Quaternary TDM-PAM and its Implications for TDMA Equipment

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Abstract *The migration towards a 20 Gb/s quaternary TDM-PAM passive optical network with chirped and non-linear optical transmitters is experimentally studied. We show that a loss budget of 27.3 dB is compatible together with a packet power ratio of 10 dB between loud and soft ONU.*

Introduction

The success of TDM in optical access relies on two cornerstones: its simplicity and the maturity of the utilized electro-optical devices. The photonic integration of laser diodes with external modulators allows to provide a cost-effective user equipment without the need for cooling or wavelength stability. In contrary to WDM, TDM has therefore reached a high market penetration through the E/GPON standards and is currently deployed as 10 Gb/s solution through 10G-EPON and XGPON.[1] On top of this, TDM is also considered for NG-PON2 and has widely influenced recent research work, especially in reach-extended hybrid WDM/TDM PONs.[2]

Still, the high peak data rate required to deliver an in average low sustainable data rate questions the feasibility of TDM for high bit-rate PONs. A migration beyond 10 Gb/s to support business-FTTH or other bandwidth demanding services is primarily limited by the electrical bandwidth of the driving circuitry in the transmitter and the receiving subsystems. To alleviate this roadblock, a TWDM scheme has been proposed by different players in the field, using wavelength stacking and coarse WDM to provide 4×10 Gb/s per ONU.[3] However, as bandwidth continues to scale up, this technique can obviously provide just an intermediate solution which also 4-folds the optical hardware at the communication terminal. Spectrally efficient modulation formats need to be taken into consideration to effectively support a high network capacity. Though OFDM provides an elegant solution,[4] it requires heavy signal processing and is therefore not the first choice for short-term deployment. On the other hand, simpler formats such as duobinary or quaternary pulse amplitude modulation (4-PAM) can pave the way for a further upgrade of the data rate.

In this work, we present 4-PAM transmission at 20 Gb/s in a TDM-PON, exploiting a low-drive chirped transmitter. A packet power ratio of 10 dB between loud and soft packets is supported at a loss budget of 27.3 dB.

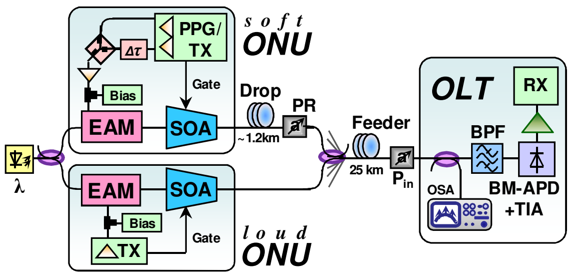

Fig. 1: High bit-rate TDM-PON featuring 20 Gb/s 4-PAM transmission with chirped transmitters.

High Bitrate TDM-PON with Low Drive 4-PAM

Transmission of 20 Gb/s quaternary TDM-PAM was experimentally validated in the PON shown in Fig. 1. Two ONUs were used to emulate a scenario where a loud and soft transmitter are present. Though this work focuses mainly on the burst-mode upstream operation, a continuous-mode downstream, typically transmitted in another waveband, can be inferred to perform not worse as long as transmitting and receiving subsystems at OLT and ONU are similar.

The seed wavelength at 1558 nm was split and modulated at each ONU by an electro-absorption modulator (EAM). A semiconductor optical amplifier (SOA) was used as optical gate to suppress light emission during the TDM off-state of the ONU, which would cause crosstalk to other ONUs. In principle this SOA can be avoided in case of having a strong enough laser diode, by simply gating the optical light source itself. An electrical 4-PAM signal was generated to drive the EAM at the soft ONU, for which several reported BER measurements have been performed. The electrical 4-PAM signal of the soft ONU was generated by two PRBS 2^{11}-1 signals and an electrical power combiner. A delay was added in one path in order to de-correlate the two PRBS streams. A preamble of alternating mark and space bits was added before the payload data. The loud ONU is transmitting a 10 GHz clock signal rather than data due to lack of a second electrical 4-PAM

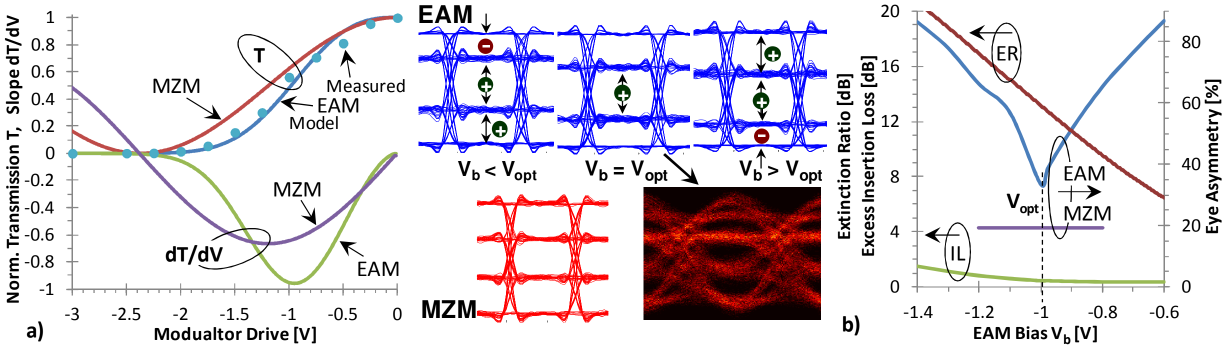

Fig. 2: (a) Non-linear EAM transfer function and (b) caused distortion and excess loss for the transmitted 4-PAM.

generator. The gating signal of the SOAs was chosen to have a guard time of 50 ns between the rising edge of the gate and the preamble of the data packet. The upstream packets were then launched with 3 dBm from the ONUs.

The optical distribution network contains a short standard single-mode drop fiber span, which is also used to coarsely interleave the packets from the different ONUs according to the chosen TDM frame. A longer 25 km feeder fiber connects the power splitter, emulated by a 50/50 coupler, to the OLT. Two attenuators have been added to the PON, determining the packet power ratio (PR) between the two ONUs (i.e. loud/soft ratio) and the loss budget of the PON.

The OLT receiver contains an optical band-pass filter to suppress amplified spontaneous emission of the ONUs and a burst-mode receiver that is based on an avalanche photo diode (APD) with trans-impedance amplifier.[5] Due to the lack of electrical equipment the received electrical 4-PAM data was then stored with a 50GS/s real-time scope for the purpose of symbol-by-symbol signal decoding with a multi-level slicer. No post-distortion or additional post-processing technique was applied to the received signal. A practical solution can be a combination of limiting and differential amplifier in order to subsequently extract the most and least significant tributary of the quaternary PAM.

Multi-level intensity modulation requires an optical transmitter response that is linear for a wide range of its input. This can be a problem especially for EAMs, since the transmission function of such modulators is highly non-linear in their low and high bias regime. The typical transfer function of an EAM follows the applied electrical drive *V* according to

$$T_{eam}(V) = (1-\varepsilon_{\min})\exp\left[-\left(\frac{V}{V_a}\right)^{\alpha}\right] + \varepsilon_{min}$$

where $\varepsilon_{\min}$ is the minimum extinction and V_a and α are fitting parameters.[6] Figure 2(a) shows the measured and modeled (V_a = -1.12V, α = 2.7) transmission *T* of the utilized EAM and a Mach-Zehnder modulator (MZM), whose V_π is adjusted to have the same modulation index per electrical drive as the typically more efficient EAM.[7] The transmission has been normalized to the intrinsic modulator loss. As can be seen, the EAM has a constant slope dT/dV only for intermediate bias values. Compared to a MZM the linearity of the EAM is clearly worse and leads to signal distortions when large-signal loss modulation is applied, as it is evidenced from the analytical 4-PAM eye diagrams at the transmitter output. The modulation extinction ratio (ER) and eye asymmetry resulting from a driving signal with limited swing is presented in Fig. 2(b) as function of the EAM bias. The asymmetry for 4-PAM is here defined as the difference between the smallest and largest eye opening with respect to the height of the largest eye opening. In principle, a high ER requires operation with a highly negative bias in order to provide good light extinction. This, however, causes an excess insertion loss (IL) due to the interplay of limited swing and finite modulation efficiency, resulting in extra losses since the maximum of the EAM transfer function cannot be reached. On top, a high or a low bias raises issues regarding the asymmetry due to large-signal operation in an area of the transfer function that does not have a constant slope (Fig. 2(a)). An optimum area of operation can be found around the moderate bias V_{opt}, for which the asymmetry has a minimum that is given by the stretched middle eye. Though this minimum for the EAM is still worse compared to a MZM, it is a good trade-off having also a high ER >12 dB and still relatively low excess IL of ~1 dB.

It is therefore required to pre-distort the electrical 4-PAM signal in order to compensate for the non-linear transfer function. On the other hand, since this will lead to increased sensitivity to noise and impairments in the driving circuitry, signal pre-distortion can be used only up to a certain degree. Note that operation solely in the linear regime of the EAM with a reduced modulation swing leads to a strongly reduced modulation extinction ratio and, consequently, to

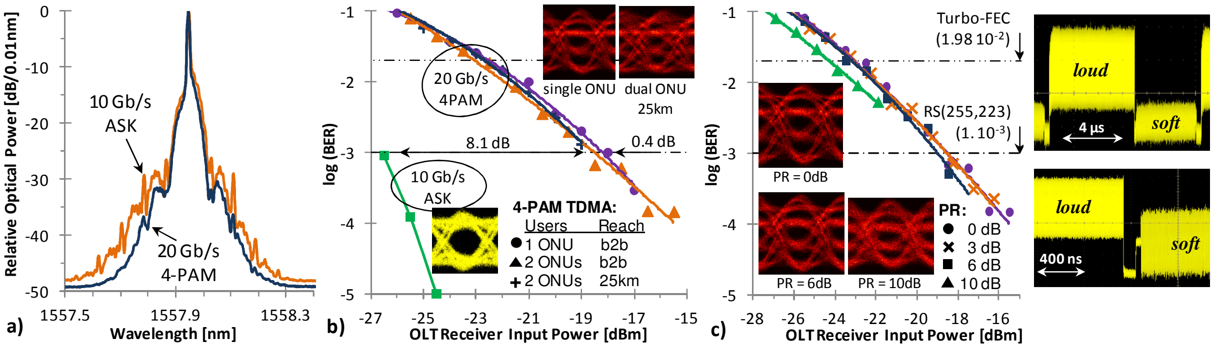

Fig. 3: (a) Signal spectra for ASK and 4-PAM upstream, (b) comparison between 10 Gb/s ASK and 20 Gb/s 4-PAM transmission, and (c) BER for 4-PAM at different packet power ratios between loud and soft packets.

a large reception penalty.

The electrical driving signal of the EAM used in the experiment was pre-distorted by 67% in order to account for the non-linear transmitter circuitry, which also includes a RF amplifier that is not optimized in its linearity. The driving voltage of 1.4 V_{pp} leads to an extinction ratio of 13.2 dB and underlines the advantage of an EAM as more energy efficient modulator than a MZM, providing at the same time a smaller form-factor and the possibility for photonic integration. The transmitted 4-PAM is shown in Fig. 2. The lower eye was left slightly increased in order to make the 4-PAM robust against bandwidth limitations and chromatic dispersion.[8]

Results and Discussion

The performance of the 20 Gb/s TDM 4-PAM was evaluated in terms of compatible loss budget and PR, and compared with 10 Gb/s ASK transmission. Burst-mode was applied according to a 10 µs long TDM frame with a loud and a soft data packet and a 100 ns guard time between them. The soft packet was 4 µs long.

The ASK and 4-PAM spectra are presented in Fig. 3(a) and normalized to the peak spectral component. Evidence is provided that the data rate of 20 Gb/s can be supported without spectral widening of the upstream and therefore without incurring penalties due to dispersive media in the transmission path, as it would be the case when the line rate is simply doubled.

The BER measurements for a configuration with a single ONU and two ONUs with equal packet power are presented in Fig. 3(b). With respect to 10 Gb/s ASK transmission, the 20 Gb/s TDM 4-PAM experiences a power penalty of 8.1 dB, which is primarily explained with the reduced eye openings in case of a four-level signal, which would cause a penalty of 5-8 dB depending on the exact spacing between the levels and their optimization towards dispersion tolerance or signal-spontaneous beat noise.[8] The remaining penalty is explained by the residual asymmetry in the eye and imperfection in the electrical driving circuitry deriving mainly from reflections at the RF power combiner. When adding a second ONU and 25 km of distribution fiber in the feeder section in order to provide realistic PON conditions, there is a penalty of just 0.4 dB while the BER became more sensitive to the decision point sampling. The compatible loss budget, defined as the difference between upstream launch and reception sensitivity, is 21.2 dB at the Reed-Solomon RS(255, 223) FEC threshold.

The BER for the weak packets in case of different PRs between loud and soft ONU is presented in Fig. 3(c). There is no penalty for a PR up to 6 dB with respect to packets with equal power. In case of 10 dB power difference, there was a limitation in the power budget, however, the BER did not worsen. In case that a stronger turbo-FEC is used,[9] a loss budget of 27.3 dB is compatible and fits to a scenario with a 1:64 split in the tree. This confirms that 4-PAM is a good candidate for high bit-rate TDM PONs with high dynamic range and high user share.

Conclusions

A 20 Gb/s quaternary TDM-PAM access network has been demonstrated as upgrade path for legacy PONs. A loss budget of 27.3 dB can be supported in combination with a high loud-soft power ratio of 10 dB. Chirped, non-linear transmitters are also compatible.

Acknowledgements

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