

Constrained Coding for WDM Systems

V. Pechenkin (1), F. R. Kschischang (1)

1: Department of Electrical and Computer Engineering, University of Toronto
{vlad, frank}@comm.utoronto.ca

Abstract Application of constrained coding to 40-Gb/s dispersion-managed fiber-optic communication systems is extended to multichannel links. When the transmitted sequences obey the so-called $(2, \infty)$ constraint, an increase in data rate of 50% is demonstrated.

Introduction

Long-haul high-speed dispersion-managed fiber-optic data transmission links are designed to balance the negative effects of fiber nonlinearity and amplified spontaneous emission noise introduced by optical amplifiers. In particular, intrachannel four-wave mixing (IFWM) is a major limiting factor for systems operating in the so-called quasi-linear regime. IFWM results in the creation of "ghost" pulses in spaces as well as energy transfer between marks.

Constrained coding has been proposed as one of the methods to suppress ghost pulses [1, 2]. The main idea is to impose certain constraints on transmitted sequences in order to avoid particular bit patterns that lead to the formation of the strongest ghosts. A drawback of the designed schemes, however, is the inevitable reduction in data rate.

In our previous work devoted to IFWM-limited single-channel systems we showed that with an accurate code construction, the application of constrained coding can not only mitigate ghost pulses, but also provide a data rate improvement of up to 50% [3, 4]. In this paper we demonstrate that the same approach is beneficial for multichannel links as well.

Benchmark system design

For simplicity, a 40-Gb/s benchmark system is designed as in [3, 4]. The dispersion map consists of a 40-km-long segment of a standard fiber with D_+ = 17 ps/(nm·km) followed by a reverse dispersion fiber of the same length and exactly opposite dispersion D_- = 17 ps/(nm·km). A precompensating fiber of length 17.5 km and dispersion D_- is used along with a postcompensating fiber of the same length and dispersion D_+ . All fibers have attenuation 0.25 dB/km and a nonlinear parameter of $2.5 \text{ W}^{-1}/\text{km}$. Optical amplifiers are placed every 80 km at the beginning of the anomalous dispersion span, their spontaneous-emission factor being 1.4. We assume no residual dispersion per amplifier spacing and perfect dispersion compensation at the receiver for all channels. Although this picture is a simplification of a real WDM system, it provides a good test for the constrained coding approach. The dispersion profile of the link is sketched in Figure 1. The transmission distance is 4835 km including the compensating

sections. Gaussian pulses of width 5 ps (full width at half maximum) are used. Previously, we showed that the optimum peak power P_0 for this single-channel link is around 6 mW. Here, a four-channel WDM system is considered. Although the number of channels is usually greater in practice, our setup allows one to see the influence of interchannel effects, while keeping the simulation time reasonable.

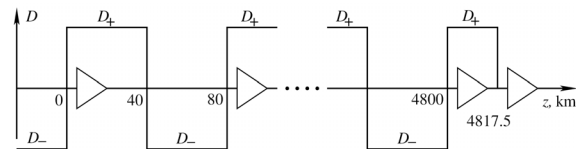


Figure 1: Dispersion profile of the link.

The receiver structure is slightly modified in comparison with [3, 4] to reject neighboring channels more efficiently. The receiver consists of an optical fifth-order Butterworth filter, a photodiode, and a 60-GHz electrical fifth-order Butterworth filter. Numerical simulations are carried out using the split-step Fourier method for 4000-bit pseudorandom input sequences. The probability of error is allowed to be as large as 10^{-2} and is measured directly by counting the number of errors at the receiver. We assume that an error-correcting code (ECC) may be applied afterwards to achieve the target bit error rate.

The system is tested for three different values of the channel spacing: 180, 160 and 140 GHz. The bandwidth of the optical filter varies accordingly: 170, 150 and 130 GHz. At $P_0 = 6 \text{ mW}$, the probability of error is indeed around $10^{-3} - 10^{-2}$ for all channels, the capacity of the worst channel being estimated as 38.0, 37.7 and 36.1 Gb/s, respectively. The results do not change significantly when P_0 varies a little.

Constrained system design

A binary channel is said to be runlength-limited (RLL), or (d,k) -constrained, if transmitted sequences are required to have at least d but at most k "0"s between any pair of adjacent "1"s. Information transmission through an RLL channel implies two necessary steps. First, an arbitrary source word must be mapped unambiguously to a sequence that satisfies the channel constraints. Second, some error control must be implemented to protect data from noise. A popular approach is to utilize a concatenation of an inner

modulation RLL (or constrained) code with an outer ECC. A message to be transmitted is first encoded with the ECC. The result is supplied to the RLL encoder (or modulator). The modulator transforms an incoming unconstrained word to a channel sequence that satisfies the required constraints. At the receiver the decoders work in the reverse order. The received word is first demodulated by the RLL decoder (or demodulator) and the ECC decoder cleans up possible errors afterwards.

A rate 1/2 modulator used in this work (see also [4]) can be fully described by a finite-state machine presented in Figure 2. At each time instance the encoder accepts one input bit and outputs two channel bits, the result depending not only on the input bit but also on the internal state of the machine. We assume that the encoder always starts and finishes in state "A." This can be achieved by appending a dummy "0" to any input word \mathbf{u} . For example, $\mathbf{u} = "1110"$ would result in a codeword $\mathbf{x} = "00010010."$ The output of the modulator satisfies the $(2, \infty)$ constraint.

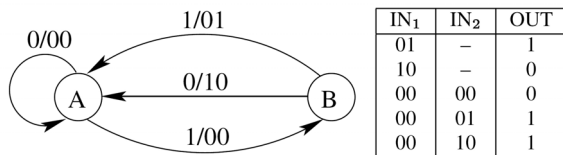


Figure 2: Encoding machine and decoding table.

A sliding-window demodulator decodes noiseless channel sequences according to the table presented in Figure 2. In general, the window size is 4 bits so the decoder has to look two bits ahead to make a decision about the current bit. Of course, the channel output may not obey the $(2, \infty)$ constraint in reality and the decoder has to deal with "illegal" contents of the sliding window. For simplicity, we output a "1" in this situation although better decoding strategies might be possible.

When channel sequences are $(2, \infty)$ -constrained, the bit slot duration T_B may be reduced by a factor of up to three, while maintaining the same minimum pulse separation and, hence, approximately the same intensity of IFWM-induced perturbations. In fact, it turns out to be less due to the following reasons. The introduction of constraints makes the channel bit stream more irregular. As observed in [5], irregularity helps in ghost pulse suppression. Moreover, certain patterns that lead to the creation of strong ghosts are either less likely to occur or entirely forbidden. For instance, an uncoded system is known to mostly suffer from sequences like "11011." An equivalent $(2, \infty)$ -constrained representation of this word is "100100001001." However, it can be seen that the encoding machine never delivers such output.

If the channel were perfect, the application of the $(2, \infty)$ constraint would give a 50% increase in data rate. In [3, 4] we showed that such gain is indeed achievable for a real single-channel system. Here, we simulate a constrained-coded WDM system with four channels and $T_B = 8.35$ ps. Simulations are carried out for 12000-bit pseudorandom constrained sequences. The receiver structure is the same as for the benchmark system except that the bandwidth of the electrical filter is changed to 90 GHz. The channel capacity is estimated based on the probability of error observed at the output of the demodulator. The eye diagrams for the first and the fourth (outer) channels are more open than for the second and the third (inner) ones. Hence, as expected, it is the inner channels that limit the system performance.

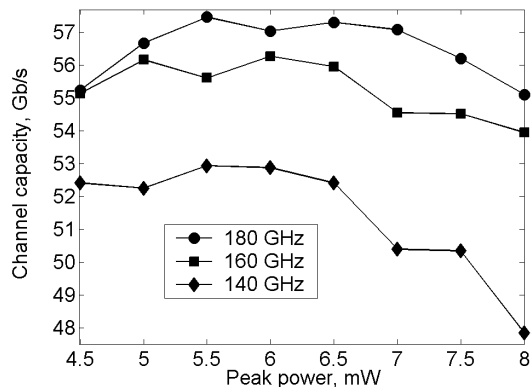


Figure 3: Channel capacity for constrained systems

Figure 3 shows the estimated capacity of the worst channel for different channel spacing. It is clear that there exists an optimum region of operation, where the probability of error is minimal. Although the results fluctuated quite a bit due to relatively short bit sequences used, the shape of the curves is in agreement with intuition, and the gain in capacity is almost the same as in the single-channel case.

Conclusion

In this paper we considered a promising application of constrained coding to a long-haul WDM system. The capacity of the link was improved by about 50% at the expense of an extra code with very simple encoding and decoding algorithms.

References

- 1 B. Vasic, V. S. Rao, I. B. Djordjevic et al, *IEEE Photonics Tech. Lett.*, vol. 16 (2004), pp. 1784 – 1786
- 2 N. Kashyap, P. H. Siegel, and A. Vardy, *IEEE Trans. Information Theory*, vol. 52 (2006), pp. 64 – 77
- 3 V. Pechenkin and F. R. Kschischang, in *Proc. OFC, Anaheim, CA, USA (2006)*, paper JThB7
- 4 V. Pechenkin and F. R. Kschischang, in *Proc. of 23rd Queen's Biennial Symp. Comm.*, Canada (2006)
- 5 S. Kumar, *IEEE Photonics Tech. Lett.*, vol. 13 (2001), pp. 800 – 802.