World's First Field Trial of 100 Gbit/s Flexible PON (FLCS-PON)

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Abstract *We completed world's first field trial of FLCS-PON, which delivers bitrates up to 100 Gbit/s and allows for flexible line and code rate to match users' channel conditions and optimize throughput. Using FLCS-PON, we demonstrated a record-high 31.5dB loss budget for 100 Gbit/s preamplifier-direct-detection ONU.*

Introduction

Flexible Passive Optical Network (FLCS-PON) provides a powerful approach to optimize capacity to groups of optical network units (ONUs) based on the available channel conditions, such as signal-to-noise ratio (SNR). By assigning modulation and coding parameters (MCP) per group of ONUs that exhibit similar channel conditions at the physical layer, a new degree of freedom for optimizing throughput in PON is introduced.

Multi-rate reception in the PON upstream (US) is used for the purpose of spectral and temporal coexistence with legacy system generations. Several groups have reported flexible rate experiments in upstream[1],[2] based on multi-rate non-return-to-zero (NRZ) modulation. However, for the downstream (DS) direction, this approach has not been yet implemented. Although several groups have reported flexible rate results on a conceptual level[3]–[10], neither details such as a practical framing structure for DS nor demonstration of such concept in an operator field trial have been presented so far. With FLCS-PON, peak throughput to many ONUs will increase compared to legacy PON systems, which offer only a fixed DS rate independent of channel conditions between an optical line termination (OLT) and each of the ONUs. Our solution additionally allows to keep ONUs having link quality below that specified by the nominal ODN class (e.g., due to repair splices), in service. This allows for the operator to monitor graceful degradation and schedule field interventions at a convenient time. Overall, users' service level agreements can be enhanced and the PON system can be made future proof for e.g., mobile x-haul, enterprise Internet of Things or broadband access (fiber-to-the-x) in which each of these use cases come with their own physical layer requirements for the optical distribution network (ODN) in terms of reach and split.

In this paper, we report key achievements of the first operator field trial for our FLCS-PON:

- Flexible modulation: using NRZ and quaternary pulse amplitude modulation (PAM-4) to achieve up to 100 Gbit/s using a novel framing structure for DS, suitable for point-to-multipoint operation.
- Forward error correction (FEC) rate adaptation: employing code rates from 0.733 to 0.889 based on shortening and puncturing of the IEEE 802.3ca[11] low-density parity-check (LDPC) "mother" code.
- Flexible modulation and code rate for efficient fine-granularity fiber capacity utilization based on channel conditions available to each ONU group.
- Record-high PON optical path loss (OPL) support enabled by FLCS-PON: >31.5 dB for 100 Gbit/s PAM-4 (100G) and >40 dB for 50 Gbit/s NRZ (50G) in the Operators' ODN of 1:32 split ratio enabled by a semiconductor optical amplifier (SOA) and digital signal processing (DSP) using only 25G-class optics.

FLCS-PON concept

The flexible modulation (flex mod)[12] and flexible FEC (flex code) in FLCS-PON is enabled by an extension of the legacy time-division multiplexed (TDM)-PON frame structure (e.g., XGS-PON[13]) with a minimal implementation impact, which we call ONU grouping[14], see Fig. 1(c). The frame duration is kept at 125 µs and is subdivided into

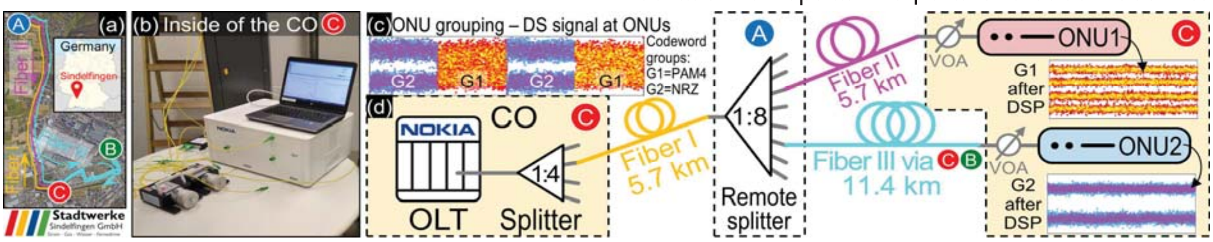

Fig. 1: (a) Location and details of the field trial. (b) FLCS-PON prototype at the Operator's CO; (c) ONU grouping concept and DS waveform received at one of the ONUs after clock recovery, before synchronization and equalization. (d) Details of the trial setup.

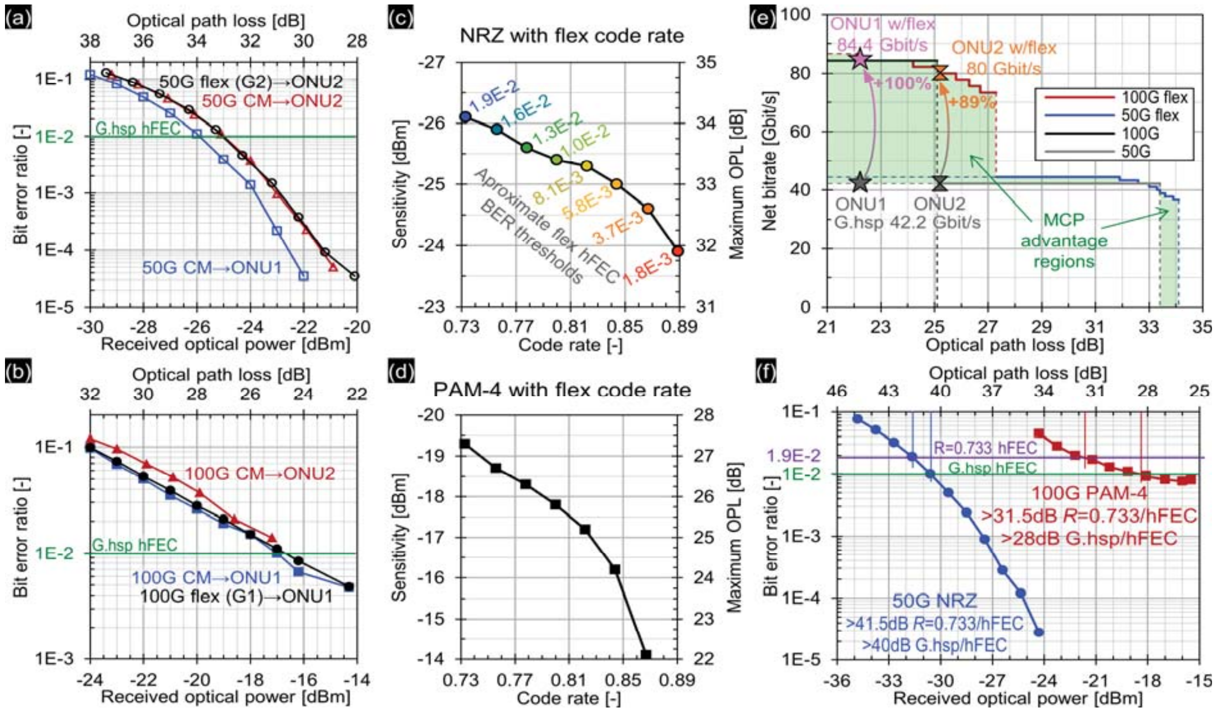

Fig. 2: (a,b) ROP and OPL in continuous and flex mode, for (a) 50G, and (b) 100G. (c,d) Experimental sensitivity vs code rate for (c) 50G and (d) 100G; approximate hFEC BER threshold are indicated in (c), also valid for (d). (e) Net bitrate vs OPL quantifying possible ODN benefits, as well as indicating improvement of our test ONUs. (f) BER vs ROP/OPL for ultrahigh OPL experiment.

a repeating allocation of codewords (CWs) sent in DS, where each CW has a fixed length, can differ in MCP, and is assigned to a group of ONUs considering their similar channel characteristics and/or capacity needs. Up to four groups allow to reap most of the benefits of throughput optimization in a typical PON deployment, while keeping complexity manageable. Each ONU decodes only CWs allocated to its group, while the knowledge of the allocation pattern and CWs' fixed length enables maintaining frame synchronization[15].

The FLCS-PON capacity optimization is enabled by the advent of DSP. The flex mod applied in our system is NRZ-OOK and PAM-4, however it can also be extended to PAM-3, -8 and even probabilistic shaping[16]–[20] to achieve a gradual tradeoff between OPL and net bitrate.

The employed FEC is based on the (17664,14592) LDPC mother code defined in the IEEE 802.3ca standard[11] and is also adopted by the upcoming ITU-T G.hsp recommendation. First, we consider the code in the context of the G.hsp 50 Gbit/s DS, where it is used with 1.5 columns puncturing (1 column is 256 bits) to achieve FEC input BER threshold of 1×10^{-2} with a hard-decision decoder (hFEC) and a codeword size of 17280 bits. Second, we consider this code in a flexible code rate context in which we vary the rate of the mother code by puncturing and shortening. The puncturing is varied between 0 and 7 columns, in steps of half a column. For a given amount of puncturing, the code is shortened to obtain a fixed CW length of 11520 bits. The reduction in code length is necessary to achieve enough flexibility in the code rate. This allows to flexibly vary the code rate from 0.733 to 0.889 in 15 steps and does not require a soft-decision FEC decoder to reach high FEC input BER (1.9×10^{-2} can be targeted with 0.733 code). By combining flex mod with flex code, the system can operate across 30 discrete configurations allowing to fully exploit the available channel conditions to maximize the users' throughput. Note that such techniques are also applicable for a flexible code rate in upstream direction[21].

FLCS-PON field trial: setup and results

The field trial is executed on an ODN deployed in Sindelfingen, Germany that is normally used to carry customers' PON traffic, see Fig. 1(a,d). At the Operator's central office (CO), a 1:4 splitter is used – a configuration common to many European PON operators. The 5.7 km feeder fiber (Fiber I) is terminated at the fiber distribution location (A), which houses a remote 1:8 splitter. Two outputs of this splitter are then connected to two fiber links: one 5.7-km-long (fiber II) looped back to the CO, and another 11.6-km-long (fiber III) routed via CO to a pulling manhole (B), and back to the CO. The OLT of the FLCS-PON prototype unit, photographed at the Operators' CO (Fig. 1(b)), is connected to fiber I, ONU1 to fiber II, and ONU2 to fiber III. The total split of this configuration is 1:32, and the fiber distances (OPL) amounted to 11.4 km (22.3 dB) for ONU1 and 17.3 km (25.2 dB) for ONU2.

The data signal at the OLT is modulated at 50 Gbaud and originates from a ≈20 GHz (3 dB) digital-to-analog converter, pre-emphasized to reduce transmitter-side inter-symbol interference to minimum. The modulation format is either

OOK-NRZ (50 Gbit/s) at 5 dB extinction ratio, or PAM-4 (100 Gbit/s) and is arranged as alternating CWs of 125/360 μs for the G.hsp FEC code or 125/540 μs for the shortened FEC code. The OLT optics included a commercial 25G-class externally modulated laser (EML) emitting at 1308.7 nm and a booster SOA. The launched optical power (LOP) is set to 8 dBm if not otherwise stated in the paper.

Each of the two ONUs include a commercial avalanche photodiode (APD) integrated with a transimpedance amplifier (TIA), and an analog-to-digital converter followed by a DSP processing chain consisting of clock recovery (CR) generating 1 Sa/symbol, CW synchronization, equalization using a 23-tap T-spaced feed-forward equalizer (FFE) and a 2-tap decision feedback equalizer (DFE) and LDPC decoding. As the system is always operated at 50 Gbaud, our digital CR can maintain lock over boundaries of CWs containing different modulation formats, even though the channel quality may be insufficient to successfully demodulate the data. Such assignment allows ONUs to demodulate words directed at them without any delay needed to reacquire sampling frequency and phase when words are alternating. The output of DSP processing of the resulting signal could be examined through a graphical user interface (GUI). The GUI was also used to configure two ONU groups: G1=PAM-4, and G2=NRZ, and assign them to ONUs. The repeating arrangement of G1 and G2, as received at one of the ONUs is shown in Fig. 1(c).

Flexible modulation: in Fig. 2(a,b) we show bit error ratio (BER) as a function of the received optical power (ROP) and the OPL, obtained by attenuating the signal at the outputs of deployed fibers II and III with extra attenuation (representing additional ODN loss). In Fig 2(a) we compare the performance of continuous mode (CM) 50G transmission without ONU grouping (legacy PON mode with the same modulation to all ONUs in downstream) at each ONU vs reception of G2 at ONU2 in flex mode. A 1 dB difference between ONU2 and ONU1 was observed, most likely caused by non-identical operating points of APDs, but no penalty is observed for flex mod vs CM on the same ONU. The hFEC OPL for 50G is 33.9 dB (at ONU2). In Fig. 2(b) we compare 100G CM signal vs group G1 at ONU1. Similarly, as before, no flex mod penalty is observed. The OPL is 25 dB at hFEC (ONU1). The hFEC thresholds were verified experimentally by setting ROP at ONUs to yield error-free post-FEC output.

Flexible code rate: Next, ONU grouping is always on, and ONU1 is assigned to G1, while ONU2 to G2. The code rate, R, in each group is separately varied and hFEC decoder was used to experimentally determine the receiver sensitivity by adjusting ROP until post-FEC error-free performance is observed. Fig. 2(c,d) shows the minimum ROP and maximum achievable OPL as a function of code rate for 50 Gbit/s (c) and 100 Gbit/s (d). For 50G, the OPL varies between 34.1 dB for R=0.733 down to 31.9 dB for R=0.889. For 100G, the OPL varies between 27.3 dB at R=0.733 down to 22.1 dB at R=0.867. In Fig. 2(c) we include theoretically estimated BER thresholds for the measured flex code rates. The same thresholds apply to respective code rates in Fig. 2(d). By comparing subfigures (c,d) with (a,b) it can be concluded that the flex code performance is slightly worse than the full-length G.hsp code which is caused by shortening to 11520 bits.

We then present net bitrates (data rates at FEC output) in Fig. 2(e), to show how the achievable net bitrate varies as a function of the OPL. The performance of conventional modulation which employs G.hsp hFEC is plotted in gray(black) for 50G(100G), while capacity achievable with the flex code is plotted in blue(red), showing the large space of possible operating points, which could benefit from MCP flexibility, by either allowing for higher net bitrate, or extending the range of applicability for PAM-4 or NRZ . As depicted in Fig. 2(e), our concept allows to increase the net bit data rate by 100% at ONU1 and by 89% at ONU2 yielding an average DS net bitrate of 82.2 Gbit/s (nearly 95% improvement compared to G.hsp).

Ultrahigh optical path loss: for this demonstration, the system is modified. First, a preamplifier, consisting of an SOA with 12 dB small-signal gain, 5.5 dB noise figure and a 2-nm-wide ASE filter is installed in front of APD of ONU1; the LOP is increased to 10 dBm; the number of equalizer taps is increased to 31 for FFE and 7 for DFE, mostly required to combat nonlinearities originating from SOA booster saturation. ONU grouping is on, and the BER performance for both 50G and 100G CWs is obtained by measuring performance of G1, and afterwards G2, at ONU1, see Fig. 2(f). We then apply FLCS-PON R=0.733 FEC code to obtain maximum OPL. This way, to the best of our knowledge, we achieve the highest OPL of more than 31.5 dB for 100 Gbit/s with intensity modulation and direct detection (IM/DD) over a deployed ODN[22],[23]. For NRZ OOK we can support more than 40 dB OPL.

Conclusions

We have successfully performed a trial of a FLCS-PON prototype unit over a deployed ODN and performed in-field validation and quantification of benefits of modulation and coding parameters flexibility allowing for trade-off between OPL and throughput. We were able to increase the average PON downstream bitrate to 82.2 Gbit/s. Using flex code we demonstrate record-high 100 Gbit/s OPL of >31.5 dB for an IM/DD ONU with a preamplifier.

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