Modelling and Performance Evaluation of Optical Burst Switched Networks with Deflection Routing and Wavelength Reservation

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***Abstract*— Methods to resolve wavelength contention are needed to improve the performance of optical burst switched (OBS) networks. Network simulations and Markovian queuing models for nodes in isolation have suggested that deflection routing (alternate routing) may be a viable method to resolve wavelength contention. However, we show that deflection routing may destabilise OBS networks operating at high loads. To prevent the destabilising effect of deflection routing, we propose and analyse a technique called wavelength reservation to intentionally limit the amount of deflection at high loads. Wavelength reservation is analogous to trunk reservation in circuit switched networks. This paper is the first to present a new reduced load Erlang fixed point analysis of OBS networks with deflection routing and wavelength reservation. We apply the new analysis to evaluate the benefit of deploying deflection routing and wavelength reservation in a sample OBS network.**

I. Introduction

Optical burst switching (OBS) [12], [13] may be a suitable switching paradigm for the envisaged Optical Internet.

In OBS, data packets, including internet protocol (IP), arriving at the same source node (edge node), with a common destination, are aggregated into bursts. Bursts are typically released into the optical layer before the acknowledgement of a successful lightpath reservation, except in the special case of wavelength-routed OBS [4], [5]. Several such one-way reservation schemes have been proposed of which the just-enough-time (JET) [13] reservation protocol has received the most attention.

In JET/OBS, a control packet is released into the optical layer, which consists of optical cross-connects (OXCs) inter-connected through a network of directed links, immediately after the burst aggregation period is complete. Each directed link contains a set of optical fibres, each of which contain a set of wavelengths. Meanwhile, the burst is buffered at the source node. As the control packet traverses the optical layer, enroute to the destination node, it attempts to reserve sufficient transmission time for the awaiting burst on each of the links it traverses. Note that the control packet is dedicated a separate wavelength on each fibre link (out-of-band signalling). At each OXC the control packet reaches, if sufficient transmission time cannot be reserved on a wavelength within an appropriate link outgoing from the OXC, the awaiting burst is blocked. If sufficient transmission time can be reserved, the control packet makes the reservation, sets the OXC accordingly and then proceeds to the next OXC. Full wavelength conversion is assumed to be available at each OXC.

After an offset time, the awaiting burst is released from the source node and traverses the lightpath previously established by the control packet. At the same time, ahead of the burst, the control packet continues to extend the lightpath, link-by-link, until the destination node is reached. The offset time is chosen to be $\delta \cdot h$, where δ bounds the time required for the control packet to make a reservation and set the OXC, and h is the maximum number of OXCs the burst can potentially traverse. Although the burst will gradually shorten its distance from the control packet during transmission, an offset time of $\delta \cdot h$ ensures that the burst can never catch-up to the control packet. Hence, explaining the term just-enough-time.

Methods to resolve wavelength contention are needed to improve the performance of OBS networks. Wavelength contention refers to a burst blocking resulting from the control packet failing to make a wavelength reservation. Two methods proposed to resolve wavelength contention are fibre delay lines

(FDLs) [7], [8], [13] and deflection routing [2], [3], [9], [17]. The former relies on FDLs to temporarily buffer the burst in the optical domain until a reservation can be made on the link that is in contention. The latter is, however, a more viable method since current FDL technology is expensive and at most can only provide a few μs of delay.

Network simulations, reported in [2], [9], [17], suggest that deflection routing may be a viable method to resolve wavelength contention for OBS networks operating at low to medium loads. Markovian queuing models for OXCs in isolation, presented in [3], [7], [8], also confirm the potential benefit of deploying deflection routing in OBS networks.

It is well known that deflection routing can destabilise circuit switched networks [1], [6], [10], [11], [16]. When operating in such an unstable mode, circuit switched networks are known to chaotically oscillate between high and low blocking probability states. It is necessary to determine if deflection routing produces an analogous destabilising effect in OBS networks. In principal, OBS differs from standard circuit switching in two main aspects. First, OBS bursts immediately follow their control packets without waiting for a reservation acknowledgement. Since buffering in optical switches is not practical, bursts may use bandwidth resources along several links and still be blocked and lost without completing their routes. In circuit switching, on the other hand, transmission starts only after an end-to-end path reservation is acknowledged. Second, in circuit switching, allocated resources are kept throughout the end-to-end transmission, while in OBS, the reserved resources at each switch and output link port are held only for the duration they are needed. To gain some initial insight into the possibility of deflection routing having a destabilising effect in OBS networks, we simulated a four-node symmetrical JET/OBS network with a particular deflection routing scheme to be defined later. Our simulation results are shown in Fig. 1.

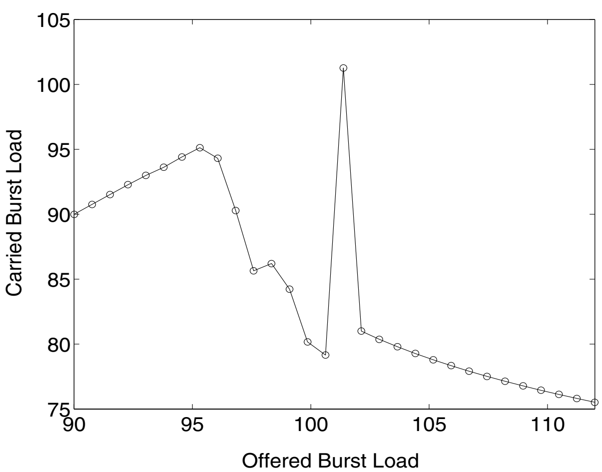

Fig. 1. Destabilising effect of deflection routing in a four-node symmetrical JET/OBS network.

In Fig. 1, observe the abrupt spike in the carried burst load which is completely out of proportion to the increase in the offered burst load. Such a spike is clearly unacceptable and suggests that the network may be operating in an unstable mode. Furthermore, observe the dramatic reduction in the carried burst load when the offered burst load is increased beyond approximately 95 units. These observations prompt further investigation and motivate the need for developing new approaches for evaluating the performance of OBS networks with deflection routing.

The remainder of this paper is organised as follows. We propose a simple deflection routing scheme for OBS networks in Section II. In Section III, we analyse the performance of the symmetrical OBS network we have simulated and we show that the destabilising effect produced by deflection routing observed in Fig. 1 may be prevented with a technique we call wavelength reservation. Wavelength reservation is analogous to trunk reservation in circuit switched networks. We then turn our attention to the performance evaluation of general asymmetrical OBS networks with deflection routing. To this end, in Section IV, we present a new reduced load Erlang fixed point analysis of asymmetrical OBS networks with deflection routing and wavelength reservation. We have presented the details of a simpler reduced load Erlang fixed point approximation for OBS networks without deflection routing, see [14]. Erlang fixed point approximations of circuit switched networks have been extensively considered, for example see [19]. In Section V, we apply the new analysis to evaluate the benefit of deploying deflection routing and wavelength reservation in a sample JET/OBS network. We also validate the assumptions made in our analysis through simulation.

II. Deflection Routing

In this section, we propose a simple deflection routing scheme for OBS networks.

For each source and destination (SD) pair, the *primary route* is defined as an ordered set of links from the source node to the destination node. In an OBS network without deflection routing, reservations can only be made on links belonging to the primary route. To reduce the probability of wavelength contention, an increased number of links can be made available for reservation by establishing deflection routes.

A *deflection route* is an ordered set of links from an OXC along the primary route, or the source node, to the destination node. For deflection routing to be of benefit, the first link in each deflection route must be: (a) distinct from the first link in all other deflection routes; and (b) distinct from the primary route. The primary and deflection routes can be chosen as the shortest hop routes to the destination node such that properties (a) and (b) are satisfied. A deflection scheme of order Q is such that either Q or the maximum possible number of deflection routes (whichever is less) are established for each OXC along the primary route and the source node. Note that it may not always be possible to establish Q deflection routes and satisfy properties (a) and (b). A general primary route with deflection routes is shown in Fig. 2 for clarification. A burst traversing a primary route will be called a primary burst, while a burst traversing a deflected route will be called a deflected burst.

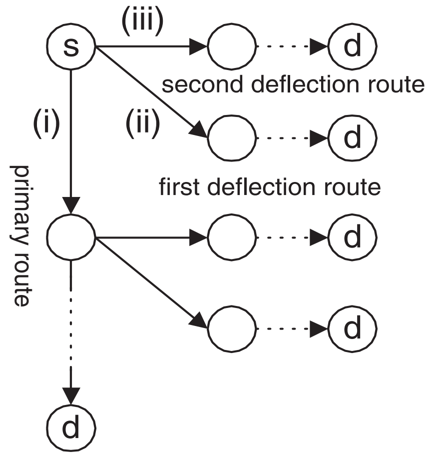

Fig. 2. Primary route with deflection routes for an isolated SD pair. To satisfy properties (a) and (b), links (i), (ii) and (iii) are chosen to be distinct. The first deflection route is chosen as the shortest route from the source to the destination that does not traverse link (i). The second shortest route is chosen similarly but does not traverse both links (i) and (ii).

When the control packet reaches an OXC, it will first attempt to make a reservation on the outgoing link belonging to the primary route, if unsuccessful, the outgoing link belonging to the first deflection route will be tried next, and so on until a reservation is made or until all the deflections routes are tried, in which case the awaiting burst will be blocked. In this scheme, a burst can be deflected only once. More sophisticated deflection schemes [9] may allow a burst to undergo multiple deflections.

Deflection routing may require an increase in the offset time $\delta \cdot h$ as a consequence of two effects. First, the maximum number of OXCs h, which a burst can potentially traverse, is likely to increase since deflection routes typically traverse more OXCs than the primary route. And second, the control packet processing time δ must be increased to accommodate the additional delay required to make reservation attempts on a greater number of outgoing links.

III. Stability and Wavelength Reservation

The earlier observations we made (about the simulation results shown in Fig. 1) suggested that deflection routing may have a destabilising effect on a symmetrical four-node JET/OBS network. In this section, we confirm our suspicions of the possible destabilising effect of deflection routing and then propose a technique that is later shown to prevent this effect even for general asymmetrical OBS networks.

The network topology we consider and all the routes traversing the link from node one to node two are shown in Fig. 3. Let N denote the total number of wavelengths within a link. To ensure symmetry, all possible SD pairs are considered excluding (1,3), (3,1), (2,4) and (4,2). We consider an order-one deflection scheme, in which the primary route consists of a single link and the deflection route consists of three links. Let $\overline{\rho}$ and ρ denote the external burst load offered to each SD pair and the total burst load offered to each link, respectively. We assume bursts are released into the optical layer at each source s according to independent Poisson processes and burst transmission times on each link are independent and exponentially distributed with a common mean. We also assume deflected bursts are generated according to independent Poisson processes. By symmetry and the Poisson arrivals assumption, the blocking probability B on each link is the same and is given by the Erlang B formula

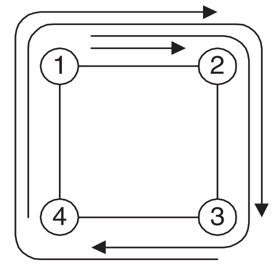

Fig. 3. Four-node symmetrical OBS network topology. Each arc represents a route traversing the link from node one to node two. Routes not traversing this link are not shown but can be deduced by symmetry.

$$B = \frac{\rho^N/N!}{\sum_{k=0}^{N} \rho^k/N^k}. \tag{1}$$

Summing the total carried burst load on a link and noting that it must equal $(1-B)\cdot\rho$, we arrive at the expression

$$\begin{aligned}(1-B)\cdot\rho &= (1-B)\cdot\overline{\rho} + (1-B)\cdot B\cdot\overline{\rho} \\ &\quad +(1-B)^2\cdot B\cdot\overline{\rho} + (1-B)^3\cdot B\cdot\overline{\rho}.\end{aligned} \tag{2}$$

Note that for circuit switched networks we would instead write $(1-B)\cdot\rho = (1-B)\cdot\overline{\rho} + 3(1-B)^3\cdot\overline{\rho}$ since the carried load is not reduced at each successive link of a deflection route. We can arrange (2) so that

$$\overline{\rho} = \frac{\rho}{1 + B + (1-B)\cdot B + (1-B)^2\cdot B}. \tag{3}$$

By assuming link blocking events occur independently from link-to-link, it can be easily shown that the end-to-end burst blocking probability for an SD pair is given by

$$P = B^4 - 3B^3 + 3B^2. \tag{4}$$

To confirm the simulation results shown earlier in Fig. 1, we are interested in plotting the carried portion of the external burst load $(1-P)\cdot\overline{\rho}$ against the external burst load $\overline{\rho}$. Given ρ, we can determine the link blocking probability B with (1). We can then determine the external burst load offered $\overline{\rho}$ with (3) and the end-to-end burst blocking probability P with (4). In Fig. 4, we plot the carried portion of the external burst load $(1-P)\cdot\overline{\rho}$ against the external burst load $\overline{\rho}$ for $N = 120$ wavelengths.

In Fig. 4, observe that the carried burst load is not always unique for a given offered burst load. Therefore, it is possible for an abrupt change in the carried burst load, which is completely out of proportion to the change in the offered burst load. This unstable mode of operation begins at an

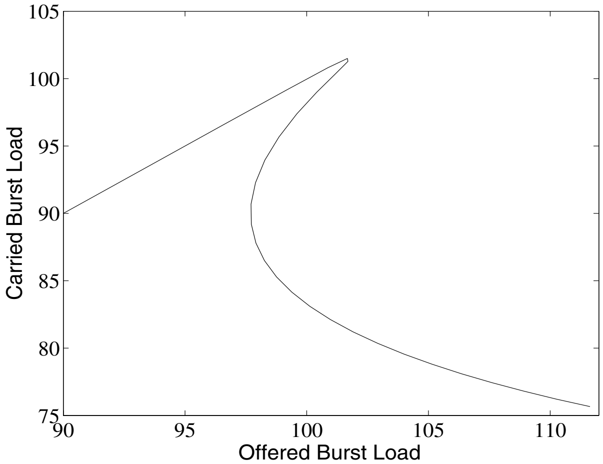

Fig. 4. Carried burst load $(1-P)\cdot\overline{\rho}$ against external load $\overline{\rho}$ for an SD pair in a four-node symmetrical JET/OBS network with deflection routing.

offered burst load of approximately 98 units and persists until approximately 102 units. Stability is restored as the offered load is increased beyond 102 units, however, the carried burst load is dramatically reduced after this value.

A similar destabilising effect and dramatic reduction in the carried load is a well known phenomenon in circuit switched networks [6], [11], [16]. The success of trunk reservation in alleviating this phenomenon in circuit switched networks motivates us to propose an analogous technique for OBS networks called wavelength reservation. *Wavelength reservation* intentionally limits the amount of deflection at high loads by reserving $N-K>0$ wavelengths on each link for the exclusive use of primary bursts. That is, a link cannot accept a deflected burst if K (out of N) or more of its wavelengths are occupied.

We now confirm that wavelength reservation alleviates the destabilising effect shown in Fig. 4. Let $\hat{\rho}$ denote the deflected burst load offered to a link. Since a link services only one primary route and a primary route consists of only one link, the deflected burst load offered to a link must equal the total offered burst load less the external offered burst load,

$$\hat{\rho} = \rho - \overline{\rho}. \tag{5}$$

Let π_j denote the probability that j, $0 \le j \le N$, wavelengths are occupied within a link. Modelling a link with an $M/M/1/N$ queue, we have a recursion of the form

$$\pi_j = \begin{cases} \rho^j \cdot \pi_0/j! & 1 \le j \le K \\ \overline{\rho}^{j-K} \cdot \rho^K \cdot \pi_0/j! & K < j \le N \end{cases},$$

where π_0 is determined with the normalization equation $\sum_{j=0}^{N} \pi_j = 1$. A primary burst will be blocked on a link if all N wavelengths are occupied, which occurs with probability

$$B = \pi_N = \overline{\rho}^{N-K} \cdot \rho^K \cdot \pi_0/N!. \tag{6}$$

A deflected burst will be blocked on a link if K or more wavelengths are occupied, which occurs with probability

$$Q = \sum_{j=K}^{N} \overline{\rho}^{j-K} \cdot \rho^K \cdot \pi_0/j!. \tag{7}$$

Summing the total carried burst load on a link and noting that it must equal $(1-B)\cdot\rho$, we arrive at the expression

$$\begin{aligned}(1-B)\cdot\rho &= (1-B)\cdot\overline{\rho} + (1-Q)\cdot B\cdot\overline{\rho} \\ &\quad + (1-Q)^2\cdot B\cdot\overline{\rho} + (1-Q)^3\cdot B\cdot\overline{\rho},\end{aligned} \tag{8}$$

and thus,

$$\overline{\rho} = \frac{(1-B)\cdot\rho}{(1-B)+\xi}, \tag{9}$$

where $\xi = (1-Q)\cdot B + (1-Q)^2\cdot B + (1-Q)^3\cdot B$. By assuming link blocking events occur independently from link-to-link, it can be easily shown that the end-to-end burst blocking probability for an SD pair is given by

$$P = B\cdot Q^3 - 3B\cdot Q^2 + 3Q\cdot B. \tag{10}$$

Note that without wavelength reservation $Q = B$ and we see that (10) reduces to (4). We are once again interested in plotting the carried portion of the external burst load $(1-P)\cdot\overline{\rho}$ against the external burst load $\overline{\rho}$. Given $\overline{\rho}$, we arbitrarily choose $\hat{\rho}$ and compute the link blocking probabilities for a deflected and primary burst with (6) and (7), respectively. We then determine the total offered burst load ρ with (9). If (5) is not satisfied by the newly determined value of ρ, we update so that $\hat{\rho} = \rho - \overline{\rho}$ and iterate until (5) is satisfied. The end-to-end burst blocking probability P can then be determined with (10).

In Fig. 5, we plot the carried portion of the external burst load $(1-P)\cdot\overline{\rho}$ against the external load $\overline{\rho}$ with $N = 120$ wavelengths for the cases: (a) deflection with wavelength reservation $(K = 110)$; (b) no deflection; and (c) deflection without wavelength reservation. In Fig. 6, we plot the end-to-end SD pair blocking probability P against the external offered burst load $\overline{\rho}$ for the three cases defined previously.

We have confirmed that deflection routing controlled by wavelength reservation may be a viable method to resolve wavelength contention in a four-node symmetrical JET/OBS network . In the next section, we turn our attention to general asymmetrical OBS networks with deflection routing and wavelength reservation.

IV. Reduced Load Erlang Fixed Point Analysis

In general, it is not possible to mimic the single variable analysis presented in the previous section for general asymmetrical OBS networks. It is these networks, however, that are of most importance to us.

In this section, we present a computationally fast approach for evaluating the performance of a general asymmetrical JET/OBS network with deflection routing and wavelength reservation. By assuming blocking events occur independently from link-to-link, we are able to decompose the network links but still model the reduced burst load resulting from blocking

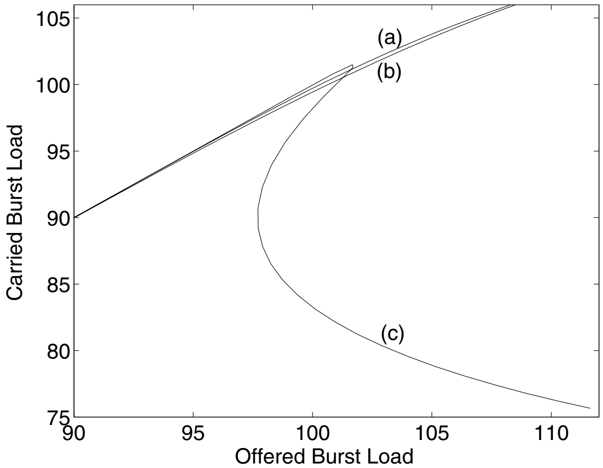

Fig. 5. Carried burst load $(1-P)\cdot\overline{\rho}$ against external load $\overline{\rho}$ for an SD pair in a four-node symmetrical JET/OBS network with 120 wavelengths.

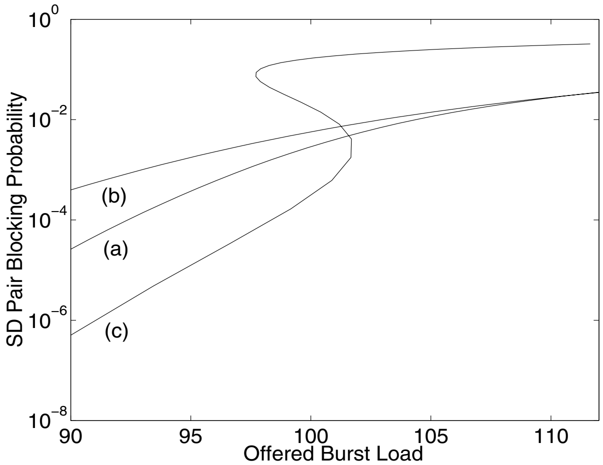

Fig. 6. End-to-end SD pair blocking probability P against external load $\overline{\rho}$ in a four-node symmetrical JET/OBS network with 120 wavelengths.

events. We first develop the Erlang map, and then present an iterative method that may find a unique solution to this map, assuming that a unique solution does exist. We finally show how to recover the overall burst blocking probability from the unique solution of the Erlang map.

We make the following three assumptions.

1) Burst transmission times on each link are independent and exponentially distributed, and bursts are released into the optical layer at each source s according to independent Poisson processes.
2) Deflected bursts are generated according to independent Poisson processes. Note that deflected bursts are actually generated according to a two-state Markov modulated Poisson process (MMPP). For simplicity, we do not consider the MMPP model here .
3) Blocking events occur independently from link-to-link.

We have omitted other marginal assumptions. Assumptions (2) and (3) will be validated in Section (V) through simulation.

We consider an order Q deflection scheme for an isolated SD pair. Let the ordered double (i,j) denote a directed link from node i to node j that is traversed by either the primary route or a deflection route. Construct the sets $\mathcal{P}$ and $\mathcal{D}$ such that $(i,j)\in\mathcal{P}$ if link (i,j) is traversed by the primary route and $(i,j)\in\mathcal{D}$ if link (i,j) is traversed by at least one deflection route. To simplify notation we assume $\mathcal{P}\cap\mathcal{D}=\emptyset$, however, this condition is not at all necessary in general. Let $N_{(i,j)}$ denote the number of wavelengths within link (i,j). Links are indexed according to the following convention. Suppose (i,j_1) and (i,j_2), $j_1\neq j_2$, are two links originating from node i along the primary route, if $j_1<j_2$, the control packet must attempt to make a reservation on link (i,j_1) *before* attempting to make a reservation on link (i,j_2). With this convention in mind, define $\mathcal{C}(i,j)=\{(m,n)|m=i,n<j\}$. For notational simplicity, assume there is only one link immediately preceding link (i,j), let $q(i,j)$ denote the link immediately preceding link (i,j). Note that $q(i,j)$ is not defined for any link originating at the source node. Let $\overline{\rho}$ denote the external burst load offered to the source node. Also, let $\tilde{\rho}_{(i,j)}$ and $\hat{\rho}_{(i,j)}$ denote the primary burst load offered to link (i,j) and the deflected burst load offered to link (i,j), respectively.

At this stage, assume the primary burst blocking probability $B_{(i,j)}$ for link (i,j) and the deflected burst blocking probability $Q_{(i,j)}$ for link (i,j) are known. Note that without wavelength reservation, $B_{(i,j)}=Q_{(i,j)}$, so there is no need to make a distinction between the two, however, with wavelength reservation $B_{(i,j)}<Q_{(i,j)}$. To simplify notation we define

$$\Gamma_{(i,j)}=\begin{cases} B_{(i,j)} & (i,j)\in\mathcal{P} \\ Q_{(i,j)} & (i,j)\in\mathcal{D} \end{cases}$$

and

$$\rho_{(i,j)}=\begin{cases} \tilde{\rho}_{(i,j)} & (i,j)\in\mathcal{P} \\ \hat{\rho}_{(i,j)} & (i,j)\in\mathcal{D} \end{cases}.$$

Under the independence assumption, a recursion of the form

$$\rho_{(i,j)}=(1-\Gamma_{q(i,j)})\cdot\rho_{q(i,j)}\cdot\prod_{(m,n)\in\mathcal{C}(i,j)}\Gamma_{(m,n)}, \qquad (11)$$

can be solved to recover $\rho_{(i,j)}$, $i\neq s$. For $i=s$, the recursion takes the form

$$\rho_{(s,j)}=\overline{\rho}\cdot\prod_{(m,n)\in\mathcal{C}(s,j)}\Gamma_{(m,n)}. \qquad (12)$$

Note that the burst load may be reduced (thinned) by both the factors $1-\Gamma_{q(i,j)}$ and $\prod_{(m,n)\in\mathcal{C}(i,j)}\Gamma_{(m,n)}$.

The recursion is repeated for each SD pair, then for each link (i,j) the resulting values of $\tilde{\rho}_{(i,j)}$ are summed to determine the total primary burst load offered to link (i,j) and the resulting values of $\hat{\rho}_{(i,j)}$ are summed to determine the total deflected burst load offered to link (i,j).

For link (i,j), $N_{(i,j)}-K_{(i,j)}$ wavelengths are reserved for the exclusive use of primary bursts. Under the independence and Poisson arrivals assumption, each link (i,j) can be modelled as an $M/M/1/N_{(i,j)}$ queuing system. Let $\pi^q_{(i,j)}$

denote the probability that q, $0 \leq q \leq N_{(i,j)}$, wavelengths are occupied within a link. A recursion of the form

$$\pi^q_{(i,j)} = (\tilde{\rho}_{(i,j)} + \hat{\rho}_{(i,j)})^q \cdot \pi^0_{(i,j)}/q!,$$

for $1 \leq j \leq K_{(i,j)}$ and

$$\pi(i,j)^q = \tilde{\rho}^{q-K_{(i,j)}}_{(i,j)} \cdot (\tilde{\rho}_{(i,j)} + \hat{\rho}_{(i,j)})^{K_{(i,j)}} \cdot \pi^0_{(i,j)}/q!,$$

for $K_{(i,j)} < q \leq N_{(i,j)}$, can be solved to recover $\pi^q_{(i,j)}$, where $\pi^0_{(i,j)}$ is determined with the normalization equation $\sum_{q=0}^{N} \pi^q_{(i,j)} = 1$.

A primary burst will be blocked on link (i,j) if all $N_{(i,j)}$ wavelengths are occupied, which occurs with probability

$$\begin{aligned} B_{(i,j)} &= E_1(\tilde{\rho}_{(i,j)}, \hat{\rho}_{(i,j)}, N_{(i,j)}, K_{(i,j)}) \\ &= \pi^{N_{(i,j)}}_{(i,j)}. \end{aligned} \quad (13)$$

A deflected burst will be blocked on link (i,j) if $K_{(i,j)}$ or more wavelengths are occupied, which occurs with probability

$$\begin{aligned} Q_{(i,j)} &= E_2(\tilde{\rho}_{(i,j)}, \hat{\rho}_{(i,j)}, N_{(i,j)}, K_{(i,j)}) \quad (14) \\ &= \sum_{q=K_{(i,j)}}^{N_{(i,j)}} \frac{\tilde{\rho}^{q-K_{(i,j)}}_{(i,j)} \cdot (\tilde{\rho}_{(i,j)} + \hat{\rho}_{(i,j)})^{K_{(i,j)}} \cdot \pi^0_{(i,j)}}{q!}. \end{aligned}$$

Combining (11), (12), (13) and (14) yields the following coupled system of nonlinear algebraic equations

$$\begin{aligned} B_{(i,j)} &= E_1\left(\tilde{\rho}_{(i,j)}(\mathbf{B},\mathbf{Q}), \hat{\rho}_{(i,j)}(\mathbf{B},\mathbf{Q}), N_{(i,j)}, K_{(i,j)}\right) \\ Q_{(i,j)} &= E_2\left(\tilde{\rho}_{(i,j)}(\mathbf{B},\mathbf{Q}), \hat{\rho}_{(i,j)}(\mathbf{B},\mathbf{Q}), N_{(i,j)}, K_{(i,j)}\right), \end{aligned}$$

which is a special case of the Erlang map [6], where $\mathbf{B}$ and $\mathbf{Q}$ are the vectors of primary and deflected blocking probabilities, respectively. We have emphasized the dependence of $\tilde{\rho}_{(i,j)}$ and $\hat{\rho}_{(i,j)}$ on all the link blocking probabilities $\mathbf{B}$ and $\mathbf{Q}$ by writing $\tilde{\rho}_{(i,j)}(\mathbf{B},\mathbf{Q})$ and $\hat{\rho}_{(i,j)}(\mathbf{B},\mathbf{Q})$. A unique solution to the Erlang map is termed the Erlang fixed point (EFP) and represents the stationary link blocking probabilities, which will be denoted with $B^*_{(i,j)}$ and $Q^*_{(i,j)}$. The existence of an EFP is not guaranteed. The successive substitution algorithm detailed below is an efficient method that may find the EFP.

ALGORITHM: SUCCESSIVE SUBSTITUTION

1) **Initialise**: Set $n = 0$. For each link (i,j), set $\tilde{\rho}^0_{(i,j)}$ and $\hat{\rho}^0_{(i,j)}$ to some random distribution on $[0,1]$.
2) **Compute Blocking**: Set $n = n+1$. For each link (i,j) update $B^n_{(i,j)}$ according to (13) with $\tilde{\rho}^{n-1}_{(i,j)}$ and $\hat{\rho}^{n-1}_{(i,j)}$. Similarly, for each link (i,j) update $Q^n_{(i,j)}$ according to (14) with $\tilde{\rho}^{n-1}_{(i,j)}$ and $\hat{\rho}^{n-1}_{(i,j)}$. If $|B^n_{(i,j)} - B^{n-1}_{(i,j)}| < \epsilon$ and $|Q^n_{(i,j)} - Q^{n-1}_{(i,j)}| < \epsilon$, then stop and return the EFP, $B^*_{(i,j)} = B^n_{(i,j)}$ and $Q^*_{(i,j)} = Q^n_{(i,j)}$.
3) **Update Burst Load**: For each link (i,j) recompute the primary and deflected offered burst load according to (11) and (12) with $\mathbf{B}^n$ and $\mathbf{Q}^n$.
4) **Loop**: Go to step (2).

Assuming the EFP exists and is found, the end-to-end burst blocking probability for an SD pair can be easily determined. Define $\mathcal{F}(i) = \{j|(i,j) \in \mathcal{P}$ or $(i,j) \in \mathcal{D}\}$. Let P_i denote the probability that a burst will be eventually blocked given its control packet has reached node i but has not yet attempted to make a reservation on a link outgoing from node i. The burst blocking probability for an SD pair is therefore given by P_s. To simplify notation we define

$$\Gamma^*_{(i,j)} = \begin{cases} B^*_{(i,j)} & (i,j) \in \mathcal{P} \\ Q^*_{(i,j)} & (i,j) \in \mathcal{D} \end{cases}.$$

Under the independence assumption, a recursion of the form

$$\begin{aligned} P_i &= \sum_{j \in \mathcal{F}(i)} P_j \cdot (1 - \Gamma^*_{(i,j)}) \cdot \prod_{(m,n) \in \mathcal{C}(i,j)} \Gamma^*_{(m,n)} \\ &+ \Gamma^*_{(i, \max \mathcal{F}(i))} \cdot \prod_{(m,n) \in \mathcal{C}(i, \max \mathcal{F}(i))} \Gamma^*_{(m,n)} \end{aligned} \quad (15)$$

can be solved to recover P_i, $i \neq d$. The recursion is initialised such that $P_d = 0$.

Finally, if the superscript $t = 1, 2, \ldots, T$ is used to index each SD pair, the overall blocking probability for the network is given by

$$P = \frac{1}{\sum_{t=1}^{T} \overline{\rho}^t} \sum_{t=1}^{T} \overline{\rho}^t \cdot P^t_s, \quad (16)$$

and the overall carried burst load for the network is given by

$$C = \sum_{t=1}^{T} (1 - P^t_s) \cdot \overline{\rho}^t. \quad (17)$$

V. VALIDATION AND EVALUATION

The purpose of this section is twofold. First, through a simulation, we quantify the error introduced to our analysis in assuming deflected bursts are generated according to independent Poisson processes and blocking events occur independently from link-to-link. And second, we evaluate the benefit of deploying deflection routing with wavelength reservation in a sample OBS network.

We adopt the T3 version of the NSFNET backbone shown in Fig. 7 as our sample network topology. The network topology comprises of 13 OXCs and 32 directed links containing one fibre, each comprising of 120 wavelengths. We consider the same 12 SD pairs and corresponding set of primary routes defined in [14]. The selected primary routes represent a variety of lengths, link sharing degrees and mixtures of external and on-route traffic processes. All deflection routes are chosen as shortest hop routes that satisfy properties (a) and (b). Each SD pair is offered the same external burst load.

For the validation process, we consider two external burst loads, $\overline{\rho} = 50, 100$, to represent a low and high load mode of operation, respectively. In Tables I and II, we present the results of our validation process for the cases when order-one and order-two deflection schemes are deployed in addition to no deflection. We choose a wavelength reservation threshold of $K = 90$ for all links. That is, a link cannot accept a deflected burst if 90 (out of 120) or more of its wavelengths are occupied. Tables I and II show the values obtained from our analysis are in good agreement with those obtained from the simulation. Therefore, it seems the error introduced by our assumptions is quite small.

Since we are satisfied with the accuracy of our analysis, we can now quickly determine the performance of our sample OBS network with considerable confidence and without the need for lengthy simulations. However, there is one very important caveat that must be discussed. The successive substitution algorithm proposed is not guaranteed to find the EFP, and worse still, the EFP may not exist. Extensive numerical testing suggests that divergence or cycling of the successive substitution algorithm may be the result of the destabilising effect produced by deflection routing. In particular, for all our numerical testing, we observe that the successive substitution algorithm can always be made to converge by decreasing the wavelength reservation threshold K. For the sample OBS network, $K = 90$ is sufficient to ensure the algorithm converges for the range of offered burst loads we consider. However, as K is increased, we observe that the algorithm enters a two-cycle, and thus fails to converge. We conjecture that as K is increased, the control of wavelength reservation is not sufficient to alleviate the destabilising effect of deflection routing. We are not able to prove that it is indeed the destabilising effect of deflection routing that hinders the convergence of our successive substitution algorithm. In any case, if the algorithm does converge, which our numerical testing suggests we can always achieve by including a sufficient level of wavelength reservation, we can use our analysis with some confidence.

In Fig. 8 and 9, we plot the overall carried burst load and the overall burst blocking probability, respectively, for the cases when order-one and order-two deflection schemes are deployed, in addition to no deflection. Once again, we choose a wavelength reservation threshold of $K = 90$ for all links. In Fig. 8, observe that no instabilities are visible, however, the carried burst load is reduced as the offered burst load is increased beyond 70 units. The wavelength reservation threshold can be decreased to improve the performance at such high loads at the expense of deteriorating performance at low loads. As previously mentioned, we are unable to analyse the case when wavelength reservation is not used since the successive substitution algorithm fails to converge. We conjecture that without wavelength reservation, similar instabilities may develop in our sample network as proven in the four-node symmetrical network. Note that when the number of wavelengths on each link is reduced to 100, we observe convergence of the algorithm even *without* wavelength reservation. Observe in Fig. 8 and 9 that the values generated by our analysis are in good agreement with those obtained from the simulation.

As shown in Fig. 8 and 9, the deployment of deflection routing with wavelength reservation in the OBS network considered can reduce the burst blocking probability to some extent at light to medium loads, and thus increase the carried burst load. As shown in Fig. 9, there is little benefit in increasing the order of the deflection scheme from one to two. Nonetheless, it seems viable to deploy an order-one deflection scheme with wavelength reservation in the OBS network considered.

VI. Concluding Remarks

We have shown that deflection routing may produce a destabilising effect in OBS networks and dramatically reduce performance at high loads. We were able to demonstrate this for a four-node symmetrical OBS network. Wavelength reservation was shown to alleviate the destabilising effect and increase the carried burst load at high loads. At high loads, we believe deflected routes congest the primary routes, thus resulting in more deflections, which in turn increase the level of congestion even more. To quickly determine the performance of general asymmetrical OBS networks with deflection routing and wavelength reservation, without the need for lengthy simulations, we presented a new reduced load fixed point analysis. We showed that our analysis was in good agreement with results generated through a simulation. Our analysis suggested that it seems viable to deploy low order deflection schemes controlled by wavelength reservation in OBS networks for the purpose of resolving wavelength contention, and thus reducing the burst blocking probability.

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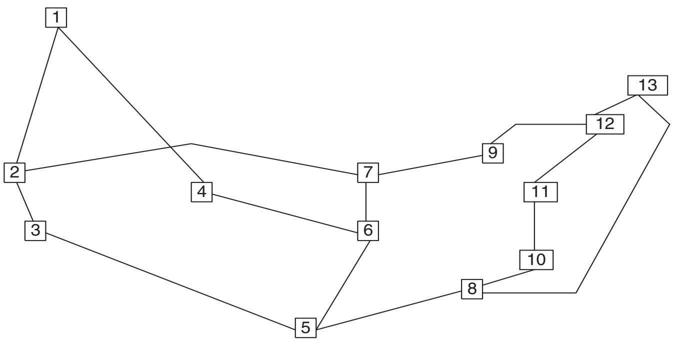

Fig. 7. Sample OBS network: NSFNET T3 comprising 13 OXCs and 32 directed links containing one fibre, each comprising of 120 wavelengths. We evaluate the performance of this sample OBS network for order-one and order-two deflection schemes with wavelength reservation.

TABLE I

ASSUMPTIONS MADE IN OUR FIXED POINT ANALYSIS ARE VALIDATED THROUGH SIMULATION. SD PAIR BLOCKING PROBABILITIES, $\overline{\rho} = 50$.

Routes\Dflct.	*No Dflct.*		*Order 1*		*Order 2*	
	Analy.	*Sim.*	*Analy.*	*Sim.*	*Analy.*	*Sim.*
R_1	0.2169	0.2273	0.1995	0.2049	0.2000	0.2109
R_2	0.2218	0.2260	0.1619	0.1586	0.1724	0.1739
R_3	0.0062	0.0095	0.0055	0.0067	0.0055	0.0041
R_4	0.0060	0.0056	0.0061	0.0069	0.0064	0.0077
R_5	0.2178	0.2256	0.2085	0.2067	0.2062	0.2080
R_6	0.0059	0.0101	0.0048	0.0049	0.0048	0.0032
R_7	0.2257	0.2333	0.1717	0.1653	0.1822	0.1909
R_8	0.2206	0.2275	0.1306	0.1385	0.0004	0.0034
R_9	0.0158	0.0149	0.0157	0.0172	0.0158	0.0105
R_{10}	0.0056	0.0056	0.0058	0.0030	0.0058	0.0080
R_{11}	0.2283	0.2367	0.2171	0.2265	0.2106	0.2202
R_{12}	0.0110	0.0122	0.0046	0.0048	0.0046	0.0025
Mean	0.1151	0.1195	0.0953	0.0943	0.0846	0.0869

TABLE II

ASSUMPTIONS MADE IN OUR FIXED POINT ANALYSIS ARE VALIDATED THROUGH SIMULATION. SD PAIR BLOCKING PROBABILITIES, $\overline{\rho} = 100$.

Routes\Dflct.	*No Dflct.*		*Order 1*		*Order 2*	
	Analy.	*Sim.*	*Analy.*	*Sim.*	*Analy.*	*Sim.*
R_1	0.6000	0.6002	0.6001	0.6074	0.6001	0.6036
R_2	0.6649	0.6627	0.6544	0.6619	0.6546	0.6560
R_3	0.4427	0.4432	0.4428	0.4357	0.4428	0.4387
R_4	0.4300	0.4279	0.4301	0.4189	0.4301	0.4225
R_5	0.5984	0.6057	0.5983	0.6150	0.5983	0.5901
R_6	0.3912	0.3950	0.3067	0.3130	0.3067	0.3151
R_7	0.7152	0.7082	0.7126	0.7114	0.7136	0.7161
R_8	0.6250	0.6168	0.3649	0.3744	0.2878	0.3015
R_9	0.5880	0.6044	0.5881	0.5953	0.5881	0.5871
R_{10}	0.3333	0.3283	0.3340	0.3241	0.3341	0.3324
R_{11}	0.7352	0.7407	0.7352	0.7379	0.7352	0.7351
R_{12}	0.5630	0.5727	0.5515	0.5605	0.5515	0.5507
Mean	0.5572	0.5588	0.5266	0.5296	0.5202	0.5207

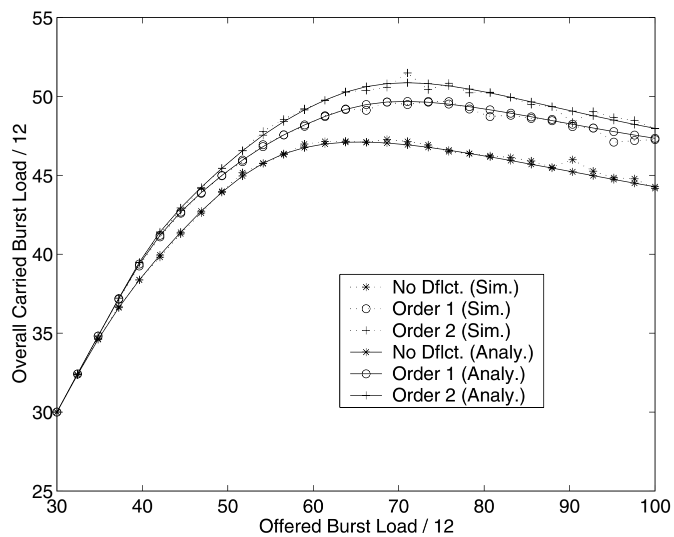

Fig. 8. Overall carried burst load.

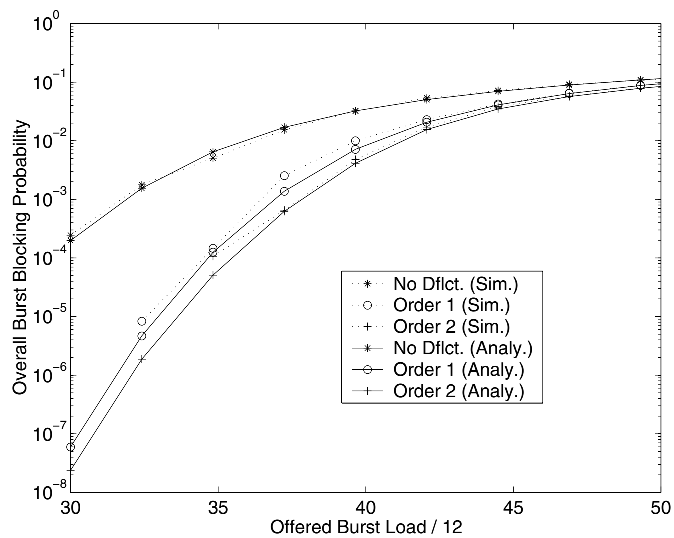

Fig. 9. Overall burst blocking probability.