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Modelling of solitons pulse in fibre loop buffer 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 present a mathematical analysis for a loop buffer based switch and brings out the aspects of designing of all optical switch. The important aspects discussed are length of the optical loop, and how the optical solitons benefits the switch performance. This paper also deals with the comparison of maximum number of circulations of the packet in the loop buffer for solitons pulses with and without filter.

Keywords: Buffering, routing, loop buffer, wavelength conversion

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 [1] are control, packet routing, packet synchronization, clock recovery, contention resolution, packet buffering and packet header replacement. This paper emphasizes the aspects of buffering.

2. BUFFERING IN PACKET SWITCHING

Considering network shown in figure 1 in which, A to E are end nodes, and 1 to 5 are switching nodes. If we suppose that node A has to send a packet to node D. The packet may choose multiple paths like A-1-4-D, A-1-5-4-D, A-1-2-3-4-D etc, the selection of the path will depend on the switch traffic and the routing algorithm. The function of the routing node is to route the packet, on the basis of the information stored in the packet header. At each switching node the payload of the packet has to be buffered until control module can decides on which path the packet has to be sent. Currently data is stored electronically, but limited access speed of electronic RAMs constraints it uses in packet buffering.

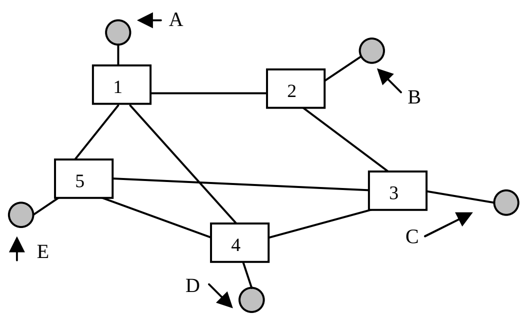

Figure 1 Schematic of an arbitrary network

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.

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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 [2]. 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 consist of multiple optical fiber delay lines whose lengths are equivalent to multiples of a packet duration T, and optical switches to select delay lines [3].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 buffer offer a kind of random access where storage time depends on the number of circulations.

3. WORKING OF ALL OPTICAL LOOP BUFFER

This architecture [4, 5] consists of N tunable wavelength converters, one at each input, 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. 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. 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

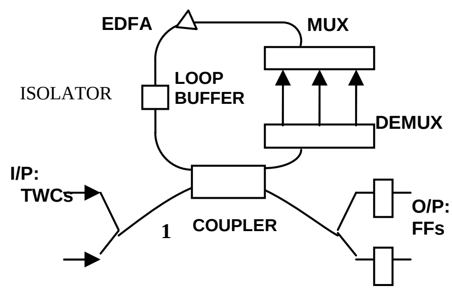

Figure 2 All Optical Loop Buffer Switch

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), as a result the packet is passed to appropriate output port.

4. OPTICAL SOLITONS

As we want to find out impact on switch performance, if solitons are used, the following section gives brief introduction of solitons in optical fiber.

A solitons is a very narrow pulse with high peak power. The solitons pulses are so stable that its shape and velocity is preserved while travelling along the medium. This means that solitons pulses do not spread in optical fiber after thousands of kilometers. In an optical fiber solitons pulses are generated by counter balancing the effect of the dispersion by the self-phase modulation. [6]

The shape of the solitons pulse can be found out by solving non linear Schrödinger equation. The envelope of an optical pulse propagating through a non-linear dispersive medium is approximately governed by the following equation [12]

$$\frac{\partial A}{\partial Z}+\beta_1\frac{\partial A}{\partial t}+i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2}=i\gamma|A|^2A \qquad (1)$$

Where $\beta_1 = \frac{1}{v_g} = \left|\frac{dK}{d\omega}\right|_{\omega=\omega_0}$ is the first order dispersion parameter, which is inversely related to group velocity v_g , β_2 is the second order group velocity dispersion parameter, γ is the nonlinear index parameter and $A(Z,t)$ represents the envelope term of the pulse.

We can define new variables

$$\tau = \frac{t - \frac{z}{v_g}}{T_0},\; z = \frac{Z}{L_D},\; u = \sqrt{|\gamma| L_D} A \quad \text{and} \quad L_D = \frac{T_0^2}{|\beta_2|}.$$

The interpretation of the above variables is as follows. since the pulse propagates with velocity β_1 (in the absence of dispersion), $t - \beta_1 z$ is the time axis in a reference moving with the pulse. The variable τ is the time in this reference frame in the unit of T_0 (pulse width of the solitons pulse).The variable z measures in the unit of dispersion length L_D , P_0 is the peak power of the pulse and u is the envelope of the pulse.

The equation (1) with new variable can be written as

$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0 \tag{2}$$

The solution of the above equation is of the form [11]

$$u(\tau) = N_0 \operatorname{sech}(\tau)\exp\left(\frac{iz}{2}\right) \tag{3}$$

The shape of the solitons pulse is secant hyperbolic in nature. For $N_0 = 1$ the pulse is called fundamental solitons, and the peak power of the pulse is related to N_0 as

$$N_0^2 = \gamma P_0 L_D = \frac{\gamma P_0 T_0^2}{|\beta_2|},$$

and the pulse width is given by $T_0 = \frac{Full\ width\ half\ \max ima}{1.763}$.

The stability of the solitons make them very good candidate for optical communication. The solitons pulses are superior to NRZ pulses in the following manner.

1). Solitons can be generated in the loss minimum region at around 1550 nm.

2). Solitons pulse transmission is possible over long distance. Solitons can be both time and polarized multiplexed.

3). There is no waveform distortion over long distances, which are useful for long distance communication.

4). Solitons are dispersion free, and the collision of the solitons are elastic in nature, after collision their amplitude and frequency remain unchanged, only position and phase changes.

5). Two counter propagating solitons pass each other without affecting each other’s motion

5. MATHEMATICAL MODEL OF THE SWITCH

5.1 LOSS IN THE LOOP

Let loss in signal power in a single circulation from entry port (1) to before reaching EDFA be A_1 and that after the EDFA be A_2. Hence A_1 and A_2 are given by

$$A_1 = L_{3dB} + L_{DEMUX} + L_{TWC} + L_{COMBINER} + 5L_s + L_F \tag{4}$$

$$A_2 = L_{ISO} + L_{BPF} + 3L_S + L_F \tag{5}$$

Let $A = A_1 A_2$ the total loss of the loop in one circulation.

Where L_{3dB} is loss due to 3dB coupler, L_{Demux} , $L_{combiner}$ L_{TWC} and L_{BPF} are losses due to demultiplexer, combiner , tunable wavelength convertor and Band Pass Filter respectively. L_s is the splice loss, L_F is the fiber loss and L_{iso} is the isolator loss.

5.2 AMPLIFIER NOISE

When solitons pulse propagate through the fiber loop, their peak power decreases because of fiber loop attenuation, and this reduction in the power of the solitons pulse will mismatch the counter balancing condition of group velocity dispersion with self phase modulation. To overcome losses optical amplifier are used. Optical amplifiers not only amplify the solitons power, but unfortunately also add ASE noise which causes variation in amplitude, frequency, position and phase of the optical pulse. The impact of ASE on the solitons pulse can be analyzed by considering the noise as a small perturbation. In this analysis it is assume that, all the losses is compensated by amplifier gain, and in the absence of any perturbation the solitons pulse maintain sech shape, but the solitons parameter varies with propagation distance z.

In the presence of perturbation the NLS equation can be written as [11, 12]

$$i\frac{\partial u}{\partial z}+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+|u|^2 u = in(z,\tau) \tag{6}$$

Where $n(z,\tau)$ is a markovian stochastic process with Gaussian Statistics, with mean $E[n(z,\tau)]=0$

And $E[n(z,\tau)n^*(z',\tau')]=S_n\delta_D(\tau-\tau')\delta(z-z')$

$$S_n = S_{sp}\frac{\gamma L_D^2}{L_A T_0}$$

And S_{sp} is ASE noise spectral density

$$S_n = n_{sp}h\nu_0(G-1)\frac{\gamma L_D^2}{L_A T_0} \tag{7}$$

The most general form of the perturbed solution can be taken as

$$u(z,\tau)= A(z)Sech[A(z)(\tau-q(z))]\exp[i\phi(z)-i\delta(z)] \tag{8}$$

In this equation A is amplitude of the solitons pulse, δ is frequency, q is initial separation between solitons and ϕ is the initial phase of the solitons pulse.

The variation of the four parameters with distance z can be described by the set of differential equation [7]

$$\frac{dA}{dz}=\mathrm{Re}\int_{-\infty}^{\infty} n(z,\tau)u^*(\tau)\,d\tau$$

$$\frac{d\delta}{dz}=-\mathrm{Im}\int_{-\infty}^{\infty} n(z,\tau)\tanh[A(\tau-q)]\,u^*(\tau)\,d\tau$$

$$\frac{dq}{dz}=-\delta+\frac{1}{A^2}\mathrm{Re}\int_{-\infty}^{\infty} n(z,\tau)(\tau-q)u^*(\tau)d\tau$$

$$\frac{d\phi}{dz}=\mathrm{Im}\int_{-\infty}^{\infty} n(z,\tau)\{\frac{1}{A}-(\tau-q)\tanh[A(\tau-q)]\}u^*(\tau)d\tau + \frac{1}{2}\left(A^2-\delta^2\right)+q\frac{d\delta}{dz} \tag{9}$$

From these equations the variance of amplitude and frequency fluctuation can be found as

$$\sigma_A^2 = S_n(z)z \qquad \sigma_\delta^2=\frac{S_n z}{3} \tag{10}$$

The amplitude fluctuation degrades the SNR of the solitons bit stream but this degradation is very small, for typical value $L_A=50$ km $T_0=10$ ps the allowed propagation distance is about 10000km. And this has been found out that 10% fluctuation in the amplitude of the solitons produces only 1% fluctuation in the energy [4]. Due to the stable nature of solitons this perturbation does not produce any significant effect on the solitons based communication system. But frequency fluctuations affect the system performance more drastically by inducing the timing jitter.

5.3 TIMMING JITTER

In a single and multi-channel system, amplified spontaneous emission noise generated by the optical amplifier induces time jitter and amplitude fluctuation. The jitter can be understood by noting a change in solitons frequency by the speed at which solitons propagates through the fiber. If frequency fluctuates due to amplifier noise, the solitons transit time through the fiber link also becomes random. This ASE induced fluctuation in the arrival time of the solitons at the receiver are referred to as the Gordon-Haus timing jitter [9, 10].

The variance

$$\sigma_q^2 \approx \frac{1}{9} S_n Z^3 \ , \qquad (11)$$

where

$$\sigma_q = \frac{\sigma_t}{T_0} \quad Z = \frac{L_T}{L_D} \ .$$

Finally we get the following expression;

$$\sigma_t^2 = \frac{n_{sp} h \nu_0 \gamma |\beta_2| (G-1) L_T^3}{9 T_0 L_A Q} \ ,$$

and

$$\sigma_t^2 = \frac{n_{sp} h \nu_0 \gamma |\beta_2| (G-1) N^3 L_A^2}{9 T_0 Q} \qquad (12)$$

Since a solitons should arrive within its bit slot for its correct identification at the receiver, timing jitter should be small fraction of the bit slot T_B. This requirement can written as $\frac{\sigma_t}{T_B} < f_b$ where f_b is the fraction of the bit slot by which a solitons can move without system performance adversely.

$$B = \frac{1}{T_B} = (2 q_0 T_0)^{-1}$$

$$BL_T < \left[\frac{9 f_b^2 L_A Q}{h \nu_0 F_n (G-1) q_0 \gamma |\beta_2|}\right]^{\frac{1}{3}} \qquad (13)$$

The typical value of $f_b \approx 0.1$ for bit error rate less than or equal to 10^{-9}

Where B is the bit rate, L_T is transmission length, L_A is the distance between two adjacent amplifiers, $Q = \frac{G \ln G}{G-1}$ where G is the gain of the amplifier, n_{sp} is the spontaneous emission factor, ν is the frequency q_0 is the normalized distance between two solitons, and f_b is a important term which describe the fraction of the bit period occupied by the solitons pulse.

For the loop buffer the design rule can be modified as $L_T = L \times N$ where L is the length of the loop buffer and N is the number of circulations, under the condition $AG = 1$

$$BLN < \left[\frac{9 f_b^2 L_A Q}{h \nu_0 F_n (G-1) q_0 \gamma |\beta_2|}\right]^{\frac{1}{3}}$$

$$(BNL)^3 < \left[\frac{9 f_b^2 L_A Q}{h \nu_0 F_n (G-1) q_0 \gamma |\beta_2|}\right] \qquad (14)$$

5.4 FILTERING

Optical amplifier induced noise limits the number of circulation of the solitons pulse in the loop buffer. This effect can be controlled by using optical filters, this filtering prevent both amplifier saturation and Gordon haus effect. In addition to, the gain spectrum of the erbium doped fiber amplifier is not flat and thus acts as a filter.

Under the action of the Fabry Parot filter new timing jitter variance is [13]

$$\sigma_t^2(f) = \frac{3 \sigma_t^2 L_A^2}{16 \delta_F{}^2 L_T^2} \qquad (15)$$

Here δ_F is excess gain which must be provided to overcome the losses of filter.

6. CALCULATIONS AND RESULTS

The length of the loop is taken equal to the packet duration and is given by $L = cb/nB$. Where c is the speed of the light, b is the stored bits, n is refractive index of the fiber and B is the data rate.

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. When we only consider the effect of noise the maximum number of circulation of the packet in the buffer is 6956, and in the presence of filter this number improves drastically to 151428 circulations.

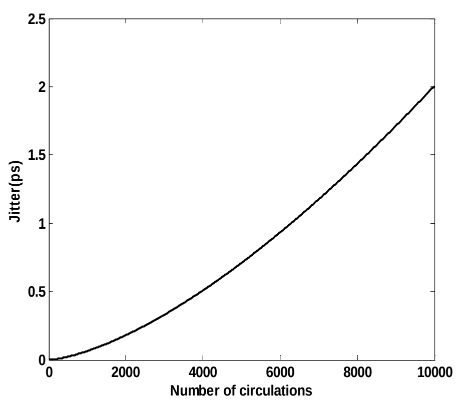

Figure 3 Jitter vs. Number of circulations (without filter)

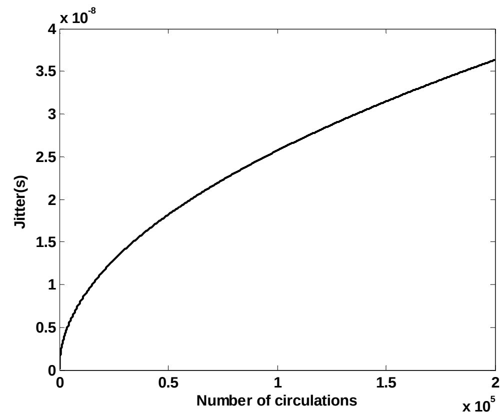

Figure 4 Jitter vs. Number of circulations (with filter)

7. CONCLUSIONS

This paper briefly discussed the aspects of Optical Loop Buffer design. It was found out that for a BER <10^{-9}, the packet can remain in the loop for up to 6956 circulations With filters this number increases drastically to 151428 circulations. This result emphasis that solitons pulses are better choice in loop buffer switch.

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