Operator Trial of 100 Gbit/s FLCS-PON Prototype with Probabilistic Shaping and Soft-Input FEC

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Abstract *We introduce probabilistic shaping and soft-input FEC to our 100-Gbit/s flexible PON concept, FLCS-PON, beside varying the modulation format and FEC code shortening/puncturing. These features improve granularity of bitrate adjustment for various channel conditions in downstream direction. We demonstrate our prototype in an operator trial.*

Introduction

Point-to-multipoint nature of passive optical networks necessitates that a wide variety of line conditions (fiber length and dispersion, signal power, varied transceiver performance) have to be simultaneously supported. For time-division multiplexing the issue is particularly severe, as only one wavelength channel is broadcasted to all ONUs, which in turn pushes cost-efficient transceiver technologies close to limits at 50 Gbit/s, in an attempt to serve all users with the same modulation format and bitrate, regardless of their actual line condition and position in the network.

Flexible Passive Optical Network[1]-[2] (FLCS-PON) is a prototype PON implementation, embodying a new paradigm for passive optical networks, where modulation and coding parameters (MCP) are assigned per user (ONU) group, thus avoiding a network-wide speed cap inherent to all previous PON generations. Early proposals to introduce flexibility in PON were based on complex transmitters[3]-[4], or lacked a frame structure[5]. FLCS-PON constitutes a practical approach to realize a flexible PON by building on top of 50G PON hardware ecosystems, and allows for adjustment of MCPs in order to maximize users' bitrates, by choosing the right group MCPs and assigning users to groups. Other systems, such as DOCSIS[6], assume a similar strategy in order to further increase bitrates.

In[1] we revealed the results of the first FLCS-PON field trial, showing that our approach may allow for up to 100 Gbit/s line rate operation (using quaternary pulse amplitude modulation, PAM-4) with a loss budget (fiber plant plus transceivers' frontends) exceeding 27 dB, using a hard-decision forward error correction (FEC) variant with a code rate of 0.7333. We subsequently showed in[2] that by increasing launch power to 11 dBm, a budget (or optical path loss, OPL) of over 28 dB could be supported for 100 Gbit/s. In addition to this, OPL exceeding 36 dB could be supported with 50 Gbit/s line rate realized with non-return-to-zero (NRZ) on-off keying modulation format.

In this paper we report on the results of FLCS-PON measurements performed jointly with Vodafone during an operator trial. The novelty of this paper is threefold: (a) introduce probabilistic shaping (PS)[7] to allow for a further degree of freedom in bitrate adjustment, (b) demonstrate the achievable performance of the system with soft-input FEC decoding; and (c) map the performance to actual operators' PON data to quantify bitrates expected in actual deployments.

New FLCS-PON features

Downstream transmission in our system comprises a pattern of codewords (CWs), each

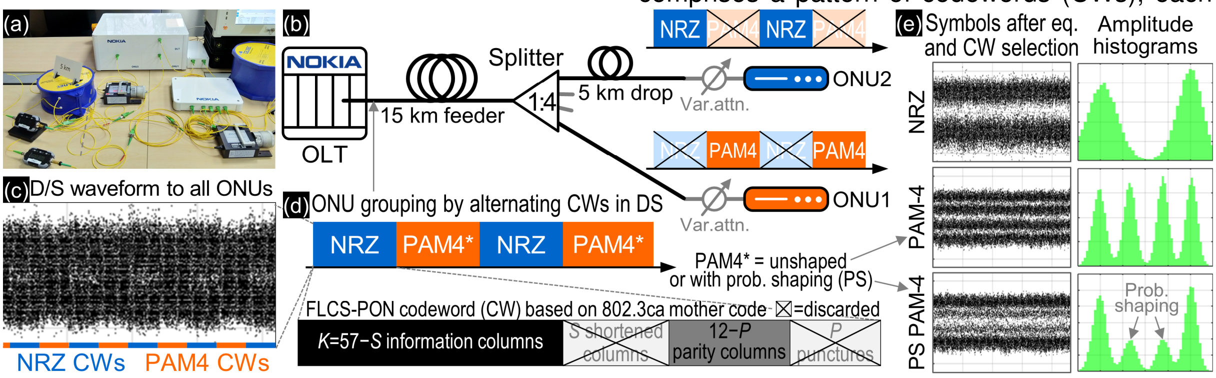

Fig. 1: Trial setup: (a) photo; (b) schematic. (c) Waveform transmitted in downstream carrying alternating codewords, as seen at one of the ONUs before processing. (d) ONU grouping concept. (e) Recovered symbols and their histograms after ONU processing.

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CW targeted at a group of ONUs experiencing similar line conditions, such that by optimizing group MCPs, the net bitrate for each group can be increased, and hence the overall network capacity can be improved. In[1]-[2] we introduced concepts of discrete modulation formats (NRZ and PAM-4) and flexible FEC. In this work, FLCS-PON is enhanced with new modes of operation: PS and soft-input FEC decoding.

Probabilistic shaping (PS)

For AWGN channels constrained by a fixed second order moment of the transmit signals, it is well known that a Gaussian distribution is the ideal distribution achieving the channel capacity. However, this constraint does not apply to PON systems[8]. A typical PON transmitter is peak-power-constrained (PPC) due to a limited electrical peak-to-peak amplitude of the signal generation stage. When applying PS, this constraint can be alleviated by using an optical booster with a dynamically adjustable gain[8]-[9]. However, the use of such amplifier may be problematic for rapidly varying signal, like in FLCS-PON, where downstream CWs with the same MCPs last only 230.4 ns. An amplifier driven in constant output power mode could introduce undesired transients and distortions between CWs with different MCPs.

For systems with a PPC, the capacity-achieving distributions are symmetrical distributions of which the inner levels have lower probabilities than the outer ones, and unequal level spacing[10]. In this paper, we perform PS by applying such *inverted* distribution to a PAM-4 signal (cf. Fig. 1(e)) using the shell mapping algorithm from MGfast as a distribution matcher[11], and place the FEC parity in the PAM-4 sign bits, similar to[12]. The applied distribution allows to maintain a fixed outer extinction ratio (ER) of PAM-4 at a value comparable to ER of NRZ. For simplicity, we maintain equal level spacings. While this practical approach does not allow to fully realize the channel capacity, it does provide the required tradeoff of net bitrate vs. OPL, as the error probability reduces when prior probability of modulation levels change. PS signal variants allows for more noise tolerance and thus extends OPL. The bitrates reported in this paper include rate losses arising from the practical shaping implementation with finite PS block length of 32 symbols, and are thus realizable.

Forward error correction (FEC) with soft-input

The CWs sent in downstream are encoded with a low-density parity check (LDPC) code, with a constant CW length of N=11520 bits ($^2/_3$ of the full 802.3ca mother code length[13]) where the code rate, R, can be independently set to different values for each group. This is achieved by varying the number of shortened, S, and punctured, P, 256-bit-long LDPC code columns, and allows to choose a code rate ranging from 0.7333 to 0.8889 (see Tab. 1). Due to unreliability of BER thresholds for soft-decision systems[14], we report and rely on the normalized generalized mutual information (NGMI)[15]. The NGMI thresholds for FEC variants with P={0,2,5,7} were established from simulations of post-FEC bit error ratio (BER) down to 10^{-12} using a layered min-sum decoder with 15 iterations where an additive white Gaussian noise (AWGN) channel is assumed. The NGMI thresholds for the remaining code variants were obtained by linearly interpolating the simulated results.

Tab. 1: NGMI thresholds for soft-input LDPC(256×45,256×[33+P])

N	K [× 256 bit]	S	P	R [–]	NGMI [–]
45	33	24	0	0.7333	0.8383
45	34	23	1	0.7555	(0.8681)
45	35	22	2	0.7778	0.8980
45	36	21	3	0.8000	(0.9134)
45	37	20	4	0.8222	(0.9289)
45	38	19	5	0.8444	0.9443
45	39	18	6	0.8667	(0.9637)
45	40	17	7	0.8889	0.9831

N – code length, K – information length, S – shortening, P – puncturing, R – code rate. NGMI values in (round brackets) were obtained by interpolation.

Experimental setup

The FLCS-PON prototype setup, which was located at the Vodafone premises, is demonstrated in Fig. 1. The OLT generates a 50 GBd downstream signal, consisting of alternating, 11520-symbol-long, frames of NRZ modulation (50 Gbit/s line rate, one CW per frame) and PAM-4 modulation (100 Gbit/s line rate, two CWs per frame). The latter was either unshaped (information rate, IR, of 2 bit/symbol), or shaped, with IR of {60/32=1.8750, 54/32=1.6875, 48/32=1.5000} bit/symbol. The OLT uses a 25G-class EML+SOA, and is set to launch 8dBm optical power with 5 dB outer extinction ratio into the 15-km-long standard single mode fiber (SSMF) feeder section. After the feeder, the signal is split with a 1:4 splitter, whose two branches are connected via drop sections to ONUs, which comprise 25G-class APD-TIA ROSA components. ONU1 is connected via a patch cable to the splitter, and is configured to receive the group containing PAM-4 signal only. ONU2 includes 5 km drop fiber, and is configured to receive NRZ signal. Both ONUs have variable optical attenuators installed in front of them to emulate higher than available in the test setup fiber attenuation or split ratios. ONU digital signal processing includes: timing recovery, downstream frame synchronization, CW group selection, digital equalization using a 23-tap feedforward equalizer and 5-tap decision feedback equalizer, NGMI and pre-FEC BER measurement, shell-mapper-based soft FEC decoding and post-FEC BER measurement.

Results

Fig. 2(a) shows the pre-FEC BER, and (b) NGMI for the unshaped transmitted signals (circles), and three 100G PS variants with different IRs. The granularity of the power sweep is 0.5 dB.

Fig. 3 shows the highest achievable net bitrate at each OPL, obtained by mapping the NGMI thresholds from Tab. 1 onto NGMI in Fig. 2(b). Net bitrate excludes FEC overhead (which constitutes majority of PON overhead) but includes PON protocol overhead (such as PSBd and downstream FS header). The overhead due to the latter depends on the operator-specific PON configuration and the number of ONUs, and is typically below 1% of the net bitrate. For instance, in ITU-T G.9804 (50G PON), for 64 BWmap allocation structures and 4 PLOAMs, the PON protocol overhead is only 0.22%. Thus, the reported results are very close to bitrates available to services running on top of a PON system. It should be mentioned that the differences between net bitrates of different MCP groups could be absorbed by proper bandwidth assignment and scheduling. Fig. 3 shows that PS helps to avoid an abrupt throughput drop due to discrete modulation formats, which was present in the results from our previous field trial that did not include PS[1]-[2]. To achieve even finer bitrate adjustment granularity, more than three PS variants, could be considered. At the same launch power, soft-input FEC enables an overall OPL increase by 1.5 dB with PAM-4 and 2 dB with NRZ, comparing to our previously published results.

Finally, in Tab. 2, we show the mapping of the obtained net bitrates onto actual operator's PON infrastructure. First, we subtract 1 dB from OPL in Fig. 3 to account for diplexers. The available operator's deployment data provide country-wide statistics of the deployed OLT ports in steps of 2 dB for three European countries: Italy, Spain and Portugal. We assume a reference scenario, where all ports are G.9804 with a nominal code

Tab. 2: Estimated net bitrate after network upgrade from 50G PON (ITU-T G.9804) to FLCS-PON

Model →	Optimistic		Pessimistic	
↓Country	Net bitrate [Gbit/s]	Increase [%]	Net bitrate [Gbit/s]	Increase [%]
Italy	80.0	89.5%	67.8	60.6%
Spain	84.1	99.2%	74.0	75.3%
Portugal	86.7	105.3%	77.8	84.3%

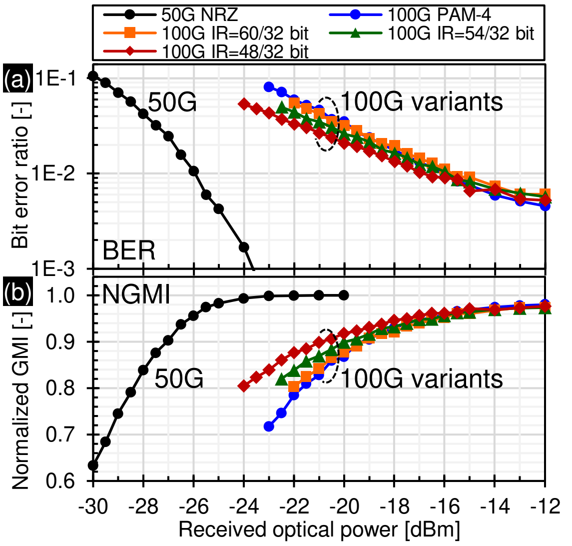

Fig. 2: (a) Pre-FEC BER and (b) NGMI for 50 GBd NRZ and PAM-4 with different PS infromation rates.

rate of 0.8444 and 50 Gbit/s line rate. We then evaluate the capacity increase after an upgrade of all ports to FLCS-PON. To account for rough granularity of the available deployment data, we assume two models: optimistic, where all OLT ports are concentrated at the lower end of the optical budget interval, and pessimistic, where all are located at the upper end. As can be seen in Tab. 2, when applied to realistic PON deployments, FLCS-PON can roughly double average net throughput compared to G.9804. Even in the worst case of the pessimistic model, the expected average net bitrate increase after upgrade exceeds 60%.

Conclusion

Jointly with Vodafone, we successfully completed operator's trial of a FLCS-PON, which is a practical concept for flexible PON realization. The test indicated feasibility of 60% to more than 100% (double) net throughput increase over actual PON deployments compared to ITU-T G.9804 (50G PON). During the trial we tested new features of our system: probabilistic shaping, which allows to fill a throughput gap between discrete modulation formats, and soft-input FEC, which improves OPL by up to 2 dB compared to hard-input FEC due to higher decoding gain.

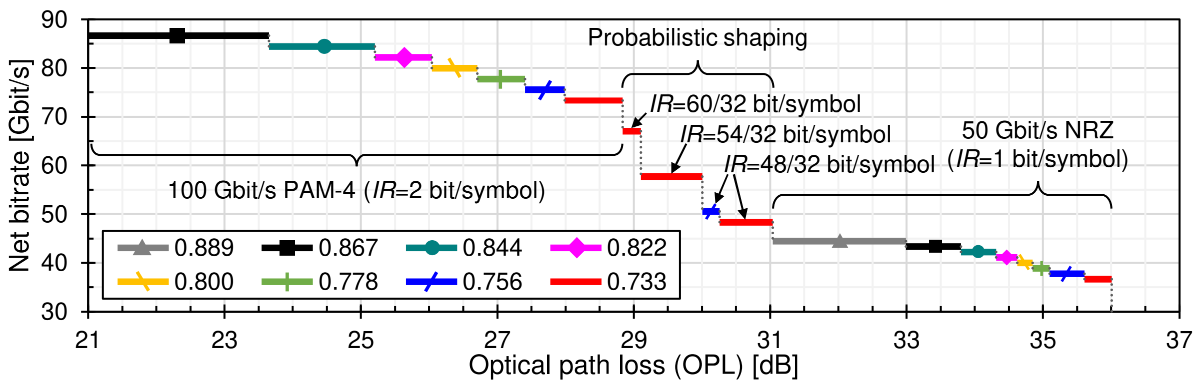

Fig. 3: FLCS-PON operating envelope, showing the highsest achievable net bitrate as a function of OPL and MCP. Color coding indicates code rate, while probablistically-shaped PAM-4 modulation is indicated with thick lines and described with arrows.

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