Increasing flexibility and capacity in real PON deployments by using 2/4/8-PAM formats

DOI:
10.1364/JOCN.9.0000A1

Document status and date:
Published: 01/01/2017

Document Version:
Accepted manuscript including changes made at the peer-review stage

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

Robbert van der Linden, Nguyen-Cac Tran, Eduward Tangdiongga, and Ton Koonen.

***Abstract*—Current PONs use OOK modulation throughout the entire network regardless of actual path losses. Statistics of commercial GPON deployments show significant path loss differences amongst the ONUs. Flexible 4/8-PAM allocation for the better-situated ONUs can significantly increase the PON's aggregated data rate. By keeping to IM/DD modulation and constant symbol rate, the introduction of adaptive, multilevel PAM does not require expensive optics investments. 8-PAM is made feasible with zero-overhead data-aided equalization.**

Two scenarios for distributing the extra capacity are explored. First, controlling the dynamic bandwidth allocation of the TDM-PON to provide equal time-length slots to both 4/8-PAM ONUs and OOK ONUs, thereby providing maximum aggregated capacity increase. Second, setting up the dynamic bandwidth allocation to provide equal capacity slots to the various ONUs, thereby the entire ONU population in the same PON can benefit from the extra capacity. Both scenarios result in a larger aggregated capacity of the PON, and provide additional options for the network operator during the network design phase.

***Index Terms*—pulse amplitude modulation; flexible modulation; passive optical networks; network optimization**

I. INTRODUCTION

CURRENT passive optical networks (PONs) use a single static modulation format throughout the network. The most common standardized PONs deploy a time division multiplexed (TDM) architecture with aggregated data rates up to 10 Gbps with on-off keying (OOK) modulation. At the same time the industry sees the need for more flexibility in the network [1]. Operating conditions within a PON are not uniform. 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 OOK modulation is used, but in the better parts a more comprehensive pulse amplitude modulation (PAM) is used, in particular 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-capable optical network units (ONUs), while maintaining the data rate for those ONUs that only support OOK. Thus providing the ability to deliver premium services to select (business) users, requiring a higher data rate than the rest of the network. Second, keeping the same data rate for PAM-capable ONUs, but using shorter time slots, thereby allowing longer time slots for the OOK ONUs and thus reducing the congestion probability.

Link adaptation has seen widespread use in wireless communication, and is specified in various standards. Due to the dynamically varying conditions of the channel, adapting modulation and coding to this channel state provides increased capacity in the wireless network [2, 3]. In meshed optical metro and long-haul networks the use of software-defined transceivers and link adaption can provide significant gain in network capacity compared to the use of a single modulation format and code rate [4, 5]. Work on adaptive modulation in PONs has been done to improve the energy efficiency of intensity modulation direct detection (IM-DD) orthogonal frequency division multiplexing (OFDM) PONs for a constant data rate [6]. In [7] adaptive modulation in PONs based on coherent transceivers using polarization multiplexed QAM signals is examined.

In the continuing search for higher data rates the PON standardization bodies FSAN/ITU-T opted for the stacked use of multiple wavelengths, in addition to time domain multiplexing (TWDM), while keeping the line rate per wavelength equal at 10 Gbps [8]. At first, 4 wavelengths will be used, raising the aggregated data rate to 40 Gbps. To further increase the capacity, FSAN/ITU-T might opt for increasing the line rate of current XG(S)-PON and NG-PON2 systems to 25 Gbps [9]. The recently started IEEE 100G-EPON Task Force envisions to increase the line rate to 25 Gbps, while at the same time using multiple wavelengths, to achieve a maximum data rate of 25, 50, or 100 Gbps, albeit on a fixed wavelength scheme, i.e., without the use of any tunable optical components [10]. Amongst the promising options to increase the data rate from 10 Gbps to 25 Gbps in a cost-effective manner is the use of more comprehensive modulation formats, as these allow to reuse current 10 Gbps optics. Especially duobinary modulation and 4-level PAM have received significant attention [11–14].

In this work we focus on adaptive modulation to increase the aggregated data rate in IM-DD PONs with the use of standard hard-decision forward error correction (HD-FEC) [15]. Statistics from a commercially deployed PON are used to examine the impact of the adaptive modulation on its overall performance w.r.t. the aggregated capacity.

The selection of the modulation format for a particular ONU is envisioned to be adaptively and automatically made by the network management, hence changes should be made in the management layer. The decision on modulation format can be

Manuscript received June 15, 2016; revised August 3, 2016

R. van der Linden (e-mail: r.v.d.linden@tue.nl) is with the COBRA Research Institute, Eindhoven University of Technology, Eindhoven, the Netherlands and with Genexis B.V., Eindhoven, the Netherlands

N. C. Tran is with Genexis B.V., Eindhoven, the Netherlands

E. Tangdiongga and A.M.J Koonen are with the COBRA Research Institute, Eindhoven University of Technology, Eindhoven, the Netherlands

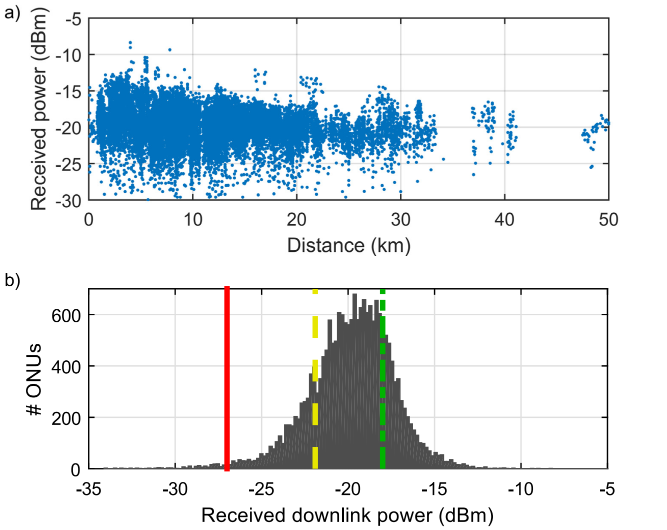

Fig. 1. Statistics of a dataset of the GPON deployments of INEA. (a) ONU received optical power for varying position of the ONU w.r.t. the OLT (b) Histogram of ONU received optical power. Vertical lines show the measured sensitivities for OOK (red, solid), 4-PAM w/o equalization (yellow, dashed), and 8-PAM w/ equalization (green, dot dash)

based on the received optical power, as already reported by the ONU and optical line terminal (OLT). Optionally the quality of this decision can be enhanced by the estimated bit error rate (BER) as provided by the FEC in the receiver. Adaptive selection of the modulation format over time is desired to counteract any changes in the network, e.g., any component aging.

Previously we have examined the potential of flexible allocation of 4-PAM in PONs [16], in this paper we extend this work by introducing downstream 8-PAM, time-interleaved with 2- and 4-PAM, which is made possible by zero-overhead data-aided equalization [17]. We demonstrate for currently deployed 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. Here we focus on downstream transmission only. Upstream, burst mode transmission has been addressed in [18].

Furthermore we will explore the interaction between flexible modulation and the distribution of time slots inside a single PON. A distinctive feature of PONs is that multiple ONUs are connected to the same OLT port. Due to the dynamic bandwidth allocation (DBA) protocol in power splitter based TDM-PONs, the OLT has control over the length of a time slot that is assigned to a certain ONU. Allocating longer time slots to those ONUs that only support OOK, will increase the equal distribution of available capacity amongst the different users, thus increasing fairness.

II. Network Statistics

The standardization of the different PONs allows for 15 dB of differential optical path loss within each class of optics [19–21]. This does not make any statement on the actual differential received optical powers encountered in the field. Figure 1 shows statistics from a dataset of approximately 20,000 ONUs from the GPON deployments of INEA, Poland. 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: only 1.6% of the ONUs is within 1 dB of this limit. More than 83% of the 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 a normal speed of 10 Gbps, being a standard line rate in PONs. The optical losses are equivalent to those in a GPON network, keeping the above network statistics valid.

III. 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). Compared to OOK modulation, multilevel PAM formats require transceivers with better linearity. The electronic components should be non-clipping, i.e., without limiting amplifiers. Given the current interest in 4-PAM and adoption in standards, more cost-effective solutions are foreseen to arise here [22,23]. 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.

According to theory, the power penalty, expressed in dB, of M-PAM relative to OOK at the same symbol rate due to the vertical eye closure 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 [24]. For 4/8/16-PAM, the theoretical penalty is 4.8, 8.5, and 11.8 dB, respectively. Multilevel PAM is more sensitive to intersymbol interference (ISI) than OOK, due to the smaller eye opening. 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 [25].

The combined use of multilevel PAM and OOK keeps the symbol rate, and thus the clock frequency of the signal, constant for each modulation format. Furthermore, as each format is transmitted by the same transmitter, no frequency or phase jumps are to be expected between the various modulation formats. Therefore, clock recovery is possible at the same frequency. This is in contrast to a multi-rate system. Depending on the particular implementation of the clock recovery, the recovery might be more complex due to the difficulty in detecting the distinct signal levels.

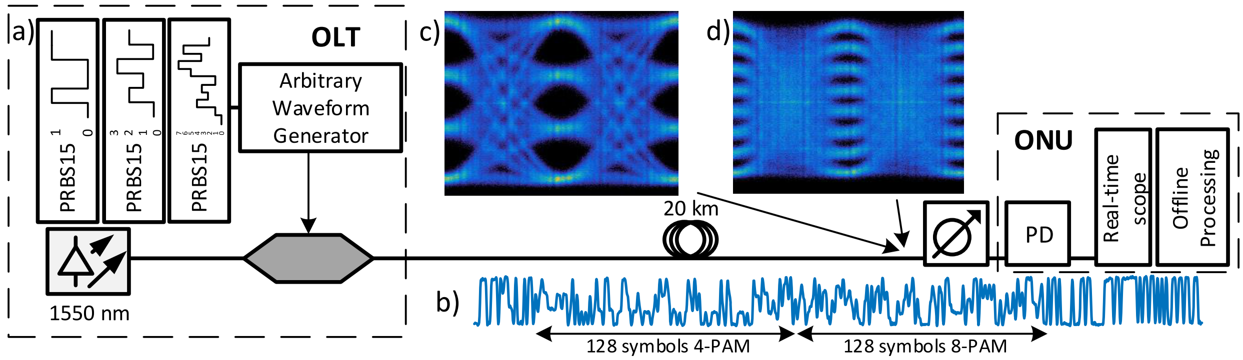

Fig. 2. a) Experimental setup b) received trace of time-interleaved OOK, 4-PAM and 8-PAM. c) eye diagram of 4-PAM after 20 km d) eye diagram of 8-PAM after 20 km.

IV. 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 or a blind algorithm [26]. 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 available decoded data of lower-order modulation formats. In a power splitter based PON all the ONUs receive all the downstream traffic. Given the relative received optical power sensitivities of 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 additional training overhead. Depending on the specific loss distribution in the PON, not all modulation formats might be actively used. However, OOK is always used in the header of the different packets, thereby guaranteeing availability of OOK signals to train the equalizer.

V. Experimental Setup

Experiments have been done in the downstream direction. 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 consisting of pseudorandom binary sequence of length 2^{15} (PRBS15). For the case of 4/8-PAM, two/three PRBS streams are decorrelated and combined together to generate a 4/8 level output. The constructed signals drive a Mach-Zehnder modulator (MZM). This MZM is used to intensity-modulate light from a 1550 nm CW DFB laser. The modulated signal is optionally sent through 20 km of standard single-mode fiber to be received by a 10 GHz PIN photodiode with an integrated transimpedance amplifier, after which the signal is captured by a real-time oscilloscope and stored for further offline processing. Downstream BER measurements have been conducted separately for OOK, 4-PAM, and 8-PAM transmission. Additionally, to examine any penalty of TDM transmission, OOK, 4-PAM, and 8-PAM packets are interleaved and transmitted with a period of 128 symbols. For time-interleaved transmission with equalization, the zero-overhead equalizer is used. For transmission of a single modulation format with equalization, a traditional training sequence based equalizer is used. In both cases, the equalizer used is a least mean squares, feed-forward equalizer (LMS-FFE).

VI. Results

Figure 3 depicts the BER measurements for B2B and 20 km fiber, both in a time-interleaved transmission and with a single modulation format. For 4-PAM transmission without equalization over 20 km fiber, the difference in received optical power for the BER 10^{-3} FEC limit between a single modulation format and time-interleaved transmission of multiple modulation formats is $<$ 0.1 dB. For 8-PAM the same comparison leads to a difference of $<$ 0.2 dB. Time-interleaved transmission of 4-PAM without equalization over 20 km of fiber compared to back-to-back transmission shows a difference of $<$ 0.1 dB. 8-PAM with equalization over 20 km compared to B2B shows a difference of 0.1 dB for the same comparison. Therefore, the influence of time-interleaving and propagation through 20 km fiber is found to be negligible in these measurements. At the 10^{-3} BER, the measured optical power penalties 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.

In the cases where in the above-mentioned measurements an equalizer is used, this consists of a least mean squares feed-forward equalizer with 15 symbol spaced taps. Figure 4 shows how the number of symbol-spaced taps of the zero-overhead data-aided equalizer influences the difference in required received optical power for a BER of 10^{-3} for 4-PAM and 8-PAM relative to B2B transmission of OOK. Although the required received optical power keeps decreasing, even beyond the 30 investigated taps, the gain is marginal after the first few taps. The additional penalty for using only a 3 tap FFE compared to the chosen 15 tap FFE is less than 0.1 dB for 4-PAM and 0.5 dB for 8-PAM.

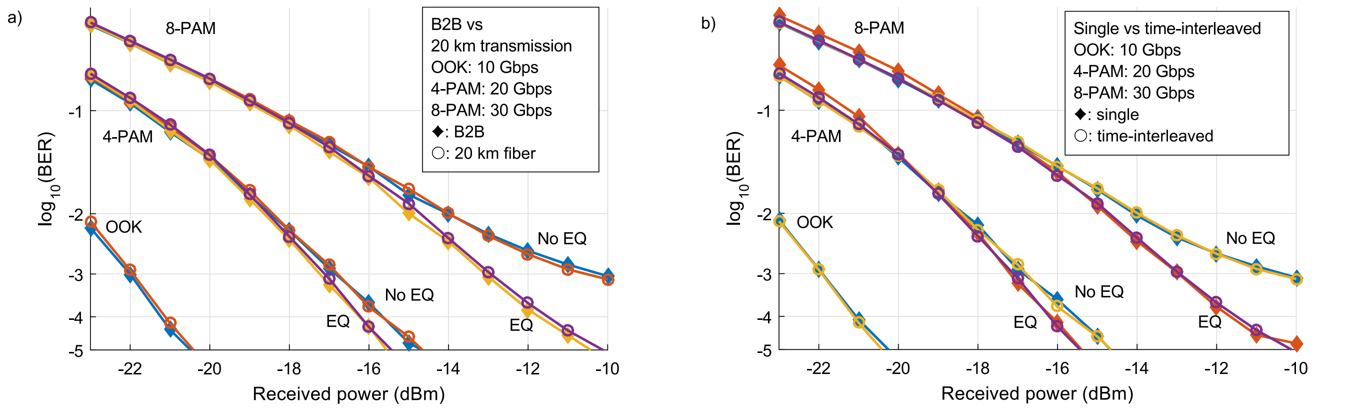

Fig. 3. BER measurements. a) B2B transmission vs. transmission through 20 km of fiber. Transmission consists of time-interleaved packets of 128 symbols. b) 20 km transmission of a single modulation format vs. time-interleaved transmission with a packet length of 128 symbols. The use of equalization is denoted by EQ.

VII. Network Capacity

In this section we explore the attainable increases in capacity due to the introduction of flexible 4- and 8-PAM in the network as discussed in section II, and subsequently the distribution of this capacity amongst the users. The percentage of attainable capacity increase can be derived from Fig. 5. This figure shows the range of ONU received powers per OLT port. The median and second-most to second-least optical received power range for ONUs at a certain OLT port are shown, thereby filtering out singular outliers. Additionally, the number of ONUs at a certain OLT port is shown. The median of the received optical powers by the ONUs is above the 4-PAM sensitivity limit without equalization (further denoted as w/o EQ) for more than 91% of the OLT ports. For 8-PAM with equalization (w/ EQ) this is the case for 25% of the OLT ports. Furthermore, for 98% of the OLT ports at least one ONU supports 4-PAM, allowing for some, albeit small, capacity increase. The sensitivity for 4-PAM as depicted in Fig. 5 is the GPON OOK sensitivity of -27 dBm plus the measured 4-PAM penalty without equalization of 5.1 dB. For 8-PAM this is the GPON OOK sensitivity plus the measured 8-PAM penalty with equalization of 9.0 dB. We use the relative optical power penalty of 4/8-PAM to OOK transmission, and not the absolute received optical powers in order to make a fair comparison between the experimental setup and the GPON deployed network in Fig. 1 and Fig. 5.

The distribution of the extra achievable data rate amongst the different users on the network is considered in two scenarios. It would be up to the network operator to decide on the use of these schemes. The first straightforward implementation is to allocate 4/8-PAM to all ONUs that support this based on their received optical power. Assuming an equal traffic load of all the ONUs, each ONU is allocated an equal portion of the available time, i.e., a 4-PAM or 8-PAM capable ONU can transmit two or three times the number of bits in their time slot. This leads to the maximum increase in aggregated data rate for the entire network.

In this scenario the total aggregated data rate of the PON is given by

$$R_{tot} = D \cdot \frac{1}{N} \sum_{i=1}^{N} m_i \,, \tag{1}$$

where D is the symbol rate, N the number of ONUs, and m_i the bits per symbol for each individual ONU. Using the previously obtained penalties of 5.1 dB for 4-PAM (w/o EQ), and 4.7 dB and 9.0 dB for 4- and 8-PAM (w/ EQ) respectively, and cross-referencing these penalties with the statistics in Fig. 1b and Fig. 5, it is seen that by using flexible OOK and 4-PAM modulation (w/o EQ), the aggregated data rate can increase with up to 83%. Using flexible OOK, 4-PAM, and 8-PAM (w/ EQ) increases the aggregated data rate with up to 108%.

Second, it is possible to redistribute the available data rate amongst the different users on a single OLT port. A distinctive feature of PONs is that multiple ONUs are connected to the same OLT port. Due to the dynamic bandwidth allocation protocol in TDM-PONs, the OLT has control over the length of time slots that are allocated to certain ONUs. Fairness amongst users in a flexible modulation based PON is increased by allocating the same capacity to each ONU located at a single OLT port, and thus allocating shorter time slots to those ONUs that support 4-PAM or 8-PAM. This increased fairness does come at the cost of a smaller increase in network throughput compared to the scenario where no redistribution of TDM time slots is applied. As OOK ONUs are allocated longer time slots, a larger portion of the time is spent transmitting at a slower data rate. In this second scenario the total aggregated data rate of the PON can be represented as

$$R_{tot} = D \cdot \frac{N}{\sum_{i=1}^{N} \frac{1}{m_i}} \,. \tag{2}$$

Comparing the statistics from Fig. 5 with the power penalty induced by the use of 4/8-PAM, and taking the varying number of users per OLT port into account, the aggregated data rate as experienced by each user can be obtained. Figure 6a shows a histogram of the resulting data rates for the use of

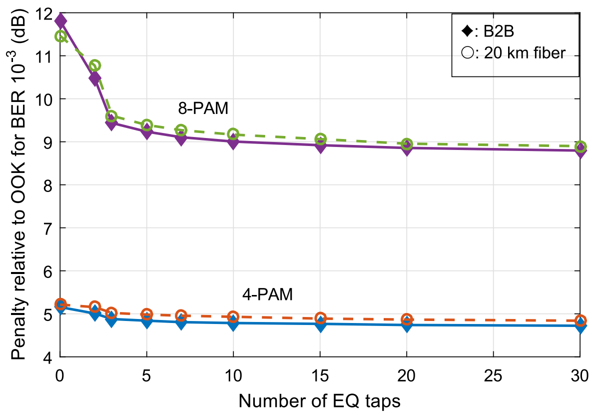

Fig. 4. Penalty in received optical power required for 4-PAM and 8-PAM compared to OOK for BER 10^{-3} as a function of the number of symbol spaced taps for the zero-overhead data-aided equalizer.

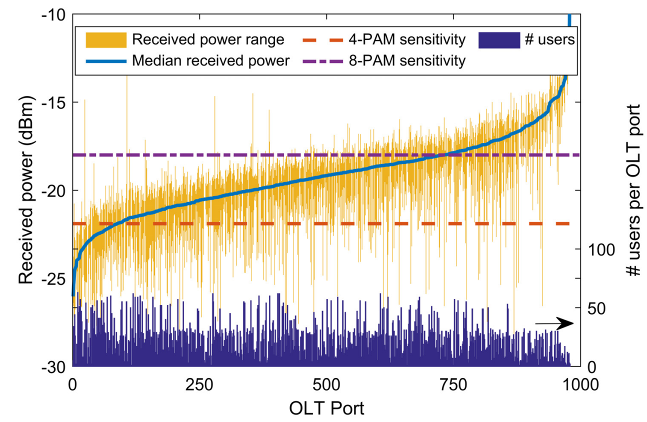

Fig. 5. Statistics of a dataset of 20,000 ONUs of the GPON deployments of INEA on a per OLT port basis, showing: The power range, consisting of the second-most to second-least of ONU optical received power per OLT port; the median received optical power; the number of ONUs per OLT port; the required optical received power for BER 10^{-3} for 4- and 8-PAM

flexible OOK and 4-PAM (w/o EQ). Figure 6b shows the resulting data rates for flexible use of OOK, 4-PAM and 8-PAM modulation (w/ EQ). Both figures depict the scenario with TDM redistribution.

In order to summarize the aggregated data rates seen by the entire network, and to compare the two previously described scenarios, a cumulative sum of the aggregated data rates is shown in Fig. 7. Figure 7a depicts this for flexible allocation of OOK and 4-PAM without equalization. It shows which percentage of users experiences a certain aggregated data rate or higher. For the non-TDM redistributed scenario it shows the binary situation of the network, attainable data rates are either 10 or 20 Gbps. 83% experiences a doubling of the data rate to 20 Gbps (denoted in Fig. 7a as point A), while the other 17% sees a data rate of 10 Gbps. The resulting average data rate is 18.3 Gbps (denoted in Fig. 7a as the dashed blue line), or an increase of 83%. For a TDM redistributed flexible network, 26% of the ONUs sees an aggregated data rate of 20 Gbps (denoted as point B). 50% of the network sees an aggregated data rate of 18.6 Gbps or higher (C), and 90% sees an aggregated data rate of 13 Gbps or higher (D). The average data rate is 17.6 Gbps in this case.

Figure 7b shows the attainable data rates for flexible OOK, 4-PAM, and 8-PAM with equalization. In the non-TDM redistributed scenario, 22% experiences 30 Gbps (point E in Fig. 7b), 64% experiences a 20 Gbps data rate (point F), and the remaining 14% a 10 Gbps data rate. Resulting in an average data rate of 20.8 Gbps (denoted in Fig. 7b as the dashed blue line), or an increase of 108%. In the TDM redistributed scenario, 2% of the ONUs experiences 30 Gbps (G), 45% experiences 20 Gbps or higher. 50% of the networks sees an aggregated data rate of 19.5 Gbps or higher (H), and 90% sees an aggregated data rate of 14.1 Gbps or higher (point I). The resulting average data rate is 19.8 Gbps. Emphasizing that with TDM redistribution the number of users that see an increased data rate grows, albeit with a lower increase compared to if no TDM redistribution is employed.

VIII. Conclusions

We proposed the use of flexible modulation in PONs, to maximally exploit the available power budget. Allocating more comprehensive, but cost-effective, modulation formats to ONUs in better, i.e., lower-loss, locations allows to increase the aggregated data rate 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.

Network operators can choose to employ the available extra capacity in various ways. In this paper we examined two options. First, allocating to those ONUs that support multilevel modulation the same amount of time in a TDM frame as their OOK-only counterparts. Second, allocating the same capacity to all ONUs, and redistributing the amount of unallocated time from multilevel supported ONUs to those that only support OOK.

In the first case 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.

The second case redistributes the length of time slots to those ONUs that only support lower orders of modulation, therefore making sure that every ONU connected to a single OLT port gets the same increased data rate. In this scenario flexible allocation of 4-PAM can increase the data rate for practically every user in the network with a certain amount, and the total capacity of the network increases with 76%. Using additional 8-PAM modulation with equalization the total capacity of the network increases with 98% to 19.8 Gbps.

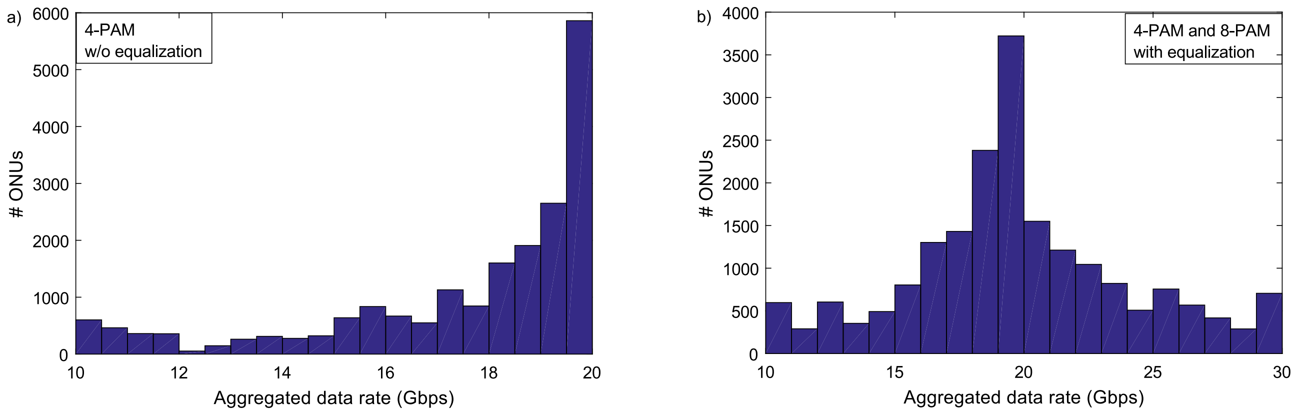

Fig. 6. Histogram of maximum data rate as observed by the ONUs when TDM redistribution is enabled in the case of a) 4-PAM without equalization, and b) combined use of 4-PAM and 8-PAM with equalization.

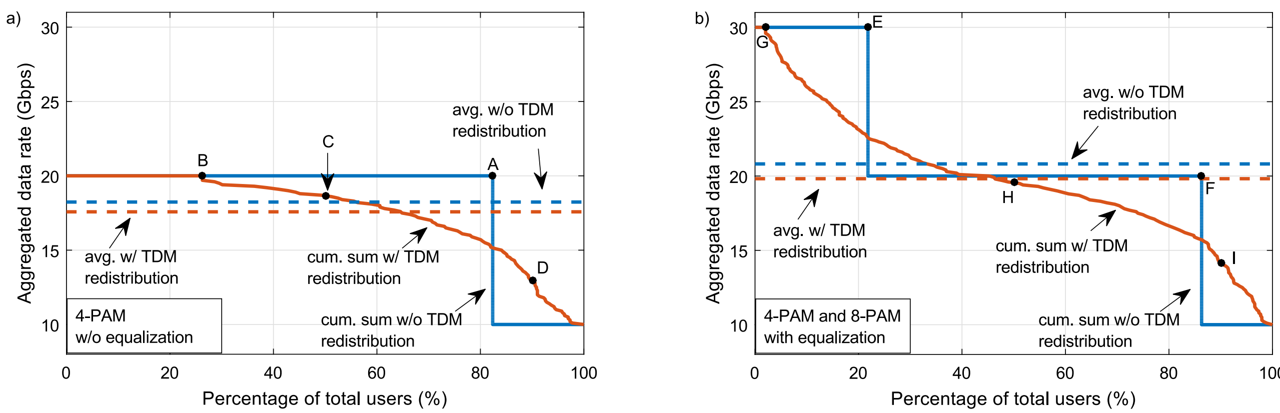

Fig. 7. Cumulative sum of the aggregated data rates. Shown is the percentage of users that experiences the aggregated data rate on the y-axis or higher for a network without TDM time slot length redistribution, where a distinct number of data rates is possible, and with TDM time slot length redistribution, where the differences between experienced speeds are smoothed out for a) 4-PAM without equalization, and b) combined use of 4-PAM and 8-PAM with equalization.

Implementation of flexible modulation in a commercial system would require the collaboration and agreement of multiple vendors. A group of vendors would need to agree on the protocol to be used, thereby strictly adhering to backward compatibility. That is, modules with flexible modulation should still be able to operate in a system with non-supporting modules, although obviously at lower data rates. Optionally, flexible modulation could also be included in an upcoming standard.

This work focused on using 4/8-PAM to increase network capacity given the standard power budget. Given the current research interests in using modulation formats other than OOK in PONs, it is important to note that the use of flexible modulation can be extended towards a network with 4-PAM as basic 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 system's performance. Opting for a higher performance ONU or OLT transceiver would not only increase system margins, but would increase the aggregated data rate supported by the network, as more ONUs will be able to support 4/8-PAM. That is, if an operator faces bandwidth shortage on a PON port, he has the option to replace class B+ optics with class C+ optics, providing a larger power budget, and thereby, with flexible modulation, increasing the data rate on this port.

Acknowledgment

This work is made possible by INEA for the GPON statistics and by Dutch Technology foundation STW through the grant 13530 Flexible Broadband Communication.

References

[1] F. Effenberger, L. Huafeng, and P. Guikai, "Beyond NG-PON2 A more flexible future," *Communicate*, no. 71, pp. 7–9, 2013.

[2] D. Qiao, S. Choi, and K. G. Shin, "Goodput analysis and link adaptation for IEEE 802.11a wireless LANs," *IEEE Trans. Mob. Comput.*, vol. 1, pp. 278–292, Oct. 2002.

[3] G. Ku and J. M. Walsh, "Resource Allocation and Link Adaptation in LTE and LTE Advanced: A Tutorial," *IEEE Commun. Surv. Tutor.*, vol. 17, no. 3, pp. 1605–1633, third quarter 2015.

[4] M. Filer, J. Gaudette, M. Ghobadi, R. Mahajan, T. Issenhuth, B. Klinkers, and J. Cox, "Elastic Optical Networking in the Microsoft Cloud," *J. Opt. Commun. Netw.*, vol. 8, p. A45, July 2016.

[5] A. Alvarado, D. J. Ives, S. J. Savory, and P. Bayvel, “On the Impact of Optimal Modulation and FEC Overhead on Future Optical Networks,” *J. Light. Technol.*, vol. 34, pp. 2339–2352, May 2016.
[6] H. Kimura, K. Asaka, H. Nakamura, S. Kimura, and N. Yoshimoto, “First demonstration of energy efficient IM-DD OFDM-PON using dynamic SNR management and adaptive modulation,” in *Proc. European Conference on Optical Communication (ECOC)*, Paper We.4.F.5, 2013.
[7] F. Vacondio, O. Bertran-Pardo, Y. Pointurier, J. Fickers, A. Ghazisaeidi, G. de Valicourt, J. C. Antona, P. Chanclou, and S. Bigo, “Flexible TDMA access optical networks enabled by burst-mode software defined coherent transponders,” in *Proc. European Conference on Optical Communication (ECOC)*, Paper We.1.F.2, 2013.
[8] ITU-T, “G.989.1 40-Gigabit-capable passive optical networks (NG-PON2): General requirements,” 2013.
[9] D. Nesset, “PON Roadmap,” in *Proc. Optical Fiber Communication Conference (OFC)*, Paper W4C.1, OSA, 2016.
[10] C. Knittle, “IEEE 100G-EPON,” in *Proc. Optical Fiber Communication Conference (OFC)*, Paper Th1I.6, OSA, 2016.
[11] H. Zhang, S. Fu, J. Man, W. Chen, X. Song, and L. Zeng, “30km downstream transmission using 4 x 25Gb/s 4-PAM modulation with commercial 10Gbps TOSA and ROSA for 100Gb/s-PON,” in *Proc. Optical Fiber Communications Conference and Exhibition (OFC)*, Paper M2I.3, 2014.
[12] X. Yin, J. Verbist, T. De Keulenaer, B. Moeneclaey, J. Verbrugghe, X. Z. Qiu, and J. Bauwelinck, “25Gb/s 3-level Burst-Mode Receiver for High Serial Rate TDM-PONs,” in *Proc. Optical Fiber Communication Conference (OFC)*, Paper Th4H.2, OSA, 2015.
[13] V. Houtsma, D. van Veen, and H. Chow, “Demonstration of Symmetrical 25 Gb/s TDM-PON With Multilevel Interleaving of Users,” *J. Light. Technol.*, vol. 34, pp. 2005–2010, Apr. 2016.
[14] D. T. van Veen and V. E. Houtsma, “Symmetrical 25-Gb/s TDM-PON With 31.5-dB Optical Power Budget Using Only Off-the-Shelf 10-Gb/s Optical Components,” *J. Light. Technol.*, vol. 34, pp. 1636–1642, Apr. 2016.
[15] ITU-T, “G.987.3 10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification,” 2014.
[16] R. van der Linden, N. C. Tran, E. Tangdiongga, and A. M. J. Koonen, “Utilizing unused power budget to increase network capacity in practical PON deployments by introducing flexible modulation,” in *Proc. European Conference on Optical Communication (ECOC)*, Paper P.7.12, 2015.
[17] R. van der Linden, N. C. Tran, E. Tangdiongga, and T. Koonen, “Increasing Flexibility and Capacity in Real PON Deployments by Using 2/4/8-PAM Formats,” in *Proc. Optical Fiber Communication Conference (OFC)*, Paper Tu3C.4, OSA, 2016.
[18] R. van der Linden, X. Yin, N. C. Tran, E. Tangdiongga, J. Bauwelinck, and A. M. J. Koonen, “Demonstration of Upstream Flexible 2-/4-PAM Formats for Practical PON Deployments,” in *Proc. European Conference on Optical Communication (ECOC)*, 2016. To be published.
[19] ITU-T, “G.984.2 Gigabit-capable Passive Optical Networks (G-PON): Physical Media Dependent (PMD) layer specification,” 2003.
[20] ITU-T, “G.987.2 10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification,” 2010.
[21] ITU-T, “G.989.2 40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification,” 2014.
[22] IEEE Std, “802.3bj-2014 100 Gb/s Backplane and Copper Cable.,” 2014.
[23] IEEE P802.3bs 400 Gb/s Ethernet Task Force. In progress.
[24] K. Szczerba, P. Westbergh, J. Karout, J. Gustavsson, A. Haglund, M. Karlsson, P. Andrekson, E. Agrell, and A. Larsson, “4-PAM for high-speed short-range optical communications,” *J. Opt. Commun. Netw.*, vol. 4, pp. 885–894, Nov. 2012.
[25] K. Szczerba, P. Westbergh, M. Karlsson, P. Andrekson, and A. Larsson, “70 Gbps 4-PAM and 56 Gbps 8-PAM Using an 850 nm VCSEL,” *J. Light. Technol.*, vol. 33, pp. 1395–1401, Apr. 2015.
[26] M. Kuschnerov, M. Chouayakh, K. Piyawanno, B. Spinnler, E. de Man, P. Kainzmaier, M. S. Alfiad, A. Napoli, and B. Lankl, “Data-Aided Versus Blind Single-Carrier Coherent Receivers,” *IEEE Photonics J.*, vol. 2, pp. 387–403, June 2010.

Robbert van der Linden (S’08) was born in Oosterhout, the Netherlands. He studied Electrical Engineering at Eindhoven University of Technology, Eindhoven, the Netherlands. He did his master internships at imec Netherlands and ETH Zurich. In 2013 he received the M.Sc. degree (cum laude) from Eindhoven University of Technology. Afterwards, he joined the COBRA Research Institute, working towards a Ph.D. degree on flexible access networks in close collaboration with Genexis B.V. His research interests include optical access networks and flexible networks.

Nguyen-Cac Tran (S’06) received the B.Eng. degree in electronics and telecommunications from the Hanoi University of Science and Technology, Hanoi, Vietnam, in 2005, the M.Sc.Eng. degree in Electrical Engineering from Korea University, in February 2008, and Ph.D. degree in optical communications from COBRA Research Institute, Eindhoven University of Technology, The Netherlands, in March 2013. From August 2005 to March 2006, he was a Junior Network Administrator at Vietnam Telecom National. In 2008, he joined Panasonic Hanoi Laboratory as a scientific assistant for the director. Since 2013, he has been with Genexis B.V. as product line manager for FTTH residential gateway equipment. His research interests include optical fiber access and in-building networks, optical network control and management, and deploying solutions for fiber to/in the home.

Eduward Tangdiongga (S’01, M’10) received the M.Sc. and Ph.D. degrees from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1994 and 2001, respectively. In 1994, he joined the COBRA Research Institute, working on high-speed optical switches. From 2001 he has participated in several European Union and Dutch sponsored research programs targeting for integration of various wired and wireless services on a single optical in-building network. In 2006, he was appointed as an Assistant Professor on short-haul optical communication. His research interest includes random signals, ultrafast dynamics in semiconductor optical devices, adaptive access networks, radio over (single mode-, multimode-, and plastic) fiber, and optical wireless.

Ton Koonen (IEEE F’07, OSA F’13) is full professor in Eindhoven University of Technology since 2001. Since 2004 he is chairman of the group Electro-Optical Communication Systems and since 2012 vice-dean of the department Electrical Engineering. Before 2001, he worked for more than 20 years in applied research in industry, amongst others in Bell Labs - Lucent Technologies. He is Bell Labs Fellow (1998), IEEE Fellow (2007), OSA Fellow (2013), and Distinguished Guest Professor of Hunan University, Changsha, China (2014). In 2011 he received an Advanced Investigator Grant of the European Research Council. His current research interests are spatial division multiplexed systems, access and in-building fiber networks, including high-capacity POF networks, radio-over-fiber techniques, and wireless optics techniques.