

# Modelling of Fibre Loop Buffer based Switch

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## ABSTRACT

Photonic all-optical switch is widely considered as one of the techniques to utilize the enormous optical bandwidth. This paper attempts to present a mathematical model for a loop buffer based switch and brings out the aspects of designing the all optical switch. The important aspects discussed are length of the optical loop and the design of EDFA. This paper also deals with the comparison of maximum number of circulations of the packet in the loop buffer both in presence and absence of cross talk.

**Keywords:** Optical switch, optical amplifiers, optical memory, optical buffer.

## 1. INTRODUCTION

The demand for higher bandwidth is ever increasing due to continuous evolution in the services. Broad acceptance of fiber optic and photonic technology in transmission systems has led to potential opportunities for using all-optical switching. The important aspects of photonic packet switching<sup>1</sup> are control, packet routing, packet synchronization, clock recovery, contention resolution, packet buffering and packet header replacement. This paper emphasizes the aspects of buffering.

### 1.1 Buffering in packet switching

When a data packet reaches a node, it has to be stored till control module decides on which path the packet has to be sent. During this time interval, the packet is sent to a delay line. Once decision has been made on the packet's routing, the packet is made available from the delay lines. It is then sent to the output port as per the decision. Limited access speed of electronic RAMs constraints its use in packet buffering. In addition this approach requires optical to electrical (O/E) conversion and vice-versa when packets are written into and read out of electronic RAMs and hence adds to the complexity and delay.

All-optical RAM suitable for photonic packet switching has not yet been found. The alternative is to use optical fiber delay lines incorporating other components such as optical gate switches, optical couplers, optical amplifiers, and wavelength converters to realize photonic buffering. A number of photonic packet buffers based on optical fiber delay lines have been proposed and demonstrated<sup>2</sup>. In general these optical fiber delay lines based buffers can be classified into two basic categories: travelling-type and recirculating type. A travelling-type buffer generally consists of multiple optical fiber delay-lines whose lengths are equivalent to multiples of a packet duration  $T$ , and optical switches to select delay lines<sup>3</sup>. The recirculating type buffer is more flexible than the travelling type buffer because the packet storage time is adjustable by changing the number of circulations. In principle recirculating type buffers offer a kind of random access where storage time depends on the number of circulations.

### 1.2 Working of all optical loop buffer

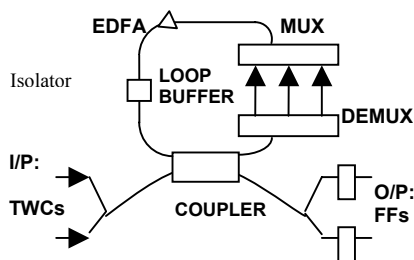


Figure1: All Optical Loop Buffer Switch

This architecture<sup>4</sup> consists of  $N$  tunable wavelength converters, one at each input, a recirculating loop buffer, and  $N$  fixed filters, one at each output. Packets from all the inputs use WDM technology to share the recirculating loop buffer. The number of buffer wavelengths depends on the switch design, desired traffic throughput, packet loss probability and size of the switch<sup>1</sup>. The allocation of the packets to the loop buffer depends on the routing and priority algorithm for the switch. The packets to be buffered are converted to the wavelengths available in the buffer; if buffer is full then packets are dropped.

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When a packet is selected for buffering, the respective TWC in the buffer is tuned to the buffer wavelength to accept the packet. As long as a packet is in buffer, the selected TWC will remain transparent, till it is desired to read out the packet or to have dynamic wavelength re-allocation. The TWCs are tuned at every cell slot either to place a packet in the loop buffer to avoid contention or to direct them to output. For reading a packet, when output contention is resolved, buffer TWC is tuned to the wavelength of appropriate output port fixed filters (FF), the packet is broadcasted to all output ports.

## 2. MATHEMATICAL MODEL

Let loss in signal power in a single circulation from entry port to before reaching EDFA be  $A_1$  and that after the EDFA be  $A_2$ . Hence  $A_1$  and  $A_2$  are given by:

$$A_1 = L_{3dB} + L_{DMUX} + L_{TWC} + L_{MUX} + 5L_s + L_F \quad (1)$$

$$A_2 = L_{ISO} + L_{BPF} + 3L_s + L_F \quad (2)$$

Where  $L_{3dB}$  is loss due to 3dB coupler,  $L_{DMUX}$ ,  $L_{MUX}$ ,  $L_{TWC}$  and  $L_{BPF}$  are losses due to Demultiplexer, Multiplexer, Tunable Wavelength Converter and Band Pass Filter respectively.  $L_s$  is the splice loss,  $L_F$  is the fiber loss and  $L_{ISO}$  is the isolator loss. Let  $A = A_1 A_2$  also let the input signal power be  $P$ . Then the output power of EDFA after one circulation is given by:

$$APG + (G-1)n_{sp}h\nu B_o \quad (3)$$

Where  $A$  is the loss and  $G$  is the gain of EDFA in one circulation, the first term represents the signal power, and second term represents Amplified Spontaneous Noise Power<sup>5</sup>. Similarly output power of the signal after  $K$  circulations is:

$$P_K = A^K PG^K + (G-1)A_2 n_{sp} h\nu B_o F \quad \text{where} \quad F = \frac{1-(AG)^K}{1-AG} \quad (4)$$

### 2.1 Crosstalk Calculation

The above calculation assumes that components in the loop do not produce any cross talk, if crosstalk is incorporated then total output power of the signal after  $K$  circulations is

$$(P_k)_T = P_K + P_{crosstalk} \quad \text{where} \quad P_{crosstalk} = \{P_{DEMUX} + P_{MUX} + P_{TWC}\}AGF \quad (5)$$

Where the crosstalk power at demux and mux and TWC is  $P_{DEMUX}$ ,  $P_{MUX}$  and  $P_{TWC}$  respectively. Other components in the loop like 3dB coupler and EDFA do not produce any significant crosstalk.

The major assumptions in the above model are:

- There is no gain saturation, i.e. the signal power after  $K$  circulation is less than the saturation power level of the EDFA.
- In each circulation gain remains constant.
- The change in wavelength when the packet is read out of the buffer does not cause any variation in gain of the last circulation.

### 2.2 Noise Analysis

Due to square law detection by the photo detector in the receiver, various noise components are generated. These noise components are shot noise, ASE-ASE beat noise, sig-ASE beat noise, shot-ASE beat noise and thermal noise denoted by  $\sigma_s^2$ ,  $\sigma_{sp-sp}^2$ ,  $\sigma_{sig-sp}^2$ ,  $\sigma_{s-sp}^2$  and  $\sigma_{th}^2$  respectively<sup>5</sup>. These terms after  $K$  circulations are given by:

$$\begin{aligned} \sigma_s^2 &= 2qRP_{sig}(K)B_e & \sigma_{sp-sp}^2 &= 4R^2P_{sp}^2(K)(2B_o - B_e)\frac{B_e}{B_0^2} \\ \sigma_{sig-sp}^2 &= 4R^2P_{sig}(K)\frac{P_{sp}(K)B_e}{B_0} & \sigma_{s-sp}^2 &= 4qTP_{sp}(K)\frac{B_e}{B_0} & \sigma_{th}^2 &= \frac{4kTB_e}{R_L} \end{aligned} \quad (6)$$

Where  $P_{sig}(K)$  is the signal power when packet passes through the 3dB coupler after  $K$  circulations and  $P_{sp}(K)$  is the ASE noise power when packet passes through the 3dB coupler after  $K$  circulations. They are given by:

$$P_{sig}(K) = \frac{(AG)^K P}{2} \quad \text{and} \quad P_{sp}(K) = A_2(G-1)n_{sp} h\nu \frac{B_o F}{2}$$

Now when crosstalk is present then the term  $P_{sig}(K)$  will be modified as

$$P_{sig}(K_c) = (AG)^K P + \{P_{DEMUX} + P_{MUX} + P_{TWC}\}AGF \quad (7)$$

The total noise power is

$$\sigma^2 = \sigma_s^2 + \sigma_{sp-sp}^2 + \sigma_{sp-sig}^2 + \sigma_{s-sp}^2 + \sigma_{th}^2$$

The SNR after K circulations can be written as

$$SNR = \frac{[R(AG)^K P]^2}{\sigma^2} \quad (8)$$

The BER in terms of SNR can be written as<sup>6</sup>

$$BER = \frac{1}{2} \operatorname{erfc} \left( \frac{\sqrt{SNR}}{2\sqrt{2}} \right) \quad (9)$$

### 2.3 EDFA Gain Formulation

Considering EDFA as a three level laser where  $N_1$ ,  $N_2$  and  $N_3$  are the population of ground state, metastable state and upper state respectively. The gain coefficient of the EDFA is given by the expression. The rate equations for the three levels are:

$$\begin{aligned} \frac{dN_1}{dt} &= -\sigma_p I_p N_1 + \frac{N_2}{\tau_{21}} + (\sigma_e N_2 - \sigma_a N_1) \frac{I_s}{h\nu_s} \\ \frac{dN_2}{dt} &= \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - (\sigma_e N_2 - \sigma_a N_1) \frac{I_s}{h\nu_s} \\ \frac{dN_3}{dt} &= \frac{\sigma_p I_p N_1}{\tau_{32}} - \frac{N_3}{\tau_{32}} \end{aligned}$$

At equilibrium:

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = 0$$

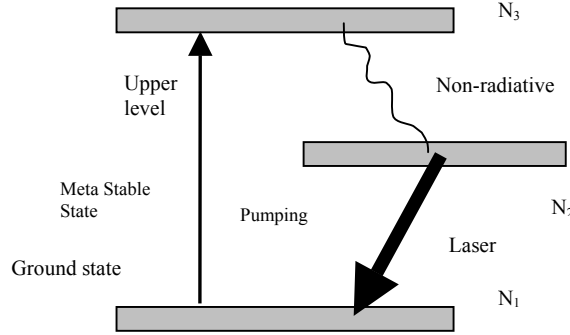


Figure2: Schematic of EDFA

Since  $N_3$  is small in comparison to  $N_1$  and  $N_2$   $N_T \approx N_1 + N_2$

Solving the above equations at equilibrium and using the formula  $g(\lambda) = \sigma_e N_2 - \sigma_a N_1$  to calculate the gain coefficient we obtain:

$$g(\lambda) = \frac{\frac{\sigma_p \sigma_e I_p}{h\nu_p} - \frac{\sigma_a}{\tau_{21}}}{\frac{\sigma_p I_p}{h\nu_p} + \frac{(\sigma_a + \sigma_e) I_s}{h\nu_s} + \frac{1}{\tau_{21}}} N_T$$

The various terms in the above equations have usual meanings. Finally the gain of the amplifier calculated as<sup>7</sup>

$$G = \exp[g(\lambda) l] \quad (10)$$

### 3. CALCULATIONS AND RESULTS

The values of various parameters used in the calculations are:

Parameter	Value	Parameter	Value	Parameter	Value
$L_{3dB}$	3.4dB	$L_{DMUX}$	1.5dB	$L_{TWC}$	2dB
$L_{MUX}$	6.8	$L_s$	$10 \times 0.2 = 2.0$ dB	$L_F$	0.2 dB/km
$L_{ISO}$	0.15 dB	$L_{BPF}$	1 dB	$l_{EDFA}$	3.6m

$n_{sp}$	1.2	$B_e$	10GHz	$B_o$	$2B_e=20$ GHz
$A_2$	-1.75dB	$A_{eff}$	$50\mu m^2$	$n_2$	$3 \times 10^{-20} m^2/W$
$\gamma$	$2.58 \times 10^{-3}$	$d_{ijk}$	6	$A_1$	-15.10dB
$\sigma_p$	$3 \times 10^{-25} m^2$	$\lambda_p$	980 nm	$\tau_{21}$	10ms
$P_p$	50mw	$R_f$	$1.8\mu m$	$N_T$	$3.70 \times 10^{24}$

The length of the loop is taken equal to the packet duration and is given by  $L = cb/nB$ . In the calculation we have assumed equal length packets of 53 bytes and 1byte period on each side taken as guard period the length is found to be 8.52m. For BER not exceeding  $10^{-9}$  the minimum SNR is 21.6 dB. The minimum power comes out to be  $5.14 \times 10^{-5}$  Watts. Since cross phase modulation is the dominant factor in fiber nonlinearity to minimize the effect of nonlinearity<sup>8</sup> the input power should not exceed 2.2 mW. The maximum number of circulations of the packet in the loop buffer can be calculated by using equation under the condition  $AG=1$  there is no crosstalk present in any component this number is found to be 40 for all four wavelengths.

In the architecture combiner is used to multiplex the wavelength. Combiner can be designed using 3-dB couplers. These 3-dB couplers are wavelength-flattened coupler, so does not produce any crosstalk. Considering four wavelength demux, for the cross talk calculation the shape of the pulse assumed to be gaussian and the isolation between two channels at the demux is  $-25$ dB. This value comes out to be 0.016 mW. Using the formula<sup>6</sup> for cross-talk due to Four-Wave mixing cross talk comes out to be  $5.6 \times 10^{-9}$  Watts.

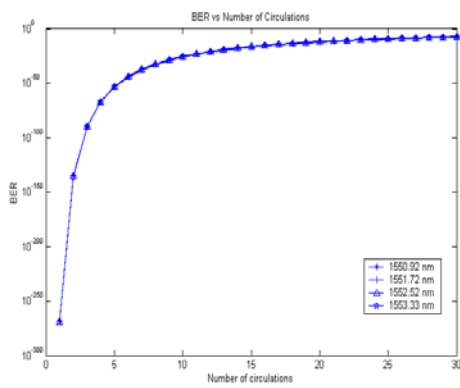


Figure3: BER vs. Number of Circulations

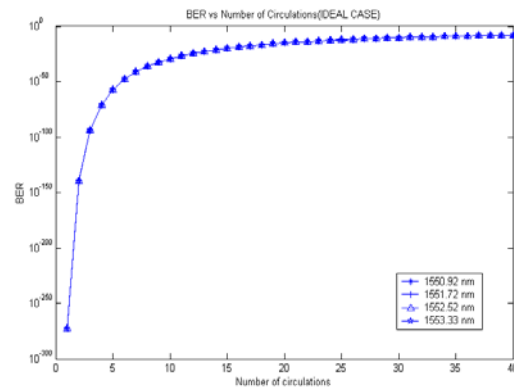


Figure 4: BER vs. Number of Circulations (IDEAL CASE)

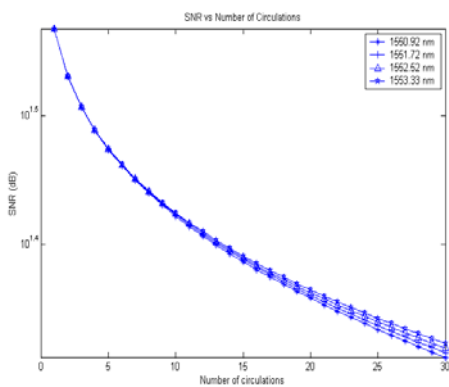


Figure5: SNR vs. Number of Circulations

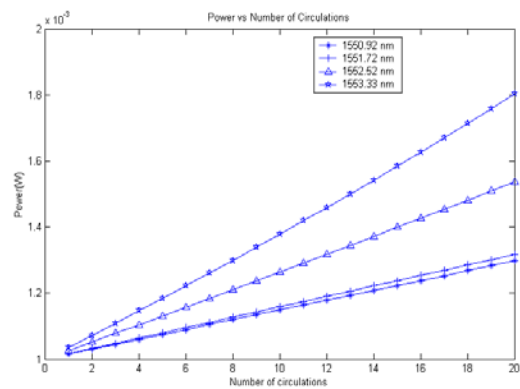


Figure 6: Power vs. Number of Circulations

#### 4. CONCLUSIONS

This paper briefly discussed the aspects of Optical Loop Buffer design. The above graphs show BER, SNR and Power plotted against number of circulations. It was found out that for a BER  $<10^{-9}$  for ideal case the packet can remain in the loop for up to 40 circulations and for non-ideal case the packet can remain in the loop for up to 27 circulations (this figure varies slightly with wavelength).

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