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Analog-based duobinary-4-PAM for electrical bandwidth limited optical fiber links

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This paper presents a demonstration of a seven level duobinary-4-PAM signal operating at 10.16 Gbit/s. The polybinary generation is achieved by a simple electrical Bessel filter of 5th order, with a frequency cut-off of 1.8 GHz. We assess the impact of the filter placement, either at the transmitter or the receiver, and find the impact is minimal in terms of bit error rate performance in transmissions of up to 40 km of single mode fiber.

Keywords: optical communications, advanced modulation formats, multilevel modulation.

1. Introduction

The always increasing demand for higher efficiency in the utilization of optical links is pushing research in the area of advanced modulation formats. This trend comprises all network scenarios, from long-haul links, to optical access networks and even short -range interconnects. In the access networks arena, fiber-based access networks are regarded as the main technological solution that can efficiently provide scalable bandwidth; copper and wireless technologies compete with fiber-bases solutions on the last few meters, but fiber-based optical access networks are indeed bond to become the main skeleton of high-performance access networks as they are scalable and can sustain large bandwidth. A challenge being currently addressed in the field is whether multilevel modulation formats are suitable for cost-sensitive access systems. Multilevel or advanced modulation formats enable to increase the effective bandwidth of a link while keeping the bandwidth of the required photonic and electronic components and the deployed optical distribution network unchanged. Since optical access networks are very cost sensitive, and electro-optic components with bandwidth beyond 10 GHz become more complex and expensive, the introduction of multilevel modulation formats seem to be a matter of timing.

Modulation formats proposed for access networks include orthogonal frequency -division multiplexing (OFDM), in where frequency bit and spatial allocation schemes can be implemented, enabling a new layer of reconfigurability [1]. OFDM however requires of digital-to-analog converters (DAC) with a large effective number of bits (ENOB) to generate the signals, adding a layer of complexity in the transmitter. Carrierless amplitude phase (CAP) [2] has also emerged as an alternative to OFDM, as it can be generated by analog or digital means and provides high spectral efficiency with simplified transmitters and receivers based on electrical passband filters. These two solutions, although relaxed in terms of electronic circuitry, placed some pressure on the optical side, as high extinction ratio and good linearity are required for the external modulator or the directly modulated laser. Purely amplitude based multilevel modulation formats such as pulse-amplitude modulation (PAM)-4 or PAM-8 are also envisioned as possible candidates to increase the efficiency of the modulation format in access networks [3] and short range communications [4], yet the spectral efficiency is not as high as with OFDM and CAP.

In this paper, we revitalize the area of polybinary signaling by demonstrating a further reduction in the bandwidth requirements of PAM-4 by using polybinary signaling [5]. Specifically, we demonstrate duobinary operation of a PAM-4 signal, leading to a multilevel duobinary-4-PAM signal. Experimentally, a PAM-4 with an effective bitrate of 10 Gbit/s is converted into a polybinary signal, reducing the necessary electrical bandwidth down to circa 2 GHz. This work also investigates the performance of the polybinary stream depending on the location of the electrical filter used for generation. The complexity at the transmitter and receiver is low, enabling the usage of GPON class optics for 10 Gbit/s optical access networks and short-range systems.

2. Generation of duobinary-4-PAM

Partial response signaling was initially proposed to increase the spectral efficiency by constructively utilizing intersymbol interference (ISI). Strong filtering of an on/off keying signal normally generates a polybinary signal; the filtering induces ISI by removing the upper part of the spectra, effectively reducing the given bandwidth. Depending on the filter bandwidth, M-level signal streams are obtained. From an early stage, it was also predicted that multilevel signals can be also used to generate polybinary signals after strong filtering [6]. Therefore, strong filtering can further boost the already increased spectral efficiency of a multilevel signal. In this work, we employed a 4-PAM signal as seed for a duobinary filter, effectively obtaining a duobinary-4-PAM 7-level signal. Because the generation method introduces correlation between adjacent bits, meaning that the current bit is also defined by the values of the k preceding bits, codification at the transmitter side is necessary in order to avoid error propagation at the receiver side. Considering a_k the original bit sequence, b_k a precoded 4-PAM sequence, and c_k the 7-level generated signal, it is possible to recover the original

4-PAM sequence from independent decisions on c_k, provided the following relationships are used:

$$b_k = a_k - b_{k-1} \bmod 4 \tag{1}$$

$$c_k = b_k - b_{k-1} \tag{2}$$

$$a_k = c_k \bmod 4 \tag{3}$$

The simplicity of the transmitter is outstanding: the digital coding is a simple bit-to-bit operation, which can be implemented either in hardware or software, and only analog filtering is needed after the 4-PAM generation; the location of the analog filter is flexible, as it can be placed at the transmitter side or at the receiver side (effectively transmitting a regular 4-PAM signal over the channel and converting it to duobinary -4-PAM before digitalization). This flexibility enables reutilization of 4-PAM transmitters. Analog solutions are already commercially available at low cost. The receiver side is equally frugal, as a simple sample point approach is used, avoiding the need for power hungry digital signal processing (DSP) methods. The only necessary DSP processing consists of a mod 4 operation.

Optimization of the filter profile and bandwidth frequency cut-off has been object of extensive research, leading to different parameters: at 10 Gbit/s receiver sensitivity has shown to be improved by employing a 3 GHz low-pass filter (LPF) [7] and amplified spontaneous emission (ASE) noise limited performance can be achieved with 2.8 GHz [8]. In polybinary signaling, Bessel filters are used because of their maximally flat group/phase delay (maximally linear phase response), which preserves the wave shape of filtered signals.

Figure 1 (left-side) shows the performance of a duobinary signal in terms of bit error rate (BER) performance, signal-to-noise ratio (SNR) and frequency cut-off of the filter used to generate the polybinary signal. Furthermore, Fig. 1 also shows the evolution of a non-return to zero (NRZ) signal when filtered at different normalized frequencies, experiencing conversion into different multilevel polybinary signals.

Our computer simulations, in agreement with the literature, indicate that a frequency cut-off of circa 30% of the linerate seems optimal to generate a duobinary signal.

3. Experimental setup and results

Figure 2 shows the experimental setup used to generate, transmit and receive the duobinary-4-PAM signal. As a goal of this research is to determine the optimal location of the electrical filter for duobinary-4-PAM generation, two scenarios were tested: generation of the duobinary-4-PAM at the transmitter, and generation of the duobinary-4-PAM at the receiver. A 5.08 Gbit/s pseudo-random bit sequence (PRBS) and a logically inverted 5.08 Gbit/s PRBS were generated by a single pulse pattern gener-

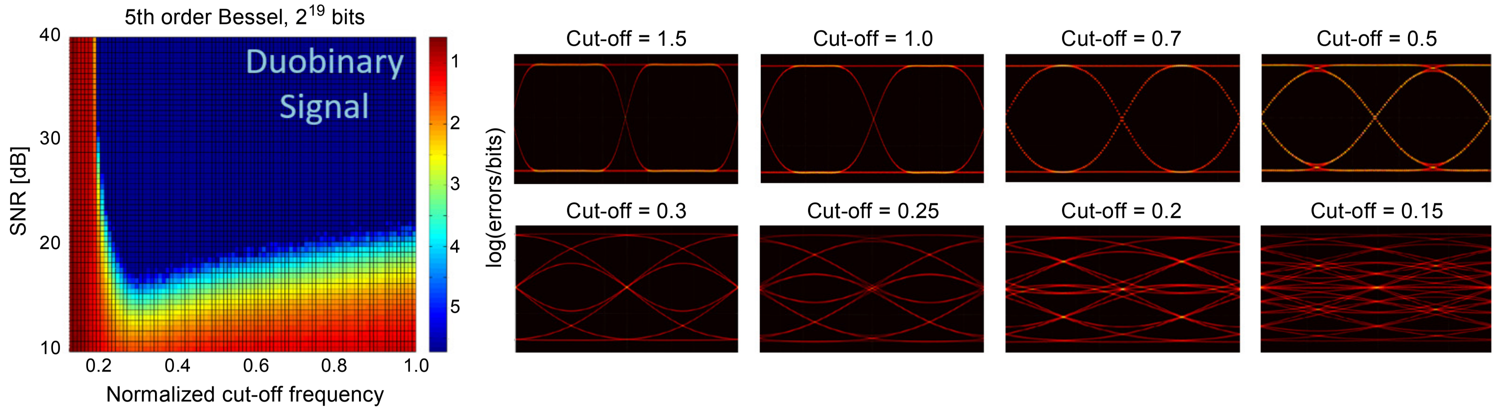

Fig. 1. BER performance for different SNR levels and cut-off frequencies of a duobinary signal (3-level polybinary). Evolution of a regular NRZ signal when filtered at different frequency cut-off points; narrower filtering generates higher order polybinary signals.

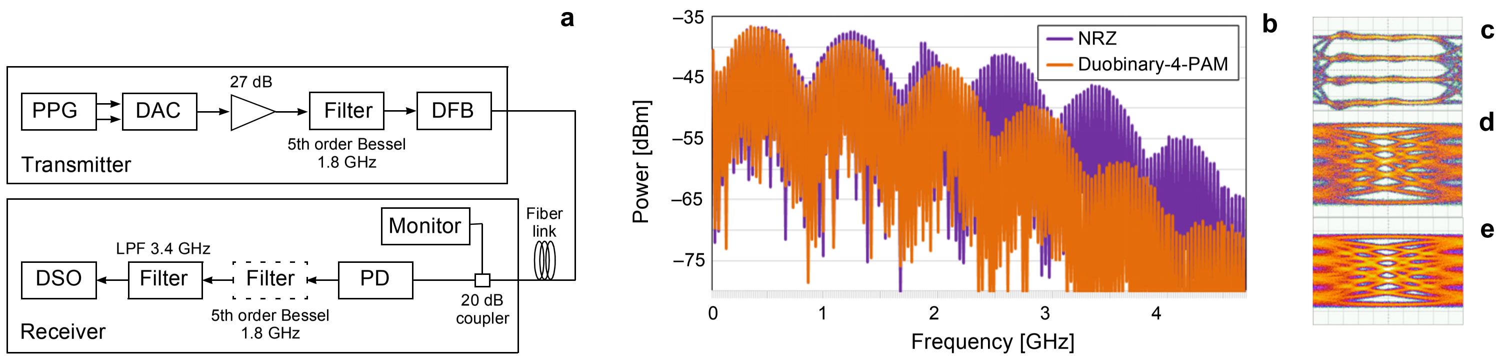

Fig. 2. Experimental setup for the generation and transmission of duobinary-4-PAM signals (**a**). Electrical spectra of the 5.08 Gbaud duobinary-4-PAM and the 5.08 Gbaud NRZ signal (**b**). Eye diagram of the original 4-PAM signal (**c**), the duobinary-4-PAM signal when generated at the transmitted (**d**) and at the receiver (**e**). PPG – pulse pattern generator, DAC – digital to analog converter, DFB – distributed feedback laser, PD – photodiode, DSO – digital sampling scope, NRZ – non-return to zero.

ator (PPG); the streams were decorrelated by means of an electrical delay. Both streams were then multiplexed with a two bit digital-to-analog converter (DAC), which effectively generated the 4-PAM signal. After amplification, the now 4-PAM signal was filtered with a 1.8 GHz Bessel filter in order to generate the duobinary-4-PAM signal at the transmitter side. This filter was placed at the receiver after the photodiode (PD) to test the generation at the receiver side. The duobinary-4-PAM signal was then used to drive a distributed feedback laser (DFB) operating at 1550 nm. The DFB is a 10 GHz bandwidth commercially available DFB, providing 0 dBm and up to 9 dB of extinction ratio at 60 mA of bias current. After transmission over various types of single-mode fibers (SMFs) the signal was detected by a 10 GHz bandwidth photodiode (PD). Before digitalization by a 40 Gsa digital storage oscilloscope (DSO), electrical out of band noise was removed by a 3.4 GHz low-pass filter (LPF). A single decision point in time per bit algorithm for off-line processing of the recorded received data was implemented in MATLAB.

Figure 2 also shows the electrical spectra of the original 5.08 Gbit/s NRZ stream and the 10 Gbit/s duobinary-4-PAM signal at the receiver side after the 3.4 GHz LPF. Furthermore, the eye diagram of the original 4-PAM signal (Fig. 2**c**), and the duobinary-4-PAM signal when generated at the transmitted (Fig. 2**d**) and at the receiver (Fig. 2**e**) are shown. The seven levels of the duobinary-4-PAM signal are clearly distinguishable.

Figure 3 shows the eye diagrams of the duobinary-4-PAM signals after transmission for the case of generation at the transmitter. Skewing of the eye due to dispersion after 40 km standard single-mode fiber (SSMF) featured the signal to be unrecoverable using simple single decision point in time; this limitation can be overcome by using clock recovery and cognitive decision thresholds for each level.

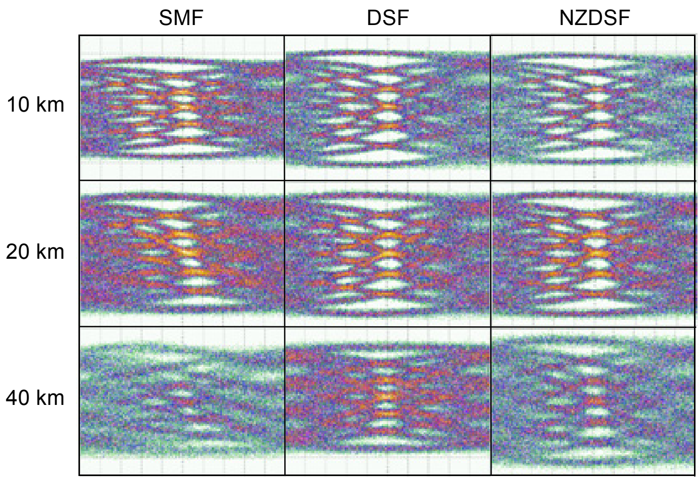

Fig. 3. Eye diagrams for transmission through 10, 20 and 40 km fiber length over different types of fibers. Dispersion effects are noticeable in the SMF case, as the eye diagram is skewed. SMF – single mode fiber, DSF – dispersion shifted fiber, NZDSF – non-zero dispersion shifted fiber.

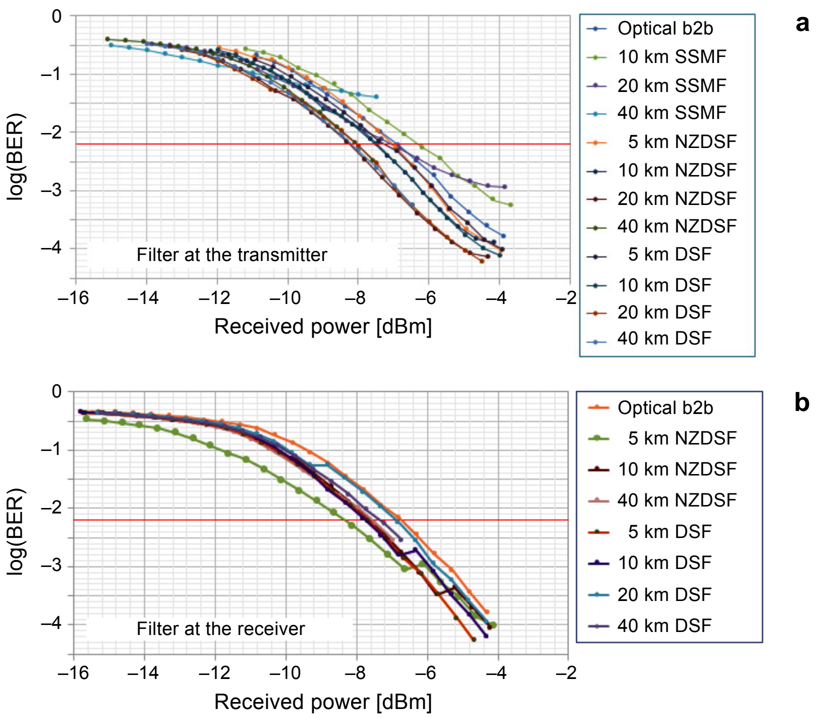

Fig. 4. BER performance for duobinary-4-PAM generation at the transmitter (**a**) and the receiver (**b**).

Figure 4 shows the measured bit error rate (BER) for duobinary-4-PAM signals generated at the transmitter and at the receiver, after transmission over different types of fibers and lengths. In the case of duobinary-4-PAM generation at the transmitter, the BER was measured for 10, 20 and 40 km SSMF, and 5, 10, 20 and 40 km for dispersion shifted fiber (DSF) and non-zero dispersion shifted fiber (NZDSF). The needed BER for error free recovery through 7%-overhead forward error correction (FEC) is 2.2×10^{-2}. The receiver sensitivity for the scenario in where the polybinary signal is generated at the transmitter is between –8 and –6 dBm for all fiber types and lengths, except 40 km SSMF which was not recoverable due to the skewing induced by chromatic dispersion and the usage of a single point recovery algorithm method. All the measurements for this case are within 2 dB range and show a similar trend. Due to fiber availability at the time of measurement, the case of generation at the receiver was only tested with NZDSF and DSF fiber. The BER curves are again consistent and within the same power range as in the previous case, as expected. The overall difference for both cases is similar, with a 0.5 dB gain when the polybinary generation is done at the transmitter; as the signal has a narrower spectra, chromatic dispersion affects slightly less the signal, leading to this marginal difference. It is worth pointing out that the performance of the duobinary-4-PAM signal is worse than an NRZ signal with the same bitrate; the reason is the increase in the number of levels effectively reduces the SNR signal. Therefore, there is a trade-off between spectral efficiency and signal performance.

4. Conclusions

Advanced modulation formats are penetrating the optical arena in its different segments, from long-haul to short-range links. Current research is mainly focused to define which modulation format fits best and maximizes the performance of the channel. Polybinary modulation enables reducing the necessary bandwidth of intensity multilevel signals, by adding controlled ISI and carving out part of the electrical spectra. This paper presents a seven-level duobinary-4-PAM signal that has been successfully generated and transmitted over a 40 km optical link. The total bitrate obtained is 10.14 Gbit/s using only a single wavelength and direct detection. The transmitter relies on a simple setup, consisting of a PPG with two output ports, a 2-bit DAC and a 1.8 GHz low-pass filter to generate the duobinary-4-PAM signal, which means the implementation is extremely simple. In case of placing the filter at the transmitter for the duobinary-4-PAM generation, the bandwidth requirements on the DFB and the ADC at the receiver side are both reduced. In case of placing the filter at the receiver for the duobinary generation, the bandwidth requirements on the ADC are reduced. The receiver side is based on direct detection with a simple digital signal processing (DSP) recovery scheme. The receiver sensitivity is reduced because of the extra generated levels compared to a standard 4-PAM signal; however, the reduced spectral usage is sufficient to compensate for this penalty in optical access networks, or eventually, in short range access networks and data center interconnects.

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