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Five-level polybinary signaling for 10 Gbps data transmission systems

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Abstract: This paper presents a revitalization effort towards exploiting multilevel polybinary signals for spectral efficient data links. Specifically, we present five level polybinary signaling for 10 Gbps signals. By proper coding to avoid error propagation and degeneracy of the bit error rate performance, a 10Gbps polybinary signal is successfully generated employing a 1.8 GHz Bessel filter with an electrical spectral efficiency of 5.5 bit/s/Hz. The experimental results show bit error rate performances below FEC level for transmission in singlemode and dispersion shifted fibers up to 20 km length.

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1. Introduction

Increasing capacity demands in optical channels is forcing technology to move from spectral inefficient non-return to zero (NRZ) to advanced modulation formats. Moreover, the associated complexity in the transmitter and receiver must be kept to the minimum in order to maintain the cost per bit contained. There are two main scenarios that require high capacity with low complexity, short reach optical interconnects [1] and optical access networks [2]. These scenarios are currently requiring 400G and 40-100G solutions, respectively. Different techniques have been used for advanced modulation, such as discrete multitone (DMT) [3], carrierless amplitude/phase (CAP) [4], orthogonal frequency division multiplexing (OFDM) [5], and N-pulse amplitude modulation (N-PAM) [6,7]. Additionally, duobinary modulation has been extensively used in high-capacity backplanes [8], where the roll-off of the backplane itself matches the spectrum profile of the duobinary signal. Duobinary modulation is in fact a particular case of the family of polybinary signaling with three levels. Polybinary signals can actually have as many as M levels, as early identified in [9,10,11]. A polybinary signal with five levels, $M = 5$, offers a competitive advantage in terms of bandwidth usage: theoretically a bit rate of B can be sustained in a channel of single-sided bandwidth $B/8$ of the original bandwidth. The advantages of a five level polybinary signal stemming from a reduced bandwidth when considering transmission are very attractive: chromatic dispersion impairments are drastically reduced, along with stimulated Brillouin backscattering (SBS), which infers higher launch power into the optical fiber can be sustained.

In this paper we provide a proof-of-concept of polybinary signaling at 10 Gbps with five levels using only 1.8 GHz of bandwidth, which effectively provides an electrical spectral efficiency of 5.5 bit/s/Hz. The electrical spectral efficiency is in this paper defined as the ratio between the bitrate and the 3 dB cut off frequency of the electrical filter used for polybinary signal generation. The end-to-end spectral efficiency considering the optical transmission is 2.25 bit/s/Hz, as the signal is conveyed using a double side band scheme. Polybinary signaling of high order provides a technical solution to overcome bandwidth limitations in optical transmitters and receivers, and paves the way to bring multigigabit capacity to end users cost-effectively. To the best of our knowledge, no experimental assessment of optical five level polybinary has been reported before at any bitrate. This paper is organized as follows: in Section 2 we present the polybinary generation and recovery method. Section 3 presents the experimental setup employed to assess the feasibility of this modulation format and discusses the results and the impact on potential application scenarios. Finally, the paper is concluded in Section 4.

2. Polybinary generation and recovery

Polybinary signaling is an advanced modulation format, also known as partial-response transmission format, which makes use of bit correlation to reduce the spectral width. This correlation is introduced through an amount of controlled Inter-Symbol Interference (ISI). This controlled ISI is introduced by a simple codification scheme [11]: considering a_k the original bit sequence, b_k a precoded polybinary sequence, and c_k the five-level generated signal, it is possible to estimate the original binary sequence from independent decisions on c_k without considering the previous estimated bits, provided the following relationships are used:

$$b_k = a_k \oplus b_{k-1} \oplus b_{k-2} \oplus b_{k-3} \quad (1)$$

$$c_k = b_k + b_{k-1} + b_{k-2} + b_{k-3} \quad (2)$$

Equation (1) shows the precoding method, consisting of conducting X-OR addition of the current bit and the previous three ones. The coded bits are then added, as indicated in Eq. (2). By using this specific coding, not only ISI is introduced but also degeneracy due of error propagation in the recovery is avoided. Degeneracy due to error propagation would occur in an uncoded polybinary signal if the receiver provides a wrongful output which is later taken as an element to decode out further bits. Equation (3) describes the straightforward estimation process at the receiver, consisting only of a modulo 2 operation on the value of the detected bit.

$$a_k \approx c_k \text{ mod } 2 \quad (3)$$

Once the coding is conducted, a low pass filter (LPF) is used to perform the correlation and remove the undesired frequency components. There have been many research efforts to optimize the LPF's bandwidth in duobinary systems: at 10 Gbps receiver sensitivity has shown to be improved by employing a 3 GHz LPF [12] and better amplified spontaneous emission (ASE) noise limited performance can be achieved with 2.8 GHz [13]. As a rule of thumb, it is well known that for a duobinary signaling, fifth order low pass Bessel filters having a 3 dB bandwidth equal to the quarter of the data rate gives a satisfactory performance. For a five level polybinary, and based on sound numerical simulations, a 3-dB bandwidth value of 1.8-2 GHz of the Bessel filter results in proper operation for the generation process.

The receiver side can be based on direct-detection (DD), followed by either digital signal processing (DSP) or by placing an analog circuit with several thresholds for decision. Either approach is employed, the complexity is in the vicinity of 4-PAM and 8-PAM receivers, which are currently considered viable solutions for 100/400G solutions [14]. DSP processing offers the advantage of flexibility and reconfigurability on the spot [15], and because the bandwidth of the polybinary signal is extremely reduced in comparison to the original NRZ, the pressure on the processing load at the receiver is reduced drastically.

3. Experimental demonstration and results

This section presents an overview of the experimental generation of the polybinary signal, its performance after different transmission links and a discussion about the obtained results.

3.1 NRZ, duobinary and polybinary generation

Figure 1(a) shows the experimental setup employed to demonstrate five level polybinary modulation. A 2^7-1 pseudorandom binary sequence (PRBS) was coded into a polybinary stream, and loaded to a pulse pattern generator (PPG). The electrical signal from the PPG was filtered by a 5th order Bessel filter with a frequency cut off of 1.8 GHz. The generated electrical polybinary signal was then used to drive a directly modulated laser (DML) with an emitting wavelength of 1550.2nm. The optical signal was then transmitted through the optical fiber transmission link and then sampled and stored by a digital sampling scope (DSO) with 13 GHz analog bandwidth at 40 Gsa/s sampling rate. Figure 1(b) shows the optical spectra of the laser source when unmodulated, and with an NRZ and a polybinary signal. As it can be observed, the emission wavelength shifts when modulating the light; this is because the laser was on coolersly operation mode.

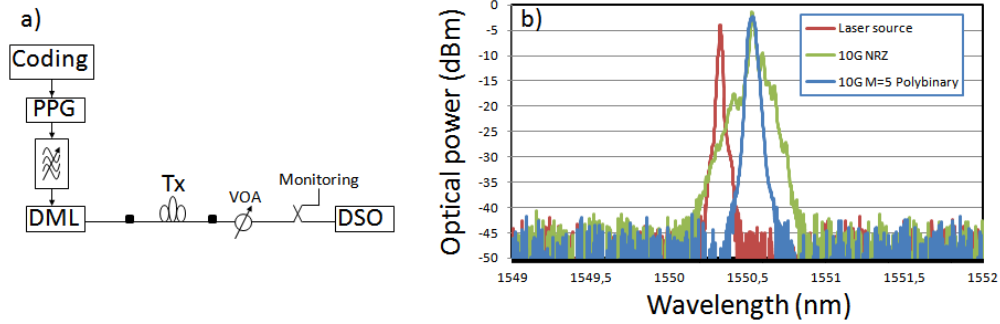


Fig. 1. Experimental setup (a) and optical spectra of the laser source (b), a 10Gbps NRZ and a 10Gbps five level polybinary signal.

The generation of a five-level polybinary signals is based on a relation of frequencies between the original NRZ signal and the electrical filter; this relation, once the filter is adjusted as in a permanent setup, can be varied in order to obtain other polybinary levels by adjusting the original bitrate from the PPG. Figure 2 shows the eye diagram generated by the system when the bitrate is adjusted to be 1 Gbps. The extinction ratio in this case was circa 10 dB. In this case, the signal goes through the filter without experiencing any distortion. By increasing the bitrate to 6.5 Gbps, the signal is converted into a duobinary signal (polybinary with three levels), as shown in Fig. 2(b). Finally, when the bitrate is adjusted to 10 Gbps, a five-level polybinary signal is obtained, as seen in Fig. 2(c). Figure 2 includes small green dots indicating the levels and the sampling point. In these eye diagrams, the effect in time domain of the strong filtering can be observed in the increase of the transition time between levels. The rise time in the case of the 1Gbps signal is barely 200 ps, or 20% of the bit duration. However, because of the filtering of the high frequency components, transitions in the case of duobinary and polybinary $M = 5$ increase to the point that the transition themselves shape the levels in amplitude and time, and therefore define the transmitted bits.

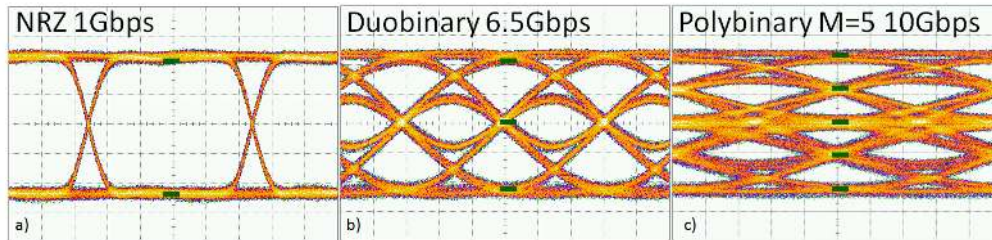


Fig. 2. Eye diagrams of an NRZ 1 Gbps (a), a 6.5 Gbps duobinary (b) and a five level polybinary 10 Gbps (c). These signals were sequentially generated using the same setup.

Figure 3 shows the measured electrical spectrum of different signals to benchmark the spectra utilization of the five level polybinary signal. The NRZ signals conveyed a PRBS 2^7-1 sequence. As it can be observed, the 10 Gbps and the 1.8 Gbps NRZ signals present lobules occupying 10 GHz and 1.8 GHz, respectively. These measurements were then completed by adding the Bessel filter; the filtering allows transferring the first three lobules of the 1.8 Gbps NRZ signal, which at practical effects does not impact its shape. However, when a five level polybinary 10 Gbps is generated, we can observe the spectra is severely reduce and restrained within the first 2 GHz.

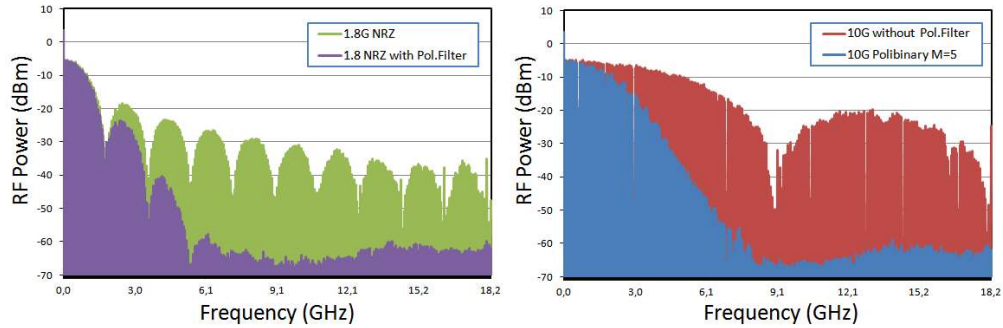


Fig. 3. Electrical spectrum of different signals, comprising a 10 Gbps NRZ, a 1.8 Gbps NRZ, a 1.8 Gbps NRZ filtered with the polybinary filter, and a five level 10 Gbps polybinary signal.

3.2 Results

Figure 4 shows the eye diagram of the five levels polybinary signal at the output of the DML source. In order to assess the transmission performance of the signal, it was transmitted through different length spans, specifically 5-, 10- and 20 km. These values were chosen because they fit the optical access network scenario. The fibers were chosen to be dispersion shifted fiber (DSF) and single mode fiber (SMF), which are arguably the most commonly deployed types of fiber. As it can be observed, the eye diagrams after 5- and 10 km remain faithful to the back-to-back. After 20 km transmission, the DSF fiber also prompts a fair eye diagram. However, transmission through 20 km of SMF degrades the signal significantly; as expected, dispersion impairs the transmitted signal, as it can be observed by the skewing to the left of the upper eye aperture

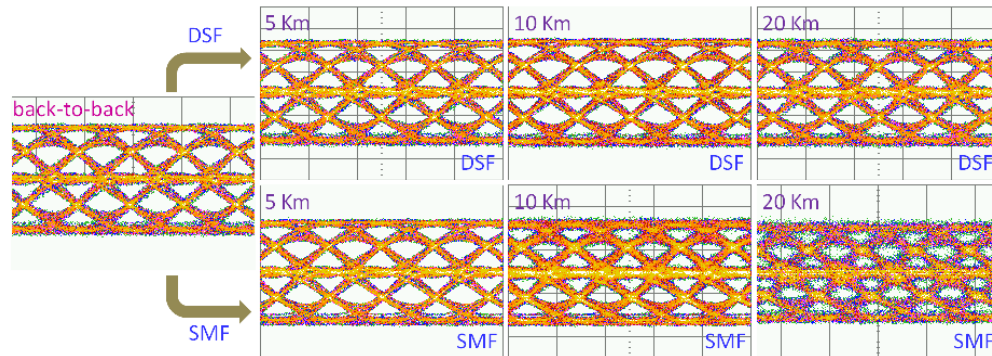


Fig. 4. Eye diagram of the back-to-back five level polybinary signal and the eyes diagrams after transmission through different length spans of DSF and SMF.

The dispersion effect is observable also in the bit error rate (BER) curves, which are presented in Fig. 5. The BER curves were measured for the back-to-back case, 10- and 20 km. As it can be observed, DSF transmission and SMF of 10 Km produce BER with an identical performance as the back-to-back case, whereas transmission through 20 km of SMF incurs in a 2 dB power penalty. The 5 km case was left unmeasured because of the insignificant difference in BER performance of the back-to-back and the 10 km case. Therefore, the eye diagrams of Fig. 4 and the BER performance of Fig. 5 are in agreement. Figure 5 includes an indicative FEC threshold for a 20% overhead hard decision FEC [16], which we employed as benchmark to evaluate the performance of the modulation format.

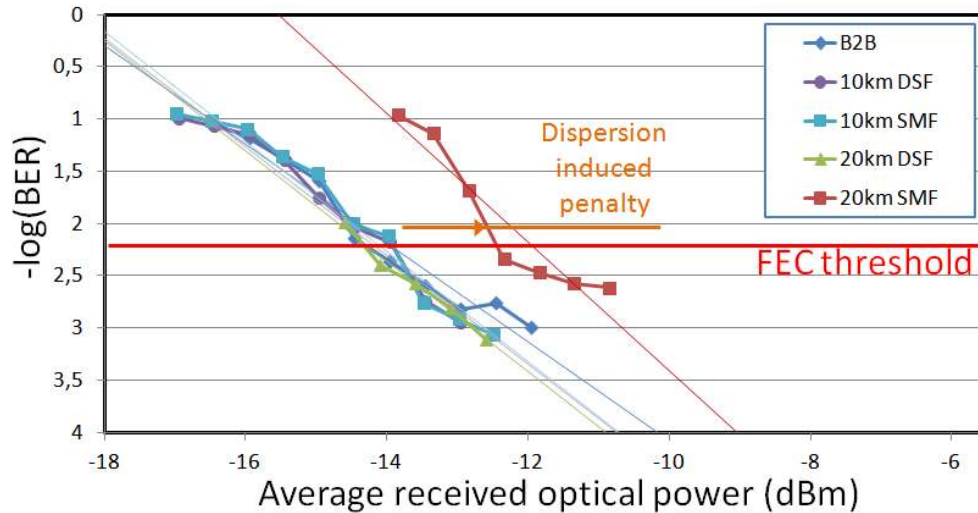


Fig. 5. Bit error rate (BER) performance of the five level 10 Gbps polybinary signal after different transmission links.

4. Conclusion

In this paper, we present a five level polybinary signaling for high-capacity optical access networks and short range data transmission systems. We experimentally demonstrated a polybinary signaling at 10 Gbps using only 1.8 GHz of bandwidth, which effectively provides an electrical spectral efficiency of 5.5 bit/s/Hz. The complexity of the transmitter, compared to regular NRZ systems, lies in the need of precoding the signal and placing a low pass band filter. However, the savings in terms of bandwidth is more than fourfold when compared to regular NRZ signaling. At the receiver side, the system needs to be able to set different thresholds, which increases its complexity. However, this complexity is at the same level of 4-PAM, and lesser than higher M-PAM systems. Therefore, polybinary signaling of high order, specifically of fifth order, provides a technical solution to overcome band limited optical transmitters and receivers with a contained complexity, and paves the way to bring multigigabit capacity to end users cost-effectively. Similarly, in short-range data transmission systems for interconnects and data centers, polybinary signal can enable simple 100G/400 communications links. In such systems, where high-capacity, low cost and simplicity is a prerequisite, polybinary modulation suits that purpose.

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