FEC code for 25/50/100G EPON

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(Acknowledging Nicola Brandonisio (Tyndall, Ireland) for interesting discussion)

IEEE P802.3ca 100G-EPON Task Force Meeting, Vancouver, BC, Canada, March 2017

Outline

- ❖ Forward error control code families
- ❖ FEC gain
- ❖ Burst mode receivers
- ❖ Error models for PON
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- ❖ Previously proposed FEC
- ❖ Comparison suitable codes propose thus far
- ❖ Conclusions

Forward Error Control Code Families

Algebraic Codes

- Symbol-based: for example RS codes, good for random and bursty errors
- Binary codes: BCH codes achieve additional coding gain with similar code compared to RS codes, but the performance is reduced for non-memoryless channels.

Algebraic Component Codes

- Concatenated codes/product codes: iterative decoding
- Folded codes: use a larger alphabet to increase coding gain
- Interleaved codes: increase burst error correction capability (increased latency)

Low-Density Parity-Check (LDPC) codes and Turbo codes

- A wide variety of code constructions and interleaver designs
- Performance and code rate tends to improve for longer code lengths.
- Ability to handle soft-input, and/or to use soft-decoding.

Forward Error Control Code Families - Algebraic Codes

Reed Solomon (RS) codes

Notation: RS(n,k) code over GF(2^m), symbol-size: m bits, length: n symbols, of which k information symbols, length in bits: $n \cdot m$.

- Guaranteed to correct up to $t = (n - k)/2$, error performance can be computed (AWGN)
- Guaranteed to correct a single burst up to length $(t - 2) \cdot m + 2$
- Flexible, easy to adjust code length and code rate
- Widely used in optical systems, DSL, …

Bose Chaudhuri Hocquenghem (BCH) codes

Notation: BCH(n,k) codes over GF(2^m), bit-oriented

- Guaranteed minimum error correction capability: $t = (n-k)/m$, for high-rate codes
- Burst error capability: t
- Flexible, easy to adjust code length and code rate

See [1,2,] for further details

Forward Error Control Code Families – LDPC codes

Low-Density Parity Check Codes

Parameters: code length n, with k information bits, and an $m \times n$ parity-check matrix $\mathbf{H}$.

- Minimum distance depends on design and may be low (possibility of an error floor)
- Code performance is typically determined by simulation
- The effect of burst errors is spread across the code by interleaving
- Adjustment of code length and code rate needs careful puncturing
- Massively parallel implementation of the decoder is possible
- Trade-offs regarding decoder performance, gate count, latency.

Turbo Codes

Parameters: generator polynomials for component code, specification of interleaver.

- A more serial encoding and decoding structure
- Particularly interesting for lower rate codes; more challenging to design good high-rate codes
- Codes are more likely to be used in combination with retransmission schemes
- Code performance is typically determined by simulation

See [1,2] for further details

FEC gain: Optical FEC gain is different from electrical FEC gain

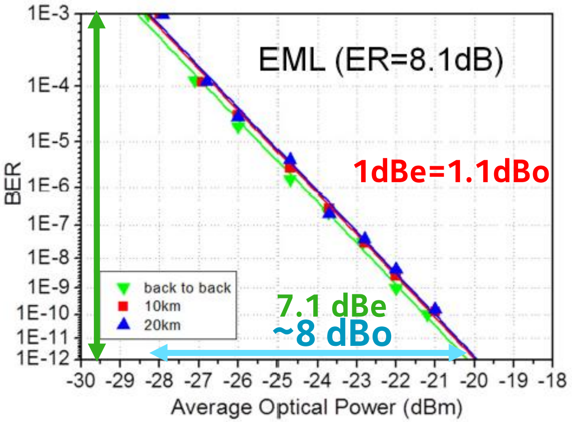
Due to optical receiver noise:

- APD receiver case

0.7-0.9 × electrical gain (depending on thermal/shot noise ratio)

>1 × electrical gain (practical links)

However the slope is important to determine optical FEC gain relative to RS(255,223)



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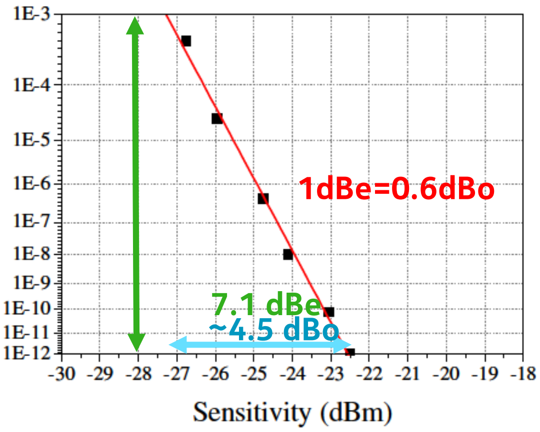

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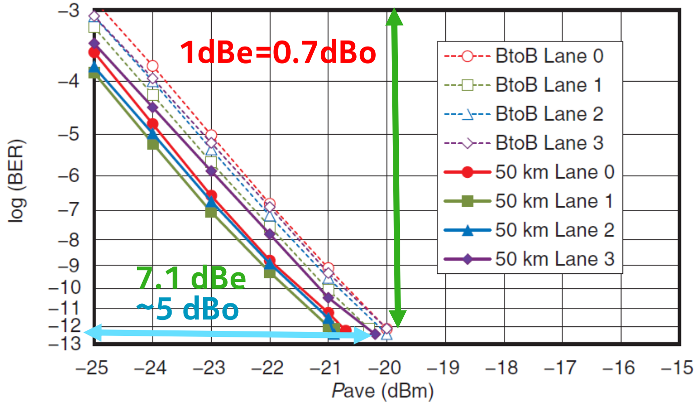

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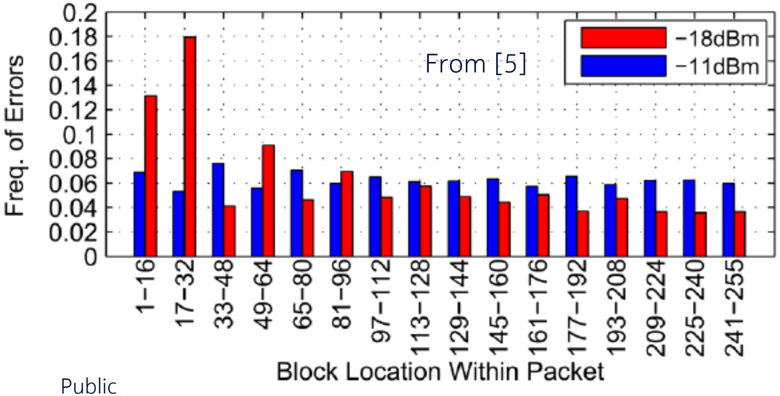
FEC gain

Other factors affecting performance after FEC:

- effect of intersymbol interference (ISI) due to chromatic dispersion and limited bandwidth: signal dependencies across symbols, burst-like errors (channel with memory)
- burst-mode receiver: Bursty errors at start of burst, BER variations between bursts of same ONU (burst mode penalty)
- twin errors in conventional NRZ-case when using precoding: twin errors are absorbed by symbol-based FEC codes with probability $(m-1)/m$, and as such have a higher relative coding gain for twin errors when compared with bit-oriented FEC codes, where the number of observed bit errors doubles.



From [5]

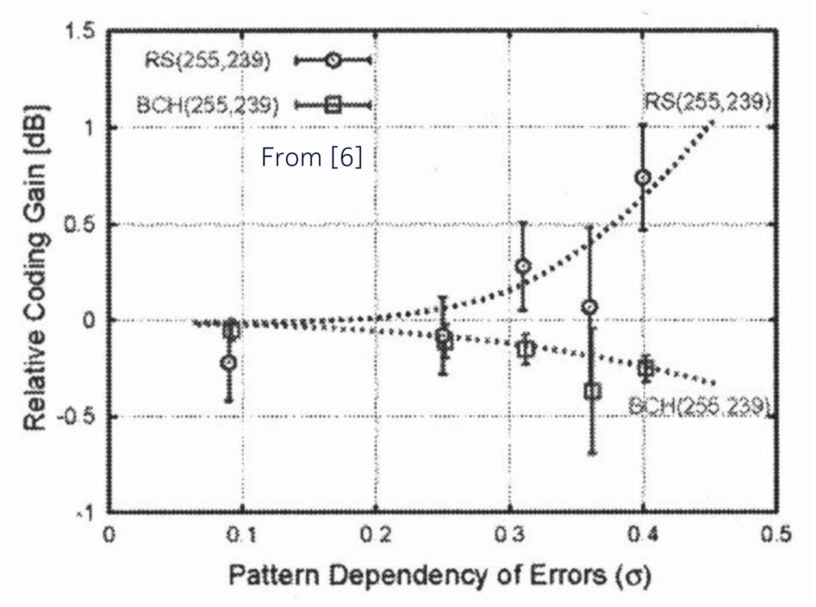
Burst mode receivers

RS-FEC for burst mode transmission

Significant reduced FEC gain due to non-random error distributions from BM receiver effects have been shown:

- in [3]: 10G AC-coupled BM Rx with RS(248,216): 8e-4->1e-12 for BM instead of 1e-3, bursty errors at start burst
- In [4]: 2.5G DC-coupled BM Rx with RS(248,232): 2e-6->1e-12 instead of 1e-4, BER not same for each burst due to for example threshold extraction errors (burst mode penalty)
- In [5]: 10G optical pre-amplified BM Rx with RS2(255,223): 5e-5/5e-6 -> 1e-12 instead of 1.1e-3, burst errors at start of burst due to transients
- In [5]: *Downstream* transmission also showed a reduced FEC gain: 2e-4->1e-12 instead of 1.1e-3, due to the 64B/66B descrambler and ISI effects

There is a trade-off between optical overhead (preamble) and the reduced FEC gain in upstream PON



From [6]

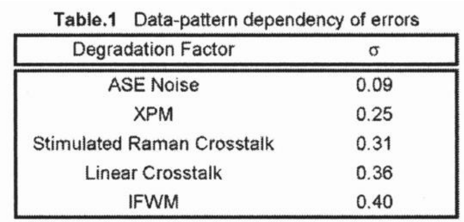


Table.1 Data-pattern dependency of errors

Degradation Factor	σ
ASE Noise	0.09
XPM	0.25
Stimulated Raman Crosstalk	0.31
Linear Crosstalk	0.36
IFWM	0.40

Normalized standard deviation σ, of number of number of errors with respect to bit position for different impairments: (from ref [6])

Error models for PON

- Even for errors occurring in the continuous mode downstream PON transmission, the ideal AWGN model is over-estimating performance of 8-bit symbol RS codes (channel is not complete random)
- Codes with shorter burst error correcting capability will perform worse for non-memoryless channels
- In upstream the errors are dependent on position in the burst, settling effects cause more bursty errors at start of the burst, causing the error correction to fail at beginning of burst
- We could introduce bursty errors similarly to for example done in the Gilbert–Elliott model [7][8] for a more correct channel model for especially the upstream direction PON (more states can be added to model burstiness throughout burst in time)

Gilbert-Elliott model has two states: *G* (for good or gap) and *B* (for bad or burst). The model uses state transition probabilities and channel parameters for the states.

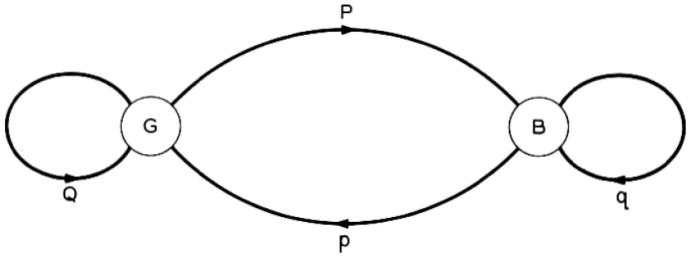
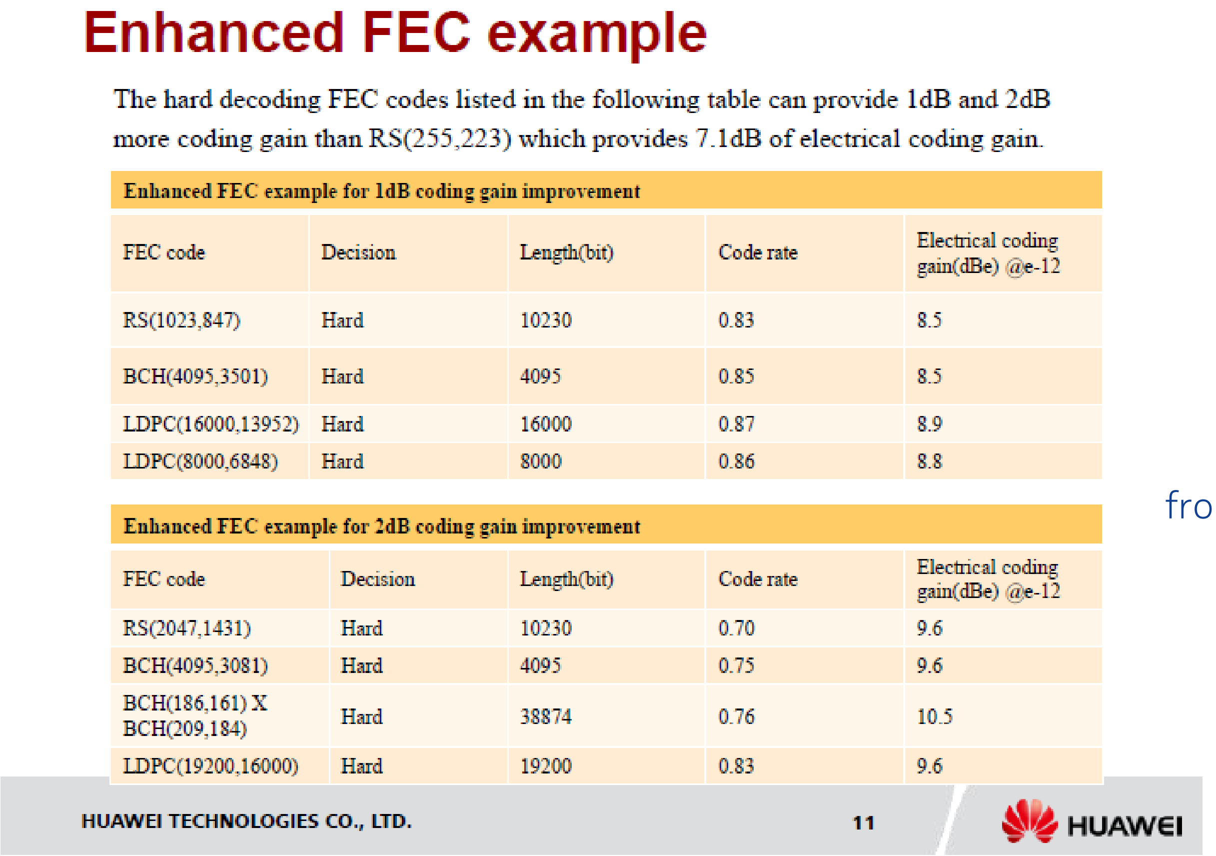


Fig. 1 — Transition diagram for the Markov chain.

Previously proposed FEC



Enhanced FEC example

The hard decoding FEC codes listed in the following table can provide 1dB and 2dB more coding gain than RS(255,223) which provides 7.1dB of electrical coding gain.

Enhanced FEC example for 1dB coding gain improvement

FEC code	Decision	Length(bit)	Code rate	Electrical coding gain(dBe) @e-12
RS(1023,847)	Hard	10230	0.83	8.5
BCH(4095,3501)	Hard	4095	0.85	8.5
LDPC(16000,13952)	Hard	16000	0.87	8.9
LDPC(8000,6848)	Hard	8000	0.86	8.8

Enhanced FEC example for 2dB coding gain improvement

FEC code	Decision	Length(bit)	Code rate	Electrical coding gain(dBe) @e-12
RS(2047,1431)	Hard	10230	0.70	9.6
BCH(4095,3081)	Hard	4095	0.75	9.6
BCH(186,161) X BCH(209,184)	Hard	38874	0.76	10.5
LDPC(19200,16000)	Hard	19200	0.83	9.6

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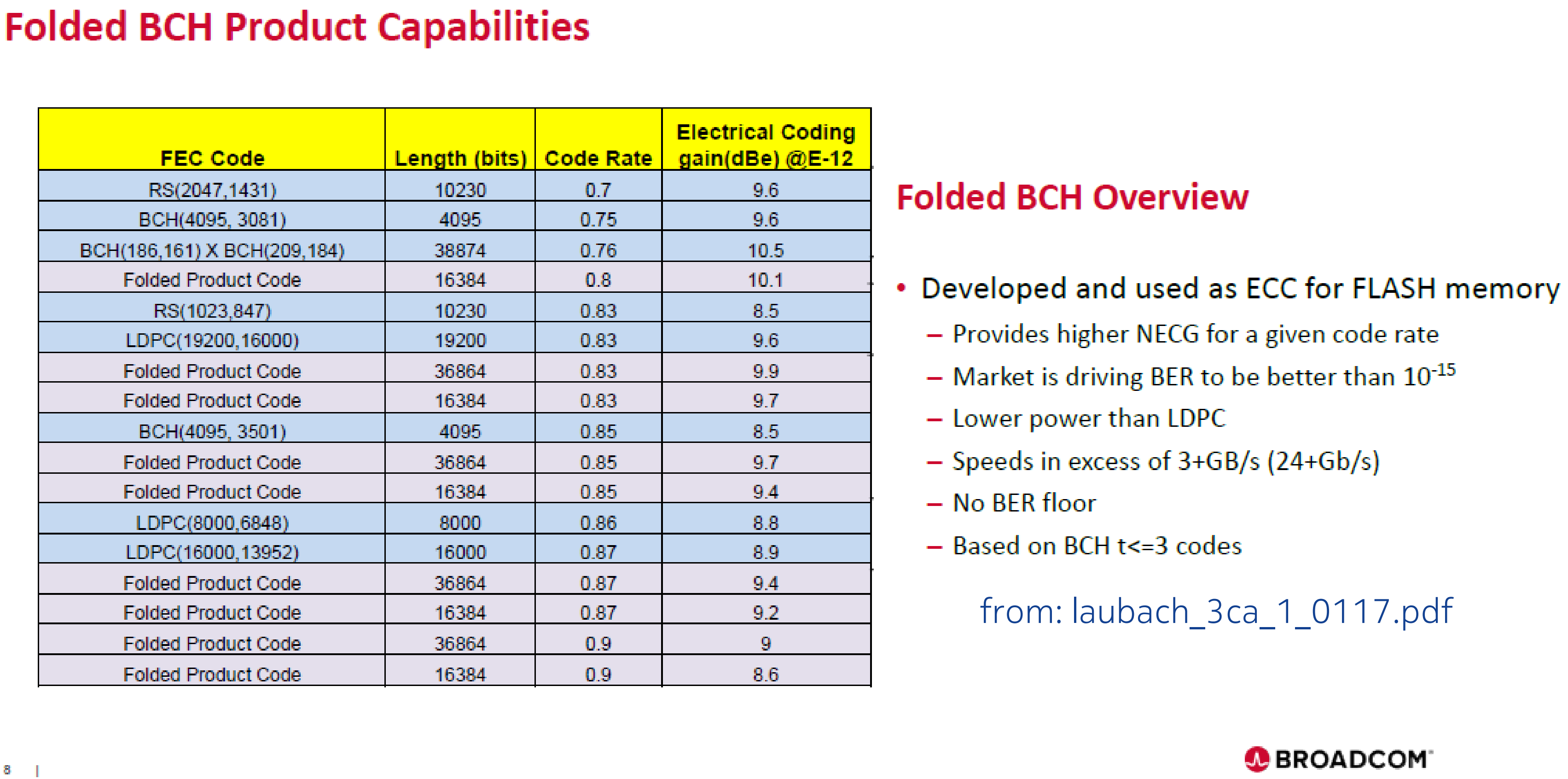
from: effenberger_3ca_1_1116.pdf

Previously proposed FEC



Folded BCH Product Capabilities

FEC Code	Length (bits)	Code Rate	Electrical Coding gain(dBe) @E-12
RS(2047,1431)	10230	0.7	9.6
BCH(4095, 3081)	4095	0.75	9.6
BCH(186,161) X BCH(209,184)	38874	0.76	10.5
Folded Product Code	16384	0.8	10.1
RS(1023,847)	10230	0.83	8.5
LDPC(19200,16000)	19200	0.83	9.6
Folded Product Code	36864	0.83	9.9
Folded Product Code	16384	0.83	9.7
BCH(4095, 3501)	4095	0.85	8.5
Folded Product Code	36864	0.85	9.7
Folded Product Code	16384	0.85	9.4
LDPC(8000,6848)	8000	0.86	8.8
LDPC(16000,13952)	16000	0.87	8.9
Folded Product Code	36864	0.87	9.4
Folded Product Code	16384	0.87	9.2
Folded Product Code	36864	0.9	9
Folded Product Code	16384	0.9	8.6

Folded BCH Overview

- Developed and used as ECC for FLASH memory
  - Provides higher NECG for a given code rate
  - Market is driving BER to be better than 10^{-15}
  - Lower power than LDPC
  - Speeds in excess of 3+GB/s (24+Gb/s)
  - No BER floor
  - Based on BCH t<=3 codes

from: laubach_3ca_1_0117.pdf

FEC requirements for 25/50/100 EPON

- Limit Overhead to 18% (coding rate 0.82), so we can support two 10G with 25G (from laubach_3ca_1_0117.pdf) *(15% OH from laubach_3ca_1_0317.pdf?)*
- Needs good burst error correction capability because especially upstream PON channel is not fully random (ISI, burst settling effects, etc.)
- Block length limited by upstream: Max. Ethernet Frame=1.5 kbytes, codeword size range of 2k to 4k bytes ("provides a workable balance of decoding latency, complexity, and Net Effective Coding Gain (NECG)" in laubach_3ca_1_0117.pdf).
- FEC gain ~8.5-10 dBe (target 1-2 dBo extra compared to RS(255,223)) ideally using channel with memory
- Hard decision (enabling conventional (direct detection) 25G NRZ)
- Same FEC for up- and downstream (from laubach_3ca_1_0117.pdf)
- Low implementation complexity
- Low power consumption
- Latency requirement?
- Flexibility?

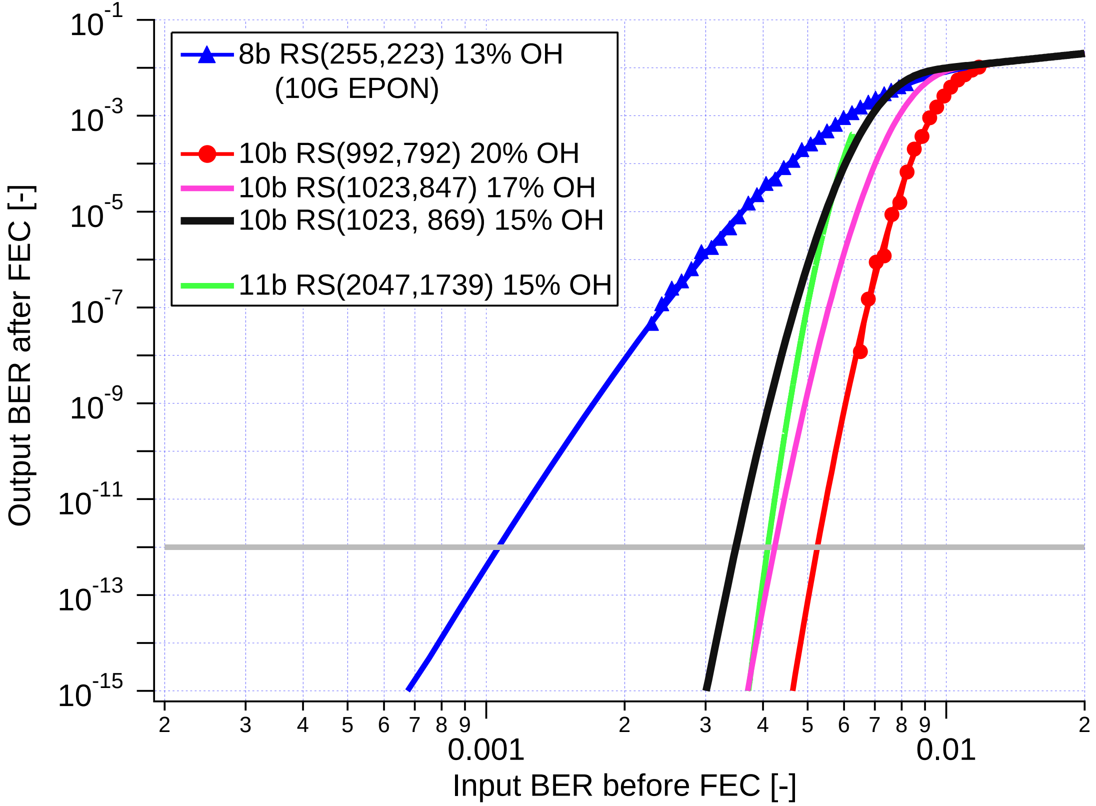
Comparison of suitable codes proposed thus far
Using ideal AWGN-model (only random errors)

*) Assuming APD-based receiver with 1 dBe = (0.7-0.9) dBo

FEC code	OH (%)	FEC Gain (dBe) @BERout =1e-12	BERin for BERout =1e-12	Optical gain delta relative to RS(255,223) (dBo)*	Length (bits)	Burst errors Capable (bits)	Power consumption	Complexity	Latency
RS(255,223)	12.5	7.1	1.1e-3	0	2040	114	low	low	low
RS(1023,847)	17.2	8.5	4.2e-3	1-1.3	10230	862	med	low	low
RS(2047,1739)	*15*	*8.5*	*4.1e-3*	*1-1.3*	*22517*	*1674*	*med/high*	*med*	*med*
BCH(4095,3501)	14.5	8.5	4e-3	1-1.25	4095	49	med	low	low
LDPC(16000,13952)	13	8.9	5.8e-3	1.25-1.6	16000	?	high	high	high
LDPC(19200,16000)	17	9.6	1e-2	1.75-2.25	19200	?	high	high	high
Folded product BCH	17	9.7	1.1e-2	1.8-2.35	16384	?	?(<LDPC)	?	?

We have to be careful when comparing FEC gain relative to RS(255, 223) for alternative codes that have shorter burst error capabilities.
Coding gain improvement might turn out smaller than expected!

RS-code performance for memory-less channel (only random errors)



- Reed-Solomon codes can be made stronger by making them longer.
- However, FEC gain improvement slows down with length.
- 10-bit RS-code with 17% OH has a similar FEC gain as a 11-bit RS-code with 15% OH
- 11-bit code has ~2x burst error correcting capability compared to 10-bit code, and ~14x compared to 8-bit code

Conclusion

We propose a RS(n,k) code with length ~1000/2000 symbols (for example RS(1023,847) or RS(2047,1739)) for 25/50/100G EPON

- RS(1023,847)/RS(2047,1739) have a burst correcting capability of 862 bits/1674 bits (34ns/67ns at 25 Gbps) which is a reasonable order of magnitude for burst mode settling effects (performing even better than RS(255,223) which can handle 4.6 ns error bursts at 25 Gbps)
- RS(1023,847) has 17% OH and RS(2047,1739) has 15% OH, they both provide >= 1 dB optical FEC gain relative to RS(255,223) (will be more for channel with memory)
- 15-17% OH enables two 10 Gbps services within 25 Gbps
- Reed Solomon codes have a proven track record in TDM-PONs
- Length of RS(n,k) codes is flexible (can easily be truncated with zero padding)
- A symbol-based RS code is very effective for mitigating 'twin errors' due to differential precoding in the conventional NRZ case, ~0.5 dB optical penalty before and <0.1 dB after FEC for the example RS code, see also houtsma_3ca_1_0916.pdf

Exact code parameters to be determined to match linecode, etc.

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