# Optical Buffering for Next-Generation Routers

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**Abstract**

This report describes the challenges in meeting the requirements for optical buffering devices in next-generation optical routers. Slow light and delay line buffering approaches are described and several recent results and issues are summarized.

## 1 Introduction

Optical buffering is a major obstacle facing optical packet switching for future optical communication networking. Optical packet switching is a highly desirable approach; however it necessitates the implementation of contention and congestion resolution within core routers. Alternatives to buffering such as deflection routing and wavelength conversion can be used to supplement optical buffers, but severely limit network performance if used as the sole solution.

Current routers use large capacities of electrical RAM to resolve contention. The state-of-the-art Cisco CRS-1 core router is based on linecards that operate with 2 GB of memory. Although this capacity is currently not feasible with any proposed optical buffering approach, recent research has shown that much smaller buffering capacities can be acceptable. Simulations show that if access links are slower than the backbone network and the traffic is smoothed, then only five packet buffers per output port are needed for 80% link utilization [1]. Thus, optical buffers may present a realistic solution.

Optical buffers must meet a list of difficult requirements to achieve acceptance. Minimally, buffers must be bit rate scalable to greater than 40 Gb/s to offer an advantage over electrical domain counterparts. For acceptable network loads they should have the capability to store packets of no less than 40 bytes with guard bands no more than several nanoseconds long. It is desirable for the buffer to be transparent to packet length and to provide dynamically variable storage time. Lastly, the number and complexity of components included in a given buffer architecture must be kept to a minimum for the technology to be practical for implementation.

Reviewed herein are the advantages and limitations of four transparent optical buffering approaches and one approach based on the electrical conversion of packets. Transparent optical buffering approaches rely on delaying packets by increasing total transmission time, either by decreasing the group velocity or increasing the physical length. Challenges are reviewed here for the two types of slow light buffers: electromagnetically induced transparency (EIT) devices and coupled resonant structures (CRS). Delay line buffers are also categorized into two subsets. Results and challenges for several feed-forward and feed-back designs are described in this presentation. Integrated recirculating buffers as a feed-back approach offer the solution to several buffering challenges encountered by other designs.

## 2 Buffering Approaches

Before comparing transparent optical buffers, it is necessary to consider the challenges in the electrical domain. Although speed appears to limit the scalability of electrical RAM, recent research shows that silicon-based CMOS RAM can be used as a storage medium for optical packets at data rates up to 40 Gb/s by using a combination of optical and electrical components [2]. Such a design offers long storage times, large capacity, and random access at arbitrary times. However, loss and component complexity limits the design to packets less than 10 bytes, thereby limiting the maximum load of the network.

Slowing mechanisms proposed for optical buffers use strong resonances between electromagnetic waves (CRS) or between an electromagnetic field and a polarizable medium (EIT). The two approaches were analyzed by J. Khurgin and found to have strict limitations, as described below [3]. In CRS such as gratings and photonic crystal defects, the group velocity is reduced by lengthening the light path through repeated reflections; the group velocity decreases drastically in the vicinity of the photonic bandgap. However, dispersion, scattering losses, and absorption losses lead to an absolute bandwidth-delay product which limits bit rates and packet lengths. Losses must be drastically reduced to below 0.1 dB/cm before CRS can be realistically applied to buffering applications. EIT devices are also limited by dispersion and absorption, suitable only for very low bit rates (less than 10 Mb/s) and storage capacities. From this study and later analyses from R. Tucker et al. [4], it is apparent that slow light mechanisms are unlikely to have success as optical buffers for contention resolution.

Over the last decade there have been several buffer architectures that have achieved good results, but whose success will be limited by either large component counts or component complexity. Optical storage of at least 0.1 ms has been demonstrated using feed-forward architectures such as a folded-path buffer [5] and fiber Bragg gratings [6], as well as feed-back architectures employing parametric nonlinearity in fiber [7] and fiber nonlinear loop mirrors [8]. High data rate results were achieved as early as 1998 using a compensating fiber loop buffer to achieve 20 μs of storage at 40 Gb/s [9]. However, scalability, footprint, and power consumption are large issues for future core routers requiring at least 5 buffers for each of more than 16 ports.

Feed-back buffers are beneficial for their low component count and small footprint. Thus far, integrated switches as developed by our group [10] and N. Chi et al. [11] show promise of offering a practical solution. Power penalties of less than 1 dB are shown in Fig.1 for our 2x2 switch. Recirculating buffers face challenges such as noise accumulation and also limit packet length, but can provide variable storage time down to one packet length.

### 3 Conclusion

Five general types of optical buffering are compared for practical implementation in an optical packet switched router. Combination electrical-optical buffers using CMOS RAM as well as EIT slow light buffers both degrade network performance by limiting packet length and therefore network load. CRS slow light buffers suffer from losses and thereby a low bandwidth-delay product, resulting in impractical bit rates and capacities. Feed-forward buffers have shown good results and do not place any limit on packet lengths, but may be impractical for implementation due to high component counts. Lastly, feed-back buffers may provide a compact solution for integration, but place some constraints on packet length and suffer from noise accumulation. These comparisons are summarized in Table 1 and demonstrate the difficulty in finding a successful buffering approach. Integrated recirculating buffers offer the most practical compromise.

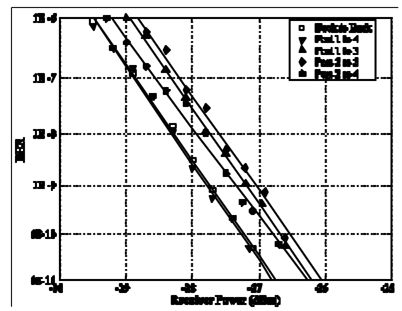

Fig. 1. BER vs. optical power at 40 Gb/s RZ $2^7$-1.

| Metrics | >= 40 Gb/s | Packet >= 40 B | Variable packet length | Low cost |
|---|---|---|---|---|
| CMOS RAM [2] | v | | | |
| Slow light | | | v | v |
| Feed-forward | v | v | v | |
| Feed-back | v | v | | v |

Table 1. Comparison of buffer approaches.

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