Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [FEC simulation results]
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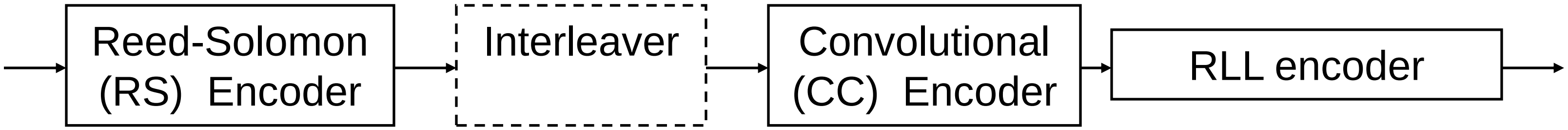
Abstract: Provides details on FEC simulations for VLC

Purpose: [Contribution to IEEE 802.15.7 VLC TG]

TX System block diagram



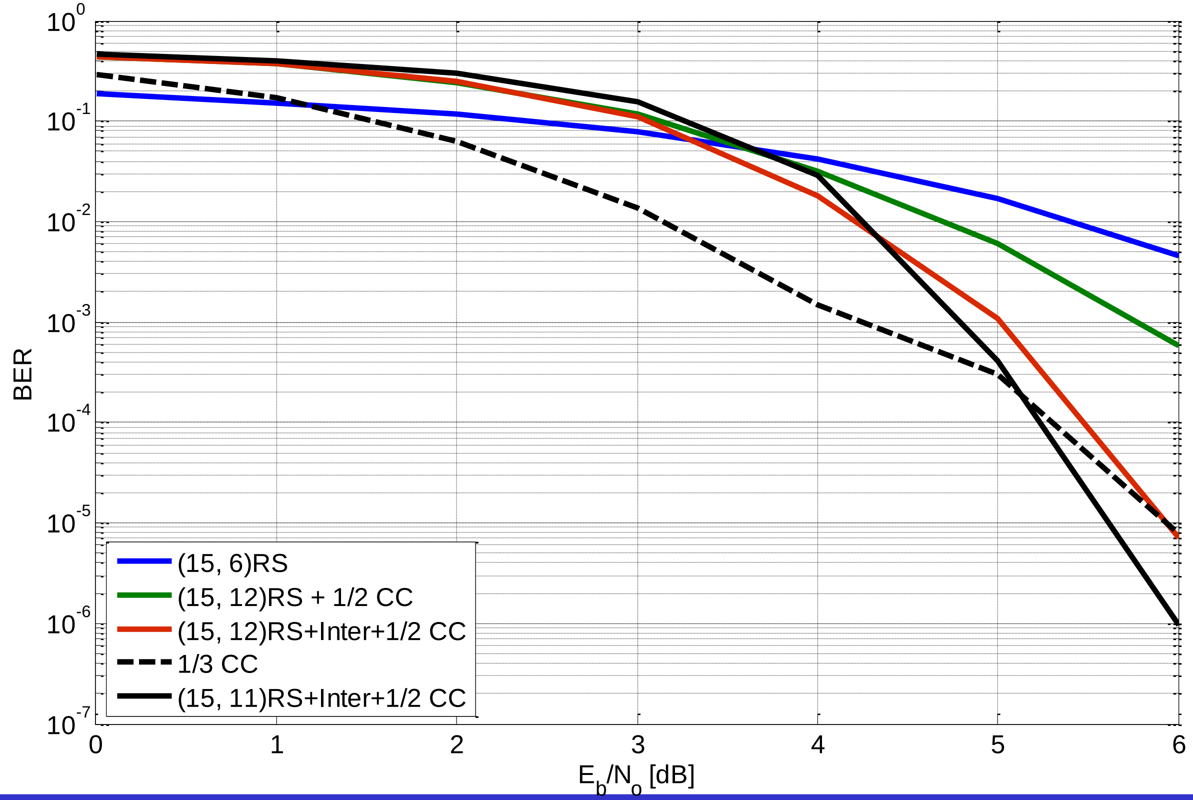
Hard-decision decoding is used in the RS and the CC decoders.

Random interleaver is used in these simulations. In practice, other interleavers such as block interleavers can also be considered.

Manchester RLL encoder is considered.

Does the convolutional code (CC) need an interleaver?

AWGN Channel

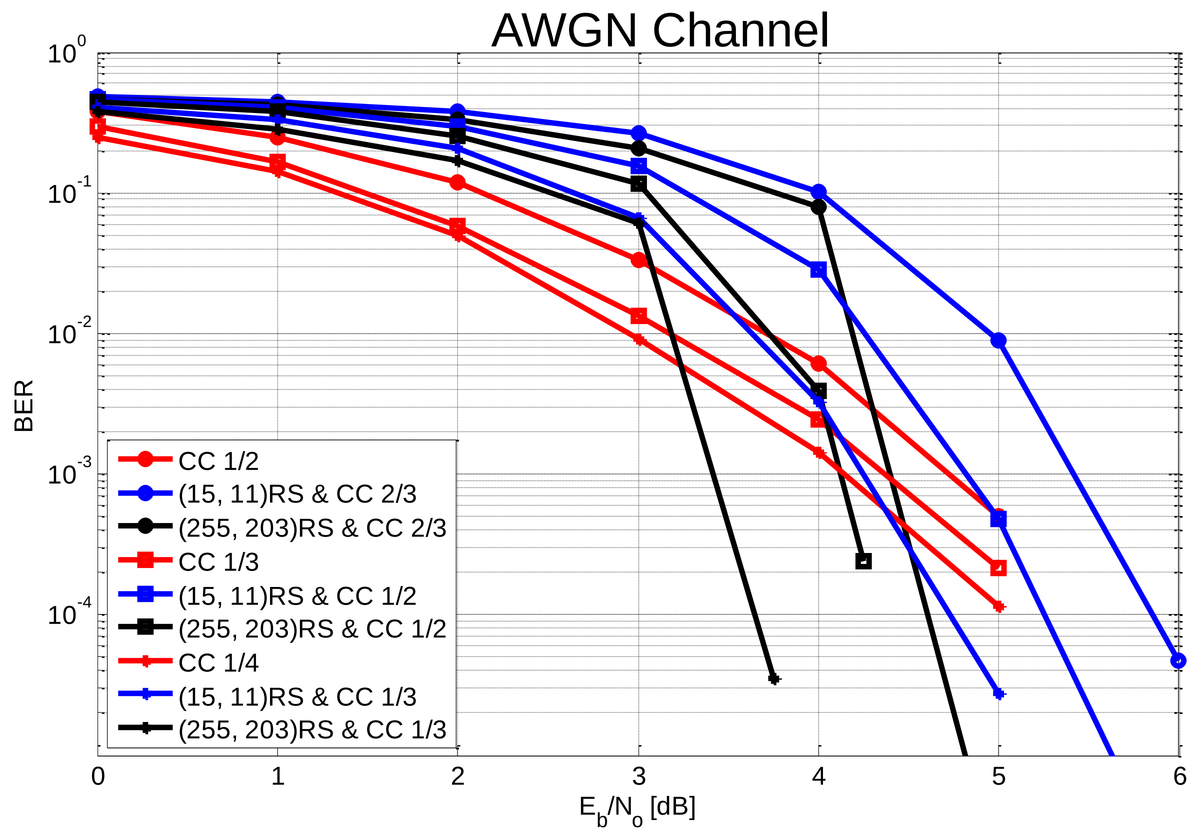


Yes, an interleaver between the RS code and the CC achieves >1dB gain.

No need for interleaver at the output of the CC.

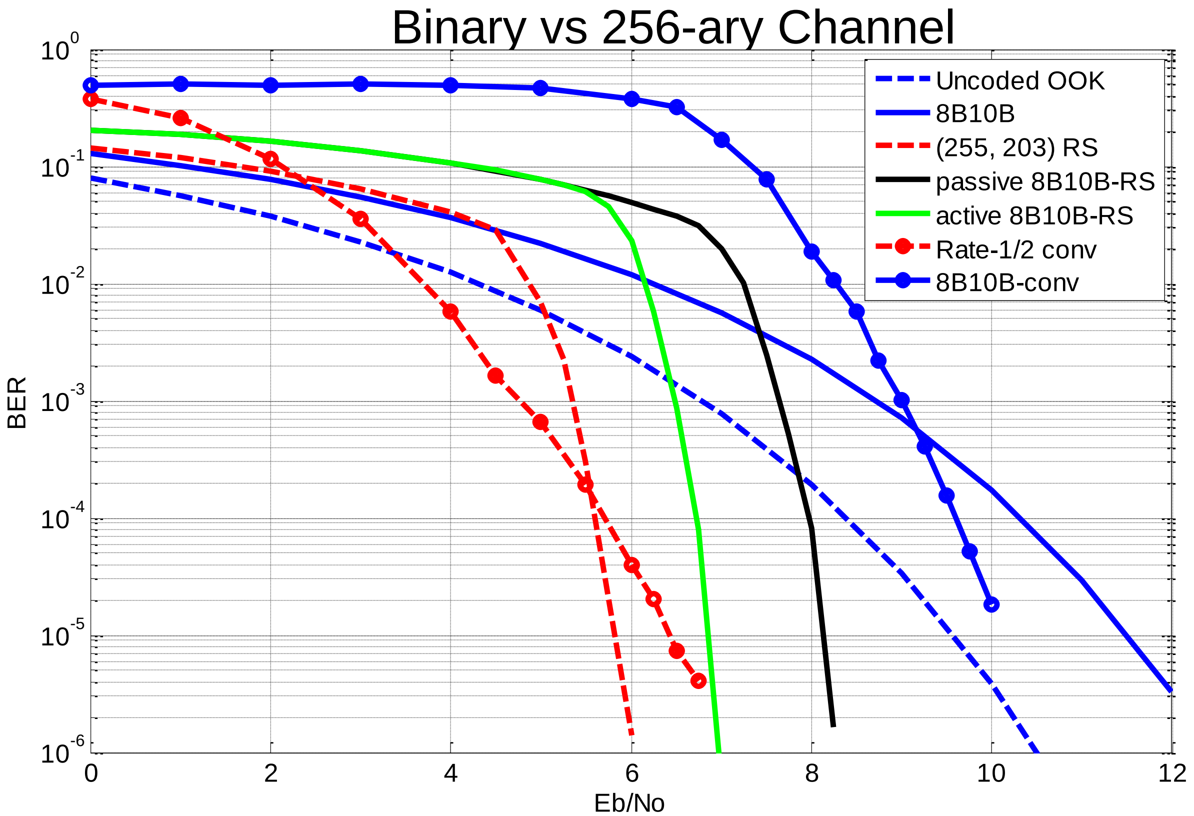
It is better to reduce coding rate of CC instead of RS, given a choice to attain same coding rate. RS code is also better for high rate implementation from complexity standpoint.

CC vs. RS+CC



- Operating in BER>1e-3: Use CC (without RS)
- Operating in BER<1e-3 (practical for PER <1e-1) : Use RS+CC
- Operating at coding rates < ¼ : Use RS+CC

CC vs. RS

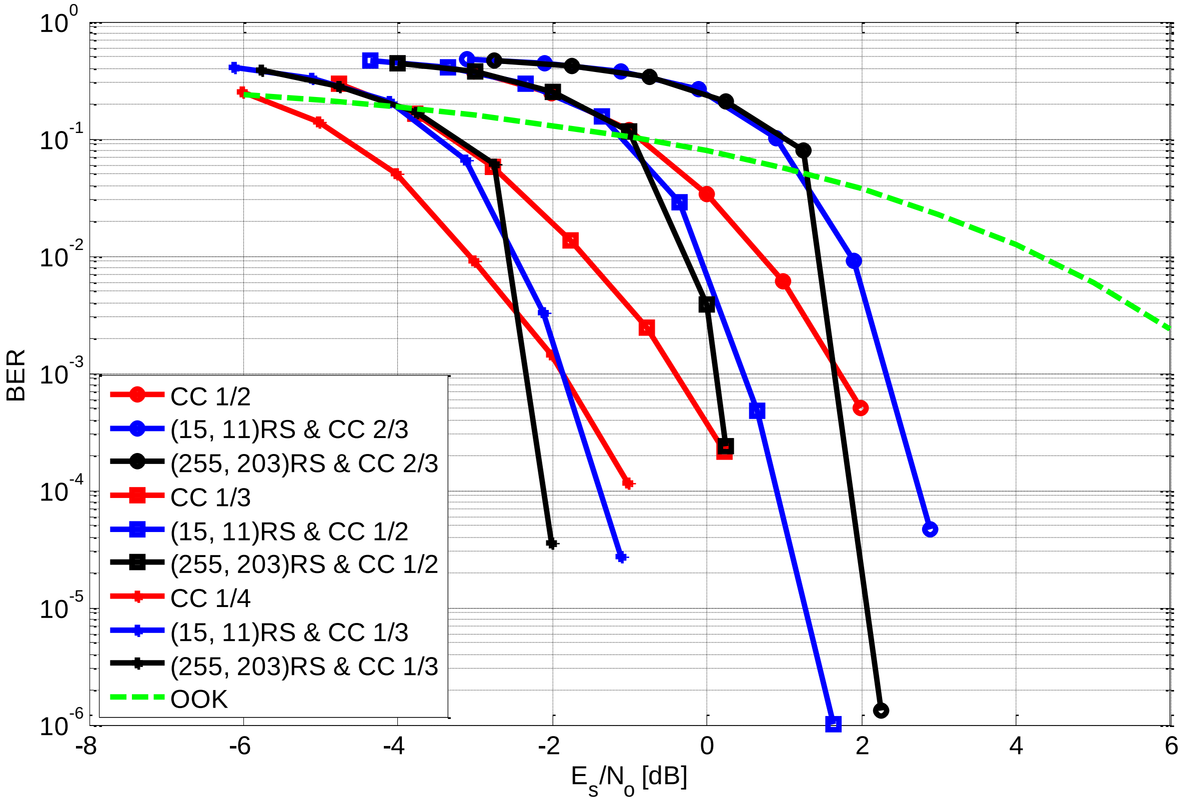


PHY I (Manchester): RS+CC

PHY I (4B6B): RS on GF(16)

PHY II : RS on GF(256)

Dynamic SNR Range



Assuming same optical rate, 2dB between rate-1/2 and rate-1/3, 2dB between rate-1/3 and rate-1/4, and >8dB between rate-1/4 and un-encoded OOK.

More simulations are needed to verify the dynamic range for all proposed MCSs, and to guarantee that there is no overlapping MCSs.

Recommendations

PHY I :

- use RS + CC for Manchester coding
- Given a choice, reduce coding rate in CC over RS code.
- Avoid use of repetition coding.
- Use RS only for 4B6B code
- Use GF(16) for RS code (short packet sizes)

PHY II

- Use RS GF(256) with 4B6B code
- Use RS GF(256) with 8B10B code

Further simulations on RS/CC choices

Assumptions

Random interleaver between CC and RS code.

RS decoder uses erasure information when available via RLL decoder.

VPM and OOK have same energy on the average

- VPM – assumes 50% duty cycle. i.e. 2-PPM in time period T
- OOK – assumes 100% duty cycle when ‘1’ over time period T, 0% when ‘0’

New rate tables (PHY I) – Clocks multiple of 2

	Optical rate	Modulation	Line coding	FEC	Data rate
PHY I	200 kHz	OOK	Manchester	(15, 3) RS + ¼ CC	5 kbps
				(15, 7) RS + ¼ CC	11.67 kbps
				(15, 11) RS + 1/3 CC	24.44 kbps
				(15, 11) RS + 2/3 CC	48.89 kbps
				(15, 11) RS	73.3 kbps
				1	100 kbps
	400 kHz	VPM	4B6B	(15, 2) RS	35.56 kbps
				(15, 4) RS	71.11 kbps
				(15, 7) RS	124.4 kbps
				1	266.6 kbps

GF(16) Reed-Solomon codes

- GF(16) generated by: x^4+x+1
- The generators for the (n, k) RS codes is given by the following narrow sense generators

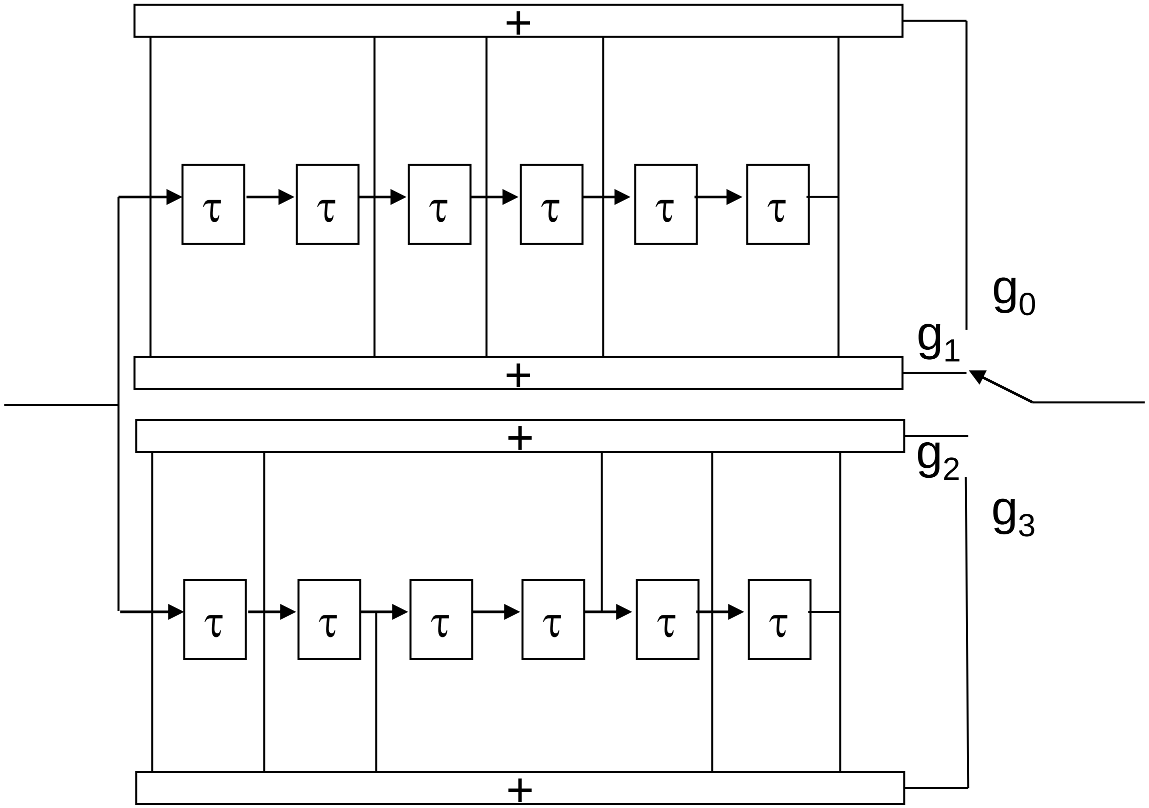
(n, k) RS	g(x)
(15, 11)	$x^4+\alpha^{13}x^3+\alpha^6x^2+\alpha^3x+\alpha^{10}$
(15, 7)	$x^8+\alpha^{14}x^7+\alpha^2x^6+\alpha^4x^5+\alpha^2x^4+\alpha^{13}x^3+\alpha^5x^2+\alpha^{11}x^1+\alpha^6$
(15, 4)	$x^{11}+\alpha^9x^{10}+\alpha^8x^9+\alpha^4x^8+\alpha^9x^7+\alpha^{13}x^6+\alpha^4x^5+\alpha^{12}x^4+\alpha^4x^3+\alpha^5x^2+\alpha^3x+\alpha^6$
(15, 3)	$x^{12}+\alpha^8x^{11}+\alpha^{14}x^{10}+\alpha^8x^9+\alpha^3x^8+\alpha^0x^7+\alpha^2x^6+\alpha^{13}x^5+\alpha^{14}x^4+\alpha^2x^3+\alpha^6x^2+\alpha^{13}x+\alpha^3$
(15, 2)	$x^{13}+\alpha^3x^{12}+\alpha^8x^{11}+\alpha^9x^{10}+\alpha^2x^9+\alpha^4x^8+\alpha^{14}x^7+\alpha^6x^6+\alpha^{10}x^5+\alpha^7x^4+\alpha^{13}x^3+\alpha^{11}x^2+\alpha^5x+\alpha$

Where, α is a primitive element in GF(16).
Note: The narrow-sense generator polynomial is $(x-\alpha)\,(x-\alpha^2)\ldots(x-\alpha^{n-k})$

Rate 1/4 Convolutional Code

Rate 1/4 ; k=7 ; $g_0 = 135_8$; $g_1 = 135_8$; $g_3 = 147_8$; $g_4 = 163_8$

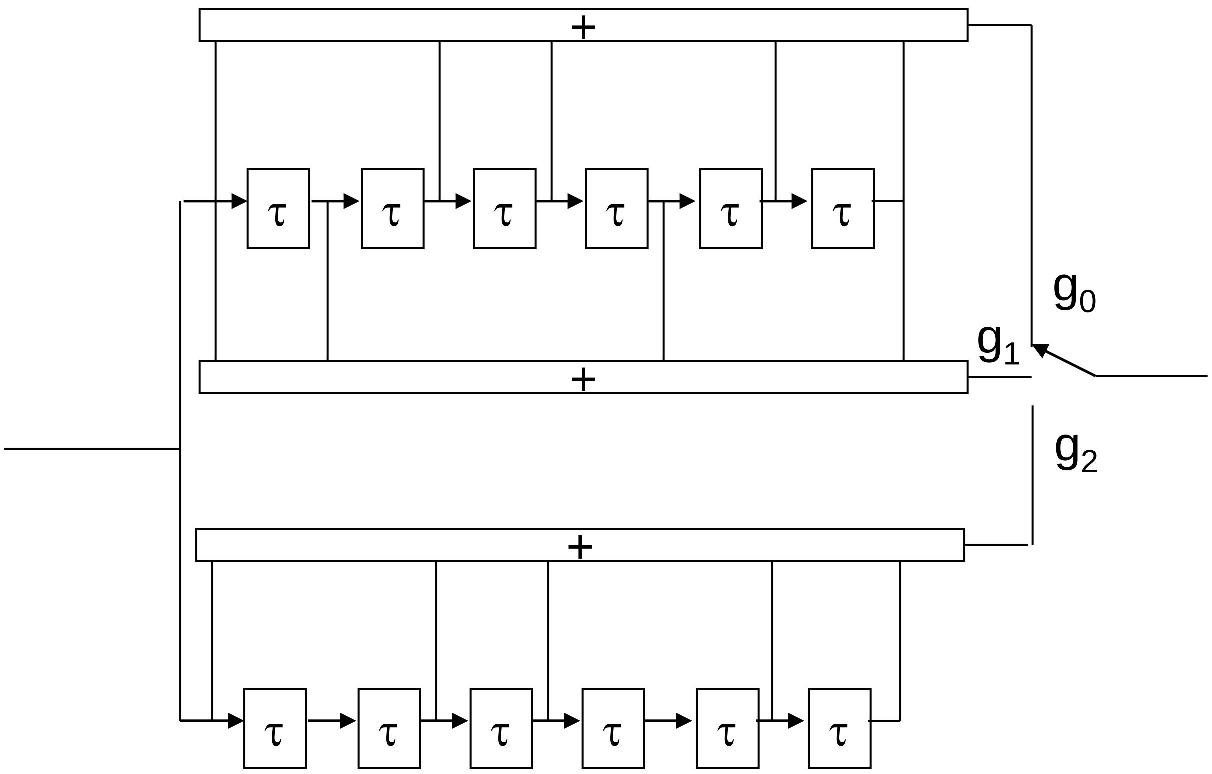
Ref: 802.15-10-0021-00-0007



Rate 1/3 Convolutional Code

Ref: 802.15-10-0021-00-0007

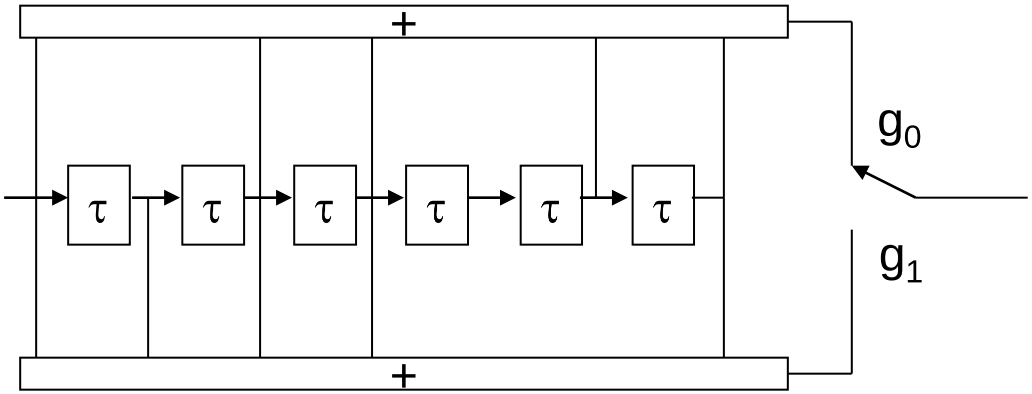
Rate 1/3 ; k=7 ; $g_0 = 133_8$; $g_1 = 145_8$; $g2 = 175_8$



Rate ½ Convolutional Code

Ref: 802.15-10-0021-00-0007

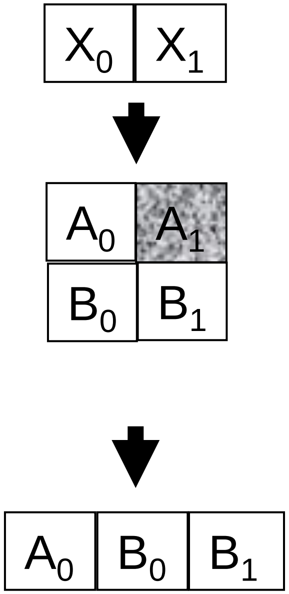
Rate 1/2 ; k=7 ; $g_0 = 133_8$; $g_1 = 171_8$



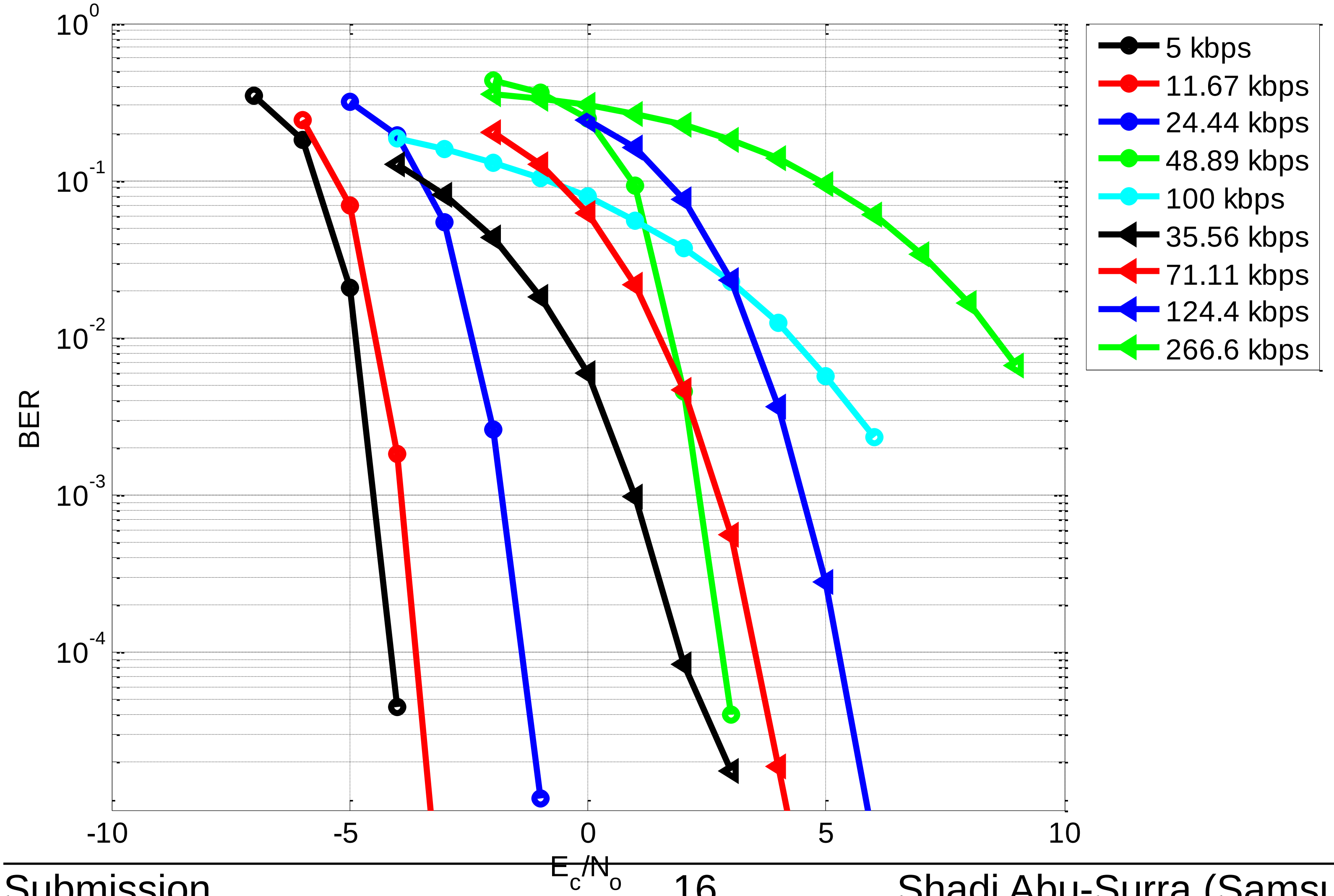
Rate 2/3 Convolutional Code

Ref: 802.15-10-0021-00-0007

Puncturing Rate 1/2 to generate Rate 2/3



PHY I simulation results



Simulation explanation

Used Ec/No (energy after coding) instead of Eb/No (energy per information bit)

Ec/No is defined at the output of the optical source (since the output to the LED is constant power)

For constant optical rate (200 KHz),

- Ec/No (dB) = Eb/No (dB) + $10*\log_{10}$(data rate/optical rate)

Ec is normalized with optical rate

- Ec (@400 KHz) = 0.5 * Ec(@200 KHz)

PHY II

	Modulation	Line coding	FEC	Optical rate	Data rate
PHY II	VPM	4B6B	(64, 32) RS	3.75 MHz	1.25 Mbps
			(160, 128) RS		2 Mbps
			(64, 32) RS	7.5 MHz	2.5 Mbps
			(160, 128) RS		4 Mbps
			1		5 Mbps
	OOK	8B10B	(64, 32) RS	15 MHz	6 Mbps
			(160, 128) RS		9.6 Mbps
			(64, 32) RS	30 MHz	12 Mbps
			(160, 128) RS		19.2 Mbps
			(64, 32) RS	60 MHz	24 Mbps
			(160, 128) RS		38.4 Mbps
			(64, 32) RS	120 MHz	48 Mbps
			(160, 128) RS		76.8 Mbps
			1		96 Mbps

GF(256) Reed-Solomon codes

- GF(256) generated by: $x^8+x^4+x^3+x^2+1$
- The generator for the (160, 128) RS code and the (64, 32) RS code is given by

$$g(x) = x^{32}+\alpha^{11}x^{31}+\alpha^{8}x^{30}+\alpha^{109}x^{29}+\alpha^{194}x^{28}+\alpha^{254}x^{27}+\alpha^{173}x^{26}+\alpha^{11}x^{25}+\alpha^{75}x^{24}+\alpha^{218}x^{23}+\alpha^{148}x^{23}$$
$$+\alpha^{149}x^{21}+\alpha^{44}x^{20}+\alpha^{0}x^{19}+\alpha^{137}x^{18}+\alpha^{104}x^{17}+\alpha^{43}x^{16}+\alpha^{137}x^{15}+\alpha^{203}x^{14}+\alpha^{99}x^{13}+\alpha^{176}x^{12}+a^{59}x^{11}$$
$$+\alpha^{91}x^{10}+\alpha^{194}x^{9}+\alpha^{84}x^{8}+\alpha^{53}x^{7}+\alpha^{248}x^{6}+\alpha^{107}x^{5}+\alpha^{80}x^{4}+\alpha^{28}x^{3}+\alpha^{215}x^{2}+\alpha^{251}x+\alpha^{18}$$

Where, α is a primitive element in GF(256)

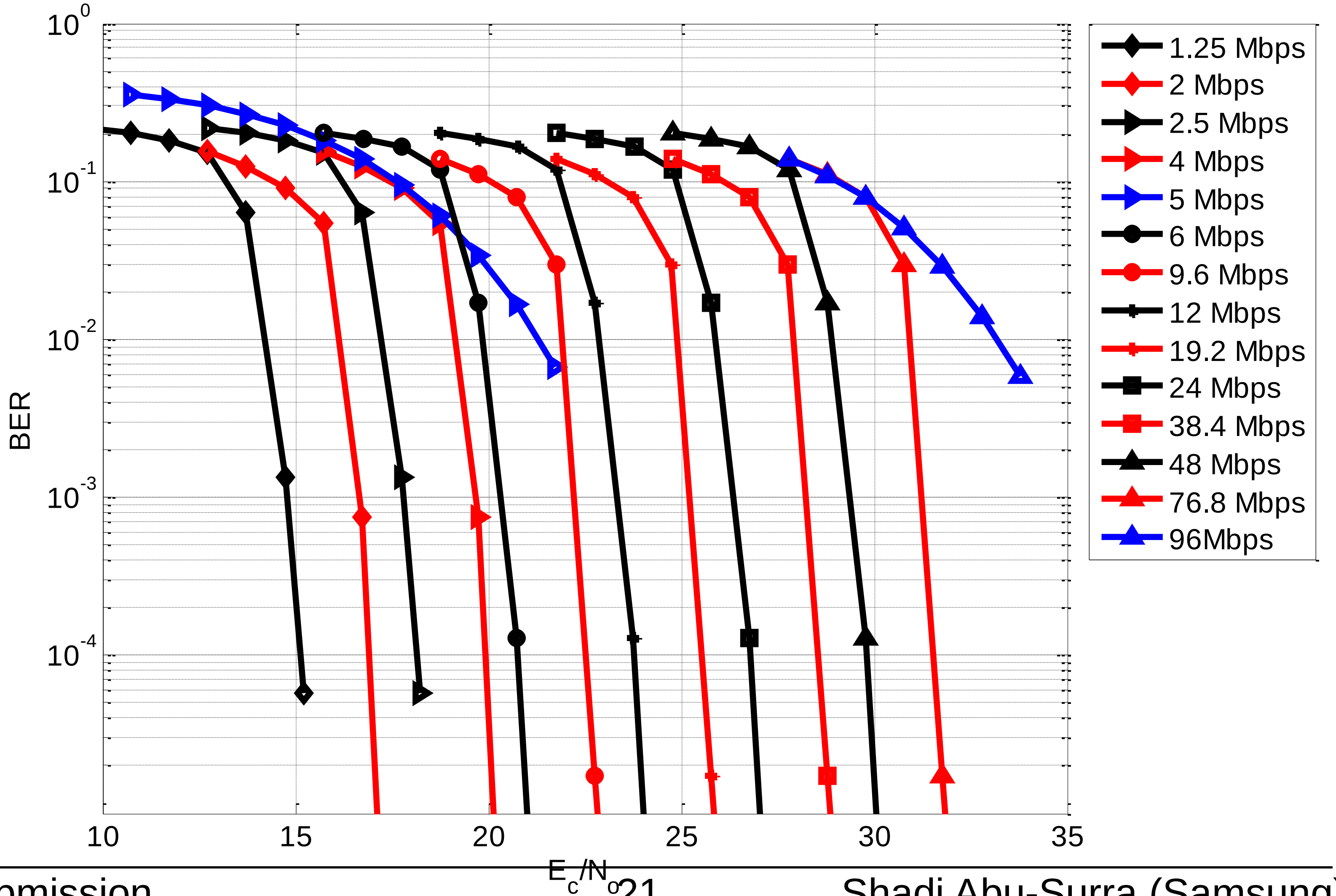
Shortened RS codes

RS codes can be shortened by padding zeros to make it into a RS codeword and then not transmitting the padded zeros

RS codes are shortened for PHY II to keep n-k = 32 for constant complexity as shown for the data rates

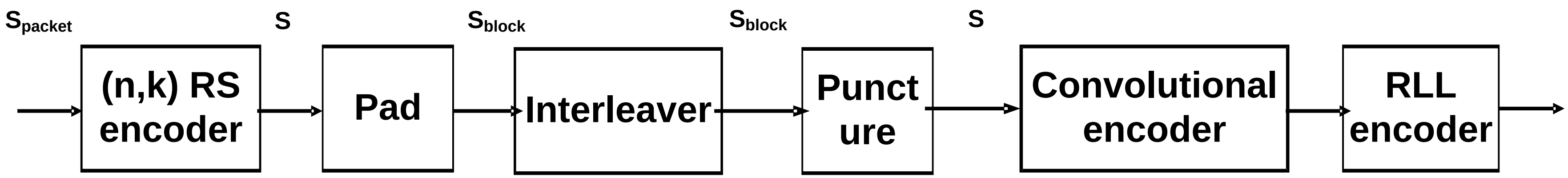
RS codes are also shortened when the packet size does not fit into a codeword boundary for both PHY I and PHY II to minimize overhead

PHY II simulation results



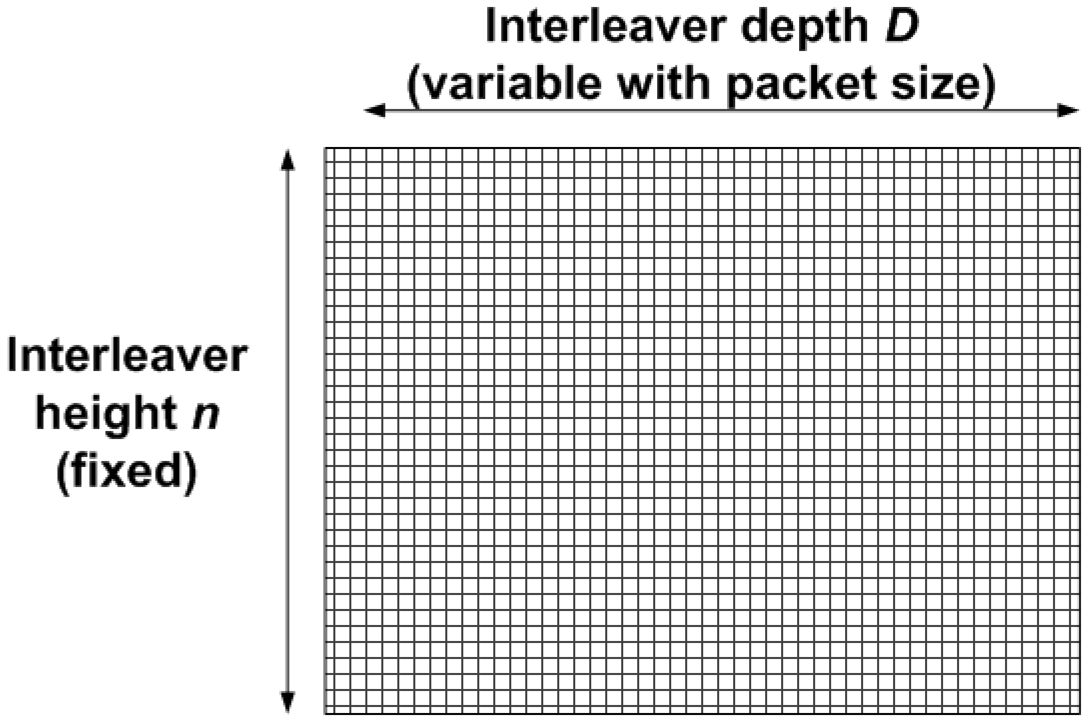
Interleaver design
(Structured interleaver instead of a random interleaver)

Interleaver design

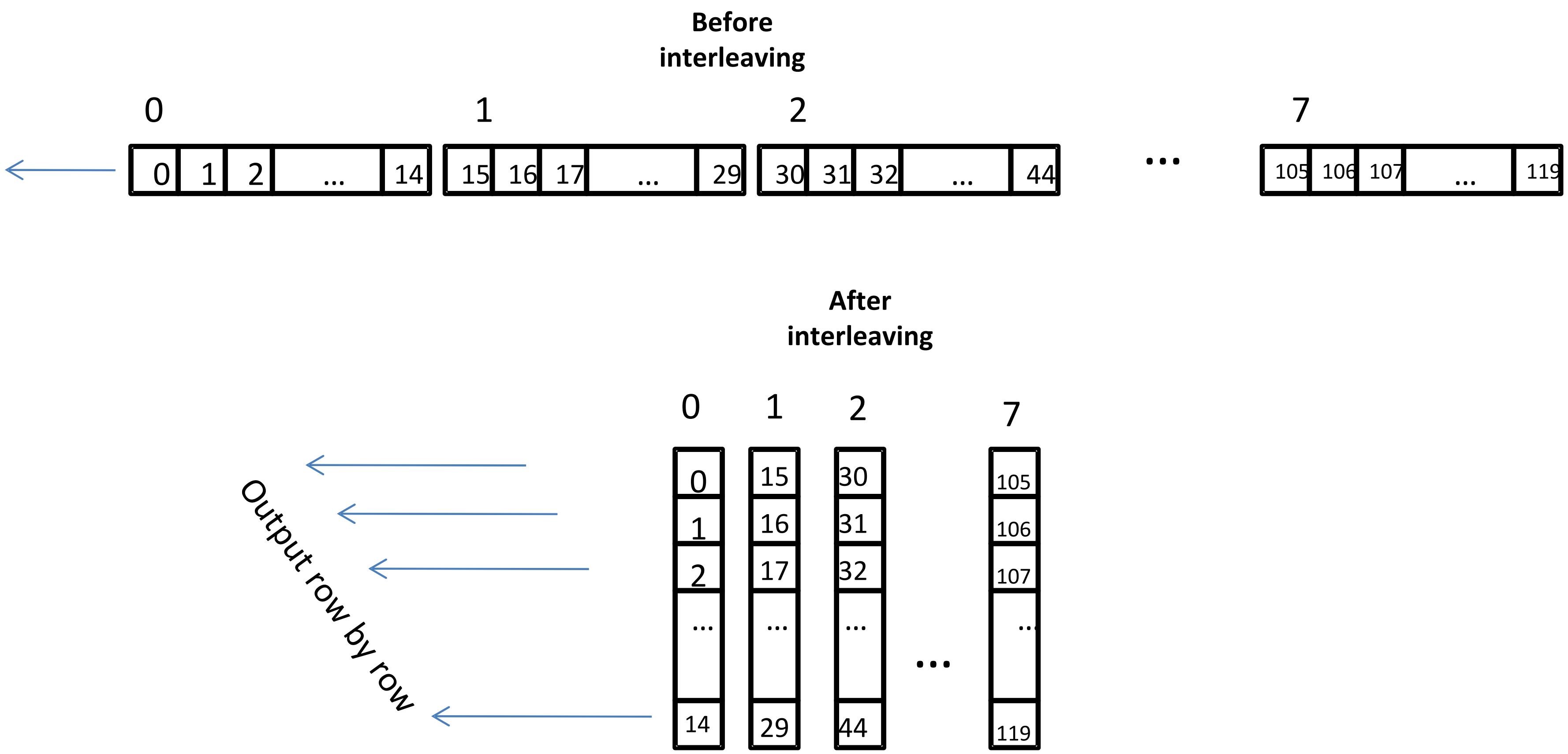


- Interleaver is a block interleaver.
- Fixed height *n*
- Flexible depth *D*, dependent on the packet size
  - Optimized for short packet sizes to eliminate padding

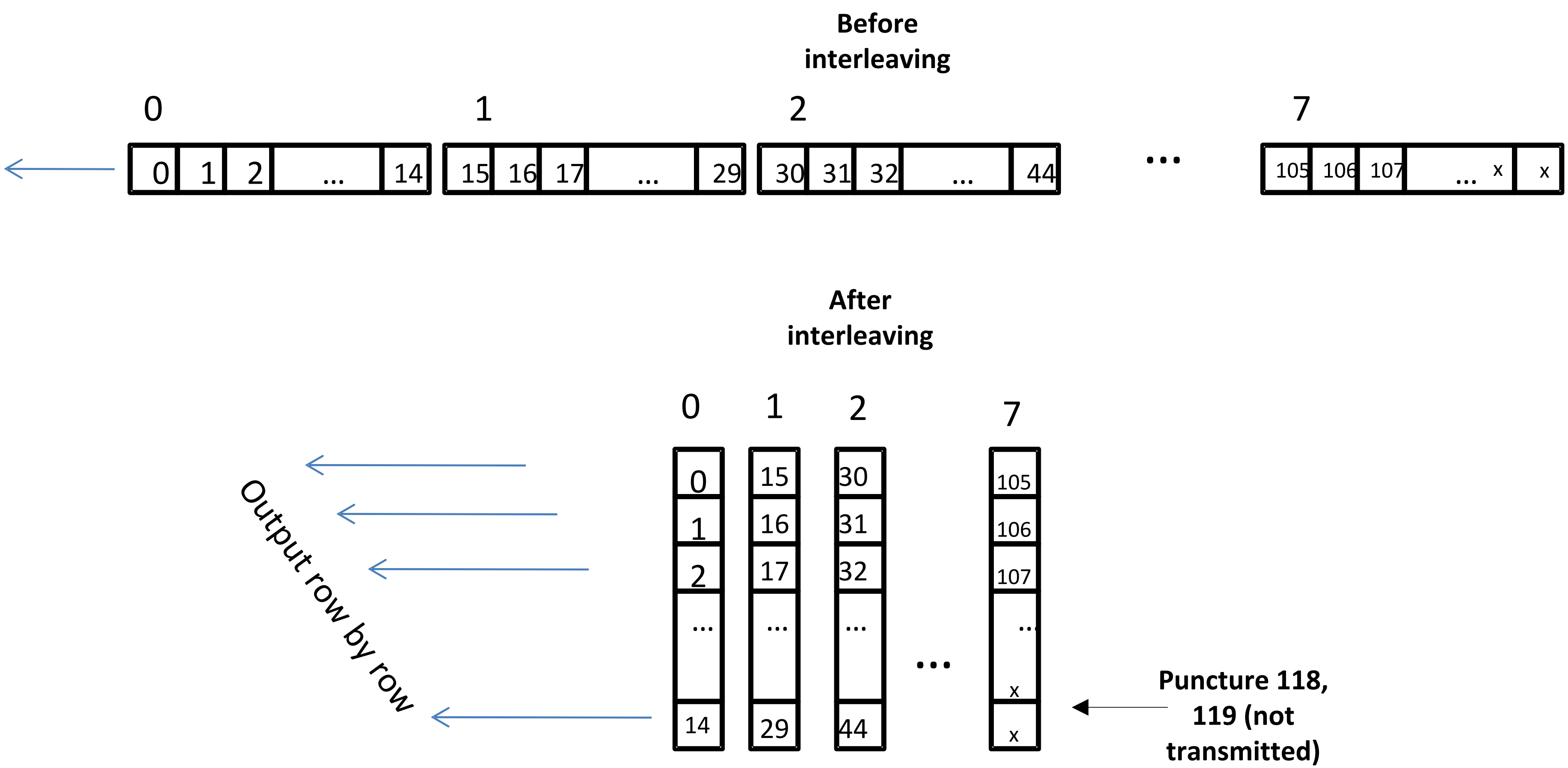
Block interleaver design



Example 1 : 120 symbols, n = 15



Example 2 : 118 symbols, n = 15



Interleaver details

- n : RS codeword length.
- k : number of information data symbols in a RS codeword.
- q : Number of elements in the Galois field : GF(q)
- L_{packet}: Input packet size in bytes
- S_{packet} : number of symbols at the input of the RS encoder
- S : number of symbols from the output of the shortened RS encoder.
- S_{block} : The size of the interleaver used
- D : the interleaving depth.
- i : ordered indices take the values 0, 1, …, S_{block}-1.
- $I(i)$: interleaved indices.
- p : number of zero symbols
- t : ordered indices take the values 0, 1, …, p.
- $z(t)$: locations of the bits to be punctured at the output of the interleaver before transmission

$$S_{packet} = \left\lceil \frac{L_{packet} * 8}{\log_2(q)} \right\rceil$$

$$S = n * \left\lceil \frac{S_{packet}}{k} \right\rceil - \left(k - \left(S_{packet} \bmod k\right)\right)$$

When *S* is a multiple of *n*, there is no padding or puncturing, The RS encoder produces *n* symbols for every codeword, which are then sent to the interleaver. When *S* is not multiple of *n*, *p* remaining symbols for the last codeword are padded with zero symbols and encoded to produce *n* symbols. After interleaving, the zero symbols are punctured out and are not transmitted.

$$D = \left\lceil \frac{S}{n} \right\rceil$$

$$S_{block} = n*D.$$

$$p = \mathrm{n} - (S \bmod n)$$

Interleaver:

$$l(i) = (i \bmod D)*n + \left\lfloor \frac{i}{D} \right\rfloor; \text{ for } \mathrm{i} = 0,1,..,(\mathrm{S_{block}} - 1)$$

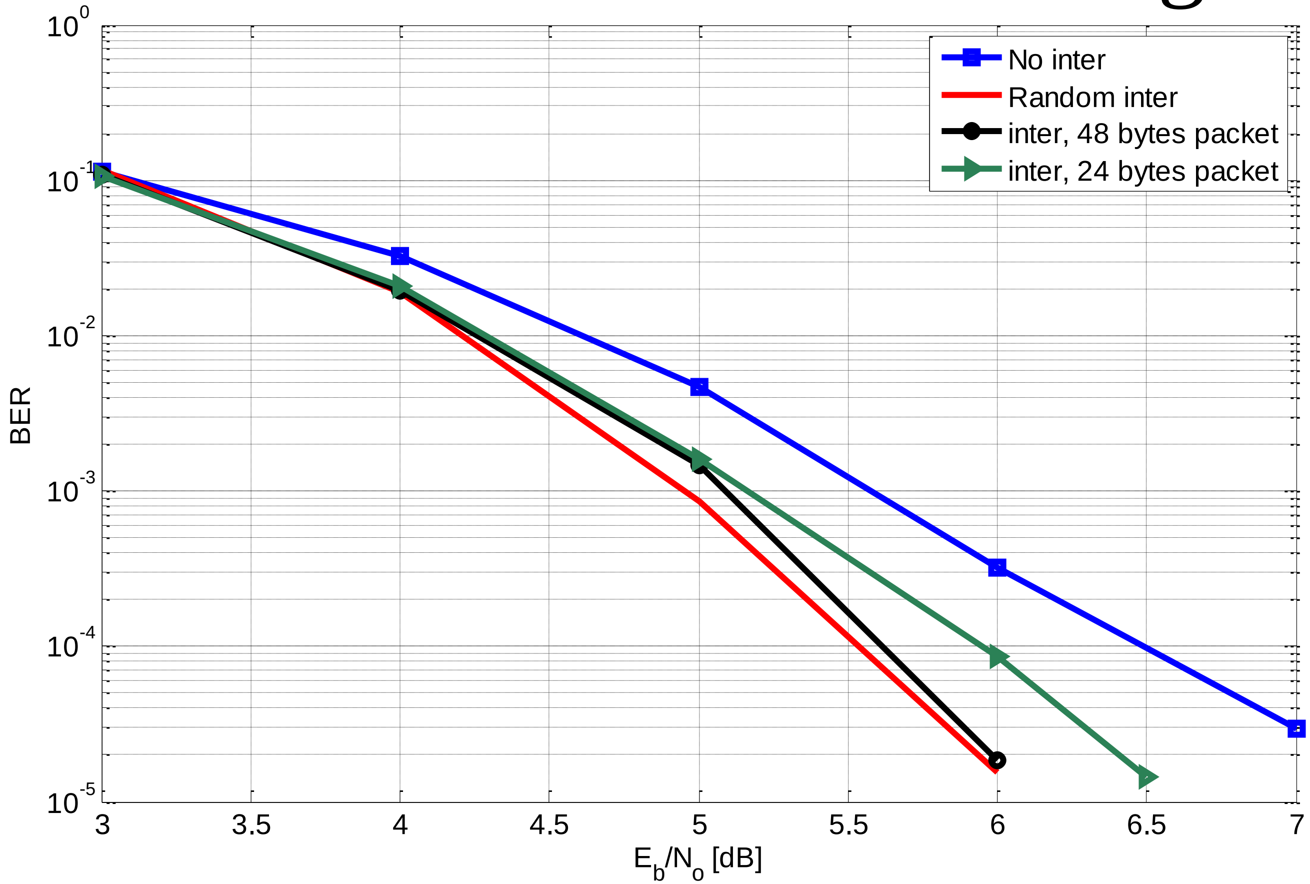
Locations to be punctured:

$$z(t) = (n - p + 1)*D + t*D - 1; \text{ for } \mathrm{t} = 0,1, .., \mathrm{p} - 1$$

Simulation assumptions

- (15, 12) RS + ½ CC
- Hard-decision decoding is used in the RS and the CC decoders.
- Manchester channel DC-balance encoder is considered.
- AWGN channel
- Small packet sizes

Benefits of Interleaving



Further gains can be expected for fading channels if increased burst errors over multiple RS symbols

Usage

The length of the packet is communicated to the receiver in the header so that the receiver can adaptively adjust the interleaver based on the packet sizes.

When the data rates corresponding to the robust transmissions using the concatenated codes are used, the header shall also be interleaved according to the above procedure.

Since the length of the header is fixed, the receiver can deinterleave the header without explicit transmission of the header length.

Summary

Symbol interleaver between RS code and CC can give performance advantages, providing increased reliability for applications such as vehicular communication

Interleaver designed for short packet sizes – no overhead due to padding

Simple, block interleaver structure

- Feasible for implementation

Interleaver works on very low symbol speed (50 KHz : 200 KHz clock, 4 bits/symbol)

Recommendations

Adopt the proposed symbol interleaver between the RS and CC code for applicable data rates