Traffic Load Bounds for Optical Burst-Switched Networks with Dynamic Wavelength Allocation

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Abstract: The maximum traffic load that can be supported by a wavelength division multiplexed (WDM) optical burst switched (OBS) network with dynamic wavelength allocation is studied. It is shown that it depends on the requirements of the class of service and on the efficiency of the dynamic routing and wavelength assignment (RWA) algorithm employed. Two methods to build the bursts are presented as well as their influence on the maximum traffic load that can be supported.

1. INTRODUCTION

There are a number of approaches for the design of optical networks. In Wavelength-Routed Optical Networks (WRONs) all-optical channels are established between pairs of nodes by means of *lightpaths* [1]. These networks have been widely investigated (see [2,3] and references there). Although they are relatively easy to design and manage, their main drawback is that the bandwidth which can be provided by established lightpaths is usually much higher than that required to accommodate the

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average traffic loads between the source-destination nodes, so that the capacity provisioning in the network may be inefficient. Moreover, they have difficulties to adapting to dynamically varying traffic demands, especially if these change on sub-millisecond timescale. A technique that has recently received a lot of attention as a possible solution to that problem is Optical Burst Switching (OBS) [4-12]. With this approach, the network consists of edge routers and core nodes. Packets are buffered in the source edge routers to form a *burst* (also known as *flow*). Then, a control packet is sent and afterwards, the burst is transmitted into the core network. There are several approaches to OBS. In this paper, we study a model called Optical Burst Switching with Dynamic Wavelength Allocation (OBS-DWA) [9-12]. A dynamic routing and wavelength assignment (RWA) algorithm is used to establish a lightpath for the transmission of the burst. Once the lightpath has been established an acknowledgement is sent to the source node, then the burst is transmitted and finally, the lightpath is deleted. This function could be fulfilled by either a centralised or distributed wavelength assignment control. The former option is considered in this paper. The main advantage of this OBS approach is that no buffers are needed in the core nodes and it is possible to ensure a deterministic end-to-end delay for time-critical applications. There are other important parameters, which must be analysed to provide different classes of service, namely the delay jitter and the packet loss rate. It is also a key question to determine the minimum number of wavelengths needed to support a set of quality of service parameters and traffic load.

In this paper, we focus on the analysis of trade-offs between the edge delay (which is related to end-to-end delay), the wavelength requirements and the traffic load of the network in the context of Optical Burst Switching with dynamic wavelength allocation. Two different methods to constructing the bursts are presented and the edge delay is analysed for both of them. Then, we determine the maximum traffic load that the network is able to support due to the imposed edge delay constraints. The wavelength requirements for quasi-static WRONs and OBS-DWA networks are also compared.

2. MODEL AND PARAMETER DEFINITION

In this section, the network model and a set of parameters used throughout the paper are presented. This work is based on the OBS network architecture presented in [9-11], for a network with N edge routers. It is assumed that each edge router has a buffer for every destination and class of service, and that the packet loss rate (PLR) in the edge routers is zero. (More efficient schemes can be applied, although they increase the PLR [12].) When a threshold in the amount of stored data or a timeout (determined by the delay requirements of the class of service) is reached, a request is sent to a centralised control node to establish a lightpath that will be used for the transmission of the burst.

The set of *possible connections* in the network is defined as the set of different {source, destination, class of service} groups so that the source and the destination edge routers are not equal. Only one unidirectional lightpath can be established between a pair of nodes for every class of service. (Throughout this paper all connections referred are unidirectional.) Therefore, considering C classes of service, the number of possible connections is $N(N-1)C$. In this paper, the analysis is limited to a network with one class of service, and so, the number of possible connections is $K = N(N-1)$. Since dynamically varying traffic is considered, a possible connection will alternate between two states. It will be *established* during periods of T_{WHT} time units (which means that a lightpath is joining the source and the destination edge routers), and *idle* (or not established) during periods of T_{idle} time units, where T_{WHT} and T_{idle} are random variables having a mean of $\bar{t}_{WHT}$ and $\bar{t}_{idle}$ respectively.

The idle time represents the elapsed time between two effective connections between a source-destination pair, but the network designer cannot directly control this parameter. The decisions faced by the network designer are the establishment of thresholds and timeouts for the transmission of the requests, and the design of the control node (scheduling of requests, number of processors, choice of the RWA algorithm). Different choices of these will lead to a different value in the average idle time. In this paper, the idle time and its optimum value as a function of the traffic load are considered only. With these assumptions, the maximum traffic load that the OBS-DWA network can support for a desired edge delay can be obtained, and these results are independent of the design options explained above.

For every possible connection the following parameters are defined:

- *Average input bit rate between source-destination nodes* ($\bar{b}_{in}$).
- *Capacity (bit rate) of a lightpath* (b_{core}).
- *Average size of the bursts or flows* ($\bar{L}_{flow}$).
- *Average wavelength holding time* ($\bar{t}_{WHT}$), the average duration of a lightpath. It is defined as the time elapsed from when the lightpath (i.e., the route-wavelength pair) is reserved until the deletion of the lightpath,

$$\bar{t}_{WHT} = \bar{t}_{ack} + \bar{L}_{flow} / b_{core} + \bar{t}_{prop}, \tag{1}$$

where $\bar{t}_{ack}$ is the time for the transmission of the acknowledgement from the control node to the edge router, $\bar{L}_{flow}/b_{core}$ is the time needed for the transmission of the burst, and $\bar{t}_{prop}$ is the propagation time (the lightpath cannot be deleted until the last bit transmitted reaches the destination node, therefore the propagation time is included in the equation).

- *Round trip-time* ($\bar{t}_{RTT}$) is the amount of time that the established lightpath is not used to transmit data. Hence,

$$\bar{t}_{RTT} = \bar{t}_{ack} + \bar{t}_{prop}\,. \tag{2}$$

- *Bandwidth utilisation* (*U*) represents the lightpath utilisation efficiency, that is, the average fraction of time that an established lightpath is used for data transmission.

$$U = \frac{\bar{L}_{flow}/b_{core}}{\bar{t}_{RTT} + \bar{L}_{flow}/b_{core}} = \frac{\bar{L}_{flow}}{b_{core}\bar{t}_{WHT}}\,. \tag{3}$$

- *Fraction of time that a possible connection is established* (ρ). As previously stated, a possible connection alternates between two states. It is *idle* during periods of random time with average $\bar{t}_{idle}$, and *established* during periods of average duration $\bar{t}_{WHT}$ (*Figure 2*).

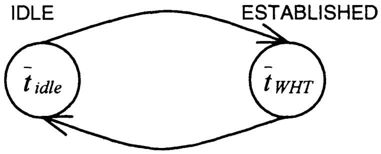

Figure 2. States diagram for the evolution of a possible connection.

Hence, the proportion of time that a possible connection is established is

$$\rho = \frac{\bar{t}_{WHT}}{\bar{t}_{idle} + \bar{t}_{WHT}}\,. \tag{4}$$

- *Traffic load* (ν),

$$\nu = \frac{\bar{b}_{in}}{b_{core}}\,. \tag{5}$$

This parameter is equal to the product of the fraction of time that the possible connection is established and the lightpath utilisation efficiency,

$$v = \rho \cdot U . \tag{6}$$

- *Average edge delay* ($\bar{t}_{edge}$), the average time elapsed from the arrival to an edge router of the first bit of the first packet making up the contents of the burst until the transmission of the burst. This parameter determines the end-to-end delay, and it should be minimised, depending on the requirements of the class of service.

The previous parameters refer to individual possible connections, but they can be extended to the complete network averaging the values of all the possible connections. The most important of these network parameters are:

- *Average normalised lightpath load* ($\bar{\rho}$), the average of the ρ parameter for all the connections. It represents the average fraction of lightpaths that are established in the network. Therefore, $0 \leq \bar{\rho} \leq 1$. Note that the average number of lightpaths established in the network ($\bar{L}$), is $\bar{L} = \bar{\rho} K$ ($0 \leq \bar{L} \leq K$).
- *Network traffic load* ($\bar{v}$),

$$\bar{v} = \frac{\bar{\bar{b}}_{in}}{b_{core}} , \tag{7}$$

where the double bar refers to the average for all the possible connections. This parameter is also equal to the product of the fraction of lightpaths established and the average lightpath utilisation efficiency,

$$\bar{v} = \bar{\rho} \cdot \bar{U} . \tag{8}$$

3. LIMITS ON THE TRAFFIC LOAD DUE TO THE EDGE DELAY CONSTRAINTS AND THE BURST (FLOW) AGGREGATION METHOD

The edge delay is a key parameter as it determines the end-to-end delay. It is, in turn, determined by the arriving packet statistics and the mechanism of burst/flow aggregation used. We propose two possible methods for the flow aggregation, which have a different effect on the edge delay. While a burst is in the process of transmission, new data arrive to the buffer. In the first method, these new data are not added to the current burst, and therefore, they must wait for another lightpath to be established for their transmission. Hence, when the lightpath is deleted, there may be some data in the buffer. In the second method, the new data arriving to the buffer are considered as part of the current burst, and hence, the lightpath is only deleted when the buffer is completely empty. We call *Limited Size Bursts* (*LS-Bursts*) to the former method and *Not-limited Size Bursts* (*NS-Bursts*) to the latter one.

In this section, it is shown that the requirements on the average edge delay may impose a bound on the maximum traffic load between a source-destination pair, depending on the flow aggregation method used. The results are obtained for every possible connection, but they hold for the entire network when averaging among all the connections.

In a quasi-static WRON where all possible connections between nodes are quasi-permanently established by means of lightpaths, there is no edge delay, as data can be transmitted directly on the lightpath. Therefore, if the network must carry a higher network traffic load than the bounds obtained in this section, the OBS option would not bring any advantages over the quasi-static WRON. If only a few possible connections must carry a higher traffic load than the bound, then it could be advantageous to establish quasi-permanent lightpaths for these.

3.1 Limited Size of the Bursts (LS-Bursts)

For the LS-Bursts method, the length of the burst is known when the data transmission begins. This value is proportional to the time elapsed to build the burst (the edge delay) and to the input bit rate. Therefore, the following relationship applies:

$$\bar{t}_{edge} = \frac{\bar{L}_{flow}}{\bar{b}_{in}}, \tag{9}$$

and using the equations (1–6),

$$\bar{t}_{edge} = \frac{\bar{t}_{WHT}}{\rho} = \bar{t}_{idle} + \bar{t}_{WHT} = \frac{\bar{t}_{idle} + \bar{t}_{RTT}}{1-\nu}. \tag{10}$$

Note that even if the idle time is zero, the edge delay cannot be zero as it depends on the round-trip time and the traffic load.

Figures 3 to *5* show the average edge delay, the bandwidth utilisation factor and the fraction of time that a possible connection is established as a function of the idle time and the traffic load. We assume that $\bar{t}_{RTT} = 5$ ms (which corresponds to a network diameter of 1000 km approximately).

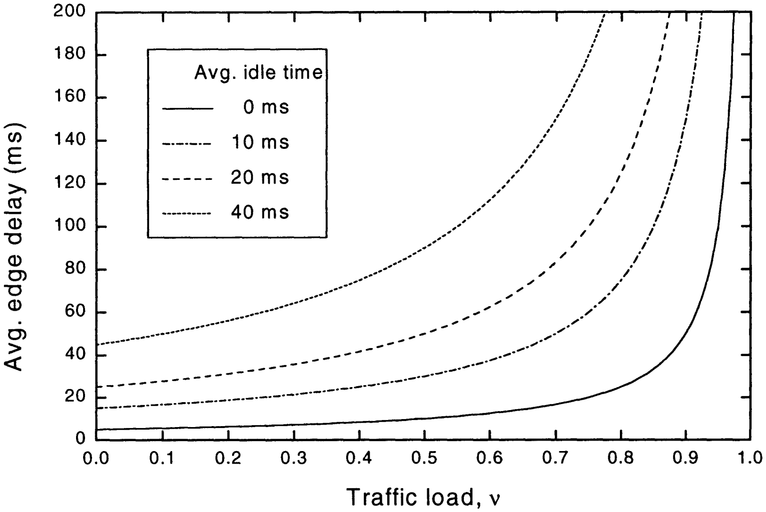

Figure 3. Average edge delay ($\bar{t}_{edge}$) vs. traffic load (ν) for different average idle times.

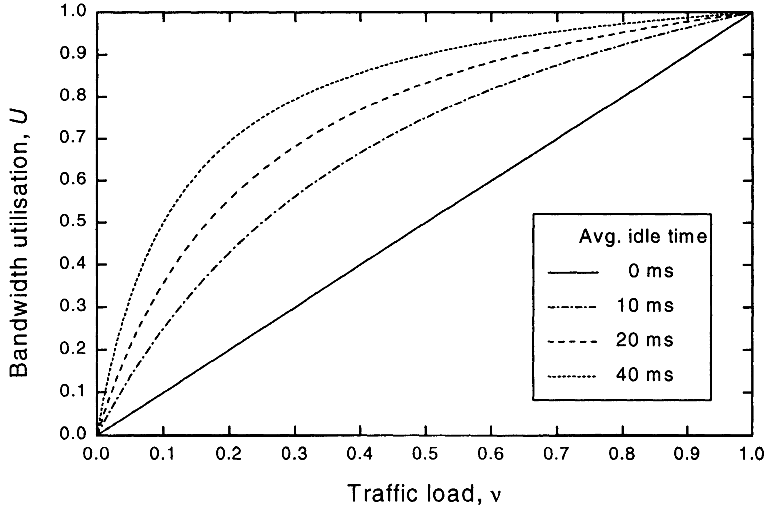

Figure 4. Bandwidth utilisation (or lightpath utilisation efficiency, *U*) vs. traffic load (ν) for different average idle times.

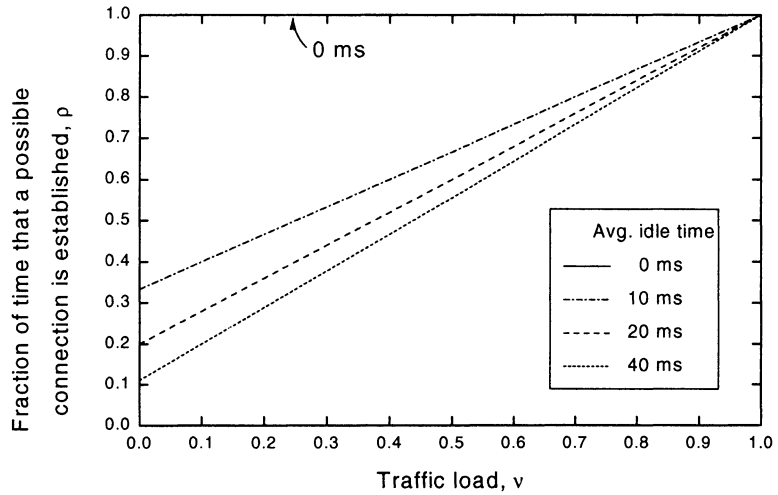

Figure 5. Fraction of time that a possible connection is established (ρ) vs. traffic load (ν) for different average idle times.

As shown in *Figure 3*, the edge delay increases with the increase in the idle time. However, the increase in idle time leads to an increase in the length of the bursts, and since the overhead ($\bar{t}_{RTT}$) remains constant, each lightpath is more efficiently used (*Figure 4*). In turn, this implies that the possible connection remains established a reduced fraction of time (*Figure 5*). Therefore, when considering the entire network[1], fewer lightpaths are needed to transport a given traffic load, and thus a lower number of wavelengths.

Hence, if the network must provide an average edge delay below or equal to a value $\bar{t}_{edge\_required}$, the optimal average idle time ($\bar{t}_{idle\_opt}$) for a given traffic load is that which provides the maximum allowed edge delay by the requirements of the class of service. Hence,

$$\bar{t}_{idle\_opt} = \bar{t}_{edge\_required}(1-\nu) - \bar{t}_{RTT} . \tag{11}$$

Since the idle time cannot be negative, the maximum traffic load for a possible connection that the OBS network can support is given by

$$\nu_{max} = 1 - (\bar{t}_{RTT} / \bar{t}_{edge\_required}) . \tag{12}$$

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[1] Note that *Figure 5* also holds for this case, assuming the parameters are the network averages instead of being the values of a single possible connection. Then, the x-axis would represent the network traffic load, and the y-axis the average normalised lightpath load.

Therefore, when this method is used to build the bursts, the edge delay places a limit on the maximum traffic load between pairs of nodes that the network can support.

3.2 Not-limited Size of the Bursts (NS-Bursts)

When using the NS-Bursts method, the duration of the burst is not known when the data transmission begins. Since data arriving to the buffer while the lightpath is still established are also transmitted using the current lightpath, eq. (9) does not hold. As mentioned previously, a lightpath is held until the buffer is completely empty. The time elapsed from the transmission of the last bit of the burst i until the transmission of the first bit of the burst $i+1$ is $\bar{t}_{prop} + \bar{t}_{idle} + \bar{t}_{ack}$. During this time, the burst $i+1$ is built. First of all, there is a finite amount of time until a bit arrives to the empty buffer ($\bar{t}_{silence}$), and then, some time elapses until its transmission, and that is the edge delay ($\bar{t}_{edge}$). Therefore, $\bar{t}_{prop} + \bar{t}_{idle} + \bar{t}_{ack} = \bar{t}_{silence} + \bar{t}_{edge}$, and using eq. (2), $\bar{t}_{idle} = \bar{t}_{silence} + \bar{t}_{edge} - \bar{t}_{RTT}$. In general, $\bar{t}_{silence} << \bar{t}_{edge} - \bar{t}_{RTT}$, except for very low traffic loads (see appendix for details), so

$$\bar{t}_{edge} \approx \bar{t}_{idle} + \bar{t}_{RTT} . \tag{13}$$

Note that *Figures 4* and *5* are also valid for this method (again with $\bar{t}_{RTT} = 5$ ms), as they are plotted as a function of $\bar{t}_{idle}$. When using this method, the minimum edge delay that the network can provide is only bounded by the round-trip time. Regarding the traffic load, the limiting case where the input bit rate between source-destination nodes were equal to the core bit rate, could be handled by the network as the lightpath would be held forever, therefore $v_{max} = 1$. Then, with NS-Bursts, the edge delay does not place any limit on the maximum load between pairs of nodes that the network can support.

4. LIMITS ON THE TRAFFIC LOAD DUE TO THE EFFICIENCY OF THE DYNAMIC RWA ALGORITHMS

As mentioned in the introduction, the OBS approach potentially allows a better utilisation of the bandwidth provided by the network. This feature can be exploited to minimise the number of wavelengths used in the network or the number of transmitters and receivers within the nodes. We consider here the first option, and we analyse the limitations on the traffic load imposed by the efficiency in terms of wavelengths of the dynamic RWA algorithm used.

In quasi-static WRONs, the RWA problem is solved through an off-line analysis and the complete set of lightpaths to be established is known a priori. Therefore, efficient algorithms can be applied [3] to obtain a solution that minimises the number of wavelengths. On the other hand, dynamic RWA algorithms must operate in real time so that they must be fast and may not lead to an optimal utilisation of the network resources, specifically the number of wavelengths. Besides, the algorithm must take decisions on a request by request basis. This process involves deciding whether to accept or not a request for a lightpath, and if it is accepted to look for a route and wavelength. If reconfiguration of the routes and wavelengths of the established lightpaths is allowed, then it would be possible to employ always a lower number of wavelengths (or equal) than in a quasi-static WRON, but in this approach, we do not consider reconfiguration due to the short duration of the connections.

For a given topology, RWA algorithm, traffic characteristics and a maximum desired lightpath blocking probability, the number of wavelengths needed is an increasing function of the average normalised lightpath load, $\overline{\rho}$. A new parameter, the *wavelength gain* ($G_W(\overline{\rho})$) can be defined as

$$G_W(\overline{\rho}) = \frac{W_{quasi-static}}{W_{dynamic}(\overline{\rho})}, \tag{14}$$

where $W_{quasi\text{-}static}$ is the number of wavelengths required in a quasi-static WRON (with all the K lightpaths established), and $W_{dynamic}$ is the number of wavelengths required in the dynamic case for a given average normalised lightpath load. The OBS approach will bring advantages when $G_W(\overline{\rho}) > 1$ as a lower number of wavelengths than in the quasi-static case would be used. Therefore, we define the *limiting average normalised lightpath load* ($\overline{\rho}_{lim}$) as the value of $\overline{\rho}$ for which the wavelength gain is equal to one. Hence, for a lightpath utilisation of $U = 1$, the maximum average network traffic load would be limited by $\overline{\rho}_{lim}$,

$$\overline{v}_{max} = \overline{\rho}_{lim}. \tag{15}$$

The maximum network traffic load is therefore limited by the efficiency in terms of wavelengths of the dynamic RWA algorithm. The more efficient the algorithm is, the closer $\overline{\rho}_{lim}$ (and therefore, $\overline{v}_{max}$) will be to one. The main problem is that a more efficient algorithm is usually slower, and therefore, it may not be adequate to fulfil the requirements on the edge delay. Besides, note that for a given RWA algorithm, the requirement of a lower blocking probability implies a lower value of $\overline{\rho}_{lim}$ (and thus of $\overline{v}_{max}$).

5. COMPARISON OF OBS AND QUASI-STATIC WAVELENGTH ROUTED OPTICAL NETWORKS

The aim is to find the range of parameters that make the OBS network with dynamic wavelength allocation a suitable option compared to a quasi-static WRON. When using LS-Bursts, the maximum *network* traffic load is given by:

$$\overline{v}_{max} = \overline{\rho}_{lim} - \frac{\overline{\overline{t}}_{RTT}}{\overline{\overline{t}}_{edge}}, \tag{16}$$

and when using NS-Bursts, the maximum *network* traffic load is given by:

$$\overline{v}_{max} = \overline{\rho}_{lim} - \left(\frac{\overline{\overline{t}}_{RTT}}{\overline{\overline{t}}_{edge} - \overline{\overline{t}}_{RTT}} \right) \left(1 - \overline{\rho}_{lim}\right), \tag{17}$$

where $\overline{\overline{t}}_{RTT}$ and $\overline{\overline{t}}_{edge}$ are the averages of the round-trip times and edge delays (respectively) of all the possible connections.

In *Figure 6* we plot these equations for different values of the edge delay for $\overline{\overline{t}}_{RTT} = 5$ ms.

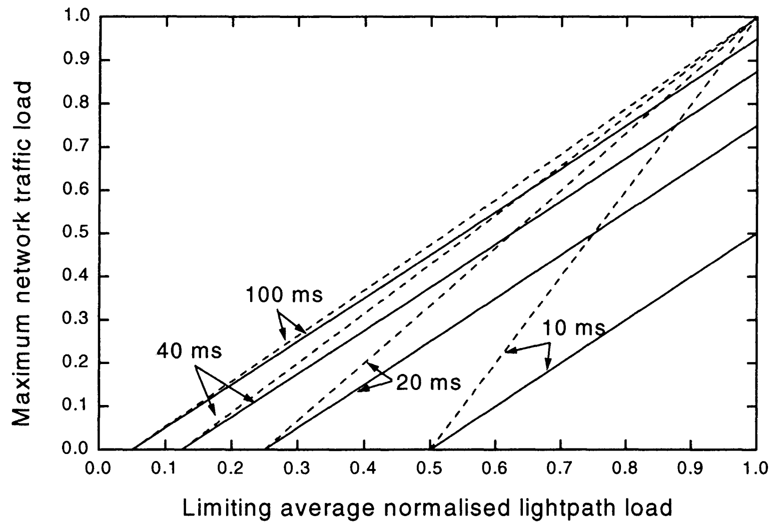

Figure 6. Maximum network traffic load ($\overline{\nu}_{max}$) vs. limiting average lightpath load ($\overline{\rho}_{lim}$) for different average edge delays ranging from 10 to 100 ms. Solid lines represent the limits for LS-Bursts, and dashed lines those for NS-Bursts.

Therefore, the maximum network traffic load that the network can support is determined by the method used to build the bursts (LS-Bursts or NS-Bursts), the requirements of the class of service (edge delay and PLR, and therefore, the blocking probability of the lightpaths) and the efficiency of the dynamic RWA algorithm. Note that if a wavelength gain higher than one is required, then the network must operate with $\overline{\rho}$ lower than $\overline{\rho}_{lim}$, implying a lower maximum network traffic load.

The comparison between NS-Bursts and LS-Bursts is not as obvious as it may seem. If the same value of $\overline{\rho}_{lim}$ were obtained for both methods, then NS-Bursts would be a better option as the network could support more traffic than with LS-Bursts. This condition approximately holds if the calculation time of the RWA algorithm is zero. But some preliminary simulations have shown that in a not ideal case where the calculation time is not zero, there is a decrease on $\overline{\rho}_{lim}$ for NS-Bursts, which may lead to a lower maximum network traffic load than for LS-Bursts.

By way of an example and comparison with the quasi-static WRON, the NSFNet topology, described in [2], is considered. In the static case, 13 wavelengths are needed to establish all the possible connections (*K* lightpaths) [2]. To study the dynamic case, we have implemented the AUR-EXHAUSTIVE algorithm proposed in [13] and set the maximum desired blocking probability to $p_B = 10^{-4}$. An ideal zero calculation time of the RWA algorithm and a round-trip time of 5 ms have been assumed. The traffic arriving to the edge buffers is modelled as an ON-OFF model (see appendix for details), and we have set a uniform traffic matrix, so that there is the same average traffic load between all pairs of source-destination nodes. When a timer (set to the difference between the desired edge delay and the propagation delay of the request to the control node) is exceeded, the lightpath is immediately established. Since the blocking probability is low, the traffic load is equal for all pairs of edge routers, and there is no interaction between the possible connections (there is no queue in the control node due to the zero calculation time assumption), the number of lightpaths approximately follows a binomial distribution (it would be exact if there were no blocking).

For this example and using LS-Bursts (*Figure 7*), the value of the limiting average normalised lightpath load is $\bar{\rho}_{lim} = 0.68$. Then, if the required average edge delay is 40 ms and $G_W = 1$, the maximum traffic load is $\bar{\nu}_{max} = 0.56$. For a higher wavelength gain, the network must operate with $\bar{\rho}$ lower than $\bar{\rho}_{lim}$, and hence $\bar{\nu}_m$ will decrease too. For instance, for a wavelength gain of 1.18 (such that 11 wavelengths are required rather than 13), the maximum mean normalised lightpath load is 0.51 and $\bar{\nu}_m$ decreases to 0.39. Note that if a lower blocking probability is required, $\bar{\rho}_{lim}$ decreases and thus $\bar{\nu}_m$.

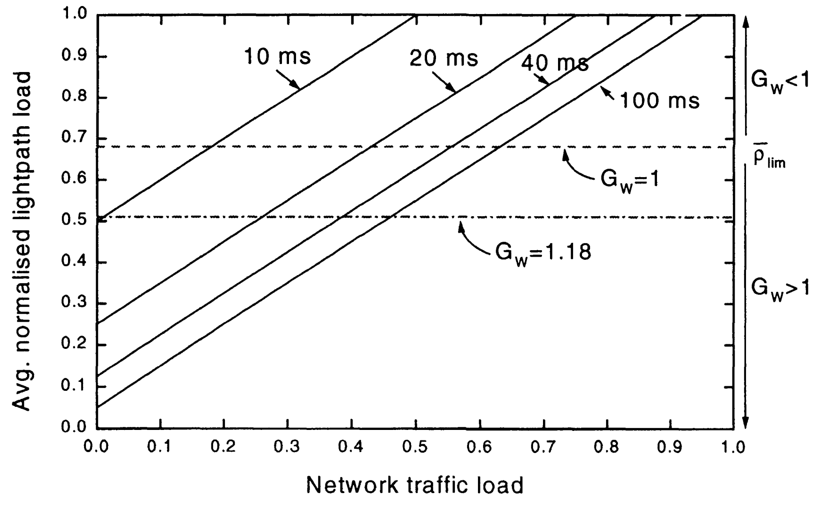

Figure 7. Average normalised lightpath load ($\bar{\rho}$) vs. network traffic load ($\bar{\nu}$) for different average edge delays. $\bar{\rho}_{lim}$ and G_W are represented for the NSFNet, setting a uniform traffic matrix. For clarity of the figure, only edge delays corresponding to LS-Bursts have been shown.

For NS-Bursts (not shown in *Figure* 7), the same value of $\overline{\rho}_{lim}$ is obtained as the calculation time was assumed to be zero, and hence, the maximum network traffic load is higher than for LS-Bursts (0.63 for $G_W = 1$, and 0.44 for $G_W = 1.18$).

6. SUMMARY

The maximum traffic load that an OBS network with dynamic allocation and centralised control can support has been studied. It has been shown that tight constraints in the required edge delay and in the blocking probability, as well as the utilisation of dynamic RWA algorithms with a low efficiency in terms of wavelengths results in a limitation on the maximum traffic load that can be carried. If the traffic load that the network must support is higher than that value, then a quasi-static WRON or semi-permanent lightpaths between selected pairs of edge routers should be used. It has also been shown that there is a trade-off between the edge delay and the number of wavelengths required in the network. Lower edge delays require a higher average number of lightpaths in the network, and therefore a higher number of wavelengths.

Two different approaches to build the bursts have been proposed: LS-Bursts and NS-Bursts. The latter option allows higher traffic loads in the network for the same edge delay assuming an ideal scenario where the calculation time of the dynamic RWA algorithm is zero, but preliminary simulations have shown that in a realistic case, the comparison between both methods is not so obvious. On the other hand, when using LS-Bursts, the length of the burst is known when its transmission starts, and that information could be used by the control node in processing other requests. Therefore, the optimisation of burst-formation requires further analysis.

APPENDIX

First of all the traffic model assumed is presented, and then, it is shown that for NS-Bursts, $\bar{t}_{idle} = \bar{t}_{silence} + \bar{t}_{edge} - \bar{t}_{RTT} \approx \bar{t}_{edge} - \bar{t}_{RTT}$

We have modelled traffic arriving to the edge buffers as an ON-OFF model. The length of the ON (packets arriving) and OFF (interarrival time) periods are modelled according to the Pareto distribution. The length of the ON periods (in bits) is $\lfloor A_{ON}/U^{\alpha} \rfloor$, where U is a random variable uniformly distributed on [0,1], $1 < \alpha \leq 2$ so that the length of the periods has finite mean and infinite variance, and A_{ON} is the minimum size of the packets. The length of the OFF periods is set using the same distribution and value of α, but the minimum size of the periods is adjusted in order to achieve the desired average input bit rate (and hence the desired traffic load). During the ON period data is arriving at a bit rate of b_{ON}, with $b_{ON} \le b_{core}$. Obviously, $b_{ON} \ge \bar{b}_{in}$. The relationship between these parameters is

$$\bar{b}_{in} = \frac{b_{ON}\bar{t}_{ON}}{\bar{t}_{ON} + \bar{t}_{OFF}},$$

where $\bar{t}_{ON}$ is the average duration of the ON periods:

$$\bar{t}_{ON} = \left(\frac{A_{ON}\alpha}{\alpha - 1}\right)\Big/ b_{ON},$$

and $\bar{t}_{ON}$ is the average duration of the OFF periods,

$$\bar{t}_{OFF} = \left(\frac{A_{OFF}\alpha}{\alpha - 1}\right)\Big/ b_{ON}$$

In order to achieve a certain traffic load v, the minimum length of the OFF periods is set to:

$$A_{OFF} = A_{ON}\left(\frac{v_{ON}}{v} - 1\right), \text{ where } v_{ON} = \frac{b_{ON}}{b_{core}}.$$

$\bar{t}_{idle} \approx \bar{t}_{edge} - \bar{t}_{RTT} \Leftrightarrow \bar{t}_{edge} - \bar{t}_{RTT} >> \bar{t}_{silence}$. The parameter $\bar{t}_{silence}$ is the average time elapsed from when the buffer is completely empty until the first bit arrives, so $\bar{t}_{silence} < \max\{\bar{t}_{OFF}, 1/b_{ON}\}$. Hence, if $\bar{t}_{edge} - \bar{t}_{RTT} >> \max\{\bar{t}_{OFF}, 1/b_{ON}\}$, then $\bar{t}_{idle} \approx \bar{t}_{edge} - \bar{t}_{RTT}$. Therefore the approximation holds if

$$\bar{t}_{edge} - \bar{t}_{RTT} >> \frac{1}{b_{ON}} \text{ and } v >> \frac{A_{ON}(b_{ON}/b_{core})}{A_{ON} + (\bar{t}_{edge} - \bar{t}_{RTT})b_{ON}\left(\frac{\alpha - 1}{\alpha}\right)}.$$

For a desired $\bar{t}_{edge}$=10 ms and $\bar{t}_{RTT}$=5 ms the first inequality holds if $b_{ON} >> 200$ bps, which is clearly satisfied. The worst case for the second inequality is obtained with $b_{ON} = b_{core}$. If we set A_{ON}=3200 bits (400 bytes), α=1.5, and $b_{ON} = b_{core}$ = 1 Gbps, the second part holds if $v >> 1.9 \cdot 10^{-3}$. Therefore, $\bar{t}_{idle} \approx \bar{t}_{edge} - \bar{t}_{RTT}$ except for very low traffic loads.

In the simulation presented in section 5, the model and parameters described have been used.

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