Suppression of the acoustic effect in soliton information transmission by line coding

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The acoustic effect significantly increases the timing jitter of solitons and the bit-error rates in communication lines. We suggest the transmission of information with fixed-length blocks that contain an equal number of ones and zeros to suppress acoustically induced timing jitter. It is shown theoretically that this approach will significantly enhance the performance of systems with bit rates per channel higher than 20 Gbits/s.

Solitons offer the possibility of constructing long-distance communication systems in which the single-channel bit rate is in excess of 20 Gbits/s. Solitons that propagate in an optical fiber experience timing jitter that limits both the bit rate and the information transmission distance. This timing jitter is due to three effects: the Gordon–Haus effect, the polarization effect, and the acoustic effect.[1,2] At bit rates in excess of 10 Gbits/s the acoustic effect becomes the dominant source of timing jitter at distances greater than a few thousand kilometers.[1,2] The acoustic effect is due to the intensity gradient of the solitons transverse to their direction of propagation. Each soliton electrostrictively excites acoustic waves that affect later solitons, altering their central frequencies.

The physical source of the Gordon–Haus and the polarization effects is spontaneous emission in erbium-doped fiber amplifiers. In standard communication theory, both of these effects are sources of additive white noise.[3] By contrast, the acoustic effect is not a noise source at all; it is rather a source of intersymbol interference.[3] The result of the acoustic effect on any particular bit depends in a completely deterministic way on the bits that preceded it, and errors are highly correlated from bit to bit.[4] In particular there is no acoustically induced timing jitter in a strictly periodic sequence of solitons, e.g., a string of all ones, although there is an acoustic effect. This observation suggests that it might be possible to reduce significantly the acoustically induced timing jitter by appropriately coding the signal. In this Letter we propose line coding schemes that will allow us to suppress the acoustic effect. These schemes are based on the observation that the time shifts of solitons are highly correlated within 1 ns and that by keeping the number of ones and zeros constant within a nanosecond one can average out the acoustic effect. This approach is analogous to Manchester pseudoternary or duobinary signals, which are commonly used in T-1 lines of the North American digital hierarchy to avoid baseline wander in ac-coupled receivers and to ease timing extraction.[5]

Each soliton that propagates in a communication line excites an acoustic wave and perturbs the fiber refractive index, and this perturbed refractive index $\delta n(t)$ affects the subsequent solitons.[2,6] If one pulse follows another at an interval T, then the first pulse changes the mean frequency of the other by

$$\frac{\mathrm{d}\omega}{\mathrm{d}z} = -\frac{\omega}{c}\,\frac{d(\delta n)}{\mathrm{d}t}\bigg|_{t=T}\,. \tag{1}$$

The index perturbation $\delta n(t)$ is proportional to the energy of the first pulse, and its functional form may be found in Refs. 2 and 6. This frequency shift leads to temporal shifts of the pulses relative to one another. A data stream 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 the time slot represents a zero. In this case, it was shown previously[2] that the time shifts are Gaussian distributed, and their standard deviation σ, referred to as the timing jitter, is

$$\sigma^2 = \left(\frac{D\lambda}{c}\right)^2 \frac{z^4}{16} \sum_{l=1}^{\infty}\left[\delta n'(lT)\right]^2 \tag{2}$$

for an unfiltered soliton system, where D is the fiber dispersion, $\delta n'(t)$ is the time derivative of the refractive-index perturbations, z is the propagation distance, and T is the pulse repetition period. The fiber parameters are the effective cross section $S_{\mathrm{eff}} = 50\ \mu\mathrm{m}^2$ and the nonlinear refractive index $n_2 = 2.6 \times 10^{-16}\ \mathrm{cm}^2/\mathrm{W}$. For bit rates greater than 10 Gbits/s Eq. (2) can be numerically approximated as

$$\sigma = 4.8\,\frac{D^2 F^{1/2}(1 - 1.1/F)^{1/2}}{\tau}\,z^2 \tag{3}$$

for in an unfiltered soliton system, where σ is in picoseconds, D is in picoseconds per nanometer per kilometer, z is in megameters, and $F = 1/T$ is the bit rate in gigabits per second. In obtaining this expression we took into account the lifetime of the excited acoustic modes, which equals 70 ns; this value is in good agreement with recent experimental measurements of the acoustic response.[6] For bit rates smaller than 10 Gbits/s this approximation is not valid. With guiding filters the acoustically induced timing jitter is

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reduced by a factor $2/\beta z$, where β is the frequency damping coefficient.[1,2] The key point is that, when the ones and zeros appear randomly with probability 1/2, the timing jitter grows with the bit rate approximately as $F^{1/2}$ with other parameters fixed.

We have found that, by coding information in blocks of limited length containing an equal number of ones and zeros, one can significantly reduce the acoustic timing jitter for a fixed information transmission rate relative to what is given by Eq (2). The procedure that we used was to build strings from blocks that are 2, 4, ..., 16 bits long. The blocks are chosen randomly with equal probability from all bit combinations that have an equal number of ones and zeros, e.g., 0–1 and 1–0 when the block length is 2 and 0–0–1–1, 0–1–0–1, 0–1–1–0, 1–0–0–1, 1–0–1–0, and 1–1–0–0 when the block length is 4. As a check on our numerical approach, we also studied the case in which all bits are randomly chosen. The strings contain a total of 128,000 bits. Using Eq. (1) to determine the frequency shift that each pulse experiences owing to the preceding pulses and determining from that the change in each pulse's group velocity, we integrate over distance to determine each pulse's time shift t. We discard the first 10,000 bits to avoid including the effect of the transient startup, and we find the timing jitter, i.e., we determine the standard deviation of the time shifts, for the remaining bits.

We will refer to the timing jitter that we calculate as $\sigma_2, \sigma_4, \ldots, \sigma_{16}$, depending on the block length. The values of the σ_j depend on the soliton energy, the dispersion and the transmission distance, and the bit rate. The ratio σ_j/σ, where σ is given by Eq. (2), depends only on the bit rate for the fixed soliton energy, the dispersion, and the transmission distance. We therefore normalize the σ_j to σ ($F = 10$ Gbits/s) given by Eq. (2). We show the results in Fig. 1. The block lengths are marked with numbers, and the curve marked ∞ corresponds to choosing all bits randomly. In the last case the timing jitter is approximately proportional to $F^{1/2}$, as predicted by Eq. (3). In the other cases we find that, when the block length is larger than ~2 ns, the jitter is once again proportional to $F^{1/2}$, but when the block length is less than ~2 ns, the jitter levels off and even decreases slightly, so there is a significant decrease in the timing jitter, particularly when the block length is short.

The reduction that is apparent in Fig. 1 strongly suggests, but does not prove, that there is a substantial benefit in the use of line coding schemes in which information is transmitted in blocks with equal numbers of ones and zeros. To demonstrate this result conclusively we must first take into account the Gordon–Haus and the polarization effects.[1] Second, we must take into account the overload associated with the proposed line coding schemes. To account for this overhead properly we must distinguish between the information bit rate and the physical bit rate. In a block of length N there are $N!/(N/2)!^2$ different ways to arrange the ones and zeros, so the relationship between the physical and the information bit rates is given by

$$F_{\text{phys}} = F_{\text{info}} \frac{N}{\log_2[N!/(N/2)!^2]} \,. \tag{4}$$

This relationship, which is shown in Fig. 2, indicates that when $N = 2$ the physical bit rate must be twice the information bit rate. When $N = 4$ this ratio falls to 1.54, and when $N = 16$ it has fallen to 1.17. In Fig. 3 we show the predicted bit-error rate when the information bit rate is 30 Gbits/s. In our simulations we assumed that the separation between pulses $T = 1/F_{\text{phys}}$ equals 5τ, where τ is the soliton FWHM. To calculate the strength of the acoustic effect we used the numerical results presented on Fig. 1, taking into account that soliton energy is proportional to $1/\tau$. The other physical parameters were $D = 0.3$ ps/(nm km) for the dispersion and $\beta^{-1} = 300$ km for the frequency damping coefficient. To calculate the strength of the Gordon–Haus effect we set the distance between amplifiers equal to 30 km, the amplifier spontaneous emission factor n_{sp} equal to 1.5, and the fiber loss equal to 0.057 km^{-1}. The reduction factor for the Gordon–Haus effect equals $\sqrt{3}/\beta z$. For systems with strong sliding the reduction factors for the Gordon–Haus and the acoustic effects are somewhat different,[7] so we are effectively assuming that the sliding rate is small compared with the critical sliding rate. We calculated the bit-error rate by assuming that an error

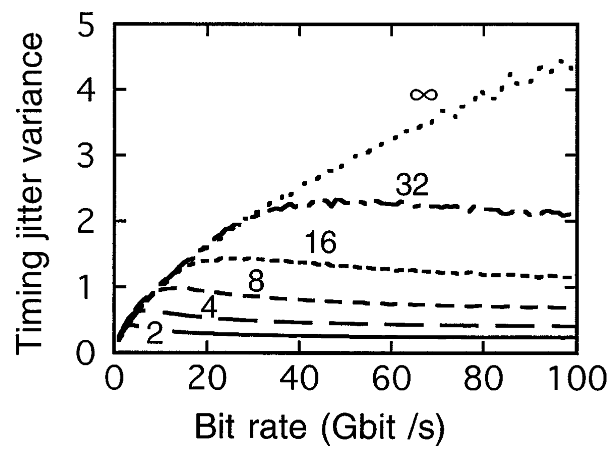

Fig. 1. Dependence of timing-jitter variance on the bit rate. The numbers near the curves indicate the block lengths. The variance is normalized to 10 Gbits/s given by Eq. (2).

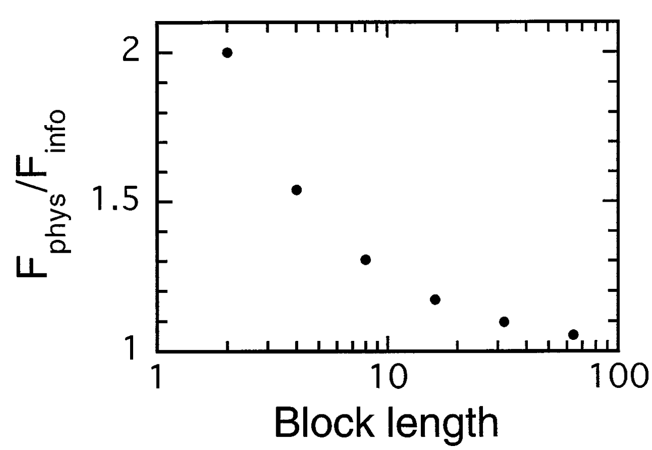

Fig. 2. Dependence of $F_{\text{phys}}/F_{\text{info}}$ on the block length.

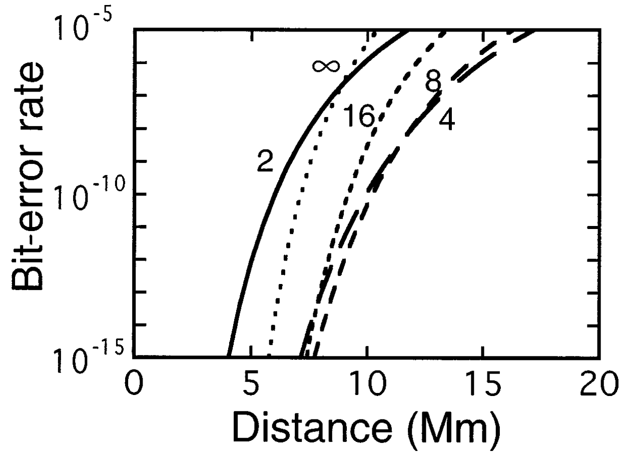

Fig. 3. Bit-error rates versus propagation distance for the information bit rate $F_{\text{info}} = 30$ Gbits/s, $D = 0.3$ ps/(nm km) dispersion, and $\beta^{-1} = 300$ km frequency damping coefficient.

occurs when the soliton is outside 80% of its time slot. Whereas it is known that the distribution of the time shifts is not strictly Gaussian,[8] it is also known that the assumption that the timing jitter is Gaussian yields qualitatively correct results. We find that using blocks with short lengths significantly improves the performance for a case when the acoustic effect is dominant.

We have suggested and shown in this Letter that by coding information in blocks of limited length containing equal numbers of ones and zeros one can minimize the acoustically induced timing jitter and enhance the performance of a soliton communication system at high data rates when the acoustic effect dominates. The suggested method can be used in wavelength-division multiplexed systems, and it will reduce not only the acoustically induced timing jitter but also the jitter from soliton–soliton collisions.

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