Forward Error Correction for IEEE 802.3bn EPoC

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Outline

- Requirements for FEC in EPoC
- Code Descriptions
  - Encoding
  - Parity Matrices
- Performance Analysis
  - Simulation results for AWGN and Burst Noise
- Summary

IEEE 802.3bn Objectives

- Objectives for IEEE 802.3bn
  - *"Provide a physical layer specification that is capable of a baseline data rate of 1 Gb/s at the MAC/PLS service interface when transmitting in 120 MHz, or less, of assigned spectrum under defined baseline plant conditions"*
  - *"PHY to have:*
    - *A downstream frame error rate better than 10^-6 at the MAC/PLS service interface*
    - *An upstream frame error rate better than 5x10^-5 at the MAC/PLS service interface"*
- Based on these objectives and on agreements achieved so far in EPoC, several requirements for the LDPC FEC can be derived
  - See next slide for further details

FEC Requirements for EPoC – Rate and Length

- The FEC scheme should support multiple rates
  - High codes rates should be supported in order to achieve large spectral efficiency
    - The highest rate should be in the order of R = 0.9
  - Lower code rates should be supported as well in order to provide sufficient robustness in severe burst noise conditions
    - The lowest rate should be in the order of R = 0.75
- The FEC scheme should support multiple code lengths
  - For bursty upstream traffic, the shortest code length should be roughly 1000 bits to serve a 64 bytes packet + overhead
  - For continuous downstream traffic, the longest code length should be roughly 15000 – 16000 bits
  - For burst modes (FDD US, TDD DS/US) intermediate length should be available

FEC Requirements for EPoC – Class of Codes

- The same class of LDPC codes should be applied in all EPoC modes
  - This allows having a common PHY in EPoC
- The FEC should have a deep error floor to avoid outer BCH codes
- Encoder and decoder should be implementable with low complexity
  - Quasi-cyclic LDPC codes should be applied in EPoC
    - For a rate $R = k/n$ code the information block size is $k \cdot Z$ and the code length is $n \cdot Z$
    - Z is called the lifting size of a quasi-cyclic LDPC code
- All lifting sizes Z of the LDPC codes should be the identical or should have a common large factor
  - An identical lifting size enables applying the same decoder for all codes of this lifting size
  - Common factors in the lifting size enable hardware reuse for codes of different lifting size

Design of the LDPC Codes

- All proposed LDPC codes are quasi-cyclic and binary
- The proposed LDPC codes fit to all modes in EPoC
  - A specific subset may be chosen for the continuous mode (FDD DS) and the burst modes (FDD US, TDD DS/US) in EPoC
    - E.g., codes with large lifting size may be chosen for the continuous mode
    - E.g., codes with short(er) lifting size and/or shorter code length may be chosen for burst modes
- The matrix M to calculate the parity bits has nearly upper diagonal form for all codes
  - In the proposed codes, only the first sub-diagonal of the matrix M is non-zero
  - The parity matrices H are constructed so that encoding can be realized with low complexity
    - A complete description is provided in the backup

Proposed Set of LDPC Codes

Code	Rate k/n	Lifting Size Z	Code Length n · Z
I	27/30 = 0.9	360	10800
II	13/15 = 0.867	360	5400
III	37/42 = 0.88	360	15120
IV	36/40 = 0.9	360	14400
V	40/45 = 0.89	360	16200
VI	12/16 = 0.75	60 / 120 / 240 / 360	960 / 1920 / 3840 / 5760
VII	16/20 = 0.8	60 / 120 / 240 / 360	1200 / 2400 / 4800 / 7200
VIII	20/24 = 0.833	120 / 240 / 360	2880 / 5760 / 8640
IX	23/27 = 0.85	120 / 240 / 360	3240 / 6480 / 9720

- The parity matrices of all codes are given in the backup slides

Edge Density, Parity Checks and Lifting Size

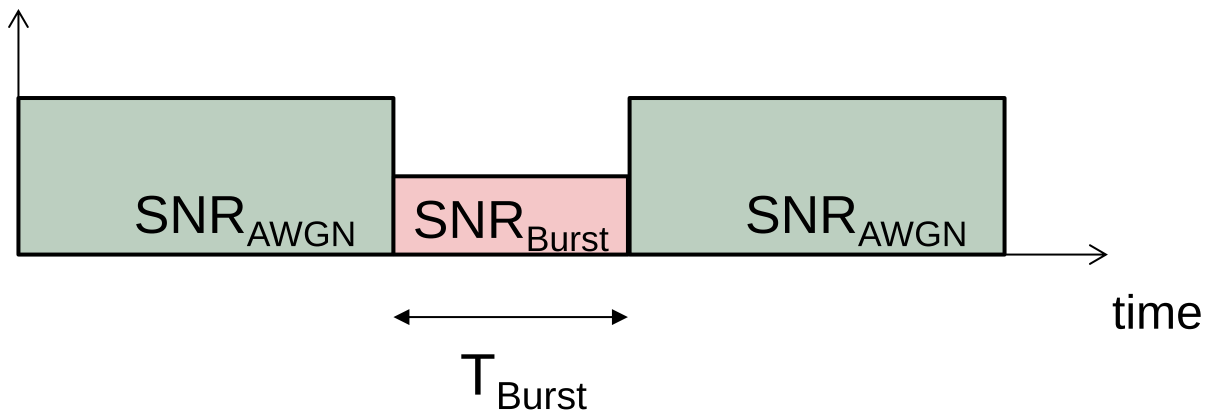
Base n	Base k	Rate	Lifting Z	Information bits	Code word length	Parity checks	Based edges	Edge density
30	27	0.9	**360**	9720	10800	**1440**	105	**3.5**
15	13	0.866667	**360**	4680	5400	**1080 (1440)**	54 (56)	**3.6 (3.73)**
40	36	0.9	**360**	12960	14400	**1800**	137	**3.425**
42	37	0.880952	**360**	13320	15120	**2160**	147	**3.5**
45	40	0.888889	**360**	14400	16200	**1800**	150	**3.33**
16	12	0.75	**60**	720	960	**300**	57	**3.56**
16	12	0.75	**120**	1440	1920	**600**	53	**3.31**
16	12	0.75	**240**	2880	3840	**1200**	51	**3.19**
16	12	0.75	**360**	4320	5760	**1800**	51	**3.19**
20	16	0.8	**60**	960	1200	**300**	72	**3.60**
20	16	0.8	**120**	1920	2400	**600**	71	**3.55**
20	16	0.8	**240**	3840	4800	**1200**	69	**3.45**
20	16	0.8	**360**	5760	7200	**1800**	67	**3.35**
24	20	0.833333	**120**	2400	2880	**600**	87	**3.63**
24	20	0.833333	**240**	4800	5760	**1200**	85	**3.54**
24	20	0.833333	**360**	7200	8640	**1800**	83	**3.46**
27	23	0.851852	**120**	2760	3240	**600**	98	**3.63**
27	23	0.851852	**240**	5520	6480	**1200**	97	**3.59**
27	23	0.851852	**360**	8280	9720	**1800**	93	**3.44**

Performance Analysis of the LDPC Codes

- In the following slides a detailed performance analysis of the proposed LDPC codes is provided
- Simulation results are shown for
  - AWGN
  - Burst noise including required time interleaving depth
  - OFDM symbol durations of 20 μs and 40 μs
- Performance is compared with the DVB-C2 LDPC code and the ITU-T G.9960 LDPC code
- Performance metric of interest is a bit error rate (BER) of 1e-8
  - A BER of 1e-8 corresponds roughly to a frame error rate of 1e-6

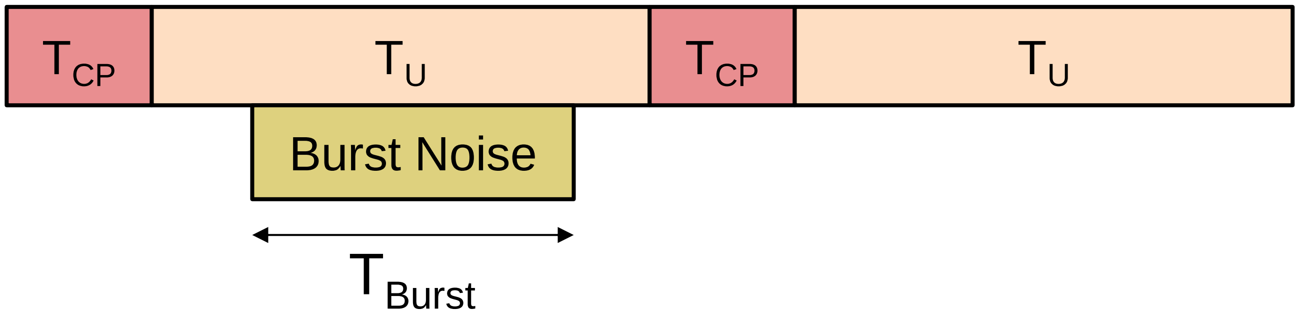
Burst Noise in OFDM

- To analyze performance in burst noise, a simple model is chosen
  - Burst noise is modeled as white Gaussian noise with a certain SNR_{Burst}
    - Burst noise is assumed to be wideband
  - Burst noise is modeled with time duration T_{burst} and burst SNR SNR_{Burst}



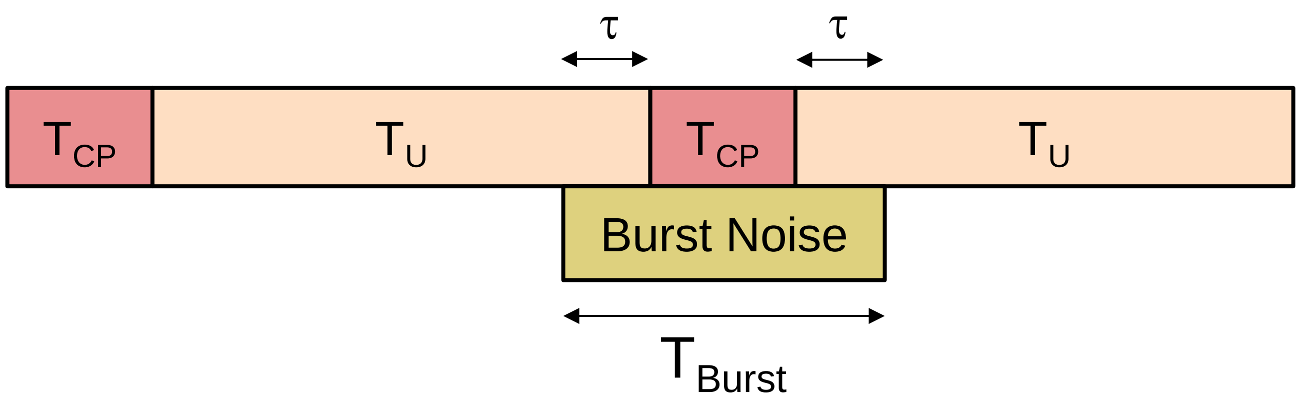
- The burst noise duration T_{Burst} is assumed to be shorter than the duration of an OFDM symbol
  - In this case, burst noise can impact one or two OFDM symbols

Burst Noise affecting One OFDM Symbol



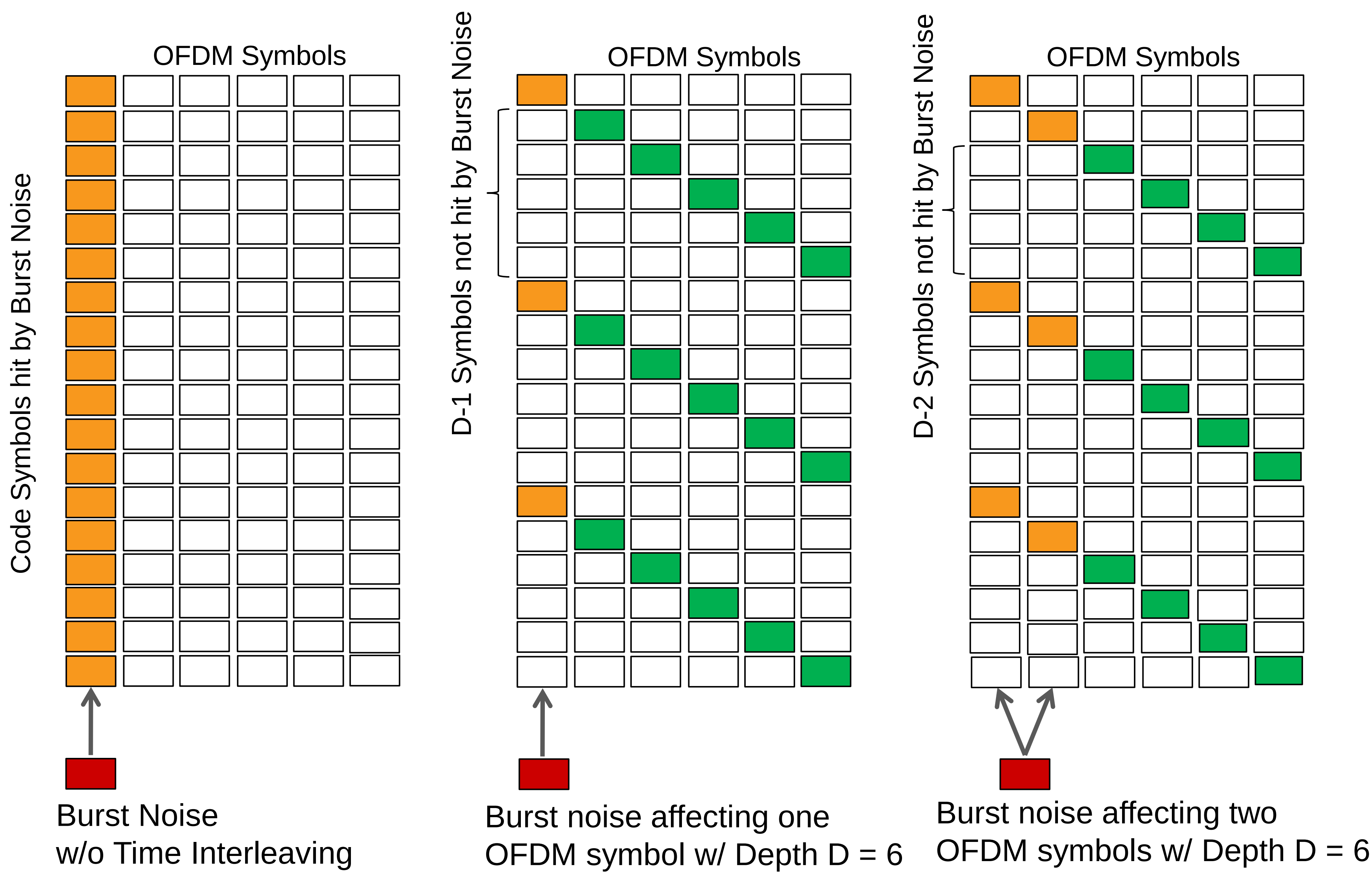
- Effective SNR in OFDM symbols hit by burst noise
  - $SNR = -10 \cdot \log_{10}(10\text{^}(-SNR_{Burst,\ effective}/10) + 10\text{^}(-SNR_{AWGN,\ effective}/10))$
    - $SNR_{Burst,\ effective} = SNR_{Burst} - 10 \cdot \log_{10}(T_{Burst} / T_U)$
    - $SNR_{AWGN,\ effective} = SNR_{AWGN} - 10 \cdot \log_{10}(1 - T_{Burst} / T_U)$
- Effective SNR in OFDM symbols not hit by burst noise
  - $SNR = SNR_{AWGN}$

Burst Noise affecting Two OFDM Symbols



- Effective SNR in OFDM symbols hit by burst noise
  - $SNR = -10 \cdot \log_{10}(10\text{^}(-SNR_{Burst,\ effective}/10) + 10\text{^}(-SNR_{AWGN,\ effective}/10))$
    - $SNR_{Burst,\ effective} = SNR_{Burst} – 10 \cdot \log_{10}(0.5 \cdot (T_{Burst} - T_{CP}) / T_U)$
    - $SNR_{AWGN,\ effective} = SNR_{AWGN} – 10 \cdot \log_{10}(1 - 0.5 \cdot (T_{Burst} - T_{CP}) / T_U)$
- Effective SNR in OFDM symbols not hit by burst noise
  - $SNR = SNR_{AWGN}$

Frequency Domain View of Time Interleaving Depth D



Consideration on Time Interleaving Depth D

- The depth D of the time domain interleaving impacts how many QAM symbols of a code word are affected by burst noise
  - For a larger interleaving depth D less symbols of a code word are impacted and performance improves
  - The drawback of a large interleaving depth D is increased PHY latency
    - However, if the depth D is to small, BER performance does not reach the BER target of 1e-8 anymore
- Hence, an important metric is the required interleaving depth D to achieve BER = 1e-8 at a fixed AWGN SNR
  - Interleaving depths are provided in the following
- Comments on required interleaving depth D
  - It can be shown that the required interleaving depth D is related to the inverse of the code rate R, i.e. $D \sim 1 / (1 - R)$

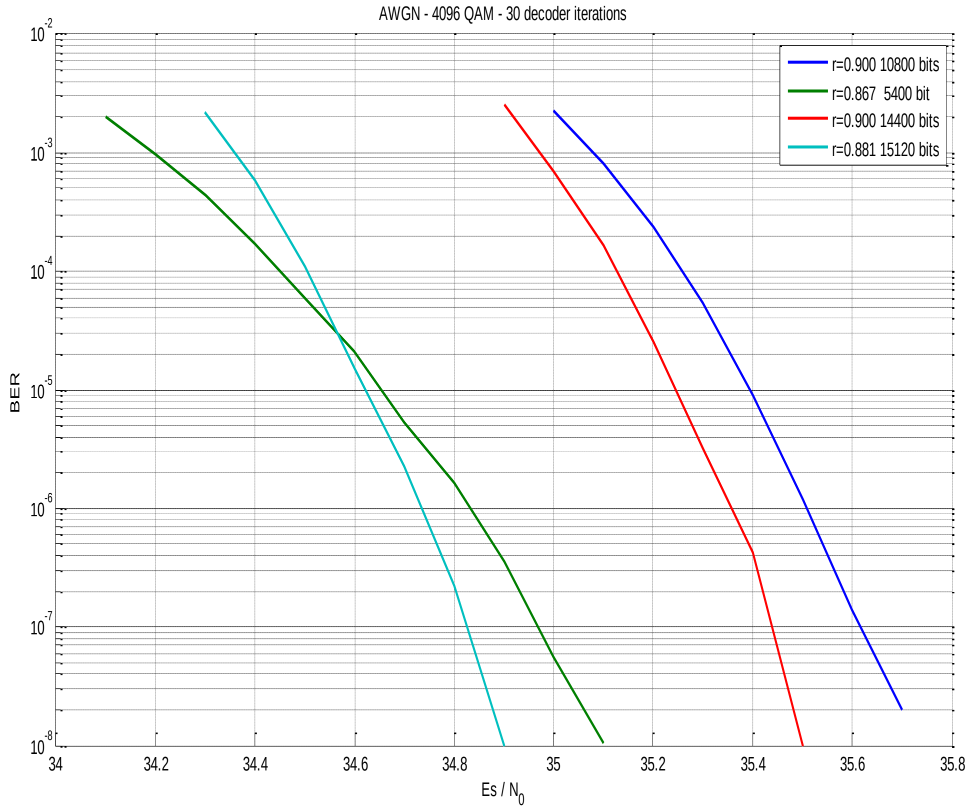
Simulation Assumptions

- Downstream
  - 4096QAM
  - OFDM symbol durations T_U = 20 μs and T_U = 40 μs
  - Cyclic prefix length T_{CP} = 2.5 μs
  - Burst noise
    a) T_{Burst} = 16 μs, SNR_{Burst} = 20 dB equally affecting two OFDM symbols
    b) T_{Burst} = 16 μs, SNR_{Burst} = 5 dB equally affecting two OFDM symbols
- Upstream
  - 1024QAM
  - OFDM symbol durations T_U = 20 μs and T_U = 40 μs
  - Cyclic prefix length T_{CP} = 2.5 μs
  - Burst noise
    a) T_{Burst} = 10 μs, SNR_{Burst} = 10 dB equally affecting two OFDM symbols
    b) T_{Burst} = 1 μs, SNR_{Burst} = 0 dB affecting one OFDM symbol only

Further Assumptions

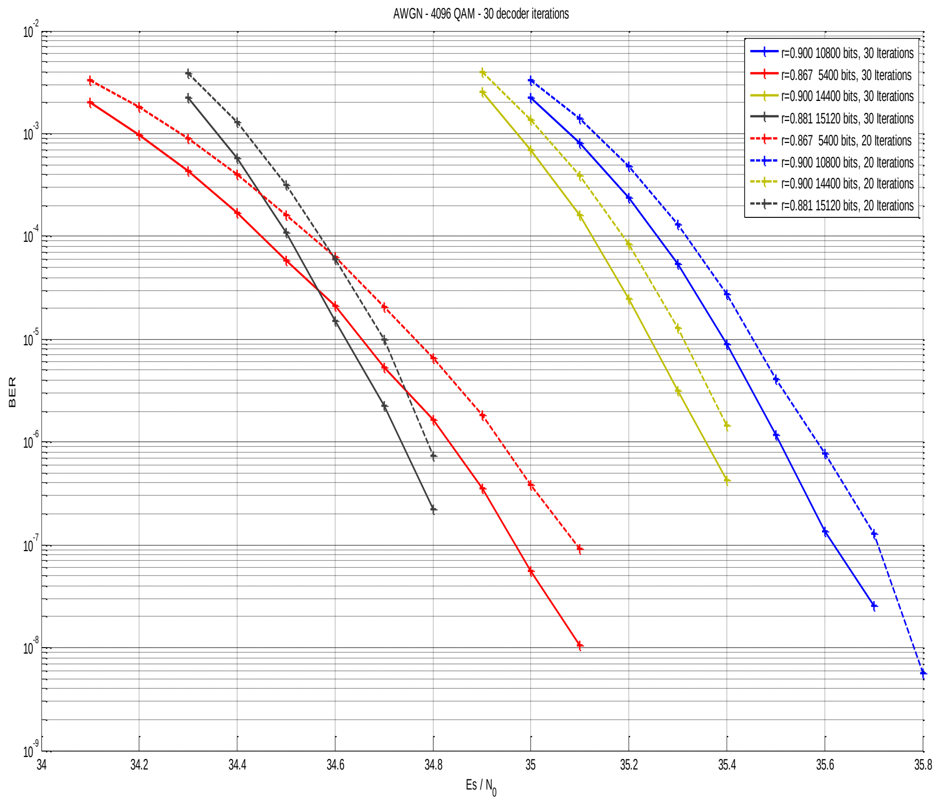
- LDPC decoder assumptions
  - Sum product decoder
  - Flooding schedule
    - No layered iterations are applied
  - The maximal number of iterations is set to 20 or 30, respectively
    - In the hardware implementation, layered iterations would be applied
      - » This allows reducing the number of iterations roughly by 50%
      - » Since the implementation and performance of a layered schedule is LDPC code specific, it is not used for code comparison
- Performance results for Codes I – IV and Code VIII are presented in the following slides
  - The burst noise results are for the downstream scenarios
- Still missing simulations
  - Codes V – IX for AWGN and burst noise scenarios
    - Results will be updated later

Performance of Codes I – IV in AWGN



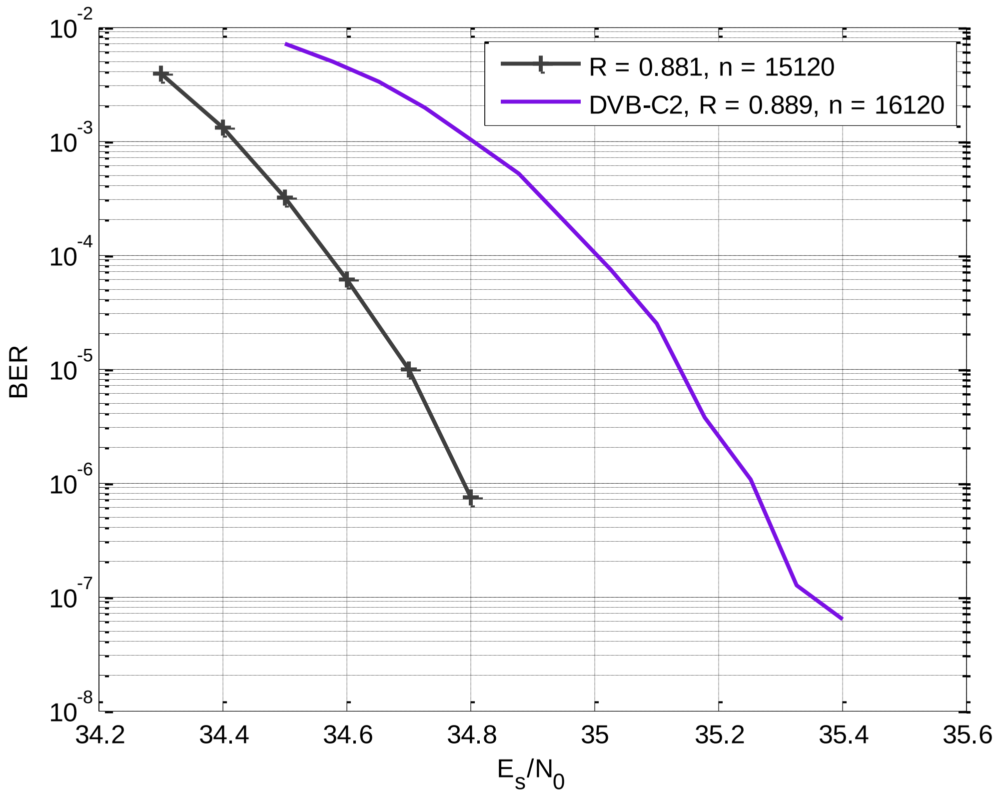
- Performance of Codes I – IV for max. 30 iterations with flooding schedule
- 4096QAM, AWGN
- Simulations still ongoing for BER ≤ 1e-8

Performance of Codes I – IV with 20 & 30 Iterations



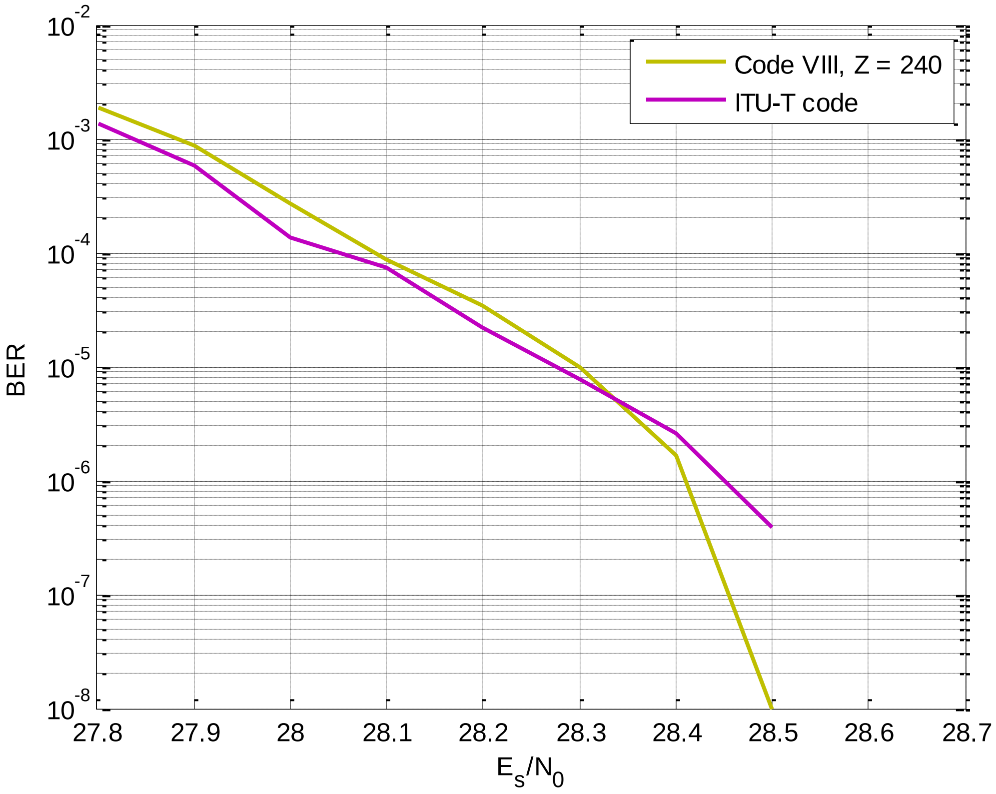
- Performance of Codes I – IV for max. 20 & 30 iterations with flooding schedule
- 4096QAM, AWGN
- The gain of 10 additional iterations is in the order of 0.1 dB

Comparison of Code III with DVB-C2 in AWGN



- Comparison of Code III and the DVB-C2 code
  - Code III: R = 0.881, n = 15120
  - DVB-C2: R = 0.889, n = 16200
- 4096QAM, AWGN
- Max. 20 iterations with flooding schedule
- Code III outperforms the DVB-C2 code by more than 0.4 dB at BER = 1e-6

Comparison of Code VIII, Z=240 with ITU-T G.9960



- Comparison of Code VIII and the ITU-T G.9960 code
  - Code VIII: R = 0.833, n = 5760, Z = 240
  - ITU-T: R = 0.883, n = 5184
- 1024QAM, AWGN
- Max. 30 iterations with flooding schedule
- Preliminary result
  - At low BER Code VIII outperforms G.9960 code
  - Simulations still ongoing for BER $\leq$ 1e-8

Performance in Burst Noise impacting One Symbol

Required Interleaving Depth @ BER ≤ 1e-8	Rate R / Length N	AWGN SNR [dB]	20 μs OFDM symbol duration		40 μs OFDM symbol duration	
			20 dB burst noise	5 dB burst noise	20 dB burst noise	5 dB burst noise
Code I	R = 0.9 N = 10800	38 dB	12	21	10	18
Code II	R = 0.867 N = 5400	37 dB	12	> 20	9	18
Code III	R = 0.881 N = 15120	37 dB	10	17	≤ 8	17
Code IV	R = 0.9 N = 14400	38 dB	10	18	9	17

Performance in Burst Noise impacting Two Symbols

Required Interleaving Depth @ BER ≤ 1e-8	Rate R / Length N	AWGN SNR [dB]	20 μs OFDM symbol duration		40 μs OFDM symbol duration	
			20 dB burst noise	5 dB burst noise	20 dB burst noise	5 dB burst noise
Code I	R = 0.9 N = 10800	38 dB	18	34	≤ 14	31
Code II	R = 0.867 N = 5400	37 dB	17	> 35	13	32
Code III	R = 0.881 N = 15120	37 dB	15	33	12	29
Code IV	R = 0.9 N = 14400	38 dB	16	> 32	12	30

Conclusions

- A set of quasi-cyclic LDPC codes has been proposed that is suited for all modes in EPoC
  - Codes with large lifting size may be chosen for the continuous mode in EPoC
  - Codes with short(er) lifting size and/or shorter code length may be chosen for burst modes in EPoC
- Low complexity implementation is ensured by the code structure and the choice of the lifting sizes
- Performance comparison
  - Code III (R = 0.88, n = 15120) outperforms the DVB-C2 LDPC code by more than 0.4 dB for 4096QAM
  - Code VIII (R = 0.833, n = 5760, Z = 240) outperforms the ITU-T G.9960 LDPC code at low BER for 1024QAM

Thank you

Backup

LDPC Parity Check Matrix Description

- In the following slides the parity check matrices H of the LDPC codes are given
- Description
  - In all tables the top row indexes columns of the parity check matrix
  - The second row of the tables indicates information (1) and parity (0) columns
  - The third row of the tables indicates transmitted columns (1) and punctured columns (0)

Parity Matrices for Code I and Code II

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	16	·	13	·	·	2	·	277	112	·	233	272	85	277	104	310	355	168	43	198	105	142	67	85	277	334	258	156	20	5
0	241	235	58	157	218	·	39	209	19	269	·	·	·	94	323	55	64	·	46	325	158	118	122	167	344	126	281	40	85	222
·	241	122	0	187	66	216	351	208	·	59	111	114	277	·	64	57	·	333	182	159	175	77	256	284	92	148	185	86	184	93
·	·	122	90	29	224	168	97	·	30	254	114	334	169	132	·	·	353	141	217	105	84	138	136	31	97	3	144	20	6	354

Figure 1: Base code information bits: 27; (max) block length: 30. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
0	·	·	45	·	92	28	·	137	111	344	2	338	190	258	328	13
0	241	·	·	284	·	·	186	·	198	185	334	76	148	236	93	190
·	241	122	119	171	17	244	303	218	356	258	53	181	330	271	279	150
·	·	122	0	287	36	135	84	72	245	208	303	239	124	176	284	121

Figure 2: Base code information bits: 13; (max) block length: 15. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Parity Matrices for Code III and Code IV

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	151	·	·	·	186	·	275	240	·	·	305	·	·	·	27	163	179	·	114	·	54	·	280	37
0	61	·	·	·	·	·	·	193	90	357	·	·	49	135	·	·	·	153	·	·	20	322	243	·
·	61	122	184	·	·	153	·	306	·	11	164	·	·	·	·	·	306	3	53	124	·	243	·	71
·	·	122	183	·	355	314	32	·	·	27	·	298	121	76	90	·	266	·	·	·	259	·	·	141
·	·	·	183	244	·	·	266	·	278	·	145	86	·	183	·	2	·	56	·	103	·	·	344	·
·	·	·	·	244	345	119	·	·	78	·	·	24	221	·	301	145	·	·	76	259	·	119	·	215

...

25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
·	125	122	258	220	111	296	·	·	122	64	·	·	88	43	·	74	252
17	273	106	·	119	·	182	72	·	168	238	228	270	127	·	·	309	278
126	306	·	156	194	234	111	42	280	·	·	·	252	313	·	320	·	221
·	·	·	·	·	342	·	76	355	153	43	233	55	320	101	150	169	132
164	208	182	65	290	352	·	140	174	35	·	36	·	·	114	331	·	17
159	·	16	13	·	·	151	·	195	·	39	259	70	·	307	231	92	46

Figure 3: Base code information bits: 37; (max) block length: 42. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	151	·	·	234	·	·	82	241	101	129	60	·	69	82	242	275	140	·	·
0	61	·	·	·	117	59	·	·	·	69	249	·	·	123	211	178	168	350	73
·	61	122	·	·	53	·	·	142	156	·	211	144	125	354	·	·	·	159	278
·	·	122	183	309	155	124	3	260	261	·	·	179	·	·	·	132	133	·	·
·	·	·	183	158	·	190	248	·	·	112	·	231	98	·	162	·	·	12	41

...

20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
·	93	84	·	·	318	·	0	99	299	·	78	344	278	316	105	20	149	·	335	341
·	·	·	313	304	232	281	14	324	114	349	312	336	·	·	·	192	129	83	27	141
345	·	239	27	·	8	64	8	88	·	271	91	0	252	48	114	215	·	20	·	91
161	268	·	262	242	343	98	·	·	106	210	240	79	233	5	163	·	230	330	278	70
84	155	111	·	202	·	244	170	354	336	119	·	·	99	348	210	313	231	155	214	256

Figure 4: Base code information bits: 36; (max) block length: 40. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Parity Matrix for Code V

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	·	203	·	·	188	278	·	·	313	·	·	·	·	56	308	248	206	142	25	309	·	355	257	·	·	·	·	99	·	42	·	303	·	·	·	·	197	126	359	308	257	342	113	·	109
0	61	·	·	·	·	·	·	319	106	·	250	153	·	·	283	32	·	·	·	·	225	·	284	·	132	71	113	·	·	130	173	194	287	129	19	294	307	·	·	265	233	·	274	·	318
·	61	113	·	·	·	268	330	·	·	142	·	·	·	·	·	·	·	202	·	279	282	·	132	99	·	203	129	26	347	·	74	181	352	84	·	293	353	212	309	·	199	·	·	303	210
·	·	113	183	·	302	·	·	221	153	349	5	334	256	269	·	·	208	61	240	·	40	·	·	194	·	·	·	·	123	·	·	·	·	1	147	288	·	109	·	122	333	152	·	275	142
·	·	·	183	244	·	·	89	·	·	105	·	301	331	·	·	·	194	·	237	155	·	36	·	·	142	248	·	182	51	51	·	·	191	·	107	54	91	·	18	254	·	75	225	111	116
·	·	·	·	244	189	45	352	118	·	·	59	·	340	99	267	122	·	·	·	·	·	213	·	159	86	·	352	·	·	·	163	151	339	225	326	·	·	147	170	·	·	7	198	110	35

Figure 1: Base code information bits: 40; (max) block length: 45. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Parity Matrices for Code VI, Z = 60 & 120

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	14	·	·	8	·	53	11	50	·	·	38	53	35	4	48	55
0	59	·	·	·	42	56	·	·	23	16	9	16	·	50	7	16
·	59	58	55	·	54	·	31	27	·	55	·	2	13	30	50	39
·	·	35	58	59	26	54	·	·	13	29	16	·	39	·	50	26
·	·	·	7	43	·	·	19	29	40	35	12	57	5	56	·	49

Figure 6: Base code information bits: 12; (max) block length: 16. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 60

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	28	·	·	21	6	83	95	24	·	·	·	7	·	31	43	80
0	118	·	·	·	95	·	·	·	11	31	71	94	12	·	22	25
·	118	62	·	·	·	·	27	33	·	67	14	9	109	102	7	104
·	·	62	3	10	·	31	·	36	92	59	·	·	118	65	110	62
·	·	·	3	5	78	74	61	·	65	·	61	·	103	7	·	90

Figure 7: Base code information bits: 12; (max) block length: 16. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 120

Parity Matrices for Code VI, Z = 240 & 360

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	61	·	·	154	·	·	·	230	70	209	·	171	·	193	75	224
0	1	·	·	·	10	134	131	47	188	·	·	11	188	·	·	206
·	1	113	·	·	143	55	·	·	·	236	27	·	37	199	68	61
·	·	113	174	198	167	·	139	·	210	172	126	207	·	·	50	192
·	·	·	174	199	·	225	2	221	·	·	216	·	193	188	228	223

Figure 8: Base code information bits: 12; (max) block length: 16. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 240

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	88	·	·	123	·	·	·	142	10	26	·	21	·	229	65	230
0	358	·	·	·	265	301	153	264	107	·	·	131	341	·	·	349
·	358	62	·	·	288	119	·	·	·	261	88	·	331	331	81	20
·	·	62	243	114	340	·	20	·	121	110	269	189	·	·	309	303
·	·	·	243	197	·	250	230	356	·	·	150	·	217	325	85	92

Figure 9: Base code information bits: 12; (max) block length: 16. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Parity Matrices for Code VII, Z = 60 & 120

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	46	·	·	53	53	·	10	44	·	7	·	·	32	27	43	2	7	58	·	25
0	31	5	·	·	·	24	22	·	20	·	8	4	21	46	·	9	38	21	9	11
·	31	52	54	·	·	49	·	23	41	0	·	6	·	·	7	53	8	56	20	14
·	·	52	31	7	10	44	41	·	·	·	9	3	13	50	9	·	·	5	27	50
·	·	·	31	52	53	·	·	40	14	28	3	30	18	31	32	34	12	·	36	1

Figure 10: Base code information bits: 16; (max) block length: 20. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 60

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	89	·	·	88	·	58	26	·	109	27	·	68	101	42	99	98	·	·	58	90
0	59	·	·	·	106	·	·	·	46	36	59	50	67	1	57	87	73	118	·	85
·	59	79	26	·	3	69	·	106	·	50	·	112	·	27	3	·	91	77	30	54
·	·	61	42	77	·	78	84	10	·	·	114	·	38	·	42	68	83	57	32	107
·	·	·	26	56	38	·	93	37	76	·	104	106	30	29	·	90	43	57	15	109

Figure 11: Base code information bits: 16; (max) block length: 20. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 120

Parity Matrices for Code VII, Z = 240 & 360

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
238	85	·	·	17	·	27	129	204	18	·	·	2	99	62	73	·	·	141	29	84
238	25	·	·	·	125	113	47	·	·	·	51	236	89	177	65	145	107	54	·	91
·	25	122	·	·	74	·	·	·	136	40	34	153	26	·	·	158	223	139	86	35
·	·	122	63	67	100	93	·	5	·	25	·	·	110	76	167	176	25	·	141	199
·	·	·	63	105	·	·	134	136	140	84	186	·	·	74	25	38	74	178	26	80

Figure 12: Base code information bits: 16; (max) block length: 20. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 240

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
354	85	·	·	317	·	·	·	·	266	155	168	61	228	101	261	125	·	305	70	285
354	355	·	·	·	136	132	358	·	·	185	·	187	341	·	223	·	137	121	327	39
·	355	62	·	·	268	189	83	341	·	·	211	·	·	132	204	328	113	220	·	83
·	·	62	183	304	·	136	·	140	49	209	·	·	7	261	327	6	349	·	28	278
·	·	·	183	37	0	·	58	172	344	·	100	203	·	·	·	78	208	185	233	347

Figure 13: Base code information bits: 16; (max) block length: 20. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Parity Matrices for Code VIII, Z = 120 & 240

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	91	·	·	74	85	74	·	103	102	·	·	87	82	28	14	77	73	17	35	·	·	48	101	90
0	61	57	·	·	·	·	37	111	53	3	11	·	·	79	86	·	23	92	67	97	110	55	112	114
·	61	0	107	·	86	110	·	·	·	81	·	82	113	·	108	2	75	·	88	80	78	9	61	113
·	·	0	57	30	·	27	91	·	114	·	108	44	17	78	·	67	·	109	·	44	86	30	67	50
·	·	·	57	0	104	·	21	12	·	63	7	·	41	113	8	5	73	19	4	70	80	·	·	9

Figure 14: Base code information bits: 20; (max) block length: 24. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 120

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	122	·	·	237	·	·	·	14	143	·	79	213	115	197	·	·	166	88	118	114	54	113	210	180
0	62	·	·	·	229	95	82	·	·	47	137	4	·	·	123	185	78	·	183	0	94	51	146	131
·	62	79	42	·	65	27	·	174	53	·	·	·	38	20	101	231	196	224	·	·	143	27	213	217
·	·	61	58	106	135	·	112	·	92	90	·	8	·	221	177	131	107	147	136	147	·	·	134	59
·	·	·	42	85	·	46	116	123	·	34	72	·	119	140	78	124	·	171	133	155	150	71	·	213

Figure 15: Base code information bits: 20; (max) block length: 24. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 240

Parity Matrices for Code VIII, Z = 360 and Code IX, Z = 120

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	·	·	·	61	356	63	·	107	229	131	·	·	·	38	279	172	215	7	313	·	3	·	107	340
0	61	·	·	·	106	229	123	·	·	52	·	14	242	305	111	249	·	189	57	205	·	140	137	46
·	61	122	·	·	·	·	188	280	240	·	167	283	·	185	·	·	84	68	267	323	336	122	264	299
·	·	122	210	332	·	176	·	319	·	·	343	288	259	119	183	240	203	·	·	248	129	120	64	216
·	·	·	210	331	133	·	262	·	221	274	125	·	273	·	126	135	148	289	354	73	254	251	·	195

Figure 16: Base code information bits: 20; (max) block length: 24. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	91	·	·	72	23	·	·	·	47	·	34	53	114	5	61	97	106	·	·	86	19	6	·	53	79	6	112
0	61	11	·	·	2	·	89	68	117	43	·	7	·	31	29	112	88	86	7	·	10	62	69	58	85	·	9
·	61	74	102	·	·	72	101	·	·	88	·	30	110	96	91	·	·	68	90	41	23	114	53	·	43	104	40
·	·	74	52	28	20	10	38	55	·	·	117	·	·	25	·	92	112	12	11	100	·	·	0	102	111	115	87
·	·	·	52	118	·	25	·	75	29	3	109	·	84	·	52	93	42	78	79	104	89	105	77	0	·	94	13

Figure 17: Base code information bits: 23; (max) block length: 27. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 120

Parity Matrices for Code IX, Z = 240 & Z = 360

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	173	·	·	216	52	25	141	173	·	238	·	·	172	71	·	·	62	128	46	·	16	70	129	7	108	·	94
0	113	·	·	·	·	·	·	·	193	126	·	164	197	81	15	146	94	195	·	99	43	66	80	·	162	109	47
·	113	79	26	·	191	·	124	213	47	190	171	·	·	·	107	·	234	118	92	37	114	·	98	222	·	167	155
·	·	61	42	85	131	33	·	168	114	·	56	166	175	·	·	206	·	225	172	25	·	166	·	88	45	19	120
·	·	·	26	64	·	79	53	·	·	·	152	109	·	29	189	131	·	·	96	132	166	196	213	225	150	52	228

Figure 18: Base code information bits: 23; (max) block length: 27. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 240

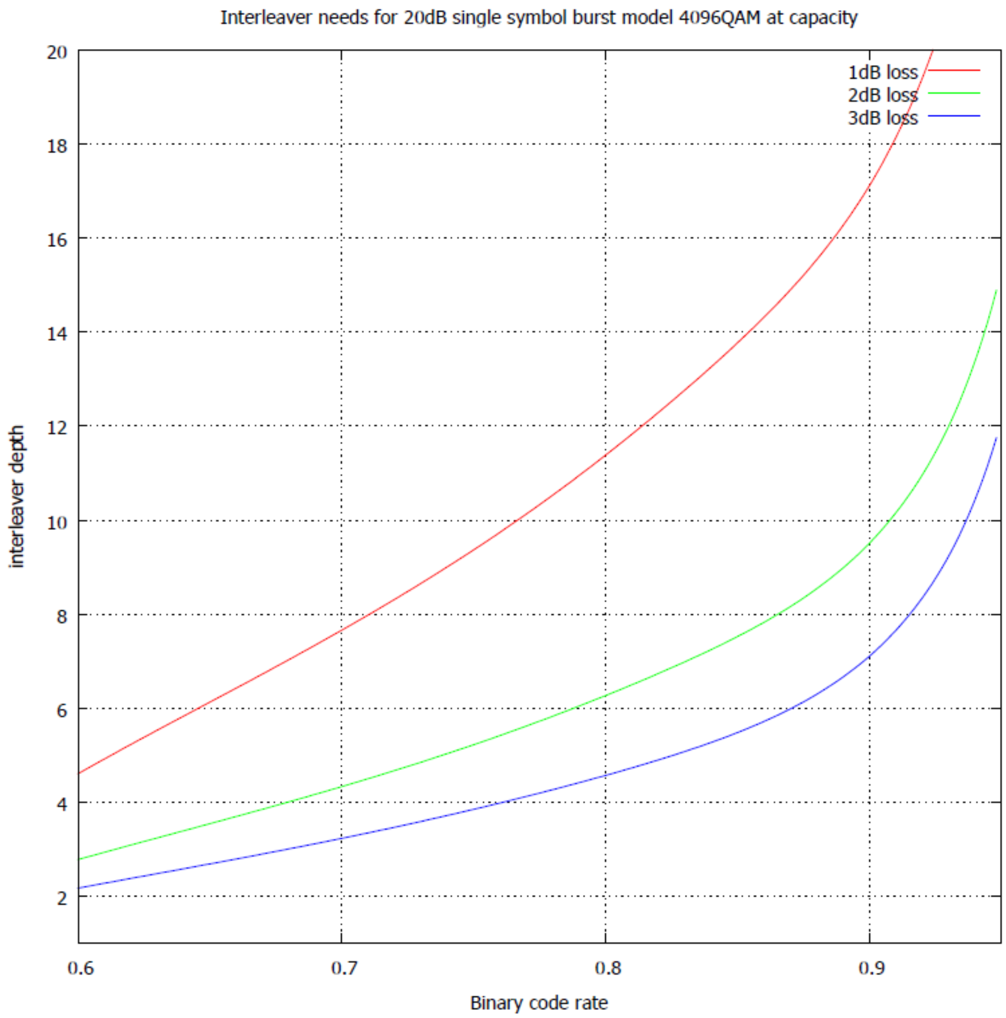
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
354	·	·	·	220	·	97	68	205	315	·	·	·	·	222	252	55	210	·	355	170	278	200	10	233	279	·	322
354	241	·	·	·	·	174	·	216	76	170	318	88	239	·	·	0	306	257	27	98	85	217	·	135	·	64	117
·	241	98	·	·	44	162	240	·	·	·	59	·	94	97	60	358	182	47	36	·	·	38	295	101	162	235	261
·	·	98	57	351	58	·	124	·	·	188	·	39	325	·	346	93	·	316	·	101	284	·	135	35	111	268	110
·	·	·	57	175	266	·	·	9	28	228	349	34	·	68	·	·	73	305	290	205	0	170	345	·	226	29	229

Figure 19: Base code information bits: 23; (max) block length: 27. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Consideration on Time Interleaving Depth D

- The depth D of the time domain interleaving impacts how many QAM symbols of a code word are affected by burst noise
  - For a larger interleaving depth D less symbols of a code word are impacted and performance improves
  - The drawback of a large interleaving depth D is increased PHY latency
    - However, if the depth D is to small, BER performance does not reach the BER target of 1e-8 anymore
- Hence, an important metric is the required interleaving depth D to achieve BER = 1e-8 at a fixed AWGN SNR
  - Interleaving depths are provided in the following
- Comments on required interleaving depth D
  - It can be shown that the required interleaving depth D is related to the inverse of the code rate R, i.e. D ~ 1 / (1 – R)

Code Rate and Interleaving Depth



- In burst noise a higher AWGN SNR is needed for the same capacity
  - This increase in SNR is called loss in the figure
  - This can be seen as required SNR margin for burst noise
- For a given margin, the figure shows the required interleaving depth as a function of code rate
- Codes with higher rate require higher interleaving depth
  - In comparisons for burst noise performance, code rates must be identical