Performance of dynamic path optical networks

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Abstract: The blocking characteristics of highly connected networks using WDM and optical space switching to provide dynamic reconfiguration have been evaluated using computer modelling techniques. It is shown that, for these types of networks, blocking and network efficiency can be improved by use of a reduced set of routes for path set up as opposed to using the entire set of available routes. However, when wavelength routing is a requirement, the reduced route set scheme suffers significant degradation due to wavelength blocking.

1 Introduction

The concept of all-optical core networks has been developed in response to the anticipated introduction of wide ranging broadband services and the associated growth in capacity requirements. The optically switched, reconfigurable multiwavelength transport network, developed by the RACE 2028 project [1], would be suitable for deployment as an optical transport overlay in either core SDH [2] networks or multihop asynchronous transfer mode (ATM) networks [3]. Wavelength routing techniques are employed to provide wavelength reuse [4]. Such a network would function in a similar fashion to existing circuit switched networks and the network configuration might be expected to fluctuate slowly in a circuit-switched fashion in response to changing traffic statistics.

Consider the situation where an electronic transport network is supplemented with an optical transport overlay. An optical path can be described as being a combination of a physical route across the network from origin to destination (a route contains the links traversed) and channel information on that route (wavelengths used on each link of the route or wavelength used on the route). Transparent optical paths connect certain of the electronic nodes and these paths are established in a wavelength-routed fashion across the optical cross connects of the overlay network. A new optical path starts its life cycle as a request from the network control or controllers which must locate a suitable routing and an available wavelength or wavelengths. The necessary optical switching operations are then implemented to effect the path. If a wavelength routing cannot be identified then the request may be blocked. If the request is accepted and the path established, it may have a finite lifetime in the network and the path will be removed and its resource made available for future requests.

In a previous investigation [5] the network blocking due to wavelength (λ) contention was investigated in a routing scheme which searched all possible routings upon a request for a path. This will be referred to as the global route set scheme or GR. The number of possible routes between two nodes is nontrivial for large networks, and it was shown in [5] that the magnitude of wavelength (λ) blocking is related to the number of wavelengths in the network and the meshing and node size of the network architecture. A wavelength routing (WR) scheme attempts to establish a path which is wavelength continuous from end to end. Wavelength blocking occurs when a λ-continuous route is not available to satisfy the path request. This situation is illustrated in the routing attempt made between nodes 1 and 3, shown in Fig. 1*a*, and occurs because every λ is used on some links of the route by other previously established paths. As a result the actual blocking exhibited by the network is greater than the blocking due to bandwidth only limitations.

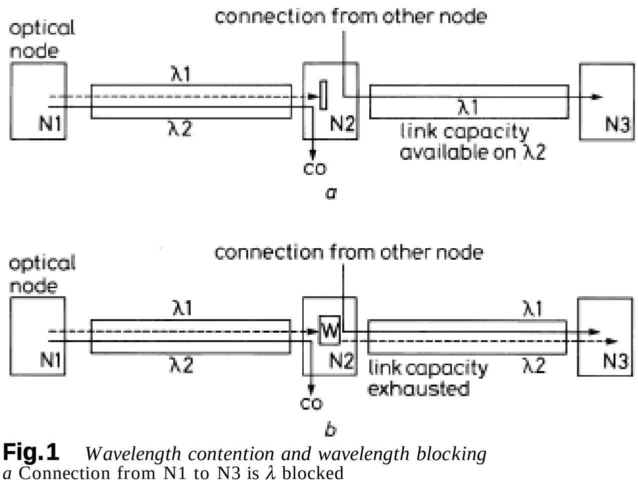

Fig.1 *Wavelength contention and wavelength blocking*
a Connection from N1 to N3 is λ blocked
b Connection from N1 to N3 is wavelength interchanged to avert wavelength blocking

A wavelength converter is a device that could be used to resolve the contention [6], as is shown in Fig. 1*b*. In this case, the network blocking is merely that associated with limited bandwidth on the available

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routes, and we call this routing scheme converter routing (CR). Currently all-optical converters are not a mature technology, but CR nevertheless provides a reference against which to compare the amount of λ blocking in the wavelength routed networks.

In a separate investigation [7], the impact upon network blocking due to wavelength (λ) contention was investigated in highly interconnected regular networks using a routing scheme which selected a path from a small set of predetermined node-diverse routes (reduced route set scheme or RR). It was shown that wavelength blocking significantly degraded performance when such a routing scheme was employed in highly meshed networks. A reduced route set scheme is most suitable for distributed implementation, where the available routes are known in advance and can be stored in look-up tables at the nodes. If the route set size is small compared to the global route set size the storage and signalling requirements will not be over demanding.

In this investigation we examine how the size of the route set made available to the routing scheme affects wavelength blocking. In order to do this we compare the two routing approaches described above when applied to a class of highly connected regular networks known as product networks. Product networks were selected for this study because of their highly connected and regular nature and easy scalability. This highly connected class of switched optical network might find useful deployment in a number of areas where high logical and dynamic connectivity were required, such as within a large exchange or in a core transport infrastructure where logical regular networks could be created from physical irregular networks by embedding the logical network in the fibres of the physical network. Obviously, many other routing schemes have route sets which lie in between those allowed by the two schemes examined here, but sensitivity analysis of the size of the route set was beyond the scope of this study.

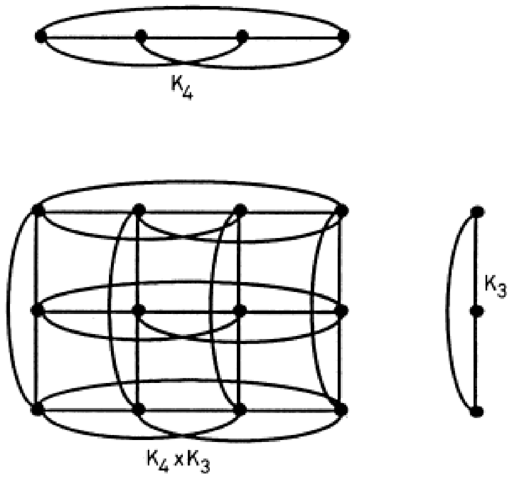

Fig. 2 *Product network topologies*

The topology of the product network is defined by the Cartesian product of complete graphs [8]. Complete graphs can be said to be fully connected i.e. there is one link between each node pair. In Fig. 2 two complete graphs, K_3 and K_4, are combined to produce the product network K_4K_3. This class of network can be said to have optimal connectivity. An optimally connected graph is one that exhibits the greatest connectivity possible with a given number of vertices and edges and in network terms this translates to nodes and links. It is easy to scale the product network by increasing the indices of the complete graphs (e.g. K_4K_4, K_4K_5, K_5K_5 etc.). Load balancing across all network links is achieved when uniform traffic statistics are applied.

It is desirable to have a routing strategy that enables a path to be selected using a simple and efficient control algorithm which can be implemented in a distributed fashion. As the network size and complexity increases, centralised control becomes less attractive, tending to increase response times to network events, reduce overall resilience and produce a proliferation of top-level network management systems [9]. When using a distributed control approach the rules and algorithms would be embedded into the network elements (switches/cross connects) so that control and management processes are achieved by exchanging local information in response to network requests and events.

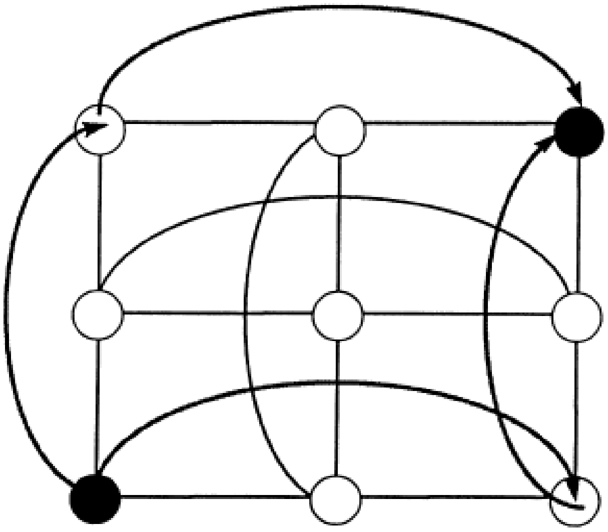

Fig. 3 *Low traffic routing using GR*

2 Routing and modelling details

2.1 Global route set scheme (GR)

A routing algorithm was used that can examine the entire route-wavelength problem space, if necessary, in response to a path request. It then selects the shortest path found, if such a path exists. Under low traffic conditions two such paths of length two spans are shown for a node pair in Fig. 3, the path chosen being the one with the lowest loading. The algorithm uses Dijkstra's shortest route algorithm [10], with modifications to accommodate the λ-continuity constraint, and exhibits polynomial worst case run time. If the available wavelengths in the group on a fibre are numbered λ_1 (lower) to λ_n (upper), then one plausible approach to wavelength routing is to preferentially allocate paths on lower wavelengths. Selecting lower λ maintains the availability of more upper λ channels globally across the network than would occur by arbitrary wavelength-route allocation. This then increases the probability of establishing a future request on a continuous λ path and simulation has validated this to be the case. This may produce circuitous routing, particularly under heavy traffic conditions, such as the routing shown in Fig. 4 where the dashed spans are fully loaded therefore blocking and the algorithm is forced to use a path of length six spans.

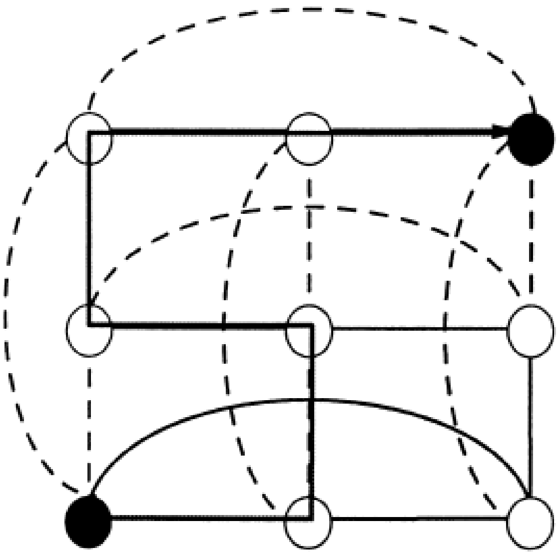

Fig.4 *High traffic circuitous routing using GR*

A link-channel is defined as one of the λ channels which are carried on the fibre transmission link. Shortest path in this scheme is equivalent to minimum cost on a route, and the cost for a path is defined as the sum of the individual link-channel costs. For GR, link-channel costs were set to be unity so that the least cost path will be also the shortest path.

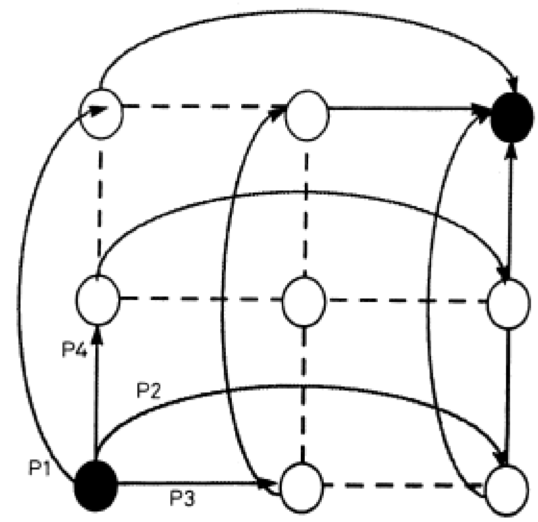

Fig.5 *Set of paths available to RR*

2.2 Reduced route set scheme (RR)

In the second algorithm the routes which could be selected for a path request were restricted to the optimal set of disjoint routes existing between the connecting node pair using an algorithm described by Torrieri [11]. For most nontrivial networks the set of available routes for establishing a request is significantly reduced from the set available under GR and for one node pair is shown in Fig. 5, the paths $P_1 \rightarrow P_4$ being the only ones available for routing for the case shown. Using RR, each node would store this set of disjoint routes and would determine which path to use by selecting the most suitable at the time of the request. This deterministic route set ensures that the number of routes tested for a path request is never more than the inherent connectivity of the end nodes.

The link channel costs were set on a dynamic basis. A link with no occupied channels has unit cost and thereafter the cost increases for each channel in use by $1/n$, where n is the number of λ in the group. This costing scheme favours lightly loaded routes and attempts to distribute the traffic load throughout the network and was found to perform well compared to a scheme which randomly selected routes from the disjoint route set.

Each edge joining two vertices on the graphs of Fig. 2 is considered to be undirectional, with one fibre link travelling in each direction. The ability to space switch all wavelength channels on incoming ports to wavelength channels on all outgoing ports at a node is assumed. The traffic was modelled using Poisson arrival statistics and exponential path holding times. Simulation runs were performed using 100 offered duplex path requests per node pair and using a confidence interval of 95%. The mean offered traffic per node pair was taken to be uniform for all node pairs across the network and the λ group size was set to be 15. A limit on path-request blocking of 0.01 was set. Above this level performance was deemed to be unacceptable and the network to be in a congested state.

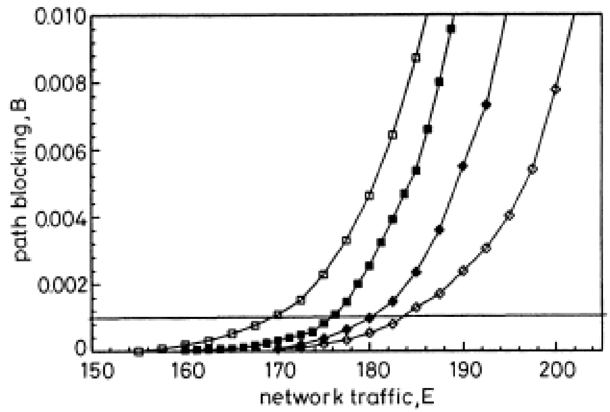

Fig.6 *K_4K_3 mean network performance*
—◇— RPath CR
—□— RPath WR
—◆— GPath CR
—■— GPath WR
B = 0.001

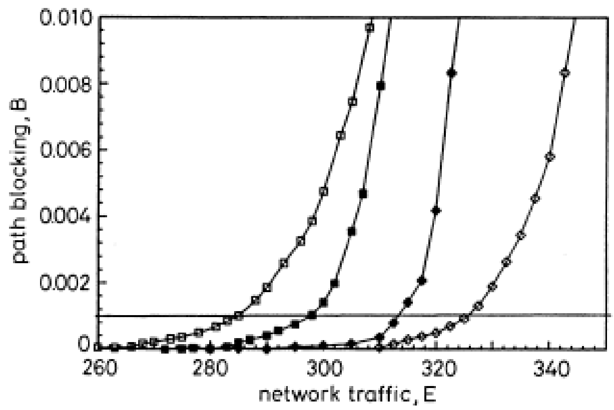

Fig.7 *K_4K_4 mean network performance*
—◇— RPath CR
—□— RPath WR
—◆— GPath CR
—■— GPath WR
B = 0.001

3 Results and discussion

In the two graphs shown in Figs. 6 and 7, the ordinate indicates the total network traffic (the sum of all the node to node offered traffic), measured in Erlangs, and the abscissa gives the probability of path request blocking (B). Figs. 6 and 7 show the set of traffic performance curves for a K_4K_3 and a K_4K_4 network, respectively. When converter routing is allowed the RR algorithm responds better to overload, as it does not permit the allocation of circuitous routes. With CR, it is much easier for such circuitous routes to be allocated than with WR; to gain an insight into the mechanism involved, consider the following analytical idealisation.

Consider a network with λ wavelengths on each fibre; this is set to 15, which is the same number as are used in the simulations. The simplifying assumption will be made that there is a probability, p, that a given wavelength on a given fibre has already been allocated to a path, and the probability of a given wavelength being occupied on a given link is independent of all other wavelength-link pairs. This probability is arbitrarily set to 0.8 for the purposes of illustration i.e. 80% of the wavelength-link pairs are occupied. Due to the assumptions made, any results will be approximations, however this is quite appropriate here since a qualitative insight into the problem is required, not an exact solution. In a path of length N with wavelength routing, the probability of blocking along any one wavelength is $1 - (1 - p)^N$; this is because the probability that a given link will be free on the desired wavelength is $1 - p$ — raising it to the power N gives the probability that all links on the path are free. To obtain the probability that all wavelengths are blocked, raise this expression to the power of the number of wavelengths:

$$P_{WR} = \left[1 - (1-p)^N\right]^\lambda$$

For converter routing, the expression p^λ gives the probability that all the wavelengths on a given link are blocked; subtract from 1 and raise to the power N to obtain the probability that all links have at least one wavelength free, giving a blocking probability of:

$$P_{IR} = 1 - (1 - p^\lambda)^N$$

The expressions for P_{WR} and P_{IR} are plotted in Fig. 8; it is quite clear that for WR, the blocking probability is greater than for CR, particularly as N becomes larger; the WR blocking probability rises very rapidly with N, until it is very nearly equal to 1 for path lengths as short as 5. CR, on the other hand, has a much lower blocking probability. This is because with WR, all the links have to be unoccupied on the same wavelength, but with CR it is sufficient for each link to have at least one wavelength unoccupied.

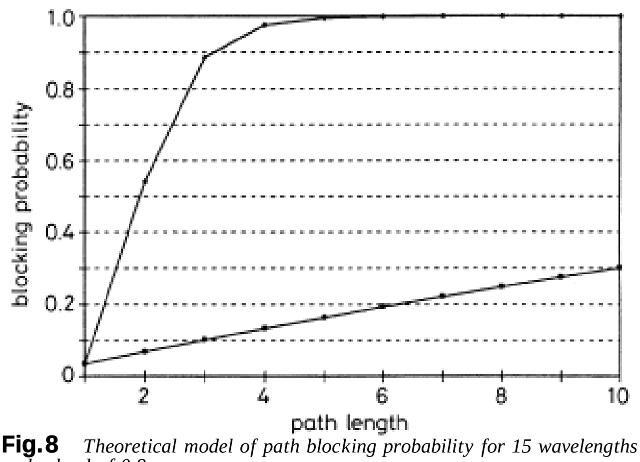

Fig. 8 *Theoretical model of path blocking probability for 15 wavelengths and a load of 0.8*
—□— WR
—◇— CR

Hence, with CR, GR can make highly nonoptimal routing decisions due to the relatively low blocking probabilities for long paths. RR cannot do so as it is constrained to use the set of optimal disjoint routes for path establishment. Clearly, such circuitous paths result in a waste of network resources, since several noncircuitous paths could use the same resources as one circuitous path. There is also a noted traffic-carrying differential at fixed blocking probability between the CR and WR schemes for RR, due to the mechanism described above. This differential is greatest in the larger network, where at $B = 0.001$ there is a 14% reduction in throughput for K_4K_4 when using WR. This penalty is reduced to 8% for K_4K_3. The CR and WR performance curves for GR show an almost negligible differential ($\leq$ 3% at $B = 0.001$ in both networks) and the GR WR scheme outperforms the RR WR scheme. The reason that RR shows greater λ blocking than GR when using wavelength routing is because the route space in searching for a continuous λ path is reduced; GR has the complete set of routes to explore but RR can only examine a subset. This may result in more acute λ contention at low congestion states where usually a path will exist somewhere in the network, though not necessarily on the disjoint route set which form a small subset of the total allowable routes. The seizing of a path by the GR algorithm, even if the path is nonoptimal in terms of resource usage, will not affect other traffic streams adversely at low congestion levels.

With WR and GR, owing to the analytical argument given above, long circuitous paths are unlikely to be routed when the network is near full loading. Hence, the paths routed are likely to be shorter paths which need not necessarily be those generated by RR, i.e. a greater selection of short paths is available, resulting in superior performance through avoiding the problems mentioned above concerning CR and GR.

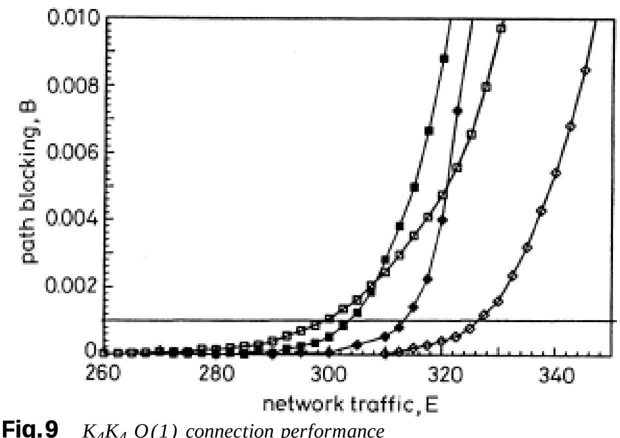

Fig. 9 *K_4K_4 O(1) connection performance*
—◇— GP CR O(1)
—□— GP WR O(1)
—◆— RP CR O(1)
—■— RP WR O(1)
B = 0.001

Finally, it is of interest to break down the mean network blocking probabilities into blocking probabilities for the different classes of path request. In the two product networks examined there are only two classes of request, those of shortest distance one hop and those of shortest distance two hops, labelled O(1) and O(2). Figs. 9 and 10 show the relative blocking probabilities for O(1) and O(2) using both RR and GR in the K_4K_4 network. It can be seen that in both cases, when using the WR scheme, the blocking experienced by the longer path requests increases rapidly compared to that experienced by the shorter path requests. This corroborates the simplified analytical model given above since the difference in blocking probability when comparing WR with CR increases as the paths become longer. O(1) and O(2) path requests using both the RR and GR schemes suffer almost identical blocking within the traffic range $B < 0.001$ using CR, but the O(2) path requests experience much greater blocking than O(1) when wavelength routing is used.

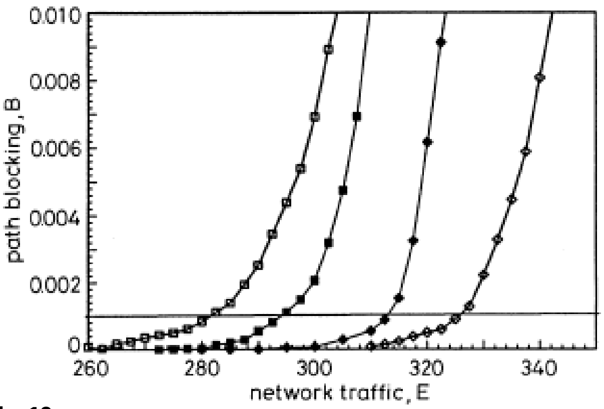

Fig. 10 *K_4K_4 O(2) connection performance*
—◇— GP CR O(2)
—□— GP WR O(2)
—◆— RP CR O(2)
—■— RP WR O(2)
B = 0.001

For WR, the blocking performance of the shorter path requests is improved at the expense of the blocking performance of the longer path requests. Thus, if CR can be used, some of the imbalance between the blocking performance of O(1) and O(2) can be alleviated.

4 Conclusions

It is important to identify fast and efficient path routing algorithms that can be applied using distributed control to wavelength-routed optical networks. A global path set and a reduced path set routing scheme have been presented for application to dynamic highly connected wavelength-routed transport networks. The reduced path scheme outperforms the global path scheme when wavelength converters are available, but exhibits greater wavelength blocking behaviour when wavelength routing is used. The magnitude of this wavelength blocking would seem to increase with network size and results in a significant reduction in carried traffic at fixed network blocking. Furthermore, the use of wavelength converters eradicates some of the inequalities in blocking performance experienced by different classes of path request.

5 Acknowledgment

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