WAVELENGTH ROUTING AND OPTICAL BURST SWITCHING IN THE DESIGN OF FUTURE OPTICAL NETWORK ARCHITECTURES

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Abstract: *Wavelength-routed optical network (WRON) architectures potentially simplify routing and processing functions in high-capacity, high-bitrate WDM optical networks. With the inherent low latency these are relatively easy to design with a number of efficient routing and wavelength assignment protocols proposed to date. However, the pressure to optimise network resources and protocols for IP traffic has focused attention on network architectures which can rapidly adapt to changes in traffic patterns as well as traffic loads. Candidate architectures for future core networks include optical burst switching (OBS) with or without end-to-end capacity reservation acknowledgement and with dynamic wavelength routing functions. Typically packets are aggregated (and queued) at the edge routers of the network (by routing destination or class of service) and routed over a bufferless core. Appropriately timed aggregation of packets into "bursts" is, therefore, a way to reduce the processing overhead and buffering, providing packet loss and delay requirements for a given class-of-service can be satisfied, although the design trade-offs between the reduction in processing and the control requirements for resource allocation require further study.*

1. Transport network design - introduction

There is an expectation that future optical transport networks will be exposed to not only increasing traffic volumes, but also the growing diversity of services and – an important assumption key to the design - dynamically varying traffic patterns. Research over the recent years has convincingly shown that wavelength-routed optical network (WRON) architectures could potentially simplify routing and processing functions in high-capacity, high-bitrate WDM networks [see, for example /1-10/]. The current debate is focused on how best to design the optical network for the future, and it can only be resolved by comparing the performance of different architectures, under equivalent operating conditions. The key performance parameters for a given network architecture and traffic load are the packet or burst loss ratio, the achievable delay and the number of wavelength channels utilised (important as wavelengths are a scarce network resource).

The simplest approach to the design of an optical network which relies on wavelength functionality for routing would be to set up end-to-end lightpaths between all pairs of end-nodes, mapped appropriately over the physical topology to avoid wavelength contention. Given that the delay in these networks is zero, the key design parameters are the number of wavelengths (lightpaths) required to satisfy the traffic demand and the optimum allocation of these wavelengths according to the physical topology of the network, taking into account extra wavelengths required for restoration /5-10/. Whilst these quasi-static WRONs are relatively simple to analyse and design current research has focused on establishing whether they are sufficiently flexible in adapting to dynamically-varying and bursty traffic loads and service diversity.

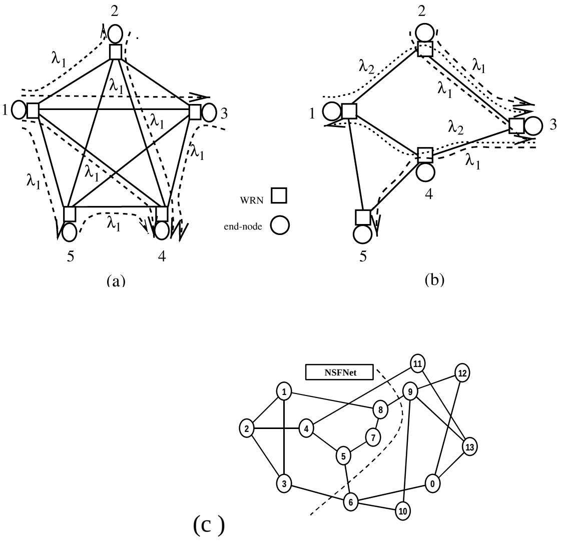
The fastest and most adaptive approach would be that of a pure optical packet network. However, the difficulties in achieving all-optical packet networks lie in the complexity of building large, fast single-stage all-optical packet switches (which must operate faster than the optical line rates) and lack of the equivalent of scaleable optical RAM/buffers, as well as the growing mismatch between electronic processors speeds (currently ~ 1 GHz) and the optical line rates - currently at 10 Gb/s and expected to exceed 40-160 Gb/s in the near future.

The answer appears to be to multiplex data from different pairs of nodes on a single path though the network, and to separate the logical 'connection' or 'flow' from the physical 'path' and there are several approaches to this, broadly falling into the category of *optical burst switched* (OBS) architectures, with different functionalities are discussed below. Optical burst switching was proposed /11-18/ as an attempt design an adaptive optical network to reduce the processing in network nodes needed for packet forwarding. Typically, packets are aggregated at the edge of the network, to reduce the processing overhead, and then routed over a bufferless core. The research questions here address of how best to aggregate packets at the edge and on the optimum assignment of these to packets to wavelengths, to minimise packet loss and delay, whilst ensuring that appropriate quality-of-service (QoS) requirements are achieved, and whether wavelength savings are possible, under dynamic wavelength operation.

By way of illustration of the above points, three different network architectures – a WRON and two OBS schemes are compared in terms of the performance parameters, namely – number of wavelengths, loss and delay for one network topology – NSFNet (shown in Fig.1).

2. Wavelength routed optical network architectures

As already mentioned, in WRONs, a given traffic matrix of demands between source-destination node pairs must be mapped over the physical topology of the network. The network physical topology with N nodes and L physical links can be characterised by the connectivity parameter $\alpha = 2L/ N(N-1)/$, as shown schematically in Fig. 1, for a 5-node network. Each source-destination pair demand is satisfied by a dedicated, quasi-static end-to-end lightpath (or lightpaths, when the offered load exceeds the capacity of a single wavelength channel). The routing and wavelength allocation problem is then aimed at minimising the number of wavelengths required to achieve this, avoiding wavelength contention, when simple wavelength routing is performed in intermediate nodes. All routes are calculated a priori and in the simplest case, there is no wavelength translation and no coordination or scheduling is necessary across the network. The network management is simple, there is no delay at the routing nodes and for a given (N, α), it is possible to calculate the wavelength requirements, with the lower bound given by $N_{\lambda,min}$ = (N-k).k/C where C is the number of physical links in the network *limiting cut* which separates the network into two sub-networks of approximately the same size, (N-k) and k /5,8/. For example, for the NSFNet, N = 14, $\alpha = 0.23$, C = 4 (shown by the dotted line in Fig 1). For NSFnet, N_λ = 13. In case of a link failure, the largest number of extra wavelengths would be requried if the failure occurred on a link within the limiting cut, so that the new wavelength lower bound $N^*_{\lambda,min}$ = [(N-k).k/(C-1)], as all the source-destination node connections would have to be routed over the reduced set of links. Whether the lower bound would be achievable either in the normal or restoration regimes would depend on the routing algorithms deployed (eg minimum number of hops or shortest physical path or other), but in most circumstances wavelength conversion would not be needed to reduce wavelength requirements – an optimised wavelength routing and allocation algorithm would achieve this – optimum algorithms have been investigated in detail for single- and multi-fibre WRONs in /2, 4-10/. A criticism levelled at the WRON approach is a potentially inefficient use of wavelength resources – after all lightpaths are assigned quasi-statically and have the minimum granularity of a single lightpath-worth of capacity. Thus - they may not reflect changes in demand – either the mean/maximum traffic volumes for a given source-destination pairs or rapid changes in the demand matrix across the network. Hence – optical burst switched schemes have been explored as a means to provide a time-domain multiplexing technique to access the lightpath bandwidth in fractions of a wavelength channel.



(a)

(b)

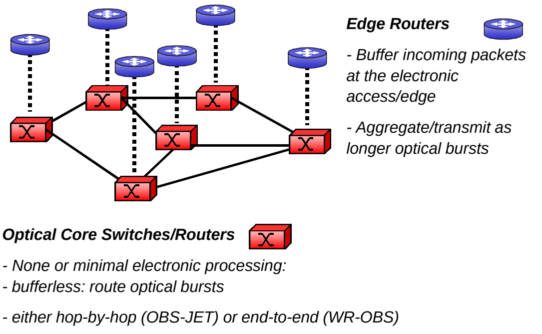
(c)

Figure 1: (a) Physically fully connected WRON with N=5, a =1 and N N_l =1; (b) example when N=5, a = 0.6 (L=5), N_l>1; (c) NSFNet topology used to compare WRONs and OBS: N=14, L=20, a=0.23, and N_l = 13, with dotted line showing the *limiting cut*.

WRN= wavelength routing node.

3. Optical burst-switch network schemes

Figure 2: Schematic architecture of an OBS network: with an electronic edge layer and an bufferless optical core layer



(a) Conventional OBS-JET scheme

Almost all burst-switching schemes proposed in to date (see, for example ref /11-17/) assume the use of separate burst header (control) and payload (data) channels, where headers are sent into a bufferless switch network with an appropriately chosen offset time, t_{offset}, from the data to reserve switch resources for routing the associated data along the selected path, in 'just-in-time' (JET) manner, with an example shown in Figure 3. In JET, network nodes have two functions. Prior to transmission, the incoming data from end-stations is buffered and aggregated according to its destination. A data signal (the burst header) is then sent to the next downstream node and some time later - $t_{offset, input)}$ - the burst is transmitted on the wavelength

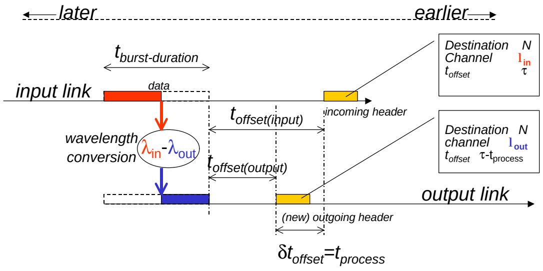


Figure 3: Schematic timing diagrams showing propagation of packet headers and data in OBS-JET and the significance of the offset time: routing is hop-by-hop and wavelength conversion is essential at every node.

specified in the header. t_{offset} is the time delay between a header and its respective data, and is sufficient for the downstream node to fulfill the second function: The arrival of a burst header on the control channel of a link signals a node to attempt to reserve a wavelength/time-slot for the soon-to-arrive data to be switched to an output link closer to the destination. Full wavelength translation capability at each link is needed so that any burst can be routed to any free wavelength on the output link; therefore the wavelength of a burst has local significance only. The downstream node then sends a new header to the next downstream node. At each hop t_{offset} is reduced (Fig.4) by the router processing time, t_{process} at each node; therefore for a burst to travel n hops, $t_{\text{offset,input}} \geq t_{\text{process}}$. The advance notice provided by the header suffices when the data-burst arrives at an intermediate node, that node is already set to route the signal from input to output channel to output channel. There are clearly a number of shortcomings with this scheme, as identified in, for example /18/.

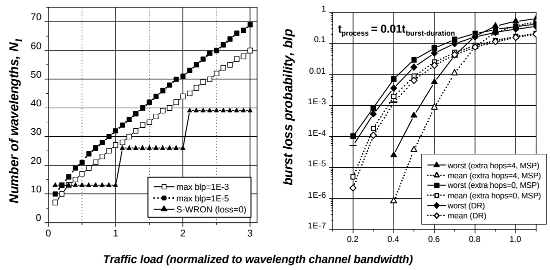


Figure 4: Left – wavelength requirements vs load for the OBS scheme over NSFNet, for different burst loss probabilities (blp) and in comparison with a WRON. Right: Blp vs load for different routing schmes – increasing rapidly with loss.

Firstly- there is no acknowledgement of path reservation as burst lengths considered are in the range of tens of kilobytes (equivalent to burst duration on microsecond timescales), and, thus, do not allow sufficient time for an acknowledgement of path reservation. Since the core is assumed to be bufferless, bursts may be dropped at any point along the path in case of burst contention – which can not be resolved, wasting the reserved resources, and this approach, therefore, may not provide the required QoS guarantees. Recognizing this as a limitation, schemes have been proposed to provide class-of-service differentiation by offset times, i.e. to assign larger offsets for higher priority traffic. This, however would have the effect of reducing the burst loss for high priority traffic, at the expense of an increase for lower priority bursts, especially for dynamically varying traffic loads. The result is reduced network capacity for acceptable packet loss rates /18/. Finally, in all the proposed schemes, wavelengths are assigned on a link-by-link basis, requiring full wavelength conversion at every node, as end-to-end lightpath reservation is difficult because of short offset times and short packets. Hence wavelengths are not used for routing but simply to increase the available transport channel capacity. The results for loss and wavelength requirements (calculated for Poisson traffic arrivals), shown in Figure 4, for NSFNet illustrate these points. Even for low loads, the burst-loss probability rapidly becomes unacceptable. The implication of such high burst loss rates are unpredictable within the TCP network environment where aggregation of large number of TCP session within a burst could and their subsequent loss, could have severely damaging implications on network performance. In terms of wavelength requirements, OBS-JET is better than WRONs for very low loads only (< 0.3) where a WRON requires a minimum number of wavelengths to avoid wavelength contention.

(b) Circuit-switched, wavelength-routed OBS: WR-OBS

An alternative OBS network architecture which requires an end-to-end reservation to satisfy specific service criteria such as latency and packet loss rate (PLR) for bursty input traffic, was proposed and analysed in / 19-21 / and termed wavelength-routed optical burst-switching (WR-OBS). The proposed WR-OBS network architecture and the edge router functionality and model are described in detail in refs. It assumes a fast circuit-switched end-to-end lightpath assignment, with a guaranteed, deterministic delay and requires an obligatory end-to-end acknowledgement. The packets are electronically aggregated into burst at the network edge, according to their destination and class of service (CoS), but with timescale of milliseconds - a typical forwarding time of IP routers, making the reservation of resources along the path prior to burst transmission feasible.

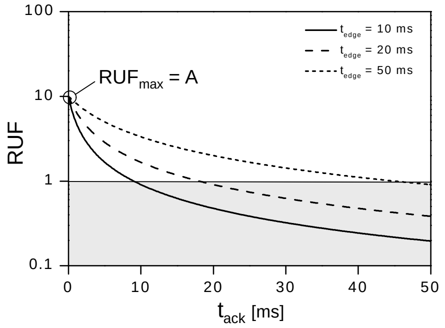


Figure 5: Wavelength re-use factor RUF as a function of t_{ack} for the edge delay values of t_{edge} = 10, 20, 50 ms (solid, dash, dot). Shaded region: network requires more wavelengths than in a static WRON. See ref / 20/.

At a defined point during the aggregation cycle ($<t_{\text{edge}}$) an end-to-end wavelength channel is requested from a network control node for transmission of the burst between edge routers. Once a free wavelength is found, the aggregated burst is assigned to it and transmitted into the core network using, for example, fast-tunable lasers, see, for example, /22/. Its further latency depends only on the propagation delay since non-deterministic buffering operations in core nodes are not required. Concentrating all the processing and buffering within the edge of the network simplifies the design of optical switches or cross-connects/routers in the core significantly, particularly important for time-critical traffic and cannot be achieved with the currently implemented IP-routers or conventional OBS which provides hop-by-hop forwarding only. Following transmission the wavelength channel is released, and can be re-used for subsequent connections. The network core can either be considered as a passive core /23/ or as a

network of fast-reconfigurable optical routers/ crossconnects, where end-to-end lightpaths - or circuits - are dynamically set-up by the same controller which allocates wavelengths, pre-calculated as in the case of WRONs. In either case it is justified to assume that wavelength conversion in core nodes is not required.

The key questions answer is under which conditions the dynamic WROBS would bring significant operational advantages, and in particular – the increased throughput over wavelength channels which are set up only for the required burst transmission time with respect to a quasi-static logically fully-meshed WRON. Typical results for the maximum achievable wavelength re-use factor for WR-OBS is shown in Figure 5 (see refs / 19-20/ for details of assumptions). These represents an upper bound for wavelength re-use as a function of the acknowledgement time which includes the time required for dynamic routing and wavelength assignment. For maximum wavelength re-reuse factor, the acknowledgement time must be as short as possible compared to the burst length (>> factor of 10) – and improves with a higher allowable edge delay. The results quantify the degree to which the WR-OBS is constrained by signalling and the required speed of the dynamic routing algorithm (such as, for example / 24/) to make a core network in which resources are assigned dynamically – an improvement over a static WRON. If these can not be met, the WRON remains optimum transport network architecture.

In summary, a number of choices exist for the design of optical transport networks. Since WRONs have no delay or packet/burst loss they are optimum for delay-sensitive traffic and the simplest to design and operate - but at the expense of potential capacity overprovisioning. Conventional OBS (JET-type) schemes appear to have shortcomings in terms of achievable wavelength requirements and burst loss probability. However, fast circuit-switched WR- OBS schemes allow an increased network throughput (with guaranteed QoS provision - ie low packet loss and delays) but their design requires further research on scheduling and coordination between the electronic and the optical network layers, and the transport network of the future may well see a combination of WRON and WROBS over the same physical topology to satisfy different traffic delay and loss constraints.

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