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Modeling and performance analysis of realizable optical queue with service differentiation capability

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ABSTRACT

We propose an optical queue architecture that can be realized by implementing the state-of-art optical buffer technology in the near future. This optical queue can be used at the output port of an optical packet switch/router in an optical switching network (OPS), which resembles its electronic equivalent in terms of operational functionality. Detailed construction and operation scenarios of the optical queue are elaborated. Analytical modeling is done to investigate the switch with this optical buffer structure. Results obtained demonstrate the capability of providing service differentiation by using our proposed optical buffer system with multiple thresholds control mechanism.

1. Introduction

All-optical networks are widely considered as the promising candidate for the next generation network (NGN) development, which offer line and switch capacities greatly exceeding those of existing facilities. The favorite concept of broadband optical Internet urges the appearance of optical packet switching (OPS) network, which can provide flexibility and efficiency as the electronics-based Internet but with tremendous improvement upon the capacity. The user data is transmitted in optical packets, which are switched within each optical packet switch entirely in the optical domain, thus an all-optical transparent network. Thus, the user data remains as an optical signal in the entire path from source to destination. No optical-to-electrical (O/E) or electrical-to-optical (E/O) conversions are required.

A major obstacle faced in building all-optical OPS networks is, however, the difficulty in implementing all-optical packet switching nodes. In a packet-switched network each packet has to go through a number of switches to reach its destination. When the packets are being switched, contention occurs whenever two or more packets are trying to leave the switch from the same output port simultaneously. In an all-optical OPS network node, contention to the same output port is inevitable for optical packets traveling through and how the contention is resolved has a great effect on network performance.

Optical buffering, being one of the contention solution methods, was, inspired by its conventional electronic network counterparts, to a great extend. In electronic routers contention is usually resolved by a store-and-forward technique by using electronic random access memory (RAM), which means that the packets in contention are stored in a queue and sent out one by one. However, without a ready-to-use optical RAM available, people have to find other approaches to temporarily store packets optically.

An all-optical buffer is defined as shown in Fig. 1. The output data $f(L,t)$ is essentially a copy of the input data $f(0,t)$. $f(L,t)$ is equal to the multiple of a proportionality constant p with a time delay τ, which is variable controlled by an external source V. The delay introduced by the optical buffer can be represented by $\tau = L/v_g$, where L is the length of the fiber being used as the optical buffer and v_g is the speed of the light traversing the fiber-based optical buffer medium.

So far, building optical buffers has two options: slow light-based (SL-based) [1–3] and fiber delay line-based (FDL-based) [4–6]. Both of them are based on fiber optics and aim to introduce a time delay τ to the optical packet that passes through. SL-based optical buffers make use of the dispersion property of optical fiber to slow down light (i.e. by decreasing v_g), whereas FDL-based optical buffers introduce the delay purely by manipulating the length of fiber (i.e. by increasing L). The optical buffer

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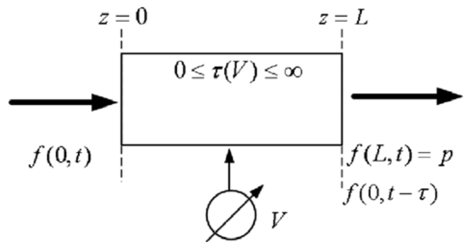

Fig. 1. Definition of optical buffer.

built on SL technology outperforms FDL-based buffer in terms of much smaller physical size. Also, since speed slowing effect varies for different wavelength, for the same length of fiber, effective buffer lengths created by different wavelengths are different accordingly. It may contribute to more flexible design and control of the final optical buffer system. However, SL-based buffer suffers from the property of constant delay-bandwidth product [7]. For example, for a 12.6 GHz system, the maximum delay introduced is 47 ps, which cannot accommodate even a single optical packet in the buffer [8]. For a delay generated around 46 ns the maximum speed of the channel is 40 MHz, which is well below today's requirements on channel capacity [9]. So unless the delay-bandwidth product issue can be overcome, the SL-based optical buffer can hardly find a role in storing high-speed optical packets (in the order of Gbps transmission rate). On the other hand, FDL-based buffer controls τ by controlling L only, hence it suffers the problems of bulky size and loss [10]. For example, in order to achieve 100 Tbps router with 2500 ports at 40 Gbps, 250 ms buffering per port, the total length used for the FDL is about the distance between the earth and the sun. An improvement to this basic FDL setup is based on recirculation-enabled FDL optical buffer [11–14]. However, current research is having problem of storing multiple optical packets in one buffer at one time because the unsolved addressing issue [15]. Hence the state-of-art optical buffer that can be used is recirculation-enabled FDL-based optical buffer, where one cycle of the FDL should support the maximum size of optical packets in the network.

In literature, there were some FDL-based optical buffer structures proposed and analyses of those buffers were carried. In [16–18], modeling and performance analysis of their optical buffer of interest were shown. However, the hardware requirement of their optical buffer can hardly be achieved based on today's technology or even near-future technology. For example, in the performance analysis of both work, delay granularity D were taken as a measurement, which can range from 0 to 1. This means their FDL or recirculation FDL should be able to delay part of a packet. However, in physical layer implementation, reading in and writing out the same optical packet from one round of FDL at the same time is not possible [15].

Besides fast speed, the ultimate goal of all-optical OPS network should also include the ability to provide service differentiation to different user traffic. In this paper, we propose an optical buffer system to be used at the output port of the optical packet switch, which can be realized by implementing the state-of-art optical buffer technology in the near future. By resembling the functionality of its electronic equivalent, it can make use of threshold control to provide differentiated QoS to different user traffic at the OPS nodes. Furthermore, we demonstrate an analytical model that is suitable for the performance evaluation for optical packets belonging to different service categories. Here, we use the terms optical queuing system and optical buffer system interchangeably.

2. Optical buffer system

Fig. 2 is the graph of the proposed optical buffer system used at the output port of the OPS switch/router. Functionally, it behaves the similar way as a First-In-First-Out (FIFO) electronic buffer. More importantly, the design of the optical buffer system only makes use of the technologies that are viable by today's physical layer development. For the simplicity of illustration, the model shown is for single wavelength operation and the effective buffer size of the system is B.

This optical queuing system takes optical packet from the "Input to Buffer Stage" and stores optical packets one by one from Line 0 down to Line $B-1$. D means the delay for the optical packet with maximum size. MU denotes the monitoring unit. As shown in Fig. 2, this buffer system consists of two stages of recirculation FDLs. stage 1 FDLs, by default, recirculate packets as many cycles as they are capable of before forwarding them to the stage 2 FDLs along the corresponding line. That means without any trigger from the MU, the optical packets will be recirculated forever before being forwarded. This is very similar to the behavior of electronic buffer, which will not force the packets to output if the output line is not available. When MU detects that stage 2 FDLs are all empty, and output link is available, stage 1 FDLs will be triggered to forward all the packets that are stored in stage 1 recirculation FDLs to their corresponding recirculation FDLs in stage 2. Stage 2 FDLs each has a fixed number of cycles ($0 \sim B-1$) that the optical packets have to be recirculated before their departure. In this way, optical packets that output from stage 2 FDLs can be ensured not to contend with each other.

Of course in the actual implementation, the limit of the recirculation cycles will be decided upon the noise accumulation if with the recirculation circuit consists of EDFAs to recover losses. Alternative, if the recirculation circuit is purely passive, the limits of the recirculation will be depended on the losses of the signal during recirculation process. But it will be not be a big issue since the number of cycles, which the optical packets can be recirculated before degrade below the level of acceptance, keeps improving throughout the years [11,19–21].

2.1. Operation principle

Let us consider three cases in order to fully understand the operation principle of the output optical queuing system.

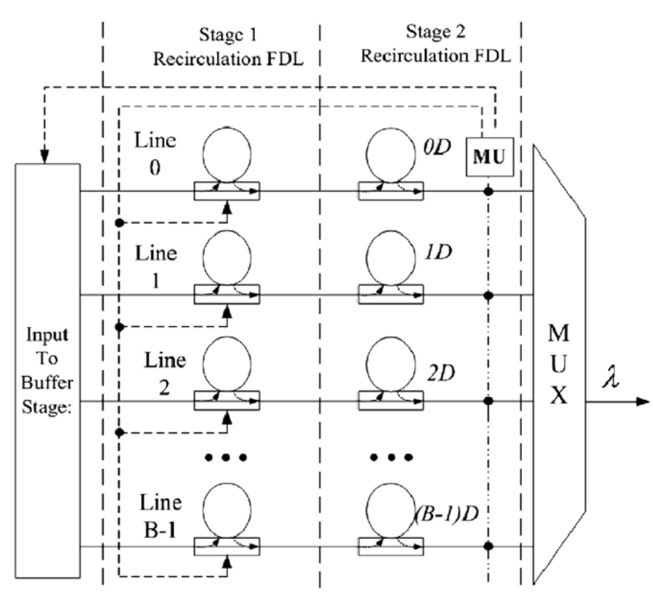

Fig. 2. Proposed optical buffer system at one output port – single wavelength case.