A Filtering Approach for Reducing Timing Jitter Due to the Acoustic Effect

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***Abstract*—We introduce a signal processing approach to compensate for the timing jitter produced by the acoustic effect in soliton communications. The other main sources of timing jitter, the Gordon–Haus effect and the polarization effect, are inherently stochastic. By contrast, the acoustic effect is deterministic and becomes the dominant source of bit error rates in standard soliton systems when the bit rates are more than 10 Gb/s and the transmission distance is more than several thousand kilometers. We exploit the deterministic nature of the acoustic effect to introduce a scheme that predicts the amount of timing jitter as a function of the previous transmitted bits and uses the information to adjust the sampling period of the received soliton pulses. We demonstrate successful application of the scheme by simulations and discuss implementation issues.**

***Index Terms*—Acoustic effect, signal processing, soliton communications, timing jitter.**

I. Introduction

SOLITONS offer the possibility of achieving long-distance communications in which single-channel bit rates can be in excess of 20 Gb/s. The main source of errors for solitons when propagating in optical fibers is the timing jitter. It limits both the bit rate and the transmission distance, and is produced by several effects: the Gordon–Haus effect, the polarization effect, and the acoustic effect [1], [3]. When bit rates are more than 10 Gb/s, the acoustic effect becomes the dominant cause of the timing jitter for standard solitons at distances greater than a few thousand kilometers.

The acoustic effect is generated by the large transverse gradient of the electric fields in the optical fiber that results from the soliton pulses. In [3], it is shown that the acoustic effect causes errors that are highly correlated, i.e., it leads to intersymbol interference (ISI) that cannot be corrected with standard, simple error correction codes such as the Hamming code. Though such error correction schemes work reasonably well to correct for errors that are due to spontaneous emission which are nearly independent, they prove ineffective for correlated errors as they do not exploit the correlation among bits. A jitter tracking demultiplexer, introduced in [2], can exploit the correlation among bits to adjust the acceptance window of a soliton pulse for considerable extension of the error-free propagation distances. Implemented by an electro-optic circuitry at the receiver, this demultiplexer is shown to be effective in reducing the timing jitter due to soliton–soliton collisions in wavelength division multiplexing (WDM) soliton communication systems [2]. However, the scheme is not as effective, as we show by simulations in this paper, in compensating for the timing jitter due to the acoustic effect where the short term correlation is not as strong as that induced by soliton–soliton collisions in WDM systems but extends up to 100 ns.

In this paper, we introduce a signal processing approach that is based on direct prediction of the timing jitter as a function of the previous bits, and we present simulation results that show its success in reducing bit error rates due to the acoustic effect. We also discuss implementation issues, and note the tradeoff in expected performance as a function of the memory length. The next section introduces the timing jitter due to the acoustic effect. In Section III, we introduce the finite impulse response filter structure for prediction of acoustic timing jitter, and present simulation results and discussion of the results in Section IV. Finally, Section V presents the conclusions.

II. Acoustic Effect

The acoustic effect in soliton communications is due to the intensity gradient of the solitons transverse to their direction of propagation. This gradient electrostrictively excites acoustic waves that affect the refractive index of the fiber, producing changes in the central frequencies and temporal locations of the solitons. In typical fibers, these acoustic waves can survive for up to approximately 100 ns and hence generate ISI within this time scale.

If we let the perturbed refractive index be denoted by $\delta n(t)$, then the mean frequency change induced by the first pulse on those that follow may be written as

$$\frac{d\omega}{dz} = -\frac{\omega}{c}\left.\frac{d(\delta n)}{dt}\right|_{t=T} \tag{1}$$

where T is the time slot of one soliton pulse. The perturbation index $\delta n(t)$ is proportional to the energy of the first pulse, and its functional form can be found in [1]. This frequency shift induces a temporal shift of the pulses relative to each other which then leads to ISI reflected in the timing jitter of the received pulses.

A binary data stream that consists of an arbitrary sequence of ones and zeros is physically implemented by a stream of soliton pulses in which a soliton in the middle of a time slot with duration T represents a one and the absence of a soliton in

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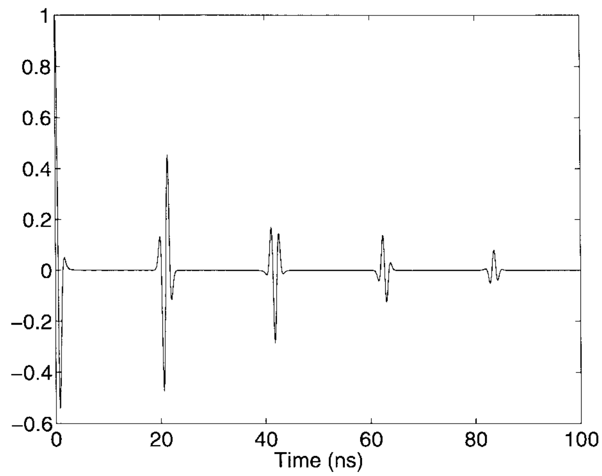

Fig. 1. Response function of the electrostrictive interaction $\delta n'(t)$.

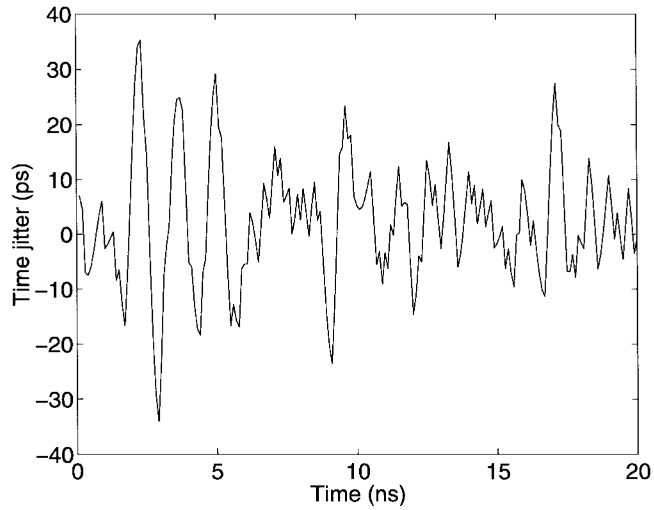

Fig. 2. Sample timing jitter due to acoustic effect ($\sigma = 12.1431$ ps).

the time slot represents a zero. It is shown that, for an unfiltered soliton system, the time shifts are Gaussian distributed and their standard deviation, referred to as the *timing jitter* is given by [1]

$$\sigma = 4.8\,\frac{D^2F^{1/2}}{\tau}\,z^2 \tag{2}$$

where D is the filter dispersion in ps/nm-km, z is the propagation distance in Mm, F is the bit rate in Gb/s, and τ is the duration of the soliton pulse. With guiding filters the timing jitter is reduced by a factor $2/\beta z$, where β is the frequency damping coefficient [1]; however, in any case, the time shifts of neighboring solitons are strongly correlated [3]. The timing jitter that accumulates along the transmission line will hence cause errors when a soliton leaves its time slot.

Fig. 1 shows the response function of electrostrictive interaction, i.e., the normalized perturbed refractive index $\delta n'(t)$. As seen in the figure, it is effective up to approximately 100 ns, which indicates the expected span of the correlation in the time shifts of the pulses. For example, in a 10 Gb/s soliton transmission system, a soliton's time shift due to the acoustic effect will be affected by as far as the one-thousandth previous soliton pulse. However, it is also important to note the decay in the power of the acoustic effect as a function of time, indicating that the first quarter of the response function shown in Fig. 1 will have the dominant effect. The time shift at the time instant t_m, can be written as a function of the response function $\delta n'(t)$ and the transmitted binary sequence $x(lT)$ as

$$\delta_m = \alpha \sum_{l=1}^{N} \left[\left.\frac{\partial n'(t-lT)}{\partial t}\right|_{t=t_m} x(lT) \right] \tag{3}$$

where α is the variable incorporating the normalization of the perturbation index. In our simulations, it is chosen such that for a given soliton communication system and transmission distance, it yields the standard deviation of the timing jitter given by (2). Fig. 2 shows a typical sample of the timing jitter as a function of time produced by (3) for a 10 Gb/s system at 20 Mm.

III. Timing Jitter Prediction

The deterministic nature of the problem, shown by the relationship in (3) suggests the use of a simple signal processing approach to compensate for the timing jitter due to acoustic effect. A finite impulse response filter (FIR) whose response matches that of $\delta n'(t)$ can be used to predict the amount of timing jitter at a given time as a function of the previous bits. The predicted timing jitter can then be used to adjust the acceptance window of a soliton pulse in order to prevent or minimize errors at the detector.

If we define the filter coefficients w_l as

$$w_l \equiv \left.\frac{\partial n'(t-lT)}{\partial t}\right|_{t=t_m} \tag{4}$$

then a simple transversal FIR filter can predict the value of the timing jitter δ_m at time t_m. The FIR predictor can be implemented by a binary shift register of length N that stores the last N detected bits, scales them by the filter coefficients w_l, and an adder to form the estimate of the timing jitter for the current pulse. The estimated timing jitter value can then be applied across a capacitor which triggers a clock circuit (e.g., as applied to an op-amp input) when discharging through the resistor in series with the capacitor. This is one candidate circuitry that can meet the required high processing speed to adjust the sampling period of the received soliton pulses. Other solutions are possible and more will be available in the near future with the advancement in high speed electronic devices.

As seen in Fig. 1, there are long time periods over which the value of the response function is almost zero. Hence, the value of w_l is approximately zero for a significant number of indexes l which implies unnecessary processing if we directly implement a transversal FIR structure of length N where N is determined by the required memory for the implementation. We thus introduce the timing jitter predictor circuit shown in Fig. 3 where a binary register of length $N$is still needed but the total number of coefficients to scale the stored bits is now given by $N' = N_1 + N_2 + \cdots + N_k$. The memory N_i for each filter coefficient group $w_{l_i}, w_{l_i+1}, \cdots, w_{l_i+N_i-1}$ is determined by the extent of the significant values of the response function. The size of the delays $l_1, l_2, \cdots, l_k$ are chosen so that they coincide with the indexes of the significant values that are at around 0, 20, 40, 60, and 80 ns, as observed in Fig. 1. If k is chosen as five, the complete 100

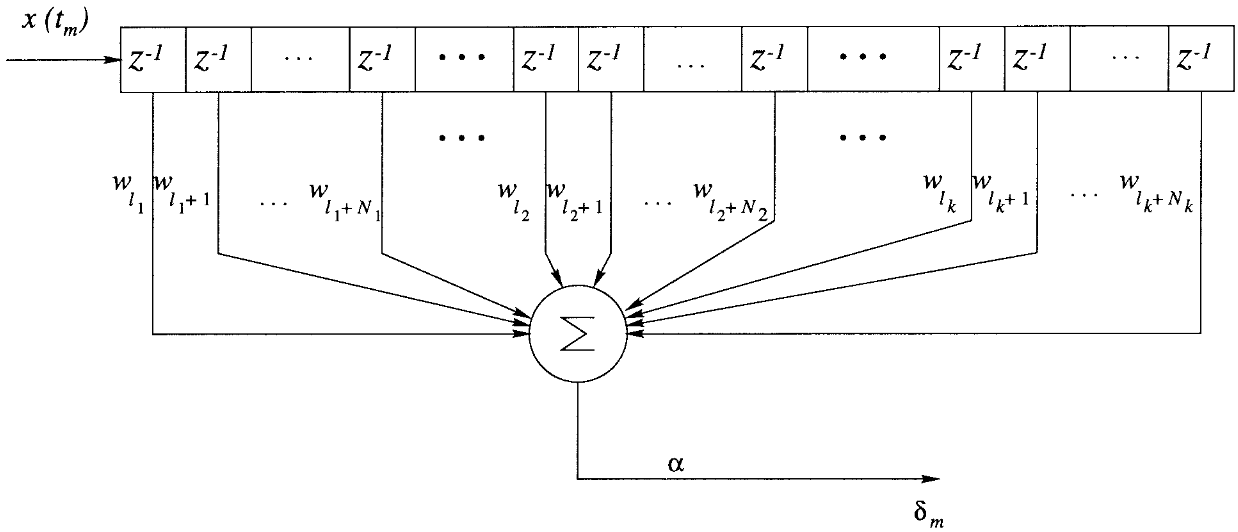

Fig. 3. Transversal FIR timing jitter predictor.

TABLE I
TIMING JITTER STANDARD DEVIATIONS BEFORE COMPENSATION

Experiment 1	σ (ps)	SSER
Calculated by (2)	12.1431	1.0×10^{-3}
Simulated value	12.0817 ± 0.2585	9.3×10^{-4}

Experiment 2	σ (ps)	SSER
Calculated by (2)	15.3687	9.4×10^{-3}
Simulated value	15.4009 ± 0.3526	9.4×10^{-3}

TABLE II
TIMING JITTER STANDARD DEVIATIONS AFTER FIR PREDICTOR COMPENSATION (EXPERIMENT 1)

# of sections k	σ (ps)	SSER
1	7.7577 ± 0.1840	2.5×10^{-7}
2	4.1168 ± 0.0928	2.6×10^{-22}
3	2.1403 ± 0.0431	6.2×10^{-78}
4	1.0167 ± 0.0191	0
5	0.1852 ± 0.0023	0

TABLE III
TIMING JITTER STANDARD DEVIATIONS AFTER FIR PREDICTOR COMPENSATION (EXPERIMENT 2)

# of sections k	σ (ps)	SSER
1	9.8841 ± 0.2414	5.2×10^{-5}
2	5.2474 ± 0.1226	2.5×10^{-14}
3	2.7266 ± 0.0584	1.0×10^{-48}
4	1.2917 ± 0.0206	0
5	0.2349 ± 0.0030	0

ns correlation can be taken into account. In the next section, we use simulations to show the effectiveness of this approach, and note that even when the jitter variance is quite high, a two section filter, i.e., a filter with total length $N' = N_1 + N_2$ does a highly satisfactory job of predicting the jitter.

IV. SIMULATIONS

We simulate the propagation of a sequence of soliton pulses $x(lT)$ through an optical fiber by using (3) to generate the timing jitter. Our simulation parameters are $D = 0.2$ ps/nm-km, $\tau = 20$ ps, and $F = 10$ Gb/s. For distances $z = 20$ and 22.5 Mm, the resulting timing jitter standard deviation is 12.1431 and 15.3687 ps, respectively. We select the acceptance window as 80% of the total time slot T. For the two jitter deviations, $\sigma = 12.1431$ and 15.3687, the probabilities of a single soliton's moving out of its time slot are 0.10 and 0.94%, respectively. Both of these values are unacceptably high in a real communication system; however, they are chosen to study the effectiveness of the method. We define this probability as the *single soliton error rate* (SSER) since the probability that a soliton leaves its time slot is not identical to the bit error rate. In [3], the effect of correlated errors on the bit error rate is explained in detail, and it is shown that this correlation can have devastating effects for simple error correction codes that assume independent errors.

For the two experiments, i.e., for each of the two jitter deviations, 50 independent simulation runs are done with the filter structure shown in Fig. 3 with different number of filter sections ($k = 1, 2, \cdots, 5$). The filter section lengths and the corresponding delays are chosen such that the magnitude of the minimum filter coefficient (the acoustic response magnitude) is 0.01. For this choice, the filter section lengths are $N_1 = 23$, $N_2 = 37$, $N_3 = N_4 = 36$, and $N_5 = 21$, and the delays are $l_1 = 1$, $l_2 = 192$, $l_3 = 400$, $l_4 = 610$, and $l_5 = 825$. Table I compares the simulation and the computed values of timing jitter deviations and Tables II and III show the reduction in timing jitter by compensation with the jitter predictor of Fig. 3. Results are shown with different number of filter sections, and as expected, with increasing memory length, timing jitter, and the corresponding SSER are significantly reduced. Since a SSER of 10^{-9} would be acceptable for a practical communication system, a two-section filter of order $N' = 60$ provides a highly satisfactory performance in both experiments.

Another approach to deal with nonrandom timing jitters is introduced in [2] where correlation among bits is used to adjust the acceptance window of a soliton. Implemented by a simple electrooptic circuitry at the receiver, it is shown to effectively reduce the timing jitter due to soliton–soliton collisions in WDM systems [2]. The compensation is based on a high-Q resonator that generates a sinusoidal control signal whose period matches that of the incoming soliton pulses. This control signal is amplified by a high-gain microwave amplifier and then used to trigger an electrooptic switch to adjust the sampling periods of the pulses. We simulated the circuitry by sampling the output voltage $V(t)$ of the resonator given by

$$V(t) = V_0 \sin\left(2\pi f_0 t - \frac{\pi f_0}{2Q^2}\,t\right) \exp(-\pi f_0 t/Q) u(t) \quad (5)$$

at a rate $T/100$ with f_0 at 10 Gb/s and used a Q factor of 12.5. We tried the two cases shown in Table I (i.e., for $\sigma = 12.1431$ and $\sigma = 15.3687$), and for three lower acoustic timing jitter deviation values; 6.0444, 2.4131, and 1.2248 ps. For all cases the method proved to be ineffective. Increasing the Q factor tended to improve the performance but in a practical implementation with increasing Q, the rapid decay of the signal power can pose implementation difficulties. In all cases, the timing jitter reduction with the simulated electrooptical circuitry was not statistically significant. The main difficulty for the resonator-based jitter tracking scheme was the fact that, though correlated, the acoustic timing jitter has a rapidly changing characteristics compared to the jitter produced by soliton–soliton collisions in WDM systems. The resonator needs a highly correlated set of pulses within its memory interval in order to generate the control signal. Another factor limiting its performance is the fact that, though the acoustic jitter exhibits a more rapidly changing characteristics, its effect actually extends up to 100 ns.

V. Conclusions

We presented a simple signal processing approach to compensate for the timing jitter produced by the acoustic effect in soliton communications. Since the acoustic effect is deterministic in nature, by using the response function of the electrostrictive interaction for predicting the timing jitter as a function of the previous bits, we can very effectively reduce the ISI. We demonstrate the successful application of the approach by simulations. We also use simulations to demonstrate that the electrooptical circuitry proposed in [2] for reducing the timing jitter due to soliton–soliton collisions in WDM soliton communication systems is ineffective for reduction of the timing jitter due to the acoustic effect. This is primarily due to the nature of the timing jitter due to acoustic effect, where the short term correlation is not as strong as that induced by soliton–soliton collisions in WDM systems, but extends up to 100 ns.

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