Experimental Performance Comparison of Duobinary Formats for 40 Gb/s Long-Haul Transmission

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Abstract: We experimentally compare the performance of various types of duobinary modulation formats for 40 Gb/s long-haul transmission. After having measured their respective robustness to accumulation of ASE noise, chromatic dispersion, PMD and intra-channel nonlinear effects, we show that transmission in excess of 2000 km can be envisaged. ©2007 Optical Society of America

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1. Introduction

Duobinary formats are known for their low spectral occupancy and high tolerance to residual chromatic dispersion [1-6]. These particular features make them very attractive for both high bit-rate and high spectral efficiency optical transmissions: up to 0.8 bit/s/Hz at 40 Gb/s per channel has been demonstrated recently [5,7]. Today duobinary formats are considered as being the most promising cost-effective solutions for the deployment of 40 Gb/s technology on existing 10 Gb/s WDM long-haul (LH) transmission infrastructures [7]. Various types of duobinary transmitter, based on delay-and-add method or low-pass filtering, applied in the electrical or optical domain, have been developed in the past few years but to our knowledge their respective performances for 40 Gb/s LH transmission have never been really compared experimentally.

In this paper, after having described the various methods for generating experimentally duobinary formats, we make an extensive experimental evaluation at 40 Gb/s of their robustness to accumulation of amplified spontaneous emission (ASE) noise, chromatic dispersion (CD), polarization mode dispersion (PMD) but also to intra-channel nonlinear transmission impairments (the most stringent non linear effect at 40 Gb/s) when using standard single-mode fiber (SSMF). We show that transmission distances higher than 2000 km can be envisaged.

2. Duobinary transmitter configurations

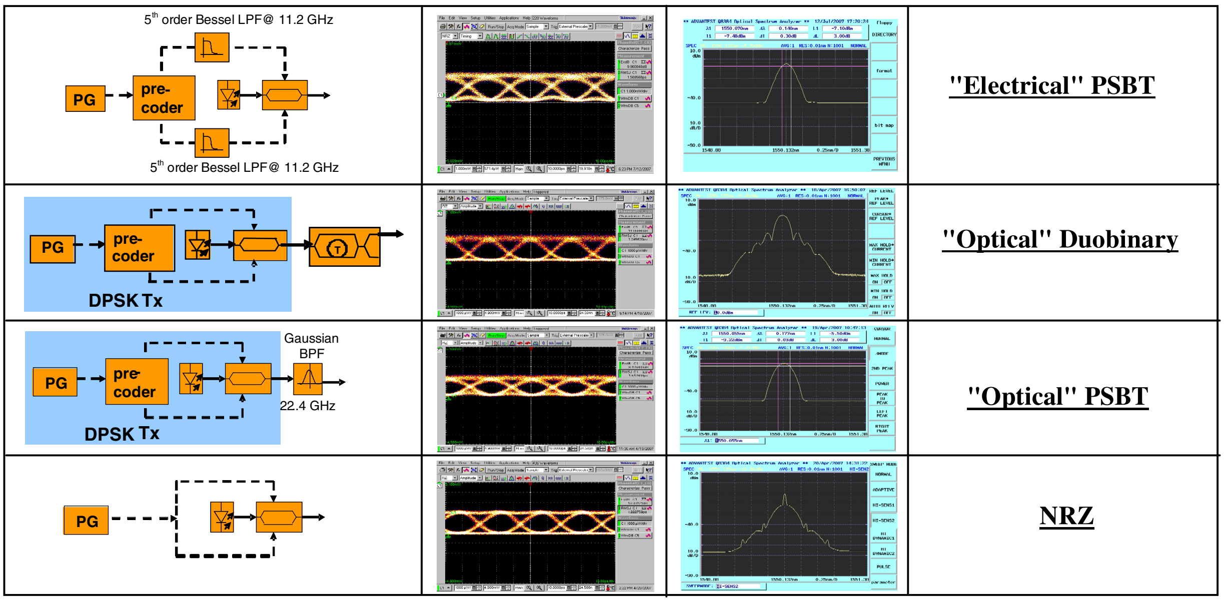

Fig. 1. 40 Gb/s duobinary transmitter configurations under study with corresponding eye diagrams and spectra

Among various developed duobinary transmitters, we can distinguish two categories of formats, which we will qualify of standard duobinary and phase-shaped binary transmission (PSBT) formats. These last ones are characterized by "0"s containing a small amount of energy and a π-phase shift occurring in their middle, which strictly limit the impact of inter-symbol interference (ISI) [2]. Classically, duobinary and PSBT formats were generated by means of electrical or optical filtering, based either on delay-and-add method (duobinary) [1] or on

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low-pass filtering (PSBT) [2]. In this study, we have tried to implement each of these two techniques. Fig. 1 shows the configuration of the three transmitters under study as well as their eye diagram and spectrum. "Electrical" PSBT is achieved through an electrical 5th order Bessel low-pass filter (LPF), located after the pattern generator (PG), whose the cut-off frequency is ~11.2 GHz [2]. "Optical" duobinary is obtained by means of the delay-and-add method applied in the optical domain: optical filtering takes place just after a DPSK transmitter and is realized owing to a Mach-Zehnder 1-bit delayed interferometer (MZDI) [3-5]. "Optical" PSBT is generated by the combination of a DPSK transmitter and an optical Gaussian band-pass filter (BPF) with a 3dB-bandwidth of ~ 22.4 GHz [4,6]. Note that NRZ is used here as a reference to evaluate the performances of duobinary and PSBT formats.

3. Results and discussion

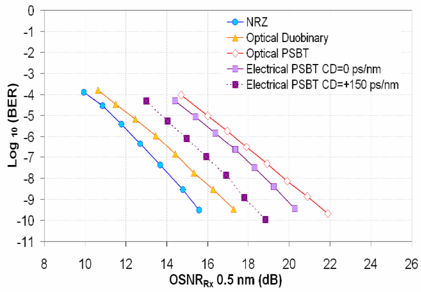

Fig. 2. Back-to-back OSNR sensitivity

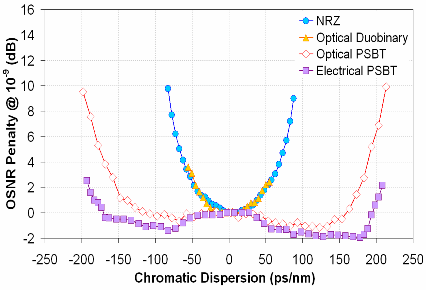

Fig. 3: Back-to-back OSNR penalty due to residual CD for a BER=10^{-9}

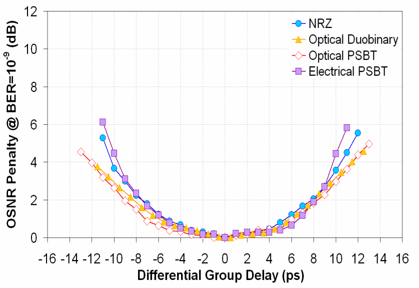

Fig. 4. Back-to-back OSNR penalty due to DGD for a BER=10^{-9}

The transmitter was constituted of eight DFB lasers (in order to operate the optical amplifiers of the experiment in suitable conditions), operating on a 200-GHz ITU grid ranging from 1544.53 to 1556.56 nm. PSBT, DPSK and NRZ modulators were driven by 2^{31}-1 pseudo-random bit sequences. Residual CD was emulated through pieces of positive or negative dispersion fiber and varied from -200 ps/nm to +200 ps/nm. Differential group delay (DGD) was produced by a commercial first order PMD emulator, and adopted values between -13 ps and +13 ps. A polarization scrambler working at 200 kHz speed was located at the emulator input. An ASE noise source was inserted just before the receiver in order to make vary the received optical signal to noise ratio (OSNR). The bandwidth of the square flat-top optical filter located at the receiver entrance was optimized in terms of back-to-back OSNR sensitivity to 75 GHz for both NRZ and "Optical" duobinary, and to 50 GHz for "Electrical" and "Optical" PSBT.

Figs. 2, 3 and 4 show the back-to-back OSNR sensitivities, OSNR penalties due to residual CD and DGD for a BER=10^{-9}, respectively. NRZ presents the best sensitivity (OSNR=15.2 dB in 0.5 nm for a BER=10^{-9}), followed by "Optical" duobinary (OSNR=16.8 dB), which is itself largely superior to "Electrical" (OSNR=19.8 dB) and "Optical" (OSNR=21 dB) PSBT. The poor performance of PSBT formats is due to the remaining energy located in the "0" bit slots, which leads to eye diagram closure. To assess the impact of chromatic dispersion, we have also plotted in Fig. 2 the OSNR sensitivity curve of "Electrical" PSBT corresponding to +150 ps/nm of residual CD. As expected, we note a substantial improvement (~ 2 dB) of the OSNR sensitivity at BER=10^{-9} with respect to the 0 ps/nm case. The degraded behaviour of "Electrical" and "Optical" PSBT with respect to NRZ and "Optical" duobinary in terms of OSNR sensitivity is fortunately counter-balanced by a particularly good resistance to residual CD. The acceptance window for "Electrical" and "Optical" PSBT at 1-dB OSNR penalty is 380 and 320 ps/nm, respectively, whereas it is only 70 ps/nm for both NRZ and "Optical" duobinary. "Optical" duobinary has in fact a behaviour very similar to that of NRZ: its comparable eye diagram and spectral occupancy explains that. Note also the typical and well-known dips which are present around +150 ps/nm and -85 ps/nm in the CD transfer function of "Electrical" PSBT. They are less pronounced with the "Optical" PSBT. When considering DGD robustness, duobinary and PSBT formats are roughly equivalent to NRZ: a DGD of 6.5 ps leads to 1-dB OSNR penalty.

Finally, we investigated the tolerance to intra-channel nonlinearities using a recirculating loop including four 100-km SSMF spans individually compensated by a slope-matched dispersion compensation fiber module (DCF), leading to a 97% compensation ratio. In order to minimize loop polarization effects, a polarization scrambler synchronously modulated with the loop circulation period was included. The SSMF/DCF map loss was compensated by means of hybrid distributed Raman / erbium-doped fiber amplifier (EDFA). The backward Raman gain was fixed to 16 dB in the SSMF, while an EDFA was added to each span (after the DCF module) to provide the additional 14 dB gain necessary to compensate for SSMF/DCF pair losses. A dynamic gain equalizer flattened the loop gain and suppressed ASE noise outside the WDM multiplex bandwidth. After a pre-determined number of loop round trips, the measured channel was selected with the square flat-top optical filter optimized previously (for the back-to-back OSNR sensitivity measurements). Finally, the post-compensation was tuned to have the best BER by means of a tunable dispersion compensation module. Fig. 5 shows BER versus span input power per channel at 1200 km for the channel at 1550.12 nm and the various modulation formats. The pre-compensation was optimized to -700 ps/nm (at 1550.12 nm). Optimal span input powers are 1 dB higher for both "Electrical" and "Optical" PSBT than for NRZ and "Optical" duobinary, showing that PSBT formats are more resistant to intra-channel nonlinear effects than NRZ and duobinary formats. Nonetheless, due to their significantly worse back-to-back OSNR sensitivity (observed on Fig. 2) and in spite of a slightly better OSNR after 1200 km (1 dB more), "Electrical" and "Optical" PSBT have a worse BER than NRZ and "Optical" duobinary.

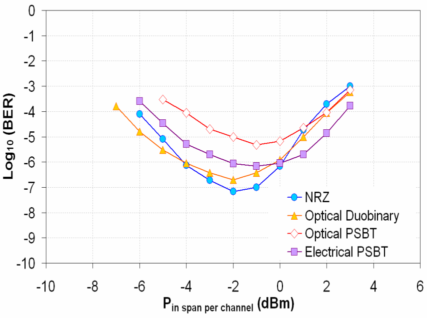

Fig. 5. BER vs. span input power for the channel at 1550.12 nm after 1200 km of transmission in the SSMF/DCF line

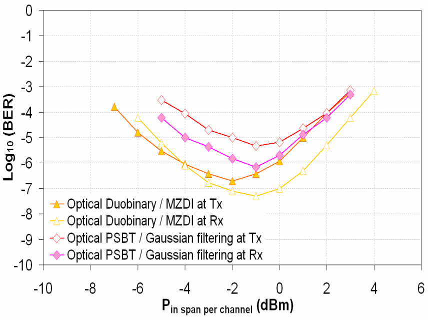

Fig. 6. Similar to Fig. 5 for the "Optical" duobinary and "Optical" PSBT with optical filtering at the Tx output or Rx input.

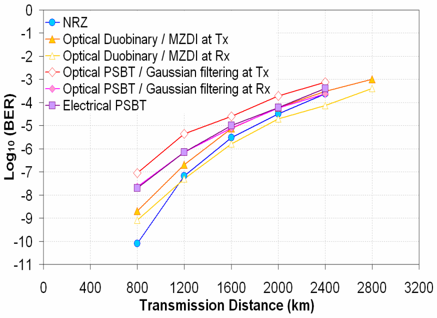

Fig. 7. BER vs. transmission distance for the channel at 1550.12 nm, for the various modulation formats.

In order to take advantage of the robustness of DPSK format with respect to nonlinearities, we decided to transfer the MZDI and the Gaussian bandpass filter located at the output of the DPSK transmitter (before the recirculating loop) to the input of the receiver (after the recirculating loop) [6]. In the case of the "Optical" duobinary, the span input power per channel was increased of 1 dB (see Fig. 6) when the MZDI was shifted at the loop output, while the BER was improved of ½ decade at the optimum, showing a clear robustness enhancement to intra-channel nonlinear effects. In the case of the "Optical" PSBT, the span input power per channel was identical but the BER was improved of ~1 decade when the Gaussian filter was transferred after the recirculating loop, demonstrating once more the enhanced robustness of this configuration when facing intra-channel nonlinearities. Finally, we plotted in Fig.7 BER versus transmission distance of the channel at 1550.12 nm for the various modulation formats. For each distance and each format, both span input power per channel and post-compensation were optimized. The pre-compensation was kept at -700 ps/nm. As expected, the significant BER advantage of both NRZ and "Optical" duobinary on PSBT formats at low transmission distances was progressively reduced with the accumulation of intra-channel nonlinearities, proving the higher resilience of PSBT formats to this degradation. At 2400 km, there was only ½ BER decade of difference between NRZ and the PSBT formats, while at 800 km the difference was of 2-3 decades. Note at last that PSBT formats reached a BER better than 10^{-3} at 2400 km, very close to the performance of NRZ and "Optical" duobinary.

4. Conclusions

Our studies of the relative robustness of duobinary, PSBT and NRZ formats have shown that "Electrical" or "Optical" PSBT are the most resistant to residual CD. However this improved CD resilience occurs at the expense of a reduced back-to-back OSNR sensitivity. "Optical" duobinary has a behaviour very similar to NRZ, with the same resistance to residual CD and a slightly worse back-to-back OSNR sensitivity. Duobinary and PSBT formats are as robust as NRZ when facing DGD. Finally, PSBT formats are more resilient to intra-channel nonlinearities. Transferring the MZDI or Gaussian filtering after the transmission line increases the performance of "Optical" duobinary and "Optical" PSBT. Note at last that PSBT formats can reach in this configuration (quasi single-channel propagation conditions) error-free distances in excess of 2000 km (if we consider error correction capability of FEC). It is promising in view of 50 GHz spaced ultra long-haul WDM transmission systems where NRZ (due to its large spectral occupancy) is not convenient.

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