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Research Article

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Challenges in Polybinary Modulation for Bandwidth Limited Optical Links

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Abstract

Optical links using traditional modulation formats are reaching a plateau in terms of capacity, mainly due to bandwidth limitations in the devices employed at the transmitter and receivers. Advanced modulation formats, which boost the spectral efficiency, provide a smooth migration path towards effectively increase the available capacity. Advanced modulation formats however require digitalization of the signals and digital signal processing blocks to both generate and recover the data. There is therefore a trade-off in terms of efficiency gain vs complexity. Polybinary modulation, a generalized form of partial response modulation, employs simple codification and filtering at the transmitter to drastically increase the spectral efficiency. At the receiver side, polybinary modulation requires low complexity direct detection and very little digital signal processing. This paper provides an overview of the current research status of the key building blocks in polybinary systems. The results clearly show how polybinary modulation effectively reduces the bandwidth requirements on optical links while providing high spectral efficiency.

Keywords: Optical communications; Advanced modulation formats; Microwave filter; Polybinary modulation

Introduction

In order to transmit bits of information between two points, it is necessary for both the transmitter and the receiver to agree on the way to carry the information. In communication systems, this is called modulation format. Current optical systems for access networks and high capacity datacenter links employ very simple on-off keying modulation formats, which are inherently inefficient (yet robust and simple to generate/recover). The current boost on traffic demands in optical systems has forced researchers to look into better modulation formats; better in the sense of efficiency in transmitting bits using fewer resources. The most common measure for efficiency is the spectral efficiency, and these formats are called advanced modulation formats. By studying advanced modulation format schemes capable of sustaining the traffic demand, the energy required to convey data will be reduced; a green internet providing affordable bandwidth for services and applications that society demands can then reach the citizenry. If we focus on advanced modulation formats that can graciously scale up to 100G regimes, we found several approaches experimentally demonstrated, including: 112 Gb/s dual polarization using 16-QAM [1], 100 Gb/s single VCSEL data transmission with 4 PAM [2], 100 Gb/s over 80-km with Multi Tone Modulation [3], and 102 Gb/s over 12-km with Multi CAP [4].

These demonstrations however required fairly complex transmitters and receivers, both in terms of hardware and software in the form of digital signal processing algorithms. Our work focuses on polybinary modulation formats, which in principle overcome these two obstacles.

Polybinary modulation was proposed originally to overcome the bandwidth limitation of copper-based transmission media. This modulation provides an increment of the number of levels of the original binary signal by introducing controlled amounts of inter-symbol interference (ISI) [5]. The primary consequence of this modulation is the redistribution of the spectral density of the original signal into energy compressed low frequencies; this compression has a price in terms of noise sensitivity [6]. However, it offers the opportunity to filter out the high-frequencies, as they no longer carry information, thereby effectively increasing the spectral efficiency.

The simplest polybinary modulation, known as duobinary, correlates a symbol with its predecessor; if the original signal is binary (two levels), the duobinary modulated signal will present three levels. Current developments in duobinary modulation include quadrature solutions achieving spectral efficiencies in the order of 4-b/s/Hz [7] and 100G solutions based on duobinary modulation [8]. Duobinary modulation can also be applied with multilevel signals such M-levels Pulse Amplitude Modulation (PAM) signals. In particular, high bit rates such as 112 and 56 Gbps polybinary systems have been achieved combining a 4-PAM signal with doubinary for 5 and 10 km transmissions, resulting in a 7-levels signal [9,10].

This paper presents our efforts in maturing polybinary modulation in all its aspects to provide a technical solution for future low-energy consumption 100G/400G communication systems. This paper presents the challenges and state-of-the-art of the different identified building blocks to develop future polybinary modulation systems and identifies the main obstacles to be overcome.

Challenges in Polybinary Modulation

Partial response signaling or polybinary modulation was proposed to increase the spectral efficiency by constructively utilizing ISI, which is in general an impairment which drastically reduces the performance of signals when transmitted. Polybinary signals are generated by following the next bit relations:

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

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

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

Where a_k is the original bit sequence, b_k a precoded binary sequence, and c_k the polybinary signal. By simply sampling c_k and conducting the modulo n operation, being n the number of levels of the polybinary signal, the original stream can be recovered.

Given the method to generate and recover polybinary signals, we can visualize the whole system as indicated in Figure 1.

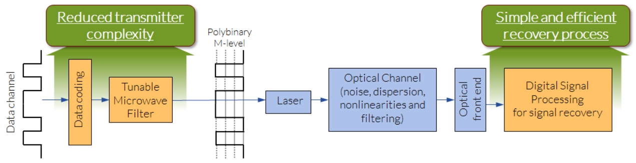

Figure 1: System overview, highlighting in orange the building blocks under study.

Figure 1 shows the two building blocks of a polybinary transmitter, the data coding block and the tunable microwave filter. Furthermore, it also highlights the digital signal processing blocks for signal recovery. The laser, optical channel and optical frontend remain normally the same regardless of the modulation format. The following sections describe our current efforts in each of these challenges.

Coding, generation and recovery

In polybinary modulation, 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 codification to remove the excess of bandwidth. The coding can be implemented employing either digital signal processing or by a hardware implementation with a delay-and-add block. Either way, the filter removing the excess bandwidth is key; the following section explains the challenges on the design and fabrication of reconfigurable microwave filters. However, here we focus on the requirements of the filters in the process of polybinary generation. Table 1 shows a comparison table on the spectral efficiency, number of amplitude thresholds and minimum signal to noise ratio (SNR) requirements of polybinary modulation (for different Bessel filter orders) compared to 4-PAM and 8-PAM.

PRM		**5 Levels**	**7 Levels**	**9 Levels**	**4-PAM**	**8-PAM**
Amplitude Thresholds		4	6	8	3	7
Spectral Efficiency		~5 Bit/s/Hz	~7 Bit/s/Hz	~7.5 Bit/s/Hz	~2 Bit/s/Hz	~4 Bit/s/Hz
Minimum	Border 3	~24.5 dB	~29.5 dB	~30 dB	~18 dB*	~22 dB*
SNR for	Border 5	~23.5 dB	~26 dB	~ 28 dB		
Maximum	Border 7		~25 dB			
Measurable BER	Border 9					

Table 1: Summary of polybinary generation features. *10 Gbaud with pulse Gaussian shapping of 7.5 GHz at 3 dB bandwidth. PRM: partial response modulation.

The challenge in generating the optical polybinary signal, beyond the filter adequacy, arises in the need of large extinction ratios. In short-range systems, vertical-cavity surface-emitting lasers (VCSELs) are the most common building block due to their manufacturability; however, VCSELs have two main drawbacks in terms of performance: reduced bandwidth compared to other directly modulated type of laser sources and limited extinction ratio [11]. State-of-the-art VCSELs have been demonstrated to work in multi-GHz regimes, providing a platform to operate in >25 Gbit/s rates [12,13], and therefore, bandwidth limitations are being overcome. Extinction ratio remains a challenge, as current values are in the vicinity of 8-9 dB [14], which provide a limited budget for multilevel formats, which in turn, degrades the performance and the maximum transmission reach.

Figure 2 shows the histogram of two multilevel signals (NRZ and 4-PAM), converted into polybinary (duobinary and duobinary-4-PAM, respectively). As it can be observed, the distribution of symbols increase from an even to an odd number, which effectively reduces the threshold spacing to effectively discern the bit probability [15]. This limitation, along with the previously mentioned challenge with the extinction ratio, highlights how the performance in polybinary suffers from a penalty compared to regular amplitude modulation formats.

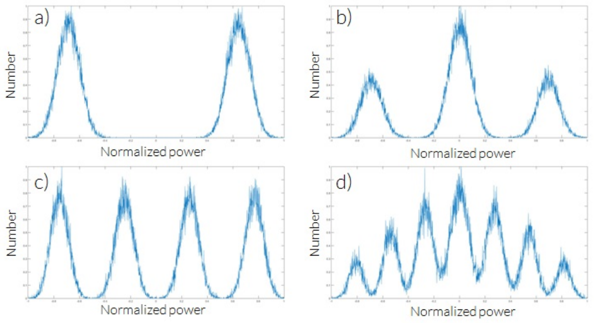

Figure 2: Histograms of an NRZ (a) and a duobinary signal (three level polybinary) (b), and a 4-PAM (c) and a duobinary-4-PAM (d).

However, Figure 2 has a different reading: bit decision processes can be implemented with simple point-and-shot algorithms, and the data does not depend on phase information. This drastically reduces the complexity of the digital signal processing blocks at the receiver side,

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and enable analog hardware implementations, which effectively reduce to a bare minimum the latency at the receiver side.

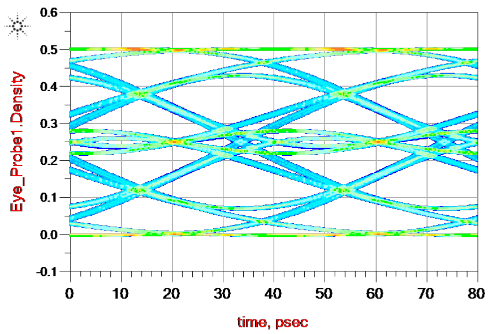

Figure 3: 4th Order Bessel LPF with cut-off 2 GHz. Signal: 5-level at 10 Gbps.

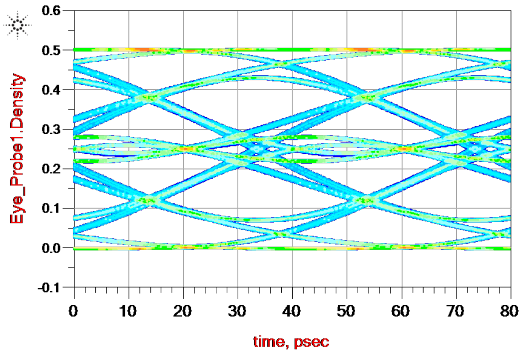

Figure 4: 4th Order Bessel LPF with cut-off 5 GHz. Signal: 5-level at 25 Gbps.

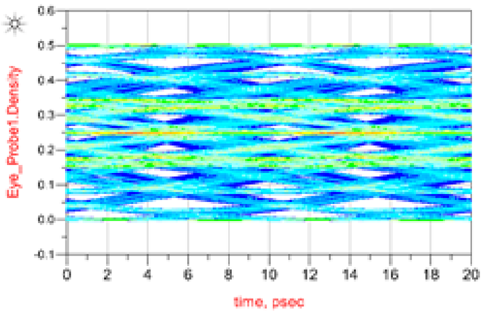

Figure 5: 6th Order Bessel LPF with cut-off 12.5 GHz. Signal: 7-level at 100 Gbps.

Microwave filters for polybinary generation

The simplest method to generate a polybinary signal is filtering the high frequency components of the original electrical signal with a Bessel low-pass filter (LPF) [11]. A Bessel filter is a filter derived using Bessel functions with a goal of linear phase, i.e., maximally flat group delay, which implies a time delay constant for any frequency component [16]. The drawback of Bessel filters is their shallow slope compared to other types such as Butterworth or Chebyshev. The properties Bessel LPFs, which generate polybinary signals from a non-return to zero (NRZ) seed, are reported in [17]. According to the simulations reported in that paper, the ratio between cut-off frequency of the LPF and the signal bandwidth has to be 17-26% for 5-levels polybinary, 13-17% for 7-levels polybinary and 12-13% for 9-levels polybinary. Current efforts are focused on implementing electrical Bessels LPFs which maximized the performance of the generated polybinary signals. There have been some attempts already: a microwave Bessel LPF at 7.5 GHz cut-off frequency is described in [18]. This filter is a combination of microstrips and suspended striplines. A microstrip stepped-impedance defected ground structure (DGS)-based [19] Bessel LPF of 5th order at 2.5 GHz is proposed in [20] and improved in [21].

An initial study on what are the optimal parameters of the LPF to generate polybinary signals, including the order, type and cut-off and stop frequency have been conducted, and a first generation of polybinary filters designed to maximize the performance of polybinary signals fabricated. Figures 3-5 show the eye diagrams generated by the designed Bessel filters for 10, 25 and 100 Gbit/s, respectively. Figure 6 shows the fabricated filters once connectorized.

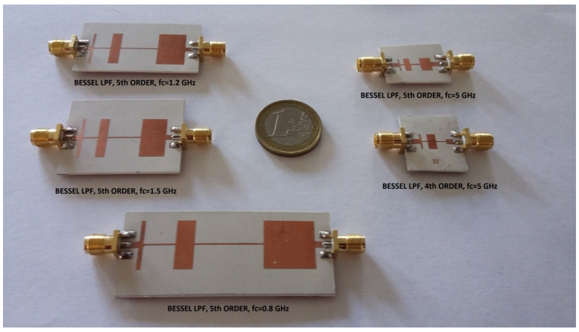

Figure 6: First generation polybinary filters designed to maximize the performance of polybinary signals.

Although these Bessel LPFs provide an accurate frequency response, phase response and tunability remains critical factors. Tunability is key as future transceivers are expected to be reconfigurable, and therefore, able to operate at different bitrates depending on the network requirements. Different technologies have been proposed addressing this field: a tunable coplanar Bessel Band Pass Filter (BPF) for a 10 Gbps wireless Monolithic Microwave Integrated Circuit (MMCI) receiver has been implemented in [22]. The central frequency is 120 GHz and the bandwidth is 15 GHz; the central frequency can be tuned between 118 and 122 GHz. Another monolithic integrated tunable LPF at 4.3 GHz cut-off frequency, which employs MMCI coplanar waveguides loaded by shunt semiconductor varactors, has been proposed in [23]. The cut-off frequency can be tuned of ±19%. However MMCI solutions change significantly the phase characteristic when the filter is reconfigured. Tunable LPFs using micro-electro-mechanical systems (MEMs) to implement reconfigurable series inductors and capacitive shunt switches have been used to demonstrate operation up to the millimeter-wave frequency range. The Tchebycheff LPF presented in [24] has a tunable cut-off frequency between 20-53 GHz. An eliptic LPF of tunable cut-off frequency of 8-10 GHz is

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reported in [25]. A tunable active elliptic LPF is presented in [26]. This filter concept is based on a high order LPF at which an active capacitor circuit has been added; the capacitor allows to compensate the overall losses of the filter and makes it tunable. This filter has a tunable cut-off frequency that ranges between 700-830 MHz. A tunable Bessel LPF for duobinary signals generation has been patented [27]. This filter uses a controller circuit to tune variable capacitors and inductors; the technology used for the variables components is not specified, but MEMS is reported to be the most suitable.

Conclusion

This paper had presented polybinary modulation as modulation of choice for bandwidth limited optical links. Polybinary modulation effectively reduces the necessary bandwidth to transmit a data stream by introducing a controlled ISI; although bandwidth reduction positively affects the strength of the signal in front of optical transmission impairments such as chromatic dispersion and Brillouin backscattering, the trade-off comes in the form of a degraded sensitivity when compared to traditional on-off keying signaling. However, this drawback may be assumable in short-range systems, where power is relatively abundant as transmission losses are low, and complexity, simplicity and power efficiency are key metrics that need to be maximized.

At the transmitter side, polybinary modulation presents a channel in selecting the specifications of the filter conducting the strong filtering leading to a reduce bandwidth signal. The order, profile, and phase and amplitude response are critical to obtain an electrical polybinary signal able to drive directly modulated laser sources, which are common building block in short-range systems.

Integrated Bessel LPF filters preserving linear phase are readily available and can be designed to maximize the performance of polybinary signals at almost any desired bitrate. Reconfigurable Bessel LPF filters are under heavy research and promise us to enable multi-bitrate transceivers.

Polybinary modulation suffers from lower sensitivity, as the bit distribution reduces the threshold spacing; in presence of amplitude noise, polybinary performs worst. However, the bit distribution is phase independent, and simple point-and-shot detection algorithms can be put in place. Furthermore, as polybinary modulation requires codification at the transmitter, error correction gain can be anticipated. The modulation also permits to implement analog receivers based on filter banks.

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