Wavelength-Time Coding for Reduction of Linear and Nonlinear Crosstalk in DWDM-Systems

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***Abstract*—By downscaling channel spacing, we increase the bit rate of a dense wavelength division multiplexing system by factor of 2. We present a wavelength-time coding scheme, which reduces the impact of linear and nonlinear interchannel interference by about 2.5 and 3 dB, respectively.**

***Index Terms*—Dense wavelength division multiplexing (DWDM), forward error correction (FEC), optical communications.**

I. INTRODUCTION

THE notable demand for Internet applications requires transmission schemes with ever-growing bit rates in all network sections. An efficient way to provide more bit rate in an optical dense wavelength division multiplexing (DWDM) system is to increase the number of wavelength channels in a given total bandwidth by downsizing the channel spacing. However, this leads to linear crosstalk between adjacent channels. Additionally, due to the higher input power into the fiber, nonlinear crosstalk occurs. Further on, both effects are refered to as interchannel interference (ICI). In [1], a novel coding scheme is introduced, which jointly encodes the data of adjacent wavelength carriers. As this scheme operates in time and wavelength direction, it is called wavelength–time coding (WTC). Another method that considers joint DWDM channels was introduced in [2]. However, this scheme was designed to reduce the impact of polarization mode dispersion (PMD) by interleaving of channels allocated far away. We turn our attention to jointly encode neighbouring channels for the reduction of ICI. In Section II, we briefly describe WTC. Then, we investigate the ICI caused by linear (Section III) and nonlinear crosstalk (Section IV) and show that WTC can significantly reduce these effects. The performance of a WTC DWDM scheme with increased bit rate is compared to a conventional DWDM scheme using the same total bandwidth, the same number of channels, and the same coding overhead. Section V concludes the paper.

II. WAVELENGTH-TIME CODING (WTC)

Fig. 1 shows a cut out of a DWDM system applying WTC. The wavelength channels are grouped in pairs, and the data bits $b_l^{(i)}$ and $b_l^{(i+1)}$ of two neighboring channels are encoded jointly first by a Reed–Solomon (RS) encoder [3] and followed by a WT encoder. $i = 1, \ldots, K$ is the channel index. The WT encoder executes the mapping

$$\begin{pmatrix} a_{k-N+1}^{(i)} \cdots a_k^{(i)} \\ a_{k-N+1}^{(i+1)} \cdots a_k^{(i+1)} \end{pmatrix} \mapsto \begin{pmatrix} c_{m-N-Q+1}^{(i)} \cdots c_m^{(i)} \\ c_{m-N-Q+1}^{(i+1)} \cdots c_m^{(i+1)} \end{pmatrix} \tag{1}$$

with $(c_n^{(i)}, c_n^{(i+1)}) \in \{(0,0); (0,1); (1,0)\}, n \in \{m-N-Q+1, m-N-Q, \ldots, m\}$. The subscripts represent discrete time, the superscripts reflect the channel index. The horizontal and vertical direction in the matrices indicate discrete time and wavelength channel number, respectively. $N = 3$ and $Q = 1$ turned out to be effective [1]. After demultiplexing (DEMUX) by optical filtering and optoelectronic conversion (RX), the sampled electrical signals $v_m^{(i)}$ and $v_m^{(i+1)}$ $(i = 1, \ldots, K)$ are fed into the WT decoder, which performs a joint soft-in-hard-out maximum-likelihood detection. An RS code (63, 59) operates as the outer code. A total of 59 words consisting of 3 bits per channel represent a RS symbol. The RS encoder adds four words redundancy. In the following, the net-bit rate per channel is always 40 Gbit/s, and the total bandwidth covered by the DWDM system and the number of channels are the same for all schemes under study. These preconditions assure a fair comparison. The 3 dB bandwidth of the multiplexer (MUX) is 70 GHz. The filters are Gaussian shaped with filter order 3.

III. LINEAR CROSSTALK

A real demultiplexer introduces linear crosstalk, which can be modeled as an additive random process. As a distortion measure, we use the following parameter

$$B^{(i)} = \frac{P_0\left(E\left[v_{m,10}^{(i)}\right] - E\left[v_{m,00}^{(i)}\right]\right) + P_1\left(E\left[v_{m,10}^{(i)}\right] - E\left[v_{m,01}^{(i)}\right]\right)}{P_{00}\left(\sigma_{m,00}^{(i)}\right)^2 + P_{01}\left(\sigma_{m,01}^{(i)}\right)^2 + P_{10}\left(\sigma_{m,10}^{(i)}\right)^2} \tag{2}$$

$$\text{with } P_0 = P_{00} + P_{10}\frac{P_{00}}{P_{00} + P_{01}}$$

$$\text{and } P_1 = P_{01} + P_{10}\frac{P_{01}}{P_{00} + P_{01}}.$$

$P_{c_m^{(i)} c_m^{(i+1)}}$ is the probability of occurance of the bit pattern $c_m^{(i)} c_m^{(i+1)}$ at the output of the WT encoder. $E[v^{(i)}_{m,c_m^{(i)} c_m^{(i+1)}}]$ and $(\sigma^{(i)}_{m,c_m^{(i)} c_m^{(i+1)}})^2$ are expected value and variance of the samples $v_m^{(i)}$ depending on the bit pattern, respectively. The numerator of $B^{(i)}$ is the mean value of the vertical eye opening of the signal $v_m^{(i)}$. The higher this value, the better the performance. The denominator is the mean variance of $v_m^{(i)}$ taken over all possible

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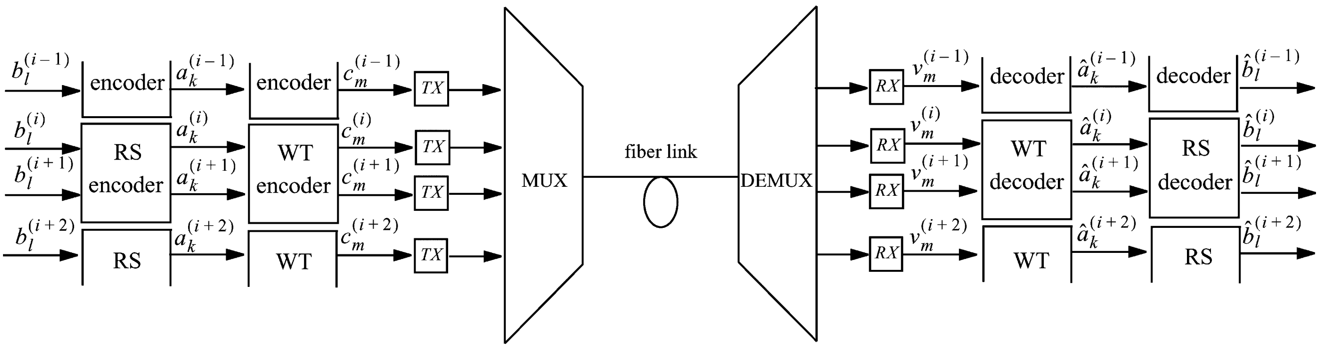

Fig. 1. Cut out of a DWDM system applying WTC (k, 1, m represent discrete time).

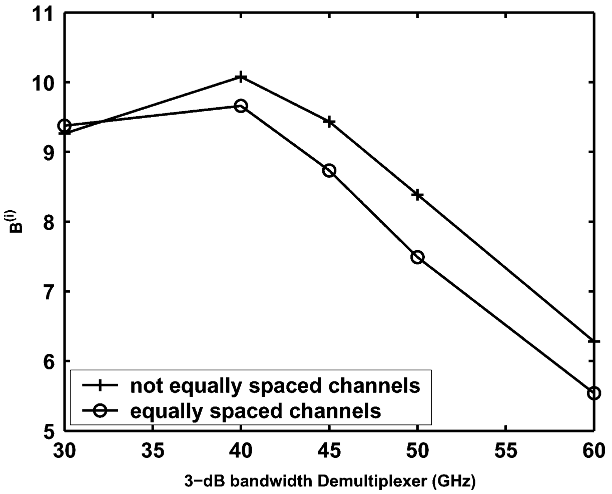

Fig. 2. $B^{(i)}$ as a function of demultiplexer bandwidth for a scheme with WTC and various channel spacings.

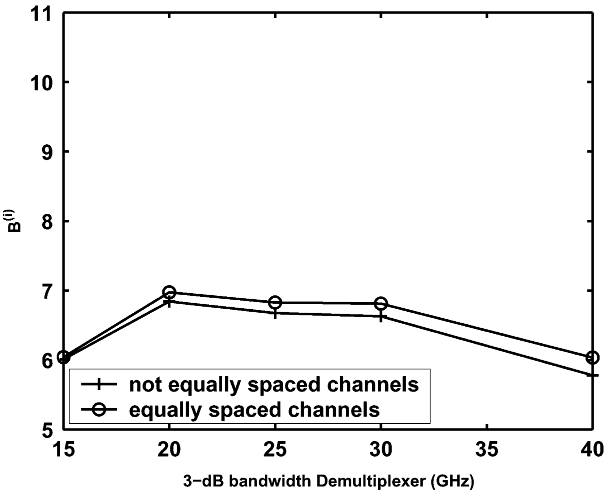

Fig. 3. $B^{(i)}$ as a function of demultiplexer bandwidth for a scheme without WTC and various channel spacings.

transmit bit patterns $c_m^{(i)} c_m^{(i+1)}$. The lower this value, the better it is, as this reflects the distortion of the linear crosstalk. High variances characterize wider transitions in the eye diagram. In summary, the larger the $B^{(i)}$, the lower the distortion due to linear crosstalk.

Fig. 2 shows $B^{(i)}$ as a function of the 3 dB bandwidth of the demultiplexer for a system with WTC. This and the next chart are derived by evaluating (2). To calculate the signal $v_m^{(i)}$, the VPI transmission maker, a commonly used simulation system, was used. Two cases are considered, "equally spaced channels" means that channel spacing is constantly 50 GHz. We also investigated a scheme with "not equally spaced channels," where the two channels in each pair have a distance of 45 GHz and the channel pairs have 55 GHz spacing. Obviously, the proposed nonequal spacing can reduce the distortion without any bandwidth penalty.

Fig. 3 shows $B^{(i)}$ for a conventional DWDM scheme without WTC. A comparison of Figs. 2 and 3 clearly indicates that WTC can reduce distortion $B^{(i)}$ by about factor 1.5. The optimal 3 dB bandwidth of the DEMUX for a system with WTC is 40 GHz, whereas a scheme without WTC should use a smaller bandwidth of around 25 GHz.

In Fig. 4, the symbol error rates before RS decoding, with and without WTC, are shown as a function of the optical signal-to-noise ratio (OSNR). As can be seen, WTC can reduce the required OSNR by about 2.5 dB at $\mathrm{SER} = 10^{-3}$. Additionally, the results for a system with only RS encoding, and the same amount of redundancy as the WTC scheme is shown. Obviously, a stronger RS code cannot outperform WTC.

IV. NON-LINEAR CROSSTALK

Depending on the input power into the fiber, nonlinear crosstalk between the signals of the WDM channels is caused due to nonlinear effects of the fiber. In this paper, we emphasize on four-wave mixing (FWM). Other sources of nonlinear crosstalk, e.g., stimulated Raman scattering (SRS), can be treated similarly. FWM can be modeled in the optical domain as additive complex Gaussian noise with variance σ^2_{FWM}, if the number of channels is sufficiently large [4], [5]. Normally, an optical amplifier (erbium doped fiber amplifier, EDFA) is present at the receiver, which is an additional noise source with variance σ^2_{EDFA}. As the signal, the amplifier noise, and the FWM noise can be assumed to be satistically independent, the overall noise

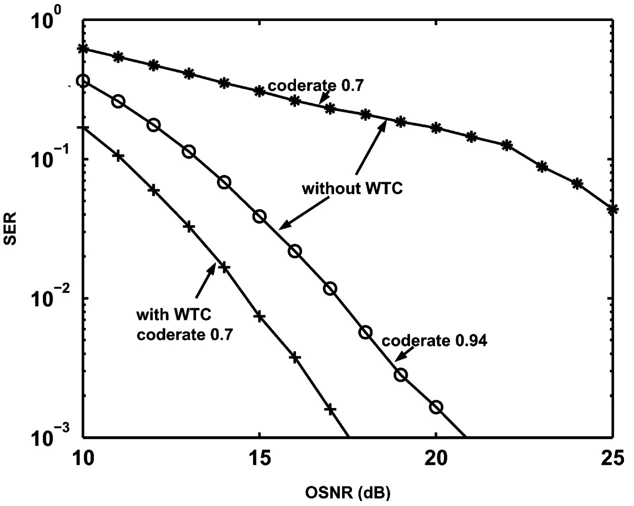

Fig. 4. Symbol-error rates (SER) before RS decoding for a system with and without WTC.

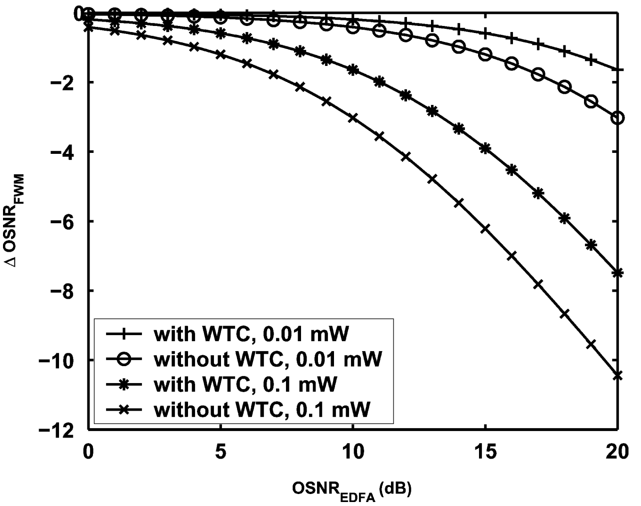

Fig. 5. $\Delta\mathrm{OSNR}_{\mathrm{FWM}}$ as a function of $\mathrm{OSNR}_{\mathrm{EDFA}}$.

variance is

$$\sigma^2 = \sigma^2_{\mathrm{EDFA}} + \sigma^2_{\mathrm{FWM}}. \tag{3}$$

The variance of the FWM noise is investigated in [4] and [5] resulting in

$$\begin{aligned}\sigma^2_{\mathrm{FWM}} &= \frac{1}{2}E\big[c_m^{(p)}\big]E\big[c_m^{(q)}\big]E\big[c_m^{(r)}\big]\sum_{p,q,r} P_{pqr}\\ &\quad + \frac{1}{2}E\big[c_m^{(p)}\big]E\big[c_m^{(q)}\big]E\big[c_m^{(s)}\big]\sum_{p,q,s} P_{pqs}\\ &\quad + \frac{1}{2}E\big[c_m^{(p)}\big]E\big[c_m^{(r)}\big]\sum_{p,q=p,r} P_{ppr}.\end{aligned} \tag{4}$$

p, q, and r are the channel indexes of the interfering channels, s the index of the channel, which is distorted (p, q, r, and $s\in\{1,2,\ldots,K\}$). $\sum_{p,q,r} P_{pqr}$ is the sum of the interference powers in the observed channel s due to all possible triples (p,q,r), if all interacting channels and the selected channel are different, $\sum_{p,q,s} P_{pqs}$ denotes the sum of the powers, if one of the interfering channels and the observed channel are identical; finally $\sum_{p,q=p,r} P_{ppr}$ is the sum, if two of the interfering channels are the same. Let P_s be the mean power of the signal in channel s, the OSNR at the input of the demultiplexer in Fig. 1, is then given by

$$\begin{aligned}\mathrm{OSNR} &= 10\log_{10}\frac{P_s}{\sigma^2_{\mathrm{EDFA}} + \sigma^2_{\mathrm{FWM}}}\\ &= 10\log_{10}\frac{P_s}{\sigma^2_{\mathrm{EDFA}}\left(1+\frac{\sigma^2_{\mathrm{FWM}}}{\sigma^2_{\mathrm{EDFA}}}\right)}\\ &= \mathrm{OSNR}_{\mathrm{EDFA}} + \Delta\mathrm{OSNR}_{\mathrm{FWM}}\end{aligned} \tag{5}$$

with

$$\mathrm{OSNR}_{\mathrm{EDFA}} = 10\log_{10}\frac{P_s}{\sigma^2_{\mathrm{EDFA}}}$$

and

$$\Delta\mathrm{OSNR}_{\mathrm{FWM}} = 10\log_{10}\frac{1}{1+\frac{\sigma^2_{\mathrm{FWM}}}{\sigma^2_{\mathrm{EDFA}}}}.$$

The degradation $\Delta\mathrm{OSNR}_{\mathrm{FWM}}$ of the OSNR is shown in Fig. 5 for various values of the interference power $\sum_{p,q,r} P_{pqr} = \sum_{p,q,s} P_{pqs} = \sum_{p,q=p,r} P_{ppr} = 0.01$ mW and $\sum_{p,q,r} P_{pqr} = \sum_{p,q,s} P_{pqs} = \sum_{p,q=p,r} P_{ppr} = 0.1$ mW.

At $\mathrm{OSNR}_{\mathrm{EDFA}} = 20$ dB the degradation is reduced by up to 1.5 dB and 3 dB, respectively, for the considered values of the interference power by using WTC.

V. CONCLUSION

By downscaling the channel spacing from 100 to 50 GHz in a DWDM system, the bit rate is increased by factor 2. The resulting linear crosstalk between channels is reduced by about 2.5 dB when applying the presented WTC scheme. Additionally, WTC can reduce the penalty due to nonlinear effects such as four-wave mixing by up to 3 dB. Equally and nonequally spaced channels are investigated, and it turns out that nonequally spaced channels with WTC provide superior performance.

REFERENCES

[1] F. Schaich and J. Speidel, “Wavelength-time coding for ultra dense wavelength multiplexing,” *ITG-Fachtagung Photonische Netze*, pp. 113–120, Apr. 2006.

[2] B. Xie, Z. Li, Y. L. Guan, and C. Lu, “FEC performance of PMD-impaired optical communication system with multiple-wavelength interleaving,” *Photon. Technol. Lett.*, vol. 16, no. 3, pp. 936–938, Mar. 2004.

[3] I. Reed and G. Solomon, “Polynomial codes over certain finite fields,” *J. Soc. Ind. Appl. Math.*, vol. 8, no. 2, pp. 300–304, Jun. 1960.

[4] K. Inoue, K. Nakanishi, K. Oda, and H. Toba, “Crosstalk and power penalty due to fiber four-wave mixing in multichannel transmissions,” *J. Lightw. Technol.*, vol. 12, no. 8, pp. 1423–1439, Aug. 1994.

[5] H. S. Carrer, D. E. Crivelli, and M. R. Hueda, “Maximum likelihood sequence estimation receivers for DWDM lightwave systems,” in *Proc. IEEE GLOBECOM*, 2004, vol. 2, pp. 1005–1010.

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