SUPPRESSION OF INTRACHANNEL NONLINEAR EFFECTS IN HIGH-SPEED OPTICAL TRANSMISSION USING MODULATION CODES

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Abstract *To suppress detrimental effects of intrachannel nonlinearities in 40Gb/s systems and beyond, the usage of modulation codes is proposed. Significant Q-factor improvement is demonstrated, ranging from 4.5 dB to 14 dB depending on modulation format, modulation code and number of spans.*

Introduction

Long-haul dispersion-managed links at 40 Gb/s and beyond are severely limited by intrachannel nonlinear effects, such as intrachannel four-wave mixing (FWM) and intrachannel cross-phase modulation (XPM), giving rise to amplitude jitter (*ghost pulse* creation) and timing jitter respectively. Common approaches to reduce ghost pulse creation are to remove phase coherence between neighboring pulses [2-3], or to implement alternate-polarization formats [4].

In this paper we propose a rather different approach to suppress the occurrence of ghost pulses and to reduce timing jitter. Our method is based on modulation coding (also known as line coding or constrained coding) [5]. Any modulation format may be viewed as a trivial modulation code with a memory of one and rate one. The code proposed in this paper is a generalization of a traditional modulation format in the sense that a channel symbol is dependent on several previous symbols. The modulation code used adds redundancy used to correctly decode transmitted data and reduces the occurrence of ghost pulses by avoiding bit patterns that cause the effect. Significant Q-factor improvement ranging from 4.5 dB to 14 dB, depending on modulation code and format and number of spans, is obtained.

Modulation code description

Our code construction is based on the constrained system theory [5]. Knowing that the major contribution to ghost pulse creation comes from the pulses that lie close to each other in time, we attempt to avoid all consecutive triples of ones. Fig. 1 shows a directed graph model of such a constraint. 256 10-bit sequences, generated by reading off the edge labels of the graph, were used to form a (8,10) block code of rate 0.8. This code is adopted from our previous paper [6] and will be referred to henceforth in this paper as “Code I”. Using Code I, sequences with more than two ones in a row are completely avoided and the number of sequences containing “11011” pattern is kept to a minimum.

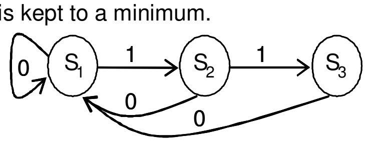

Fig. 1 Directed graph model of a modulation code completely avoiding all streams of 3 or more consecutive “1”s. (Code I)

It is possible to design a code that completely avoids the pattern “11011” (and thus the resonance patterns “1101” and “1011”) with the directed graph shown in Fig. 2. Following the orientation of the edges, we can read off the labels as we move from state to state. The sequences thus generated will follow our constraints. The adjacency matrix for the directed graph shown in Fig. 2 is given by,

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

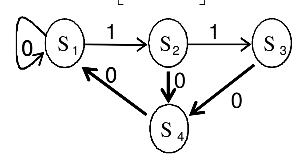

Fig. 2 Directed graph model of a modulation code completely avoiding “1101” and “1011” patterns in addition to all streams of 3 or more consecutive “1”s. (Code II)

Using the largest eigenvalue of the matrix *A*, capacity is calculated to be *C*=0.6942. This means that a code with data rate up to 0.6942 can be designed for this constrained system. We constructed a (6,10) block code of rate 0.6 (Code II). System performance is improved drastically since encoding is successful in completely avoiding all streams of more than two consecutive “1”s as well as the resonance patterns “1101” and “1011”, at the price of reducing the code rate to 0.6. (The code rate can be increased up to 0.6942 by increasing the code length, and therefore encoder complexity.)

Simulation results

In order to concentrate on intrachannel nonlinear effects, the noise generated by EDFAs was not considered. The influence of modulation format, extinction ratio, realistic models of transmitter, optical filter and electrical filter, ISI, crosstalk effects, Kerr nonlinearities (self-phase modulation, XPM, FWM), and dispersion effects (chromatic dispersion, second order dispersion) are taken into account. The propagation of the signal through the fiber was simulated by solving the nonlinear Schrödinger equation [7] using the split step Fourier method.

To study the intrachannel nonlinear effects we use a noiseless, dispersion managed 40 Gb/s single channel system. The dispersion map consists of many spans of length *L*=48 km, and each span

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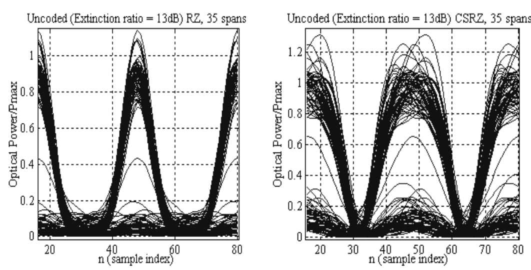
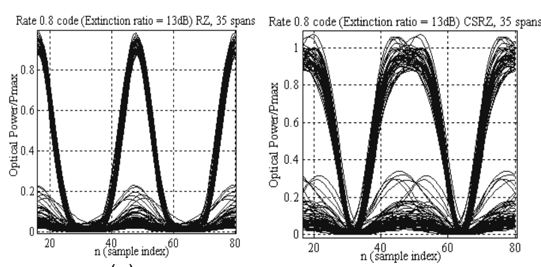
consists of 2L/3 km of D+ fiber followed by L/3 km of D- fiber. Linear pre-compensation and post-compensation are also applied. Fiber parameters are identical with [8], except for the central wavelength set here to 1552.524 nm (193.1 THz). 25 to 60 spans of this map are used to form a system that is 1200 to 2880 km long. The simulations were carried out with an average channel power of 0 dBm using RZ and carrier-suppressed RZ (CSRZ) modulation formats. A 1024 bit long PRBS was used to generate the uncoded eye diagram. The same sequence was encoded and sent over the channel to generate the encoded eye diagrams. EDFAs are deployed periodically after every section of fiber to overcome loss, but in order to concentrate on the effects of intrachannel FWM and XPM ASE noise was ignored.

Figure 3 shows the eye diagram observed at receiver input after 35 spans of the map. The extinction ratio is set to 13 dB, which is typical for MZ modulators available at 40 Gb/s. Two cases are observed: (a) RZ (b) CSRZ. Fig. 4 shows the eye diagrams observed for the bit stream encoded using Code I. For RZ the improvement in Q factor is 4.509 dB, while that for CSRZ is 5.362 dB. (The Q-factor is calculated after optical filtering, photodetection and electrical filtering.)



(a) (b)

Fig. 3 Eye diagrams (32 samples/bit) of uncoded signal after 1680 km, for average power of 0dBm, with a pre-compensation of -320 ps/nm for: (a) RZ, (b) CSRZ

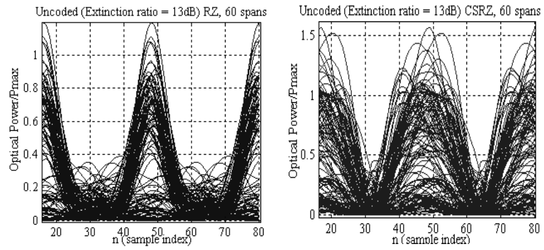


(a) (b)

Fig. 4 Encoded (Code I) eye diagrams for: (a) RZ (b) CSRZ

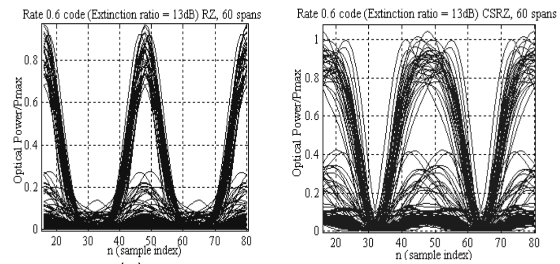
Fig. 5 shows the eye diagram observed at receiver input after 60 spans of the map. The extinction ratio is set to 13 dB. Once again, two cases are observed: (a) RZ and (b) CSRZ. Fig. 6 shows the eye diagrams observed for the bit stream encoded using Code II. For RZ modulation the improvement in Q factor is 9.809 dB, while that for CSRZ is 11.475 dB.

Fig. 7 plots the Q-factor improvement (defined as $20\log(Q_{\text{encoded}}/Q_{\text{uncoded}})$ [dB]) for different number of spans for both codes. The simulation results presented here are in excellent agreement with VPItransmissionMaker WDM version 5.5.



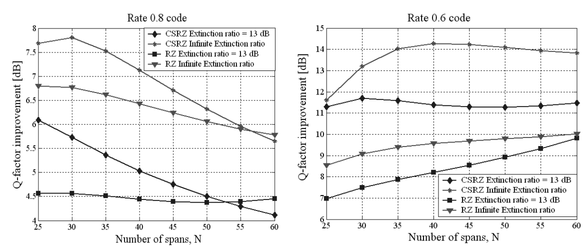
(a) (b)

Fig. 5 Eye diagrams of uncoded signal after 2880 km, for average power of 0dBm, with a pre-compensation of -320 ps/nm for: (a) RZ, (b) CSRZ



(a) (b)

Fig. 6 Encoded (Code II) eye diagrams for: (a) RZ, (b) CSRZ



(a) (b)

Fig. 7 Q-factor improvement for different number of spans for: (a) Code I, (b) Code II

Conclusions

To tackle the effects of intrachannel nonlinearities we propose the usage of modulation codes. Simulation results presented here show a significant performance improvement ranging from 4.5 dB to 14 dB depending on modulation code, modulation format, extinction ratio and number of spans. (Notice that infinite extinction ratio was assumed in [2-4] - thus over-estimating the performance improvement.)

References

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