Increasing Flexibility and Capacity in Real PON Deployments by Using 2/4/8-PAM Formats

Robbert van der Linden\textsuperscript{1,2}, Nguyen-Cac Tran\textsuperscript{2}, Eduward Tangdiongga\textsuperscript{1}, Ton Koonen\textsuperscript{1}

\textsuperscript{(1)} COBRA Research Institute, Eindhoven University of Technology, the Netherlands, 
\textsuperscript{(2)} Genexis B.V., Eindhoven, the Netherlands 
\texttt{r.v.d.linden@tue.nl}

Abstract: Current PONs use OOK throughout the network regardless of actual path losses. Flexible 4/8-PAM for better-situated ONUs can significantly increase the aggregated data rate, without expensive optics investment. 8-PAM is made feasible with zero-overhead data-aided equalization.

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1. Introduction

Current passive optical networks (PONs) use a single modulation format throughout the network, while industry sees the need for more flexibility in the network [1]. In parts of the network, where conditions are better (e.g. lower losses) a more comprehensive modulation format may be used, yielding a higher data throughput while keeping the symbol rate uniform across the whole PON. Therefore, we propose a flexible modulation scheme, where in parts of the PON on-off keying (OOK) modulation is used, but in the better parts a more comprehensive pulse amplitude modulation (PAM) is used, more specifically 4- and 8-level PAM. This enables the network operator access to various benefits. First, doubling, or tripling, the data rate for the better-positioned PAM ONUs, while maintaining the data rate for the OOK ONUs and thus reducing the congestion probability. This increases the net capacity of the PON as a whole.

The use of 4-PAM has been suggested for the recently started NG-EPON standardization in IEEE 802.3 [2]. This work focuses on using 4-PAM to increase network capacity given the standard power budget, but the use of flexible modulation can be extended towards a network with 4-PAM as base modulation. Retaining OOK support, or including 8-PAM support, for a 4-PAM PON would allow more flexibility in the network design phase in which splitting ratio, reach, and aggregated capacity can be traded off against each other in order to maximize the systems performance.

Previously we have examined the potential of flexible allocation of 4-PAM in PONs [3], here we will extend upon this work by introducing 8-PAM, time-interleaved with 2- and 4-PAM, which is made possible by zero-overhead data-aided equalization. We will demonstrate for existing networks an 83\% increase in aggregated data rate with 4-PAM without equalization, and a 108\% increase with 8-PAM, although with the use of equalization. This work is made possible by INEA for the GPON statistics and by Dutch Technology foundation STW through the grant 13530.

2. Network Statistics

Fig. 1 shows statistics from a dataset of approximately 20,000 ONUs from the GPON deployments of INEA, Poland. As observed, the network utilizes the 15 dB of allowed differential optical path loss within each class of optics [4].

Fig. 1: Statistics of a dataset of the GPON deployments of INEA. (a) ONU received optical power for varying position of the ONU w.r.t. the OLT (b) Histogram of ONU received optical power. Vertical lines show the measured sensitivities for OOK (red, solid), 4-PAM w/o equalization (yellow, dashed), and 8-PAM w/ equalization (green, dot dash)
Only a small portion of the ONUs is close to the prevalent received power sensitivity limit of -27 dBm (class B+ optics) for this network. More than 83% of ONUs in the network have a received optical power surplus of at least 5 dB. In this paper, the induced downstream power penalty of 4/8-PAM compared to OOK is experimentally verified for a PON with standard speeds of 10 Gbps. Upstream, i.e., burst mode, reception is left for a future study. This network addresses the need for higher data rates and differs from the GPON network. The optical losses are equivalent to a GPON network, keeping the above network statistics valid.

3. Pulse Amplitude Modulation

Multi-level PAM is deemed an economically attractive method to increase the data throughput in a PON, while keeping the symbol rate the same, without significantly increasing the cost price of the ONU and OLT. The optics, i.e., BOSA (bi-directional optical sub assembly), account for more than one third of a single-family-unit ONU’s cost-price, and utilizing it to its full extent brings significant benefits. On the other hand, using PAM will likely not add significant cost to the PON ASIC (application-specific integrated circuit). Using PAM does introduce optical power penalties, therefore the use of 16-PAM and higher formats is not deemed feasible for an economically attractive PON, given the maximally allowed 15 dB of differential received optical power. The power penalty, expressed in dB, of $M$-PAM relative to OOK at the same symbol rate is $P_p = 10 \log_{10}(M - 1)$. This formula is only valid under the assumption of additive white Gaussian noise and does not take into account additional penalties, e.g. noise on the electrical driving signal, relative intensity noise (RIN), timing jitter, and chromatic dispersion [5]. For 4/8/16-PAM, the theoretical penalty comes down to 4.8, 8.5, and 11.8 dB, respectively. PAM is more sensitive to intersymbol interference (ISI) than OOK. This penalty becomes more pronounced at higher orders of PAM. As it is common to have a bandwidth slightly lower than the symbol rate, this hinders higher levels of PAM. For example at a symbol rate to bandwidth ratio of 1.5, OOK, 4-PAM and 8-PAM have an ISI penalty of 0.6 dB, 1.2 dB, and 2.9 dB, respectively due to vertical eye closure [6].

4. Data-aided Equalization with Zero-Overhead

The increased penalty due to ISI in a higher order PAM system can be largely mitigated by the use of an adaptive equalizer in the receiver. The weights of adaptive equalizers can be updated by either a data-aided algorithm or a blind algorithm. Data-aided algorithms require a known training sequence to be added to the data, thereby introducing overhead. Blind equalization does not require prior knowledge of a training sequence at the receiver side, however it is not guaranteed to converge to a correct solution.

Taking advantage of the structure of a flexible PON where multiple modulation formats coexist, we propose to replace the training sequence in a data-aided equalizer with already existing decoded data of lower order modulation formats. In a power splitter based PON network all the ONUs receive all the downstream traffic. Given the relative optical power sensitivities between 2/4/8-PAM, an ONU that is capable of receiving 8-PAM after equalization will receive OOK and 4-PAM virtually error-free before equalization. Therefore the decoded stream of OOK and 4-PAM packets can function as a training sequence for the equalizer, allowing for correct convergence without the need of training overhead.

5. Experimental Setup

The experimental setup is depicted in Fig. 2. A 7.5 GHz, 10 GSa/s Arbitrary Waveform Generator (AWG) is used to generate the driving signals for a Mach-Zehnder modulator (MZM). This MZM is used to modulate light from a
6. Results

Fig. 3 depicts the BER measurements, measured B2B and through 20 km fiber, both in a time-interleaved transmission and with a single modulation format. The influence of time-interleaving and propagation through 20 km fiber is found to be negligible in these measurements. At the $10^{-3}$ BER FEC (forward error correction) limit, the measured optical power penalty of 4-PAM and 8-PAM without equalization relative to OOK are 5.1 dB and 11.4 dB, respectively. With zero-overhead data-aided equalization the penalties become 4.7 dB and 9.0 dB, for 4-PAM and 8-PAM respectively.

Cross-referencing these penalties with the statistics in Fig. 1, it is seen that by using flexible OOK and 4-PAM modulation without equalization, the aggregated bandwidth can increase with up to 83%. Using flexible OOK, 4-PAM, and 8-PAM together with zero-overhead data-aided equalization increases the aggregated bandwidth with up to 108%.

7. Conclusions

We proposed to use flexible modulation in PONs, to exploit unused power budget. Allocating more comprehensive, but cost-effective, modulation formats to ONUs in better positions allows to increase the aggregated bandwidth of the PON. Keeping to IM-DD modulation and constant symbol rate refrains from the need to invest in expensive optics. Especially the use of 4-PAM, without mandatory equalization, is considered to be a cost-effective solution to increase the flexibility and capacity of real PON deployments. Introducing 8-PAM increases the capacity even more, although this comes with the cost of equalization. Flexible allocation of 4-PAM can increase the capacity of this network with up to 83% to 18.3 Gbps. To eliminate the increased penalty due to ISI, we proposed and demonstrated the use of a data-aided equalizer without the need of training overhead in downstream power splitter based PONs. With this equalizer, the combined use of 4/8-PAM can increase the aggregated capacity of this network with up to 108% to 20.8 Gbps.

8. References