# Forward Redundancy: A Loss Recovery Mechanism for Optical Burst-Switched Networks

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***Abstract*— Optical burst switching is one of the most promising new optical transport paradigms for efficiently transporting data over an all-optical network. In this paper, we discuss *Forward Redundancy* as a candidate for loss recovery in an optical burst-switched network. We develop a simulation model to investigate the proposed forward redundancy loss recovery mechanism and to compare the performance of our proposed mechanism with the existing retransmission-based backward loss recovery mechanism. Our results show that the proposed forward redundancy mechanism significantly reduces packet loss as compared to a retransmission-based backward loss recovery mechanism, without the need for large ingress electronic buffers or high retransmission delays.**

***Keywords:* WDM, TCP/IP, OBS, Retransmission.**

## I. Introduction

In wavelength division multiplexed (WDM) networks, channels are created by dividing the bandwidth into a number of wavelength bands, each of which can be accessed by the end-user at peak electronic rates. WDM networks are able to offer huge bandwidth on the order of 50 THz at optical fiber links. In order to efficiently utilize this bandwidth, we have to design efficient transport architectures and protocols based on the state-of-the-art optical device technology [1]. This transport method must be also able to handle asynchronous bursty traffic by quickly provisioning resources while also minimizing the use of optical buffering. Optical burst switching (OBS) is one such method for transporting traffic directly over a bufferless optical core network [2], [3].

In an OBS network, a data burst consisting of multiple IP packets is switched through the network all-optically. A burst header packet (BHP) is transmitted ahead of the burst in order to reserve the data channel and configure the switches along the burst's route. In a popular OBS signaling technique called just-enough-time (JET) [2], the burst transmission follows an out-of-band BHP after a predetermined offset time. The offset time allows the BHP to be processed before the burst arrives at the intermediate nodes; thus, the burst does not need to be delayed at the intermediate nodes. The BHP also specifies the duration of the burst so that each node knows when the resources being used by the burst will be released. Other OBS signaling techniques, such as just-in-time (JIT) [4], [5], [6] are also implemented in an one-way unacknowledged manner.

Optical burst-switched networks are typically connectionless in nature; thus, it is likely that there will be contention for resources in the core network, leading to packet loss. Contention resolution is an important research issue in OBS networks. When two or more bursts are destined for the same output port at the same time, contention occurs. When a contention cannot be resolved, one of the contenting burst is lost. If the dropped burst cannot be recovered at the OBS layer, higher layers (such as TCP) will need to handle the retransmission of the lost data at a later time.

In order to satisfy the high bandwidth-delay requirements of higher-layer applications and to overcome the lossy nature in OBS networks, a reliable OBS network must be developed. In this paper, we propose a novel loss recovery mechanism called *forward redundancy* to improve the loss performance for an OBS network. We also evaluate the performance of forward redundancy in combination with burst segmentation [7], to further improve the reliability of the OBS network. In the proposed forward redundancy mechanism, some or all the original data packets of each burst are copied and sent in the forward direction from the source to the destination. Inside the OBS core network, we assume that if a burst experiences contention, segmentation is employed so as to drop only the overlapping segments of the contenting bursts. The dropped segments of a burst can be recovered using the redundant packets at the OBS egress node, resulting in lower packet loss. We develop a simulation model to investigate the proposed forward redundancy mechanism and compare the performance of our proposed mechanism with the existing burst retransmission backward loss recovery mechanism. In general, forward redundancy makes it possible to transmit at much higher data rates if additional bandwidth is available. Forward redundancy is particularly well suited for optical transmissions, where bandwidth is reasonable but end-to-end latency across long-haul networks is significant [8].

The rest of this paper is organized as follows: Section II provides a brief overview of loss minimization and loss recovery mechanisms necessary to support a reliable OBS network. Section III proposes the forward redundancy loss recovery mechanism. Section IV evaluates the performance of the proposed forward redundancy mechanism and compares the performance with the existing burst retransmission mechanism. Section V concludes the paper.

## II. BACKGROUND: RELIABLE OBS

In this paper, we focus on the goal of implementing a reliable optical burst-switched network using loss minimization and loss recovery mechanisms. In this section, we classify and describe the different loss minimization and loss recovery mechanisms.

### A. *Loss Minimization: Contention Resolution Vs. Contention Avoidance*

We classify all loss minimization mechanisms into two broad categories, namely, *Contention Resolution* and *Contention Avoidance*. Contention resolution mechanisms attempt to minimize data loss when a contention has already occurred. On the other hand, contention avoidance mechanisms attempt to minimize the occurrence of contentions. We now discuss the details of the two mechanisms.

*1) Contention Resolution Mechanisms:* The primary contention resolution mechanisms are optical buffering [9], wavelength conversion [10], deflection routing [11], [12], [13], and burst segmentation [7]. These mechanisms minimize data loss when a contention has already occurred. Since we will apply burst segmentation in our proposed mechanism, we now briefly describe burst segmentation.

In burst segmentation [7], the burst is divided into basic transport units called *segments*. Each of these segments may consist of a single IP packet or multiple IP packets, with each segment defining the possible partitioning points of a burst when the burst experiences contention in the optical network. All segments in a burst are initially transmitted as a single burst unit. However, when contention occurs, only the overlapping segments of one of the bursts in contention will be dropped, as shown in Fig. 1. If switching time is not negligible, then additional segments may be lost when the output port is switched from one burst to another. There are primarily two approaches for dropping burst segments during a contention. The first approach, tail dropping, is to drop the tail of the original burst (Fig. 1(a)), and the second approach, head dropping, is to drop the head of the contending burst (Fig. 1(b)) [7].

Segmentation is a well accepted contention resolution mechanism that combines the benefits of a relaxed switching constraint based optical burst switching with the optimal packet-level loss granularity of photonic packet switching [14], [15], [16], [17], [18]. Through extensive simulations and analytical modelling, it has been previously shown that segmentation can reduce the loss probability in an optical burst-switched network by up to 50% [7].

*2) Contention Avoidance Mechanisms:* The contention resolution mechanisms minimize packet losses based on the local information at the nodes where contentions occur, but do not address the more fundamental problem of congestion in the OBS core. In [19], two dynamic load-balanced routing techniques are proposed to avoid burst contentions. The simulation results show that the proposed contention avoidance techniques improve the network utilization and reduce data loss. In [20], [21], and [22], the authors investigated similar load-balancing routing (or path switching) approaches using adaptive alternate path routing and concluded with similar observations as [19]. In addition, other edge-based admission control techniques, such as proactive edge-scheduling [23] can be incorporated to minimize the number of contentions in the core.

### B. *Loss Recovery: Reactive Vs. Proactive*

Burst loss may still occur after using the different loss minimization mechanisms. Hence, loss recovery mechanisms are essential in addition to loss minimization mechanisms to support a reliable OBS transport network. We classify all loss recovery mechanisms into one of two categories, namely, *Reactive* and *Proactive*. Reactive loss recovery mechanisms are generally optimistic about the successful reception of the transmitted burst at the destination. Reactive mechanisms only attempt to recover when they receive an explicit failure message. On the other hand, proactive loss recovery mechanisms are generally pessimistic about the successful reception of the transmitted burst at the destination. Proactive mechanisms transmit additional information (overhead) along with the original burst so as to handle certain loss scenarios. Broadly speaking, reactive mechanisms are better suited when burst loss is rare and bandwidth utilization needs to be optimized. Proactive mechanisms are better suited when burst losses are high and delay needs to be optimized.

We now describe the different loss recovery mechanisms for an OBS network.We first briefly discuss *burst retransmission*, a backward (or reactive) loss recovery mechanism, and then discuss *burst cloning*, a forward (or proactive) loss recovery mechanism. Note that a combination of loss recovery mechanisms can be implemented to further reduce the loss in the network.

*1) Retransmission:* The basic idea of burst retransmission is to allow contending bursts to be retransmitted

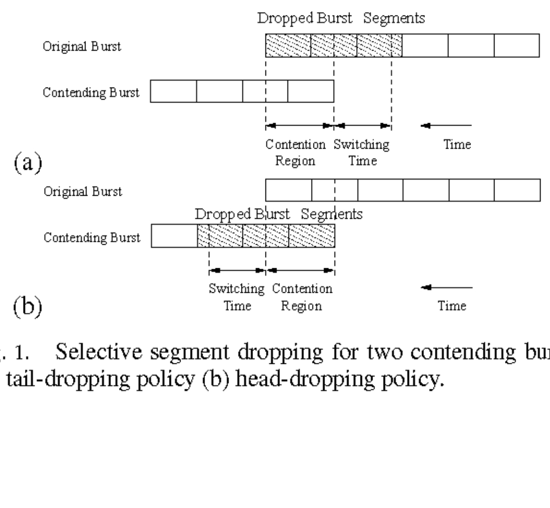


Fig. 1. Selective segment dropping for two contending bursts (a) tail-dropping policy (b) head-dropping policy.

in the OBS layer. In OBS, BHPs are transmitted prior to data burst transmission so as to reserve resources along the path, while the burst is transmitted after an offset time. During data transmission, the ingress node stores a copy of the transmitted burst for possible retransmissions. As the BHP traverses through the core nodes, if the channel reservation fails due to a burst contention, the core node will send an *Automatic Retransmission Request* (ARQ) message to the ingress node in order to report the reservation failure. Upon receiving an ARQ message, the ingress node retransmits the corresponding duplicate preceded by its duplicate BHP. Additional details about retransmission can be found in [24], [25]. We now briefly discuss the proactive loss recovery mechanisms.

*2) Burst Cloning:* In burst cloning [26], the idea is to replicate a burst and send duplicated copies of the burst through the network simultaneously. If any one of the burst copies is lost, the destination egress nodes can recover from the core loss using the other duplicate burst. Additional information needs to be stored in the BHPs to identify duplicates. So that, in the case both original and duplicate burst reach the destination, the destination will select one of the bursts, disassemble the burst, and forward the constituent packets on to the corresponding destination hosts. Based on the load on different links in the network, the original and the clone could be sent on different paths. Primary design issues in burst cloning are to select the optimal node at which to clone and to prevent cloned bursts from contending for resources with their original bursts.

In this paper, we propose a forward redundancy loss recovery mechanism for optical burst switching. The forward redundancy mechanism aims to eliminate the fundamental limitations of the burst retransmission mechanism, such as requirement of large ingress electronic buffers to store copies of transmitted bursts and additional delay incurred in retransmitting bursts after the original burst has been dropped in the OBS core network. Forward redundancy mechanism can also provide a flexible level of reliability (or redundancy) for each burst or flow, unlike burst cloning that only provides a fixed 100% redundancy for each burst. In the following section, we describe the forward redundancy loss recovery mechanism.

## III. Forward Redundancy

In the forward redundancy mechanism, some or all the original packets of a burst are copied and sent in the forward direction along with the original burst from the source to the destination. Based on the requirement of the data traffic, we define several forward redundancy schemes. Based on the loss requirement, we can provide *partial forward redundancy* ($< 100\%$) or *complete forward redundancy* ($\geq 100\%$) to combat packet loss due to contentions and segmentations. Based on the type of burst assembly and edge burst scheduling, the redundant packets can be transmitted in series or in parallel (refer Fig. 2). In a *serial forward redundancy* scheme, the redundant packets are placed before or after the original burst (packets), the resulting data stream could be assembled into a single burst or multiple bursts. On the other hand, in a *parallel forward redundancy* scheme, the redundant packets are assembled as a new *redundant* burst and transmitted in parallel with the original burst. Finally, forward redundancy can also be performed based on the fault-tolerance requirement of the application traffic. The redundant burst(s) and the original burst are transmitted along one or multiple paths from the source to the destination. If the paths are link-disjoint (or node-disjoint), protection against a link (or a node) failures in addition to protection against core contention losses is provided. In

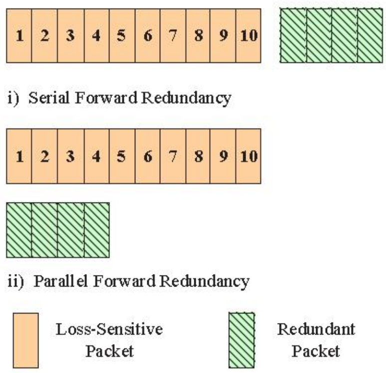


Fig. 2. Different forward redundancy schemes i) serial forward redundancy and ii) parallel forward redundancy.

this paper, we evaluate the serial forward redundancy loss recovery mechanism with burst segmentation support. In our mechanism, redundant packets can be placed after the original burst packets, so that the receiver can recover from selective packet loss of each burst in the forward direction. As discussed before, segmentation drops only the overlapping packets of a burst in contention to minimize packet loss. Note that without segmentation, there is no benefit of placing the original packets and the redundant packets into a single burst.

## IV. Simulation Results

In this section, we develop a network-wide simulation model in order to evaluate the performance of loss minimization and loss recovery mechanisms. We compare the performance of the forward redundancy loss recovery scheme, the burst retransmission scheme, the segmentation scheme, and a baseline scheme that drops the entire burst on a contention. We simulate on the NSF network as shown in Fig. 3. The number of wavelengths on each link is 8 and the transmission rate on each wavelength is 10 Gb/s. We assume that all core nodes are bufferless (no FDLs) and have full-wavelength conversion capability. The data traffic simulated traverse through eight

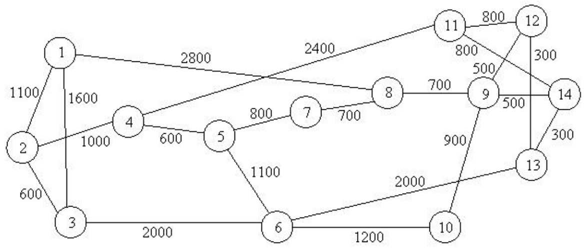

Fig. 3. NSF network topology (distance in km).

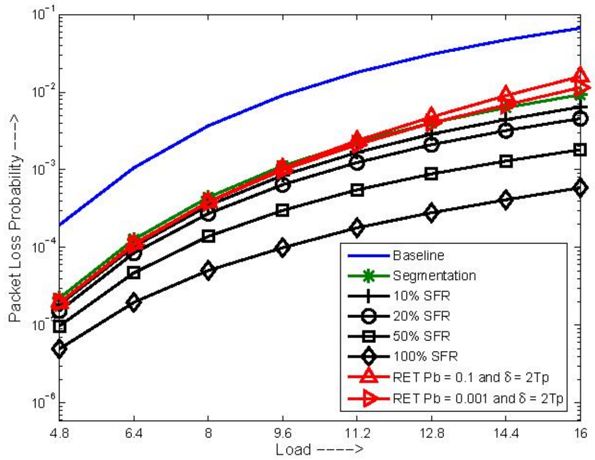


Fig. 4. Packet loss probability vs. network load.

ingress-egress node pairs: (1,11), (3,11), (2,9), (3,9), (1,13), (2,10), (4,12), and (7,13). Burst arrivals follow a Poisson process and are uniformly distributed among the eight flows. Each burst generated has a fixed length of 100 packets and each packet is 1250 bytes long. We also assume that each new burst may be electronically queued for a maximum of 0.1 ms at each ingress node in order to resolve edge contentions in the forward redundancy scheme, the segmentation scheme, and the baseline scheme. *The load value in each plot is the original input traffic load in to the entire network in Erlang, without considering the load due to redundant or retransmitted bursts.*

Figure 4 plots the average packet loss probability versus load for the OBS network with different loss minimization and loss recovery mechanisms. We simulate the serial forward redundancy loss recovery mechanism with 10%, 20%, 50%, and 100% redundant packets. In the burst retransmission scheme (RET), we set the delay constraint to be $2T_p$ and the different retransmission buffer blocking probability, $p_b$, to be 0.1 and 0.001. Note that $2T_p$ is the round-trip propagation delay between the source and the destination and $p_b$ is the probability of a incoming burst being blocked at the ingress retransmission buffer. We observe that with higher redundancy, the packet loss probability of the forward redundancy scheme reduces. We also observe that the forward redundancy schemes performs better than all the other schemes, especially at high loads.

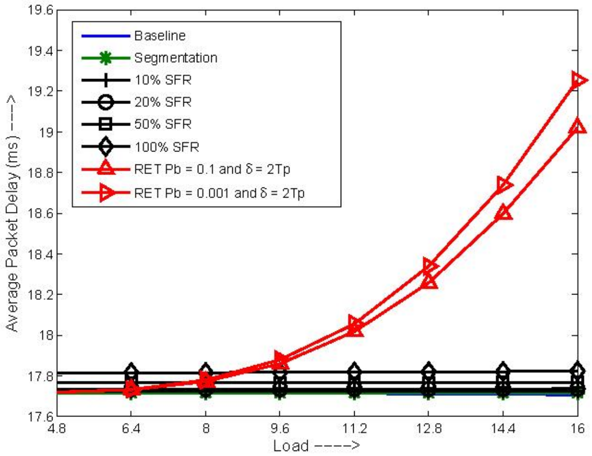


Fig. 5. Average packet delay vs. network load.

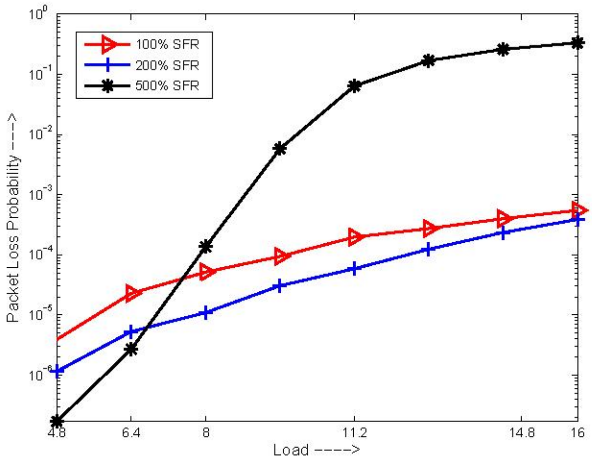


Fig. 6. Packet loss probability vs. network load with very-high serial forward redundancy.

Figure 5 plots the average packet delay versus load for the OBS network with the different loss minimization and loss recovery mechanisms. We observe that the retransmission scheme has the highest average packet delay. This is due to the fact that the delay incurred in the forward redundancy scheme includes only one-way propagation delay and data transmission delay, but the retransmission scheme incurs an additional retransmission delay. Also, the forward redundancy scheme with higher redundancy values results in higher packet delay, since higher redundancy generates larger-sized bursts resulting in higher data transmission delay.

However, the performance of the forward redundancy loss recovery mechanism degrades at higher values of redundancy. Fig. 4 plots the average packet loss probability versus load for the OBS network using the forward redundancy loss recovery mechanism with 100%, 200%, and 500% redundancy. We notice that at the highest load of 16 Erlang, the packet loss probability of the forward redundancy scheme with 200% redundancy is similar to that of the forward redundancy scheme with 100% redundancy. This is because the available network resource reduces with higher redundancy, and the gain due to redundancy reduces. We also observe that at loads higher than 7 Erlang, the performance of the forward redundancy scheme with 500% redundancy degrades dramatically since the size of a burst increases significantly with higher values of redundancy leading to high loss at OBS edge nodes.

## V. Conclusion

In this paper, the different proactive and reactive loss minimization and loss recovery mechanisms are introduced and evaluated. We evaluated complete, partial, and serial forward redundancy schemes and we compared the performance of forward redundancy with segmentation scheme with the burst retransmission scheme using the NSF network. Our simulation results show that forward redundancy significantly reduce the packet loss without any additional delay as compared to any other known OBS loss recovery mechanism. We developed an analytical loss model for the forward redundancy loss recovery mechanism and also verified its correctness through discrete-event simulations.

In this paper, we limit our study to static forward redundancy, wherein the ratio of the data packets to the redundant packets is fixed. We intend to extend the static forward redundancy mechanism to a dynamic feedback-based forward redundancy mechanism such that the redundancy ratio of different traffic streams is dynamically adjusted based on the experienced loss (and load) along the path so as to add the optimal redundancy to each burst. Another area future work is to evaluate the effect of forward redundancy schemes on different TCP flavors so as to achieve better performance in high bandwidth-delay optical networks.

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