A hybrid optical buffer

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Abstract: We proposed a hybrid optical buffer architecture which combines the advantages of fiber loop optical buffers and fast electronic buffering.

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1. Introduction

Optical buffering in optical packet-switched networks is rather limited in its capability because the optical equivalent of electronic random access memory is not available [1]. Current optical buffers are built with fiber delay lines which delay the data packets rather than storing them. Re-circulating loops or fiber loops are typically used to construct optical buffers [1], [2]. Fiber loop optical buffers are relatively compact and can provide a large number of choices of delay value when compared to other types of optical buffers. Fiber loop optical buffers however still suffer from a number of limitations such as (i) the delay of packets can only be integral multiples of the fiber loop circulation time, (ii) the packet length must be shorter than the fiber loop length, (iii) the signal quality degrades with the number of times the packets circulating in the fiber loop, and (iv) large number of such buffers in a switch/router is not feasible yet because they are still bulky.

The limitations described in (i) and (ii) may be neglected in some cases such as slotted optical packet-switched networks. But the limitations described in (iii) and (iv) are fundamental to all networks [1], [2]. At a packet loss rate of $10^{-11}$, the required buffer size will be up to thousands of packet length for bursty system traffic [1]. Besides a large amount of fibers, thousands of circulations by the packets in the loops will be required. To compensate the signal quality degradation as a result of the circulations, it is necessary to regenerate the signal either by optical-electrical (O/E) conversion [3] or by all-optical approaches [4]. Both of which will increase the complexity and physical size of the optical buffers.

To date, compact large optical buffers with no limitation on the storage time are not available yet. Slow light technology shows promises in optical signal processing, but whether it can be used to build large optical buffers is still unclear [5]. Since an all-optical solution is not likely to be available soon, fast electronic buffering is gaining interests recently. The technological hurdles are shifted to the data conversion between the optical and electrical domains. Packet by packet electronic buffering has been proposed using optical serial to parallel (S/P) conversion to match the speed differential between optical fiber transmission and electronic memory read/write operation [6]. For fiber transmission rate up to tens of gigabits per second, however, the required S/P ratio will be up to hundreds or more. At the moment, only converters of small S/P ratio such as 16 are practical [6], [7]. New approaches of electronic buffering with data conversion rate much slower than the fiber transmission rate are therefore necessary to avoid the data conversion bottleneck.

In this paper, we propose a hybrid optical buffer that combines the merits of both fiber loop optical buffers and fast electronic buffering. Multiple sets of fiber loops and electronic buffering modules are connected and form the proposed hybrid optical buffer. Incoming packets are first placed in the fiber loops for temporary storage. If the packet cannot be sent out after a certain period of time, the packet will be converted and stored in the electronic memory. We show that the slow operations of data conversion and electronic memory read/write will no longer be a problem if there are a number of $K$ fiber loop modules installed, where $K$ is independent of the system loading and packet loss rate. Consequently, large electronic memory can be used to reduce the packet loss. The proposed hybrid optical buffers will significantly simplify the implementation of optical packet routing node using current technology.

2. The proposed hybrid optical buffer

Figure 1 shows the architecture of the proposed hybrid optical buffer for slotted optical packet-switched networks. SW1 and SW2 are $1\times K$ and $K\times 1$ optical switches, respectively. OB-1 to OB-$K$ are optical fiber loop modules. EB-1 to EB-$K$ are electronic buffering modules. Since multiple packet transmission times are required to convert and read/write a packet to/from the electronic memory, the packets must be temporarily stored in a fiber loop before the completion of the operations. Besides serving as a packet buffer [2], a fiber loop can also be configured as a packet expander [8] and a packet compressor [9] depending on the switch operation as shown in Table I. When a fiber loop functions as a packet expander or compressor, the packet is required to circulate in the fiber loop $K$ times such that a $K$ times slower
The proposed buffer. The system loading (\( \rho \)) is the ratio of average packet arrivals per time slot to the average represented by lines with crosses, asterisks, circles, and squares, respectively. From Fig. 2, the required buffer size and heavily loaded system, we plot the required buffer sizes for system loadings of 0.85, 0.9, 0.925, and 0.95 which are longer apply. A possible shortcoming is that the sequence integrity of the incoming packets may not be preserved by the installed electronic memory. The limitations (iii) and (iv) of the fiber loop optical buffers discussed in Section 1 no configuration, the proposed hybrid optical buffer becomes an optical buffer with a buffer size equal to that of the channels into a single fiber loop. In principle, we can use one fiber loop and \( \lambda \) channels into a single fiber loop. At the same time, the electronic buffering module EB-\( K \) will begin to convert and store packet \( x \) into the electronic memory and simultaneously build a copy of packet \( x \) at wavelength channel \( \lambda_{\text{out}} \) of the fiber loop assuming that channel \( \lambda_{\text{out}} \) is empty. To simplify the discussion, we assume that the electronic buffers (EBs) can read from channel \( \lambda_{\text{in}} \) and write to channel \( \lambda_{\text{out}} \) simultaneously. The whole process will be completed in \( K \) circulations if packet \( x \) cannot be sent out during this time. After EB-\( K \) completes the conversion of packet \( x \), channel \( \lambda_{\text{in}} \) of OB-\( k \) will become available for new arrival packets. The packet in channel \( \lambda_{\text{out}} \) will be refreshed by the electrical memory stored in EB-\( k \) every \( K \) time slots as discussed in [3]. Thus there will be no limit on the number of circulations a packet can have on channel \( \lambda_{\text{out}} \).

When the output is available, the buffer will first send out the oldest packet in the \( \lambda_{\text{out}} \) channels of the optical buffers. The packets in the \( \lambda_{\text{in}} \) channels will be considered next if all \( \lambda_{\text{out}} \) channels are empty. Finally, a new arrival packet will be served if there are no packets in all the \( \lambda_{\text{in}} \) and \( \lambda_{\text{out}} \) channels. In the proposed design, an EB will place a packet on the empty \( \lambda_{\text{out}} \) channel whenever the electronic memory is not empty. The EB will clear the corresponding data in the electronic memory immediately if the packet on the \( \lambda_{\text{out}} \) channel is sent out. Otherwise, the packet is refreshed every \( K \) time slots. Finally, if a packet on channel \( \lambda_{\text{in}} \) is sent out during the packet conversion time in the initial \( K \) time slots after the packet arrival, all the associated data in the electronic memory and channel \( \lambda_{\text{out}} \) will be cleared immediately.

If the output is temporarily unavailable, all arrival packets are stored into the electronic memory with \( K \) slots conversion time for each packet. Hence, no packets will be discarded if \( K \) sets of OBs and EBs are installed. With this configuration, the proposed hybrid optical buffer becomes an optical buffer with a buffer size equal to that of the installed electronic memory. The limitations (iii) and (iv) of the fiber loop optical buffers discussed in Section 1 no longer apply. A possible shortcoming is that the sequence integrity of the incoming packets may not be preserved by the proposed buffer.

To make the buffer more compact, the number of OBs can be reduced by multiplexing the different wavelength channels into a single fiber loop. In principle, we can use one fiber loop and \( 2K \) wavelength channels \( \lambda_{\text{in},1} \) to \( \lambda_{\text{in},K} \) and \( \lambda_{\text{out},1} \) to \( \lambda_{\text{out},K} \) to form the \( K \) OBs. However, multiple wavelength converters will be required.

### 3. Performance evaluation

We model the input packet arrival and the output service of the proposed hybrid optical buffer with Bernoulli random distribution [1]. The system loading (\( \rho \)) is the ratio of average packet arrivals per time slot to the average service rate at the buffer output. Figure 2 gives the buffer size required in the proposed optical buffer for different system loadings and packet loss rates. The average output service rate is set to 0.5 packets/slot. To simulate a bursty and heavily loaded system, we plot the required buffer sizes for system loadings of 0.85, 0.9, 0.925, and 0.95 which are represented by lines with crosses, asterisks, circles, and squares, respectively. From Fig. 2, the required buffer size grows quickly with the system loading and the tolerated packet loss rate. For a system loading of 0.95, we need a buffer size of around 160 packets even for a moderate packet loss rate of \( 10^{-8} \) [1]. It is simple to construct a buffer with such a size for the proposed hybrid optical buffer but will be quite challenging for buffers built with fiber delay lines only.

### Table 1: Designs of packet buffer, expander, and compressor using fiber loops and fast switch.

<table>
<thead>
<tr>
<th>Fiber loop configuration</th>
<th>Function/circulation time</th>
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<tbody>
<tr>
<td>1</td>
<td>packet buffer: the number of circulations depends only on output availability [2].</td>
</tr>
<tr>
<td>2</td>
<td>packet expander: the packets circulates ( K ) times in the fiber loop [8].</td>
</tr>
<tr>
<td>3</td>
<td>packet compressor: the packets circulates ( K ) times in the fiber loop [9].</td>
</tr>
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</table>
The proposed hybrid buffer can easily increase its buffer size by electronic memory. Only $K$ sets of optical fiber loops are required for packet conversion and temporarily buffering. Unlike the all fiber delay lines based optical buffers, the number of fiber loops $K$ in the proposed hybrid optical buffers is independent of the system loading and packet loss rate. The optical hardware can therefore be significantly simplified when compared to all fiber delay lines based optical buffers. Figure 3 shows the savings of fiber loop optical buffers with the proposed hybrid optical buffer under different system loadings and output service rates. The parameter $K$ is set to 10 and the required packet loss rate is $10^{-8}$. In the simulations, the traffic burstiness will increase if we keep the $\rho$ unchanged but simultaneously reduce the output service rate and packet arrival rate. From Fig. 3, the savings from the proposed hybrid optical buffer is large if either the system loading is high or the traffic is bursty. From Fig. 2, we also observe that larger savings can be obtained with lower packet loss rates.

4. Conclusion

We have proposed a hybrid optical buffer that uses optical fiber loops for packet conversion and temporarily buffering. The packets are converted and stored in electronic memory for long term buffering. We have demonstrated that the demand on optical hardware can be significantly reduced using the proposed design.

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References: