Simulation of the Passive Recirculating Fiber Loop Buffer

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ABSTRACT

The current trends within ultra high-speed optical time division multiplexed (OTDM) based communication systems dictate the increasing need for all optical buffering systems. Such systems inherently avoid the bottlenecks associated with opto-electrical (O/E) and electro-optical conversions (E/O). These buffers would enable the storage of data for discrete time intervals, and are necessary for many OTDM applications. Storage time limitations within passive recirculating fiber loop buffers are mainly due to the dispersive, nonlinear and loss properties of the fiber. These result in both amplitude decay and pulse spreading which may have a detrimental effect on data integrity. In this paper, we examine the propagation of both standard soliton and Gaussian-soliton shaped pulses within a recirculating fiber loop buffer. The simulation model is based on the nonlinear Schrödinger equation (NLSE) and accounts for fiber loss within the communications channel. At this stage pulse interactions are not considered and direct modulation of the launched pulses is assumed. Simulation results for bit error rate performance at different buffer loop numbers is presented.

Keywords - Optical Buffer, Soliton, Optimal Threshold Value, Intersymbol Interference, OTDM, Non-linear Schrödinger equation, Beam Propagation.

1 INTRODUCTION

In optical time division multiplexed networks many message signals are combined for transmission on a single wavelength. Each signal from a lower bit-rate source is broken up into many packets, each having very short duration, and are multiplexed in a rotating repeating sequence onto a high bit-rate transmission line. The use of short duration pulses allows information to be transmitted at very high bit rates (>100 Gb/s). An asset of OTDM is its flexibility, which allows for variation in the number of signals being sent along the line, and constantly adjusts the time intervals to make optimum use of the available bandwidth. Consequently, it is believed that OTDM networks are excellent candidates for meeting the future system requirements for massive ultrafast networks.

Within such networks a mechanism for resolving contention among multiple input ports going to a single output port is a crucial requirement. Thus it becomes necessary to provide a temporary storage element in order to avoid the loss of packets. Since electronic buffering and retransmission reduces system throughput, an all-optical approach is preferred option especially at very high bit rates. Buffers may be located at transmitting or receiving end. At the former, optical buffers may hold data packets while they wait for access to the network, whereas at the latter buffers may be used to present multiple copies of the incoming data packets to a demultiplexer or rate converter. In addition, they may also be employed to compensate for the slow speeds inherent to the O/E interface. As such, it becomes very important to determine the optimal configuration for given applications and network topology. This is to ensure that both bit and packet integrity is maintained and maximum storage times are achieved without unrealistic expectations on power or energy requirements. In section 1.1, a brief description of the beam propagation method is given and the effects of initial pulse shape on the propagating pulse profile are highlighted. The simulation model is described in section 1.2. Finally, the simulation results and conclusions are present in sections 2 and 3, respectively.
1.1 Beam Propagation Method (BPM)

The non-linear Schrödinger equation, which defines the evolution of a pulse as it propagates within a single mode fiber is given as [8]:

\[
\frac{i}{\partial z} \frac{\partial A(z, \tau)}{\partial z} + \frac{i \alpha}{2} \frac{\partial^2 A(z, \tau)}{\partial \tau^2} + \frac{\beta_2}{2} \frac{\partial^4 A(z, \tau)}{\partial z^4} + \frac{\gamma}{2} |A(z, \tau)|^2 A(z, \tau) = 0 ,
\]

(1)

where \( \tau = t - z/V_g \), \( \alpha \) is the fiber power loss coefficient, \( \beta \) is the fiber first order dispersion coefficient, \( \gamma \) is the fiber non-linear coefficient, and \( V_g \) is the group velocity. Note that \( A(z, \tau) \), which represents the slowly varying amplitude of the propagating pulse, is a function of both distance \( z \) and time \( \tau \) measured in a frame of reference relative to the group velocity. When \( \alpha = 0 \), (1) governs the evolution of amplitude profile of a pulse propagating in a dispersive non-linear medium. The third and last terms represent the first order dispersion, and the non-linear effect of the fiber.

With (1) being a non-linear partial differential equation, therefore it can't be solved analytically. Thus a numerical approach, such as BPM, is used to solve it. BPM gives an approximate solution for the NSE, by assuming that both the dispersive and non-linear effects can be treated as acting independently on the optical field propagating over a small distance. Therefore (1) can be separated into its dispersion and loss (\( D \)), and non-linear operators (\( N \)) given by:

\[
\frac{\partial A(z, \tau)}{\partial z} = (\hat{D} + \hat{N}(A(z, \tau))) A(z, \tau)
\]

(2)

where:

\[
\hat{D} = -i \frac{\beta_2}{2} \frac{\partial^2}{\partial z^2} - \frac{\alpha}{2}
\]

(3)

\[
\hat{N} = i \gamma |A(z, \tau)|^2
\]

(4)

As illustrated in Figure 1 in BPM the whole propagation distance is split into a large number of small segments of length \( \Delta z/2 \). The dispersion and loss effects are considered as the pulse propagates over the first and second halves of any given segment whereas the non-linear effects are assumed to be lumped at the Center. For a comprehensive review of the BPM algorithm the reader is referred to [8].

![Figure 1 Schematic illustration of Beam Propagation technique](image)

1.2 Passive Recirculating Fiber Loop Buffer

Figure 2 highlights a typical passive recirculating fiber loop optical buffer (RFLB) \(^{10-11}\). Pulses entering the buffer circulate for a discrete period of time until switched out. For a fiber length \( L \) the maximum delay per loop traversal \( T_{\text{loop}} \) is defined as:
\[ T_{\text{loop}} = \frac{nL}{c} \]

where \( n \), \( L \) and \( c \) are the refractive index and length of the fiber, and the free space speed of light, respectively. Moreover, the maximum number of bits \((M)\) that can be stored within that length of fiber for a given bit rate \((B)\) is defined as:

\[ M = \frac{nL}{c}B \]

Figure 2 Passive recirculating fibre loop buffer

Two different pulse waveforms, namely soliton and Gaussian, are input to a buffer of length 500 m. The pulses are defined as:

\[ S(t) = \text{Sech} \left( \frac{t}{T_0} \right), \]

\[ G(t) = e^{-\left( \frac{t}{\sigma n} \right)^2}, \]

where \( T_0 = \) Full width half maxima/1.763.

Figures 3 and 4 show the resulting output power versus the buffer loop number and time for the soliton and Gaussian-soliton shaped pulse waveforms, respectively. Note that fiber loss limits the propagation distance of soliton transmission, since soliton needs sufficient optical power to balance the non-linearity against dispersion. In both cases the peak power is getting lower and the width of the pulse is getting wider as the propagation distance increases. The pulse broadening is due to the dispersion and non-linearity. To sustain soliton propagation it is necessary to employ optical amplifier to maintain the peak power level. Note that in both cases, the initial pulse width \( T_0 \) is 10 ps and the conditions necessary for \( N = 1 \) soliton propagation are employed. Observe that after a few loop traversals the Gaussian shape is in the transformation process of becoming a fundamental soliton shape in nature before dispersing due to the intrinsic loss within the fiber. Thus in essence, the input waveform can be viewed as having an initial chirped. There is no reason why should not employ Gaussian shaped pulse propagation within an optical buffer, provided it has enough peak optical power to sustain soliton properties. Furthermore, as both pulse profiles attenuate exponentially it suggests that using higher input powers and dispersion compensation fiber would result in longer storage times.
Figure 3: Power profile of propagating soliton pulse ($T_0 = 10 \text{ ps}$)

Figure 4: Power profile of propagating Gaussian pulse ($T_0 = 10 \text{ ps}$)
2 SIMULATION RESULTS

In the following section several performance criteria are presented to fully characterize the performance of the passive RFLB. In particular we examine the BER performance of the buffer as a function of optimal threshold detection level, the input pulse profile, and delay (loop number). These results are considered across a range of SNRs. Figure 5 shows the block diagram of the a typical OTDM system. It consists of an OTDM source, additive white Gaussian noise (AWGN) channel, an optical buffer, photo-detector, matched filter and a detector. The number of errors is obtained by comparing the regenerated data with the transmitted data. It is assumed that the photodetector has a responsivity of unity and that the noise added is representative of the cumulative effect of the amplifiers noise, which may typically line the communication path, and other sources. A final assumption is that this noise should not change the fundamental soliton into a higher order soliton.

![Figure 5 Block diagram of OTDM system](image)

Table 1 lists the global simulation parameters. Note that under these conditions $T_{loop} = 2.5 \mu s$ and $M = 6250$ bits given that $B=2.5 \text{ Gb/s}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength of signal ($\lambda$)</td>
<td>1.55 \text{m}</td>
</tr>
<tr>
<td>Refractive index of fiber ($n$)</td>
<td>1.5</td>
</tr>
<tr>
<td>Speed of light ($c$)</td>
<td>$3 \times 10^8$ \text{ms}^{-1}</td>
</tr>
<tr>
<td>Effective fiber core area ($A_e$)</td>
<td>50 $\mu$m$^2$</td>
</tr>
<tr>
<td>Non-linear refractive index ($n_2$)</td>
<td>3.2$\times 10^{-3}$ $\mu$m$^2$ w$^{-1}$</td>
</tr>
<tr>
<td>Loop unit length ($L$)</td>
<td>500 m</td>
</tr>
<tr>
<td>First order dispersion parameter ($\beta_2$)</td>
<td>$-18$ ps$^2$ km$^{-1}$</td>
</tr>
<tr>
<td>Fiber loss parameter ($\alpha_m$)</td>
<td>0.2 dB/loop</td>
</tr>
<tr>
<td>Number of bits generated</td>
<td>2e$^7$ bits</td>
</tr>
<tr>
<td>Data rate</td>
<td>2.5 Gb/s, 5Gb/s and 10Gb/s</td>
</tr>
<tr>
<td>Pulse shapes</td>
<td>Soliton and Gaussian</td>
</tr>
</tbody>
</table>

Table 1 Global Simulation Parameters

Figure 6 shows the BER versus signal-to-noise ratio (SNR) at the input of the matched filter for different detector threshold level values for unbuffered soliton transmission. As can be seen, the best performance is achieved at a optimum threshold value set midway (50%) between the maximum and minimum signal level at the output of the matched filter. This performance is similar to the on-off-keying (OOK) transmission. As expected the BER performance degrades when changing the optimum threshold level. For example, at BER $= 1e^{-3}$ an additional 0.3-0.4 dB is required if the threshold value is set at either 45% or 55%.
Figure 7 shows the eye diagrams of the received data signal for a buffered and unbuffered soliton pulse ($T_0 = 10 \text{ ps}$) at SNR = 10 dB, respectively. In Figure 7a the number of loop circulation is 20, which results in reduced SNR and therefore reduced eye opening compared with Figure 7b. An important feature of the eye diagram is that it may be employed as a tool to gauge the optimal threshold level setting. Careful examination of these diagrams confirms $T_{\text{opt}}$ to be half of the maximum eye opening for both cases. Note that in the presence of thermal and shot noise this value is expected to shift slightly. 

Figure 7 Eye diagrams for received photocurrent at: (a) buffered, and (b) unbuffered.
For 2.5 Gb/s the BER performance versus the SNR at different buffer circulation loop numbers for soliton and Gaussian-soliton shaped pulses are shown in Figs. 8 and 9, respectively. In each case both 10 and 40 ps pulse widths are considered. For comparison, the theoretical BER performance for unbuffered OOK is also shown. For a clear description of the curve legends refer to Table 2. For an unbuffered case, the 10 ps soliton pulse ST10LO display a performance which is identical to OOK. However, the BER performance degrades significantly as the number of loop circulation increases. For example, for BER of $10^{-5}$, the SNR penalty for 10 loop circulation is about 2.5 dB compared with unbuffered case. Moreover, there is a 6 dB power penalty between loop circulation numbers 10 and 40. Comparing Figs. 8 and 9 reveals that the performance of the soliton pulse is the virtually the same as the Gaussian-soliton shaped pulse. In addition, the performance at a given loop circulation number is the same for the 10 and 40ps pulse widths regardless of the input shape pulse. While larger pulse widths facilitate easier synchronization they become a limiting factor when the data rate is increased. That is, as the data rate is increased the shorter pulse widths would be a definite asset, as this would minimize the crosstalk between neighboring pulses which degrades the overall system performance.

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**Figure 8** Simulation results for buffer performance over a range of SNRs

**Figure 9** Simulation results for buffer performance over a range of SNRs
Figure 10 shows the BER as a function of loop number for SNR = 16 dB and 10 ps pulse width for both soliton and Gaussian-soliton shaped pulses. Due to limited computation resources the performance for loop numbers 0-4 could not be obtained. The BER performance is the same for both pulses increasing exponentially as the loop number increases.

![Figure 10 Buffer performance as a function of loop number at SNR = 16 dB](image)

Lastly, for soliton pulse of 40ps width the BER versus SNR for 10 loop at different data rates is shown in Figure 11. Observe that BER performance is the same for 2.5 and 5 Gbps, whereas at 10 Gbps, there is deterioration in BER performance. For example at BER of $10^{-3}$ 10 Gb/s data rate requires additional 0.5 dB of SNR.

![Figure 11 Buffer performance at different data rates using 40 ps soliton pulses](image)

A practical application for the RFLB would be to temporally store incoming packets at a router while the header information is being processed or secondly, to act as a contention resolution device where packets compete for a given port. Note that in the second scenario if the delay approaches a critical value where the data integrity is will compromised then the signal may be transferred from the RFLB to an electronic backup system\(^{13}\). This rare event prevents the electronic backup system from becoming an information throughput bottleneck.
3 CONCLUSIONS

In this paper we have examined the propagation of both soliton and Gaussian-soliton shaped pulses around a passive recirculating fiber loop buffer. The effects of data rate, and threshold level on bit error rate performance were investigated. Key simulation results indicate that although the literature recommends the use of solitons for high-speed communication, the optimal input pulse shape need not be described by the sech function. More specifically, a Gaussian shaped pulse propagated with the \( N = 1 \) parameters would give the same performance as the soliton transmission. Moreover, for a given delay the buffer could be engineered to so that optimal performance is achieved. In a future publication, pulse interaction and measures to combat the dispersive and loss effects intrinsic to the optical fiber will be examined.

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REFERENCES