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Partial response signaling for improved chromatic dispersion tolerance in intensity modulation optical transmissions

CRISTIAN PRODANIUC,[1,2,*] NEBOJSA STOJANOVIC,[1] FOTINI KARINOU,[1] AND ROBERTO LLORENTE[2]

[1] *Optical and Quantum Technologies, Huawei Technologies Duesseldorf GmbH, Riesstrasse 25, 80992 Munich, Germany*
[2] *Centro de Tecnologia Nanofotónica de Valencia, Universitat Politècnica de València, Edificio 8F, Camino de Vera, s/n, 46022 Valencia, Spain*
**cristian.prodaniuc@huawei.com*

Abstract: We investigate partial response signaling (PRS) as a way of increasing the transmission length achievable by direct detection optical systems. The performance of the duobinary and PRS modulations is evaluated against that of conventional on-off-keying (OOK). We prove by simulation and experimentally that duobinary increases the link distance by up to 1.5 times and PRS by up to 3 times, when no signal processing is employed. The gain is preserved even when equalization is used. PRS is employed also with 4-level pulse-amplitude modulation (PAM-4) and is shown to improve the transmission distance by almost 3 times.

OCIS codes: (060.4510) Optical communications; (060.4080) Modulation; (070.4790) Spectrum analysis.

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1. Introduction

Over the last years the internet traffic has been steadily rising [1]. The advent of new technologies like 5G and 4K resolution will further increase the demands on short-reach metro-access networks. For transmission distances lower than 100 km coherent and non-coherent solutions are competing for market share. While coherent technologies provide better performance and higher data rates, they require more expensive components and complex digital signal processing (DSP) at the receiver side. That is why intensity modulation and direct detection (IM-DD) implementations are usually preferred over coherent ones for next generation 100G/400G metro-access optical networks [2–4]. The most investigated intensity modulation formats for such networks are on-off keying (OOK) [5,6] and PAM-4 [7–9]. One of the main issues with IM-DD transmissions is that they cannot cover more than a few tens of kilometers at data rates of 28 Gbps or higher [10,11], due to chromatic dispersion (CD), without the use of a dispersion compensation module (DCM), dispersion compensating fibers (DCF) or CD pre-compensation. All these solutions are imperfect and there is always some residual CD leftover after transmission. Employing a higher order modulation like PAM-8 can improve the residual CD tolerance by lowering the baud rate [12], however the increased required optical signal-to-noise ratio (OSNR) makes such modulation unfeasible for most metro-access network scenarios. Another approach to handling the CD problem is to transmit the signal in the O-band, instead of the C-band. In the O-band, at wavelengths of around 1310 nm, the dispersive effects in the fiber are negligible [13]. The downsides of this solution are that the optical fiber attenuation coefficient is higher in the O-band than in the C-band and that erbium doped fiber amplifiers (EDFAs) operate only in the C and L-bands. These problems limit the maximum range of an optical transmission at 1310 nm to around 40 km at bit rates of 56 Gbps [13,14].

Transmitting an optical signal over a standard single-mode fiber (SSMF) will introduce phase distortion which scales squarely with frequency [15,16]. This means that higher frequencies will be affected more by CD than lower frequencies. This, in turn, implies that the less bandwidth a signal's spectrum occupies the less said signal is affected by dispersive effects. In order to reduce the spectrum occupancy at higher frequencies without changing the baud rate it is necessary to introduce some controlled inter-symbol interference (ISI). This technique is widely referred to as PRS. In this article we propose PRS as a way of increasing the CD tolerance of an optical transmission in the C-band and we discuss the advantages and disadvantages of this approach. We also demonstrate both in simulation and experimentally, that a simple PRS scheme can be employed to more than double the transmission distance of IM-DD systems and that they can substitute more complex DSP algorithms while keeping a constant performance. To the best of our knowledge this is the first time PRS is optimized for improving CD tolerance in a short-reach IM-DD optical transmission and the only other similar approaches are the narrowly filtered on-off-keying (NF-OOK) modulation format [17] and the so called combined amplitude-phase shift (CAPS) coding scheme [18,19].

2. Duobinary signaling

The most common form of PRS employed currently in optical transmissions is the duobinary signaling. This way of transmitting data implies summing up the currently transmitted symbol with the previously transmitted symbol, resulting in a 3-level signal when OOK is considered or a 7-level signal for PAM-4. In order to recover the original data at the receiver side two main solutions are available [20]. One way is to apply differential encoding at the transmitter side and then use a simple modulo n operation (where n is the number of levels of the modulation format, e.g. for OOK $n = 2$) at the receiver side. If a_k is the initial information sequence, then:

$$\begin{aligned} b_k &= \left(a_k - b_{k-1}\right) \bmod n \\ c_k &= b_k + b_{k-1} \\ d_k &= c_k \bmod n \end{aligned} \tag{1}$$

where c_k are the transmitted data and d_k are the received, decoded symbols. The other method employs the maximum likelihood criterion in order to detect the original sequence of symbols.

In recent years there has been a growing interest in the duobinary signaling. It is employed mostly as a means of improving the performance of heavily bandlimited optical systems [21,22]. Since the spectrum in the fiber of a duobinary signal after transmitter is half of that of the original signal, as shown in Fig. 1(a), it follows that this form of PRS should help increase the CD tolerance of a transmission. In order to prove that this is the case a simulation was performed at 28 Gbps, emulating a 10 GHz and a 20 GHz bandwidth Mach-Zehnder modulator (MZM) transmitter and PIN receiver. No DSP algorithms were employed. The results of this simulation can be observed in Fig. 1(b), where duobinary is denoted by DB. In the back-to-back (BTB) case, OOK and duobinary have approximately the same performance with 20 GHz components. However, when the bandwidth is limited at 10 GHz, the duobinary will outperform OOK by roughly 2 dB in terms of OSNR. When looking at the CD tolerance of the two modulation schemes it can be seen that while OOK can handle transmission over up to 14.7 km of fiber, duobinary can handle up to 22.4 km, for OSNR values below 24 dB. For bandlimited systems (i.e. the 10G bandwidth case) duobinary can help improve transmission distance by roughly 1.8 times, while for higher bandwidth systems (i.e. the 20G bandwidth case) the gain is only around 1.4 times.

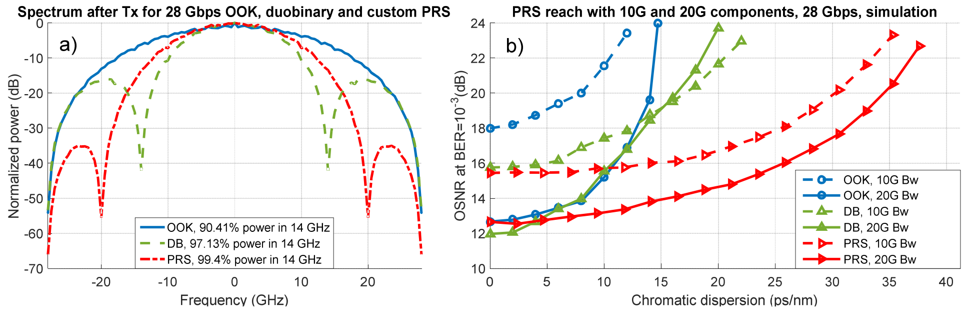

Fig. 1. Spectrum comparison between OOK, duobinary and PRS (a) and CD tolerance comparison between OOK, duobinary and PRS in low and high bandwidth scenarios (b)

3. Advanced partial response signaling

It has been shown in the previous chapter that DB improves the CD tolerance of a signal. From Fig. 1 a correlation between the spectral power concentration of a signal and the CD tolerance of the same signal can be deduced. A 28 Gbps OOK signal has 90.41% of its spectral power concentrated at low frequencies (i.e. in a 14 GHz bandwidth). Meanwhile its duobinary equivalent has 97.13% of its power concentrated in the −14 to + 14 GHz frequency range. It follows that if a signal has even more spectral power concentrated at low frequencies then it should also be more efficient at handling CD. In order to maximize the spectral power at low frequencies the transmitted pulse should approximate the prolate spheroidal wave shape [23,24], which is very similar to the Gaussian waveform shape. As a result, the DB pulse is adjusted to resemble more the Gaussian pulse (Fig. 2, bottom left), thus obtaining a more CD tolerant form of PRS (to which we will simply refer as PRS throughout the rest of this paper). In Fig. 2, a comparison between the OOK, DB and improved PRS pulses and eye diagrams is shown. For simplicity and a fair comparison between DB and PRS the introduced ISI of the PRS is limited to just one symbol period.

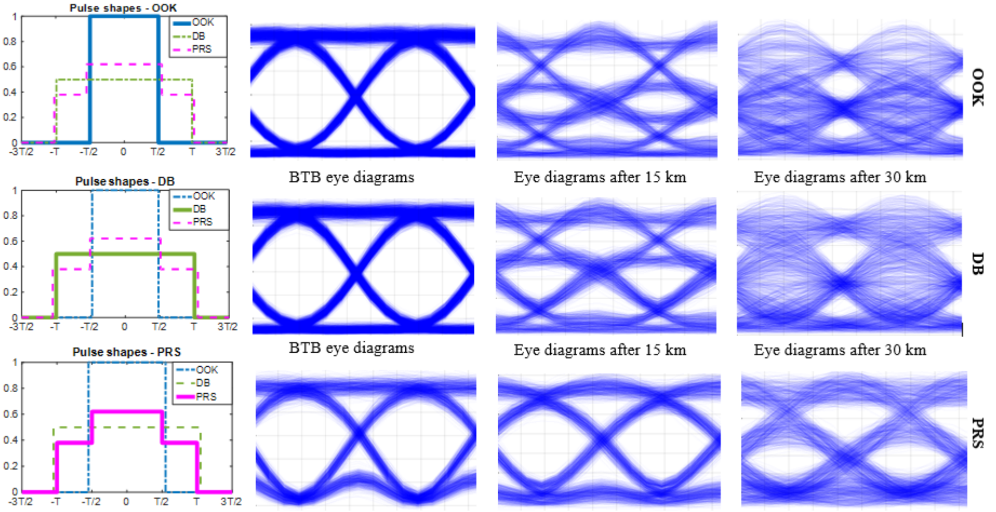

Fig. 2. Pulse shapes (first column) for OOK (first row), DB (second row), and PRS (third row) and the corresponding eye diagrams for BTB (second column), 15 km (third column), and 30 km (fourth column). The eyes are obtained employing 20G components and a MZM at the transmitter side, OSNR = 25 dB.

The performance of the PRS was tested in the same simulation scenarios described in chapter 2 and the results are displayed in Fig. 1. It can be seen there that the spectrum of the

PRS is even more concentrated than that of the DB at low frequencies, having 99.4% of its power within the −14 to 14 GHz bandwidth. This also translates into a significant increase in reach. When using PRS, link lengths of up to 37.6 km can be achieved in simulation, which is almost double of what is possible when using DB and approximately 2.5 times better than OOK.

The PRS scheme can be extended to higher order intensity modulation formats, like PAM-4. However, when employing the PRS with this kind of modulation schemes, there is an additional issue that has to be considered. So far the results shown in this article were obtained with a MZM. When using OOK in an IM-DD scenario only half of the modulation range of the MZM can be employed. On the other hand DB and PRS can use the whole range since their lowest and highest levels encode the same symbol, as illustrated in Fig. 3(a). That is why there is no OSNR penalty for the 3-level DB and PRS when compared with the 2-level OOK. In the case of DB PAM-4 however, the highest and lowest levels do not encode the same symbol anymore and thus the modulation is again restricted to just half the range of the modulator.

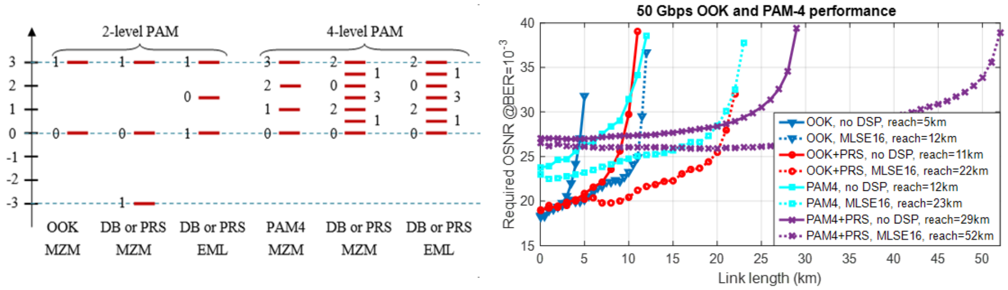

Fig. 3. Symbol mapping for different modulation/modulator combinations (left) and OOK/PAM-4 versus PRS OOK/PAM-4 BER curves.

Another simulation was performed, this time at a bit rate of 50 Gbps (a different bit rate than in Fig. 1 is chosen to show that the relative gains provided by PRS are not influenced by the transmission speed), in order to evaluate the capabilities of PRS PAM-4. The results of this simulation are displayed in Fig. 3(b). It can be observed in this plot that pure PAM-4 has more or less the same performance as PRS OOK in terms of CD tolerance but comes with a 4-5 dB OSNR penalty. PRS can help improve transmission length also when equalization is employed. To prove this a 16-state maximum likelihood sequence estimation (MLSE) equalizer is implemented. For regular OOK the addition of the 16-state MLSE more than doubles the link length, from 5 to 12 km. The same holds true for PRS OOK, where adding MLSE extends reach from 11 to 22 km. In the case of PAM-4 the addition of PRS increases the transmission distance by about 2.6 times (from 11 to 29 km), having the downside of a 3 dB OSNR penalty over regular PAM-4. Furthermore, by employing the 16-state MLSE the PRS reach can be almost doubled, from 29 to 52 km. When comparing PRS OOK with PRS PAM-4 it can be observed that PAM-4 extends the link by approximately 2.4 times, with MLSE (from 22 to 52 km) or without (from 12 to 29 km). The high OSNR requirements of PRS PAM-4 and the limited linearity of commercially available electrical components make it difficult for this modulation scheme to be implemented experimentally and thus experiments are focused on PRS OOK.

4. Experimental setup and results

In order to validate the simulation results an experimental setup was built, as shown in Fig. 4. The first step is to generate a pseudo-random bit sequence (PRBS) of length 2^{15} and then create the OOK or PRS signal from this PRBS and applying a pulse shaping filter. The data is then loaded into a 14 GHz bandwidth 84 GSamples/sec DAC which converts it to the analog domain. The signal is amplified and sent to the modulator. To take full advantage of the PRS properties a 25 GHz bandwidth MZM is employed, however other modulators like EML are valid options (although they come with an OSNR penalty cost for PRS). After the signal is converted into the optical domain amplified spontaneous emission (ASE) noise is added in order to control the OSNR. After 0 to 60 km of fiber an erbium doped fiber amplifier (EDFA) is employed, followed by an optical band-pass filter (OBF) which filters out the out-of-band noise. A 25 GHz bandwidth photo-detector is used to detect the signal and then an 80 GSamples/sec real-time oscilloscope captures the data. Next, timing recovery is performed, followed by either no receiver DSP whatsoever or by a 16-state MLSE. Finally, the bit-error rate (BER) is calculated.

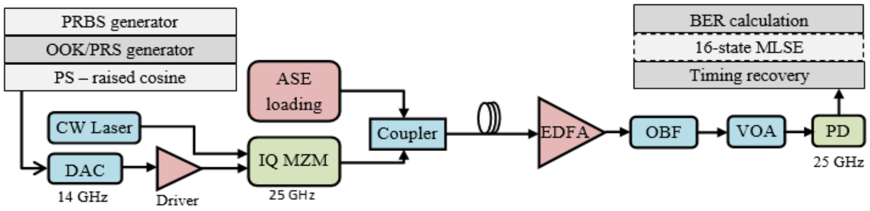

Fig. 4. Experimental setup.

The experiments were performed with link lengths of 0 (BTB), 10, 15, 20 and 25 km for OOK and 0 (BTB), 10, 20, 30, 40, 50, 60 and 70 km for PRS. The results of these experiments are displayed in Fig. 5. In Fig. 5(a) the required OSNR for a BER of 10^{-3} at different link lengths is plotted. When looking at the BTB performance it can be seen that PRS provides around 1 dB of OSNR gain. This is due to the fact that the experimental setup is bandwidth limited and that PRS, just like duobinary, is more resilient to bandwidth limitation than regular OOK. The OOK modulation is successfully transmitted over a maximum of 10 km of fiber at OSNR values below 20 dB and without the use of receiver equalization. If a 16-state MLSE is added then the transmission distance is increased to 20 km. When PRS is employed the transmission range is extended to 30 km without equalization and to 60 km with a 16-state MLSE equalizer. If the reach of OOK and PRS are directly compared it can be observed that PRS triples the transmission distance, both with or without MLSE. The minimum length fiber spool available for this experiment was of 5 km, thus the real link lengths might be a few kilometers longer (but less than 5 km) than those presented in Fig. 5(a).

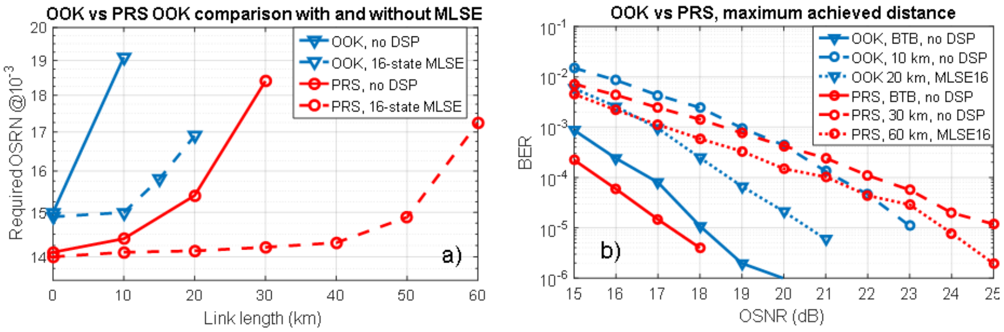

Fig. 5. OOK versus PRS experimental results, without DSP (left) and employing a 16-state MLSE (right).

The BER versus OSNR curves for the BTB case and for the longest achieved reach for OOK and PRS are plotted in Fig. 5(b). While the longest reach is achieved for OSNR values below 20 dB, in order to achieve very low BERs, below 10^{-5}, an OSNR of up to 25 dB is required. It can be observed that (both with and without MLSE) when going down to lower

BERs (BER<10^{-3}) OOK scales better than PRS. While having very low complexity, PRS (without extra DSP) outperforms OOK with 16-state MLSE and thus can be used to decrease complexity of non-coherent optical system in the C-band. It can be concluded from this experiment that, both when not using any equalization and when using a 16-state MLSE equalizer, PRS can improve CD tolerance by almost 3 times in comparison with regular OOK.

5. Conclusions

In this article we propose PRS as a means of increasing the CD tolerance of IM-DD optical systems. As far as we are aware, this is the first time PRS has been optimized specifically to combat the effects of CD. The duobinary signaling, one of the most widespread forms of PRS, is explained and we show that besides requiring less bandwidth it also improves transmission distances by approximately 1.4 to 1.8 times when compared with regular OOK. We also proposed a more advanced form of PRS derived from duobinary which increases the CD tolerance of a system by up to 3 times, as shown by the experimental results. When using MZMs there is no OSNR penalty when employing PRS, however, with other types of intensity modulators, an OSNR loss of around 4 to 5 dB for BTB can be observed. The PRS scheme presented here can be extended to higher order intensity modulation formats like PAM-4. When doing this the full range of the MZM can no longer be employed and thus we will see the 4-5 dB OSNR penalty regardless of modulator.