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Demonstration and Application of 37.5 Gb/s Duobinary-PAM3 in PONs

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Abstract: Duobinary-PAM3 enables up to 37.5Gb/s with 10G receivers. It has less linearity requirements on transmitters and gains 2dB sensitivity compared to equal-bitrate PAM8. In a 10G flexible modulation scheme, DB-PAM3 enables 190% network utilization increase.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

Higher capacity passive optical networks (PONs) continue to be a topic of interest with the upcoming standardizations of 100G PONs by IEEE and ITU-T. Various modulation formats have been proposed to increase the peak data rate of the access network. Among others electrical duobinary (DB-OOK), pulse amplitude modulation (PAM), discrete multitone (DMT), and duobinary-PAM4 (DB-PAM4) formats have been discussed [1, 2]. In PONs in particular, the power budget is important, and puts stringent requirements on the sensitivity degradation of the receiver due to the modulation format. Therefore, tradeoffs have to be made between capacity, reach, power budget, and complexity of implementation. Of the above-mentioned modulation formats, DMT requires the most complex implementation due to sophisticated signal processing. Simpler DB-PAM4 offers high capacity, but is limited in both reach and sensitivity [3, 4].

As a new adaptation to an already existing family of modulation formats, duobinary-PAM3 (DB-PAM3) can offer a good tradeoff in this respect for certain applications. Duobinary-PAM3 is based on transmission of standard PAM3 signals at a higher symbol rate. Due to low-pass filtering in the channel and at the receiver, the 3 transmitted levels are received as 5 electrical levels after the receiver frontend. At an identical symbol rate it offers 1.5 times the capacity of normal duobinary, while having better sensitivity than DB-PAM4. Furthermore, the increase in spectral efficiency enables a reduction in the symbol rate, thereby making DB-PAM3 more resilient to dispersion than standard duobinary at the same net data rate. Finally, the linearity requirements of DB-PAM3 for the transmitter are significantly reduced compared to PAM4 and other higher-order modulation formats, as only 3 levels of regular PAM3 are transmitted.

In this work we focus on modulation formats that provide higher capacity through 10 Gb/s based receivers. We do allow a larger bandwidth at the transmitter, due to the less cost-sensitive nature of the OLT side as the costs are being shared among multiple subscribers. Furthermore, the expectation is that cost-effective 25 Gb/s transmitters will be available before 25 Gb/s receivers will be. Upstream burst mode transmission is not considered in this paper. This work is made possible by Dutch Technology foundation STW through the grant 13530.

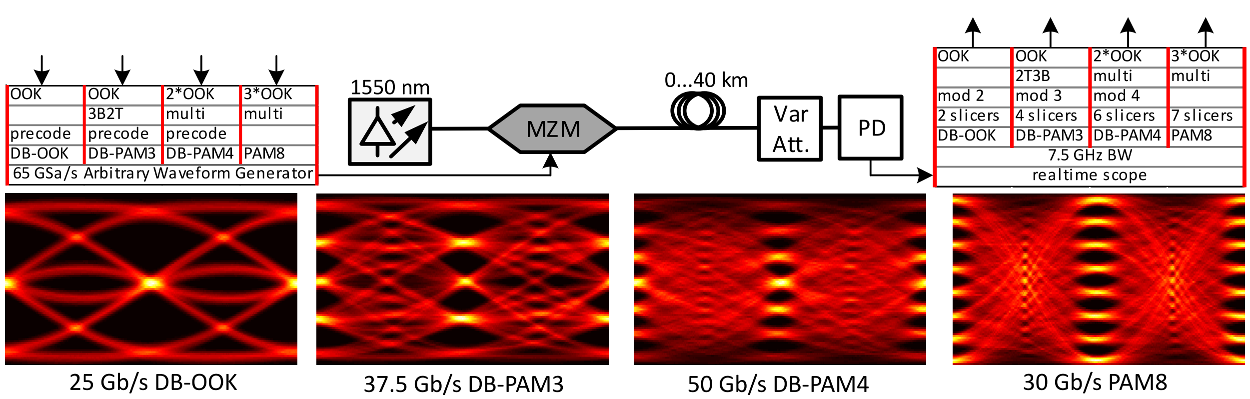

Fig. 1: Top: Experimental setup. Bottom: Eye diagrams as generated by upsampling of the filtered data after the receiver in offline processing.

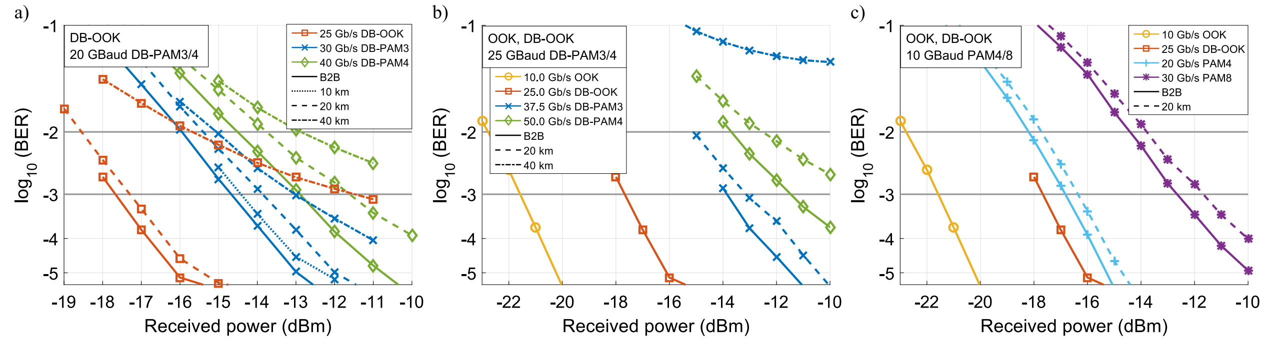

Fig. 2: BER measurements of a) 20 GBaud DB-PAM3 and DB-PAM4, b) 25 GBaud DB-PAM3 and DB-PAM4, c) 10 GBaud PAM4 and PAM8. Figures also show 10 Gb/s OOK and 25 Gb/s DB-OOK.

2. DB-PAM3

Duobinary-PAM3 is part of the partial response family of modulation formats. Similar to standard duobinary, low-pass filtering a multi-level PAM format introduces a controlled amount of intersymbol interference (ISI). This allows transmission of a higher data rate through a smaller bandwidth, and forms additional signal levels in the received signal. As the amount of ISI added is known, this can easily be removed at the receiver side. To the best of our knowledge DB-PAM3, the intermediate form between DB-OOK and DB-PAM4, has not been considered as a modulation format before. In this paper we focus on 37.5 Gb/s DB-PAM3 (25 GBaud) and 30 Gb/s DB-PAM3 (20 GBaud). Similar to 25 Gb/s duobinary, DB-PAM3 requires approximately the same analog bandwidth as 10G NRZ receivers provide. For reference purposes we also include measurements with DB-PAM4 at 50 Gb/s (25 GBaud) and 40 Gb/s (20 GBaud), and PAM8 at 30 Gb/s (10 GBaud).

3. Experimental Setup

We used the experimental setup shown in Fig. 1 for measurements of 10 Gb/s OOK, 25 Gb/s duobinary, 30 Gb/s PAM-8, 30 Gb/s and 37.5 Gb/s DB-PAM3, and finally 40 Gb/s and 50 Gb/s DB-PAM4. Data signals are generated by a 65 GSa/s arbitrary waveform generator (AWG) and drive a Mach-Zehnder modulator (MZM), thereby modulating the light from a 1550 nm CW DFB laser. The generation of the data varies by the modulation format used. For duobinary OOK, the original data is precoded to prevent error propagation. For PAM8, three binary sequences are combined to form the multilevel signal. In the case of DB-PAM3, a binary data stream is first mapped to the three-level PAM3 signal, and subsequently precoded in the same manner as normal duobinary. To keep complexity for mapping bits to the PAM3 symbols low, a simple 3B2T coding is used to convert the binary input to PAM3 symbols, resulting in an efficiency of 1.5 bit/symbol. At the expense of a longer and more complex coding, this could be increased up to the limit of 1.59 bit/symbol, which is not considered in this experiment. The 4-level signal required for transmission of DB-PAM4 is constructed by combining two binary sequences.

At the receiver side, the receiver consists of a 10 GHz PIN+TIA, subsequently low-pass filtered to a -3 dB bandwidth of 7.5 GHz during offline processing. The same bandwidth is used for all modulation formats examined. Depending on the received modulation format various steps are performed. Duobinary is taken modulo 2 to convert it back to binary data. PAM8 is sliced by 7 slicers and converted to three individual binary streams. The received 5(7) level DB-PAM3(DB-PAM4) signal is first sliced by 4(6) slicers, taken modulo 3(4), and subsequently mapped back to a binary datastream. To keep implementation complexity low, we do not perform pre- or post-equalization to compensate for the channel response, apart from the standard electrical B2B, cable only, calibration of the AWG.

4. Results

Fig. 2a shows the BER results for DB-PAM3 and DB-PAM4 at 20 GBaud, with data rates of 30 and 40 Gb/s respectively. Fig. 2b shows the results of DB-PAM3 and DB-PAM4 at 25 GBaud, corresponding data rates are 37.5 and 50 Gb/s respectively. Fig. 2c shows the BER for 20 Gb/s PAM4 and 30 Gb/s PAM8 for reference purposes. The figures show also 10 Gb/s OOK and 25 Gb/s duobinary. The measured sensitivity of 25 Gb/s duobinary at BER $= 10^{-3}$ is -17.7 dBm, showing a penalty of 3.9 dB relative to 10 Gb/s OOK. 30 Gb/s DB-PAM3 has a sensitivity of -14.7 dBm, thus a penalty of 3.0 dB relative to 25 Gb/s duobinary. 37.5 Gb/s DB-PAM3 has a penalty of 3.8 dB relative to 25 Gb/s duobinary. For comparison BER results of DB-PAM4 are also shown. At data rates of 40 and 50 Gb/s, it offers higher capacity than DB-PAM3, but increases the power penalty relative to 25 Gb/s duobinary even more up to 4.8 and 6.2 dB.

Two observations are highlighted. First, 30 Gb/s DB-PAM3 shows 2.0 dB better receiver sensitivity than PAM8 at the same data rate. 37 Gb/s DB-PAM3 even offers 7.5Gb/s higher capacity while still having 1.2 dB margin to PAM8. Second, even though we transmit with a MZM, 25 Gb/s duobinary experiences a severe dispersion penalty of 6.2 dB after 40 km of fiber at 1550 nm. Due to the lower symbol rate of DB-PAM3 at 30 Gb/s, its 40 km fiber penalty is only 1.6 dB. Even with the lower B2B base sensitivity of DB-PAM3, it outperforms normal duobinary after 40 km of fiber.

5. Applications of DB-PAM3

Among the various possible application scenarios of DB-PAM3 we highlight the following three scenarios.

First, current efforts for 100 Gb/s PONs focus on 4 wavelengths with 25 Gb/s each, therefore requiring 4 transceivers. With the use of 25 GBaud DB-PAM3, the available data rate per wavelength is 37.5 Gb/s. Thus, with the use of 3 transceivers a data rate of 112.5 Gb/s can be achieved. The additional 12.5 Gb/s can be utilized for the FEC overhead, thereby bringing the net data rate available to the users closer to 100 Gb/s. While it is unlikely that in the near-term the extended power budgets (e.g. PR30) can be met by DB-PAM3 due to the additional 3.8 dB receiver penalty relative to normal duobinary, the low and medium power budgets, PR10 and PR20, seem plausible, due to the at least 5 dB smaller channel insertion loss at these power budgets. A significant number of applications are actually in these lower power budget classes [5, 6]. Thus a smaller size PON can be served closer to a net 100 Gb/s data rate in a cost-effective manner by a 25% reduction in number of transceivers.

Second, if longer reach and receiver sensitivity is required, the symbol rate of DB-PAM3 can be reduced to 20 GBaud. Using 4 transceivers a total data rate of 120 Gb/s would be available, allowing room for a stronger FEC with 20% overhead. Depending on the particularly chosen FEC, this can raise the pre-FEC BER limit to 10^{-2}. Under these conditions the difference between duobinary and DB-PAM3 at their respective FEC limits reduces to 1.7 dB, while DB-PAM3 still offers at least 10% higher net data rate than DB-OOK.

Finally, a promising application is the use of DB-PAM3 in a flexible modulation scheme [6]. The tradeoff of DB-PAM3 in capacity and receiver sensitivity is well suited for the use inside such a scheme. Flexible modulation allocates higher-order modulation formats to those ONUs that receive enough optical power to support it, while at the same time retaining support for lower-order modulation formats for those ONUs that require it. Therefore the deployed network can be utilized more efficiently, resulting in an increase in aggregated data rate of the network and reduction in congestion probability. Using the statistics of a deployed network as previously shown in [6], the aggregated downstream data rate of a 10G based PON can be increased by 192% to 29.2 Gb/s if 10 Gb/s OOK, 25 Gb/s DB-OOK, and 37.5 Gb/s DB-PAM3 are used together. Due to the use of the flexible modulation scheme, this additional aggregated data rate comes from the more efficient use of the deployed network and would not require any sensitivity upgrade of currently deployed 10G receivers in the ONUs. It would be expected that the OLT transmitter would require a higher bandwidth than the currently deployed 10G transmitters. As shown previously [6, 7] the use of multiple modulation formats within a PON does not introduce any penalty, furthermore TDM time-slot redistribution allows nearly all users to experience an increase in network capacity.

6. Conclusions

We demonstrated up to 37.5 Gb/s duobinary-PAM3. DB-PAM3 offers an increase in capacity while reusing current 10 Gb/s based receivers. It offers an interesting mid-point between on the one hand duobinary-OOK that has a smaller receiver sensitivity degradation and on the other hand DB-PAM4 with high capacity but poorer receiver sensitivity.

Compared to the use of PAM8, DB-PAM3 is able to provide the same data rate, with 2 dB improved receiver sensitivity, and less strict linearity requirements. For a small-scale PON, a cost-attractive attribute is the possibility to provide 112.5 Gb/s data rate over only 3, instead of 4, transceivers. In a flexible modulation scheme, DB-PAM3 enables the combined use of 10 Gb/s OOK, 25 Gb/s DB-OOK, and 37.5 Gb/s DB-PAM3. This more efficient use of the deployed network can increase the downstream aggregated data rate of a 10G PON from 10 Gb/s to 29.2 Gb/s.

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