Distributed discovery of wavelength paths in multi-service WDM networks

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Abstract: This work proposes a distributed method for wavelength channel provisioning in multi-service WDM networks, where subject to constraints on wavelength routing such as transmission quality or resource availability, the best of the multiple feasible paths can be found. The numerical examples and simulation study of multi-service wavelength-routed networks under dynamic traffic conditions have shown the applicability of our methods for the optical network services yet to emerge.

1. INTRODUCTION

The on-demand provision of wavelength circuits in a service-specific fashion is becoming increasingly important due to the ever-growing deployment of IP networks and the requirements for quality-of-service(QoS)-delivery within transport layers. The wavelength-routed transport networks are nowadays characterised by an excessive architectural and operational diversity, in particular with regard to technology of optical components, internal architecture of optical nodes and control protocols. In a networking scenario, where internetworking with a variety of candidate client networks (e.g. SDH, IP, ATM) is an assumption, while dealing with heterogeneous

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architectures and optical technologies, efficient and technology-independent algorithms and protocols for dynamic and service-differentiated wavelength circuit provisioning will play a key role [1].

Due to the several intrinsic properties related to the wavelength-routed connections, the maintenance of the network state information is becoming an important issue. The additive nature of signal degradations, which limits the cascadeability of optical components, as well as the type-of-user-dependent accommodation of wavelength connections (e.g. SDH-suited optical cross-connects), are some of the reasons that make the global (centralised) routing essentially impractical, particularly for open network structures handling various services in a heterogeneous environment. In addition, there is a growing necessity to leverage and co-ordinate the wavelength routing control with IP/MPLS distributed routing control. For that purpose, the distributed *path-selection* computation among intermediate nodes between source and destination arises as a solution for a scalable and accurate wavelength channel provisioning.

In this paper, we propose a generic approach to distributed connection set-up in QoS-routed WDM networks applicable to services yet to emerge in regular network operation as well as for wavelength-routed restoration. The proposed method relies on service-specific characterisation of optical network elements, such that the network state information, related to transmission quality, reliability, manageability and traffic conditions, is autonomously maintained. We use the term network element (NE) in a broader sense: it stands for any physical resource or *autonomously manageable* group of resources along optical paths (e.g. fibres, amplifiers, filters, switches, transceiver, regenerators, links, nodes, etc.) that might affect the wavelength channel performance associated with a certain optical network service. With our method, a choice between a number of selected feasible paths is made based on service-dependant transmission quality requirements and network constraints. This method can also yield the solution to the constraint-based routing problem, i.e. provision of service-specific guarantees under quality constraints, as it is necessary for the MPLS control plane, a feature that is still missing from the existing architectures.

2. NETWORK MODEL

We model the WDM network $\boldsymbol{G}(N,L,\Lambda,\boldsymbol{S})$ with the number of nodes N, number of WDM links L, a pool of possible wavelengths $\Lambda=\{\lambda_1,\lambda_2,\ldots,\lambda_F\}$, and a set of supported optical network services $\boldsymbol{S}=\{S_1,S_2,\ldots S_P\}$. We keep to the definition of optical network service S_i to be the handling of optical signals carrying data originating from optical network clients, such as SDH or IP, where *optical* QoS is guaranteed by appropriate allocation of particular wavelengths on concatenated physical resources, i.e. from transmitters via fibres and nodes to receivers, by which service-specific (optical) requirements on transmission quality, survivability and management functions are taken into account.

We consider the total number of network elements H, where

$$H: = \sum^{N,L} \sum^{T} h_k \text{ , k=1,2...T,}$$

h_k referring to a network element (NE) of type k within a node N or link L from $\boldsymbol{G}$. Since T different network elements per node or per link are considered at maximum, H is upper-bounded by $(LT+NT)$. For simplicity, a network element associated with a node or link from $\boldsymbol{G}$ is denoted as $h_k^{N,L}$, k=1,2,...T, for example $h_1^{N_1}$ being transmitter (Tx) at N_1, $h_1^{N_2}$ being Tx at N_2, $h_2^{N_2}$ being receiver (Rx) at N_2, $h_5^{L_2}$ being fibre amplifier at L_2, etc. Upon a request for a wavelength-routed connection, for a certain service type all NEs (up to H totally) relevant to that service might be considered.

For the purposes of our distributed path discovery and selection, each NE is characterised by the so-called *Service-specific Wavelength Set*, Λ_{SWS}, defined as the following [1]:

> *For each network element* $h_k^{N,L}$*, k=1,2,..T, relevant to the performance of a service* $S_r \in \boldsymbol{S}$*, r=1,2,..P, we define a Service-specific Wavelength Set (SWS),* $\Lambda_{SWS}[S_r,\ h_k^{N,L}] \subseteq \Lambda$*, such that by allocating a wavelength* $\lambda_m \in \Lambda_{SWS}[S_r,\ h_k^{N,L}]$ *on that network element, the requested optical network service is provided with sufficient transmission quality and all necessary management and surveillance functions.*

In other words, for path searching and wavelength allocation, only the wavelengths from Λ_{SWS} on a certain NE are considered. For example, if for a certain optical network service, e.g. S_1, the Λ_{SWS} for the transmitting laser is defined as $\Lambda_{SWS}[S_1,\text{Tx}]=\{\lambda_6, \lambda_7\}$, for S_1 accommodation with quality guarantees, only these two wavelengths can be allocated, even when the tuneable transmitter range includes more wavelengths, e.g. $\{\lambda_1, \lambda_2, \ldots\lambda_8\}$, which might be suitable for other service types.

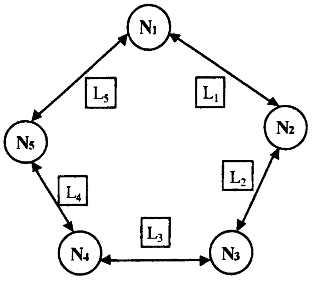
The actual task of dynamic wavelength channel provisioning is to find a path from source to destination node using the minimum amount of network resources under the constraints on various metrics for wavelength routes such as SNR, dispersion, jitter, crosstalk, link load, availability or restorability. Hence, an accurate network state information $\boldsymbol{a}[h_k^{N,L}, S_i, \lambda_i]$ has to contain those parameters related to concatenated NEs along the routed path, which will make it possible to consider the service-specific requirements, defined as a vector of **quality bounds**, such as

$D(S_i)$ = [*max. allowed transmission quality degradation (d);*
max. acceptable (monetary) cost (c);
min. sufficient availability / reliability (r);
min. sufficient manageability/signalling (m)].

The various parameters of the network state information ***a***, may be additive, multiplicative or restrictive in nature [2]. Thus transmission degradation and monetary costs can be summed along the path, reliability for concatenated components is the product of each single reliability, while restrictive attributes such as residual link capacity may excluded channels from the path discovery and selection.

3. AN EXAMPLE WDM NETWORK

For illustration, let us consider an example WDM network in a bi-directional ring configuration with five nodes and two wavelengths per link, capable of accommodating two service classes, S_1 and S_2 (Fig. 1). Assume that S_1 is required between N_1 and N_3, for which the max. transmission quality degradation (e.g. degradation of SNR) should not exceed 30 dB, i.e. $d_{max}(S_1)=30$. For this service type, we consider the following manageable, S_1-specific NEs: $Tx(N_1)$, Rx (N_3), and network nodes and links, with their associated service-specific wavelength sets and quality properties. The network state information is expressed as a parameter-vector $[d,r]$, corresponding to transmission quality degradation and reliability. Here, rather than considering two additive quality metrics (e.g. transmission degradation and cost), as the second attribute, the reliability is considered, calculated as the product of reliabilities of the concatenated NEs along the path [3]. The restrictive attributes are automatically taken into account by the definition of Λ_{SWS}: the wavelengths outside Λ_{SWS} are simply excluded from the path discovery (e.g. for service S_1 the wavelength λ_1 cannot be used along the links L_3, L_4, L_5). The quality attributes related to switches, filters, fibres, amplifiers, etc. are accumulated to a single "link" set, described by a common attribute, e.g. $[d(L_1), r(L_1)]$.



(a)

S_1-specific NE		d[dB]	r×100 [%]
Tx @N_1	λ_1	4	0.95
	λ_2	6	0.99
Rx @N_3	λ_1	5	0.97
	λ_2	7	0.97
L_1, L_2	λ_1	6	0.98
	λ_2	9	0.98
L_3, L_4, L_5	λ_1	$\notin \Lambda_{SWS}$: not avail. for S_1	
	λ_2	5	0.99

(b)

Fig. 1: Example WDM network: (a) physical topology, (b) S_1-specific network state representation.

In this example, the best path in terms of transmission quality appears to be Tx-N_1-L_1-N_2-L_2-N_3-Rx at λ_1, with overall transmission degradation Σd= 4+6+6+5=21 (<30). However, if the request on reliability for this service were $r(S_1)>0.90$ (90%), this path would show unsatisfactory performance: $\prod r$=0.95×0.98×0.98×0.97=0.885, due to the "Tx(λ_1)-bottleneck". On the other hand, by allocating λ_2 over the same route, an unacceptable degradation, i.e. Σd=31, is obtained. Alternative path, e.g. Tx-N_1-L_5-N_5-L_4-N_4-L_3-N_3-Rx at λ_2, however, would satisfy both bounds (d and r), i.e. Σd=28 (<30) and $\prod r$=0.932 (>0.90). Hence, optimising one single metric is necessary, but not sufficient to find a feasible path. Note that the NE quality attributes and the routing decision completely change, if a service of type S_2 has to be set-up.

4. DISTRIBUTED PATH DISCOVERY METHOD

To overcome the fundamental problems of multiple constrained path discovery, which are NP hard, we propose the following distributed method [2,4]. For simplicity, we will limit our consideration to three types of quality attributes: additive d (e.g. SNR, jitter, delay), multiplicative r (e.g. reliability), concave b (minimal value, e.g. residual capacity in wavelengths, inserted crosstalk minimisation), but any other attributes can be similarly treated.

Distributed discovery of wavelength paths (DWP)

Step 1:

*Get a connection request between (*src, dest*) for a service* S_r, *with particular QoS requirements [here: max. allowed transmission degradation* $d_{max}(S_r)$, *min. reliability* $r_{min}(S_r)$, *min. residual capacity* $b_{min}(S_r)$*].*
Forward this request and the message containing the initial values (e.g. [d, r, b]) from src *to all neighbouring NEs for every* $\lambda \in \Lambda_{SWS}[S_r, NE_{src}]$.

Step 2:

The neighbouring NEs forward the received requests and messages with actualised values of [d, r, b] to all their neighbours which have not been previously visited, until dest *is reached.*

The messages are actualised according to the following rule:
For all $\lambda \in \Lambda_{SWS}[S_r, \text{previous } NE]$, *if* $\lambda \in \Lambda_{SWS}[S_r, NE_i]$, *i=NE-counter (e.g.* NE_i *is the* i^{th} *NE in the path), update the values of [d, r, b], so that d is summed along the precedent NEs, r is multiplied, while b of the considered path is the minimal value:*

$$\begin{aligned} d(p) &= (\text{previous } d(p)) + d(NE_i), \\ r(p) &= (\text{previous } r(p)) * r(NE_i), \\ b(p) &= \min\{ (\text{previous } b(p)), b(NE_i) \}. \end{aligned}$$

The wavelength paths and channels with insufficient quality in terms of [d(p), r(p), b(p)] are sorted out and not forwarded. Finally the NE-id (k) and wavelength (λ) is added to the surviving path-sequences.
At the destination node dest *we finally obtain:*

$$\begin{aligned} d(p) &= \Sigma d(NE \in (path)) = \\ &= \{..\{..\{\{d(srcNE)+d(1stNE)\}+d(2ndNE)\}+..+d(NE_i)\}+..+d(destNE)\}, \\ r(p) &= \Pi r(NE \in (path)) = \\ &= \{..\{..\{\{r(srcNE) \times r(1stNE)\} \times r(2ndNE)\} \times .. \times r(NE_i)\} \times .. \times r(destNE)\}, \\ b(p) &= min\{b(NE \in (path)) \} = \\ &= \min\{. \min\{.. \min\{\min\{b(srcNE), b(1stNE)\}, b(2ndNE)\}.., b(NE_i)\}.., b(destNE)\}, \\ path &= [(k_{src}, \lambda), (k_1, \lambda), (k_2, \lambda), .., (k_i, \lambda), .., (k_{dest}, \lambda)], \end{aligned}$$

for each feasible path at every $\lambda \in \bigcap\{\Lambda_{SWS}[S_r, NE \in (path)]\}$.

Step 3:

From the obtained set of all feasible wavelength-paths $\mathcal{P}$ *for which* $r(\mathcal{P}) > r_{min}(S_r)$, $d(\mathcal{P}) < d_{max}(S_r)$, *and* $b(\mathcal{P}) > b_{min}(S_r)$, *i.e. each path from* $\mathcal{P}$ *satisfies the given requirements, the destination node* dest *can select the best path according to one or more criteria as follows: minimum hop, min. cost, minimum signal degradation, minimum number of traversed NEs of particular type, etc.* [*Obviously, a number of different strategies exists and might be chosen according to network properties, traffic conditions or types of services.*]

Step 4:

From dest, *send the acknowledgement message back along the selected path to* src, *for the purpose of resource reservation. At the time the acknowledgement message reaches the source node, the wavelength circuit is set up and ready for the optical network service provision.*

The distributed strategy proposed above refers to route and wavelength allocation, if applied to the whole network, while it returns wavelengths only, if applied on a statically routed, predefined path (e.g. N_1-L_1-N_2-L_2-N_3), where only those NEs are visited which belong to that path. As shown in the example from Fig. 1, routing over a single predefined path might lead to a poor blocking performance. On the other hand, by applying the method DWP to the whole network, the signalling effort can significantly increase, especially in wavelength-converting and densely connected networks.

To overcome these problems, one method might be to pre-route a set of candidate paths and apply DWP on this set. In order to define which paths are candidate paths, a single wavelength independent parameter, e.g. number of hops, can be chosen to break a tie. Refer to the example network shown in Fig. 1 once more. If for defining the candidate paths, the number of hops was limited to three, i.e. $n \leq 3$, we could find two candidate routes for a connection request between N_1 and N_3. At the same time, for a connection request N_1 and N_2, only a singe candidate path can be found (i.e. the connecting link).

Note that for a simple ring-topology, the reduction of the computational complexity is not as significant as for a mesh topology. For example, in a full-mesh topology with five nodes, a limitation in number of hops to two, e.g. $n \leq 2$, reduces the number of possible routes from 16 to 4, while the number of necessary updates for message-parameters (Step 2, DWP) is reduced from 49 to 7 per wavelength.

Finally, a possible implementation strategy might be to send *wavelength probes*, which run DWP at all idle wavelength channels independently, or to send *wavelength probes* within one separate service channel, updating the message-parameters for every surviving wavelength at each traversed node.

5. PERFORMANCE STUDY AND NUMERICAL RESULTS

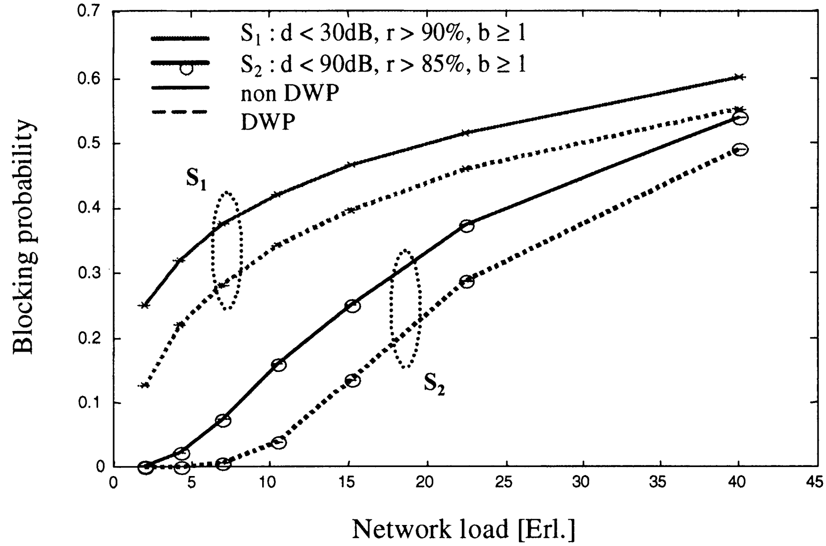
For the simulation results, the connection requests arrive according to Poisson process with call holding time being negative exponentially distributed. Traffic distribution and service requests are uniform; all results are obtained with a confidence level of 95%. For simplicity, we assume the network elements with service independent properties along the network, which is not necessarily a realistic assumption. We also assume reliability to be constant over time, which is also not generally the case; availability might be a better measure, but this is out of the scope of this paper [3]. For distributed (multi-path) routing strategies, we adapted the Bellman-Ford shortest path algorithm for routing and connectivity information update at each node, for all loop-free paths [2]. In order to show the applicability of our method, we study three different network topologies: bi-directional ring, full-mesh and mesh-torus. The proposed algorithm (DWP) is compared with such a centralised one, where a single path is found according to a certain criteria (here: least load links) for which then, other quality attributes are checked (transmission degradation, reliability, residual capacity). Least load routing is used to overcome the problem of blocking due to the overloaded links and it provides an easy combination of resource and load optimisation.

In the first example, we study the bi-directional ring topology, the same one as shown in Fig. 1a. In order to demonstrate the handling of non-uniform NE-properties in multi-constrained routing four wavelengths are assumed, with which the wavelength-dependent properties related to the network elements are shown in Fig. 2a. The service-specific requirements on quality are as follows: $S_1[d<30\text{dB}, r>90\%, b\geq1]$ and $S_2[d<90\text{dB}, r>85\%, b\geq1]$.

As it can be seen from Fig. 2b, the distributed, multi-path strategy yields superior results for both services. This is because the distributed method yields several feasible paths, out of which the best can be selected (here: min. number of hops), in contrast to the non-DWP methods where a single path, optimised for one quality attribute (here: least load), is checked on remaining requirements (transmission degradation, reliability, residual capacity). While for service S_1 the results are as expected due to the fact that for some calls the shortest path found for a single constraint was not feasible with respect to other constraints, the results shown for service S_2 also improved. In Fig. 2b, it can be seen that in a lightly loaded network the multiple paths yielded by DWP reduce the blocking also for S_2, where all shortest paths (due to a single routing criteria) are feasible without constraints.

NE definitions		d[dB]	$r\times100$ [%]
Tx	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	4, 4.66, 5.33, 6	0.95, 0.963, 0.977, 0.9
Rx	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	5, 5.67, 6.33, 7	0.97
L_1, L_2	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	6, 7, 8, 9	0.98
L_3, L_4, L_5	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	35, 25, 15, 5	0.99

(a)



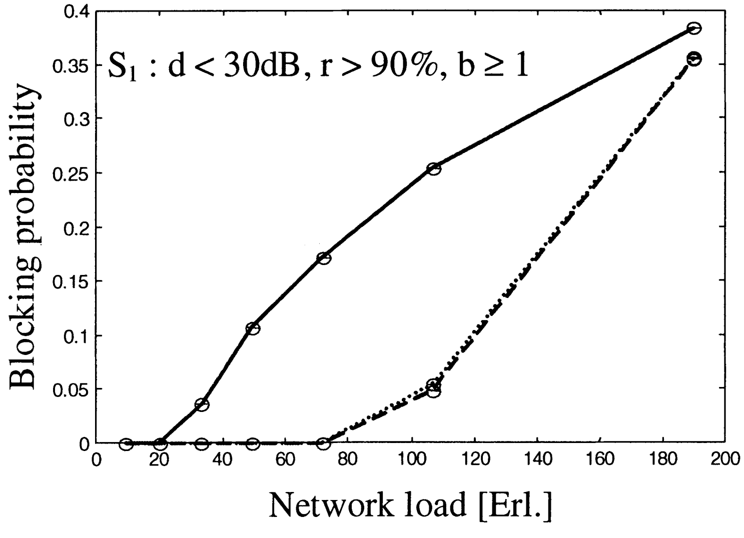
(b)

Fig. 2: Five nodes bi-directional ring: (a) NE-properties, (b) blocking probability per service.

We next study a five-node full-mesh network with the scope of proving the reduction of computational running time with the reduced set of the scanned, pre-routed paths, as previously discussed. To define a hop limit that automatically adapts to different calls and network loads, we use a limit relative to the number of hops of the shortest path found, according to a single constraint. For example, if the relative limit is defined as +1 hop, and if the shortest path according to a certain constraint is 2 hops, we consider only the paths up to 3 hops. The path length limitation as used here reduces the computation time, as shown in Section 4. Generally, the relative limit in the path length of the paths to consider can be set lower for a network with higher connectivity. Since we are using least load routing, we also use the accumulated load to limit the number of considered paths. An additional relative limit is set to +25% to the network load found by the 'shortest' path. (i.e. if the path with minimum accumulated load, the 'shortest' path , yields a total load in number of occupied wavelengths of 0.6, we pre-route paths only up to a maximum total load 0.75). Therefore the cost variable of the Bellman-Ford algorithm is set to link loads. Number of hops is an intrinsic variable of the algorithm and therefore always accessible [2].

For simplicity, we assumed only nodes and links as network elements, all with same properties per wavelength along the network (links[*d*=1dB, *r*=99%], nodes [*d*=3dB, *r*=99%]). Transmitters and receivers are modelled as ideal [*d*=0dB, *r*=100%]. The network uses 8 wavelengths for all NE's, which generally increases the traffic accommodation complexity, as all wavelengths are equal in terms of constraints. Due to this assumption and due to a higher connectivity, compared to 5-node ring network from the previous example, the network is simulated with higher loads. As in all examples, we assume reliability to be constant over time, and compare the proposed algorithm (DWP) with the centralised one. Here, two versions of DWP are used, one scans only a reduced set of paths, while the other considers all paths. The reduced set of paths is limited relative to the least loaded path (here: +1 hop, +25% of the accumulated link load). Since this exercise aims at measuring the simulation running time, only one single service is considered. The S_1-specific service constraints are as follows: [d<30dB, r>90%, b≥1].

Also here, the distributed, multi-path strategies yield superior results up to the limit where the load is too high and no idle (longer) paths can be found. Already below this limit the reduction in the number of scanned paths (relative as defined), compared to DWP presented directly to the network, where all paths are scanned, does not contribute to the increased blocking probability. As the longer paths in number of hops are more likely to be occupied, there are only a few feasible paths which are not included in the reduced set. However, the reduction in computation time is significant. In fact, the computational effort decreases for higher network loads, as many probes are rejected in course of the DWP process. Due to this effect, and, more important, due to the reduction of scanned paths, with the reduced set of pre-routed paths, a faster solution for the multi-constrained routing can be achieved (Fig. 3b).



(a)

Single path (solid)	268 time units =100%
Reduced set (dashed)	672 time units =2.5x
All paths (small dashes)	2281 time units =8.5x

(b)

Fig. 3: Five-nodes full-mesh network: (a) blocking probability, (b) computation effort measured via total simulation time.

Finally, we study a mesh-torus network, a topology widely accepted for simulation and analytical results related to wavelength-routed networks. We study a mesh-torus network of size 5x5, with 8 wavelengths per link [5]. The properties related to the network elements are taken from the previous example (links[d=1dB, r=99%], nodes [d=3dB, r=99%], transmitters and receivers ideal). Here two different service classes: S_1 and S_2 are studied again, S_1 being the same as in the previous examples [d<30dB, r>90%, $b \geq 1$], i.e. requiring higher transmission quality and higher reliability than S_2 [d<60dB, r>75%, $b \geq 1$]. According to the previous example, the method DWP is applied to the reduced set of paths (here +1hop, +25% of accumulated load) and is again compared to the centralised method. Fig. 4 shows the comparison. For both services, the distributed, multi-path strategy again yields superior results.

6. CONCLUSION

In this paper, we proposed a distributed, QoS-based, methodology for the solution to the problem of wavelength routing tailored to specific clients of the upcoming optical transport networks. The distributed path-selection computation among the intermediate nodes between source and destination is likely to be the straightforward solution for appropriate handling of network state information with multiple resource and QoS attributes. In fact, the contradictory requirement for a scalable but accurate maintenance of the network state information is the main reason which makes the global (centralised) wavelength routing essentially impractical, particularly for multi-service networks with quality constraints.

While being strongly dependent on a particular service definition and networking scenario, the numerical examples show important directions for further study: (i) technological feasibility of service-specific characterisation of optical network elements, a necessary feature for co-ordination between higher-layer network elements (e.g. IP routers or data NEs) and optical NEs, and (ii) applicability of distributed protocols for QoS-delivery, resource management and restoration within the optical control layer.

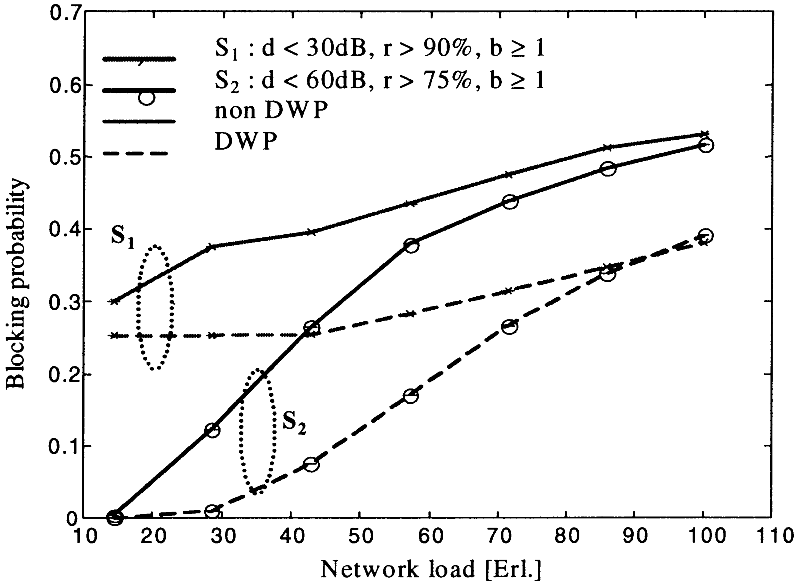


Fig. 4: 5x5 mesh-torus network: blocking statistic probability per service.

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