25 Gbit/s Duobinary and 4-PAM for Access Networks

R. van der Linden,[1,2] N.C. Tran,[2] E. Tangdiongga,[1] and A.M.J. Koonen[1]

[1] Institute for Photonic Integration, Eindhoven University of Technology, the Netherlands
[2] Genexis B.V., the Netherlands

Access networks are no exception in the ever continuing increase in data rates. Due to the cost-sensitive nature of these networks it is of interest to be able to reuse the current 10G optics for the upgrade to higher data rates. Therefore, higher order modulation formats can be considered to transmit higher data rates through a reduced bandwidth. At the same time, complexity of the modulation format has to be kept low. In this paper we will present 25 Gbit/s transmission of Duobinary and 4-PAM modulation formats. Comparisons between the two modulation formats will be made.

Introduction

Access networks are no exception in the ever continuing increase in data rates. The latest standards for passive optical networks (PONs) that are already commercially deployed in the field are ITU-T G.987 XG-PON and IEEE 10GE-PON [1, 2]. These define the way of operating of a PON. For IEEE down- and upstream speeds are 10 Gb/s. For ITU-T downstream speeds are 10 Gb/s and the maximum upstream speed is 2.5 Gb/s. To accommodate the need for symmetric data rates, mostly coming from business users, ITU-T defined last June the XGS-PON standard, offering both up- and downstream 10 Gb/s of data rate [3]. Also ITU-T defined the NG-PON2 standard, offering a total of 40 Gb/s of aggregated data rate in both the up- and downstream direction over 4 wavelengths [4]. Using a fixed wavelength grid at the optical line terminal (OLT) in the central office (CO), and tunable transmitters and receivers in the optical network units (ONUs) at the users' home. As bandwidth aggregation is not defined in this standard the maximum data rate a single user would be able to use stays limited at 10 Gb/s.
To further increase the data rates, both IEEE and ITU-T have started defining new standards for 100 Gb/s PONs [5]. Both bodies have elected to use 4 wavelengths of 25 Gb/s each. IEEE will not use any wavelength tunable components, ITU-T will most likely build upon the NG-PON2 framework and will keep tunability in the ONU. Due to the cost-sensitive nature of access networks the bandwidth requirements of the high-speed transceivers form an issue. High-volume 25 Gb/s O-band transmitters might become available due to increased interest in datacenters, but the rise of high-volume 25 Gb/s APD-based-receivers is not foreseen before 2021 [6]. Therefore the challenge has arisen to transmit 25 Gb/s of data through the bandwidth provided by 10 Gb/s components.
Two main modulation formats can be considered a candidate to increase the data rate from 10 Gb/s to 25 Gb/s over the same analog bandwidth: duobinary (DB) and 4-level pulse amplitude modulation (PAM4) [7]. In this work we present results of both modulation formats. We focus on the lower bandwidth receiver, and do allow a larger bandwidth transmitter. A third alternative considered for standardization by IEEE to increase the data rate in the same bandwidth is the transmission of standard 25 Gb/s OOK. At the receiver heavy digital signal processing will be used to counteract the experienced intersymbol

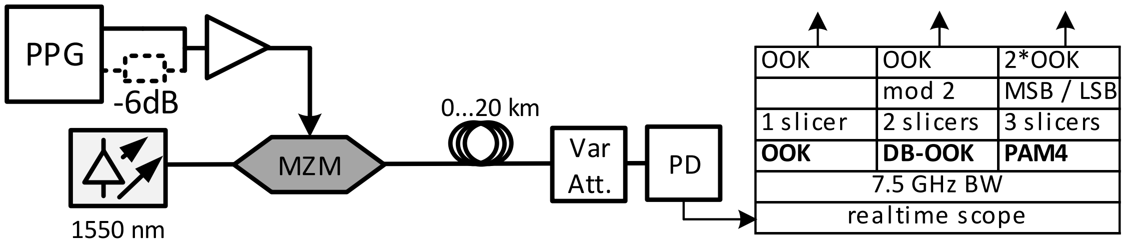

Figure 1: Experimental setup.

interference (ISI), e.g. a Maximum-Likelihood Sequence Estimation (MLSE) equalizer. This approach is not considered in this work.

PAM4 and duobinary

The PAM4 format is based on increasing the number of signal levels to increase the number of transmitted bits per symbol. The capacity increase by increasing the number of levels M scales by $\log_2 M$, whereas the required SNR for successful transmission scales by $M-1$. Therefore increasing the number of constellation levels is a case of diminishing returns, and especially the lower M factors are of interest. 25 Gb/s PAM4 over 10 Gb/s transceivers is still somewhat hindered by the bandwidth of the transceivers. First, 25 Gb/s PAM4 has a symbol rate of 12.5 GBaud, 25% higher than what the transceiver is intended for. Second, higher-order multilevel modulation formats experience a stronger eye closure penalty if the bandwidth is slightly lower than the symbol rate [8]. Nevertheless, good performance can be achieved by PAM4.
Duobinary is part of the partial response family of modulation formats [9]. The concept is based on introducing a controlled amount of correlation or ISI to the transmitted signal. In the transmitter this can be implemented by a delay-and-add filter. This produces an eye diagram with 3 levels instead of the normal 2. The resulting spectrum has a null at half the symbol rate. Thereby allowing transmission through a smaller bandwidth than would be possible with standard OOK transmission. At the receiver, as the introduced ISI is known, it can easily be removed. For PONs in particular the interesting property of duobinary is that the delay-and-add filter at the transmitter can be replaced by a low-pass filter at either the transmitter, channel, receiver, or a combination of these. This allows the 25 Gb/s transmission through only $\sim$7 GHz of bandwidth.

Experimental Setup

The experimental setup shown in Fig. 1 is used to transmit 10 Gb/s OOK, 25 Gb/s PAM4 and 25 Gb/s duobinary. In all cases a 32 Gb/s Pulse Pattern Generator is used to generate PRBS sequences in real time. OOK is the direct output of the PPG, and doesn't need any extra processing before it is used to modulate a Mach-Zehnder modulator. The PAM4 format is constructed by combination of one 6 dB attenuated and decorrelated 12.5 Gb/s OOK stream with a second 12.5 Gb/s OOK stream. As such, the PAM4 signal consists of a most significant bit (MSB) and least significant bit (LSB). Duobinary can be transmitted as standard OOK, just at a higher symbol rate. If actual (user) data would to be transmitted in duobinary format a precoding operation would have been required to prevent error-propagation. Due to the nature of a PRBS stream, this is not required for our setup.

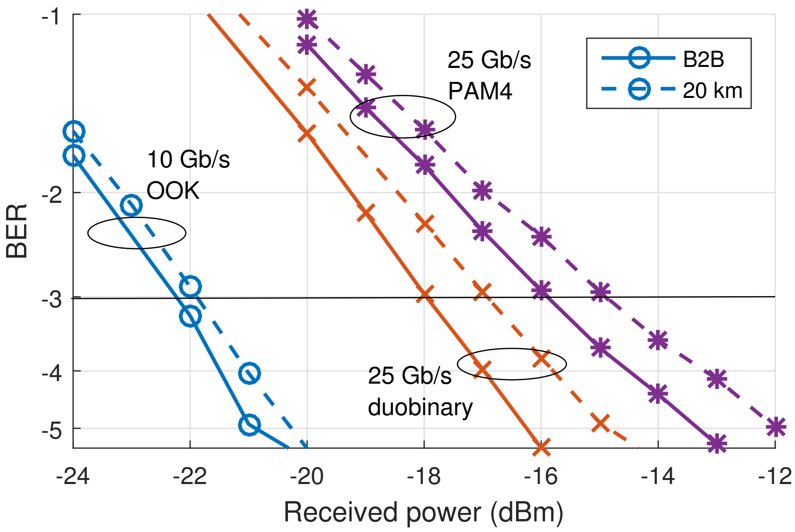

Figure 2: BER results of OOK, PAM4 and duobinary after reception by through an effective bandwidth of 7.5 GHz.

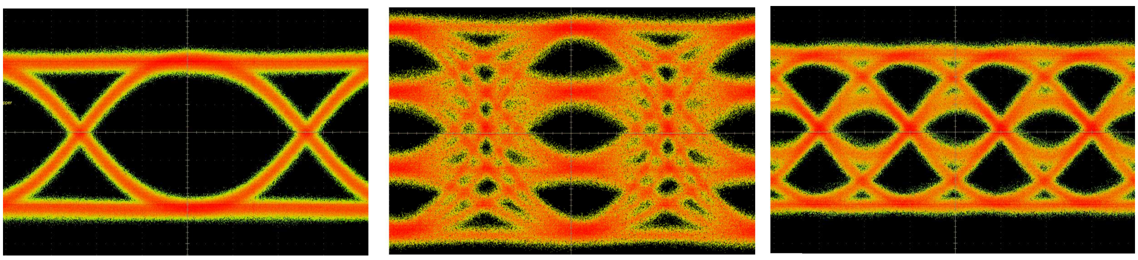

Figure 3: Eye diagrams of 10 Gb/s OOK, 25 Gb/s PAM4, and 25 Gb/s duobinary.

The receiver is based on offline processing. To keep complexity low we refrain from any complex digital signal processing, and perform just the bare minimum required to be able to decode the data. After reception by a 10 GHz PIN+TIA receiver, the data is stored by a realtime scope. In processing, all data is filtered to a -3 dB bandwidth of 7.5 GHz. After downsampling to 1 sample per symbol the processing depends on the received modulation format. In the case of OOK, demodulation is straightforward performed by a single amplitude slicer, followed by bit-error-rate (BER) analysis. PAM4 is sliced by 3 amplitude slicers. The output of the middle amplitude slicer determines the value of the MSB. The LSB is determined by performing an XOR operation on the upper and lower slicers. Hereby the original two streams that formed the PAM4 data are converted back to OOK. For duobinary, similarly, the result of two slicers is fed to an XOR to regain the original OOK stream.

Results

Fig. 2 shows the BER results for both optical back-2-back and transmission through 20 km of fiber. The crossing points with the BER = 10^{-3} limit for error-free transmission after FEC are shown in Table 1, together with the received optical power penalties relative to B2B transmission of 10 Gb/s OOK. Fig. 3 shows the received eye diagrams of 10 Gb/s OOK and 25 Gb/s PAM4 and duobinary. Please note that these eye diagrams show the sig-

Table 1: Sensitivity at the BER 10^{-3} limit and optical power penalty w.r.t. OOK B2B for various formats.

Modulation Format	Sensitivity (dBm)		Penalty (dB)	
	B2B	20km	B2B	20km
OOK	-22.2	-21.9	N/A	0.4
Duobinary	-18.0	-16.9	4.3	5.3
PAM4	-15.9	-14.9	6.3	7.3

nal as it exists after reception by the $\sim$10 GHz receiver. In the following offline processing the bandwidth is filtered down to an effective bandwidth of approximately 7.5 GHz before demodulation.

Considerations

Remarks can be made regarding both modulation formats. A benefit of PAM4 over duobinary is that it facilitates interleaving of users. In a regular PON, not a single ONU uses the entire available aggregated data rate. However, all the electronics in the transceiver have to operate at this high aggregated data rate. Due to the multiplexing capabilities of the MSB and LSB in PAM4, the data rate actually processed in the ONU only has to be half of the aggregated data rate of the network. Furthermore, the costs of PAM4 transceivers are expected to piggyback on the increasing popularity of PAM4 in, among others, data centers. Finally, PAM4 is well suited to be incorporated in a flexible modulation scheme [10]. Using PAM4 together with OOK and PAM8 inside a single network allows to optimize the utilization of this network, without the requirement for different clock rates inside this network. Benefits of duobinary are the lesser requirements on transceiver linearity. On the transmitter side, regular OOK is transmitted. At the receiver only 3 instead of 4 levels are to be received. Furthermore, as seen in the results section, the sensitivity of duobinary is slightly better than that of PAM4.

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