Demonstration of Upstream Flexible 2-/4-PAM Formats for Practical PON Deployments

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Abstract *Adaptive 2-/4-PAM modulation in PONs leverages the distribution of optical path losses to increase capacity. Upstream 2-/4-PAM burst transmission is demonstrated with a selectable fixed 4-tap FIR-filter, improving the performance of each gain mode of the burst-mode receiver.*

Introduction

Recently, increasing the data rate of passive optical networks (PONs) above 10 Gbps has received a lot of attention. A main consideration is the use of low-cost optical and electrical components, with a limited bandwidth[1]. Low complexity higher order modulation formats provide more effective use of the available bandwidth. Even further improvement in the utilization of deployed components can be reached by considering the distribution of received optical powers in PONs. Current PONs use a single, static, modulation format throughout the network. By contrast, conditions within the PON are not uniform. In parts of the network, where conditions are better (e.g. lower losses) a higher order modulation format may be used, yielding a higher data throughput while keeping the symbol rate uniform across the entire PON. Therefore, we opt to use a flexible modulation scheme, where in parts of the PON on-off keying (OOK),a.k.a. 2-PAM modulation is used, but in the better parts a more comprehensive 4-level pulse amplitude modulation (4-PAM) is used. This offers the network operator a choice in flexibility. First, doubling the data rate for the better-positioned PAM ONUs, while maintaining a lower data rate for the OOK ONUs. Second, for a given OLT port, the available time slots can be redistributed by allocating more time slots to OOK-only ONUs, thereby increasing the experienced data rate for all the ONUs of a certain OLT port. Last, the use of 4-PAM could be pre-planned for ONUs serving hotspots, as a mechanism to fight congestion of the network.

Previously, we have examined the potential of flexible allocation of 4-PAM in PONs in the downstream direction[2], and 4-/8-PAM in the downstream direction, aided by zero-overhead data-aided equalization[3]. Here, we will extend upon this work by demonstrating upstream, burst-mode, flexible allocation of 4-PAM and OOK. We will demonstrate an increase of up to 75% for the aggregated data rate in the upstream direction.

Fig. 1 shows statistics from a data set of approximately 20,000 ONUs from the field-deployments of INEA, Poland. These statistics originate from the 2.5 Gbps GPON deployment, operating at 1490 nm. Only a small portion of the ONUs approaches the standardized class B+ received power sensitivity limit of -27 dBm for this network. More than 70% of ONUs in the network have a received optical power surplus of at least 6 dB. In this work we target 10 Gbps based PON systems, as the distribution of optical path losses of the outside plant remains the same regardless of data rate, above statistics remain valid.

Burst-mode Transmission

Burst-mode transmission is facilitated by a 10 Gbps burst-mode receiver (BM-RX)[4,5]. The receiver consists of an APD with a bandwidth of ∼7 GHz and a 10 Gbps linear BM-RX IC. The linear BM-RX IC consists of a transimpedance amplifier (TIA) stage, a variable gain amplifier (VGA),

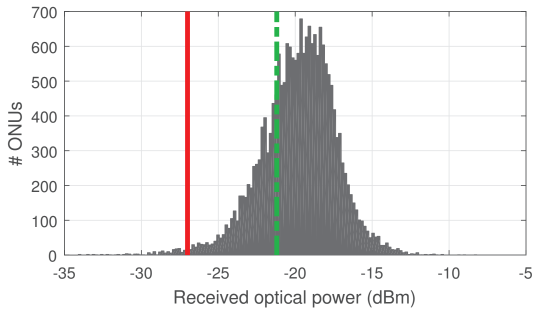

Fig. 1: Histogram of ONU received optical power position, operated by INEA-PL. The solid red vertical line depicts the OOK sensitivity limit for OOK, the dashed green line for 4-PAM

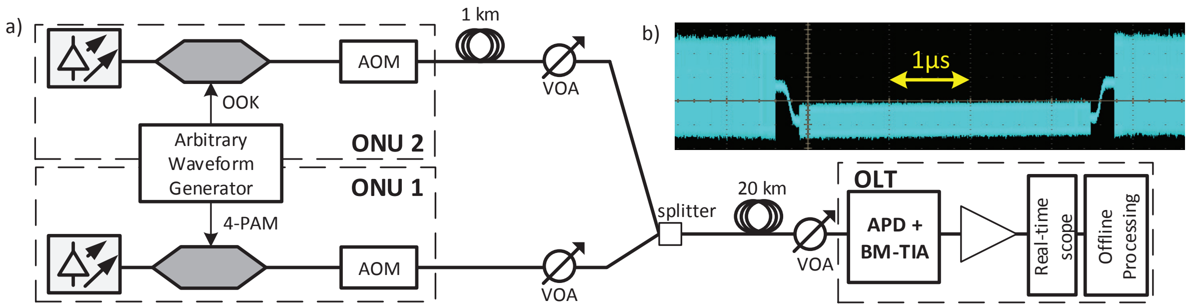

Fig. 2: a) Experimental setup. b)Transmitted bursts

and a linear output buffer. In the beginning of each burst the Automatic Gain Control (AGC) sets the TIA and VGA gain level according to the incoming power level. After this initial adaptation, the gain is locked to prevent further fluctuations during reception of the burst. The linear BM-RX was designed for a high linearity (no internal hard decisions) for the whole operating range. In addition, a coarse DC-offset compensation block sets the balanced signal to keep the amplifier circuit working near the middle of the linear range. The simulated total harmonic distortion (THD) was always below 10% for the whole testing operation range.

Compared to OOK, 4-PAM transmission is more susceptible to linearity impairments and requires a slightly larger bandwidth of the transmitter and receiver for optimal operation. In post-processing of the data we implement a symbol spaced 4-tap FIR filter after the receiver. The weights of the taps are pre-computed and are non-adaptive. This fixed FIR filter is used for all received powers and particularly improves the performance for higher received powers. The bandwidth of the receiver is slightly different for each gain mode of the BM-RX. Therefore, alternatively a different set of fixed filter weights can be selected depending on each gain mode of the receiver. For a particular gain level, the same weights are used for all measurements in this work. Due to the non-adaptive nature of both filters, real-time integration is deemed readily possible. In the second case, selection of the FIR weights is envisioned together with the AGC algorithm in the BM-RX to be readily implemented through a look up table and programmable gain amplifiers.

Experimental Setup

Fig. 2 depicts the experimental burst-mode setup. A 7.5 GHz, 10 GSa/s Arbitrary Waveform Generator (AWG) drives two Mach-Zehnder modulators, each fed by a laser source. The outgoing light is alternately gated by two Acousto-Optic Modulators (AOMs), controlled by the AWG to emulate TDMA transmission. After optional transmission through 20 km fiber, the signal is received by the burst-mode receiver and captured by a real-time oscilloscope. Each burst consists of a payload of 3.3μs, and starts with a preamble of 100 ns. Between two bursts a gap of 300 ns is inserted, to facilitate the switching of the AOMs. After reception, the data is further processed offline with the earlier mentioned single or selectable FIR filter. The BER of the payload is assessed with constant decision thresholds. To compensate for the AC-coupled amplifier between the TIA and real-time oscilloscope, a varying DC level is employed in decoding.

Results

Fig. 3 depicts the burst-mode BER measurements for alternating consecutive bursts of OOK and 4-PAM with equal magnitude for both B2B transmission, and transmission over 20 km of fiber. The weights of the selectable fixed FIR filter are selected depending on the gain mode of the receiver. The weights are the same within a gain region for both B2B and 20 km transmission. The weights of the single fixed FIR filter are the same for all measurement in this work. At the BER 10^{-3} FEC (forward error correction) limit, 4-PAM with a selectable fixed FIR filter, compared to OOK, has an optical power penalty of 5.8 dB. For OOK no fiber penalty is observed, whereas 4-PAM with selectable FIR filter has a 0.4 dB fiber penalty over 20 km. Comparing 4-PAM with a single fixed FIR filter to 4-PAM with a selected fixed FIR filter, it is seen that the selectable FIR filter outperforms the single filter, at BER 10^{-3} the difference is 1.3-1.6 dB, and this becomes larger for higher received powers. Between -15 dBm and -12 dBm

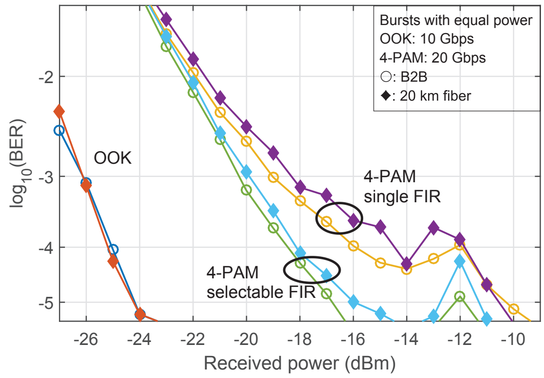

Fig. 3: BER measurements of alternating OOK and 4-PAM packets with equal power, B2B vs 20 km fiber.

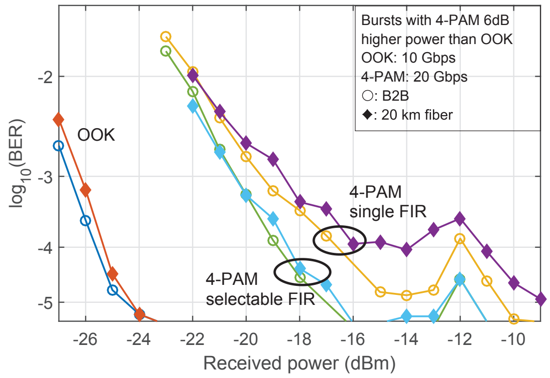

Fig. 4: BER measurements of alternating OOK and 4-PAM packets with 6dB power ratio, B2B vs 20 km fiber.

a temporary BER floor is observed, attributed to a sub-optimized DC threshold which causes saturation in the BM-RX. For even higher input powers the BM-RX becomes linear again, as it switches to a lower gain. BER measurements for consecutive bursts with 6 dB optical power difference are shown in Fig. 4. The soft packets consist of OOK modulation, while the loud packets contain 4-PAM modulate data. Compared to reception of equal bursts no large differences are observed. OOK B2B even slightly outperforms the case of equal burst amplitudes.

Overall, the difference in required optical received power at the FEC limit ranges between 5.8 and 6.7 dB. Comparing these results with the statistics of the GPON deployment in Fig. 1, it is seen that in the upstream direction between 61% and 75% of the ONUs support 4-PAM.

A comparison with aggregated data rates for 2-/4-PAM and 2-/4-/8-PAM with equalization in the downstream direction is made in Tab. 1.

Conclusions

The use of flexible 2-/4-PAM modulation in PONs exploits the unused power budget of a particular ONU. Allocating more comprehensive, but cost-effective, modulation formats with constant symbol rate to ONUs in better positions allows to increase the aggregated data rate of the PON.

Tab. 1: Overview of attainable capacity increase for up- and downstream transmission

	4-PAM[2]	4/8-PAM[3]	4-PAM
Direction	Down	Down	Up
Remarks	-	Equalization	Fixed FIR
Penalty (dB)	5.4	4.7 / 9.0	5.8 - 6.7
Percentage of users (%)	79	86 / 22	up to 75
Aggregated data rate (Gbps)	17.9	20.8	up to 17.5

IM-DD modulation in the same bandwidth as traditional OOK transmission requires no need to invest in expensive optics. The large dynamic range of upstream reception, together with 4-PAM, puts extra constraints on the linearity and bandwidth of the receiver. Implementing a selectable, but fixed value FIR filter in the receiver, successfully mitigates these extra constraints. Flexible 2-/4-PAM modulation is feasible both in the up- and the downstream direction of the PON. In the upstream direction up to 75% of the network is able to support 4-PAM, increasing the aggregated data rate with 75% to 17.5 Gbps.

Acknowledgements

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References

[1] D. van Veen et al., “High Speed TDM-PON Beyond 10G,” in Proc. OFC, Tu3C.3, Anaheim (2016)

[2] R. van der Linden et al., “Utilizing Unused Power Budget to Increase Network Capacity in Practical PON Deployments by Introducing Flexible Modulation,” in Proc. ECOC, P.7.12, Valencia (2015)

[3] R. van der Linden et al., “Increasing Flexibility and Capacity in Real PON Deployments by Using 2/4/8-PAM Formats,” in Proc. OFC, Tu3C.4, Anaheim (2016)

[4] X. Yin et al., “A 10Gb/s APD-based linear burst-mode receiver with 31dB dynamic range for reach-extended PON systems,” Optics Express, Vol. 20, no. 26, p. B462-B469 (2012)

[5] J. Verbrugghe et al., “Quaternary TDM-PAM as upgrade path of access PON beyond 10Gb/s,” Optics Express., Vol. 20, no. 26, p. B15-B20 (2012)