Flexible Upstream FEC for Higher Throughput, Efficiency, and Robustness for 50G PON

Amitkumar Mahadevan[1], Yannick Lefevre[2], Ed Harstead[3], Werner van Hoof[4], Doutje van Veen[1], and Vincent Houtsma[1]
1. Nokia Bell Labs, 3. Nokia Fixed Networks: 600-700 Mountain Ave., Murray Hill, NJ, 07974, USA
2. Nokia Bell Labs, 4. Nokia Fixed Networks: Copernicuslaan 50, Antwerp, Belgium
amitkumar.mahadevan@nokia-bell-labs.com

Abstract: A low-complexity flexible forward error correction scheme based on different shortening and puncturing of the standard G.hsp 50G PON LDPC mother code to achieve enhanced throughput and robustness in upstream PON is motivated and presented.

1. Introduction

The recently consented ITU-T G.hsp (G.9804) TDM PON standard [1] employs 50 Gb/s per wavelength (λ) non-return to zero (NRZ) transmission in the downstream (DS) and either 12.5 Gb/s or 25 Gb/s per λ NRZ in the upstream (US). A forward error correction (FEC) scheme based on a (17280, 14592) binary low-density parity-check (LDPC) code obtained by puncturing 384 bits from a (17664, 14592) mother code was selected to ensure that the stringent loss budget requirements are met at these high bit rates [2]. While a key motivation for choosing a length of 17280 for DS was to ensure an integer number of codewords in the DS frame, the same code was adopted for US for consistency.

PON standards so far have been designed for the worst case to ensure that an optical network unit (ONU) operating under the maximum path loss and dispersion can still meet the performance requirements. Until now, design for the channel conditions of individual ONUs has not been specifically considered. Unlike continuous mode broadcast transmission in the DS, US communication from the various ONUs to the optical line terminal (OLT) is achieved via burst mode time-division multiple access. Hence, mechanisms that flexibly adjust the US throughput on a per ONU basis to adapt to the ONU's individual channel can be more easily implemented. Introducing flexibility for the US is very appealing since US burst mode is typically more challenging than DS continuous mode. Modifying the FEC code rate by different puncturing and shortening of the same mother code to provide a throughput (code rate) vs. FEC-input bit-error ratio (BER) trade-off is especially attractive since it can be realized with small additional complexity. In this paper, we motivate the benefits of flexible FEC for G.hsp US in detail. We also analyze the throughput versus BER performance trade-offs that can be achieved by such a scheme and discuss aspects pertaining to its implementation.

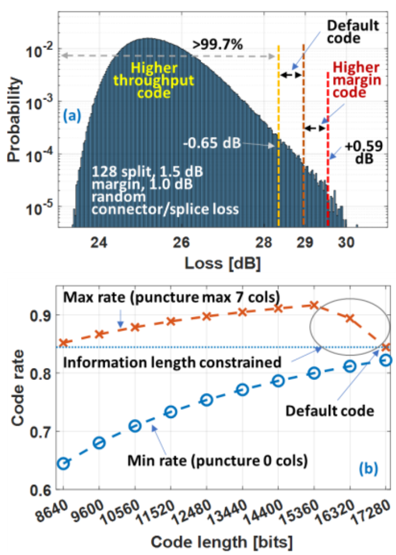
2. The case for flexible US FEC in PON

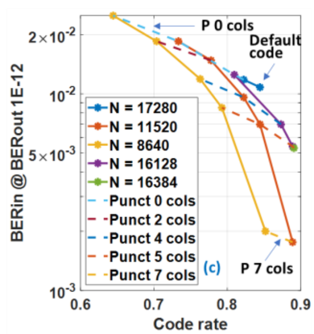
Figure 1(a) shows the predicted distribution of class B+ optical distribution network (ODN) optical path losses based on Monte Carlo simulations over 800,000 ONUs, extrapolated from field data modeling by Orange [3], specifically for ODNs with ≥ 48 ONUs. The extrapolation to path losses is carried out assuming 1×128 split, 1.5 dB margin, and 1.0 dB random connector/splice loss ($\mu = 1$, $\sigma = 0.3$). This plot shows that most of the ONUs experience significantly less loss compared to the 29 dB loss budget used for specifying the default FEC code in the standard [1]. The benefit of using a higher throughput FEC code for such ONUs is obvious. In such an approach, even the small number of ONUs operating with the default code will benefit from the lower-loss ONUs using the higher-throughput FEC code, as the latter will occupy less transmission time in the US frame, making more time available for the higher loss ONUs.

While the majority of ONUs experience milder conditions, Fig. 1(a) and the GPON field data from [3] also reveal the presence of a small fraction of 'tough' cases, i.e., ONUs operating at or beyond the loss budget. It should also be noted that mean OLT-ONU lengths are only expected to increase in the future as ODNs further penetrate into rural areas, thereby leading to more challenges for connectivity at the higher bit-rates [3]. Thus, FEC codes that can ensure sustained connectivity in such cases by providing additional margin as compared to the default code at the expense of reduced throughput are also highly desirable. Such codes also provide several tangible benefits in a real-world environment: (a) *Mitigation of the impact of an uncontrolled environment on the ONU transmitter:* An example is when operating temperatures exceed equipment ratings (i.e., an ONU in a closet with winter coats pushed up against it). (b) *ONU transmitter life extension:* When its lifetime is exceeded, the transmitter may fall out of specification. A higher-margin FEC can extend the life of the transmitter. (c) *Margin for asymmetric fiber loss:* The US fiber loss for 50G PON is higher than in the DS because the shorter US λ produces more Rayleigh scattering. The loss difference between 1260 nm (shortest US λ) and 1342 nm (nominal DS λ) is about 0.086 dB/km (5 km: 0.4 dB, 20 km: 1.7 dB). The higher-margin FEC could be used by operators to ameliorate less margin in their ODN plant design. (d) *Margin for burst mode specific penalties:* Burst mode operation has to contend with additional penalties such as optical beat interference [4], which worsen with increased US rates and higher split factors. E.g., penalties of 0.5 – 1.8 dB were reported in [4] for 25G US at BER = 1E-2. (e) *Performance guarantee in the absence of bit-interleaving (BI):* Optional BI across four codewords has been adopted for 50Gb/s DS [2] to mitigate the impact of correlated errors, which was shown to cause an optical penalty of up to 0.6 dB that was recovered almost completely by BI [6]. A similar impact of correlated errors is also expected for 50 Gb/s US that is likely to be defined in a future amendment to [1]. However, employing BI across multiple codewords is challenging in the US due to the variable burst size. A more robust FEC could instead provide increased margin against such penalties, especially for ONUs operating near the loss budget.

US bursts have varying lengths. G.9804 [1,2] allows for shortening of the last (or only) codeword of an US burst by fixing unused information bits in a FEC codeword to 0. The amount of transmitted parity in the last codeword is the same as all other codewords. The concept of flexible US FEC may also be extended to employ different FEC codes for different portions within an US burst beyond what may be supported in the standard. Use cases for such flexibility are: (a) *Tolerance to settling transients:* The beginning of an US burst may experience a higher BER as compared to the rest of the burst on account of transients associated with laser activation and receiver settling, or due to insufficient convergence of the receiver equalizer [5]. Configuring the first or first few codewords of an US burst to a reduced code rate can provide additional margin against these transients. (b) *Better efficiency for last codeword in burst:* Excessive shortening of the last codeword of the burst leads to inefficient transmission. For a specific code rate, this inefficiency is higher for a longer code length since the parity portion scales with length. The inefficiency in the last codeword can be reduced by applying a different amount of additional puncturing (i.e., a different burst-terminating code) in case the last codeword is sufficiently short while still achieving the performance of the default code [7].

Different considerations are more relevant for different line rates. At 50 Gb/s and 25 Gb/s, increased tolerance to settling transients, tolerance to ONU transmitter optics, and decreasing the aging margin could be more pertinent factors. At 50 Gb/s, performance guarantee in the absence of BI becomes significant, while at 12.5 Gb/s, improved throughput and burst efficiency is more germane since most ONUs will be operating with excess margin.





N [bits]	K [bits]	P [cols]	S [cols]	Code rate	BERin	ECG [dB]	OCG [dB]
17280	14592	1.5	0	0.844	1.08E-2	Default code	
8640	5568	0	35.25	0.644	2.5E-2	+1.38	+0.97
8640	7360	7	28.75	0.852	2E-3	-1.98	-1.39
11520	8448	0	24	0.733	1.85E-2	+0.84	+0.59
11520	10240	7	17	0.888	1.76E-3	-2.07	-1.45
16128	13056	0	6	0.810	1.25E-2	+0.21	+0.15
16128	14336	5	1	0.889	5.4E-3	-0.90	-0.63
16384	14592	5	0	0.891	5.3E-3	-0.93	-0.65

N: Codeword length, *K*: Information length, *P*: Punctured parity columns, *S*: Shortened columns (column = 256 bits), BERin: Input BER to achieve post-FEC BER < 1E-12, ECG: Electrical coding gain w.r.t default code, OCG: Optical coding gain w.r.t default (OCG = 0.7×ECG). (d)

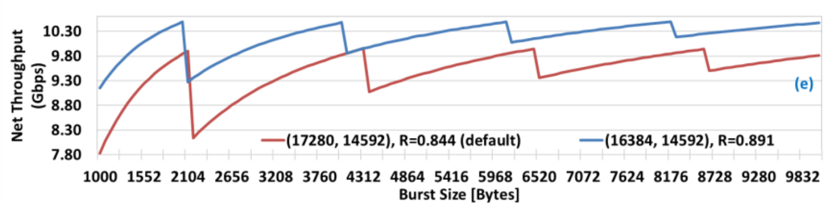


Fig. 1: (a) Estimated distribution of class B+ ODN optical path losses (max. 29 dB loss) extrapolated from modeling of field data by Orange [3]. (b) Achievable code rate vs. code length for different shortening and puncturing of the LDPC mother code [2]. (c) LDPC decoder input BER (for output BER of 1E-12 assuming a BSC) vs. code rate; each solid curve represents a fixed code length, each dashed curve represents a fixed puncturing amount. (d) Table listing performance of relevant LDPC codes from Fig. 1(c). ECG and OCG are computed with respect to the default code (*N* = 17280, rate 0.844). (e) Net throughput at 12.5 Gb/s line rate vs. burst size in bytes (payload + parity) assuming 94.7% frame utilization.

3. Complexity impact and performance trade-offs of flexible US FEC

In order to minimize the impact on implementation, US FEC variants based on different puncturing and shortening of the default US LDPC mother code are an attractive solution. For an ONU, the FEC encoder already must support shortening due to burst-mode operation. Hence, the use of shortening for the higher-margin variant does not introduce any added complexity. Any higher-throughput FEC variant will require the generation of fewer bits of parity and can therefore be supported with no further increase in encoder complexity. Any higher-margin FEC variant will require the generation of at most 1.5 additional columns of parity which leads to a negligible overall increase in ONU SoC complexity. For the OLT, the FEC decoder must support decoding of one or more variant codes, at additional complexity on the same order of magnitude as those of the ONU encoder. Finally, both encoder and decoder need to be capable of supporting sustained processing with the higher throughput or higher margin FEC variants that are likely to be shorter than the default LDPC code. This may be achieved by enforcing a lower limit on the code length of variants. For example, a lower limit of about 8700 bits (~½ the default code length) has been provided as a guidance in [2]. Thus, the resources to implement such a scheme are expected to be of low additional hardware complexity.

Next, we explore the BER vs. code rate trade-offs for codes obtained by different puncturing and shortening of the US mother code, which is performed as illustrated in Fig. 2 of [8]. For a fixed code length, the lowest code rate is obtained when no parity is punctured. We limit puncturing to a maximum of 7 (out of 12) columns of parity to obtain the highest code rate, which is primarily driven by the observation that the code performance degrades drastically with more aggressive puncturing. Fig. 1(b) plots the achievable range of code rates as a function of code length (e.g., for length 11520, rates are in [0.733, 0.889]). Only lengths of 8640 and higher are considered, which is consistent with the sustained processing lower limit discussed above. When the code length exceeds 62×256, it is no longer possible to puncture 7 columns of parity since the maximum information length is 57×256; thus, beyond this point, the maximum achievable code rate starts decreasing as shown by the "information length constrained" region in Fig. 1(b). Figure 1(c) shows the input BER vs. code-rate for an output BER of 1E-12 for different lengths and different amounts of shortening and puncturing assuming a binary symmetric channel (BSC). These results are obtained via simulations employing a layered min-sum decoding algorithm with 14 iterations. Figure 1(d) tabulates the performance of certain codes in terms of electrical coding gain (ECG) and optical coding gain (OCG) with respect to the default code; here, we compute OCG = 0.7×ECG which is an approximate rule of thumb for avalanche photo detectors. From the figure, we see that a higher input BER (higher coding gain) is achieved by shorter codes with lower code-rates. Also, for a specific code rate, the longest achievable code gives the best BER performance, and hence, is most desirable.

Figures 1(b), (c) and (d) demonstrate the range of flexibility achievable by different amounts of shortening and puncturing; however, it is not necessary for a flexible US FEC scheme to support all the variations. Rather, a significant amount of flexibility can be achieved by considering only a small subset of codes; for instance, the (11520, 8448) code with rate 0.733, the (16384, 14592) code with rate 0.891 (both indicated by highlighted rows in Fig. 1(d)), as well as the default DS code. The rate 0.891 code provides a 5.4% improvement in throughput at the expense of 0.65 dB in optical loss budget. From Fig, 1(a), we see that such a code may be beneficial for >99% of deployed ONUs. The higher-margin rate 0.733 code is capable of tolerating an input BER of >1.8e-2 and provides an additional 0.59 dB of optical margin for improved robustness at the expense of a 13% throughput reduction. Additionally, the rate 0.644 (8640, 5568) code may also be considered for even higher optical margin (~1 dB) at a 24% rate reduction.

Finally, Fig. 1(e) compares the throughput of the default code vs. the rate 0.891 code in a scenario where 12.5 Gb/s line rate ONUs transmit several short US bursts. A frame utilization of 94.7% is assumed based on an objective overhead time of 206 ns [1] with 32 bursts per US frame. The (16384, 14592) code not only provides better throughput across different burst sizes since the higher code rate of 0.891 raises the peak level, but also shows a reduction in the amplitude of the discontinuities (at codeword boundaries) on account of its smaller parity size. Consequently, over the range of considered burst sizes, the (16384, 14592) code has a 7.5% higher average throughput over the default code, which exceeds the value of 5.4% calculated purely based on the ratio of code rates. Additionally, in comparison to the rate 0.871 RS(248, 216) code used in 10 Gb/s US, this code not only has a higher rate, but it also provides better input BER performance (>5E-3 vs ~1E-3 for RS(248, 216): OCG of 1.1 dB). Thus, it is also capable of absorbing higher penalties which enable the reuse of 10G optics for 12.5G operation.

4. Summary and Conclusions

We discussed the rationale for adopting a flexible FEC scheme for G.hsp PON [1]. We demonstrated that choosing at least one code variant with higher throughput and one with higher margin compared to the default can improve the robustness and throughput of US transmission. Deriving code variants from the same mother code using different shortening and/or puncturing ensures minimal additional complexity for the OLT and ONU. Taking these considerations into account, there has been agreement in ITU-T that flexible US FEC is indeed worthy of further study for definition in a future amendment of the G.hsp TDM PON standard.

5. References

[1] "50-gigabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification," ITU-T G.9804.3 (2021).

[2] "Higher Speed Passive Optical Networks: Common Transmission Convergence Layer Specification", ITU-T G.9804.2 (2021).

[3] G. Simon *et al.*, "50Gb/s TDM PON Digital Signal Processing Challenges: Mining current G-PON Field Data to Assist Higher Speed PON", ECOC 2020, Tu2J.7.

[4] J. Potet *et al.*, "Optical Beat Interference in Burst Mode Upstream Links of the Higher Speed-PON: Situation, Penalties and Solution", ECOC 2021, Tu1F.6.

[5] M. Yang *et al.*, "Real-Time Verification of Soft-Decision LDPC Coding for Burst Mode Upstream Reception in 50G-PON," JLT, '20.

[6] A. Mahadevan *et al.*, "Hard-input FEC evaluation using Markov models for equalization-induced correlated errors in 50G PON," JOCN, '21.

[7] Y. Han *et al.*, "HSP Upstream LDPC Scheme", contribution D47, ITU-T SG15/Q2 conf. call, July 6-10, 2020.

[8] R. Borkowski *et al.*, "FLCS-PON – A 100 Gbit/s Flexible Passive Optical Network: Concepts and Field Trial", JLT, '21.

This work was partially supported by the Flemish Government funding agency VLAIO, through the SPIC project (HBC.2020.2197).