Linear Program Formulation for Routing Problem in OBS Networks

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Abstract

In this paper we present a linear programming formulation for the routing problem in optical burst switching networks (OBS). Unlike in conventional wavelength routed networks, in an OBS network (light)paths are allowed to clash. One should, however, try to minimize the number of clashes as each of them can potentially cause a burst occassionally to be blocked. Thus, by choosing the paths and wavelength channels carefully one can decrease the blocking probability and also improve fairness among the different connections. In this paper we propose an OBS-aware routing policy, which is shown to improve the overall performance in terms of blocking probability and fairness.

1. Introduction

Optical burst switching (OBS) is seen as an intermediate step from wavelength routed (WR) WDM networks towards optical packet switching. In an OBS network the data are transmitted in bursts consisting of several packets going to the same destination. Before sending the actual burst a header packet is first sent along the same path. The header packet reserves the resources and acknowledges the corresponding nodes about the coming burst. Meanwhile, the source node begins to send the actual burst after a certain offset time without waiting for any acknowledgement message. In case there is congestion on some link a NAK packet is sent back to the source node and the burst is dropped at the point it meets the NAK packet.

The optical burst switching scheme was originally proposed by Qiao and Yoo in [1] and has since then been studied actively, see e.g. [2, 3, 4, 5] among others. The basic idea behind OBS is to share the available network resources efficiently without introducing complex capacity reservation schemes. In order to do this one accepts a possibility of bursts being blocked occasionally and relies on higher protocol layers to take care of the lost data.

Furthermore, the OBS paradigm may create unfairness among the different connections, unless explicitly taken care of. In [1] and [6] Qiao and Yoo have proposed the use of an additional offset time before sending the actual burst for higher priority flows. The same mechanism could be used to balance the blocking probability among different traffic classes, whereas in this paper we try to achieve the fairness by using appropriately chosen routes. The fairness issue is also addressed in [7], where it is reported that fibre delay lines (FDL) have a positive effect on fairness.

1.1. Routing Problem in OBS Networks

The routing and wavelength assignment (RWA) problem has been studied extensively in the context of wavelength routed (WR) optical networks, where so called wavelength clashes are not allowed. This constraint, often referred to as distinct channel assignment (DCA) constraint, simply means that no two connections can share the same wavelength on any common link (fibre). The DCA constraint complicates the RWA problem especially in a case where nodes are not capable of performing wavelength translation. In particular, without wavelength translation the network consists of W identical parallel wavelength layers. For more information on routing problem in WR networks see, e.g., [8, 9, 10].

In WDM networks, WR or OBS, a configuration of a connection (i.e. a lightpath) involves determination of a route and a wavelength channel (rw-pair). The RWA problem in OBS networks combines some features from the RWA problem in WR networks as well as from the traditional (packet) routing problem. In an OBS network several flows can share a same channel by using it at different times. In this paper we refer to the paths the bursts travel as lightpaths, even though they are only temporary reservations. The obvious drawback with the proposed reservation schemes (e.g. JET) is that a burst can get blocked on some link, where two or more flows meet. Thus, such meeting points are critical points with regard to the blocking probability and it seems advantageous to choose routing which minimizes such occasions. If one manages to arrange the routes so that the number of clashing flows decreases on some link, the burstiness of the offered traffic to the link also decreases and eventually the overall blocking probability tends to become smaller as well. Hence, it is advantageous to keep flows on the same route instead of constantly "splitting" and "combining" them in order to avoid burst clashing. Generally we have several design criteria for the routing in OBS networks:

- minimize the blocking probability, i.e. roughly speaking minimize the link loads,
- minimize the average delay in the network.

In an OBS network the total delay consists of:

- Burstification delay, i.e. the time from the arrival of the packet to the time when the burst is sent.
- Initial offset time between the header packet and the actual burst, which depends on the used protocol.
- Queueing delays, which are not typically an issue in OBS network unless FDLs are (extensively) used.
- Propagation delay, which corresponds to minimizing the average route length.

Delay due to the offset time between the header and the burst is likely to be the dominant factor in OBS networks. Thus, instead of minimizing the propagation delay the number of hops is often the quantity to be minimized.

Furthermore, with properly chosen routes the bursts are more likely to be blocked in the early stage of their path rather than later, and, as a consequence, less network resources are wasted on average. For example consider a case where a burst which has travelled a long way (and consumed a lot of resources) gets blocked by a new burst with a destination only a few hops away. Clearly, it would be more advantageous to block the newer burst (and transmit it later). This concept can be expressed in terms of priorities. Namely, it would be advantageous to increase the priority of the burst as it goes further along its path. In an OBS network the offset times can be used to support priority classes [1]. A longer offset time corresponds to a higher priority class. Unfortunately, e.g. with the JET protocol, the offset time decreases instead on each hop due to the processing time of the header. This can be avoided by using a FDL to delay each burst by a time which is longer than the processing time of the header. Still, in order to ensure that no lower priority burst ever blocks a higher priority burst ("hard priorities") one needs to have a difference in header offset times larger than the maximum burst size. Assuming a maximum burst size of 500 μs the respective FDL should be about 100 km long, which clearly is not practical. Thus, in order to prevent bursts from being blocked during the last few hops other means must be sought.

In [11] the authors propose a hybrid switching and routing, where a virtual topology is first established using a set of lightpaths. Optical bursts are then transmitted using the predetermined lightpaths. The use of lightpaths reduces the average number of logical hops leading to smaller offset times on the average. In this paper we propose a slightly different routing scheme for OBS networks, which we refer to as the *OBS-aware* routing policy. The key idea is that we require that each lightpath is "filled" within the first m hops, and do not allow any new connections to join the same lightpath later. That is, lightpaths are allowed to clash only within the m first hops from each connection's point of view. Furthermore, we assume that no wavelength translations are possible, even though similar reasoning should be applicable also for networks having wavelength conversion capable nodes. We can expect the following improvements:

1. As the flows compete on common resources at most m times, fairness is likely to be improved.
2. The overall efficiency is improved as bursts do not get blocked within the last hops, i.e. the later the blocking occurs the more resources have been wasted.
3. The NAK packets will arrive earlier at the source allowing a faster retransmission cycle (if implemented).

Whether these objectives are met or not will be explored by numerical examples, where the proposed OBS-aware strategy is compared to a normal shortest path (SP) routing.

The rest of the paper is organized as follows. In Section 2 we present a mixed integer linear programming formulation for the routing problem in OBS networks. Next, in Section 3 we present some numerical examples which suggest that the overall performance can be improved by a careful choice of routes. Finally, Section 4 contains the conclusions and some comments about the future work.

2. Mathematical Formulation

In this section we present a mixed integer linear programming (MILP) formulation for the RWA problem in OBS networks. The resulting configuration is referred to as the OBS-aware routing. As was mentioned earlier, the idea is to combine burst flows as early as possible and keep them then together as long as possible.

Let $\{p_i\}$ be any set of paths consisting of, e.g. n shortest-paths between each node pair. Our job is to route the given traffic using these predetermined paths on W wavelength channels. To this end we introduce an additional constraint on rw-pairs that "wavelength clashes" are only allowed within the m first hops, $m = 0, 1, 2, \ldots$. If the paths p_i and p_j meet at a link which is at least $m+1$ hops away from the start of either path, then paths p_i and p_j are not allowed to be used at the same wavelength. As result there is a dedicated light tree for bursts which have entered into the tree before the $m+1$th hop (similar to idea proposed in [11], where an OBS network was constructed on top of virtual topology established by a set of lightpaths). This can be expressed as a relation,

$$f_m(i,j) = \begin{cases} 0, & \text{if paths } p_i \text{ and } p_j \text{ are allowed to clash} \\ 1, & \text{if paths } p_i \text{ and } p_j \text{ are not allowed to clash} \end{cases}$$

For a given set of possible paths and a given value of parameter m, the function $f_m(i,j)$ can be easily determined. Note that we have chosen to explicitly prohibit wavelength clashes after the mth hop, but one could as well incorporate this in the form of cost function. Furthermore,

m	corresponds to static RWA problem with/where
0	wavelength clashes are not tolerated,
1	tree topologies, each source node is a root of tree(s),
2	a burst can actually get blocked once sent, and
∞	traditional (OBS) routing problem.

t_{ij}	traffic matrix, $i \to j$
p_k	path k: $p_k(1), \ldots, p_k(n_k)$
$\lambda_k^{(w)}$	flow at path k using wavelength w, $\lambda_k^{(w)} \geq 0$
$b_k^{(w)}$	1 if path k is used at wavelength w, otherwise 0
$\tilde{\lambda}_\ell^{(w)}$	total flow on link ℓ using wavelength w
$\tilde{\lambda}_{\max}$	the maximum load over the links

The used notation is given above and the objective shall be the minimization of the maximum link load, i.e.

$$\min \tilde{\lambda}_{\max}, \tag{1}$$

with the following constraints,

$$\sum_w \sum_{\substack{k:p_k(1)=i,\\ p_k(n_k)=j}} \lambda_k^{(w)} = t_{ij} \quad \forall\, i,j, \tag{2}$$

$$\tilde{\lambda}_\ell^{(w)} = \sum_{k:\ell \in p_k} \lambda_k^{(w)} \quad \forall\, \ell, w, \tag{3}$$

$$\tilde{\lambda}_{\max} \geq \tilde{\lambda}_\ell^{(w)}, \quad \forall\, \ell, w, \tag{4}$$

$$\sum_{i \neq j} \lambda_i^{(w)} \cdot \lambda_j^{(w)} \cdot f_m(i,j) = 0, \quad \forall\, w. \tag{5}$$

Note that the clash constraint (5) is not a linear constraint. Nonetheless, one can replace it by an equivalent linear constraint by introducing a new decision variables, $b_k^{(w)} \in \{0,1\}$, which define whether path k at wavelength w is in use or not. Then constraint (5) can be replaced by

$$t_{\max} \cdot b_k^{(w)} \geq \lambda_k^{(w)}, \quad \forall\, k, w \qquad (t_{\max} = \max_{(i,j)} t_{ij}) \tag{6}$$

$$f_m(i,j)\left(b_i^{(w)} + b_j^{(w)}\right) \leq 1, \quad \forall\, i,j,w. \tag{7}$$

Furthermore, if seen appropriate, it is straightforward to set an upper bound on the number of paths each (s,d) pair can use, or the number of wavelengths each node can use (i.e. the number of (fixed) transmitters). Due to the nature of the OBS scheme the link loads should be reasonably low under normal operation. As a consequence, the queueing delays in the intermediate nodes can be neglected (queueing delay corresponds to the case where a burst is guided to a fibre delay line acting as optical buffer). This justifies the use of link load as the optimization criterion instead of, e.g., the mean waiting time in M/M/1 queue.

3. Numerical Examples

In this section we will present some numerical results. First a regular ring topology with $2n$ nodes and n wavelength channels is studied both analytically and numerically. Then, in the next example a mesh network is considered. For both cases we compare the presented OBS-aware routing to the standard shortest path (SP) routing using the JET protocol.

Each (s,d) pair constitutes a traffic class. From the numerical simulations we estimate the average blocking probability for each traffic class,

$$B^{(sd)} = \text{estimated blocking probability of bursts } s \to d,$$

the average blocking probability over the M traffic classes,

$$B_{\text{flow}} = \frac{1}{M} \sum_{(s,d)} B^{(sd)},$$

and the average burst blocking probability,

$$B_{\text{burst}} = \frac{1}{T} \sum_{(s,d)} t_{sd} \cdot B^{(sd)},$$

where T is the total arrival rate of bursts, $T = \sum_{(s,d)} t_{sd}$. As a fairness measure we use the estimated "variance" of the flow blocking probabilities,

$$\hat{\sigma}^2 = \frac{1}{M-1} \sum_{(s,d)} \left(B^{(sd)} - B_{\text{flow}}\right)^2,$$

where M is the number of traffic classes. Another quantity characterizing fairness is the coefficient of variation,

$$C_v = \sqrt{\hat{\sigma}^2} / B_{\text{flow}}.$$

3.1. Ring Topology

Consider an optical burst switched ring network with

- N=$2K$ core nodes ($K \geq 1$),
- W=K wavelength channels,
- f unidirectional fibre pairs on each link,
- Poissonian traffic with a pair wise intensity of a,
- no optical buffers nor wavelength conversion,

with three RWA configuration schemes:

i) OBS-aware routing with m=1, where each node i uses one fixed wavelength channel, $1 + (i \mod W)$.

ii) The "standard" OBS scheme, i.e. tunable transmitters at each node and a random wavelength selection.

iii) OBS-aware routing with m=2, i.e. it is required that after two optical hops no blocking may occur.

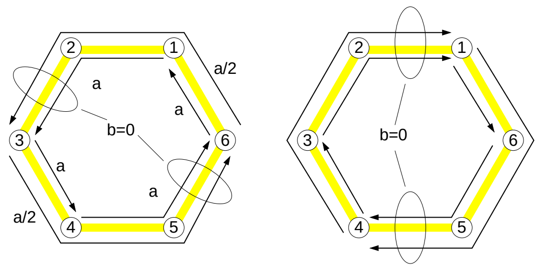

Figure 1. One layer of scheme iii) for N=6 nodes. Note the collision free links where no burst is blocked.

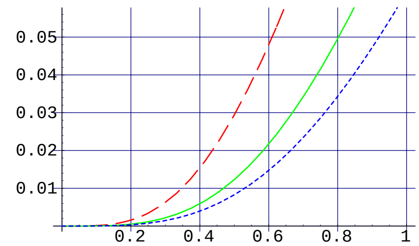

Figure 2. Estimated blocking probabilities for N=6 and W=3 with f=4 fibres. The RWA schemes are i), ii) and iii) (from worst to best).

Furthermore, the nodes are assumed to have enough receivers, i.e. no blocking occurs at the receiver, and the optical bursts are routed using the shortest paths. In schemes i) and ii) in case of two equally long paths the offered traffic is split evenly among them. Fig. 1 illustrates one wavelength layer of the OBS-aware configuration corresponding to scheme iii) with N=6 nodes. The other two layers are simply rotated versions of the one illustrated in Fig. 1. Next we will derive an analytical model to estimate the blocking probability in each case and then present some numerical examples.

3.1.1. Analytical Models

The mean blocking probabilities can be estimated by applying Erlang's blocking formula for the M/G/n/n-systems. Let $B_i(k)$ denote the blocking probability of connections consisting of k optical hops in the ith scheme.

i) Connections from two different source nodes do not interfere with the SP routing and hence the blocking may only occur on the first link when two or more bursts originating from the same source collide. There are $2K-1$ connections originating from each node from which only the longest connection uses both directions. Thus, the total offered load to the first link (in each direction) is $a_1 = (K-\frac{1}{2})a$, and consequently,

$$B_1 = \text{Erl}(f, (N-1)\frac{a}{2}).$$

Note that with the JET protocol longer connections have initially a higher offset time and a higher priority on the first hop, i.e. $B_1(1) > B_1(2) > B_1(3)$.

ii) (reduced load approximation) Consider first an arbitrary wavelength channel λ on link $\ell = 1 \rightarrow 2$. The offered traffic from node 1 to (ℓ, λ) is $\frac{(K-\frac{1}{2})a}{W} = \frac{N-1}{N}a$. Similarly the offered traffic from node N is $(1-b)\frac{N-3}{N}a$, where $(1-b)$ corresponds to the proportion of traffic, which is not blocked on the previous link $N \rightarrow 1$.

Hence, generally we have

$$\begin{cases} a_2 &= ((N-1)+(1-b)\cdot(N-3)+ \\ &\qquad \ldots+(1-b)^{K-1}\cdot 1)\cdot\frac{a}{N}, \\ b &= \text{Erl}(f, a_2), \end{cases}$$

which can be determined numerically by successive iterations yielding an estimate for the link blocking probability b. The average blocking probability B_2 depends on the number of hops, k, the connection has and can be estimated similarly,

$$B_2(k) = 1-(1-b)^k.$$

iii) In case of $N=6$ there are three kinds of links as depicted in Fig. 1. Link ℓ_1 (e.g. link 6→1) has an offered load of $3a/2$. Let b_1 denote the respective blocking probability, $b_1 = \text{Erl}(f, 3a/2)$. Link ℓ_2 (e.g. link 1→2) has an offered load of $a+(a/2)\cdot(1-b_1)$, and hence $b_2 = \text{Erl}(f, a+(a/2)\cdot(1-b_1))$, and link ℓ_3 (e.g. link 2→3) has a zero blocking probability as the arriving bursts are already aligned in time. The connection specific blocking probabilities are,

$$B_3(1) = b_1, \qquad B_3(3) = 1-(1-b_1)(1-b_2).$$
$$B_3(2) = b_2,$$

Note that the presented analytical estimates neglect offset times, which generally depend on the used protocol. In [6, 5], a model is presented which takes into account different offset times and the same approach could be applied here as well. However, for simplicity we ignore the offset times, i.e. assume that the offset time of each traffic class is kept constant on every link by an appropriately chosen fibre delay line. This assumption may result in small inaccuracy when, e.g. the JET protocol is used and a flow has a relatively high offset time on a bottleneck link when compared to other flows, as is the case with scheme i).

In Fig. 2 the average blocking probabilities predicted by the analytical models are depicted as a function of the pairwise load a for N=6, W=3 and f=4. A curve depicted

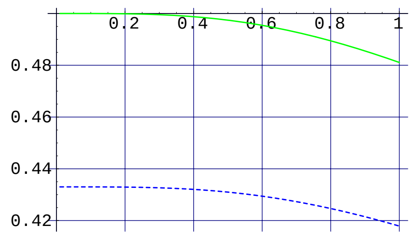

Figure 3. Estimated C_v of blocking probability between the different traffic flows for N=6 and f=4 fibres. The RWA schemes are ii) (upper) and iii) (lower).

with long dashes corresponds to scheme i), where a dedicated transmission wavelength was reserved for each node. The continuous curve corresponds to scheme ii), i.e. the scheme using a random wavelength selection with SP routing. The curve with short dashes corresponds to scheme iii), i.e. OBS-aware routing with $m = 2$. From the figures it can be noted that the performances of schemes ii) and iii) are clearly superior to scheme i). This is due to the fact that scheme i) does not fully exploit the capacity in the "furthest links". Furthermore, it can be seen that scheme iii) offers the best performance in terms of the average blocking probability.

Another important factor is fairness between traffic classes. In Fig. 3, the estimated coefficient of variation, $C_v = \sigma/m$, is depicted as a function of pair-wise load a for the same case ($N = 6$, $W = 3$ and $f = 4$). Scheme i) is not shown in the figure as the used model neglects the offset times and the blocking probability estimate is the same for each traffic class. The continuous curve corresponds to scheme ii) and the dashed curve to scheme iii). It can be seen that OBS-aware scheme iii) provides also a higher degree of fairness.

3.1.2. Numerical Results

In order to assess the quality of the analytical models the ring topology was simulated with the following parameters:

- N=6 nodes and W=3 wavelength layers.
- f=4 fibres on each link.
- 200 km link length, i.e. a 1000 μs propagation delay.
- Offered load between each node pair of a=0.5.
- Uniform burst length distribution in $1, \ldots, 499\,\mu$s.
- JET protocol, initial offset of each burst was set to $n \times T_\mu$, where the processing time is T_μ=1 μs and n is the number of nodes along the route.

As the offered load is uniform we have $B_{\text{flow}} = B_{\text{burst}}$. The simulation results together with the respective analytical results are presented in Table 1. It can be seen that the obtained analytical estimates match reasonably well with

k	scheme i)		scheme ii)		scheme iii)	
	sim.	anal.	sim.	anal.	sim.	anal.
1	0.032	0.029	0.0063	0.0062	0.0069	0.0062
2	0.028	0.029	0.011	0.012	0.0062	0.0062
3	0.024	0.029	0.015	0.018	0.012	0.011

Table 1. Connection specific blocking probabilities with ring topology with a load a=0.5. Parameter k represents the length of connection in hops.

the simulation results. In the RWA scheme i), as was expected, the traffic class specific blocking probabilities differ slightly from the constant estimate due to the different offset times (JET protocol). In summary it can be concluded that the analytical model seems to over estimate the blocking probabilities of long connections and under estimate the blocking probabilities of short connections. This is a consequence of neglecting the offset times and means that the estimate predicts a too high variance (and C_v).

In Table 2 the mean and variance of the blocking probabilities over the different traffic classes are presented based on the simulation results. It can be noted that the OBS-aware configuration with m=2 provides the lowest blocking probability and also the lowest variance, i.e. the different traffic classes are treated more equally.

	scheme i)	scheme ii)	scheme iii)
B_{flow}	0.028	0.011	0.008
C_v	0.15	0.40	0.30
$\hat{\sigma}^2$	$16 \cdot 10^{-6}$	$19 \cdot 10^{-6}$	$5 \cdot 10^{-6}$

Table 2. Results with ring topology with a load a=0.5.

3.2. Mesh Topology: 8 Core Nodes

Next we show the numerical results obtained with an example mesh network depicted in Fig. 4. The network consists of N=8 nodes and L=11 bi-directional links. There are f=4 fibres on each link and each fibre is capable of carrying traffic on W=4 wavelength channels. The link propagation delays T_{prop} are order of 1000 μs. It is assumed that the network nodes are not capable of performing wavelength translation and there are no fibre delay line buffers. The header processing time at the intermediate nodes is assumed to be a constant T_μ=1 μs. The burst length distribution is assumed to be uniform from 1 to 499 μs corresponding to the average burst size of about 300 kbytes assuming that the capacity of each channel is 10 Gbit/s. The offered load between each (s,d) pair is a=0.5 corresponding to the average burst arrival rate of $1/500\,\mu$s, i.e. about 600 Mbytes/s. Thus, there are 56 traffic flows to be configured into the network, and as the offered traffic is uniform we have B_{burst}=B_{flow}.

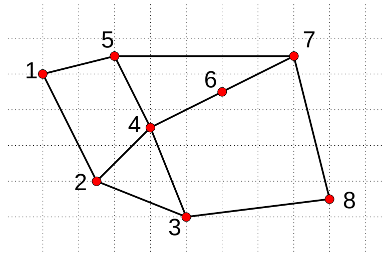

Figure 4. A mesh network consisting of 8 core nodes.

The linear programming problem giving the OBS-aware routing for $m=2$ was first solved using a MILP solver. As a reference case we use the shortest path routing with a random wavelength channel selection. That is, for each (s,d) pair, i.e. traffic class, we first fix one shortest path. Then upon arrival of a new burst the wavelength channel for the given burst is chosen randomly.

Then the resulting routes, wavelength assignment and traffic matrix were given as an input to the OBS network simulator developed in [12]. The numerical results are presented in the Table 3. From the simulation results it can be concluded that by introducing an OBS-aware routing we have managed to reduce the average blocking probability by about 22% and at the same time the fairness has been improved considerably.

quantity	shortest-path	OBS-aware
B_{flow}	0.0055	0.0043
$\hat{\sigma}^2$	$18 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$
C_v	0.77	0.28

Table 3. Numerical results with Fig. 4 mesh network.

4. Conclusions and Future Work

The numerical results suggest that it is possible to reduce the burst blocking probability considerably by introducing an OBS-aware routing policy, e.q. the one proposed in Section 2. A carefully chosen set of routes also seems to promote fairness among connections of different lengths. In this paper our aim was to provide equal service level to each traffic class, while in QoS routing one favours certain traffic classes at the expense of others. As a generalization to the presented OBS routing problem one could try to achieve the QoS routing goals in the same context. The arguments behind the given OBS-aware routing constraints are heuristic and chosen in order to simplify an already complex problem. Nonetheless, the resulting MILP problem is likely to be intractable when the problem size increases, e.g. the number of network nodes and wavelength channels grows. Hence, it seems that in practice one still needs to come up with further simplifications for the routing problem. Perhaps using some heuristic routing algorithm resembling the ideas behind the proposed OBS-aware routing policy will result in a reasonably good solution with a manageable computational effort. This is a subject for further study.

References

[1] C. Qiao and M. Yoo, "Optical burst switching (OBS) - a new paradigm for an optical internet," *Journal of High Speed Networks (JHSN)*, vol. 8, no. 1, pp. 69–84, 1999.

[2] J. Turner, "Terabit burst switching," *Journal of High Speed Networks (JHSN)*, vol. 8, pp. 3–16, 1999.

[3] K. Dolzer and C. Gauger, "On burst assembly in optical burst switching networks – a performance evaluation of just-enough-time," in *the 17th International Teletraffic Conference, ITC-17*, Sept. 2001, pp. 149–161.

[4] L. Xu, H. Perros, and G. Rouskas, "A survey of optical packet switching and optical burst switching," *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 136–142, Jan. 2001.

[5] K. Dolzer, C. Gauger, J. Späth, and S. Bodamer, "Evaluation of reservation mechanisms for optical burst switching," *International Journal of Electronics and Communications (AEÜ)*, vol. 55, no. 1, 2001.

[6] M. Yoo and C. Qiao, "Supporting multiple classes of services in IP over WDM networks," in *Global Telecommunications Conference - GlobeCom'99*, vol. 1b, 1999, pp. 1023–1027.

[7] L. Nieminen and E. Hyytiä, "Performance of the JET protocol with optical delay lines," in *Optical Network Design and Modelling, ONDM*, Budapest, Hungary, Feb. 2003, pp. 769–784.

[8] R. Ramaswami and K. N. Sivarajan, "Design of logical topologies for wavelength-routed optical networks," *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 840–851, June 1996.

[9] R. Dutta and G. N. Rouskas, "A survey of virtual topology design algorithms for wavelength routed optical networks," Department of Computer Science, North Carolina State University, Tech. Rep. TR-99-06, 12, 1999.

[10] D. Banaree and B. Mukherjee, "Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study," *IEEE/ACM Trans. Networking*, vol. 8, no. 5, pp. 598–607, Oct. 2000.

[11] B. Chen and J. Wang, "Hybrid switching and P-routing for optical burst switching networks," *IEEE J. Select. Areas Commun.*, vol. 21, no. 7, Sept. 2003.

[12] E. Sirén, "Optical packet switching," Master's thesis, Helsinki University of Technology, 2002.