Nonlinear Transmission Performance of 160-Gb/s Phase-Modulated On-Off Keying Signals

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Abstract: We study the nonlinear transmission performance of CSRZ, pairwise-alternating-phase CSRZ and group-alternating-phase CSRZ signals at 160 Gb/s. We compare their performance in suppressing ghost pulses induced by intra-channel four-wave mixing.

1. Introduction

With the advance of high-speed electronics, transmission systems at high data rates offer potentially lower cost per bit, reduced power consumption and footprint of the terminal equipment, simplified wavelength management, and higher signal spectral efficiency. With the commercialization of 40-Gb/s transmission systems, the next data rate hierarchy will clearly be 160 Gb/s, as the fundamental speed limitation of electronics is above this rate. Currently, almost all 160-Gb/s transmission systems for research purposes are built on optical time-division-multiplexing (OTDM) technique. In such systems, typically the data are generated by 40-Gb/s electronics to encode the short optical pulses, which are multiplexed in time to form a 160-Gb/s data stream. Hence the phase correlation between the pulses cannot be maintained.

In the past few years there have been extensive studies on 10- and 40-Gb/s phase-modulated signals such as carrier suppressed return-to-zero (CSRZ), differential phase-shift keying (DPSK), duobinary and modified duobinary, as these signals provide attractive features in linear and nonlinear transmissions. However, at 160-Gb/s rate, phase coding cannot be performed with conventional OTDM signals due to the relative phase drift between tributaries when they are interleaved in the OTDM multiplexers. Recently we have demonstrated a method to generate ultra-high-speed phase-coded signals including RZ [1], CSRZ [2], pairwise-alternating-phase (PAP) CSRZ [3], group-alternating-phase (GAP) CSRZ [4], and DPSK [5][6].

In this paper we investigate the nonlinear transmission performance of three on-off keying phase-modulated signals: CSRZ, PAP-CSRZ, and GAP-CSRZ through an analytical study. Previously only PAP-CSRZ was numerically analyzed and compared to CSRZ with a relatively short pattern length [7]. In 160-Gb/s transmission regime, the pulses diverse rapidly over short fiber length and may overlap tens of bits or even more. To fully characterize the nonlinear interactions of the signal, a minimum number of interacting bits are needed in the study to capture those intra-channel effects, as given in [8]. This requirement is difficult to satisfy with the conventional simulation of long pseudo-random bit sequences (PRBSs), which would be prohibitively time consuming. Thus our focus is placed on analytical estimation of the three formats considering long pattern lengths.

Here we compare the nonlinear performance of the three formats in suppressing intra-channel four-wave mixing (IFWM), which is a major transmission impairment at 160 Gb/s.

2. Signal formats and analytical model

The phase modulation schemes for the three formats are shown in Fig. 1. The phases in CSRZ, PAP-CSRZ and GAP-CSRZ alter by π for every other bit, two bits and four bits, respectively. CSRZ is a widely used format in long-haul transmission with high spectral efficiency. PAP-CSRZ has shown certain improvement in nonlinear tolerance by numerical simulations [7] and experimental verifications [3]. GAP-CSRZ is advantageous in simplifying clock recovery [4] since its spectral-tone spacing is 40 GHz, therefore standard 40-GHz components can be used for clock recovery.

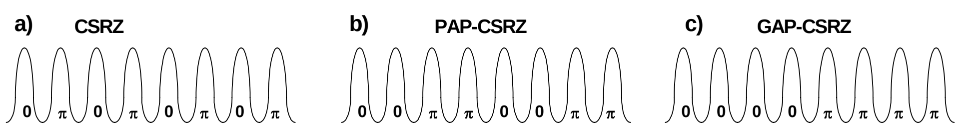


Fig. 1: Three phase-modulation schemes.

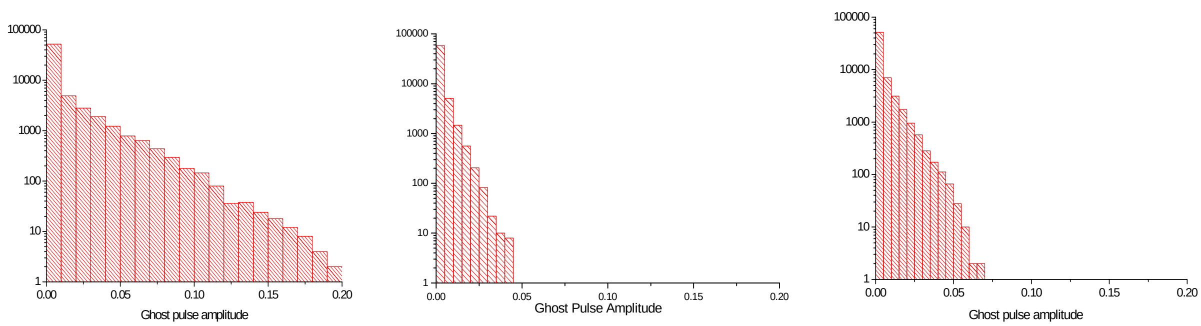
When assuming a symmetric dispersion map and loss-less transmission the ghost pulse amplitude generated at the 0-*th* bit slot (k=0) can be approximately expressed [9] by:

$$\Delta u_0 \cong -i\frac{2\gamma\tau^2}{\sqrt{3}\left|\beta^{"}\right|}\sum_{l,m} A_l A_m A_{l+m}{}^{*} \times Ci\left(\frac{2lmT^2}{\left|\beta^{"}\right|L}\right)$$

where l, m, and $l+m$ are the indices of the interacting pulses, A is the complex amplitude of the corresponding pulse, γ is the fibre nonlinear coefficient of the transmission fibre, τ is the half-width of the Gaussian pulses, T is the bit period, β'' is the fibre dispersion, L is the fibre length, and Ci is the cosine integral function. For a CSRZ signal with alternating phase between adjacent bits, the terms in the form of $A_lA_mA_{l+m}$ are always positive since the sign of A_{l+m} is the opposite of A_lA_m. As a result, the IFWM contributing terms add up and the resulting ghost pulse generation is the same as in the RZ signal case. While for a PAP-CSRZ or a GAP-CSRZ signal, some IFWM components may cancel out if the signs of two contributing terms are the opposite. In the following section we investigate the ghost pulse amaplitude distributions with all possible bit combinations for the three formats.

3. Results

We investigate the ghost pulse generation of the three formats in a 30-km non-zero dispersion-shifted fiber (NZDSF) with a D = 4 ps/nm/km. We use the above approximation to compute the ghost pulse amplitudes for a pulse train with a *zero* bit at the center and all possible bit combinations on the two sides. The duty cycle of the pulses is set to 33%, or 2.08 ps at 160 Gb/s. The length of the pulse train in the study is determined by the criteria in [8], which is calculated to be 17 including the central *zero* bit. We populate the remaining 16 bits with $2^{16} = 65536$ possible combinations. The optical power launched into the NZDSF is 15 dBm. The calculated ghost pulse amplitudes are presented as histograms in Fig. 2, with a logarithmic scale to identify those large-amplitude ghost pulses with small occurrences causing possible error floors. Clearly, the CSRZ histogram shows a long tail reaching an amplitude of 0.2, while PAP-CSRZ and GAP-CSRZ suppress the ghost pulses significantly better. Furthermore, we observe PAP-CSRZ slightly outperforms GAP-CSRZ. However, the resulting difference in BER measurements could be small.



CSRZ **PAP-CSRZ** **GAP-CSRZ**

Fig. 2: Histograms of ghost pulse amplitudes for the three formats.

Transmission in single mode fibers (SMFs) would cause the pulses to spread much wider, thus even analytical study would become extremely time-consuming. Here we attempt to investigate the nonlinear transmission performance of the three formats in SMFs through the numerical simulations using PRBSs with relatively short lengths that are limited by the computing power. Although short PRBSs cannot generate the worst-case ghost pulse scenario, it is still helpful to compare the eye diagrams of the three formats and verify if phase inversion in pairs and in groups could be effective in reducing the nonlinear transmission impairments in SMF. Fig. 3 is a set of simulations of the three signals with the same launch powers of 15 dBm. We performed simulation with the PRBS lengths of 2^7-1 and 2^{11}-1. Clearly, a longer PRBS length causes more fluctuations of the signal. In both cases, PAP-CSRZ and GAP-CSRZ show improvement over the CSRZ signal. Note that with the large dispersion in SMF, a significantly long PRBS is needed to fully capture all pattern related effects, which is currently only possible with experimental investigations.

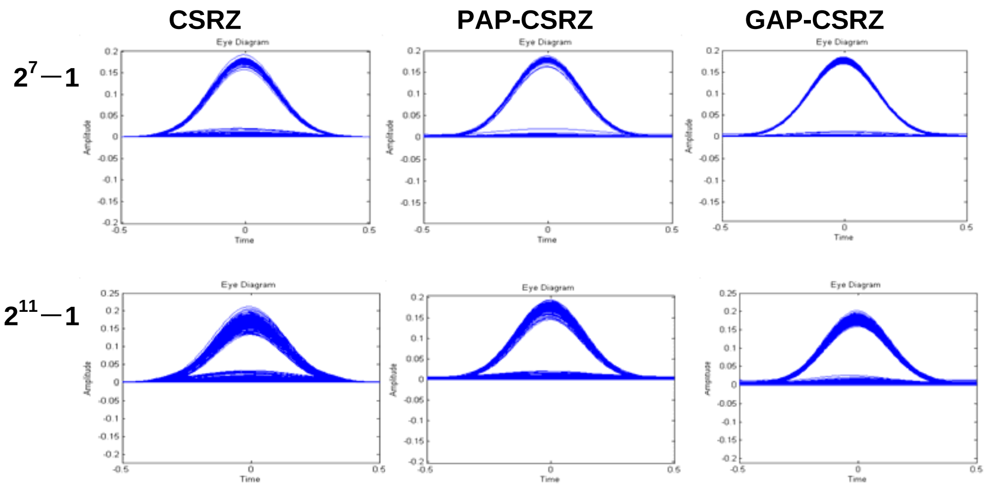


Fig. 3: Eye diagrams of the three signals with different pattern lengths after transmission through 30-km SMF fiber with a launch power of 15 dBm.

4. Conclusion

We investigated the ghost pulse generation of CSRZ, PAP-CSRZ and GAP-CSRZ signals at 160 Gb/s in NZDSF. The histograms of the three formats show that PAP-CSRZ and GAP-CSRZ clearly outperform a CSRZ format, while the difference between the PAP-CSRZ and GAP-CSRZ is small. We also performed numerical simulations of their transmission performance in SMF Although the current computation capability limits the PRBSs to relatively short lengths, it still can be observed that PAP-CSRZ and GAP-CSRZ outperform CSRZ signal.

Acknowledgement

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