Application of Modulation Codes to Ghost Pulse Suppression

Varsha S. Rao, Ivan B. Djordjevic and Bane Vasic
University of Arizona, Department of Electrical and Computer Engineering, Tucson, AZ 85721, USA
E-mail: {vrao,ivan,vasic}@ece.arizona.edu

***Abstract*— A simple modulation code to suppress the detrimental effects of intra-channel FWM in 40 Gb/s systems is proposed. A Q-factor improvement of at least 6.11 dB is demonstrated.**

***Index Terms*— Intra-channel four-wave mixing, ghost pulses, modulation codes, optical communications**

High speed transmission over long-haul dispersion-managed links is severely limited by non linear effects, especially by intra-channel four-wave mixing (FWM) causing ghost pulse creation. Interactions among pulses in different positions, especially pulse triples in what are called "resonance" positions, cause heavy energy transfer [1]. Ghost pulses are formed when this energy is transferred to a "0" bit and over a number of spans, these "ghost" pulses gain sufficient energy to be detected as "1"s by the detector at the output of the channel.

A good modulation format which aims to remove phase coherence between neighboring pulses is a method commonly used [2-4] to tackle this effect.

In this letter a rather different approach for reducing the occurrence of ghost pulses is proposed. Instead of inventing novel modulation formats we propose the usage of modulation codes (also known as line codes or constrained codes) [5]. Any modulation format may be viewed as a trivial modulation code with a memory of one and rate one [5]. The code proposed in the paper may be viewed as a generalized modulation format, in which the channel symbol is determined by several previous symbols. The modulation code used a) adds redundancy which is used to correctly decode transmitted data and b) reduces the occurrence of ghost pulses by avoiding bit patterns that cause the effect. Given the improvement in Q-factor, the slight loss in user data rate and increase in encoder/decoder complexity are reasonable trade-offs.

Our code construction is based on the constrained system theory [5], and terminology from [5] is employed in the rest of the paper. In designing our code, we use the knowledge that the worst of the ghost pulses are caused by pulses that lie close to each other in time. So the first step is to avoid all consecutive triples of ones. Further we can attempt to avoid the patterns "11011" and "1101". Fig. 1 shows a directed graph model of such a code. Following the orientation of the edges, we can read off the labels as we transition from state to state. The sequences thus generated will follow our constraints. The adjacency matrix for the directed graph shown in Fig. 1 is

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

Following the allowed transitions we see that in addition to sequences with more than two ones in a row not being possible, the two sequences indicated above are also avoided. As we are not allowing the generation of all possible bit patterns, the capacity of such a system will be less than 1. In fact the capacity is given by $C = \log_2 \lambda_0$ where λ_0 is the largest eigen value of the adjacency matrix.

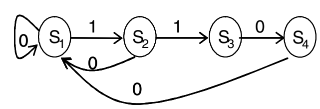


Fig. 1 Directed graph model of modulation code that completely avoids the patterns "11011" and "1101" in addition to avoiding all sequences of more than 2 "1"s in a row.

Using the largest eigen value of the matrix *A*, capacity is calculated to be *C*=0.8114. This means that a code with data rate up to 0.8114 can be designed for this constrained system.

In order to design a code, we need to raise *A* to the power *n* such that the largest number on the main diagonal is greater than or equal to some 2^k. This gives us a *k/n* rate code. On analyzing *A* we see that if we are to achieve a reasonable code rate of around 0.8, we will need an unreasonably large look-up table. To overcome this issue, we use the strictly-allowed 10-bit sequences as well as a few sequences with the patterns "1101" and "11011". Thus we are able to build a block code of rate 0.8. System performance improves on encoding the user bit stream since encoding is successful in completely avoiding all streams of more than two consecutive "1"s. Further, we are able to keep the occurrence of the above mentioned patterns to a minimum.

In order to concentrate on FWM, the noise generated by EDFAs was excluded. We take care of modulation, extinction ratio, realistic models (except for noise) of transmitter, optical filter and electrical filter, ISI, crosstalk effects, Kerr nonlinearities (self-phase modulation, cross-

This work is funded by the NSF under Grant CCR 0208597 and ITR 0325979.

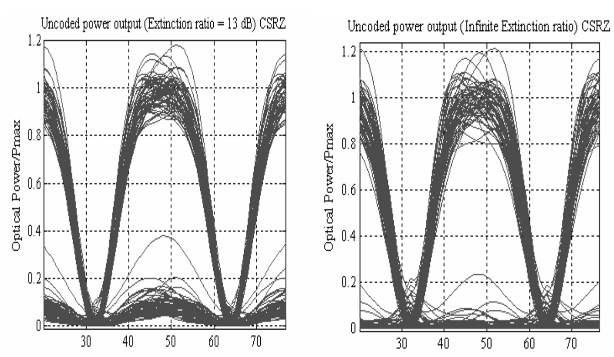
phase modulation, four-wave mixing), and dispersion effects (chromatic dispersion, second order dispersion). Light propagation through the fiber was simulated by solving the nonlinear Schrödinger equation [6] using the split step Fourier method.

To study FWM we use a noiseless, dispersion managed 40Gb/s single channel system. The dispersion map is of length L=48 Km and consists of $2L/3$ km of D+ fiber followed by $L/3$ km of D- fiber. Linear pre-compensation and post-compensation are also used. Fiber parameters are identical with [7], except for the central wavelength set here to 1552.524 nm. 25 spans of this map are used to form a system that is 1200 km long. The simulations were carried out with an average channel power of 0 dBm with carrier-suppressed RZ (CSRZ) modulation. A 1024 bit long PRBS was used to generate the uncoded eye diagram. This same sequence was encoded and sent over the channel to generate the encoded eyes. EDFAs are deployed periodically after every section of fiber to overcome loss, but in order to concentrate on the effects of FWM, ASE noise was ignored.

Figure 2 shows the eye diagram observed at receiver input. Two cases are observed: (a) extinction ratio set to 13 dB, typical for MZ modulators available at 40 Gb/s, (b) extinction ratio is assumed to be infinite (b). Fig. 3 shows the eye diagrams observed for the encoded bit stream. For the system with infinite extinction ratio, the improvement in Q factor is 7.7 dB, while for the system with an extinction ratio of 13 dB, a Q-factor improvement of 6.11 dB is obtained. (The Q-factor is calculated after optical filtering, photo-detection and electrical filtering.) Fig. 4 plots the Q-factor improvement (defined as $20\log(Q_{\text{encoded}}/Q_{\text{uncoded}})$ [dB]) for different number of spans. The simulation results presented here are in excellent agreement with VPItransmissionMaker WDM version 5.5.

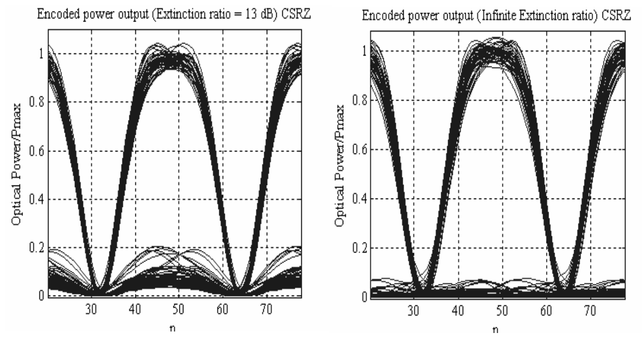
In conclusion, to tackle the effect of intra-channel FWM we propose the usage of modulation codes. Simulation results presented here show a significant performance improvement of at least 6.11 dB in Q-factor (for 25 spans).

.



(a) (b)

Fig. 2 Eye diagrams (32 samples per bit) of uncoded signal after 1200 km, for average power of 0dBm, with a pre-compensation of -320 ps/nm for: (a) extinction ratio of 13 dB, (b) infinite extinction ratio.



(a) (b)

Fig. 3 Encoded eye diagrams for: (a) extinction ratio of 13 dB, (b) infinite extinction ratio.

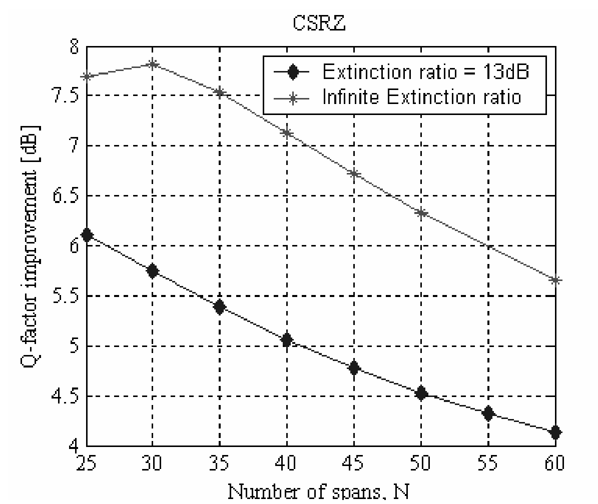


Fig. 4 Q-factor improvement for different number of spans

REFERENCES

[1] R. J. Essiambre *et al.*, "Intra-channel cross-phase modulation and four-wave mixing in high-speed TDM systems", *Electron. Lett*, vol. 35, pp 1576-1578, 1999.

[2] M. Forzati *et al*, "Reduction of intrachannel four-wave mixing using the alternate-phase RZ modulation format", *Photon. Technol. Lett.,* vol. 14, pp 1285-1287, Sep. 2002.

[3] A Hodzic, B Konrad and K. Petermann, "Alternative modulation formats in Nx40 Gb/s WDM standard fiber RZ-transmission systems", *J. Lightwave Technol.*, vol. 20, pp 598-607, Apr. 2002.

[4] X. Liu *et al,* "Suppression of interchannel four-wave-mixing-induced ghost pulses in high-speed transmissions by phase inversion between adjacent marker blocks", *Opt. Lett* , vol. 27, pp 1177-1179, Jul. 2002.

[5] D. Lind and B. Marcus, *Symbolic Dynamics and Coding,* Cambridge, U.K.: Cambridge Univ. Press, 1995.

[6] G. P. Agrawal, *Nonlinear Fiber Optics*. San Diego, CA: Academic, 2001.

[7] J. Zweck, C. R. Menyuk, "Analysis of four-wave mixing between pulses in high-data-rate quasi-linear subchannel-multiplexed systems", *Opt. Lett.,* vol. 27, pp 1235-1237, Jul. 2002.