Multi-Level High Speed Burst-Mode Receivers

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Abstract: We review recent burst-mode receiver technologies beyond 10Gbps for broadband access and fast optical-switching networks, focusing on multi-level modulations. The Performance of newly developed 25Gbps 3-level burst-mode receiver using low-cost 10Gbps APDs is also presented.

Keywords: burst-mode receiver, pulse amplitude modulation, 3-level duobinary, passive optical networks, optical packet switching.

I. INTRODUCTION

The Internet has become the ubiquitous tool that is transforming the lives of all of us. New broadband applications in the field of entertainment, commerce, and social interactions demand increasingly higher data rate. In order to support such bandwidth growth in optical access networks, both ITU-T and IEEE standard bodies, during past years, endorsed their efforts in developing various passive optical networks (PON) standards up to 10 Gbps line rate. In parallel, upstream 10 Gbps burst-mode receivers (BM-RX), the most critical PMD components of PON systems, have been experimentally demonstrated and reviewed in [1]. Meanwhile, the rapid growth of the Internet traffic is boosting the requirement of higher capacity data center networks (DCN). In such networks, optical packet switch (OPS) with nanosecond time-scale operation could be a preferred solution to efficiently realize the flat DCN. Besides a necessity in broadband TDM-PON access networks, the BM-RX is also considered as a key enabling technology for fast packet-based optical switching systems [2].

Recently, a number of researches have been working on higher serial rate TDM-PONs beyond 10 Gbps [3][4][7]. Based on those efforts, the investigation of a practical low-cost solution for high serial rate PONs is gaining a lot of interest in IEEE NG-EPON initiative. IEEE NG-EPON is currently focusing its efforts on 25-Gbps single-wavelength and 50-Gbps two-wavelength pair solutions [5]. This is in line well with the recent rapid shift in datacenter from 10-Gbps technologies and processes to 25 Gbps, including both VCSEL and single-mode optics. However, increasing burst-mode line rate beyond 10Gbps remains very challenging, due to limitations in the cost, availability and performance of optical components. For instance, while APDs have been used extensively in 10G-class PONs to improve the receiver sensitivity, high-speed 25Gbps APD devices are still not widely available as low-cost 10Gbps APDs. Therefore, multi-level modulation needs to be taken into consideration as a new dimension to effectively support a high network capacity without increasing usable bandwidth of those critical components. In this paper, we review the most applicable multi-level modulation schemes for burst-mode operation, including 3-level duobinary modulation and pulse amplitude modulation (PAM).

II. MULTI-LEVEL BURST-MODE MODULATION

So far, only non-return to zero (NRZ) on-off keying (OOK) has been specified in the ITU and IEEE PON standards. As the NRZ is a simple form of pulse amplitude modulation, i.e. PAM-2, a natural upgrade path is to use 4 or 8 levels in the amplitude. However increasing number of amplitude levels will reduce the eye height accordingly, resulting in a worse signal to noise ratio (SNR). Therefore, PAM-4 appears to be a ready candidate of multi-level burst-mode modulation [6]. Recently, increasing line rate with 3-level duobinary has received a lot of attention [3][4]. Duobinary data encoding is a form of partial response signaling, which allows reducing bandwidth with a mount of intentionally-controlled inter-symbol interferences (ISI). Different from optical duobinary (ODB), the 3-level BM detection de-stresses optical components requirement and therefore lower the cost of the burst-mode transceivers [7].

Fig. 1 illustrates the difference in eye diagrams for NRZ, PAM-4, and 3-level duobinary. Since PAM-4 transmits 2 bits per symbol, the unit interval (UI) of PAM-4 is twice that of NRZ, which significantly relaxing the required minimum transmission bandwidth. For instance, as shown in Fig. 1(a) and 1(b), when normalized receiver bandwidth (with respect to data rates) is less than 0.5, the eye height of the NRZ signal significantly drops while little impact is shown in the PAM-4 case. On the other hand, PAM-4 eyes have 16 different transitions against NRZ with 4 transitions. The skewed transitions result in extra horizontal eye closure and cause PAM-4 more vulnerable to offset and ISI. The simulated eye width versus different receiver bandwidth is also shown in Fig. 1, indicating smaller horizontal eye open in UI for PAM-4 modulation. The 3rd option, duobinary modulation, has a better SNR than PAM-4 because of larger vertical eye opening. Unlike PAM-4, duobinary has no skewed crossing edges that makes its BM clock-and-data recovery (BM-CDR) synchronization faster and more reliable. The duobinary encoder can usually be implemented in two different approaches, either a low-pass filter (LPF) with ½ data rate bandwidth [7] or using a digital delay-and-add filter. In Fig. 1(c) the duobinary signal is generated with a delay-and-add filter in the transmitter. In this case, both
vertical eye height and horizontal eye width decrease gently with receiver bandwidth, showing a nice compromise between NRZ and PAM-4.

III. PAM-4 BURST-MODE EXPERIMENTS

In [6] we presented burst-mode PAM-4 transmission at 20 Gb/s in a TDM-PON, exploiting a low-drive chirped EAM transmitter and a 10Gbit/s linear BM-RX. The received upstream 4-PAM data was stored with a 50 GS/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. Since the transmission function of the EAM transmitter is highly non-linear (Fig. 2(a)), biasing in its low and high bias regime will result in asymmetric eyes in large-signal operation. In order to compensate for the non-linear transfer function of the EAM, the electrical PAM-4 signal is pre-distorted 67% by means of simply varying the amplitude ratio of the constituent binary PRBS signals before the electrical power combiner.

The BER measurements for a configuration with a single ONU and two ONUs with equal packet power are presented in Fig. 2(b). With respect to 10 Gb/s NRZ transmission, the 20 Gb/s TDM 4-PAM experiences a power penalty of 8.1 dB. The excessive penalty is primarily explained by the eye closure caused by the ringing/ISI in the transmitter eyes. For the worst TDM scenario, there is no penalty for a loud/soft ratio up to 6 dB compared with equal-power packets. In case of 10 dB power difference there was a limitation in the power budget; however, the BER did not worsen. In another experiment, the BM-RX is used with MZM based burst-mode transmitters (BM-TXs). As can be seen in Fig. 2(a), compared to EAM the linearity of the MZM is clearly better and leads to improved transmitted signal quality without pre-distortion. The burst-mode PAM-4 experiments with MZM at ≥20 Gb/s are currently being performed with a further optimized linear BM-RX and will be discussed during the presentation.

IV. 3-LEVEL DUOBINARY BURST-MODE EXPERIMENT

A newly developed 3-level APD BM-RX [7] was evaluated using the 25Gb/s experimental set-up as shown in Fig. 3. Two 1.3 µm BM-TXs named TX #1 and TX #2, are alternately sending burst packets. At the OLT, the linear BM APD-TIA was integrated with the 3-level decoder IC. After 3-level duobinary decoding, one of the 4 de-multiplexed outputs at 6.25 Gb/s was fed into a BER analyzer for real-time BER measurement. A gated semiconductor optical amplifier (SOA) was used to increase the optical output power of the TX #2 to +5dBm, in order to generate a sufficiently large loud/soft ratio for this experiment.
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V. Conclusions

We have compared and demonstrated experimentally 20-25 Gb/s PAM-4 and 3-level duobinary in burst-mode transmissions. It is shown that the BM-RX employing simpler multi-level modulation schemes can pave the way for a further upgrade of next-generation broadband access and fast optical-switching networks.

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