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Prediction and Pre-booking for Guaranteed Service Provisioning in Future Wavelength-Division Multiplexing (WDM) Networks

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Abstract: Future Wavelength-Division Multiplexing (WDM) networks should not only support flexible resource-provisioning, but also transport various services with regulated end-to-end delay. In large-scale backbone networks with dynamic lightpath provisioning, the resource reservation overhead is high due to the latencies involved, thus limiting the capability of end-to-end delay guaranteed service provisioning. This paper proposes a traffic prediction and pre-booking mechanism to reduce the reservation overhead in traditional reactive two-way reservation protocols and consequently enhance the network performance. The proposed mechanism is investigated with regard to end-to-end delay and on blocking probability with both constant bit rate and self-similar traffic. The results demonstrate that in large networks, such as NSFNET, the proposed pre-booking mechanism is able to bring significant benefits beyond familiar Wavelength-Routed Optical Burst Switching (WR-OBS) in terms of burst/bit blocking probability and lightpath bandwidth efficiency.

Keywords: end-to-end delay, dynamic WDM network, prediction, pre-booking.

1. INTRODUCTION

Future Wavelength-Division Multiplexing (WDM) networks are expected to support dynamic resource provisioning, as well as providing Quality of Service (QoS) - guaranteed and differentiated services. Current quasi-static Wavelength Routing (WR) places the lightpaths semi-permanently, so it is not adaptive to short-term varying traffic patterns and consequentially yields low bandwidth efficiencies. Optical Burst Switching (OBS) provides a packet-switching-like buffer-less transportation medium [1]. However, this connection-less protocol suffers from unpredictable blocking rates, thus being hard to provide guaranteed services. Wavelength-Routed OBS (WR-OBS) combines OBS with dynamic lightpath assignment under fast circuit switching to provide end-to-end guaranteed services without requiring wavelength conversion support [2]. WR-OBS yields both of the desired features for future WDM networks, so it is a prospective candidate for future WDM networks.

However, new optical services, such as online multimedia services, are relatively sensitive and constrained by the lightpath setup delay. In large optical backbones, the two-way reservation overhead in WR-OBS becomes an impediment for end-to-end delay guaranteed service provisioning [3]. To this end, the concept of “delayed reservation” in Just-Enough-Time (JET)-based OBS [4], where the bandwidth is only reserved as necessary, appears very attractive for WR-OBS in terms of reservation overhead reduction. This paper takes WR-OBS as an example of the future WDM network, and proposes a traffic prediction and pre-booking mechanism as an enhancement. The key feature of the proposition is that it excludes the lightpath acknowledgement delay from the lightpath holding time by "pre-booking" each burst/flow based on the estimated characteristics of arriving traffic, thus empirically improving resource utilization.

Specifically, in order to compensate for the lightpath reservation overhead, the WR-OBS reservation request is sent before the completion of the burst aggregation, taking the estimated burst length information to the lightpath assignment segment. Existing research with WR-OBS is mostly based on constant bit rate traffic or perfect knowledge of the burst length. Therefore, the first contribution of this paper is to investigate the aggregated burst length characteristics for widely observed self-similar traffic, and introduce a prediction mechanism for this type of incident traffic. It also deduces an analytical model for the bit loss rate calculation with the proposed prediction mechanism.

Additionally, this paper proposes a pre-booking mechanism to better support traffic with strict requirements on end-to-end delay and blocking probability in spatially large backbone networks. The pre-booking mechanism takes advantage of traffic prediction to proactively obtain lightpaths from the central reservation node, and send bursts during these reserved time slots. The lightpath is only established during the burst transmission, so the wavelength resources are only consumed, as necessary. The exclusion of lightpath acknowledgement propagation time effectively increases the wavelength resource utilization and lightpath bandwidth efficiency, because the acknowledgement delay may comprise a significant portion of the lightpath holding time in geographically large networks.

The remaining text in the paper is organised as follows: Section 2 describes the burst length distribution and prediction mechanism for self-similar incoming traffic. Section 3 then describes the proposed pre-booking mechanism in detail and Section 4 provides representative simulation results. Finally, in Section 5, the paper is concluded.

2. BURST LENGTH PREDICTION MECHANISM

Self-similar behaviour is widely observed in multi-service networks. Generally, there is a cut-off timescale beyond which the traffic exhibits mono-fractal scaling with a constant Hurst parameter *H*, whilst within short timescales the traffic displays complex multi-fractal behaviour. Although the cut-off timescale is around the round-trip time on the order of a few hundred milliseconds or seconds In Wide Area Networks (WAN) [5], the cut-off timescale is expected to decrease due to the high bandwidth and aggregation level [6] in ultra-high speed long-haul WDM backbones (beyond 10Gbps). It has been observed that the traffic trace collected from OC3/12/48 links of a US tier-1 backbone network manifests almost mono-fractal behaviour within timescales from 1 to 100 milliseconds [7] [8]. In our proposal, the bursts aggregation time ranges from milliseconds to tens of milliseconds, so we can safely assume that the traffic within the aggregation timescale is stationary *H*-self-similar.

2.1. Burst Length Statistics

By the additive property of *H*-self-similar traffic, many researchers have found that if the aggregation time is much longer than the packet length (in time scale), the burst length follows normal distribution [2] [6] [9]. Particularly, in [6], the burst length is quantified as a Gaussian random variable with mean value $\overline{L}$ expressed in equation (1), and the variance v as shown in equation (2), where T_{aggr} is the burst aggregation time, μ is the average incoming traffic bit rate, σ^2 is its variance, and *H* is the Hurst parameter.

$$\overline{L} = T_{aggr} \times \mu \tag{1}$$

$$v = T_{aggr}^{2H} \times \sigma^2 \tag{2}$$

2.2. Prediction Mechanism and Burst Aggregation

Since the *Central Limit Theorem* applies to the burst length distribution, we propose to continuously monitor the average incoming traffic bit rate μ , its variance σ^2 , and the Hurst parameter *H*. The burst length can be predicted as the aggregated mean value plus *k* times the corresponding standard deviation, where *k* is an adjustable parameter, as shown in equation (3).

$$L_{predicted} = T_{aggr} \times \mu + k \times T_{aggr}^{H} \times \sigma \qquad (3)$$

In future carrier WDM networks, bandwidth is no longer a particular bottleneck. Therefore, the introduction of extra *k* times of the standard deviation can effectively decrease the probability that the actual burst length is longer than reservation time window.

More specifically, in WR-OBS, two burst aggregation mechanisms have been proposed, namely: *Limited-Burst Size* (LBS) and *Unlimited-Burst Size* (UBS). In the LBS approach, the burst aggregation completes when the lightpath acknowledgement is received at the edge node. Therefore, the predicted burst length can be easily derived from equation (3), and T_{aggr} is the duration from the arrival of the first bit till the arrival of the lightpath acknowledgement at the edge node. However, in the UBS approach, the aggregation does not stop when the acknowledgment is received and the existing bits start transmission. Instead, the aggregation continues until the buffer is empty. In this case, the aggregated burst length by the time when the acknowledgement is received can be estimated as in equation (4) and is denoted as $L_{predicted}^{ack}$. The term t_{ack} is the time when the acknowledgement is received by the edge node, and t_{first_bit} is the time when the first bit of the burst arrives at the buffer.

$$L_{predicted}^{ack} = (t_{ack} - t_{first\_bit}) \times \mu + k \times (t_{ack} - t_{first\_bit})^{H} \times \sigma \qquad (4)$$

Knowing $L_{predicted}^{ack}$, the time needed to empty the buffer, denoted as t_{trans} , can be deduced by solving the equation (5), where B_{out} denotes the emitted bit rate.

$$L_{predicted}^{ack} + t_{trans} \times \mu + k \times t_{trans}^{H} \times \sigma = t_{trans} \times B_{out} \qquad (B_{out} > \mu) \qquad (5)$$

If the factor of $k \times t_{trans}^{H} \times \sigma$ is small, t_{trans} can be approximated as shown in equation (6).

$$t_{trans} = \frac{L_{predicted}^{ack}}{B_{out} - \mu} \qquad (B_{out} > \mu) \qquad (6)$$

Therefore, the total predicted burst length for UBS approach $L_{predicted}^{UBS}$ can be finally expressed as in equation (7).

$$L_{predicted}^{UBS} = t_{trans} \times B_{out} = \frac{L_{predicted}^{ack} \times B_{out}}{B_{out} - \mu} \qquad (B_{out} > \mu) \qquad (7)$$

Fig.1 shows that each burst is firstly aggregated at the edge node for a short period denoted by *Taggr*. Then, a lightpath reservation request is sent to the central reservation node to request a lightpath. The reservation request includes the predicted burst length and the maximum lightpath calculation time information so that the central reservation node knows how long the lightpath should be maintained or whether the request should be rejected due to excessive request process queuing delays spent in the central node. When the reservation request reaches the central node after time *Tsig*, it is buffered in the central scheduler, and the queued requests will be scheduled via the Earliest Deadline First (EDF) principle, and processed via a Routing and Wavelength Assignment (RWA) algorithm. If the lightpath is found by the RWA algorithm, the lightpath is set to occupied and an acknowledgment is sent back to the edge node indicating that the optical switch is appropriately configured, consuming the time *Ttune*. The burst is then transmitted using time *Ttrans* and propagated using *Tprop*. However, if no lightpath is found, the request will be put into a temporary queue until a lightpath is released from the core network. The request will be rejected if it spends too long in the central node (*Tcentral*) such that the end-to-end delay parameter cannot be satisfied anymore.

Therefore, given a fixed end-to-end delay requirement *Tmax_ete*, the maximum allowable time for *Tcentral* should be expressed as equation (9), where *Tmin_prop* is the minimum end-to-end propagation delay for the specified source-destination pair.

$$T_{\max\_central} = T_{\max\_ete} - T_{aggr} - 2 \times T_{sig} - T_{tune} - T_{\min\_prop} \tag{9}$$

The lightpath holding time can be expressed as in equation (10).

$$T_{lightpath} = T_{sig} + T_{tune} + T_{trans} + T_{prop} \tag{10}$$

The lightpath bandwidth efficiency can be calculated as in equation (11).

$$E_{WROBS} = \frac{T_{trans}}{T_{lightpath}} = \frac{T_{trans}}{T_{sig} + T_{tune} + T_{trans} + T_{prop}} \tag{11}$$

3.2. Proposed Pre-booking Mechanism

The operation of our proposed pre-booking mechanism can be illustrated as shown in Fig.2.

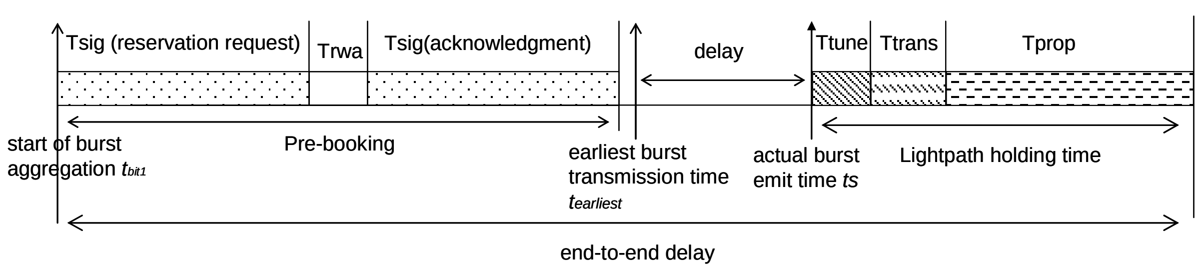

Fig.2. Time Parameters and Operations of Pre-booking Mechanism

The lightpath pre-booking request is sent at the very beginning of the burst aggregation. The request takes the earliest burst transmission time $t_{earliest}$, and the maximum edge delay *max_delay* information to the central node, such

mechanism in WR-OBS networks, we run a set of experiments for the NSFNET topology by means of simulation using OPNET™. The structure of NSFNET is shown in Fig.3, where each link yields 12 wavelengths. Pennsylvania (PA) is selected as the location of the centralised reservation node such that the maximum propagation delay from the edge nodes to the central node is minimised. In the simulations, the same amount of traffic is generated for each source-destination pair, and we define the *traffic load* as the ratio of incoming traffic bit rate at each source-destination pair to the outgoing bit rate (wavelength rate), where the outgoing bit rate is set to 10Gbps. Two traffic models are used in the simulations, namely Constant Bit Rate (CBR) and self-similar traffic. For self-similar traffic, each traffic source is aggregated from 10 independent ON-OFF Pareto sources, with α=1.5 for both ON and OFF periods, and the minimum ON period is the time taken to transmit 2.5 Kbytes.

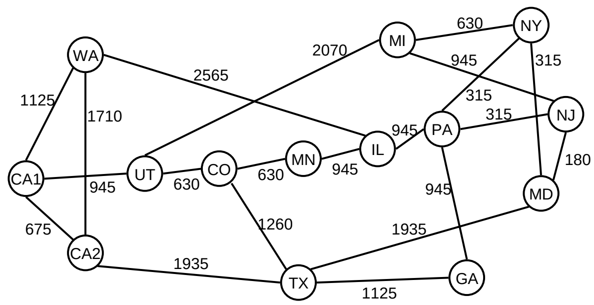

Fig.3. Original Scale of NSFNET (fiber length in kilometer)

We run the simulations placing strict constraints on end-to-end delay and on burst blocking probability. The maximum end-to-end delay is set to be 90 milliseconds, which is a typical requirement for videoconference services. The target maximum average burst/bit blocking probability was set to 10^{-4} to meet current ITU recommendations.

For comparative purposes, the parameters used in our experiments are mostly the same as the ones used in [3]. The time required by the tuneable laser to switch the wavelength, T_{tune}, is set to 1 millisecond. The average RWA calculation time in conventional WR-OBS follows a Beta distribution, bounded by 0 and 0.2 ms, and with average 0.1ms. As the RWA in pre-booking is more complicated than that in WR-OBS, we set the RWA time in pre-booking three times of that in WR-OBS. The propagation delay depends on the physical fiber length, where the propagation delay is 1 millisecond per 200 kilometres. In addition, as UBS aggregation approach is said to be able to obtain better performance than LBS aggregation approach [10], we adopt UBS as the aggregation mechanism in all our experiments. More detail of scheduling principle and RWA algorithm in WR-OBS can be found in [3], and we adopt strategy B also described in [3] to derive the results for WR-OBS.

We demonstrate the benefit of our proposed mechanism by comparing our results with the best performance obtained in conventional WR-OBS. Three major performance metrics are investigated, namely: the average burst blocking probability, the average bit loss rate, and the average lightpath bandwidth efficiency. The burst blocking probability is defined as the ratio of blocked bursts to the total number of generated bursts. The bit loss rate is the proportion of abandoned bits among the total offered bits. The lightpath bandwidth efficiency is the ratio of burst transmission time to the lightpath holding time. All the results are obtained with a 95% confidence interval.

4.1. Performance with Constant Bit Rate (CBR) Traffic

With CBR traffic, the burst length can be linearly and precisely calculated. The results shown for the CBR traffic case demonstrate the benefits of the pre-booking mechanism’s economic use of signalling. In the experiments, all the source-destination pairs yield the same value of maximum allowable edge delay, *max_delay*. Fig. 4 shows the burst

4.2. Performance with Self-Similar Traffic

With self-similar traffic, our proposed prediction strategy is applied to both pre-booking and WR-OBS architectures. The results, in terms of burst blocking probability and bit loss rate, are shown in Fig. 6, where both the *max_delay* in pre-booking mechanism and $T_{\max\_central}$ in WR-OBS are set to 20 milliseconds.

The results for burst blocking probability illustrate that our pre-booking mechanism supports higher loads than the WR-OBS mechanism for a target blocking probability. As increased *k* values correspond to a higher reservation load, the burst blocking probability performance degrades with the increase of *k* value.

However, the burst blocking probability does not provide a true measure of the total traffic loss. In fact, the overall traffic loss is not only affected by lightpath availability in terms of requested time slots, but is also affected by insufficient prior reservations. As expected, in both pre-booking and WR-OBS, the bit loss rate reduces with increasing *k* value, and the benefits of our pre-booking mechanism become apparent. For example, when *k* equals 8, our pre-booking mechanism yields a much lower bit loss rate than WR-OBS, and can support a traffic loads up to 0.4 with the targeted loss probability, whilst, WR-OBS can only support a traffic load of 0.2.

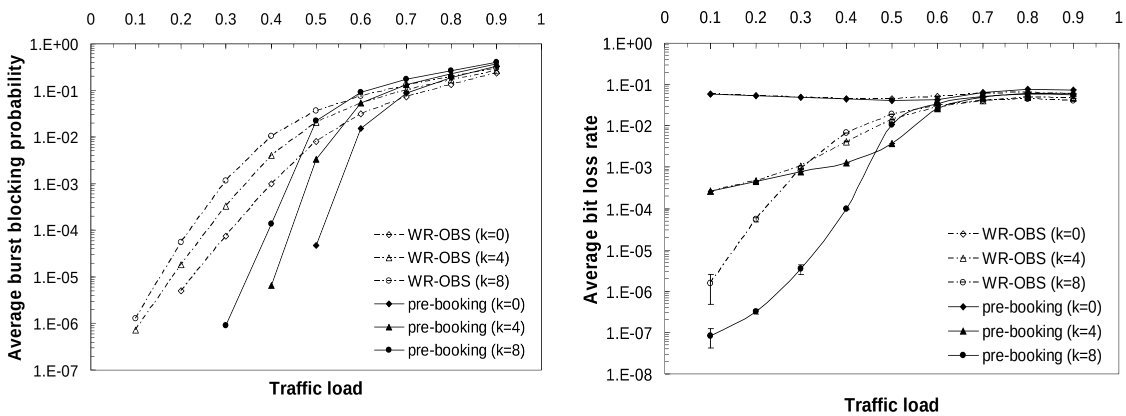

Fig.6. Traffic Loss Rate with Self-similar Traffic

Similarly, in terms of lightpath bandwidth efficiency, as shown in Fig.7, the proposed pre-booking mechanism is significantly more efficient than the WR-OBS. However, the lightpath bandwidth efficiency decreases with increasing *k* value, as larger *k* values imply a higher level of resource over-provisioning, reducing the bandwidth efficiency.

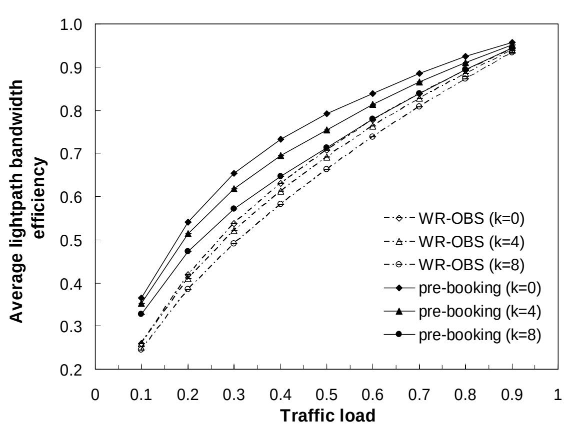

Fig.7. Lightpath Bandwidth Efficiency with Self-Similar Traffic