Flexible-Rate PON with Loss-Configurable ODN Splitters for Throughput Optimization

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Abstract We propose, analyze, and experimentally verify the effectiveness of combining flexible-rate passive optical networks with power-adjustable splitters for enhancing user throughput. We demonstrate the possibility of increasing the fraction of users capable of supporting PAM4 by more than 100% in an exemplary optical distribution network. ©2023 The Author(s)

Introduction

Flexible-rate passive optical network (PON) concepts have been demonstrated for throughput maximization of a given optical distribution network (ODN) [1] and enhanced PON system robustness [2]. Flex-rate PON comprises flexible modulation and flexible forward error correction (FEC). The modulation format as well as the FEC code can be adapted according to the available channel conditions for the optical line terminal (OLT) to optical network unit (ONU) link. These link conditions are given by the attenuation of the ODN, the chromatic dispersion, and by the OLT and ONU transceiver margins. The option to apply flex-rate PON is typically constrained by the available margins from transceivers and ODN. So far, our investigations [1-3] have applied ODN conditions of a static outside plant. However, with the research [4] and development of adjustable variable optical splitters (AVS) and intelligent optical splitter modules [5], modifications to the loss within ODNs are possible with minimal intervention, yielding loss-configurable ODNs.

In this paper, we propose and demonstrate ODN throughput enhancements achieved by combining flex-rate PON with power-adjustable splitters.

Flex-rate PON with loss-configurable ODN

Current time-division multiplexed (TDM) PON generations use the same modulation format and FEC code for data transmission from the OLT over a fixed ODN with static power split ratio to all ONUs irrespective of individual channel conditions, see Fig. 1(a). Traditional TDM-PON transceiver technologies apply optical intensity modulation and direct detection (IM/DD). The latest ITU-T PON Recommendation, G.9804, specifies 50 Gbit/s transmission on a single wavelength [6] which pushes IM/DD to its limits. It uses non-return-to-zero (NRZ) on-off keying (OOK) modulation and a low-density parity check (LDPC) FEC code with a pre-FEC bit error ratio (BER) of 1E-2 to establish a 1E-12 BER output; it is the first PON generation to rely on digital signal processing (DSP)-based equalization (EQ) to meet the loss budget targets. This DSP-EQ enables flexibility schemes in the PON domain.

Flexible approaches like the flexible-rate PON (FLCS-PON) concept [3], extend the traditional IM/DD TDM-PON architecture with new features, which allow doubling of the line rate in downstream (DS) from 50 Gbit/s to 100 Gbit/s by changing the modulation format from NRZ-OOK to 4-level pulse amplitude modulation (PAM4)



Fig. 1: System and ODN for PONs with N split points (NRZ-OOK in blue; PAM4 in green). (a) Classical PON with constant PHY layer line rate and static ODN, (b) Flex-rate PON with static ODN, (c) Flex-rate PON with configurable ODN.

while preserving the symbol rate. The use of FEC code variants based on the same LDPC mother code to provide a finer trade-off between power vs. throughput has also been explored. FLCS-PON targets ODN throughput maximization by grouping ONUs sharing similar signal quality metrics together and assigning modulation and coding parameters on a per-group basis, see Fig. 1(b). The ODN is still static so that it is compatible with existing fiber plants.

In Fig. 1(c), we introduce the extended flexibility concept in which we combine flex-rate PON with a loss-configurable ODN. Using AVS, the power for each branch can be adapted according to the desired power distribution under the constraint that the sum of the output powers for all splitter arms is equal or lower than the splitter input power reduced by the splitter insertion loss. The use of such an AVS enables an adjustment of the available signal to noise ratio for ONUs or a group of ONUs. Thus, the link attenuation becomes a configurable parameter that can be modified in conjunction with system parameters like modulation format and FEC to maximize ODN throughput. Here, we explore an optimization strategy that aims to move as many ONUs as possible from NRZ to PAM4 modulation by borrowing power from ONUs that either already support PAM4 with excess margin or observe too high losses to support PAM4 but have excess margin for NRZ operation.

Different implementations for AVS have been discussed in research [7] and some devices are commercially available [8-9]. Possible implementation technologies for AVS are based on magneto-optical effects, mechanically strain sensitive couplers, Spatial light modulator (SLM) based couplers or field-induced waveguides in liquid crystals. Some exemplary parameters are [10]: split ratio adaptability 5-95 %, granularity 1 % steps, excess loss 0.1 dB.

To configure and assign the split levels, the Intelligent Splitter Monitor (ISM) concept [5] with communication path and remote powering could be used but alternatively also mechanically setand-forget splitters could be applied.

Tab. 1: Estimated PAM4 coverage (%) with equal split compared to optimized last-stage AVS for various group sizes (G). Two optimization methods (C = conservative, A = aggressive) are analyzed at two PAM4 BER operating points.

Throughput increase	Equal split [%]	Method	G=2 [%]	G=4 [%]	G=64 [%]
2x (PAM4 @	35.8	С	41.9	48.3	58.7
1e-2)		А	63.9	75.7	85.7
1.74x (PAM4	72.2	С	78.8	83.4	88.7
@ 1.8e-2)		А	86.3	91.9	96.0

PAM4 coverage for loss-configurable ODNs

To investigate the benefits of employing AVS, we analyse their impact on the fraction of ONUs that can support PAM4 operation in an exemplary ODN [11] combined with transceiver marginmodelling [12]. We first generate a distribution of class B+ ODN optical path losses via Monte Carlo simulations over 1E5 ODNs, each with 64 ONUs. These are extrapolated from field data modelling of mean OLT-ONU reach and ODN distance disparity by Orange [11] (ODNs with \geq 48 ONUs), and by assuming fiber loss of 0.31 dB/km, 0.5 dB excess loss per 1:2 split (i.e., total loss of 21 dB for 1:64 split), and 1.0 dB random connector/splice loss ($\mu = 1, \sigma = 0.3$). A fixed loss of 1.5 dB is further added for temperature and aging. The margins with respect to the B+ loss budget (28 dB) are computed and added to transceiver component margins inferred from N1class XGS PON vendor data [12] to generate the joint distribution of margin and reach, which is shown in Fig. 2(a). Transmitter margins are added on a per-ODN basis ($\mu = 1.89 \text{ dB}, \sigma = 0.28$ dB), while receiver margins are added on a per-ONU basis (μ = 3.5 dB, σ = 0.7 dB). The figure also overlays the required margin to use PAM4 at the default FEC BER threshold of 1e-2 [6] assuming the worst-case dispersion of 3.86 ps/nm/km (red surface). This corresponds to doubling the throughput for PAM4 over 50G NRZ. This margin is derived by combining PAM4 penalty results from VPI simulations assuming 18.75 GHz receiver bandwidth [13] with similarly simulated worst case optical path penalty (OPP)



Fig. 2: ODN and transceiver margin density. The red surface shows the minimum margin required to allow PAM4 operation at BER = 1e-2; (a): Equal split; (b): optimized last stage 1:4 AVS using only excess PAM4 margin (conservative method); (c): using both NRZ and PAM4 excess margin (aggressive method). Note the z-axis scale in (b) is different from (a) and (c).

for 50G NRZ. From Fig. 2(a), ~ 36% of ONUs can support PAM4 transmission with 2x throughput of NRZ for an ODN with static equal splits.

The use of AVS inside the PON is possible, because the ODN is normally not designed up to the limit and power margins are available. While several strategies can be envisioned to introduce AVS in the ODN, we choose a simple approach for analysis where the ODN is modified by replacing the final stage conventional 1:G splitter (G = 2, 4, ..., 64) with a fully configurable AVS. When G < 64, equal split ratios are assumed for all previous stages and the ONUs are not reassigned to different last stage splitters. The split factors for each group of G ONUs can then be optimized to provide maximal PAM4 coverage. Fig. 2(b) and 2(c) show the resulting margin distribution after such optimization for G = 4 for two different methods. A first conservative method utilizes margin from only existing PAM4 users to enable PAM4 for other users, with the split of NRZ users maintained at the nominal 1:G factor. A second aggressive method involves utilizing excess margin from NRZ users as well as existing PAM4 users. The conservative method is more applicable when ONUs are not provisioned on all splits in an ODN and the channel condition in such cases is not known. The aggressive method may be used when the channel conditions of all ONUs in an ODN are fully known. In both Fig. 2(b) and 2(c), the PAM4 ONU margins after split optimization are concentrated just above the required margin (red surface). Fig. 2(c) also shows that many ONUs with NRZ have their margins concentrated just above the NRZ OPP level, since their excess margin is used to enable PAM4 on other ONUs.

Table 1 compares the PAM4 coverage (in %) for ODNs with equal 1:64 split versus ODNs with configurable last-stage 1:G splitters with optimized split factors for various G for the two methods. The upper rows show results for PAM4 operation at the default BER of 1e-2 (2x throughput). While PAM4 coverage is just 36% with equal split, when AVS are used for the entire ODN (G = 64), PAM4 coverage can be supported for more than 85% of the ONUs with the aggressive method, and more than 58% of the ONUs with the conservative method. The lower rows show results for PAM4 operation at a higher BER threshold of 1.8e-2, which may be achieved by employing a stronger FEC of rate 0.733 [3] (this corresponds to 1.74x throughput of NRZ).



Fig. 3: Flexible PON test set-up.

PAM4 coverage increases from 72% with equal split to 96% and 89% for G=64, respectively for the aggressive and conservative methods.

Note that this analysis focuses on PAM4 for DS only. NRZ operation in upstream (US) is assumed. In general, different component margins are expected in the US and adjustments to the split ratio will also affect US loss. The conservative method is benign in its impact on US since power is not borrowed from NRZ users. Meanwhile, the aggressive method could impact US NRZ operation of some users whose margin is pushed lower. This may be rectified by either jointly optimizing with US margins or by employing stricter limits on power borrowed from NRZ users, and is a topic of further research.

Experimental proof of concept

For an experimental proof of concept, we combined the Nokia Bell Labs FLCS-PON setup [1] with a remotely reconfigurable variable ratio coupler (VRC) from Corning Incorporated. The test set-up with the FLCS PON OLT and two ONUs is shown in Fig. 3. To emulate a realistic ODN, attenuators (Att1 and Att2) are used to achieve an 8dB difference in the input power to the ONUs. For standard splitter configuration with 50% split ratio, the ONU power levels are shown in the first row of Table 2 and allow only ONU 2 to operate in PAM4 mode [1]. However, by tuning the split ratio in the range shown in the second row of Table 2, both ONUs can operate in PAM4 mode. A split ratio higher than 75% and 12% is required for ONU1 and ONU2, respectively.

Conclusions

The combination of the FLCS PON approach with AVS enables a new evolution step for passive optical networks into a fully flexible access system. Analysis and optimization of margins in an exemplary ODN show that the fraction of ONUs supporting PAM4 can be significantly increased (more than doubled in the best case) by replacing the conventional splitter in the final stage with an AVS. The concept is also demonstrated in a lab measurement.

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ODN	Tap1	PM1 [dBm]	ONU1 modulation	Tap2	PM2 [dBm]	ONU2 modulation
Fixed	50%	-20.3	NRZ (42.22Gbps)	50%	-11.9	PAM4 (84.4Gbps)
Variable	75 – 88%	-18.618.3	PAM4 (84.4Gbps)	25 – 12%	-14.917.9	PAM4 (84.4Gbps)

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