) \ \forall \text{ risks } r \text{ of primary} \\ & \quad \text{path,} \\ W & \text{else if } p_w(n) + p_w^0(n) + b_w(n) < c(n), \\ \infty & \text{otherwise.} \end{cases} \tag{4}$$

Herein is $u_w(n, r)$ the number of backup converters currently reserved at node n to protect against a failure of risk r. $p_w^0(n)$ (= 0 or 1) is the number of converters used at node n by the primary path for which a backup path is sought. δ is a small cost that serves the same purpose as ϵ in (3). Notice that since nodes are assumed not to fail, backup paths can use converters in the same nodes as primary paths. The costs of the links in the WG connecting the pseudo source nodes and pseudo destination nodes are set to zero. Consequently, a backup path may start and terminate on different wavelengths than its primary path.

By modifying the cost ratio C/W, it is possible to control the RWA algorithm's inclination to include wavelength converters in the selected path. For small values of C/W, i.e., wavelength converters are expensive, the algorithm will choose longer paths (more wavelength-links) if it can avoid the use of wavelength converters. On the other hand, for large values of C/W, i.e., wavelength converters are cheap, the algorithm will use a wavelength converter if it results in a reduced number of wavelength-links. By choosing a low cost ratio for primary path routing and a high one for backup path routing, it is, for instance, possible to discourage the use of converters in primary paths and to promote the use of converters in backup paths (where they can be used more efficiently by sharing).

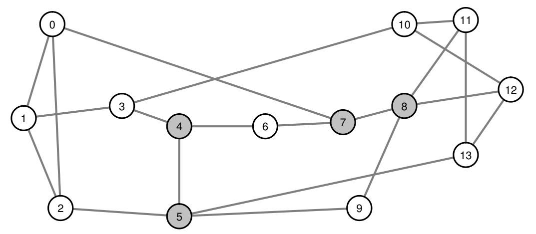

Figure 1 Topology of the 14-node NSFNET T1 backbone network.

5 Performance evaluation

This section presents the results of a computer simulation experiment to assess the performance achievable by survivable optical networks with sparse-partial converter configurations. The purpose of the experiment is to find optimum values of the C/W cost ratio for both primary and backup path routing depending on the wavelength conversion capabilities available in the network.

5 1 Experimental setup

The topology of the NSFNET T1 backbone network, as it existed in the early 1990s (Fig. 1), is used for the performance evaluation. It consists of 14 nodes, which are interconnected by 42 (= 2 × 21) unidirectional links. Each link consists of a single fiber, and each fiber carries 8 wavelength channels. Links are assumed not to have common risks, i.e., in the event of a fault only a single unidirectional link will be affected.

It has been determined that in an optimum sparse-partial configuration, the nodes numbered 4, 5, 7, and 8 require the largest number of wavelength converters [4]. By placing different numbers of wavelength converters at these nodes, the sparse-partial configurations considered in this experiment are obtained (Table 1). Nodes that are not specified in Table 1 have no conversion capabilities. For comparison purposes, also the no converters and the full-complete configurations are considered. These two configurations represent the cases for the lower and upper bound on the performance, respectively.

Table 1 Number of wavelength converters applied in the sparse-partial converter configurations considered.

Converter configuration	Node 4	Node 5	Node 7	Node 8
Sparse-complete	24	32	24	32
Sparse-partial (6-8-6-8)	6	8	6	8
Sparse-partial (3-4-3-4)	3	4	3	4
Sparse-partial (1-2-1-2)	1	2	1	2

Lightpath setup requests arrive according to a Poisson process with exponentially distributed holding times. Source and destination nodes of the lightpaths are uniformly distributed.

5 2 Blocking probability

First, we present the lightpath setup blocking probability as a function of the total network load for each converter configuration (Fig. 2). The value of C/W has been set to 0.67 for both primary and backup path routing. The curves show the usual behavior of

(8): In this study, $C^p(e, w)$ is independent of the fiber utilization, resulting in a *pack* routing strategy, whereby lightpaths are packed on as few wavelength-links as possible. A *spread* routing strategy, whereby the cost of a wavelength-link increases with the fiber utilization, gives performance improvement [15].

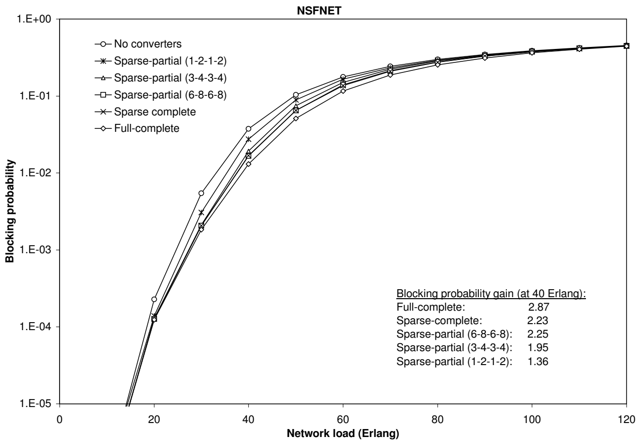

Figure 2 Blocking probability in the NSFNET network (1 fiber/link, 8 wavelengths/fiber, C/W = 0.67 for both primary and backup path).

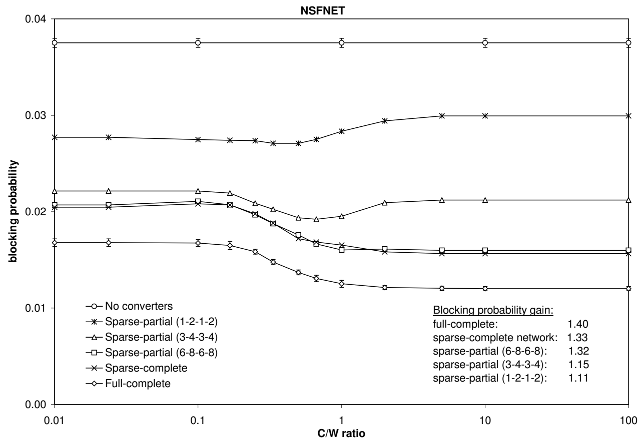

Figure 3 Blocking probability in the NSFNET network (1 fiber/link, 8 wavelengths/fiber, 40 Erlang network load, same C/W ratio for primary and backup path).

increasing with the network load, gradually approaching the value 1 as the network load approaches infinity. Furthermore, a converter configuration with a larger number of converters always has a lower lightpath setup blocking probability than a converter configuration with a smaller number of converters.

The blocking probability gain for a wavelength converter configuration can be defined as the ratio of the blocking probability for the configuration with no converters and the blocking probability for the configuration of interest [16]. Fig. 2 specifies the blocking probability gain for each converter configuration at a network load of 40 Erlang. Notice that although there is quite a difference in the number of converters between the sparse-partial (6-8-6-8) configuration and the sparse-complete configuration, there is no significant difference in blocking probability gain (2.25 vs. 2.22).

5 3 Cost ratio of wavelength channels and converters

Next, we investigate how the cost ratio C/W can influence the blocking probability. The C/W ratio is set to the same value for primary path routing and for backup path routing. For C/W ratios less than 0.1, wavelength converters are relatively expensive. The routing algorithm favors longer paths without wavelength converters to shorter paths with wavelength converters. For C/W ratios larger than 10, wavelength converters are relatively cheap, and the routing algorithm will favor shorter paths with wavelength converters to longer paths without wavelength converters.

Fig. 3 shows for each converter configuration the blocking probability as a function of C/W at a constant network load of 40 Erlang.[注9] The full-complete, sparse-complete, and sparse-partial (6-8-6-8) configurations show a decrease of the blocking probability when the C/W ratio is increased from 0.1 to 10. These configurations can be considered to have an *abundance* of wavelength converters. For low C/W values, the available wavelength converters remain largely unused, while for high C/W values an appropriate utilization is achieved, leading to lower blocking probabilities. The sparse-partial (1-2-1-2) configuration shows an increase of the blocking probability when the C/W ratio is increased from 0.1 to 10. This configuration can be considered to have a *shortage* of wavelength converters. For high C/W values, the available wavelength converters are quickly exhausted, while for low C/W values an appropriate utilization is achieved, leading to lower blocking probabilities. The sparse-partial (3-4-3-4) configuration shows a somewhat intermediate behavior. Its blocking probability first decreases and then increases with increasing C/W.

Fig. 3 specifies the maximum blocking probability gain for each converter configuration that can be achieved by selecting the optimum value for C/W. The largest gain is obtained by the full-complete configuration, which shows more than 40 % improvement. The sparse-partial (1-2-1-2) configuration has the smallest gain (11 %).

5 4 Separate cost ratios for primary and backup paths

Finally, we investigate whether the C/W ratio for primary path routing and the C/W ratio for backup path routing should be set to different values to achieve optimum performance. Now, the C/W ratios for primary and backup paths are varied independently between 0.01 and 100 at a constant network load of 40 Erlang. Due to lack of space, the blocking probability graphs cannot be incorporated in this paper. Instead, Fig. 4 summarizes the simulation results. It indicates optimum ranges of the primary path routing C/W and the backup path routing C/W for each converter configuration.

Fig. 4 indicates that the full-complete, sparse-complete, and sparse-partial (6-8-6-8) configurations achieve lowest blocking probability when the converter cost is (much) smaller (e.g., $0.1\times$) than the wavelength channel cost. The sparse-partial (3-4-3-4) configuration achieves lowest blocking probability when the converter cost is roughly the same as the wavelength channel cost. The sparse-partial (1-2-1-2) configuration achieves lowest blocking probability when the converter cost is much higher (e.g., $10\times$) than the wavelength channel cost. Moreover, as a rule of thumb, the C/W ratio for backup path routing should be somewhat larger than the C/W ratio for primary path routing by a factor between 1 and 10. The reason is that wavelength converters are more beneficial in the backup path than in the primary path due to sharing.

6 Concluding remarks

In this paper, we have investigated the performance of survivable optical networks with sparse-partial converter configurations under

(9)：90 % confidence intervals are marked for the ‘No converters’ and ‘Full-complete’ curves. 90 % confidence intervals for the other curves have similar sizes.

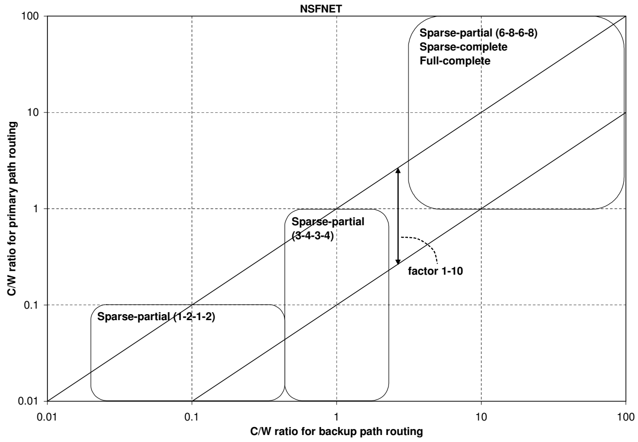

Figure 4 Optimum combinations of C/W for primary path routing (vertical axis) and backup path routing (horizontal axis) in the NSFNET (1 fiber/link, 8 wavelengths/fiber, 40 Erlang network load).

dynamic traffic conditions. Routing and Wavelength Assignment for both primary and backup path is performed by using a dynamic Shortest Path Routing algorithm in the Wavelength Graph (SPR-WG). The algorithm uses two cost values, i.e., C for wavelength-links and W for wavelength converters. The NSFNET topology was used to simulate several sparse-partial configurations with different numbers of converters at four selected nodes. For comparison purposes, also the no converters and the full-complete configurations were considered. It was found that configurations with larger number of converters need a high value for C/W (≈5–100) to achieve maximum performance, while configurations with a small number of converters need a low value (≈0.01–0.5). Moreover, the C/W for backup path routing should be somewhat higher than for primary path routing, since backup paths can make better use of the scarce converters by means of sharing. Finally, it was found that the sparse-partial configuration with only 25 % of the number of converters in the sparse-complete configuration achieves almost the same performance as the sparse-complete configuration. To make these conclusions more general, network topologies other than the NSFNET should be considered as well. Initial results for the 19-node European Optical Network (EON) and the 24-node ARPANET show that the dependence of the network performance on C/W is smaller for larger networks.

Several topics are considered for future research on survivable optical networks with limited wavelength conversion capabilities. One of these is to explore potential resource sharing between primary resources and backup resources to improve the utilization of the network resources. Yang et al. [12] have employed sharing of wavelength converters between a primary path and its backup path. It is, however, possible to take such sharing a step further by including potential sharing between primary wavelength channels and backup wavelength channels. Another approach for improving utilization of the network resources is to establish fault dependent backup paths. In this approach, backup paths are established for the failure of each link of the primary path. If a failure occurs, the appropriate backup path is activated, depending on the failed link. Another area important of research is the development of algorithms for placing wavelength converters in survivable networks.

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