Data-Dependent Phase Coding for Suppression of Ghost Pulses in Optical Fibers

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***Abstract*—A novel data-dependent phase-encoding scheme for mitigation of intrachannel four-wave mixing is introduced. The scheme relies on energy redistribution among 1-bits, which reduces leakage of optical power into 0-bits time slots and is applicable for a wide range of input powers in return-to-zero transmission. The introduced data-dependent coding scheme increases the Q factor by as much as 4 dB.**

***Index Terms*—Modulation formats, nonlinear distortion, optical fiber communication, optical propagation in nonlinear media, return-to-zero (RZ).**

NUMEROUS research efforts during the past ten years have dealt with transmission impairments caused by the optical fiber channel. A recent example of such studies is the attempt to reduce the formation of ghost pulses that arise in long-haul dispersion-managed links with lumped all-optical amplification. The "ghost" pulses emerge in return-to-zero (RZ) time slots carrying 0-bits in the transmitted data stream. They are generated by repeated nonlinear four-wave mixing (4WM) of the dispersion-broadened partially overlapping data pulses carrying 1-bits. The greatest risk for bit errors comes from the ghosts arising in a single 0-bit slot surrounded by symmetric patterns of ones (e.g., 11011, 1 110 111, etc.) [1], [2]. As an approach for reducing the strong ghost pulse formation, use of phase coding [e. g., duobinary coding (DBC), modified DBC (MDBC), and alternate mark inversion (AMI) (the last method introduces a π phase shift at every incidence of a mark in the bit stream)] has recently been proposed and demonstrated [3], [4], [9]. The proposed phase coding schemes rely on the fact that the phase of a ghost pulse has a fixed relationship to the phases of the genuine "ones" in the bit stream that enter the 4WM process. Thus, the strongest ghosts can be eliminated by tailoring the phase of the surrounding 1-bit slots to cause destructive interference between the various contributions to a ghost. However, while the above-mentioned coding techniques are highly efficient in eradicating strong ghosts, they do not mitigate weaker "side ghosts" that materialize in the time slots of multiple consecutive 0-bits. With the intention of suppressing these side ghosts as well, efforts should aim at energy redistribution among the 1-bits in a block of marks, instead of just manipulating the phases of marks to achieve destructive interference of the echo pulses (as they were first termed by Mecozzi and Shtaif [5]), since, in a general case, no code can achieve destructive interference in several consecutive time slots. In this manuscript, we focus on nonlinear intersymbol interference effects in low launch-power RZ systems, commonly referred to as the strongly dispersion-managed solitons (SDMS). We introduce a novel data-dependent phase encoding that provides a three to ten times reduction in energy leakage from 1-bits slots to 0-bit slots as compared to existing coding schemes [3], [4], and consequently, significantly improves the performance. To the best of our knowledge, this is the first proposition of efficient data-dependent coding for alleviation of nonlinear effects in fiber-optic transmission systems.

Pulse propagation in single-mode optical fibers is modeled by the nonlinear Schrödinger (NLS) equation. In a dispersion-managed link, NLS has the following form $iu_z = (1/2)\cdot\beta_2(z)u_{tt} + G(z)|u|^2u$, where $u = u(z,t)$ is the pulse (or a bit stream) complex amplitude of the optical field, z is the spatial coordinate in the direction of propagation, t is the retarded time, and $\beta_2(z)$ and $G(z)$ are periodic functions such that $\beta_2(z)$ is the fiber chromatic dispersion [and it includes periodic dispersion management (DM)], while $G(z)$ incorporates fiber nonlinearity, loss, and gain. In our study, we consider a bit stream consisting of N pulses with a pulse shape $q(t)$ in a bit cell of duration T. The total field of the bit stream $u(t)$ is described by $u(t) = \sum_{k=-N/2}^{N/2-1} a(k)A_k q(t-kT)$, where $a(k)$ is either one or zero, depending on whether the corresponding information bit is equal to "one" (referred to as a "mark"), or "zero" (commonly called a "space"). A_k is the pulse amplitude. In order to provide an illustration and a mathematical framework for the data-dependent codes, we first examine a three-pulse interaction. Assuming a nonsolitonic transmission system with small nonlinear effects, the nonlinearity can be treated as a perturbation to the solution of the linear part of the NLS [5], [6]. The solution of the linear propagation equation for a Gaussian input pulse $q_k(0,t)$, normalized such that $\max(|q_k(0,t)/A_k|) = 1$, is given by [6], [7]: $q_k = A_k\sqrt{r(z)}\exp\left[-(p^2 - iC/2)(t-T_k)^2 + i\theta_k\right]$, where $p^2(z) = T_0^2/(T_0^4 + D^2(z))$; $D(z) = \int_0^z \beta_2(s)ds$; $C(z) = -D(z)/(T_0^4 + D^2(z))$; $r(z) = T_0^2/(T_0^2 - iD(z))$, such that A_k is the pulse amplitude ($k = 1,2,3$), θ_k is the initial phase of the pulse, $T_0 = 0.655 \cdot T_{\mathrm{FWHM}}$ (T_{FWHM} is the input pulse full-width at half-maximum), T_k is the time slot corresponding to the kth pulse, and β_2 is the fiber group velocity dispersion parameter. The amplitudes A_k can be calculated from the pulse energy transfer equations. For instance [6], [8]

$$A_2(z) = \frac{E_0}{1 + 2\exp\left[-2E_0F(z)\right]} \tag{1}$$

Manuscript received June 17, 2003; revised July 31, 2003. This work was supported the Applied Micro Circuits Corporation, by the UC Grants Office, by the National Science Foundation, and by the Defense Advanced Research Project Agency.

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Digital Object Identifier 10.1109/LPT.2004.824621

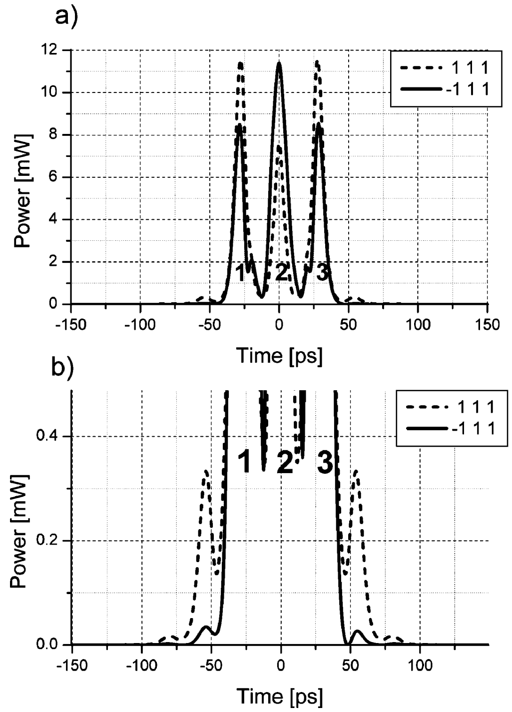

Fig. 1. Three-pulse interaction in a DM link of 1200 km. (a) Effect of changing the phase of a side-pulse ($k = 1$) by π. (b) Magnified version of (a) that emphasizes the reduction of side ghosts.

where, $F(z) = -\int_0^z \gamma(s)D^2(s)p(s)T_0\sin(C\Delta T^2 - \Delta\theta)\exp(-2p^2\Delta T^2)ds$, $A_2^2(z)+2A_1^2(z) = A_2^2(0)+2A_1^2(0) \equiv E_0$, and $a^2(z) = \exp\left(-\int_0^z \alpha(s)ds\right)$ with $\alpha(z)$ and $\gamma(z)$ being the fiber attenuation and nonlinear parameters, respectively. $\Delta T = T_{k+1} - T_k$ is the temporal pulse separation in the bit stream. For our three-pulse example, the phase difference is $\Delta\theta = 2\theta_2 - \theta_1 - \theta_3$. For values $\theta_2 = \theta_1 = \theta_3 = 0$, (1) implies that energy will leak from the central pulse into the side pulses, however, by choosing $\theta_2 = \theta_1 = 0$ and $\theta_3 = \pi$, this development will be reversed and the two side pulses will pump the energy into the central pulse. This process is illustrated in Fig. 1, showing the split-step simulation result of the output power distribution obtained from the three-pulse interaction in a dispersion-managed 1200-km fiber link. The features of interest, which are highlighted in Fig. 1(b), are the side ghost pulses. It can be noted that, if the appropriate phase coding is applied (i.e., $\theta_2 = \theta_1 = 0$ and $\theta_3 = \pi$), the side pulses will aliment the central pulse and less energy will leak into the side ghosts.

The existence of more than three pulses leads to more complex interactions that are difficult to analyze in a closed form. Consequently, by means of simulation, we have determined data-dependent phase encoding patterns that yield the best ghost suppression. These investigations have been performed in dispersion maps with a fixed amount of precompensation in settings with complete, as well as residual, dispersion per span. The number of overlapping pulses used in our simulations was varied between 8 and 20 pulses. Our observations can be summarized as follows: 1) code has to be skew-symmetric about an isolated 0-bit surrounded by two blocks of marks to prevent strong ghost formation [4]; 2) alternate mark-doublet inversion (AMDI) of blocks of marks (dividing a block of marks into doublets and changing the phase by π of every other doublet) should be used to impede energy leakage into multiple successive 0-bit slots; and 3) interaction between antipodal doublets within blocks of more than three consecutive marks, coded by AMDI, leads to an undesirable variance in the power of 1-bits after ten dispersion map periods, implying that for these long blocks of marks, the AMI is preferable. Table I summarizes empirically determined phase encodings that achieve the best suppression of ghost pulses in the most frequent short bit patterns. Strictly speaking, it is not proper to refer to our method as a code based just on Table I, since it does not include all possible bit patterns. Nevertheless, based on rules 1–3 above, it is not difficult to fill in the remaining part of Table I, thus completing the code that was used in our simulations.

TABLE I
BINARY PHASE ENCODING PATTERNS YIELDING THE STRONGEST GHOST SUPPRESSION

Bit pattern	Phase Encoding
1101	1-101 or 110-1
11001	1100-1 or 1-1001
110001	1-10001
110011	11001-1 or 1100-11
1100011	11000-11
11101	11-10-1 or –11101
111011	11-101-1
111001	11-100-1 or –111001
1110011	11-10011
11100111	11-1001-1-1
1110001	11-10001
11100011	11-10011
111000111	11-1000-111
1111001	1-11-100-1
11110011	1-11-100-11

We have applied phase encoding patterns described above to pseudorandom bit sequences (PRBS) of 128 bits to quantify the performance. Fig. 2 shows eye diagrams obtained for a 40-Gb/s stream after 3000 km ($T_{\rm FWHM} = 5$ ps). The simulated dispersion map consisted of approximately 95 km of nonzero dispersion-shifted fiber (NZDSF) with $D = 7.06$ ps/nm-km and 5 km of dispersion compensating fiber (DCF) with 20-ps/nm residual dispersion per span and with -450 ps/nm precompensation. Applying code patterns described in Table I resulted in reduced values of mean and variance in the signal power of spaces (see Fig. 2). The high launch power in Fig. 2 was chosen to create a clearer illustration of the effect of coding. The dependence of performance improvement on the launch power, based on 20 PRBS, is summarized in Table II. The unusually large values of Q are attributed to the fact that the amplifier noise was excluded from calculations, primarily to show the deterioration in performance due to ghost pulses.

Compared to AMI, which suppresses only the strong ghosts appearing in symmetric patterns, our data-dependent coding technique reduces the average power-leakage into multiple 0-bit slots and, in so doing, further decreases probability of bit errors. Notice that symmetric patterns occur with low probability, making the data-independent AMI less effective. In contrast, our novel data-dependent coding approach increases

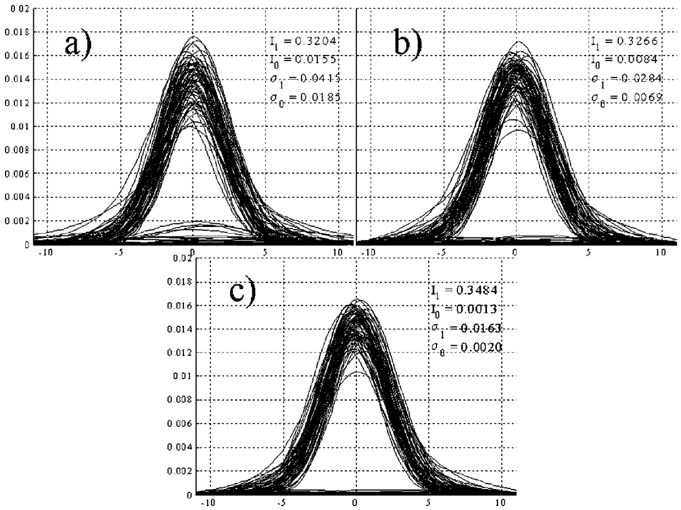

Fig. 2. Eye diagrams after 3000 km for average launch powers of 6 dBm. Means and deviations cited in arbitrary units. (a) Uncoded stream, (b) stream coded by AMI, and (c) data-dependent phase encoding method. Simulated link consists of 30 spans of 100 km (approximately 95-km NZDSF fiber ($D = -7.06$ ps/nm-km) and 5-km DCF) with residual 20-ps/nm span and precompensation of -450 ps/nm.

TABLE II
VALUES OF THE Q FACTOR AND CORRESPONDING PERFORMANCE IMPROVEMENTS FOR THREE DIFFERENT LAUNCH POWERS

	Q [linear]		
	Encoding method		
Launch Power	no coding	AMI	Data-dependent
-4 dBm	81.0	95.0	127.4
0 dBm	30.2	36.5	57.3
6 dBm	7.1	9.5	12.8
	Q Improvement (20log(Q_{coded}/Q_{nc}))[dB]		
	Encoding method		
Launch Power	no coding	AMI	Data-dependent
-4 dBm		1.4	4.0
0 dBm		1.6	5.8
6 dBm		2.6	5.2

the Q factor by 4 dB showing an additional improvement of about 2.6 dB at realistic input power levels (-4 dBm). On the other hand, in the case of complete compensation per span, both AMI [4] and our data-dependent phase codes, defined in Table I, increase the Q by approximately 2.8 and 6 dB, respectively. We would also like to stress the fact that the phase coding approaches cannot substantially increase the error-free distance in an ultralong-haul link, however, they do ensure an improved performance at any given point of propagation, which was demonstrated quite recently in [9]. The extension of the error-free distance is determined by the gain in performance and amounts to approximately eight to ten dispersion map periods for our data-dependent phase encoding scheme. In our simulations, we have noticed that the improvement of the Q factor and the error-free reach depend on the dispersion map used, however, further discussion of these issues is beyond the scope of this manuscript and will be published elsewhere.

In conclusion, a novel phase coding technique for the diminution of ghost pulses is introduced. Our approach involves the introduction and use of a data-dependent phase encoding to suppress small ghost pulses that are resistant to previously proposed coding methods (e.g., DBC, MDBC, and AMI [3], [4]). Our method is useful for low-power RZ systems (SDMS), providing approximately 4-dB improvement of the Q factor. It shows about 2.6-dB additional improvement over that provided by previously suggested phase coding methods on a typical terrestrial 100-km dispersion map period. The novel coding scheme provides comparable improvements for a broad interval of average launch powers, both in dispersion maps with residual dispersion per span, as well as in those with complete compensation.

ACKNOWLEDGMENT

The authors would like to acknowledge helpful suggestions by Dr. G. Papen, as well as the useful comments made by the reviewers, which considerably improved the clarity of the material presented.

REFERENCES

[1] P. V. Mamyshev and N. A. Mamysheva, "Pulse-overlapped dispersion-managed data transmission and intrachannel four-wave mixing," *Opt. Lett.*, vol. 24, no. 21, pp. 1454–1456, Nov. 1999.
[2] M. J. Ablowitz and T. Hirooka, "Resonant nonlinear intrachannel interactions in strongly dispersion-managed transmission systems," *Opt. Lett.*, vol. 25, pp. 1750–1752, 2000.
[3] K. S. Cheng and J. Conradi, "Reduction of pulse-to-pulse interaction using alternative RZ formats in 40-Gb/s systems," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 98–100, Jan. 2002.
[4] X. Liu, X. Wei, A. H. Gnauck, C. Xu, and L. K. Wickham, "Suppression of intrachannel four-wave-mixing-induced ghost pulses in high-speed transmissions by phase inversion between adjacent marker blocks," *Opt. Lett.*, vol. 27, pp. 1177–1179, 2002.
[5] A. Mecozzi, C. B. Clausen, and M. Shtaif, "Analysis of intrachannel nonlinear effects in highly dispersed optical pulse transmission," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 392–394, Apr. 2000.
[6] S. Kumar, "Intrachannel four-wave mixing in dispersion managed RZ systems," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 800–802, Aug. 2001.
[7] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. New York: Academic, 1995, ch. 3, pp. 64–67.
[8] M. J. Ablowitz and T. Hirooka, "Intrachannel pulse interactions in dispersion-managed transmission systems: Energy transfer," *Opt. Lett.*, vol. 27, pp. 203–205, 2002.
[9] P. J. Winzer, A. H. Gnauck, G. Raybon, S. Chandrasekhar, Y. Su, and J. Leuthold, "40-Gb/s return-to-zero alternate-mark-inversion (RZ-AMI) transmission over 2000 km," *IEEE Photon. Technol. Lett .*, vol. 15, pp. 766–768, May 2003.