Dual Coding Concatenation for Burst-Error Correction in Probabilistic Amplitude Shaping

Pavel Skvortcov*, Toshiaki Koike-Akino, David S. Millar*, Keisuke Kojima,
Kieran Parsons

* *Currently with Infinera Corporation*

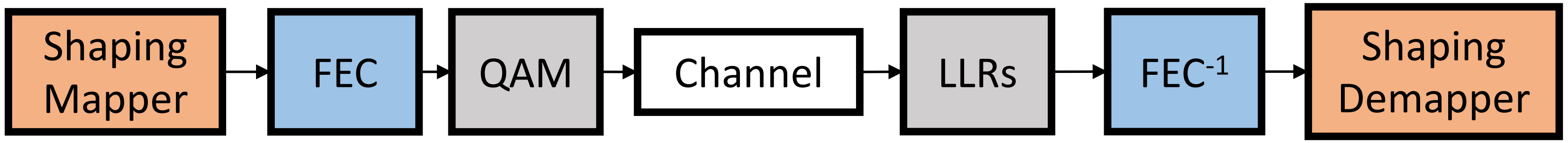
ECOC 2021, September 2021

MITSUBISHI ELECTRIC RESEARCH LABORATORIES (MERL)
Cambridge, Massachusetts, USA
http://www.merl.com

koike@merl.com

Background

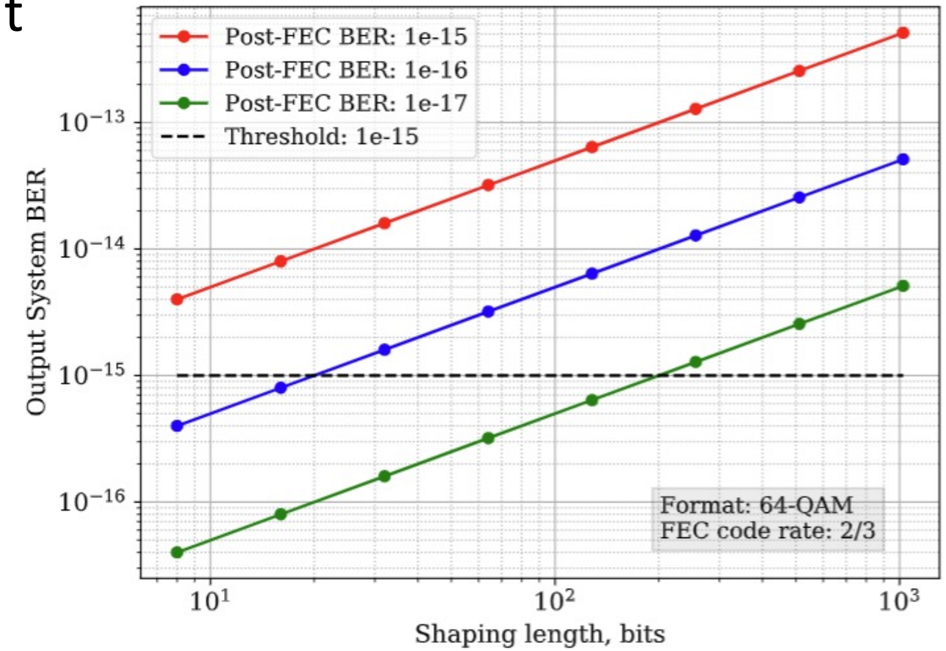
- Probabilistic shaping in coherent optical communication systems became a mature commercial technology
  - Key enabler is probabilistic amplitude shaping (PAS) architecture
  - Low-complexity implementation: independent design of FEC coding and shaping



- PAS architecture typically employs *reverse* concatenation of shaping and FEC
  - FEC coding is performed on shaped bits
    - Powerful SD-FEC + low-overhead HD-FEC
  - Received bits are first decoded with FEC, then demapped to information bits
    - For demapping we assume that all received bits are correctly decoded
    - In practice FEC systems can have a non-zero probability of errors

BER enhancement in PAS

- The common bound on acceptable performance: post-FEC BER threshold of 10^{-15}
  - Typical FEC performance target for conventional systems with uniform signaling
- For PAS systems BER enhancement may occur after shaping demapping:
  - Uncorrected post-FEC errors in shaping sequences may result in burst errors
  - Single error in shaping sequence of length *L* may result in burst error of length *L* after shaping demapping
    - 50% of bits are flipped within a burst
- BER enhancement increases with shaping length!



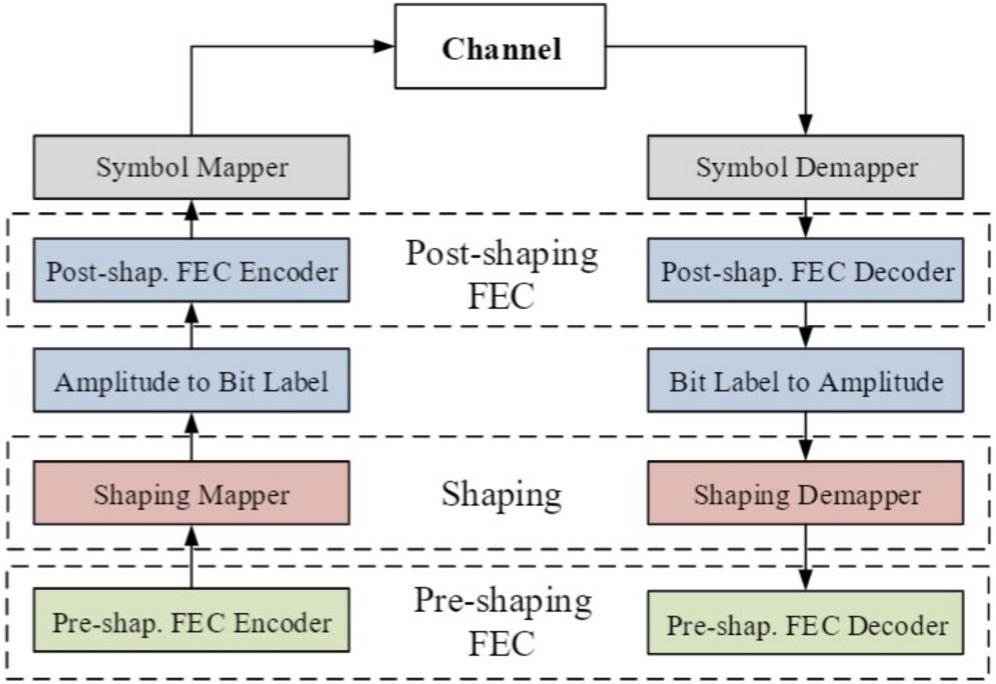
- Possible solutions:
  - Target lower post-FEC BER
  - **Post-correction of burst errors**

Dual-concatenation for PAS

- We propose *dual coding concatenation* for PAS systems
  - Pre-shaping (forward concatenation) and post-shaping (reverse concatenation) FEC layers
    - Shaping precedes FEC coding in reverse concatenation, while opposite in forward concatenation

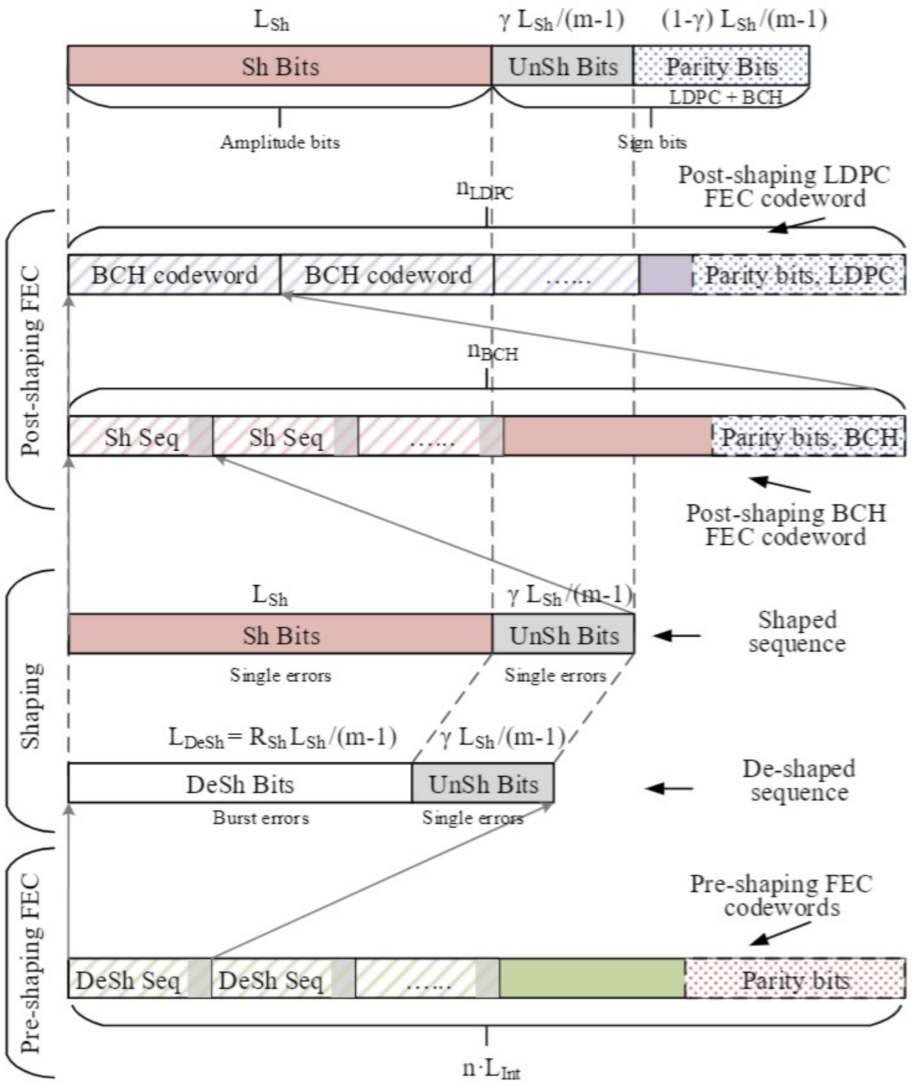
- For post-shaping FEC layer we consider concatenation of codes:
  - Powerful SD LDPC code
  - Low-complexity BCH code

- Pre-shaping FEC layer is placed outside the shaping layer and designed to correct burst errors after shaping demapper
  - Various burst-error correction approaches can be considered for pre-shaping FEC



Dual-concatenation for PAS

- Framing and mapping of shaping sequences and FEC words at the receiver
  - Decoding with LDPC code
  - Decoding with BCH code
  - De-shaping
    - De-shaped sequences are shorter than shaped sequences
    - Burst can occur in de-shaped bits, but not in un-shaped bits
  - Decoding with pre-shaping FEC code



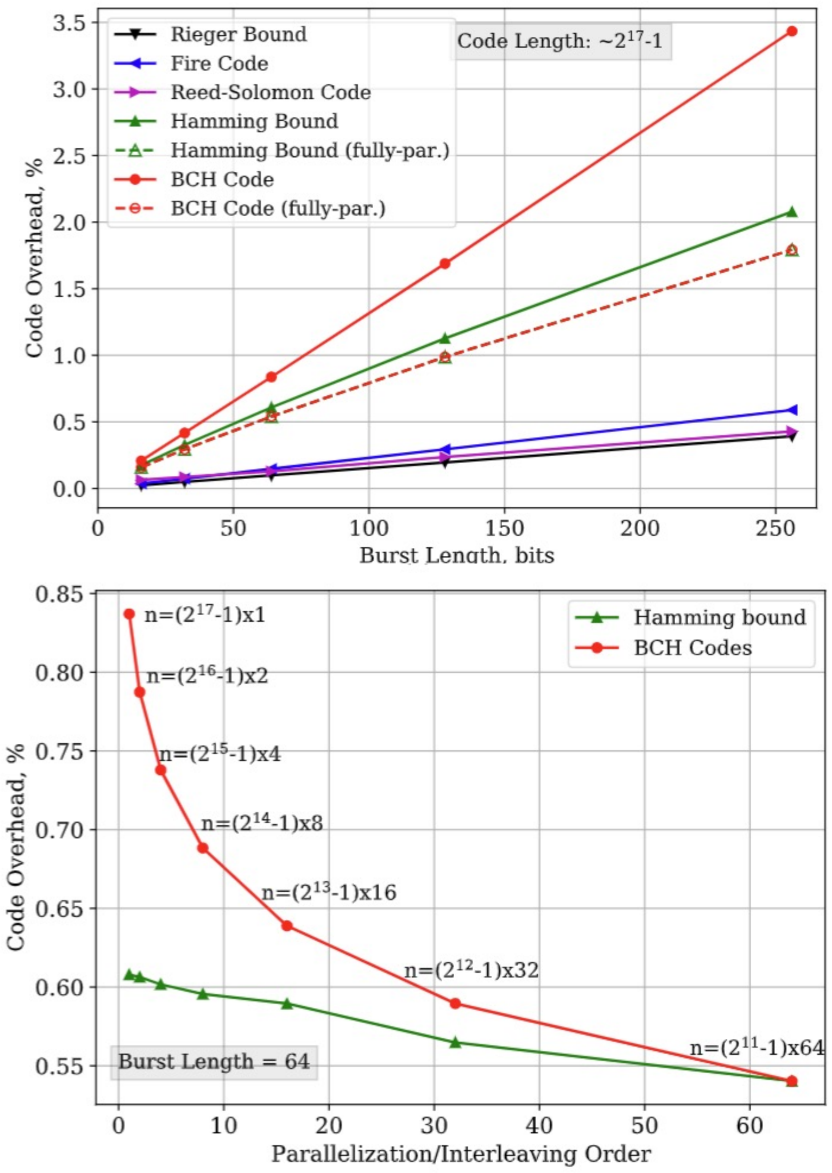
Burst error correction bounds

- We compare various burst error correction approaches/bounds:

Type	Bound
Rieger Bound	$k = n - 2l$
Fire Code	$k = n - 3l$
Reed-Solomon Code	$k^{\text{sym}} = n^{\text{sym}} - 2l^{\text{sym}}$, where $l^{\text{sym}} = 1 + \lfloor \frac{l+s-2}{s} \rfloor$, s – symbol size
Hamming Bound	$k = n - \left\lceil \log_2\left(\sum_{l=0}^{t} \binom{n}{l}\right) \right\rceil$
BCH Code	$k = n - l\log_2(n+1)$

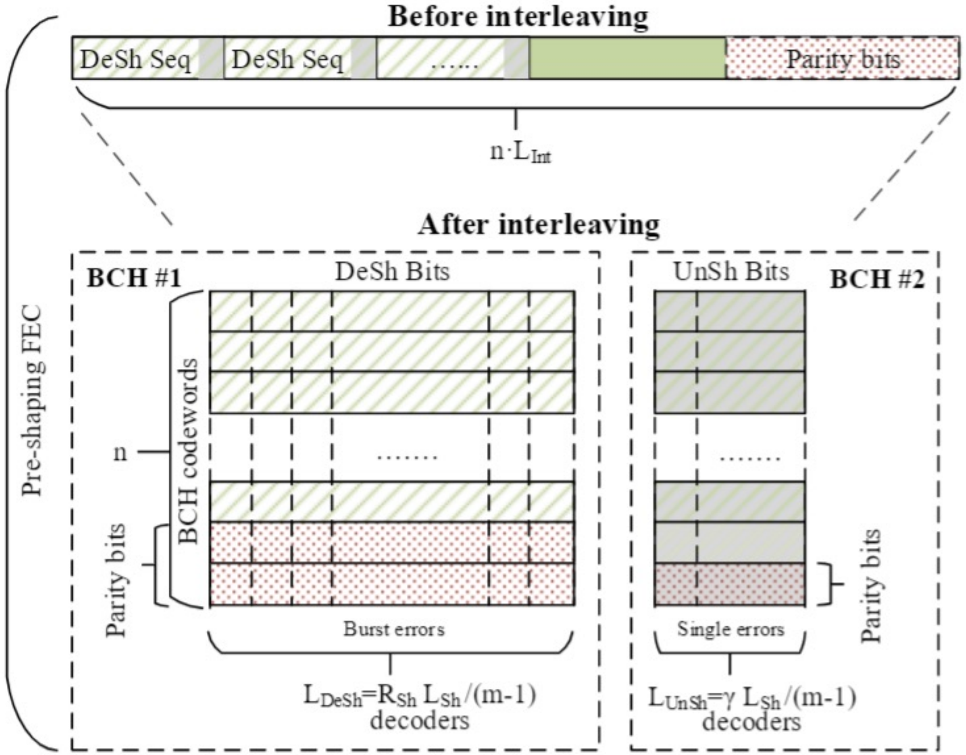
- Parallel structures based on block interleaving to enhance burst error correction ability of random error correction approaches
  - Burst error is spread among multiple shorter codewords
  - Short codes with reduced error correcting ability can be used

Single burst correction



Parallel BCH code

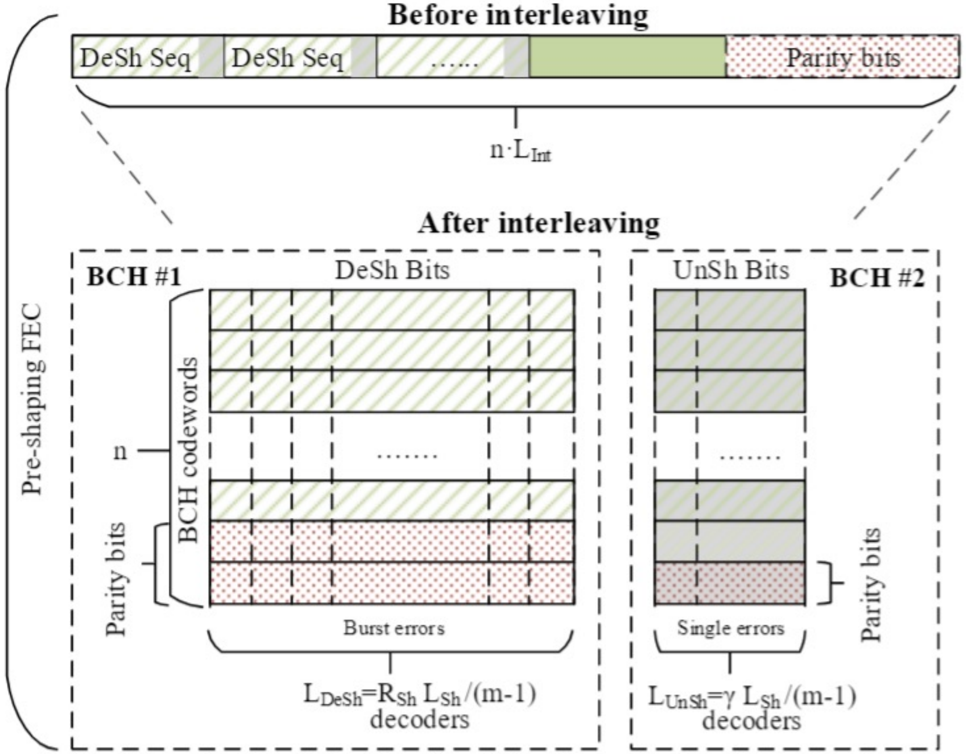
- While random error correction approaches are in general less efficient, parallel approach can offer:
  - Low-complexity
  - Scalability
  - Ability to correct multiple burst
- We propose architecture based on BCH codes and block interleaving of shaping sequences
  - Each column in interleaved structure is a codeword
    - Enables fully-parallel encoding/decoding, suited for high-throughput systems
    - Separate BCH codes can be used for shaped/unshaped bits
  - Can be scaled with shaping rate
    - Adaptivity is achieved by enabling/disabling decoders



- For full interleaving we have no more that T errors per parallel codeword after interleaving when T burst occurs within non-interleaved structure

Parallel BCH code

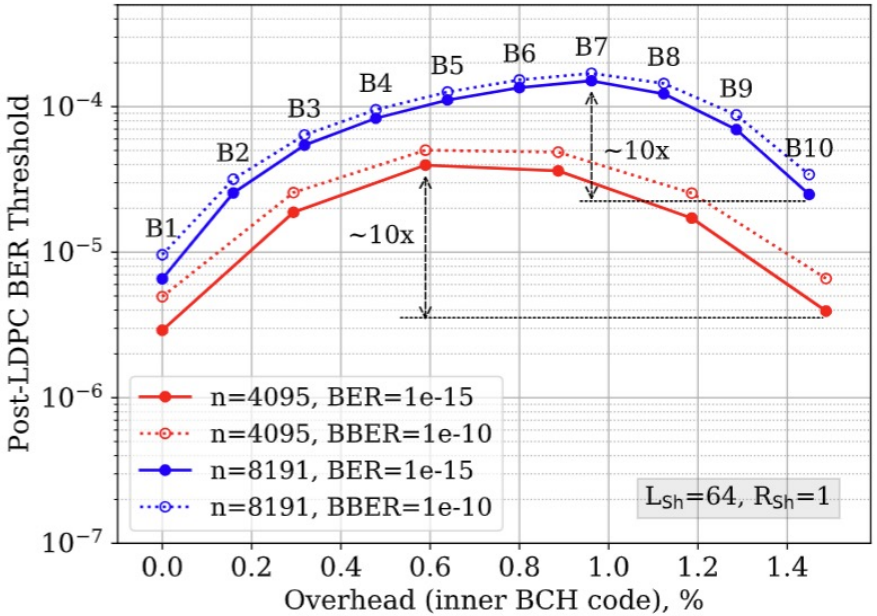
- Pre-shaping vs post-shaping FEC:
  - Pre-shaping FEC is performed on shorter bit sequences compared to post-shaping FEC
    - Lower bit-throughput in pre-shaping FEC
    - Complexity reductions in pre-shaping FEC
  - Not the full alphabet of shaped bit sequences is utilized for signaling, while post-shaping FEC protects all possible sequences
    - Results in extra parity bits and increased overhead for post-shaping FEC



- We keep LDPC code fixed and compare pre-shaping BCH with post-shaping BCH
  - When considering matching transmission rates, overhead for pre-shaping BCH can be higher than post-shaping BCH!

Results: Optimal concatenation

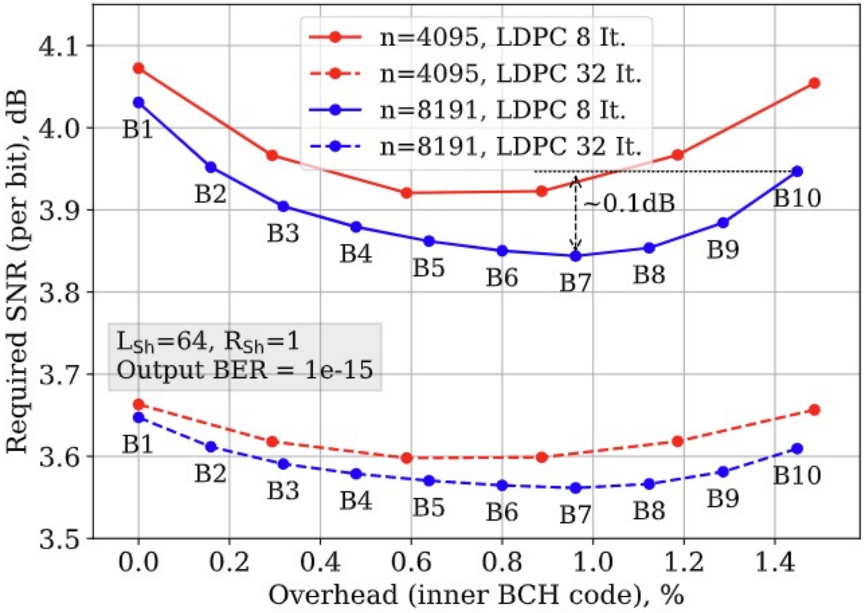
- We analytically evaluate the performance of post-shaping and pre-shaping BCH codes:
  - PS-64QAM format
  - Fixed LDPC code rate: 0.72
  - Metrics: BER of 10^{-15} and BBER of 10^{-10} (OTUC1 frame)
- Various options for concatenation of pre-shaping and post-shaping BCH codes while targeting same overall transmission rate
  - Two length of BCH code (same for post- and pre-shaping)
  - We change OH for post-shaping code and come up with complimentary OH for pre-shaping code to keep fixed overall rate
  - Order of magnitude BER gain can be achieved with optimal *dual-concatenation*!



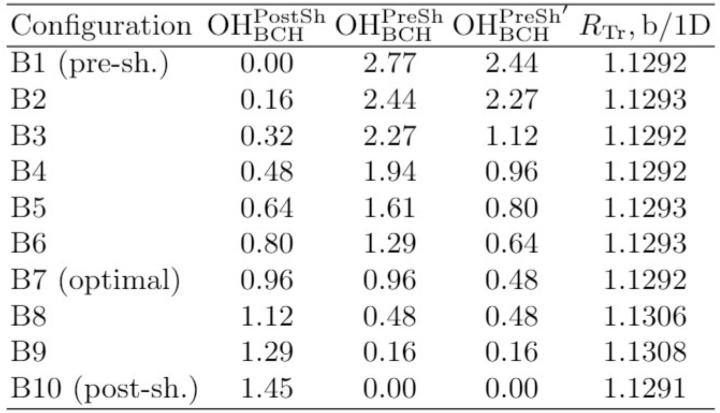
Configuration	OH_{BCH}^{PostSh}	OH_{BCH}^{PreSh}	$OH_{BCH}^{PreSh'}$	R_{Tr}, b/1D
B1 (pre-sh.)	0.00	2.77	2.44	1.1292
B2	0.16	2.44	2.27	1.1293
B3	0.32	2.27	1.12	1.1292
B4	0.48	1.94	0.96	1.1292
B5	0.64	1.61	0.80	1.1293
B6	0.80	1.29	0.64	1.1293
B7 (optimal)	0.96	0.96	0.48	1.1292
B8	1.12	0.48	0.48	1.1306
B9	1.29	0.16	0.16	1.1308
B10 (post-sh.)	1.45	0.00	0.00	1.1291

Results: Optimal concatenation

- Required SNR analysis with pre-characterized LDPC codes:
  - Code rate: 0.72
  - Code length: 13200
  - Sum-product decoding over 8 or 32 iterations



- SNR gain of 0.1 dB for 8 iterations
- SNR gain of 0.05 dB for 32 iterations

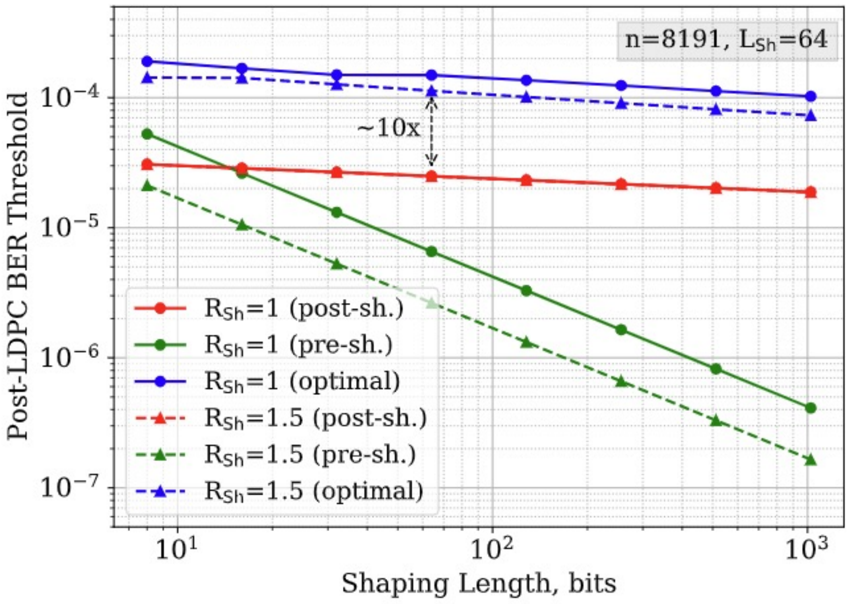


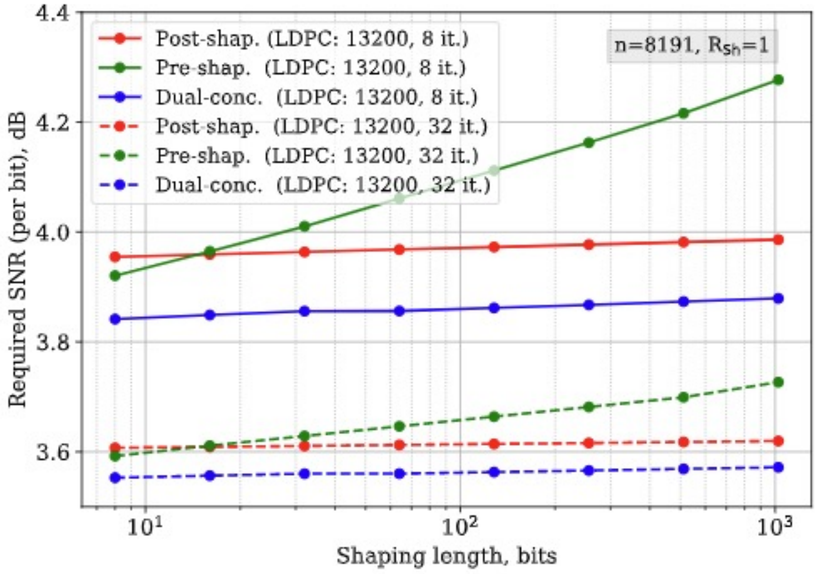
Configuration	$\mathrm{OH}_{\mathrm{BCH}}^{\mathrm{PostSh}}$	$\mathrm{OH}_{\mathrm{BCH}}^{\mathrm{PreSh}}$	$\mathrm{OH}_{\mathrm{BCH}}^{\mathrm{PreSh}'}$	R_{Tr}, b/1D
B1 (pre-sh.)	0.00	2.77	2.44	1.1292
B2	0.16	2.44	2.27	1.1293
B3	0.32	2.27	1.12	1.1292
B4	0.48	1.94	0.96	1.1292
B5	0.64	1.61	0.80	1.1293
B6	0.80	1.29	0.64	1.1293
B7 (optimal)	0.96	0.96	0.48	1.1292
B8	1.12	0.48	0.48	1.1306
B9	1.29	0.16	0.16	1.1308
B10 (post-sh.)	1.45	0.00	0.00	1.1291

Results: Shaping length and rate

- We consider impact of shaping length and rate
  - Shaping length range: 8 – 1024 bits
  - Two shaping rates: 1 bit/amp and 1.5 bit/amp

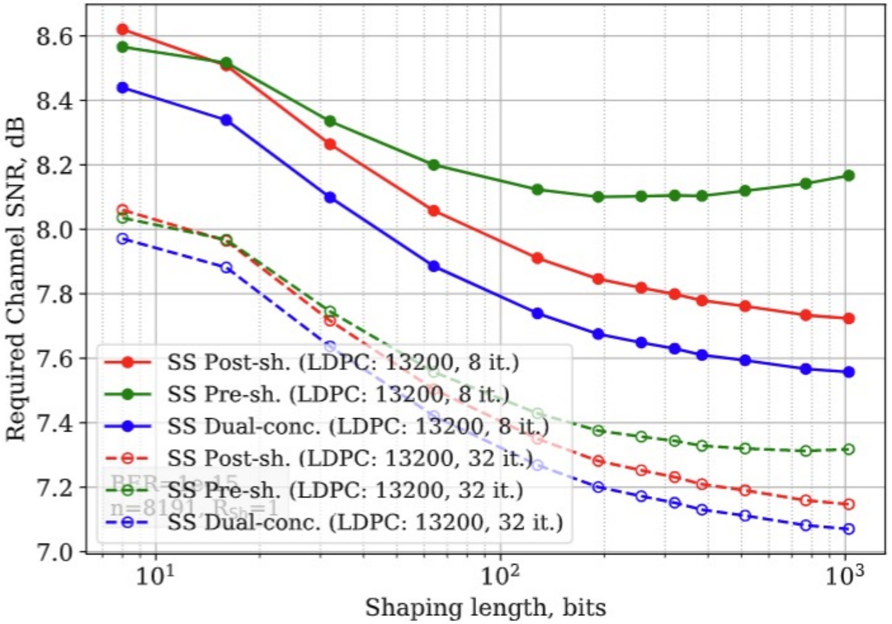
- Performance of post-shaping BCH does not depend on shaping rate, while pre-shaping BCH is more advantageous with smaller shaping rate
- For short-length shaping pre-shaping BCH offers comparable performance to post-shaping BCH
- Optimal concatenation offers performance gain regardless of shaping length!





Results: AWGN channel performance

- AWGN channel simulations:
  - DP PS-64QAM
  - Spherical shaping: Rate of 1 bit/amp
    - No particular mapping/demapping algorithm is considered
    - BER enhancement is modelled as bursts with 50% flipped bits
    - BER target is 10^{-15}
- We combine shaping gain and coding gain:
  - LDPC performance is based on nGMI mapping
- Classic assumption: longer length shaping offers better performance in AWGN channel
- In practice coding may affect this: max performance is observed at finite-length



Summary

- We analyzed the concept of *dual coding concatenation* for PAS
  - Parallel BCH architecture for pre-shaping FEC layer
    - Scalability/flexibility for shaping rate adaptation
    - Potentially reduces implementation complexity

- Advantages of pre-shaping coding for PAS:
  - For short-length shaping pre-shaping BCH can offer similar performance to that of standard *reverse concatenation*
  - Optimally concatenated dual-coding configuration can relax the post-LDPC BER and equivalently required SNR

- FEC coding aspect may have impact on shaping length considerations in PAS systems!

MITSUBISHI
ELECTRIC

Changes for the Better