FEC Considerations for 802.3bp 1000Base-T1

Beijing, China

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BZ Shen, Mehmet Tazebay, Will Bliss, Ahmad Chini, Mehdi Kilani

Broadcom Corporation

Outline

- **Date Rate & Channel Noises**
  - AWGN, NBI and impulse noise
- **Latency Definition**
- **Constellation & Mapping**
- **Considered FEC Options**
  - Classic FEC Codes (BCH & RS)
  - Modern LDPC codes
- **Size 2K codes for lower latency, smaller area and lower power**
- **Size 3K codes for bandwidth efficiency**
- **Conclusions**

Date Rate & Channel Noises

- **Data rate requirement:** 1Gbs on payload data
  - Rate on FEC coded data:
    - w/ 75% FEC: 1/0.75=1.33Gb/s
    - w/ 90% FEC: 1/0.90 =1.11Gb/s
- **Channel noises are considered:**
  - AWGN
  - Narrowband interference (NBI)
  - Impulse noise
    - Duration: 0.2μs
    - Burst SNR: $\mathrm{SNR}_{\mathrm{Burst}}$

$$\textbf{AWGN}\ \text{channel noise at time k}: n(\sigma_{AWGN}, k)$$

$$\sigma_{\mathrm{AWGN}}: \text{noise variance} = \sqrt{\frac{\mathrm{P}}{\mathrm{SNR}_{\mathrm{AWGN}}}},$$

$$SNR_{AWGN}: \text{signal to noise ratio}$$

$$P: \text{average power of the modulation constellation}$$

$$\text{pdf}: f_{AWGN}(x) = \frac{e^{\frac{-x^2}{2\sigma_{AWGN}^2}}}{\sqrt{2\pi\sigma_{AWGN}}}$$

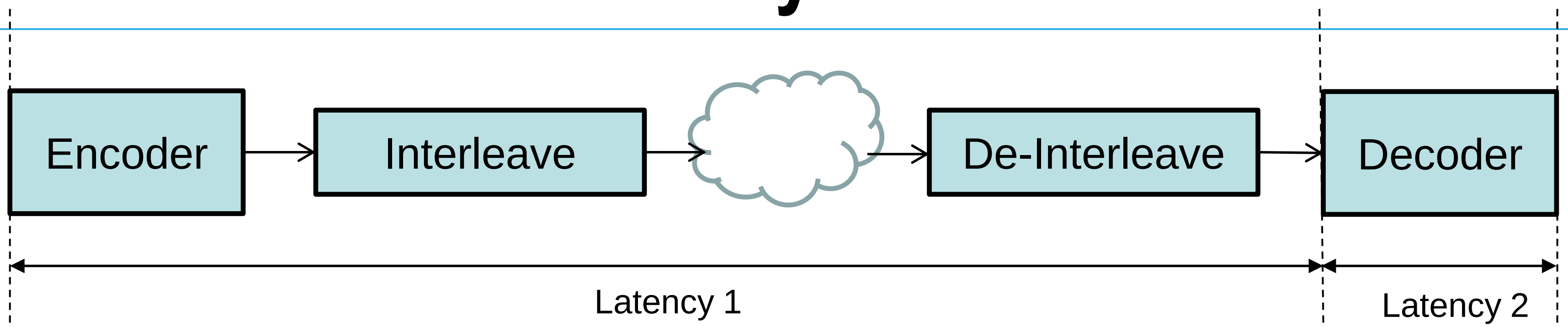
$$\textbf{NBI}\ \text{at time}\ k\ \text{with an amplitude}\ A: n_I(A,k) = A\cos\left(\phi + \left[2\pi\left(\frac{f_c}{f_s}\right)k\right]\right)$$

$$RMS: \sigma_{NBI} = \frac{A}{\sqrt{2}},$$

$$\text{Random phase carrier}: \phi \in [-\pi, \pi], \text{Sampling /carrier frequency}: f_s / f_c.$$

$$\text{pdf}: f_{NBI}(x) = \begin{cases} \frac{1}{\pi\sqrt{A^2 - x^2}} & |x| \le A \\ 0 & \text{otherwise} \end{cases}$$

Latency Definition



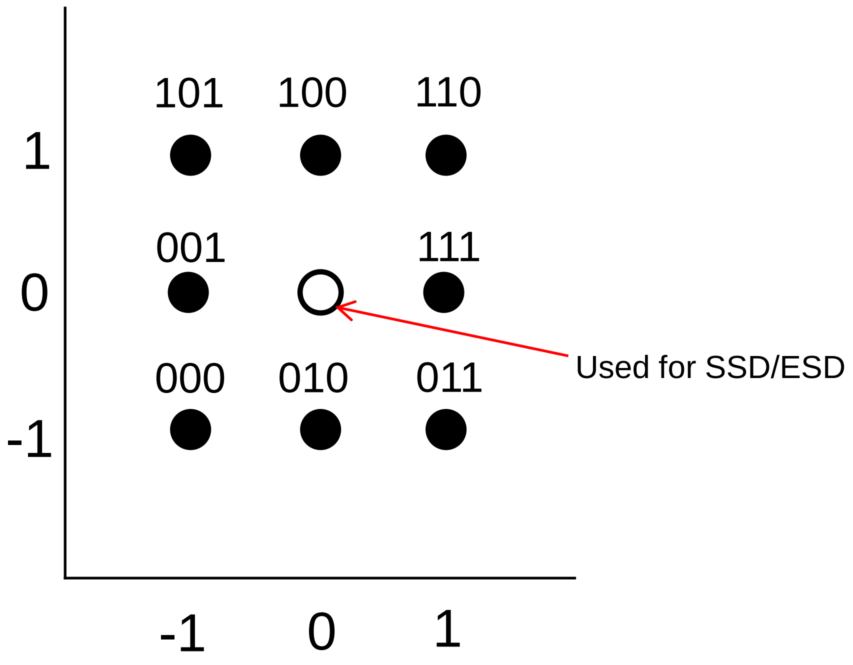
- **Latency-1:**
  - The period of time counting from the time of the first bit sent to the interleaving encoder to the time of the last bits input to the decoder.
- **Latency-2**
  - The period of time counting from the time of the last the received bit to the decoder to the time the first bit output from the decoder.
- **Interleaving**
  - Using de-mux → no latency required
- **Encoding**
  - Systematic encoder is used → couple of cycle time latency, assume 0.02μs at the most for the rates that are being considered here.

Constellation and Mapping

- **PAM-2 and PAM-3 are considered**
  - Only PAM-3 results are discussed in this document

PAM-3 constellation and mapping

Sdn[2:0]	Ternary A	Ternary B
000	**-1**	**-1**
001	**-1**	**0**
010	**0**	**-1**
011	**1**	**-1**
Used for SSD/ESD	**0**	**0**
100	**0**	**1**
101	**-1**	**1**
110	**1**	**1**
111	**1**	**0**



Classic FEC codes

- **Binary BCH codes**
  - Good for correcting random bit errors
- **m-bit RS (Reed-Solomon) codes**
  - MDS (maximal distance separate) codes
  - Best for bonded distance decoding
- **Decoding**
  - Bounded distance hard-decision (HD) decoding
    - Using 'threshold detector‘ to estimate PAM symbol
    - Decoding on m-bit symbol with the minimum distance
    - Cannot take advantage of the soft information of received signals
  - Soft-decision decoding
    - Not practical
    - Not well developed

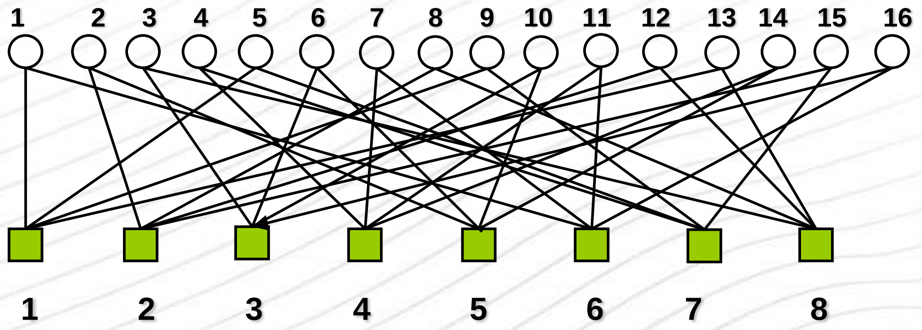
Modern FEC: LDPC Codes

- Specified by a (parity-check) matrix containing mostly 0’s and relatively few 1’s (R. G. Gallager 1960, rediscovered in 1998)
  - Capacity approaching codes
  - Soft-decision decoding (take advantage of received signals)
- A simple example

$$H = \begin{bmatrix} 1000 & 1000 & 1000 & 1000 \\ 0100 & 0001 & 0001 & 0010 \\ 0010 & 0100 & 0100 & 0001 \\ 0001 & 0010 & 0010 & 0100 \\ 0100 & 0100 & 0100 & 0100 \\ 1000 & 0010 & 0010 & 0001 \\ 0001 & 1000 & 1000 & 0010 \\ 0010 & 0001 & 0001 & 1000 \end{bmatrix}$$

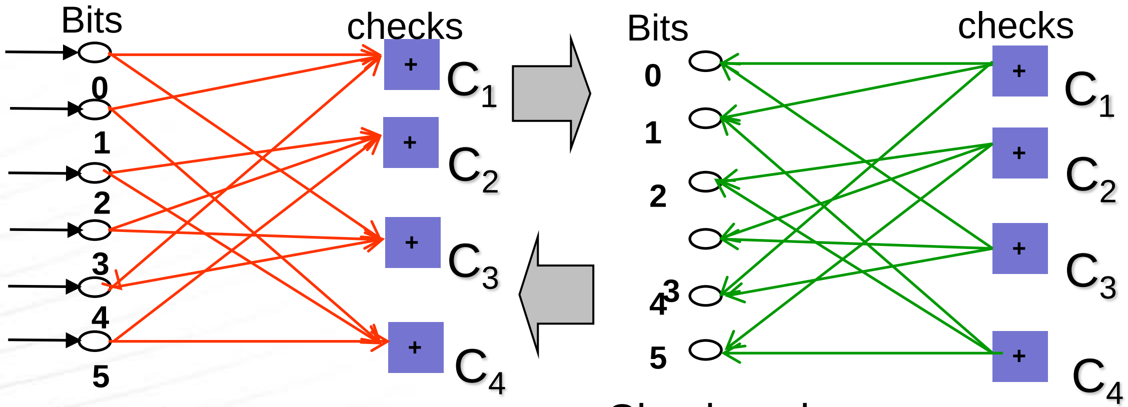
Parity check matrix of (16,9) regular LDPC code

32 1’s , 128 0’s, density of 1’s = 0.25



check nodes

Tanner graphs



Bit nodes process (passing information to check nodes)

Check nodes process (passing information to bit nodes)

Iterative decoding

SIZE 2K CODES

– LOW LATENCY, SMALL DIE AREA & LOW POWER

Size 2K FEC Codes

- Data rate on data after rate r FEC encoding: $s=1/r$ Gbps
- Receiving time of a size n codeword: $n/(s*10^9)$ seconds
- Total latency limitation 4μs

Rate	Code Types	Code	Correction Capability	Latency-1 (μs)	Maximum allowed Latency-2 (μs)
0.747	Binary BCH	(2000,1494)	HD t=47	1.52	2.48
0.75.5	Byte RS	$(250,188)_8$ $[(2000,1504)_2]$,	HD t=31 bytes	1.52	2.48
0.75	Binary LDPC	(2000,1500)	SD	1.52	2.48
0.9	Binary BCH	(2000,1802)	HD t=18	1.82	2.18
0.898	Byte RS	$(255,229)_8$ $[(2040,1832)_2]$	HD t=13 bytes	1.85	2.15
0.896	Binary LDPC	(2496,2236)	SD	2.256	1.744

- **With lower Latency-1**
  - Either total latency can be reduced to 3μs
  - Or decoder area and power can be reduced
- **Advantage of LDPC code**
  - Capacity approaching
  - Capable of doing soft-decision decoding
- **2K LDPC decoder hardware is little bit more than RS decoder (<2x)**

NBI impact on AWGN channel

- **Transmitted signal at time k:** $tx(k)$
- **Received signal:** $rx_0(k)$
  - Under AWGN channel:

$$rx_0(k) = tx(k) + n_{AWGN}(\sigma_{AWGN}, k)$$

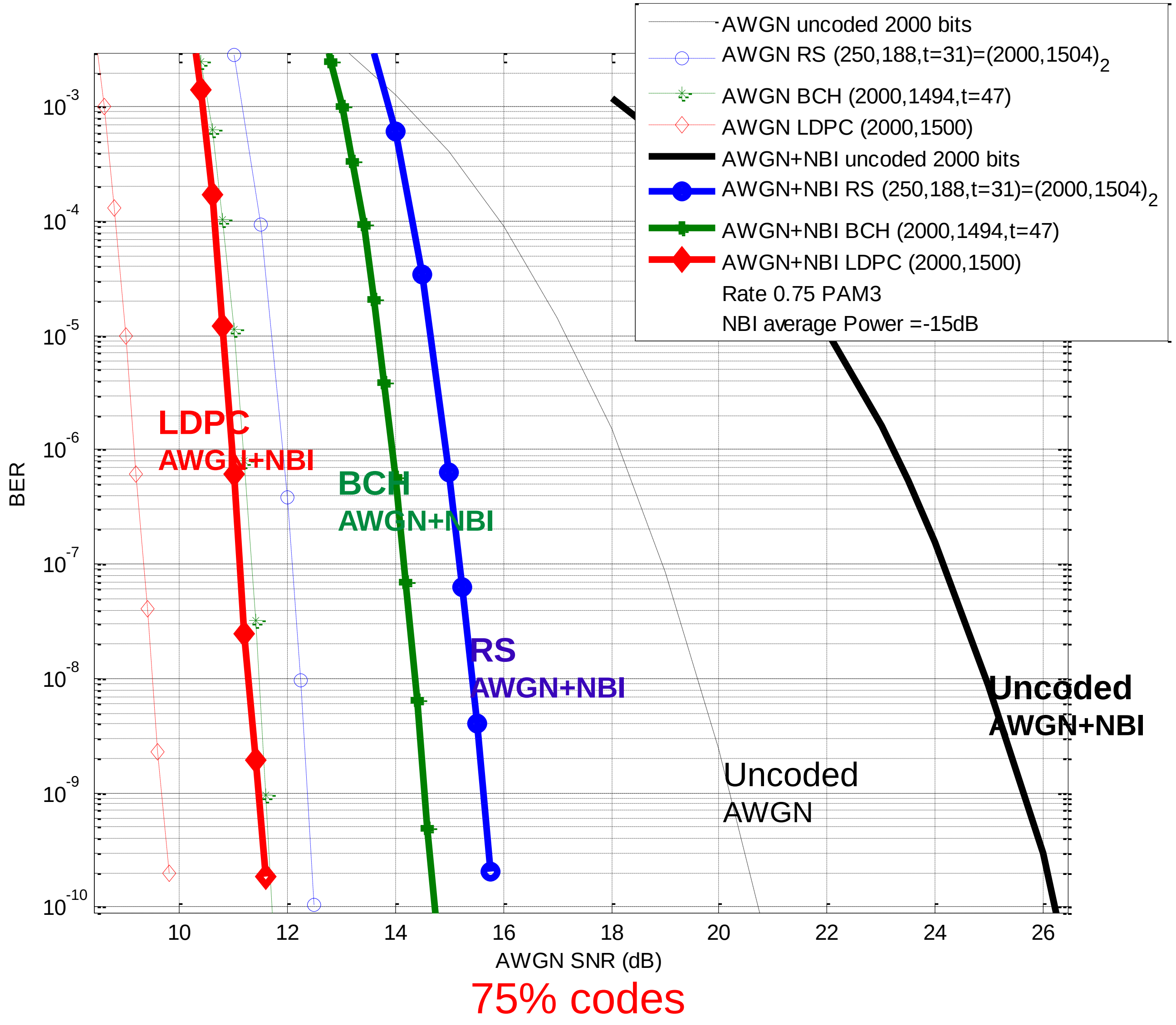
  - Impacted by NBI

$$rx(k) = rx_0(k) + n_{NBI}(A, k)$$

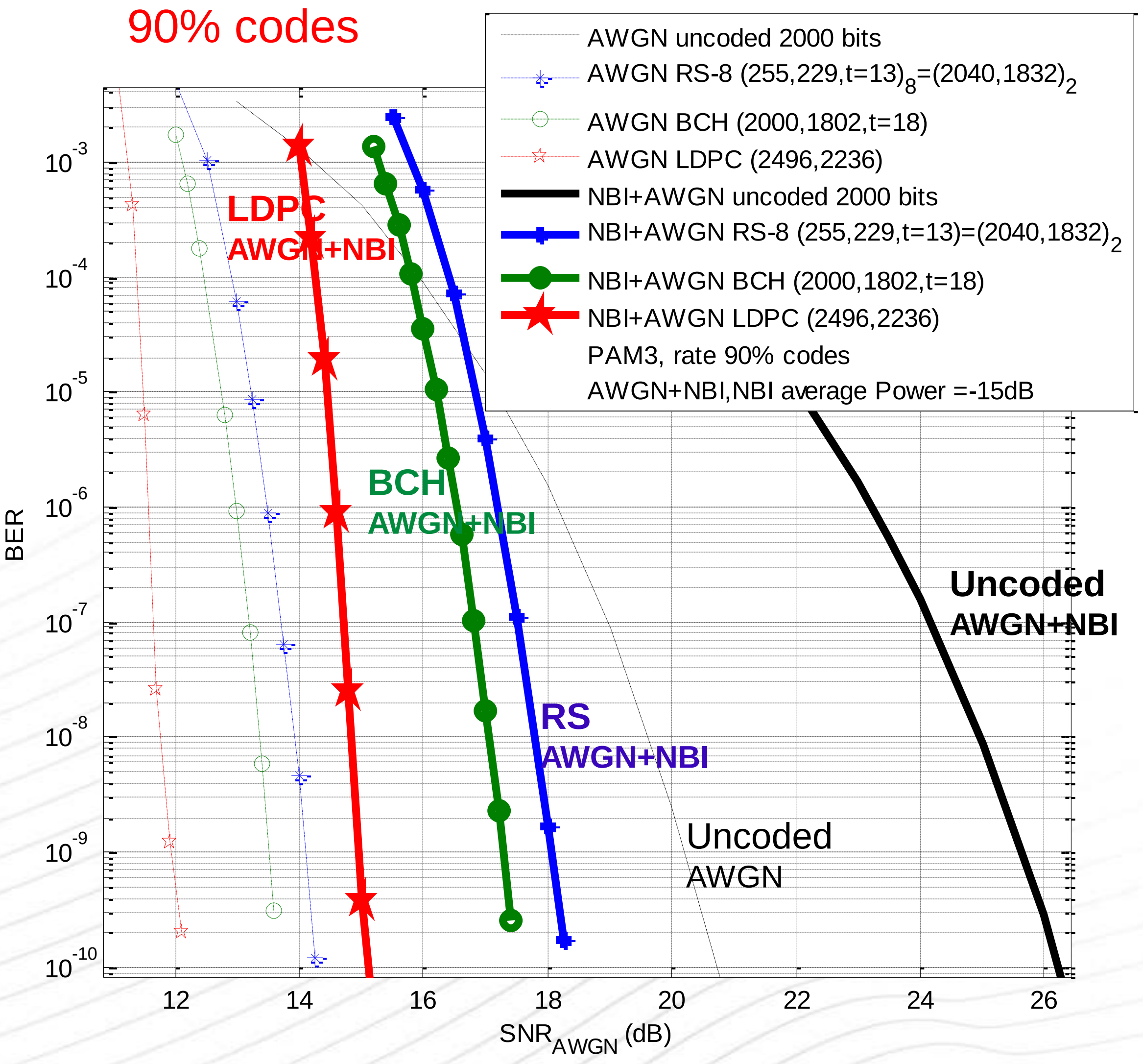
NBI at time k with an amplitude $A: n_I(A,k) = A\cos\left(\phi + \left[2\pi\left(\frac{f_c}{f_s}\right)k\right]\right)$

$RMS: \sigma_{NBI} = \frac{A}{\sqrt{2}}$

- **Simulated case:**
  - Sweep AWGN
    - w/ a fixed NBI
      - Average power (σ^2) = -15dB
        - » Amplitude A= 0.251487
      - f_c/f_s = 0.05



NBI impact on AWGN channel



NBI: Average power (σ^2) = -15dB

Amplitude A= 0.251487

Rate	Code Types	Code	SNR_{AWGN} @BER=2e-10
0.747	Binary BCH	(2000,1494)	14.7dB
0.75.5	Byte RS	$(250,188)_8$ $[(2000,1504)_2]$,	15.7dB
0.75	Binary LDPC	(2000,1500)	11.6dB
0.9	Binary BCH	(2000,1802)	17.4dB
0.898	Byte RS	$(255,229)_8$ $[(2040,1832)_2]$	18.2dB
0.896	Binary LDPC	(2496,2236)	15.1dB

- With a fixed NBI
  - BCH code outperforms RS code ~ 1dB (SNR_{AWGN})
  - LDPC code outperforms BCH code > 3dB(SNR_{AWGN})
  - LDPC code outperforms RS code > 4dB(SNR_{AWGN})

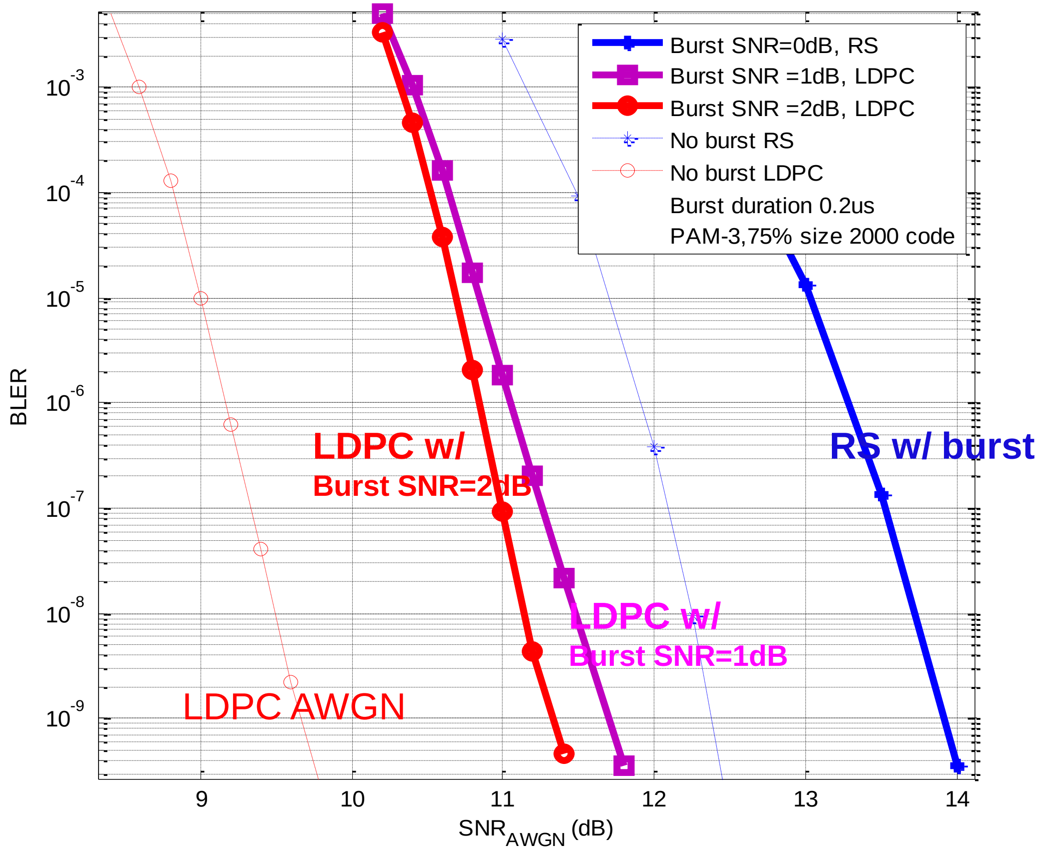
Impulse Noise Impact

- **Impulse noise**
  - Duration on one code block: 0.2μs
    - Impulse noise impact with ν data receiving time: (0.2/ν) of total codeword bits
  - Simulated case: starting location is randomly selected
- **Decoding requirement:** Need to know the location of the burst noise
  - HD (hard-decision) for BCH and RS: burst size ≤ d-1
  - SD (Soft-decision) for LDPC: bounded burst noise SNR
- **Interleaving**
  - Pros: same erasure capability but less hardware and less decoding latency
    - Example: binary (3240,2880) codes
      - Single 9-bit RS (360,320,d=41) : corrects 40*9=360 bits erasure
      - 12-interleaved 6-bit (45,40,d=6): correct 12*5*6=360 bits erasure
  - Cons: less random error corrections
      - Single 9-bit RS (360,320,d=41) : corrects 20 9-bit symbol errors
      - 12-interleaved 6-bit (45,40,d=6): correct 2 6-bit symbol errors
  - **Decoding power ≈** power of decoding for non-interleaved single code

Impulse Noise Impact (2K size codes)

Rate	Code	Burst Noise Impact ratio	Decoding
75%	LDPC(2000,1500)	13.3%	Limited burst SNR
	BCH (2000,1494)	13.3%	Not capable (266 bits>d=94)
	RS $(250,188)_8$	13.3%	33 bytes erasure
90%	LDPC (2496,2236)	8.9%	Limited burst SNR
	BCH (2000,1802)	11%	Not capable (200bits>d=37)
	RS $(255,229)_8$	10.9%	Not capable (28 bytes>d=27)

- **75% codes**
  - LDPC code outperforms RS > 2dB (SNR_{AWGN})
    - Simulated $SNR_{burst} \geq 1dB$
- **90% codes**
  - RS code is not capable to correct 0.2 μs burst
  - LDPC codes can decode burst with $SNR_{burst} \geq 6$ dB



75% codes

SIZE 3K HIGH RATE CODES

– BANDWIDTH EFFICIENCY

Size 3K FEC Codes

- Data rate on data after rate r FEC encoding: $s=1/r$ Gbps
- Receiving time of a size n codeword: $n/(s*10^9)$ seconds
- Total latency limitation 4μs

Rate	Interleave	Code	Correction capability	Latency-1 (μs)	Maximal allowed Latency-2 (μs)	burst noise Impact ratio
8/9	no	9-bit RS $(360,320,)_9$ $[(3240,2880_2]$	HD (d=41 9-bit symbol)	2.9	1.1	6.94% (225 bits)
8/9	4-codewords	9-bit RS $(90,80,)_9$ [total:$(3240,2880)_2$]	HD (d=11 9-bit symbol)	2.9	1.1	6.94% (225 bits)
8/9	12-codewords	6-bit RS $(45,40)_6$ [total:$(3240,2880)_2$]	HD (d=6 6-bit symbol)	2.9	1.1	6.94% (225 bits)
8/9	no	LDPC(3240,2880)	SD	2.9	1.1	6.94% (225 bits)

- Advantage of raising the size to 3K
  - Allow higher rate code for bandwidth efficiency
  - Increase burst correction capability
    - RS codes (interleave/none-interleave) are capable to decoding 0.2μs erasures
- LDPC decoder hardware is still not so big (slightly bigger than RS decoder but small area impact in <=40nm process geometry) (<2x)

For a Fixed NBI Power

- **Transmitted signal at time k:** $tx(k)$
- **Received signal:** $rx_0(k)$
  - Under AWGN channel:

$$rx_0(k) = tx(k) + n_{AWGN}(\sigma_{AWGN}, k)$$

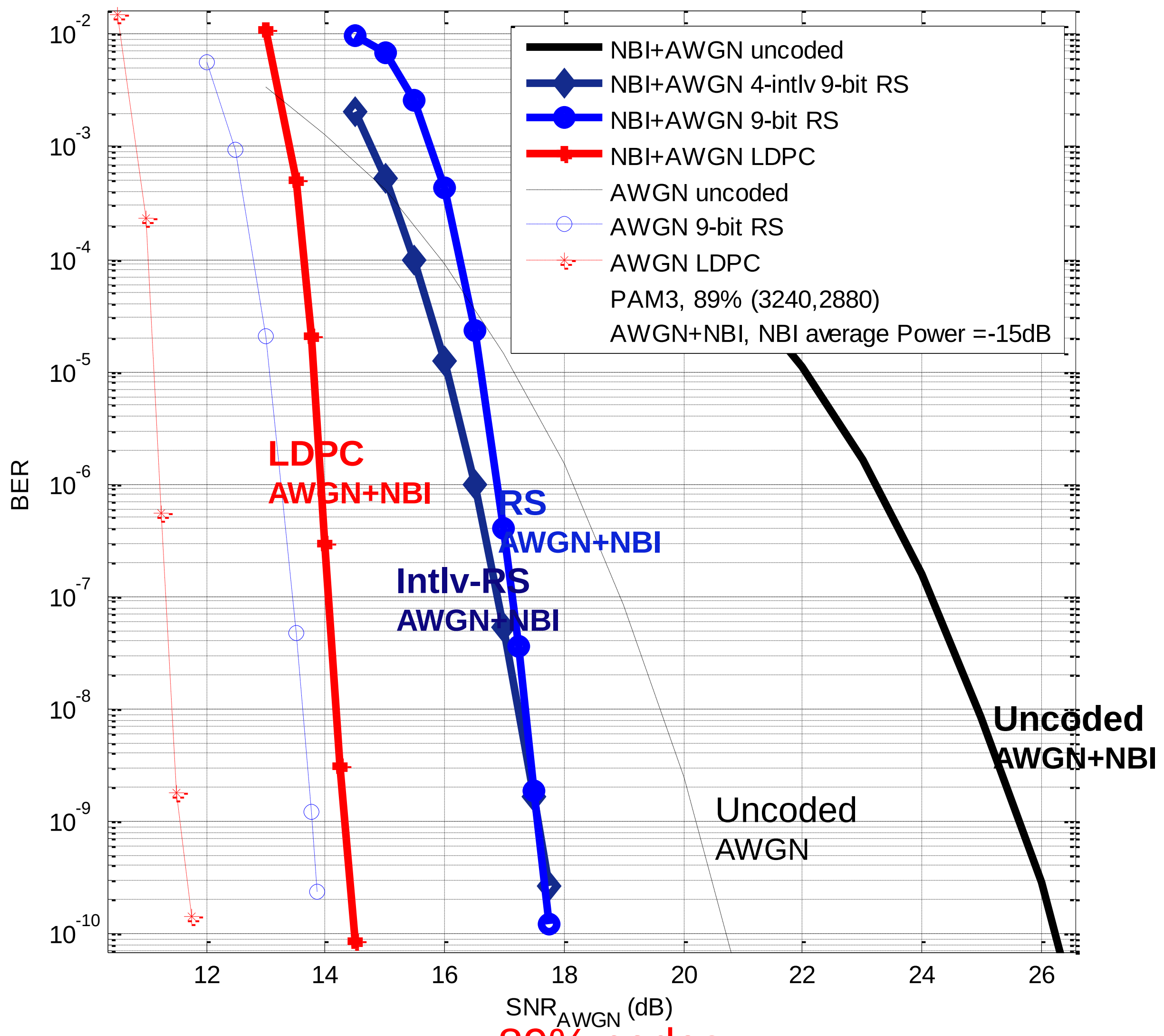
  - Impacted by NBI

$$rx(k) = rx_0(k) + n_{NBI}(A, k)$$

NBI at time k with an amplitude $A: n_I(A,k) = A\cos\left(\phi + \left[2\pi\left(\frac{f_c}{f_s}\right)k\right]\right)$

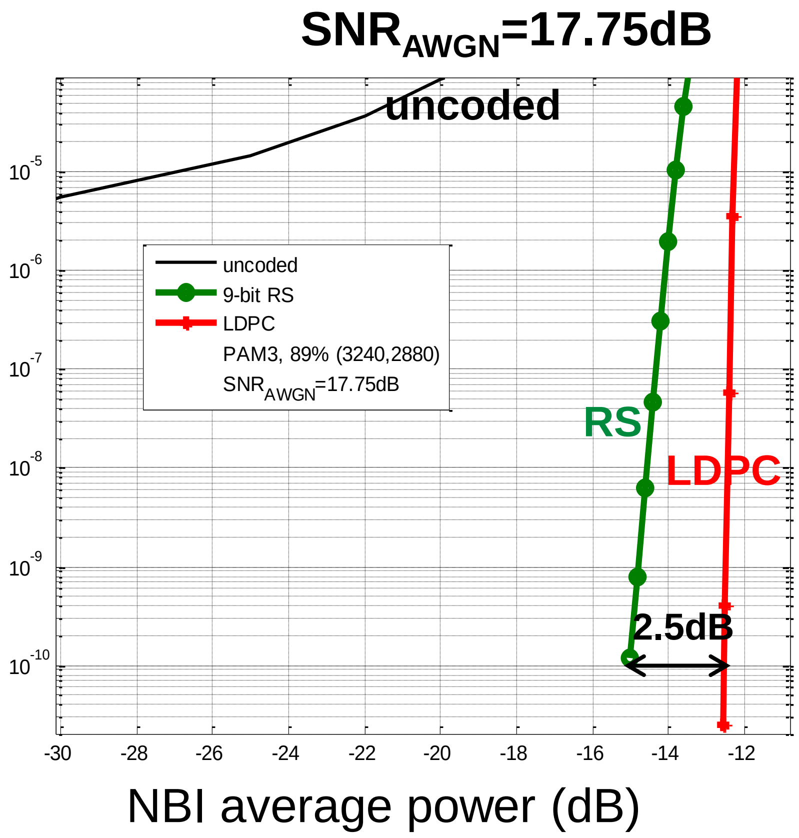
$RMS: \sigma_{NBI} = \frac{A}{\sqrt{2}}$

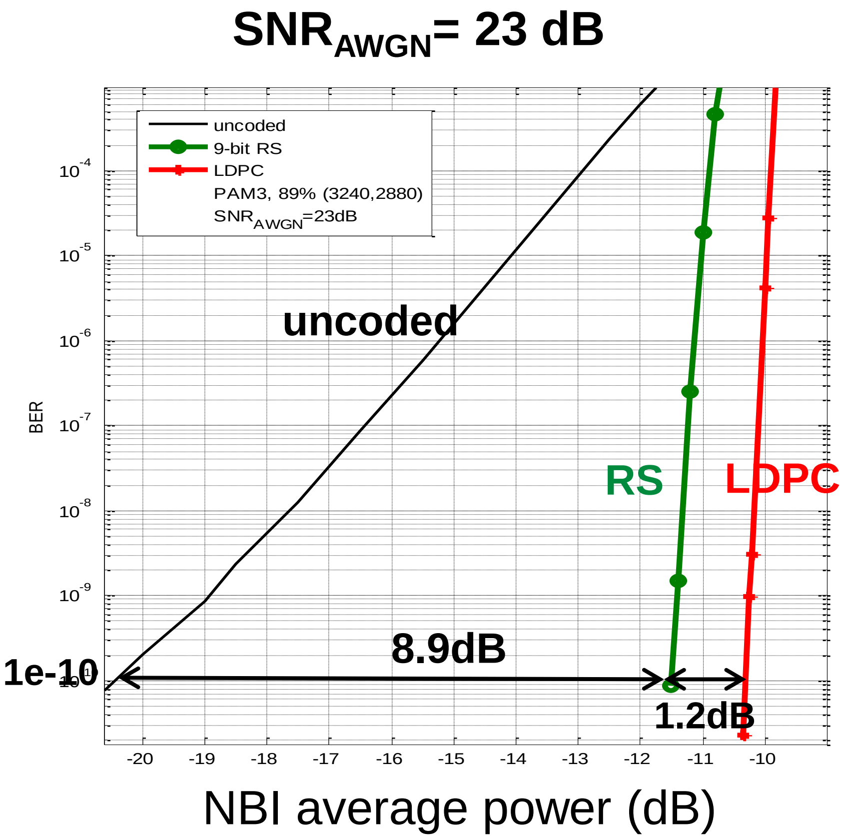
  - NBI Average power (σ^2) = -15dB
    - Amplitude A= 0.251487
    - f_c/f_s = 0.05
- **Performance Comparison**
  - LDPC outperforms RS ~ 3.8dB

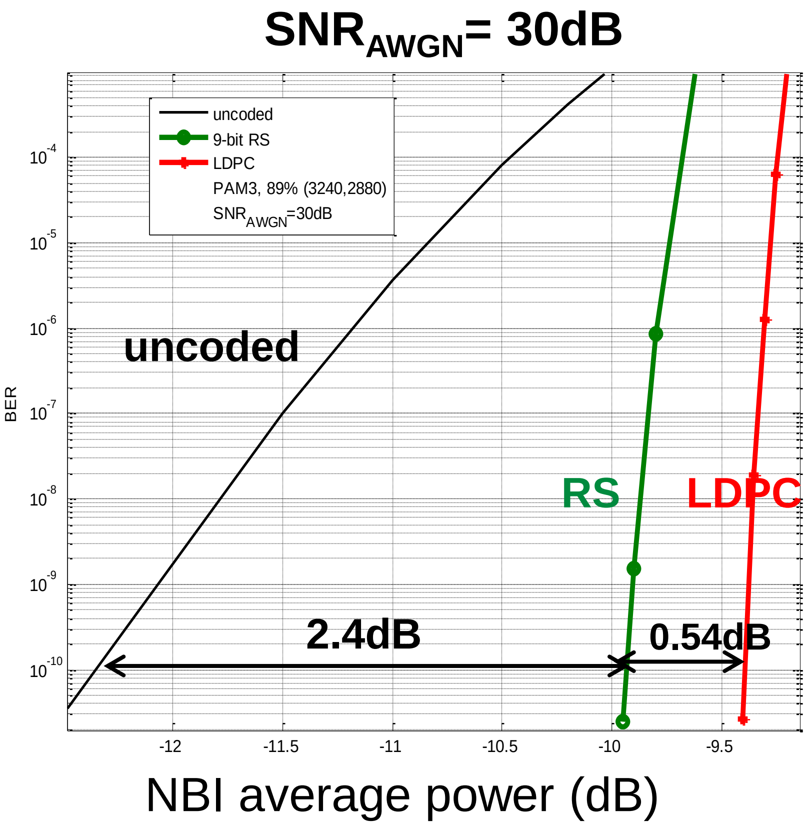


89% codes

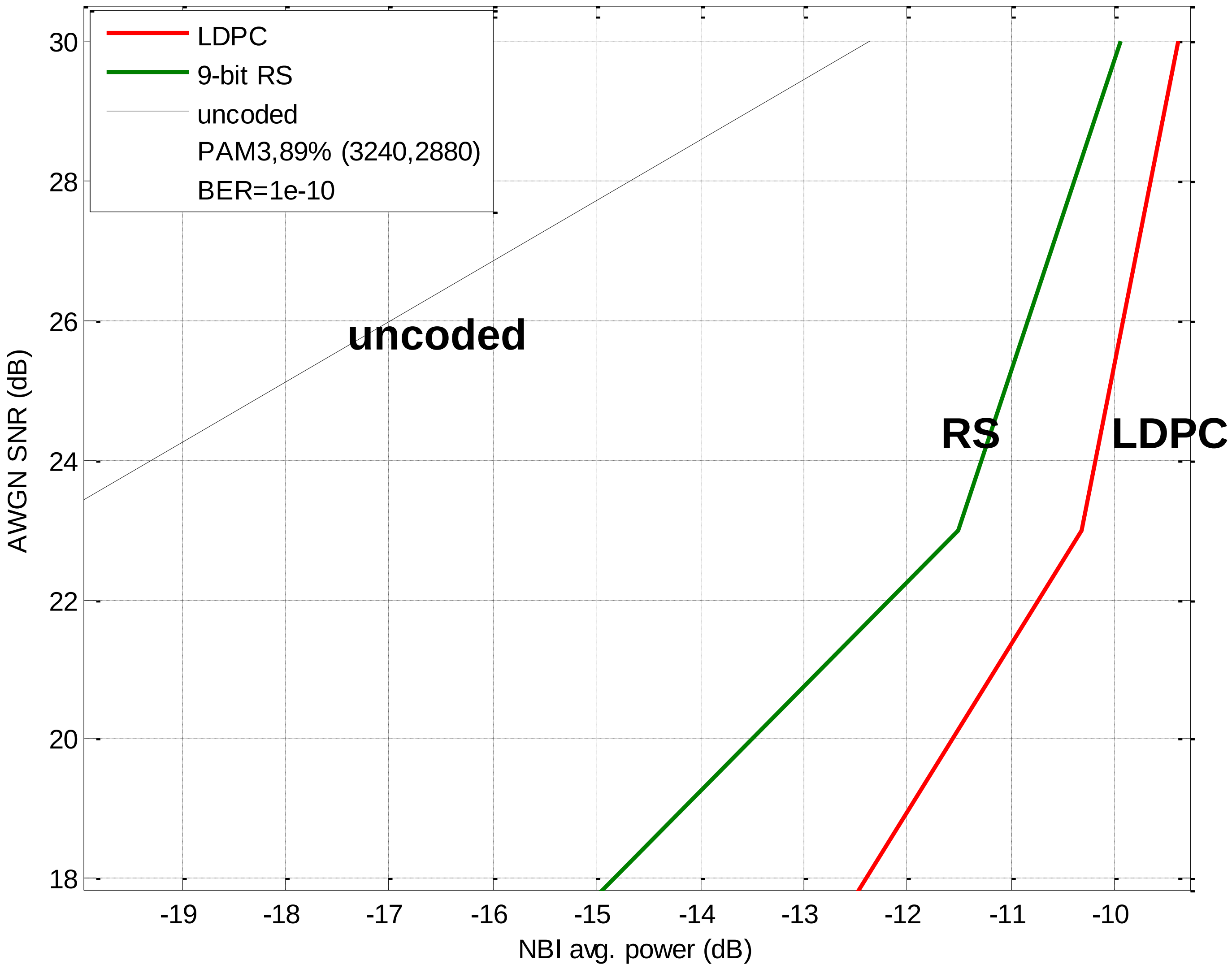
FEC Gain over NBI with Fixed AWGN SNR





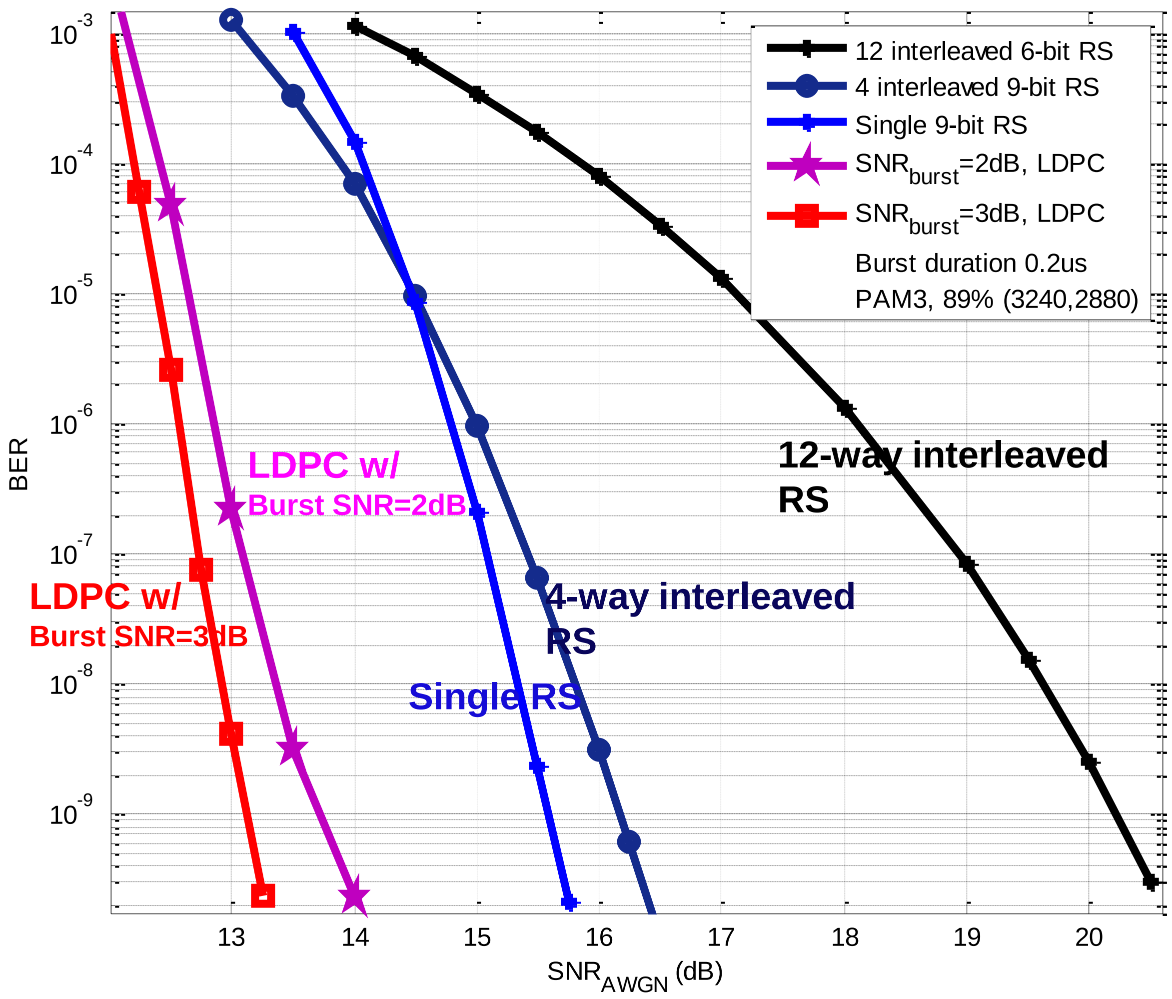


FEC does help recovering from NBI (!)



Impulse Noise Impact (3K size codes)

- **Impulse noise duration 0.2μs**
- **RS codes**
  - Single 9-bit RS code outperform interleaved codes
  - 12-way interleaved 6-bit RS code leaves no random error correction in some sub-blocks
- **LDPC codes**
  - Outperform RS codes ~2dB
    - W/ burst SNR ≥ 2 dB



89% codes

Conclusions

- **Two different rates codes are considered**
  - 75% 2K codes for lower latency or lower area and power
  - 89% 3K codes for bandwidth efficiency

Size range	Rate	Interleave	Code	Latency 1 (μs)	Maximal allowed Latency 2 (μs)	Impulse noise
2K	0.747	no	BCH (2000,1494)	1.52	2.48	Not capable
	0.75.5	no	8-bit RS $(250,188)_8$ $[(2000,1504)_2]$,	1.52	2.48	
	0.75	no	LDPC(2000,1500)	1.52	2.48	
	0.9	no	BCH (2000,1802)	1.82	2.18	Not capable
	0.898	no	8-bit RS $(255,229)_8$ $[(2040,1832)_2]$	1.85	2.15	Not capable
	0.896	no	LDPC (2496,2236)	2.256	1.744	
3K	8/9	no	9-bit RS $(360,320)_9$ $[(3240,2880_2]$	2.9	1.1	
	8/9	4-way	9-bit RS $(90,80)_9$ $[\text{total:}(3240,2880)_2]$	2.9	1.1	
	8/9	12--way	6-bit RS $(45,40)_6$ $[\text{total:}(3240,2880)_2]$	2.9	1.1	
	8/9	no	LDPC(3240,2880)	2.9	1.1	

- **On NBI:**
  - **<u>FEC does help recovering from NBI</u>**
    - At BER=1e-10 and SNR_{AWGN}=30dB →coding gain ≥ 2.4dB
    - At BER=1e-10 and SNR_{AWGN}=17.75dB →coding gain = ∞
  - **<u>LDPC code outperforms RS code</u>**
    - 0.54dB @ BER=1e-10 and SNR_{AWGN}=30dB
    - 2.5dB @ BER=1e-10 and SNR_{AWGN}=17.75dB

- **On 0.2μs impulse noise**
  - **<u>With the known burst location</u>**
    - RS code is for any burst SNR
    - LDPC code is for bounded burst SNR
  - **<u>LDPC code outperform RS code ~2dB</u>**
    - 75% code w/ burst SNR≥1dB
    - 89% w/ burst SNR ≥ 2dB