MODELING AND PERFORMANCE EVALUATION OF IMPROVED DATA FORMATS FOR OPTICAL COMMUNICATIONS

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Abstract – *Simple on-off keying with intensity modulation using NRZ or RZ-data format is not optimum in the sense of spectral efficiency and robustness towards channel impairments. In this contribution alternative modulation formats are investigated.*

INTRODUCTION

In very high capacity optical networks we are facing several design constraints. It is necessary to utilise the available bandwidth as efficiently as possible and the channel impairments like dispersion, noise, non-linear fibre effects and interference in dense wavelength division multiplex (DWDM) systems should be minimised.

One possible approach is to use alternative modulation formats. In this contribution, we concentrate on formats that require less bandwidth (in Hz) per given data-rate (in bit/s). Several candidates are investigated in detail both theoretically and experimentally: Partial-response line-coding, single-sideband-modulation and multi-level phase shift keying. For real world applications it is necessary that these formats not only offer bandwidth reduction but also prove sufficient performance with respect to interference and intermodulation from adjacent channels, non-linear fibre properties, and noise resistance. Last but not least the implementation-effort at high speed must comply with economic constraints.

Duobinary modulation (DB) is one special implementation of partial-response line-codes which is very well suited for optical systems e.g.[1], [8]. Compared to conventional modulation only two additional devices are necessary: (i) an electrical low-pass filter with a bandwidth of approximately one quarter of the bit-frequency, and (ii) a differential encoder. As the conventional receiver may remain unchanged compared to binary transmission, this format may be used as a relatively simple enhancement of existing transmission systems. A minimum complexity solution is presented in [2]. The DB-signal requires only approximately 50% of the bandwidth of a conventional binary NRZ-signal and is thus not only bandwidth-efficient but also much more robust against dispersion effects. Transmission spans of 252km over uncompensated dispersive standard single-mode fiber (SSMF) have been achieved experimentally [2].

Single-sideband modulation (SSB) has in principal also the potential to reduce the required bandwidth by a factor of two. However, strict SSB signals require coherent detection in the receiver and are thus impractical. Thus vestigial-sideband modulation (VSB) is more promising because conventional receivers may be used. In [3] this has been used for a record transmission capacity experiment. The square-law-detection in the optical receiver is then able to perform an approximate signal demodulation. Substantially more hardware-effort is required compared to DB-modulation. Uncompensated transmission spans of 200km over dispersive SSMF have been achieved experimentally [4].

Following latest developments in optical modulation formats, phase shift keying (PSK) has attracted attention, first as two-symbol (binary) transmission and recently as quaternary (4 symbols) QPSK which reduces bandwidth occupancy by a factor of two [5],[6]. In order to reduce the complexity, differential encoding at the transmitter is used, which allows simple receiver structures without carrier synchronization needs.

DUOBINARY SIGNALLING

The duobinary transmission scheme is well known in digital communicatons since many years [7]. It turned out, that this format is conceptually very attractive for optical communication as it can be implemented with readily available optical components. The bandwidth occupancy is reduced by nearly a factor of two by transmitting a three level signal (+1, 0 –1) over the fibre. The three level optical signal is produced by driving a push-pull Mach-Zehnder Modulator with a duobinary (three level) electrical signal, which is generated using an electronic differential encoder (duobinary precoding) and e.g. analogue low-pass filters [8]. A conventional intensity detecting photo diode may be used as a receiver, so that the additional complexity for this format is low. Therefore, this is an attractive method for upgrading existing binary on-off keying intensity modulation (IM) systems.

Duobinary modulation is a carrier suppressed format as is CSRZ etc. This helps overcoming the SBS effect. The duobinary format has proven a substantionally better dispersion tolerance allowing longer span lengths and relaxed dispersion compensation. However, for optical power levels where the SPM-effect occurs, this advantage rapidly disappears, if we approach the non-linear duobinary limit (see fig. 1). Proper prechirping may however overcome this limit as is shown in [9]. Also this format is more robust against frequency dependent (higher-order) PMD compared to binary IM [10]. Fig. 2 shows the performance of various narrow-band modulation formats in a DWDM environment.

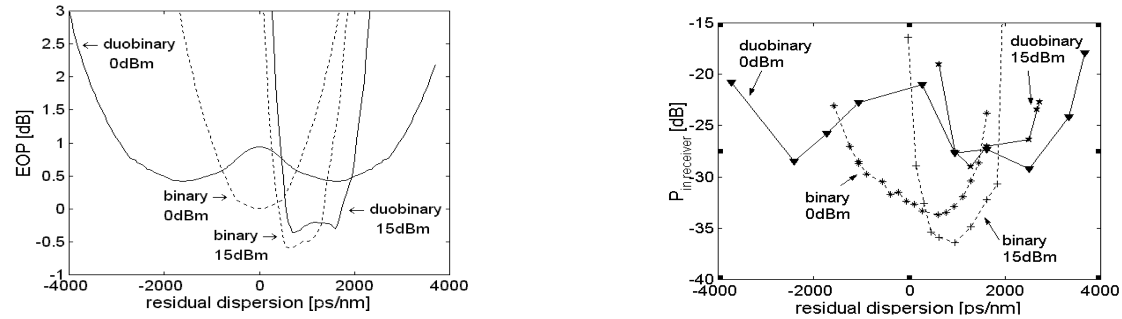

Fig 1: Dispersion tolerance of duobinary and conventional binary format in the linear (0 dBm opt. power into fibre) and non-linear (15 dBm) regime, 10Gb/s, left simulation, right measurement.

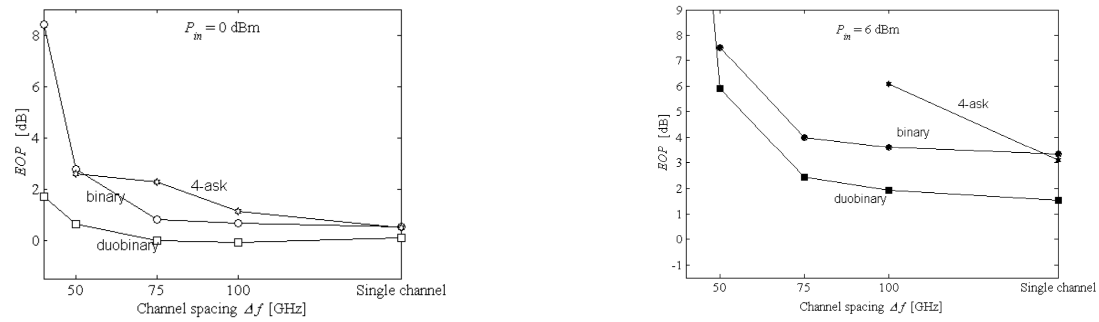

Fig. 2: Eye opening penalty for various modulation formats in a WDM system (40Gb/s channel data rate) with different channel spacings in the linear (0dBm opt. power into fibre) and non-linear (6dBm) regime.

SINGLE- AND VESTIGAL SIDEBAND MODULATION

SSB and VSB have in principle also the potential to reduce the required bandwidth by nearly a factor of two. However, strict SSB signals require coherent detection. Therefore VSB is preferred because conventional receivers may be used [3]. The square-law-detection in the optical receiver is then able to perform an approximate signal demodulation. A possible implementation of a VSB-modulation scheme is described in [4]. Substantially more hardware-effort is required compared to DB-modulation (fig. 3). Uncompensated Transmission spans of 200km over dispersive SSMF have been achieved experimentally [4] (see fig. 3). In [11] experiments have been shown which compare DB-, VSB-, and binary transmission formats in the presence of dispersion and nonlinear fiber effects with an overall conclusion that DB modulation is the most promising approach.

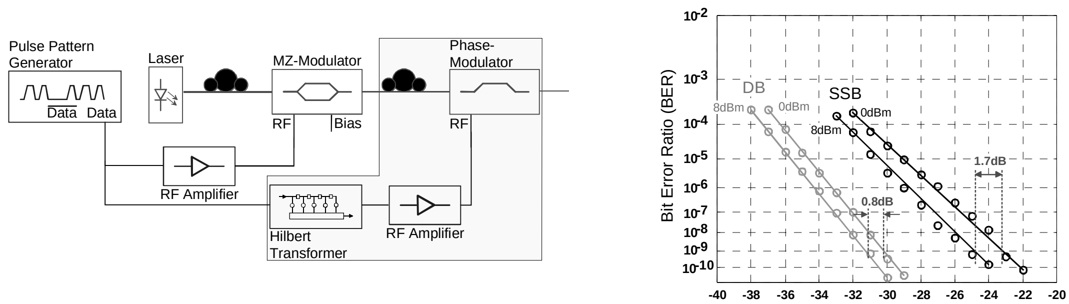

Fig. 3: Left: a possible implementation of a near SSB transmitter using an approximation of a Hilbert delay line filter; right: measured BER for 10Gb/s after 200km uncompensated standard single mode fibre using duobinary (DB) and near SSB modulation.

DIFFERENTIAL PHASE SHIFT KEYING

For DPSK and DQPSK, the optical power as a function of time is approximately constant (for NRZ signalling) or periodic (for RZ signalling). This is an advantageous property for the reduction of non-linear effects like SPM and XPM. The transmitter setup is shown in fig. 4. The data is modulated onto the carrier with a Mach-Zehnder modulator (MZM) in push-pull-operation, which results in chirp-free (CF) transmission. The

MZM is driven such that the ‘1’-bit corresponds to the carrier phase shift of 0 and the ‘0’-bit corresponds to carrier phase shift of π. Therefore, after the first MZM an optical NRZ-DPSK signal is generated. The subsequent MZM is used to create an RZ pulse shape. This is done by driving it with the 10GHz clock signal.

Differential PSK is used because no carrier recovery and synchronization is needed, which allows simple reception by a self-homodyne concept. Therefore, an optical delay-and-add filter (delay interferometer) is inserted in front of the photodiode [12]. Nevertheless, to receive the original data it is necessary to use a differential precoder.

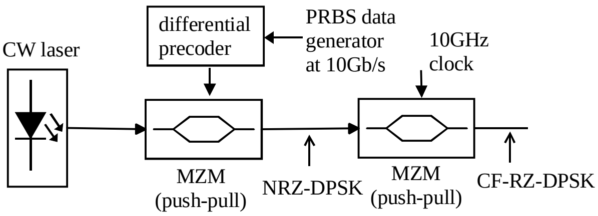

Fig. 4: Transmitter setup for CF-RZ-DPSK modulation format at 10Gb/s.

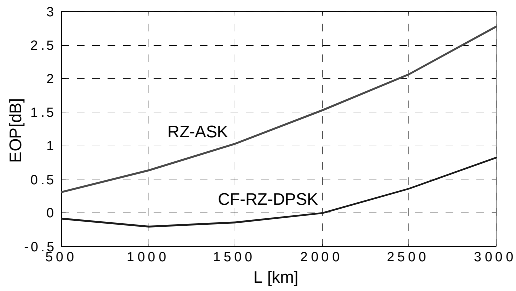

Fig 5: 8x10Gb/s with Δf=100GHz, P_{in} =9dBm/ch: EOP of 4^{th} channel with increasing length.

The performance of the DPSK-modulation is shown in fig. 5 for a dispersion managed 8-channel long-haul CF-RZ-DPSK DWDM setup over 3000km of single mode fiber. Up to 2000km no penalty for the PSK-format can be seen in contrast to the on-off-keying (=amplitude-shift-keying, ASK) technique that shows a penalty of 1.5 dB. Even for 3000km the penalty for the PSK-format remains under the 1dB limit.

For RZ-DQPSK, the transmitter is extended by a subsequent phase modulator (PM) with a phase shift of either 90° or 0° , which generates four symbols out of the binary PSK signal. In contrast to the parallel structure [13] known from classical communications, this concept requires only electrical tuning of the PM input data within a bit duration by a delay compensation. The robustness of RZ-DQPSK towards fibre nonlinearities has been shown to be comparable to RZ-DPSK in [6], although twice as much data is transmitted within the same bandwidth. The receiver sensitivity is investigated in [14].

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