Performance of a Dynamically Wavelength-Routed Optical Burst Switched Network

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***Abstract*—This letter describes a novel network architecture combining optical burst switching with dynamic wavelength allocation to achieve a guaranteed quality of service. All processing and buffering functions are concentrated at the network edge and bursts are assigned to fast tuneable lasers and routed over a bufferless optical transport core using dynamic wavelength assignment. Burst aggregation is evaluated for a range of traffic statistics in terms of delay and packet loss rate, and an analytical model is given to quantify the benefits of dynamic wavelength reuse. The results define the operational gain achievable with dynamic wavelength assignment compared to quasi-static wavelength-routed optical networks.**

***Index Terms*—Burst switching, networks, optical communications, packet switching, wavelength-division multiplexing, wavelength routing.**

I. INTRODUCTION

IN FUTURE telecommunication networks, traffic with different performance requirements will be merged in the same physical layer, and will require new, adaptable network architectures. Although quasi-static wavelength-routed optical networks (WRONs) [1] are relatively simple to design and operate, they are not easily adaptable to dynamically varying traffic, and optical burst-switched (OBS) networks [2]–[5] can potentially more efficiently accommodate dynamic traffic variations by appropriately aggregating packets at the network edge. However, most conventional OBS schemes assume unacknowledged one-way reservation of network resources, and thus, cannot take into account quality of service (QoS) differentiation, or suffer from high burst loss rates (PLR) [4] at high traffic loads. Reducing loss rates for high priority traffic leads to significantly increased loss rates for lower priority traffic, the overall network performance, and is especially unfair for longer bursts [5]. To reduce burst loss, full wavelength conversion must also be assumed, and wavelengths are not used for routing, but to provide point-to-point connections only. To overcome these limitations, a wavelength-routed OBS (WROBS) network architecture was proposed in [6], the main features of which are acknowledged wavelength reservation with guaranteed latencies. In this letter, we describe new analysis and results on the burst aggregation process at the network edge, and the tradeoffs in the design of edge delay, core-to-input bitrate ratio, and the round-trip time. These results quantify bandwidth utilization and dynamic wavelength allocation gain, and define the bounds on the overhead time required for acknowledged lightpath assignment under dynamic network control.

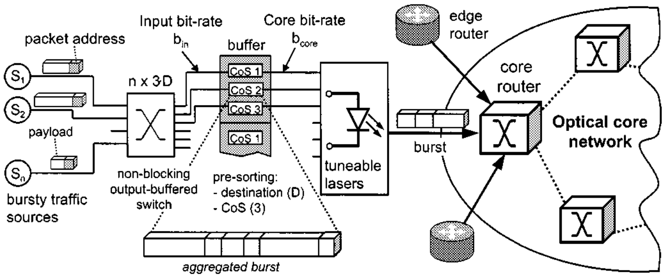

Fig. 1. Edge router model for the proposed WROBS architecture linked to the optical core network.

II. NETWORK ARCHITECTURE AND BURST AGGREGATION

The analysis in this work extends that proposed in [6] and is based on the WROBS architecture shown in Fig. 1, where electronic edge routers are connected to an optical core. The optical core is assumed to be transparent by using dense wavelength-division-multiplexing (DWDM) transport and active or passive routers to avoid the processing of header information and buffering in the core routers [7]. It is assumed that there is no wavelength conversion in core nodes, since it was previously shown that the wavelength requirements are only marginally reduced if wavelength agility is provided at the network edge [1]. Packets are presorted in the edge routers according to their class of service (CoS) and destination into separate buffers, aggregated to bursts, and dynamically assigned to an available wavelength; this occurs either when packets are dropped due to buffer overflow, or when a timeout signal dictates the release of time-critical packets to meet latency requirements. The incurred delay in the edge router t_{edge} is, thus, both deterministic and adjustable to meet the latency requirements of different traffic classes. Once predefined performance parameters, such as latency or packet loss rate (PLR) are exceeded, a wavelength request is sent to a control node, an acknowledgment is received, and the buffer content is dynamically assigned [8] to a free wavelength.

The burst aggregation was analyzed for traffic with the same mean bitrate (10 Gb/s) as shown in Fig. 2, but different packet length and packet interarrival time statistics as a function of the edge delay for a buffer size of 400 Mb (48.8 MB); this buffer size is sufficient to hold 40 ms of traffic arriving with an average bitrate of 10 Gb/s

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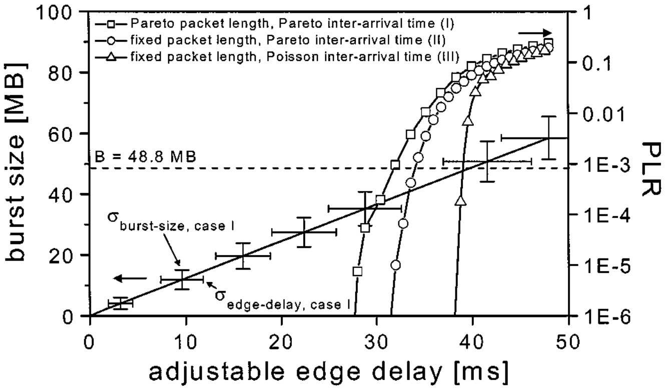

Fig. 2. Simulation results for burst size and PLR as a function of the edge delay $t_{\rm edge}$ and a mean input bit rate $\rm bin = 10$ Gb/s for different packet length and packet interarrival time statistics.

i) Pareto packet length, Pareto inter-arrival distribution;
ii) fixed packet length, Pareto inter-arrival distribution;
iii) fixed packet length, Poisson inter-arrival distribution.

In all cases, the minimum packet length was 5 kB, $\alpha = 1.5$ for the Pareto distribution [6]. The Pareto distribution describes traffic burstiness in data networks, and the Poisson distribution is an established traffic model in circuit-switched networks. Longer edge delays may be appropriate for less delay-sensitive best-effort type traffic, and will reduce wavelength requirements with dynamic network operation, as shown in Section III.

It can be seen from Fig. 2 that the largest variance of both burst size and edge delay distribution was observed for case i, resulting in significant packet loss and reducing the allowable edge delay accordingly. To maintain a mean $\rm PLR < 10^{-6}, t_{\rm edge}$ <28 ms is required for case i, whereas the same PLR can be achieved for edge delays up to 38 ms in case iii. The results indicate that the burst sizes in the WROBS scheme are not only significantly larger compared to other OBS schemes [2], [3] with a few MB of size, but that the mean burst-size behavior can be approximated by a continuous bitrate (CBR) model.

III. NETWORK MODELING RESULTS

In this model, a uniform distribution of packets addressed to other edge routers and no loss of packets in the output-queued switch are assumed. The time duration before a burst is assigned to a free wavelength, and released into the network is defined as the edge delay $t_{\rm edge}$. As described in the previous section, a CBR traffic model was assumed, for which the burst size $L_{\rm burst}$ increases linearly with the edge delay $L_{\rm burst} = t_{\rm edge} \cdot b_{\rm in}$. The wavelength holding time $t_{\rm WHT}$ denotes the period for which a given wavelength is assigned, typically in milliseconds

$$t_{\rm WHT} = t_{\rm ovhd} + \frac{L_{\rm burst}}{b_{\rm core}} = t_{\rm ovhd} + \frac{t_{\rm edge}}{A} \qquad (1)$$

where $A = b_{\rm core}/b_{\rm in}$ is the bitrate ratio. $t_{\rm ovhd}$ is the overhead time required for the lightpath setup, including propagation delays. In these calculations, a value of 5 ms was assumed, based on a network with a 1000 km diameter. The equivalent bandwidth used by a lightpath is defined as bandwidth-per-wavelength $\rm BPW = L_{\rm burst}/t_{\rm WHT}$. For high resource utilization in the physical layer, it is important that a given lightpath is used as efficiently as possible, and the bandwidth utilization U can, thus, be defined as

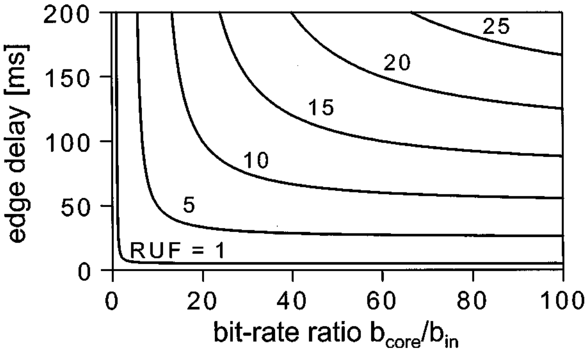

Fig. 3. Mean wavelength reuse factor (RUF) as a function of the edge delay $t_{\rm edge}$ and bitrate ratio A for overhead time $t_{\rm ovhd} = 5$ ms.

$$\rm U = \frac{BPW}{b_{core}} = \frac{t_{edge}}{A \cdot t_{ovhd} + t_{edge}}. \qquad (2)$$

As $b_{\rm core} \gg b_{\rm in}$ can be assumed for a high-speed optical core $t_{\rm WHT} \ll t_{\rm edge}$. In this case, the time required to transmit a burst, and therefore, the time for which a given wavelength is used is much shorter than the edge delay. In the case of dynamic wavelength allocation, an unused wavelength can be assigned to another edge router, and the resultant increase in the wavelength reuse is denoted by a wavelength reuse factor RUF defined as

$$\rm RUF = \frac{t_{\rm edge}}{t_{\rm WHT}} = \frac{A \cdot t_{\rm edge}}{A \cdot t_{\rm ovhd} + t_{\rm edge}} = A \cdot U. \qquad (3)$$

and is plotted in Fig. 3 for 0 ms $\leq t_{\rm edge} \leq$ 200 ms, $0 \leq A \leq 100$, and $t_{\rm ovhd} = 5$ ms. These results clearly show that with this network approach the following different types of traffic could be accommodated: low delays, required for time-critical types of traffic, are achievable, but with low values of utilization U, especially for large bit rate ratios. It is possible to design a network with $U > 80\%$ for $A > 10$ and delays > 50 ms. From Fig. 3, it can be seen that RUF reaches maximum values with both increasing $t_{\rm edge}$ and A. For comparison, Fig. 3 also shows the equivalent to the case of a static WRON where $\rm RUF = 1$. For values of $\rm RUF < 1$, the network would theoretically require more wavelengths than in a static WRON, and this represents the region of network instability, where the total input load exceeds the network throughput.

The time to set up a lightpath is $t_{\rm ovhd}$, required for signalling between edge routers and the network control element, either central or distributed. To ensure that $\rm RUF > 1$ as defined in (3), it is required that $t_{\rm ovhd} < (A-1) \cdot t_{\rm edge}/A \Leftrightarrow t_{\rm ovhd} < t_{\rm edge}$ for $A \gg 1$. The variation of RUF is plotted against $t_{\rm ovhd}$ for given edge delays (10, 20, 50 ms) and $A = 20$ in Fig. 4. An important result is that for $A \gg 1$ as in high core bit rate networks, a high reuse factor is achieved only for $t_{\rm ovhd}$ of a few milliseconds. It

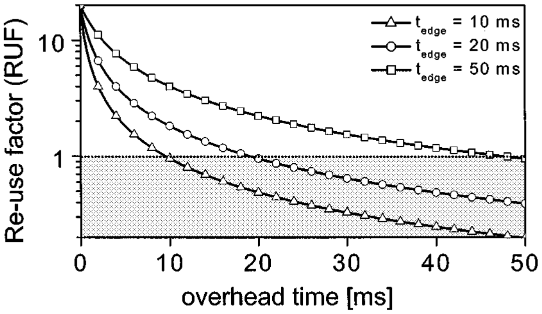

Fig. 4. Wavelength reuse factor (RUF) as a function of the overhead time $t_{\rm ovhd}$ for edge delays $t_{\rm edge} = 10, 20$, and 50 ms. Shaded region: Network requires more wavelengths than a static WRON.

should be noted that to achieve efficient wavelength reuse, the lightpath setup time must be as small as possible, and for a fixed $t_{\rm edge}$, the upper bound in RUF is given by $\mathrm{RUF}_{\max} = A$.

The proposed architecture can, therefore, accommodate traffic with a wide range of delay requirements over the same network. Delay-sensitive traffic, such as voice, would only be queued at the edge for 10–20 ms before being assigned to a free wavelength with the penalty of a relatively low reuse factor (<5) as shown in Fig. 3. Less delay-sensitive traffic, such as data, can be routed over the network in parallel, but with longer edge delays allowing for a higher reuse of wavelength resources.

The lower bound for the required edge delay is the overhead time required for lightpath setup $t_{\rm ovhd}$ as shown in Fig. 4. Providing, therefore, the acceptable $t_{\rm edge}$ significantly exceeds $t_{\rm ovhd}$, high values of $A > 10$ allow to improve network design, although a high bitrate does not necessarily improve bandwidth utilization if the signalling overhead dominates the lightpath setup time. It should be noted that the overhead time is a lower bound on the lightpath setup time and whether it can be achieved depends on the efficiency of the deployed routing and wavelength assignment (RWA) algorithm.

IV. SUMMARY

New analysis of an adaptive optical burst-switched network is reported, which allows to quantify the operational gain achievable with dynamic wavelength allocation. It was shown that for the limiting case of CBR traffic, an analytical model for the edge router can be derived, and that this architecture allows to achieve a range of edge delays to satisfy the latency requirements of different traffic types using the same physical infrastructure. Bandwidth utilization and wavelength reuse were introduced to calculate the gain with dynamic wavelength allocation, which has the two-fold benefit of reducing wavelength requirements and enabling the network to respond to variable traffic demands. For the proposed network architecture wavelength reuse factors greater than 25 and 10 could be achieved for edge delays up to 170 and 50 ms, respectively. The time required for lightpath setup $t_{\rm ovhd}$ is a lower bound on the achievable edge delays and must be minimized by a fast RWA algorithm. The results are applicable to the design and the dimensioning of WROBS networks and the optimization of RWA algorithms under dynamic network control.

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