DOWNSTREAM FEC PROPOSAL FOR IEEE 802.3 EPOC

— CODES, PERFORMANCE AND COMPLEXITY

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OUTLINE

- **Proposed LDPC code sets**
  - Matching 16K DVB-C2 LDPC code
  - Two LDPC code sets
  - BRCM LDPC code matrices
- **EPOC FEC criteria and simulation**
  - Downstream FEC Evaluation Criteria: performance metrics, code parameters, decoding procedure
  - AWGN and impulse noise simulation set-up and results
- **AWGN channel and impulse noise performances and complexity**
  - ~90% rate longer codes performance and complexity comparison
    - Spectral efficiency on AWGN channel and complexity
    - Minimum interleave depth in impulse noise
  - 85% rate shorter codes performance and complexity comparison
    - Spectral efficiency on AWGN channel and complexity
    - Minimum interleave depth in impulse noise
- **Conclusions**

PROPOSED LDPC CODES

MATCHING 16K DVB-C2 LDPC CODE PARAMETERS

- **DVB-C2**
  - LDPC (16200, 14400)
    - Sub-matrix size = 360
  - Auxiliary coding and interleaving:
    - Outer code: BCH (14400,14232)
    - Twisted interleave for mapping
  - FEC rate: 0.8785
- **BRCM**
  - LDPC (16200, 14400)
    - Sub-matrix size = 360
  - Auxiliary coding and interleaving : NONE
  - FEC rate: 8/9 (= 0.8889)
- **Broadcom provides an LDPC code with the same codeword size, the same sub-matrix size, and the same code rate of DVB-C2 LDPC code, BUT *no* auxiliary coding and interleaving!**

10K RATE 90% LDPC CODE

- **Qualcomm**
  - LDPC (11160, 9720)
    - Sub-matrix size = 360
  - Puncture 360 bits
  - Final code rate 0.9 (10800,9720)

6K RATE 85% LDPC CODES

- **Qualcomm**
  - LDPC (6120, 4680)
    - Sub-matrix size = 360
  - Puncture 720 bits
  - Final code rate 13/15 (0.867)
- **Broadcom**
  - LDPC (6480, 5520)
    - Sub-matrix size = 240
  - Code rate 23/27 (0.852)

LDPC CODES MATRICES DESCRIPTION

- **All codes are QC (quasi-cyclic)-LDPC code**
- **A definition of an (n, k) QC-LDPC code**
  - (n-k)-by-n parity check matrix H
  - H is expanded from a binary base matrix H_b of size v-by-*u*
  - The base matrix H_b is expanded by replacing each 1 in the base matrix with a size *z* permutation matrix, and each 0 with a *size z* zero matrix.
    - The permutations used are circular right shifts, and the set of permutation matrices contains the *size z* identity matrix and circular right shifted versions of the identity matrix.
  - Because each permutation matrix is specified by a single circular right shift, the binary base matrix information and permutation replacement information can be combined into a single compact model matrix H_{bm}. The model matrix H_{bm} is the same size as the binary base matrix H_b, with each binary entry (*i*,*j*) of the base matrix H_b replaced to create the model matrix H_{bm}. Each 0 in H_b is replaced by a blank or "-1" negative to denote a size *z* all-zero matrix, and each 1 in H_b is replaced by a circular shift size $p(i,j) \geq 0$. The model matrix H_{bm} can then be directly expanded to H.

BROADCOM LDPC CODES PARITY CHECK MATRICES

Rate 8/9 (16200,14400) LDPC code (base matrix 5x45,sub-matrix size 360)

359	330	68	134	336	207	341	318	-1	242	99	-1	158	338	5	-1	229	233	267	164	-1	290	306	-1	178	123	-1	-1	17	89	323	309	133	67	348	245	0	-1	-1	-1	179	-1	-1	-1	-1
-1	236	132	14	83	31	-1	58	56	15	78	203	24	13	-1	172	228	-1	248	-1	246	297	314	222	-1	27	24	-1	-1	-1	337	127	-1	-1	31	271	-1	136	27	276	64	354	-1	-1	-1
246	67	181	59	356	-1	312	191	180	-1	255	174	63	109	168	358	-1	156	86	29	99	201	-1	219	223	-1	349	58	304	199	70	305	236	115	58	-1	-1	-1	-1	-1	-1	67	251	-1	-1
113	285	79	-1	-1	67	35	214	172	254	-1	210	3	-1	42	333	26	11	183	325	190	-1	143	44	108	242	211	198	-1	-1	-1	-1	245	-1	-1	106	321	19	91	319	-1	-1	168	282	-1
217	-1	-1	284	162	351	36	-1	162	275	92	34	-1	85	82	58	223	358	-1	179	46	112	166	276	200	236	-1	74	86	145	-1	-1	-1	141	-1	-1	140	193	65	294	-1	-1	-1	265	226

Rate 0.852 (6480,5520) LDPC code (base matrix: 4x27, sub-matrix size 240)

156	90	88	22	175	134	47	74	150	124	15	75	106	60	224	239	38	139	189	173	11	200	-1	131	-1	-1	-1
177	215	64	50	29	77	112	153	84	199	151	121	25	146	165	149	129	78	106	146	238	48	23	237	232	-1	-1
220	50	19	29	110	24	162	157	181	231	9	17	82	71	162	123	40	177	159	2	93	-1	233	-1	145	9	-1
13	135	85	232	20	108	225	235	85	181	11	119	61	143	229	163	239	72	2	199	-1	222	162	-1	-1	232	230

EPOC FEC CRITERIA AND SIMULATION SET-UP

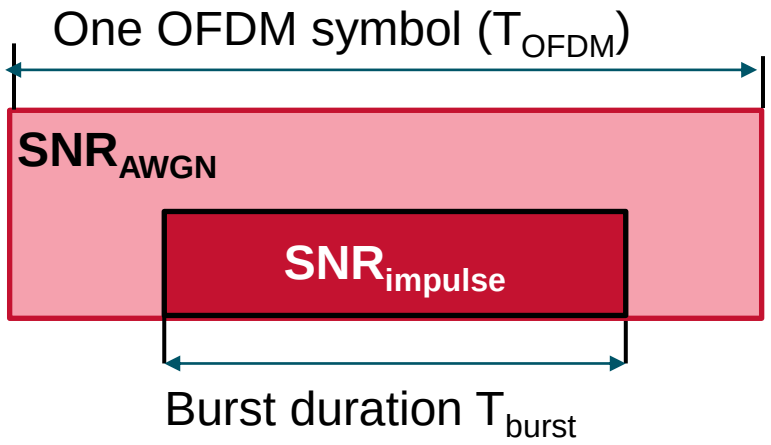
DOWNSTREAM FEC EVALUATION CRITERIA

- **Performance metrics**
  - Constellation: 4096 QAM
  - AWGN channel
    - SNR achieving BER=1e-8
  - Burst noise channel
    - OFDM symbol durations 20 and 40 us
    - Cyclic prefix 2.5 us
    - Interleaver depth and SNR achieving BER=1e-8
- **LDPC code parameters**
  - Sub-matrix size(lifting value)
  - Taking the throughput into account the following two parameters impact decoding hardware efficiency
    - Ed/cb ≡ edges per coded bits = (number of edges)/(received codeword size)
    - Eq/cb ≡ parity check equations per coded bits = (number of equations)/(received codeword size)
- **Decoding procedure**
  - Iterative Sum-Product algorithm
  - Floating point
  - Maximum of 20 and 30 flooding iterations

DOWNSTREAM IMPULSE NOISE SIMULATION SET-UP

- **Two OFDM symbol durations**
  - 20 µs
  - 40 µs
- **Cyclic prefix**
  - 2.5 µs
- **Channel assumption**
  - Burst noise duration: 16 µs
  - Burst noise SNR: 20 dB or 5 dB
- **BER target**
  - 1e-8
- **Minimum interleaver latency and noise margin**
  - For each burst noise condition find the minimum interleaver depth to achieve the BER target of 1e-8
  - This minimum interleaver depth will be a function of the background AWGN SNR
  - The result will be a plot of BER vs. AWGN SNR for each interleaver depth

SNR CALCULATION WITH IMPULSE NOISE



- **Case I: the burst hits one OFDM symbol**
  - SNR experienced by all sub-carriers in the OFDM symbol due to burst noise only is:

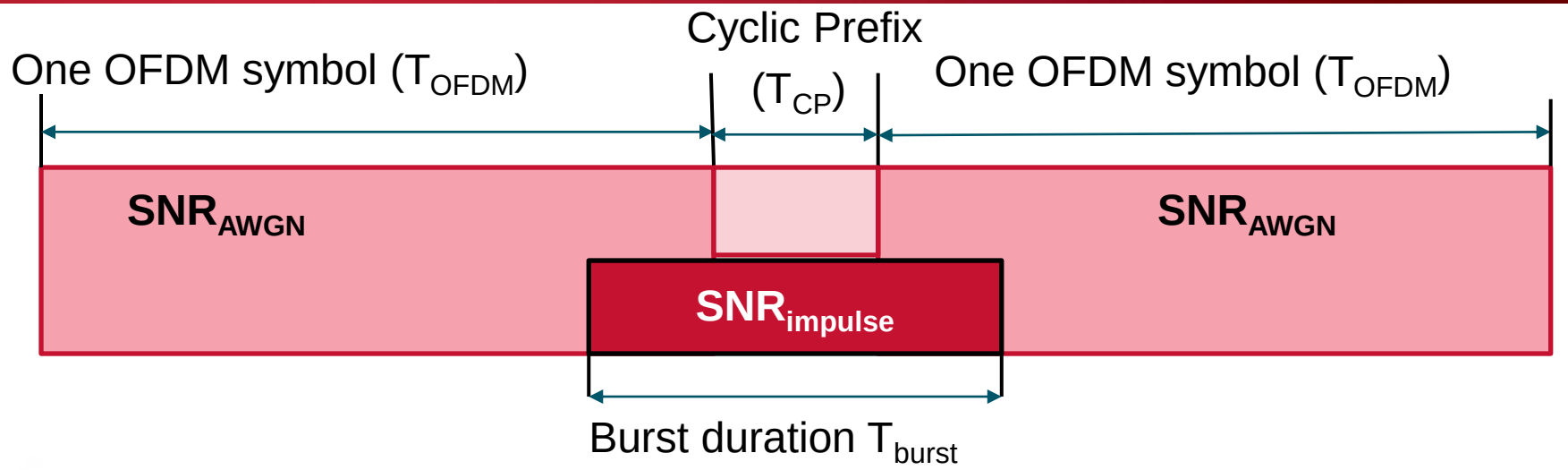
$$SNR_{burst} = SNR_{impulse} - 10 \log (T_{burst} / T_{OFDM})$$

T_{OFDM}:	OFDM symbol duration without cyclic prefix
T_{CP} :	duration of cyclic prefix
T_{burst}:	burst duration
$SNR_{impulse}$:	impulse SNR

  - SNR experienced by all sub-carriers in the two OFDM symbols due to background noise only is:

$$SNR_{background} = SNR_{AWGN} - 10 \log (1 - [T_{burst} / T_{OFDM}])$$

SNR CALCULATION



- **Case II: the burst hits two consecutive OFDM symbols equally**
  - SNR experienced by all sub-carriers in the two OFDM symbols due to burst noise only is:

$$SNR_{burst} = SNR_{impulse} - 10 \log (0.5 * (T_{burst} - T_{CP}) / T_{OFDM})$$

T_{OFDM}:	OFDM symbol duration without cyclic prefix
T_{CP} :	duration of cyclic prefix
T_{burst}:	burst duration
$SNR_{impulse}$:	impulse SNR

  - SNR experienced by all sub-carriers in the two OFDM symbols due to background noise only is:

$$SNR_{background} = SNR_{AWGN} - 10 \log (1 - [0.5 * (T_{burst} - T_{CP}) / T_{OFDM}])$$

SNR CALCULATION

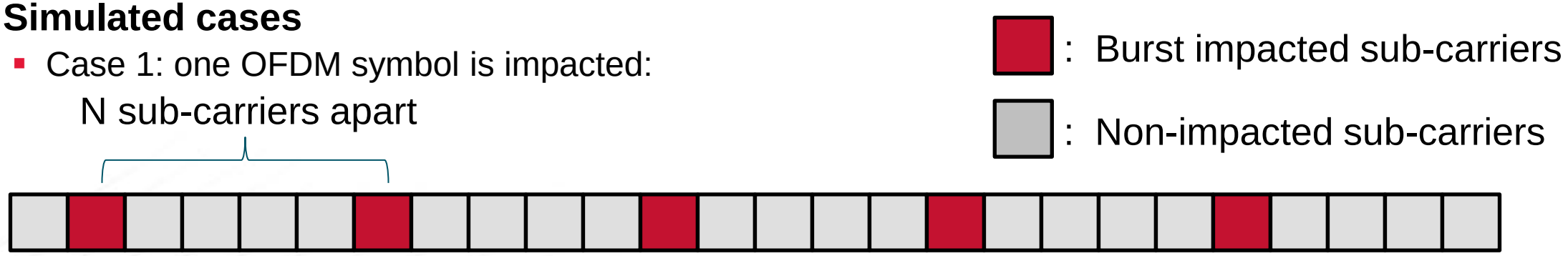
- **SNR on the burst noise impacted subcarrier in the presence of background AWGN is:**
  - $SNR_{sub\text{-}carrier} = -10 \text{ Log } (10^{[-SNR_{burst} / 10]} + 10^{[-SNR_{background} / 10]})$

$SNR_{sub\text{-}carrier}$: SNR experienced by all sub-carriers in the OFDM symbol
$SNR_{background}$: Background (thermal) Additive White Gaussian noise contribution
SNR_{burst}: impulse SNR contribution

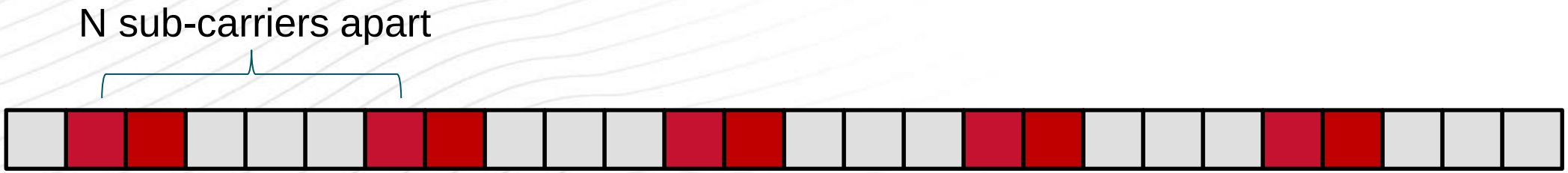
- **SNR assumptions for downstream simulation:**
  - Burst length is 16 µs spanning two OFDM symbols equally with a 2.5 µs cyclic prefix between
  - SNR during the impulse is either 20 dB (moderate impulse noise) or 5 dB (strong impulse noise)

INTERLEAVE DEPTH

- **Our simulations show the minimum value for interleave depth N in order for the BER to reach 1e-8 for a given worst case burst noise position at a specified duration and SNR and the associated minimum background AWGN SNR**
- **Simulated cases**
  - Case 1: one OFDM symbol is impacted:



  - Case 2 two consecutive OFDM symbols are impacted equally:



AWGN CHANNEL AND IMPULSE NOISE PERFORMANCE AND COMPLEXITY

RATE 90% LONG CODES - AWGN PERFORMANCE AND COMPLEXITY

AWGN channel, 4096QAM

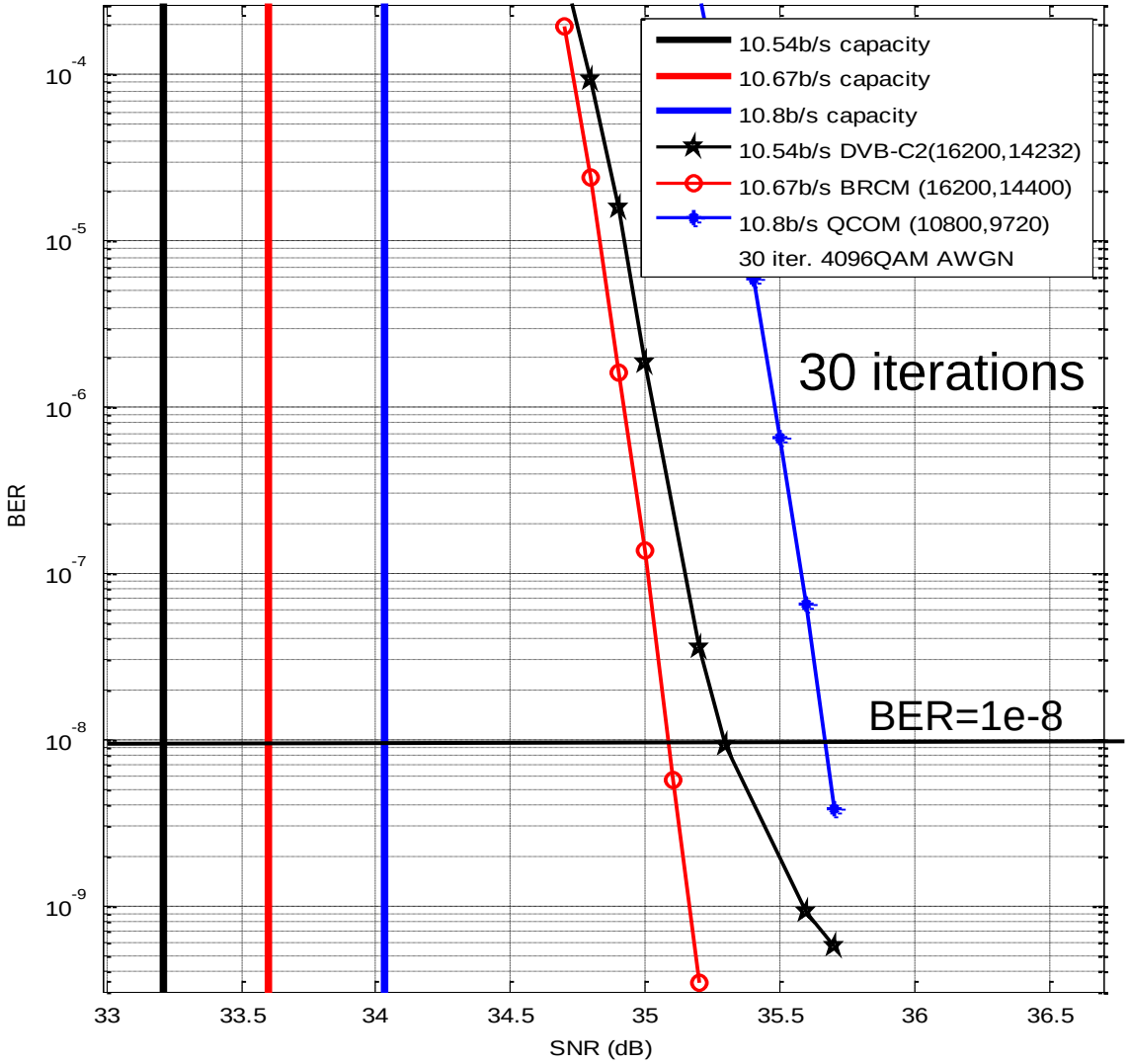
Code	Rate (b/s)	Outer code	Inter-leave	4096QAM Capacity	K	N	I	SNR @BER=1e-8 (4096QAM)	Distance to capacity (4096QAM)	Spectral efficiency SNR gain compare to DVB C2	Eq/cb	Ed/cb
DVB-C2 8/9 based SM=360	0.8785 (10.54)	BCH	Twisted	33.21dB	14232	16200	20	35.53dB	2.32	.	0.111	2.9999
							30	35.36dB	2.15	.		
BRCM SM=360	8/9 (10.67)	No	No	33.6dB	14400	16200	20	35.17dB	1.57	0.75dB	0.111	3.4444
							30	35.08dB	1.48	0.67dB		
QCOM SM= 360	0.9 (10.8)	No	No	34dB	9720	10800	20	35.74dB	1.74	0.56dB	0.133	3.5
							30	35.667dB	1.66	0.49dB		

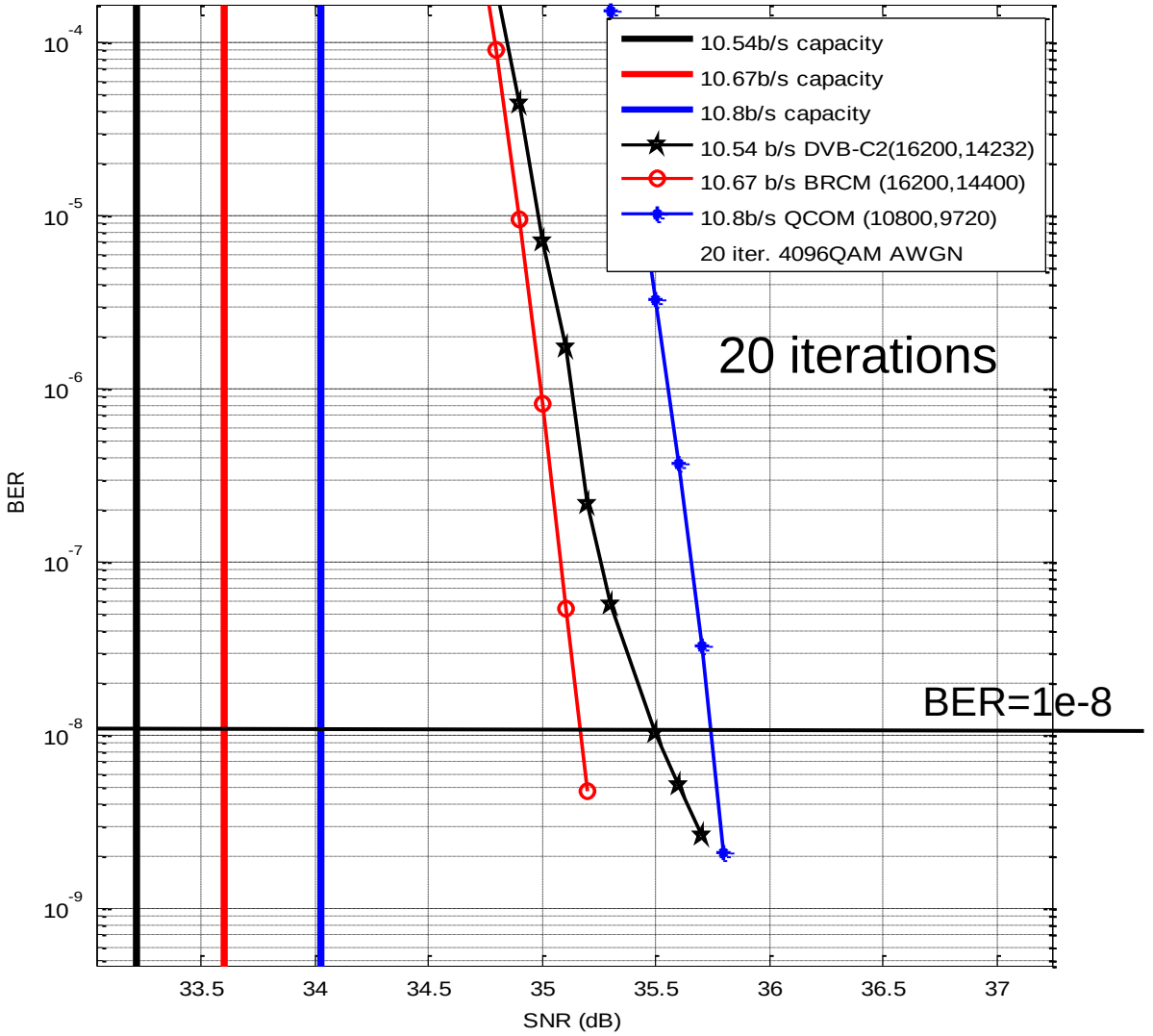
K: information size (bits) .N: codeword size (bits) I: number of maximum iterations

BRCM 16K 89% code is the closest to the Channel Capacity limit

RATE 90% CODES AWGN CHANNEL PERFORMANCE CURVES

AWGN channel, 4096QAM





RATE 90% CODES PERFORMANCE IN IMPULSE NOISE

Minimum depth and background SNR to achieve BER=1e-8 (4096-QAM, 30 iterations)

	Burst duration	Burst SNR	DVBC2 87.8%	BRCM 89%	QCOM 90%
20µs symbol (two affected)	16us	20dB	**11** 247.5µs@39.5dB	**10** 225µs@40.8dB	**13** 292.5µs@40dB
	16us	5dB	**21** 472.5µs@40dB	**20** 450µs@40.2dB	**25** 562.5µs@40.4dB
40µs symbol (two affected)	16us	20dB	**9** 382.5µs@39dB	**8** 340µs@39.4dB	**10** 425µs@39.9dB
	16us	5dB	**19** 807.5µs@39.5dB	**18** 765µs@40.5dB	**22** 935µs@41.7dB

Minimum depth and background SNR to achieve BER=1e-8 (4096-QAM, 20 iterations)

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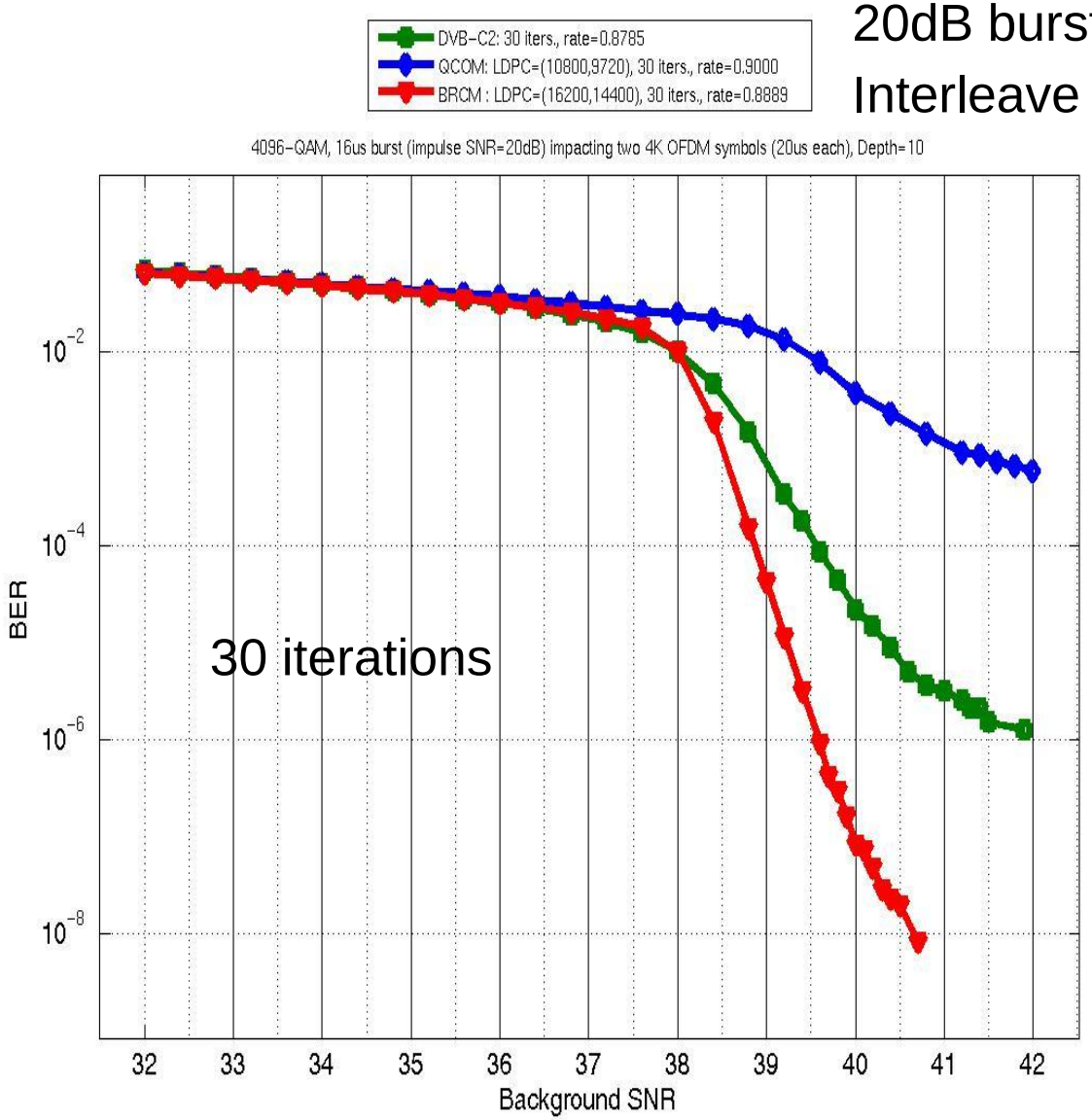
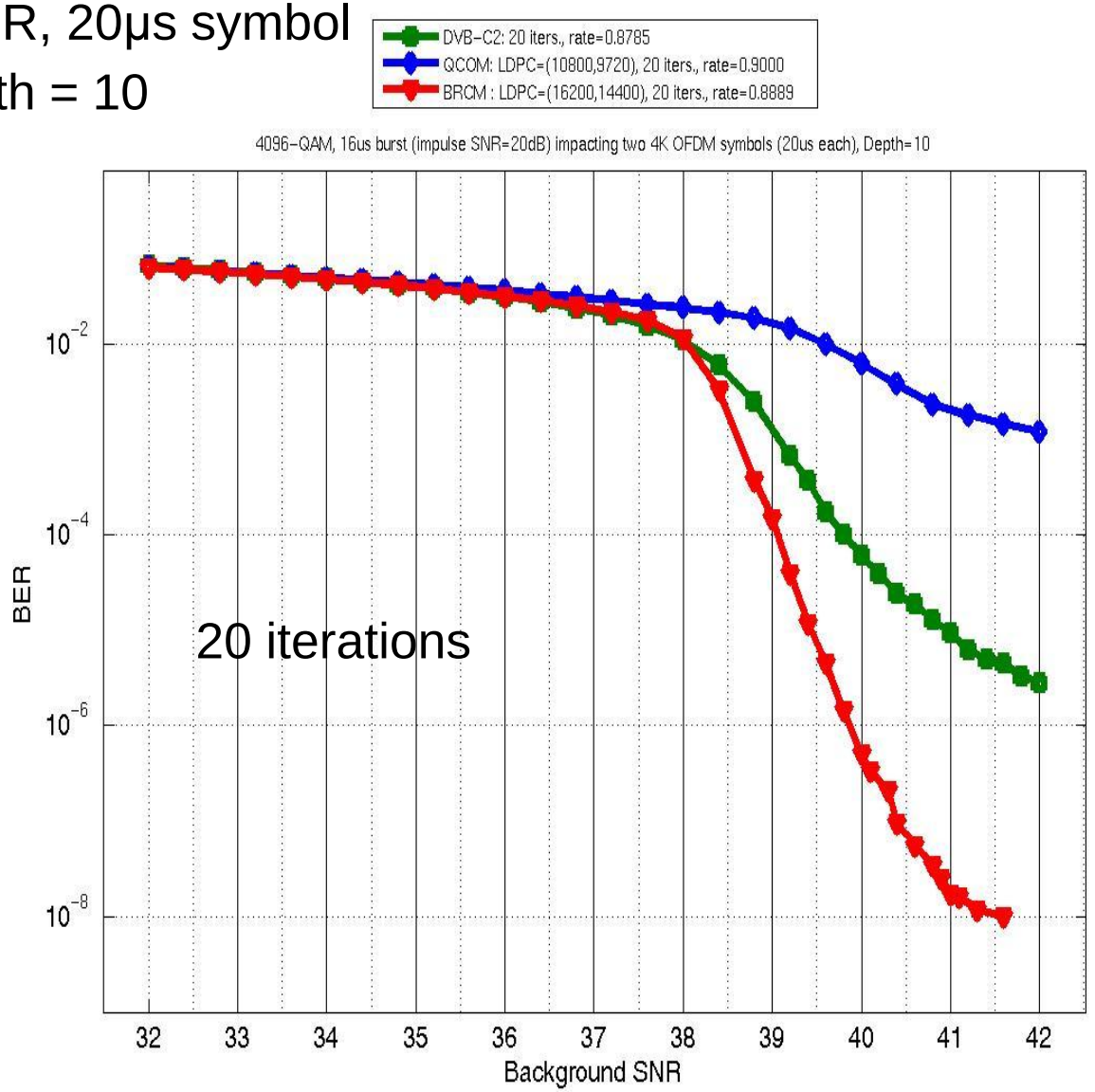
40µs symbol (two affected)	16us	20dB	**9** 382.5µs@39.25dB	**8** 340µs@39.5dB	**10** 425µs@40.1dB
	16us	5dB	**19** 807.5µs@39.7dB	**18** 765µs@40.6dB	**22** 935µs@41.7dB

RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 20μs symbol

Interleave depth = 10

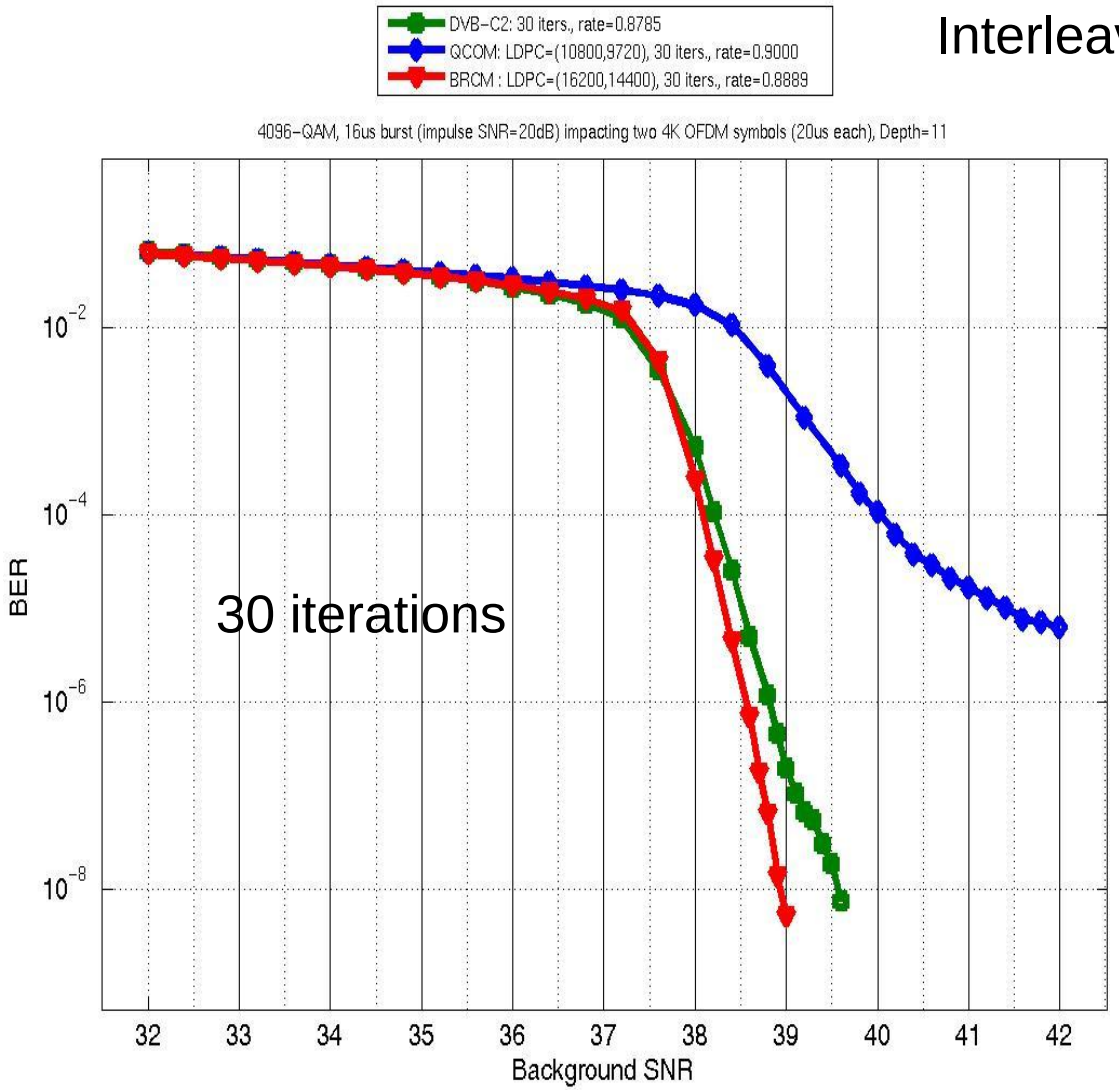


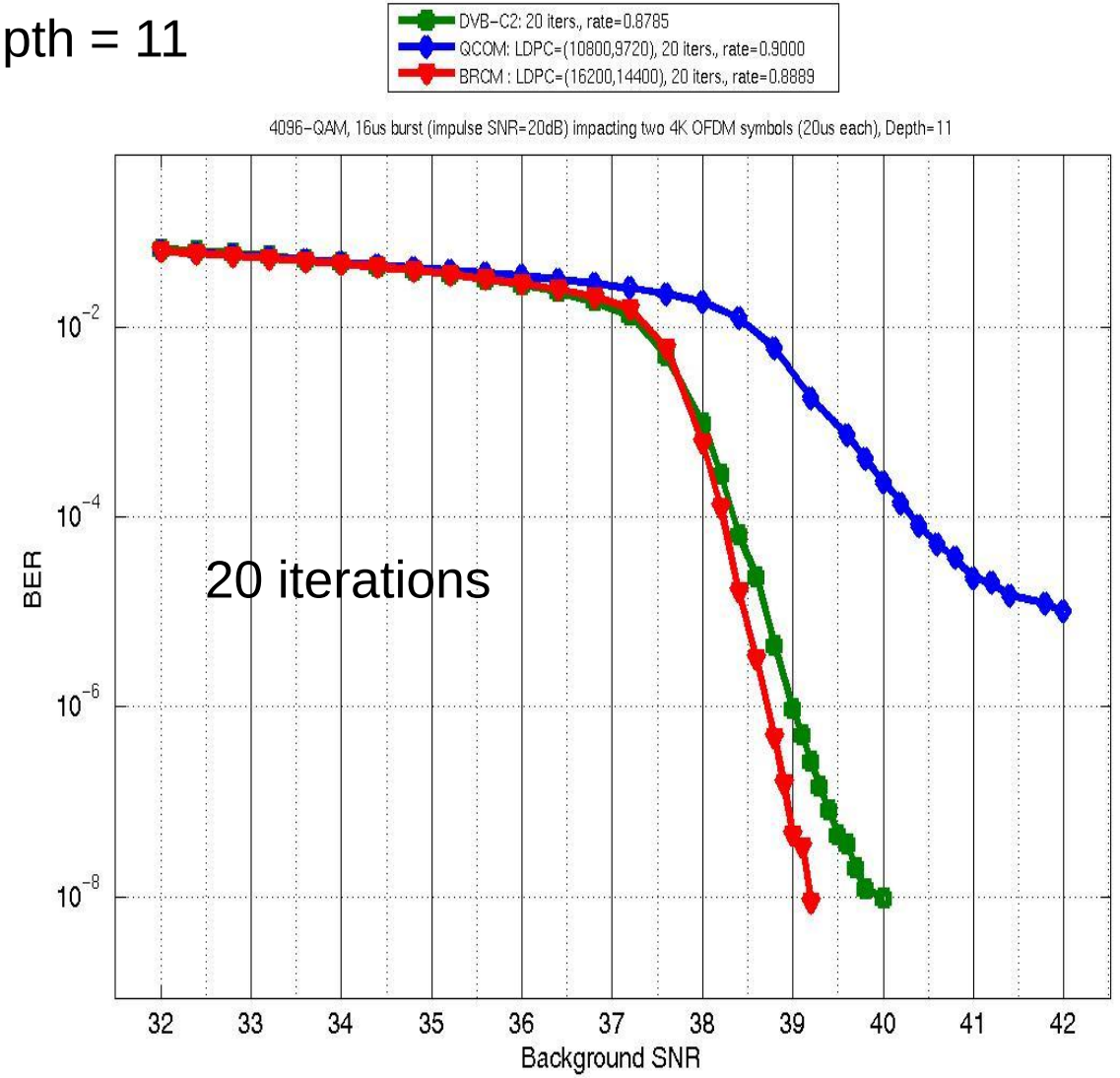


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 20μs symbol

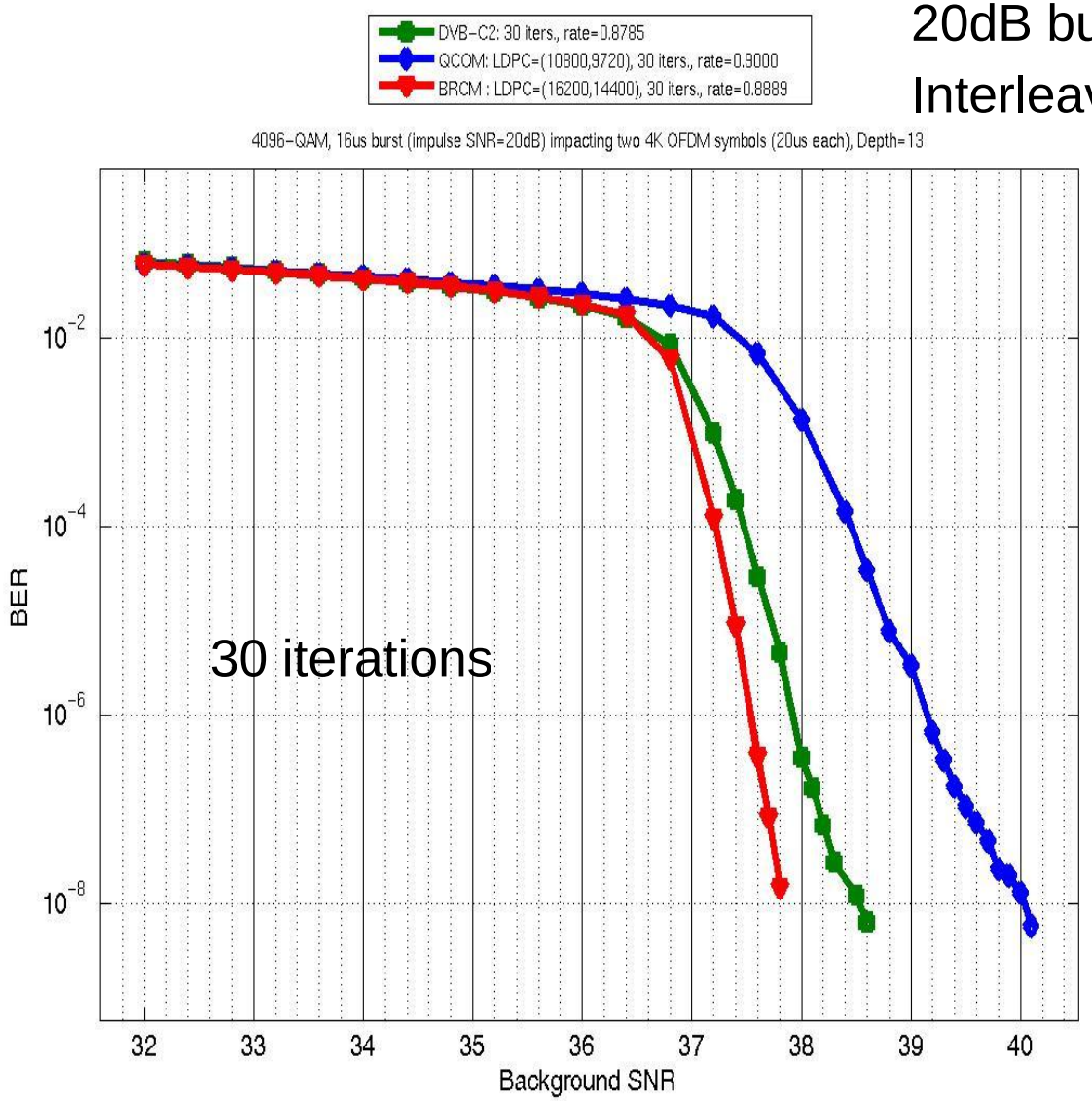
Interleave depth = 11

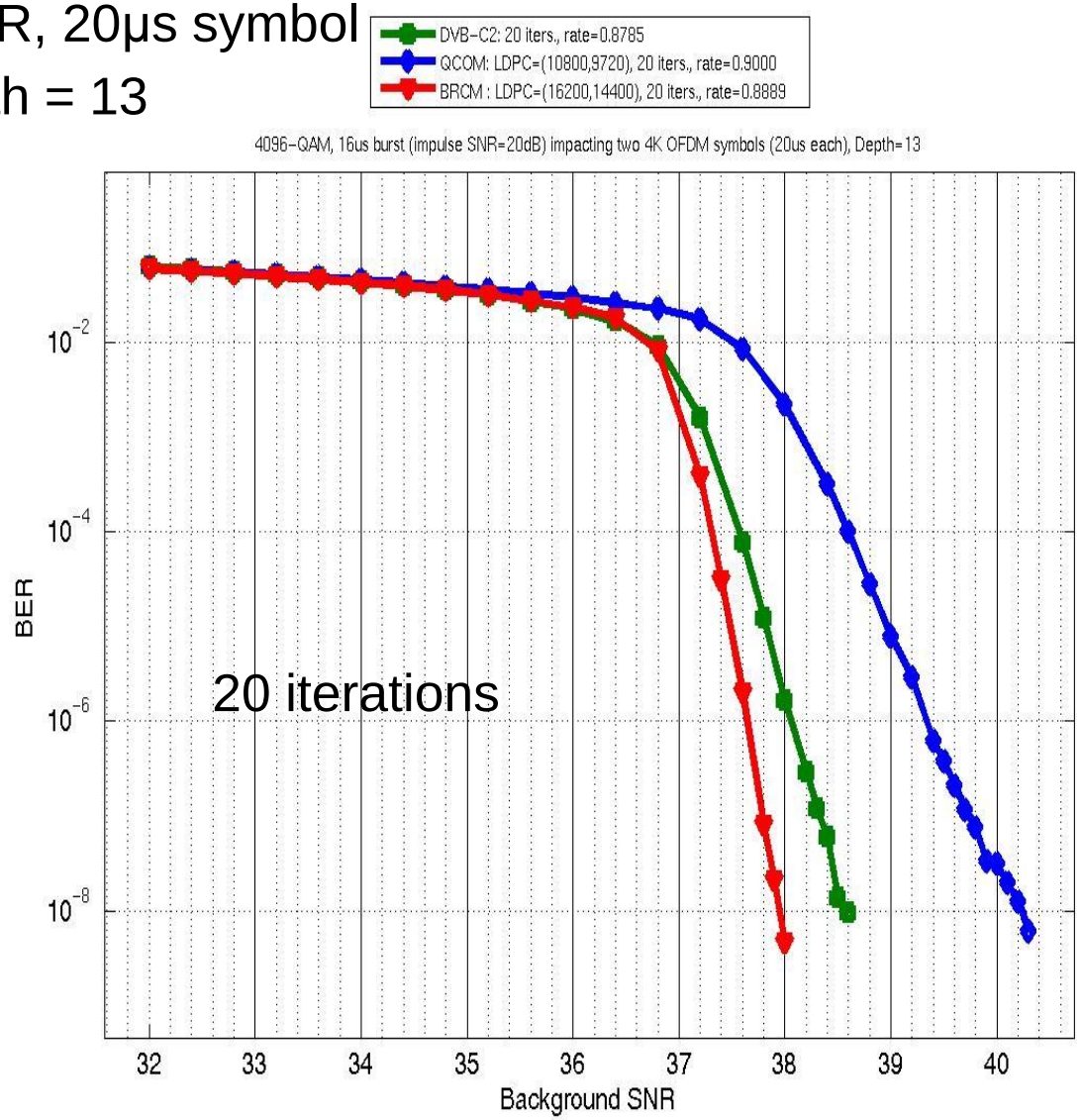




RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

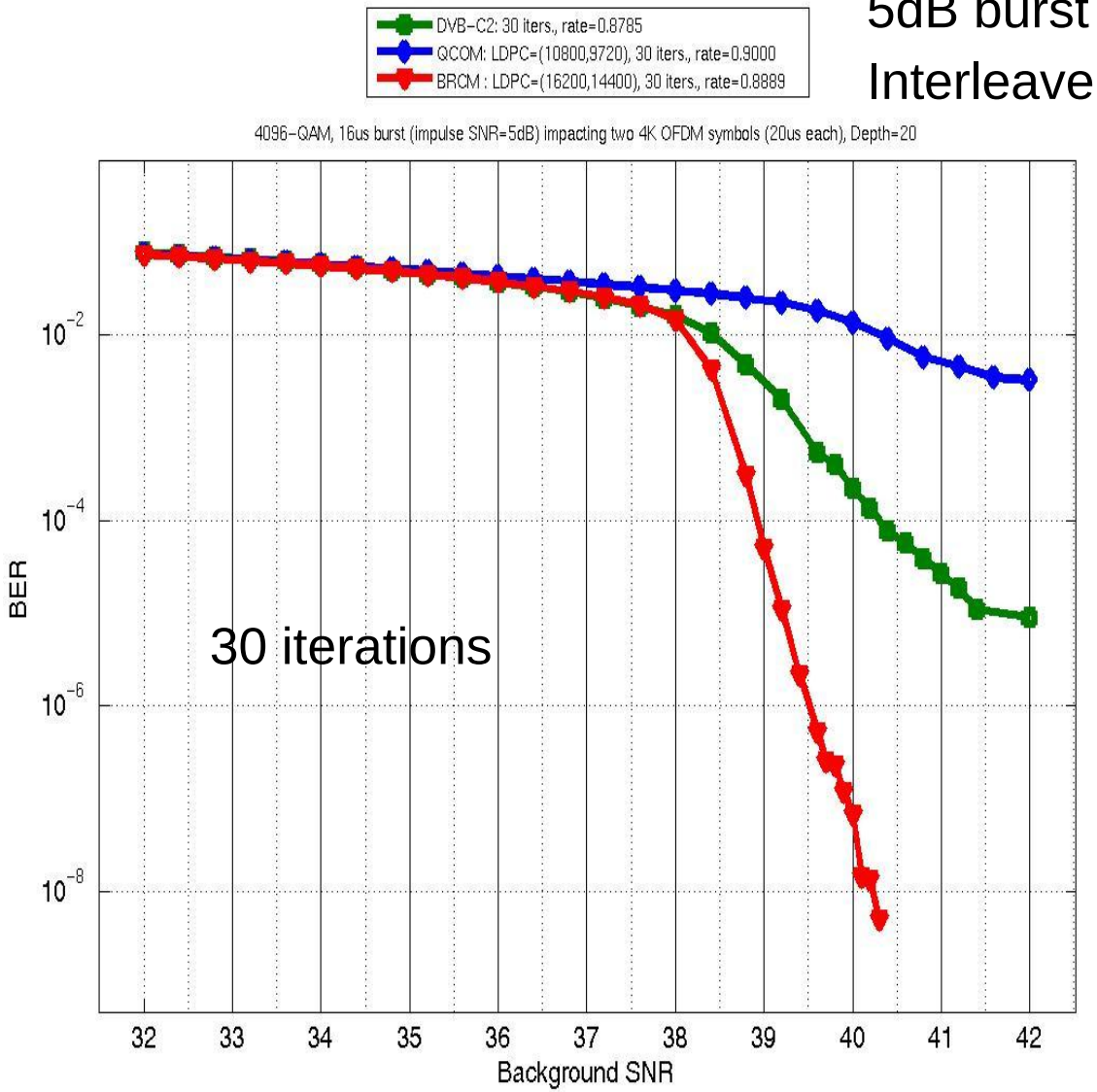
20dB burst SNR, 20µs symbol
Interleave depth = 13

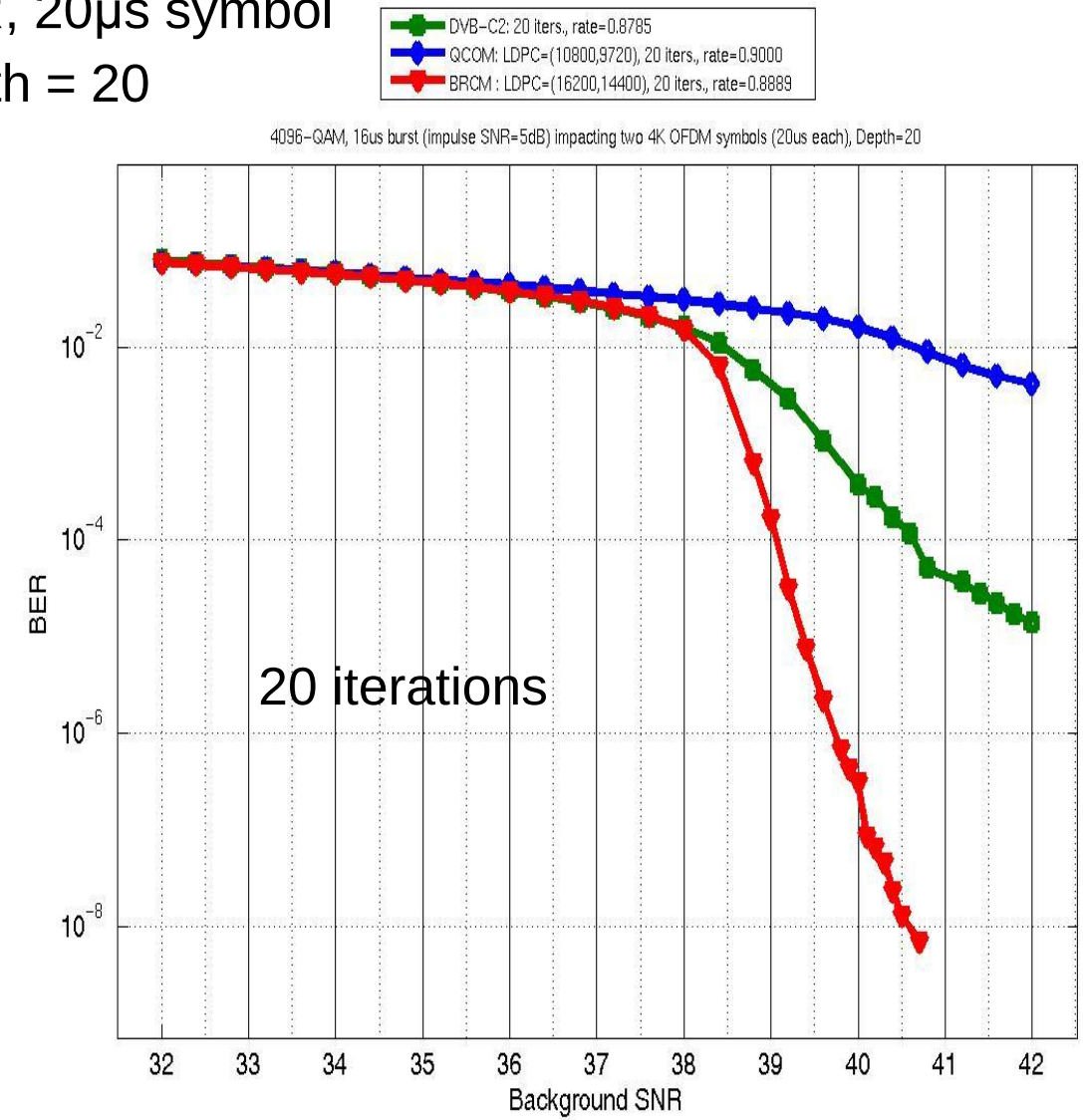




RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 20μs symbol
Interleave depth = 20

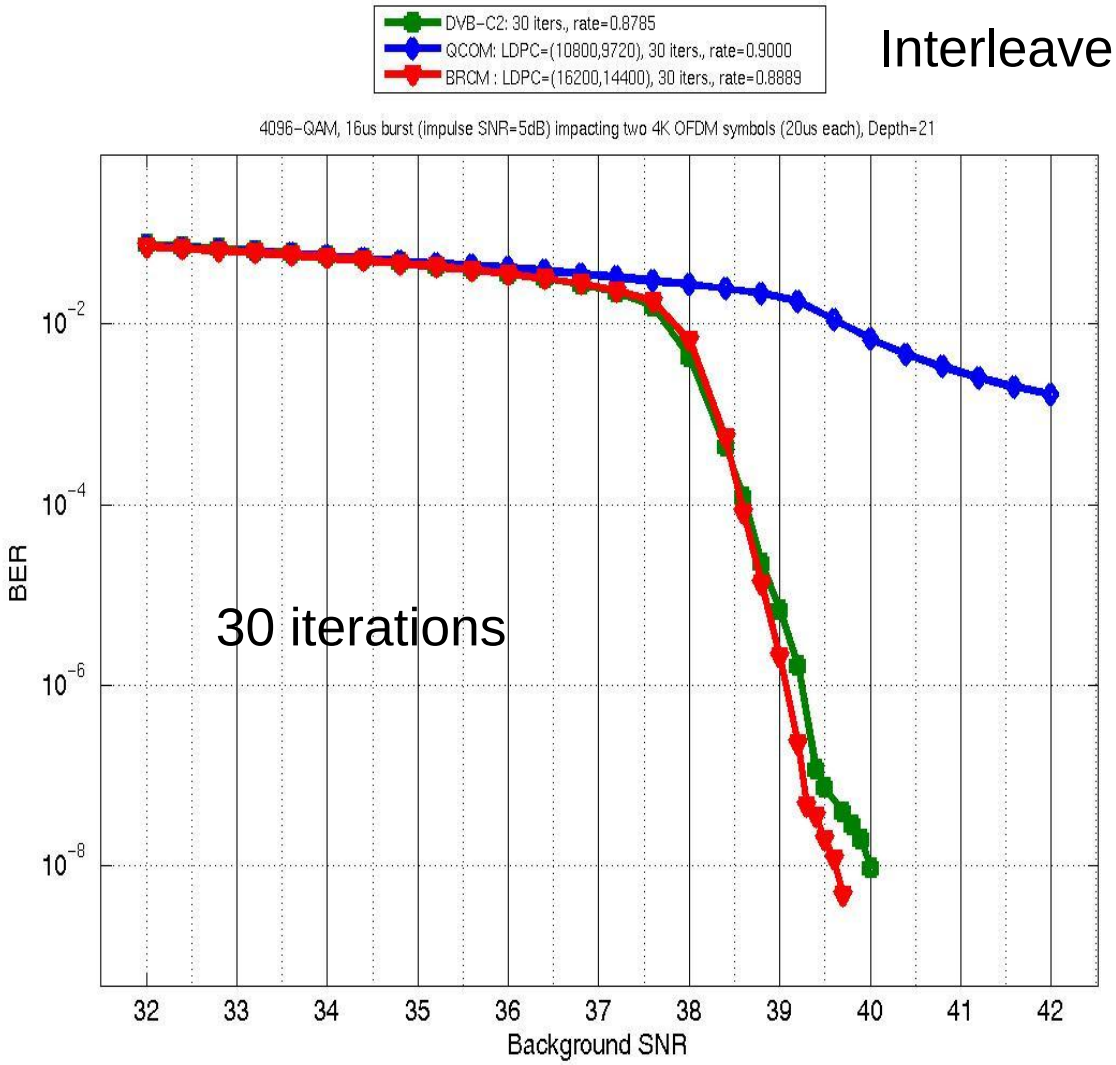


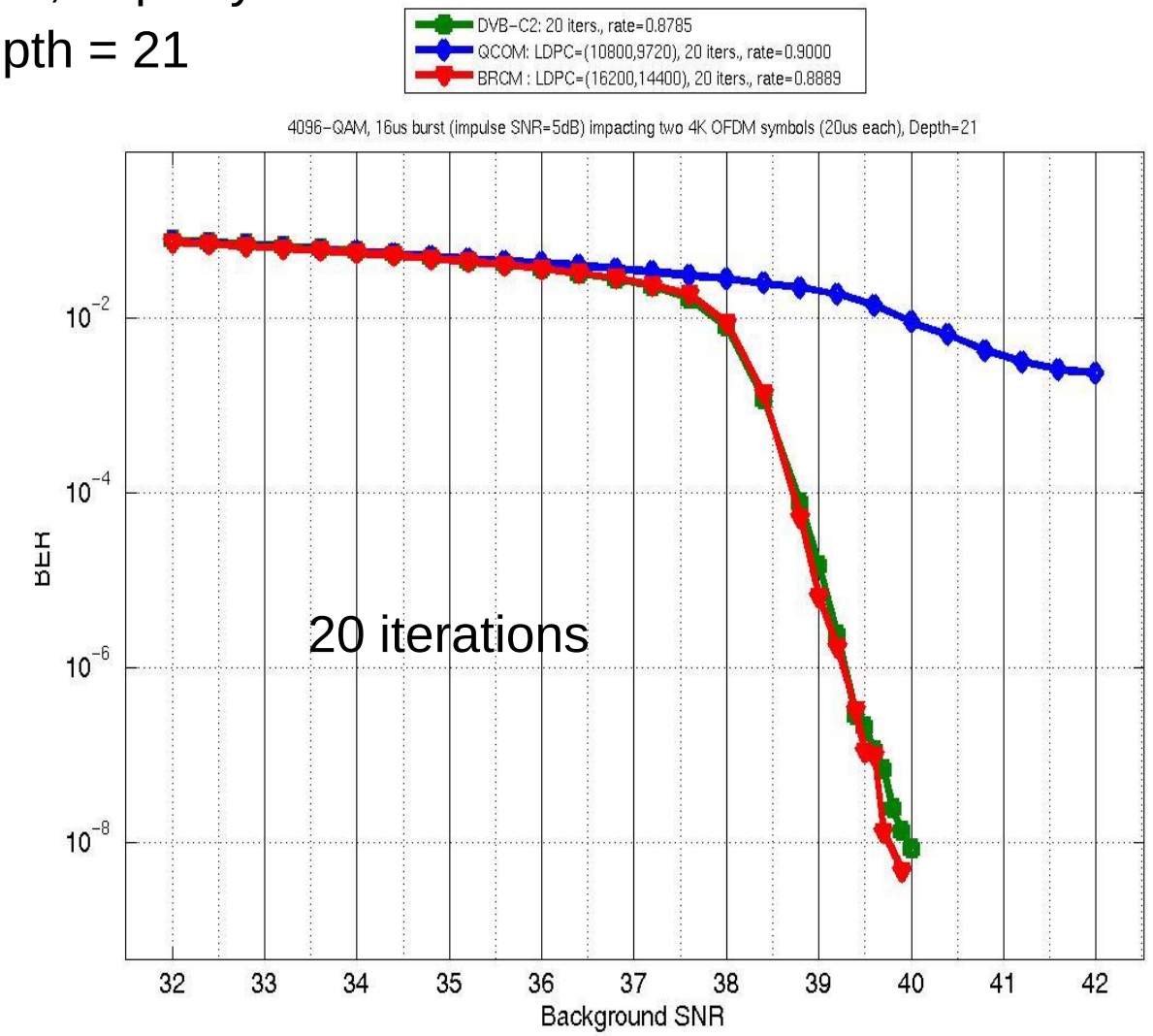


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 20μs symbol

Interleave depth = 21

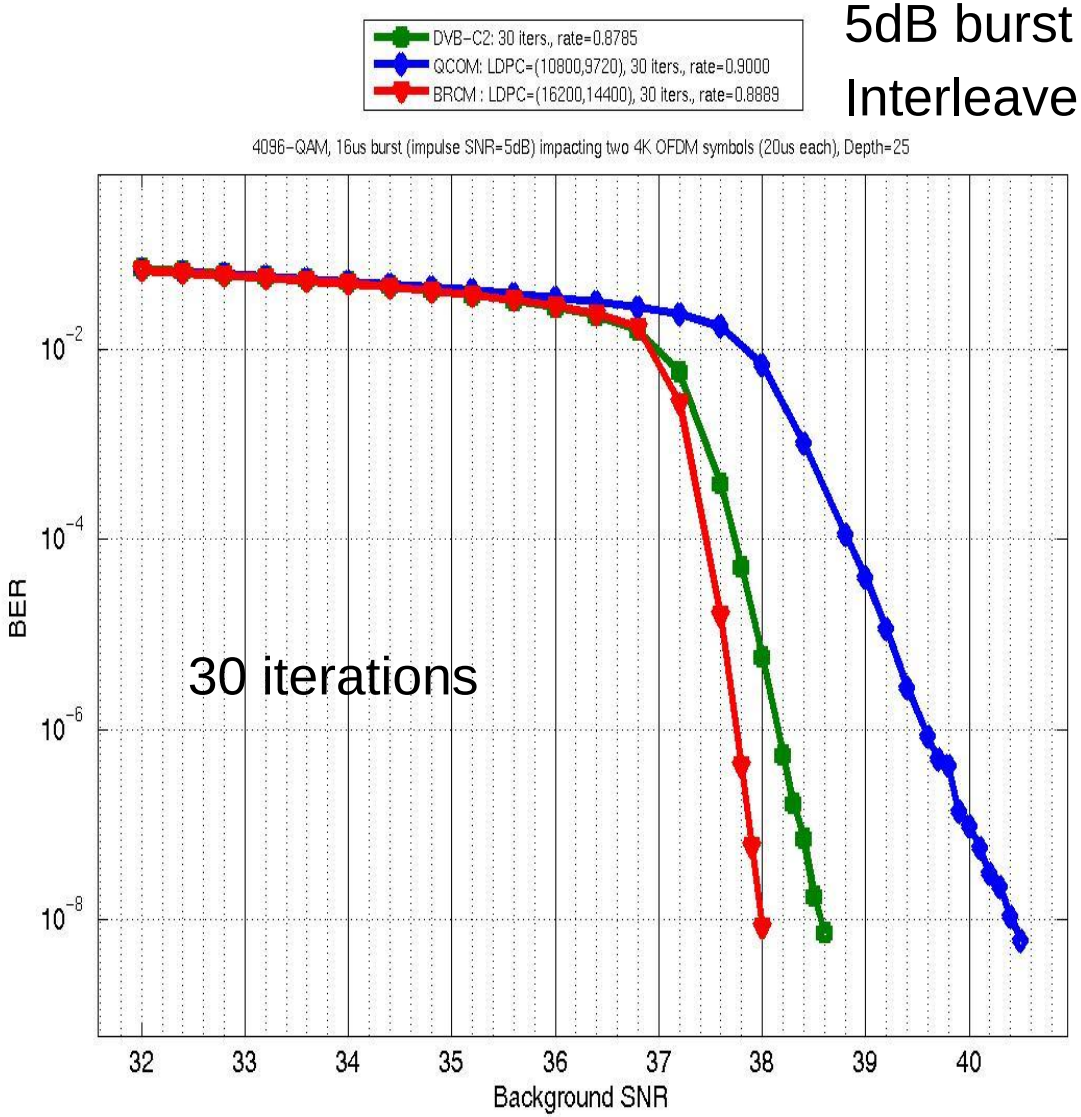


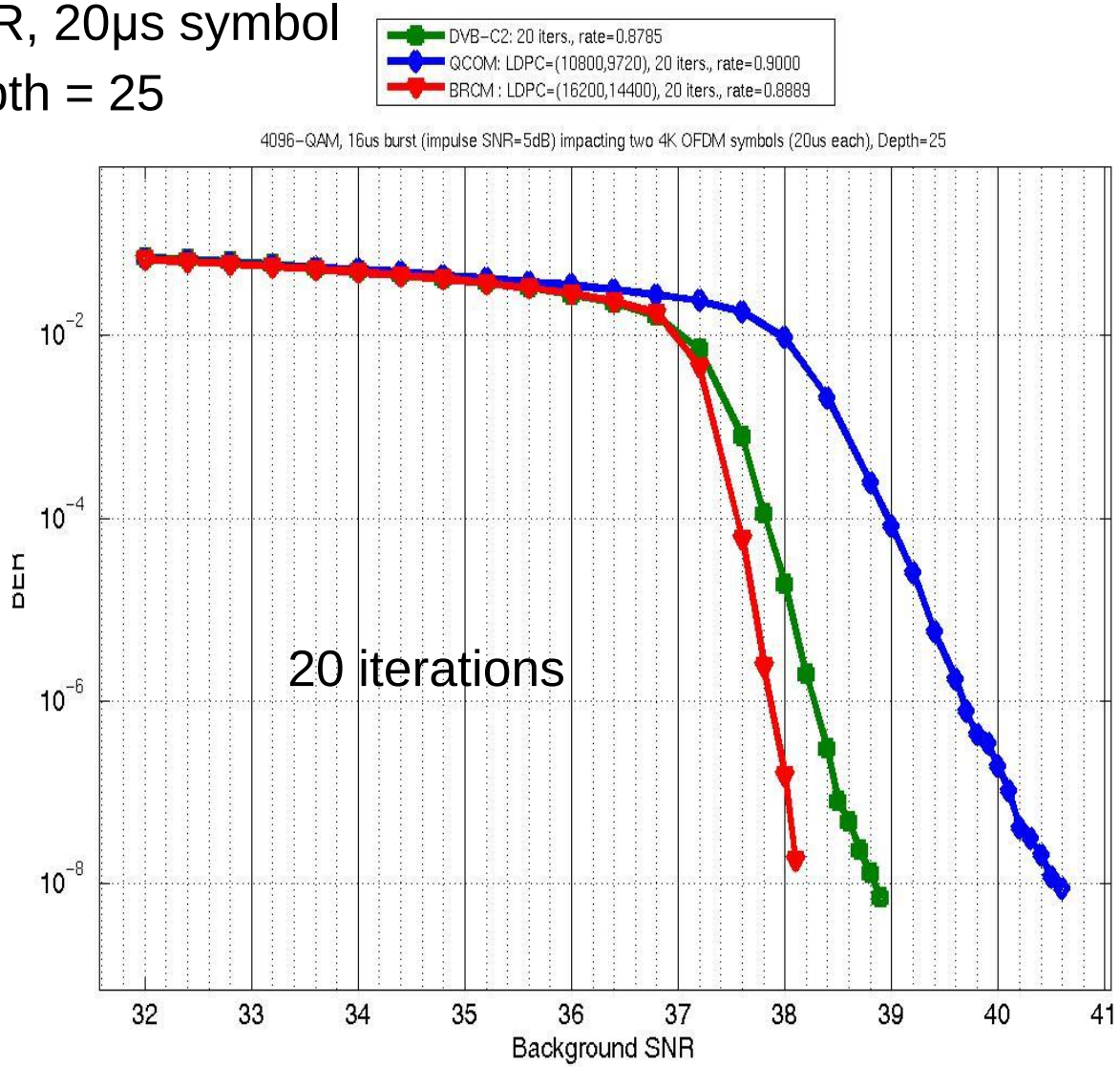


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 20μs symbol

Interleave depth = 25

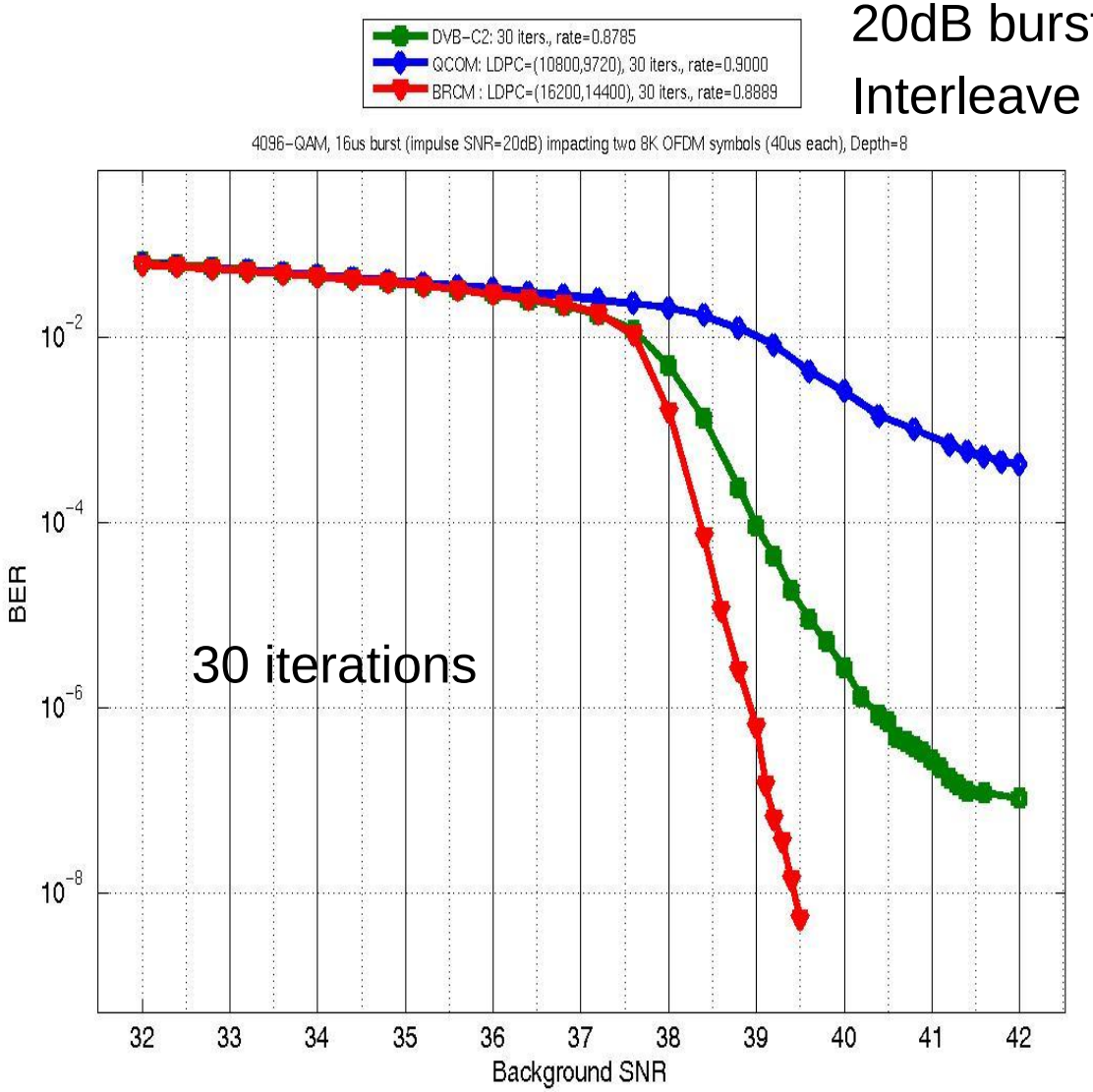


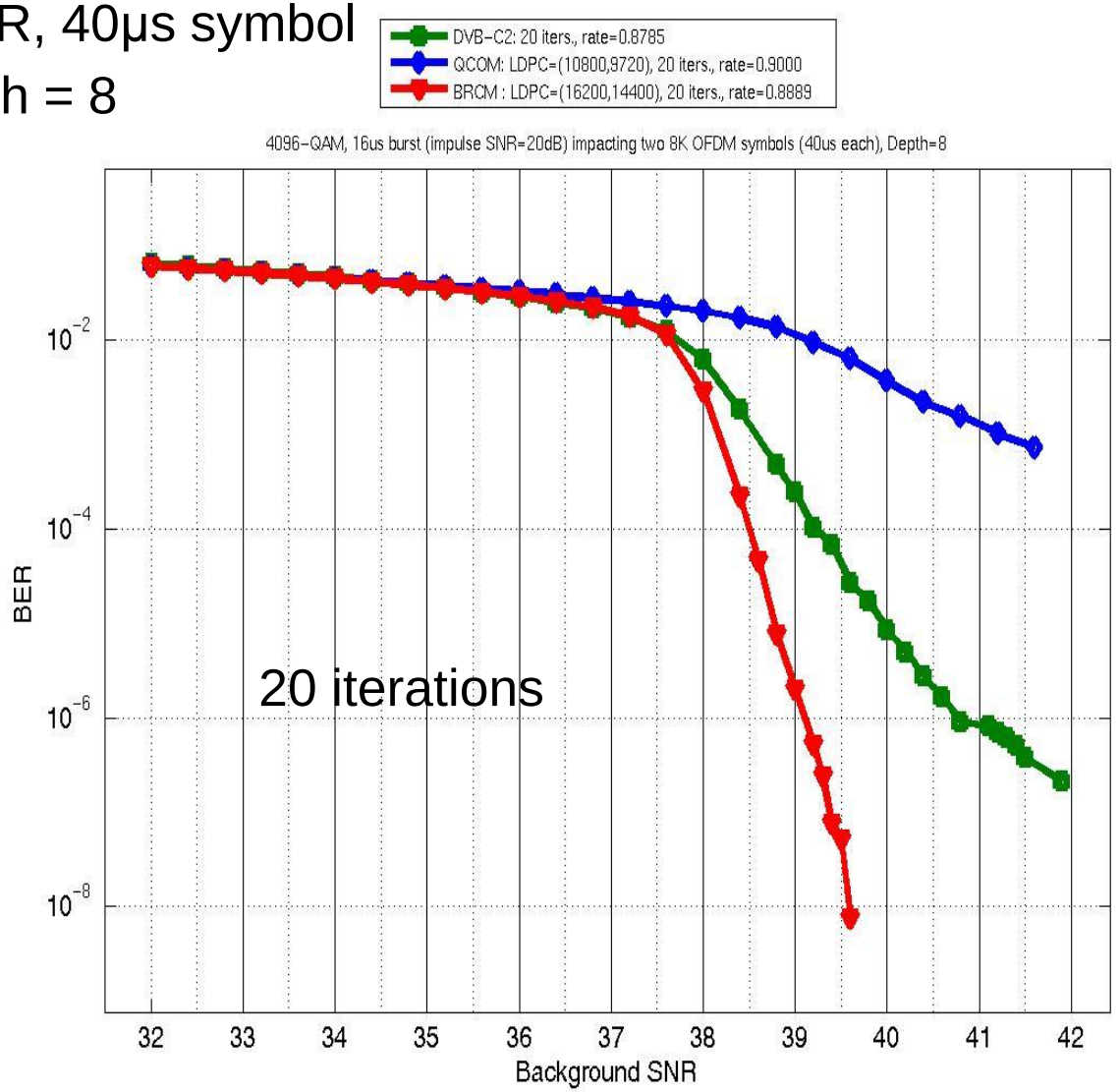


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 40μs symbol

Interleave depth = 8

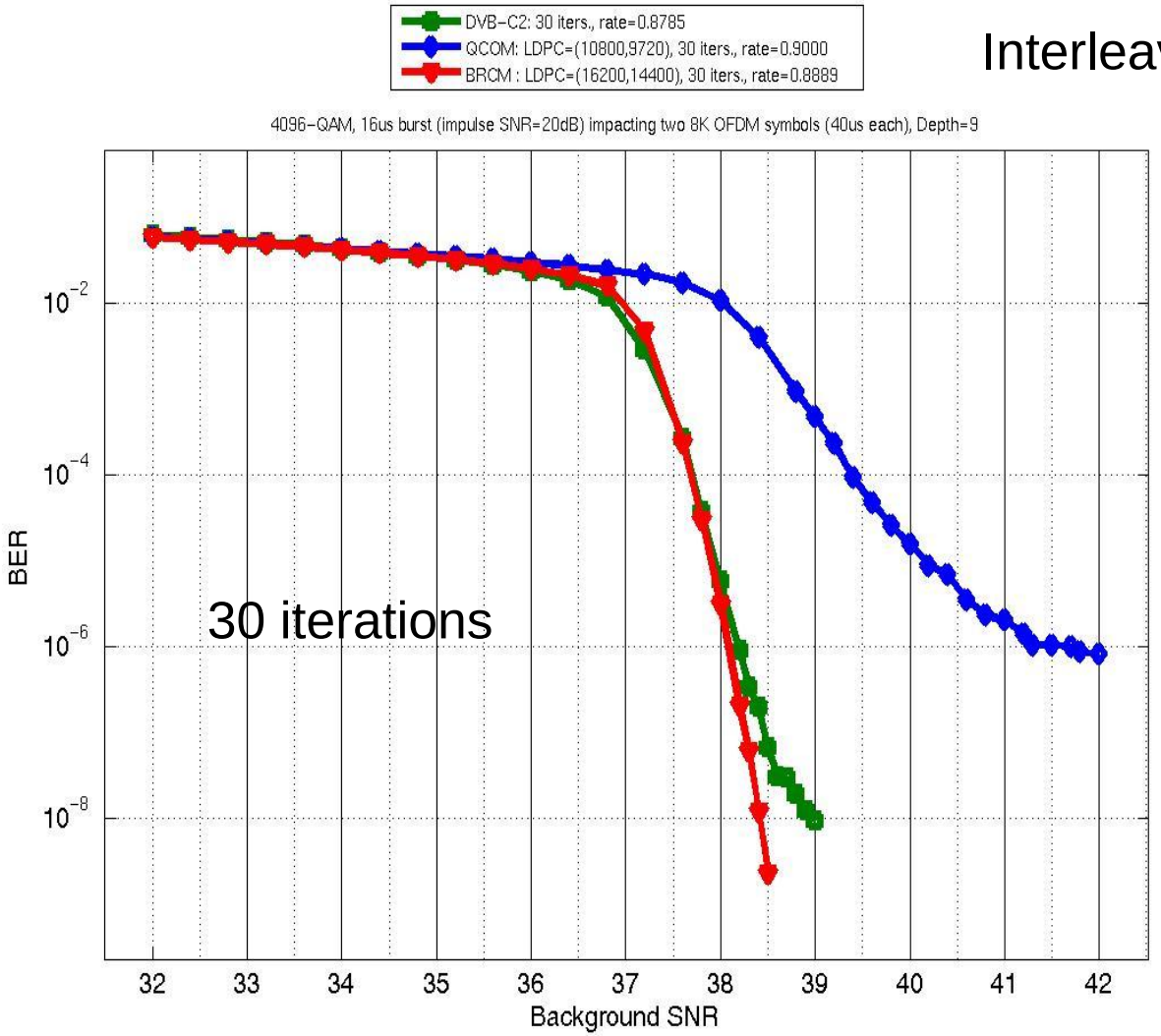


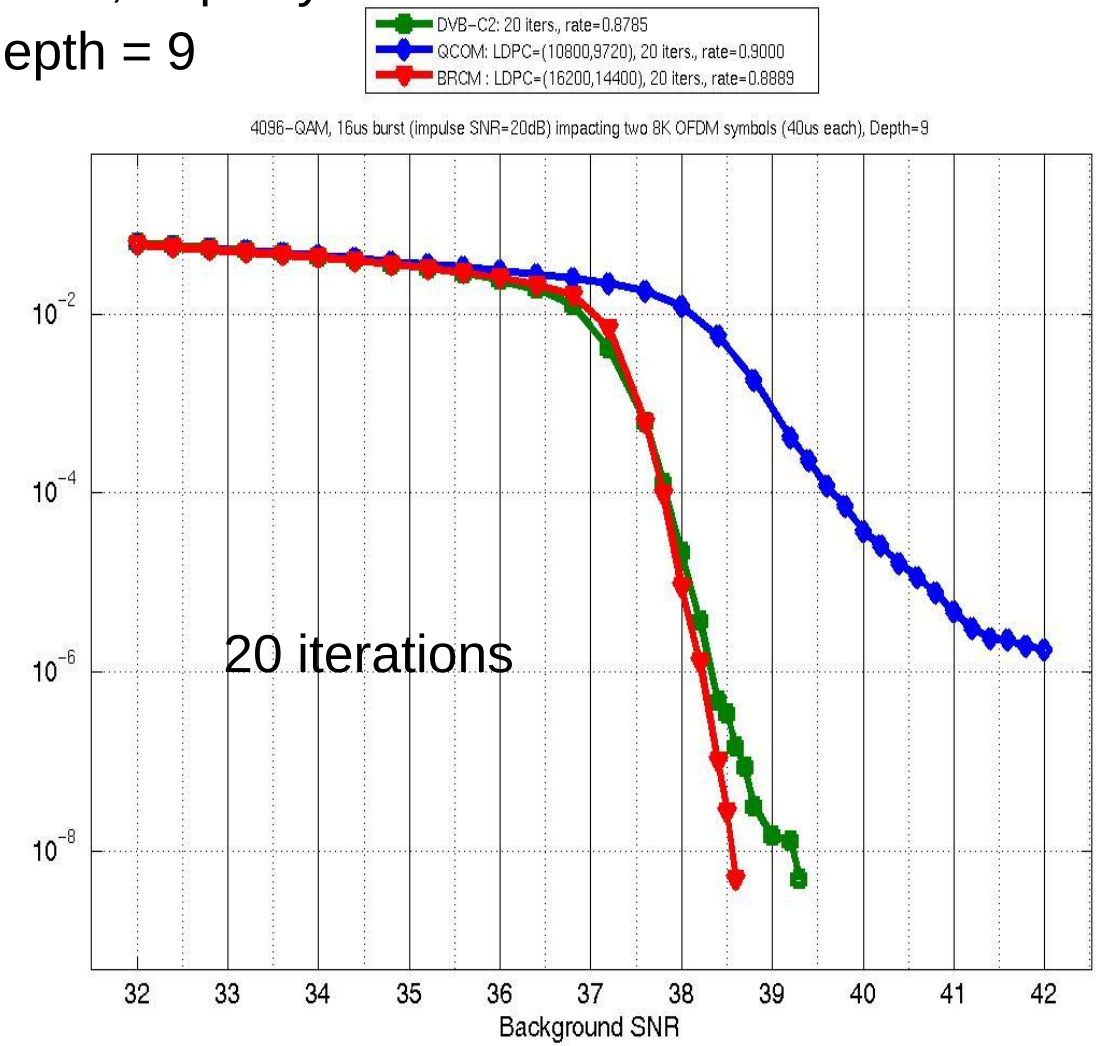


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 40μs symbol

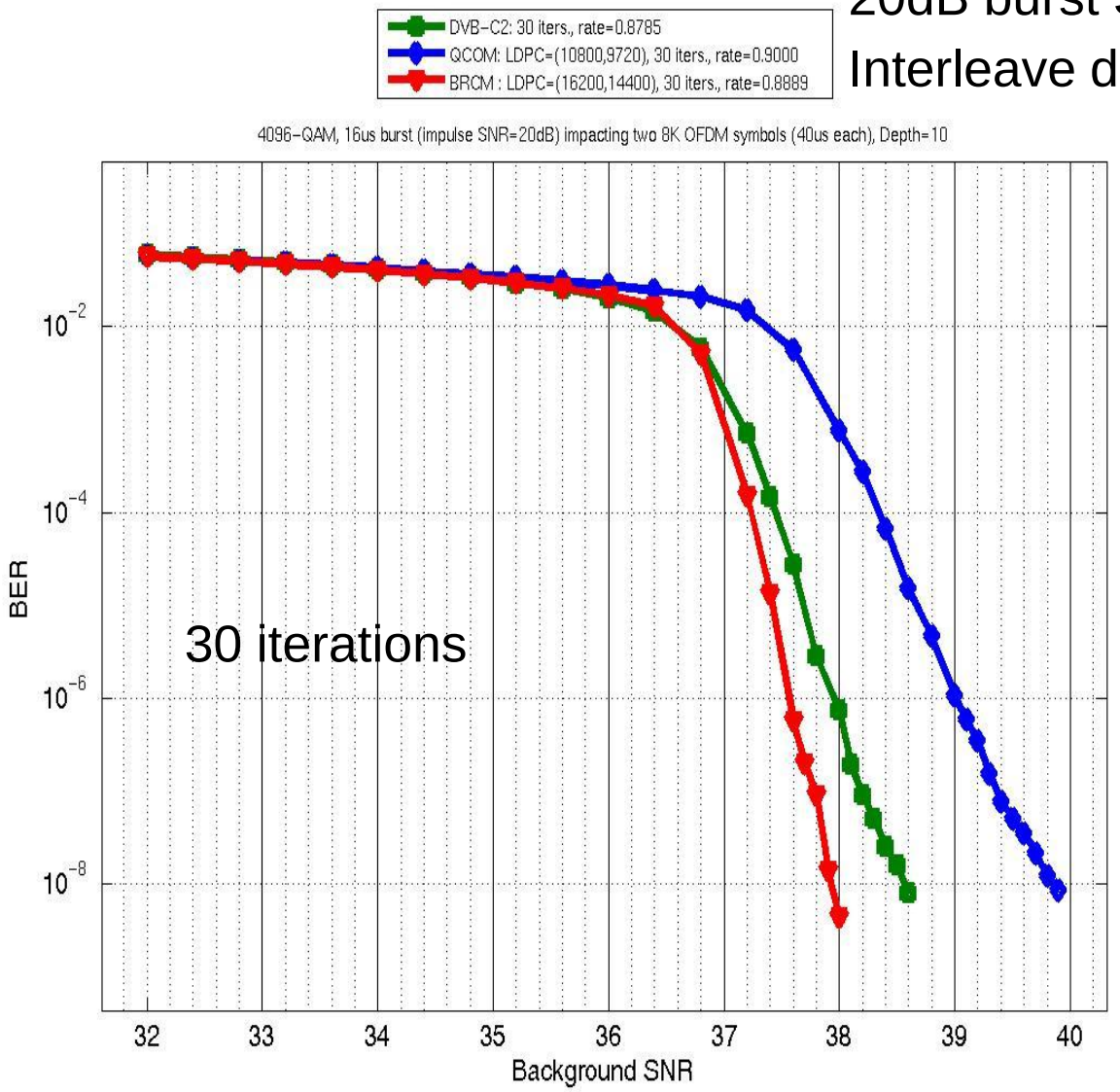
Interleave depth = 9

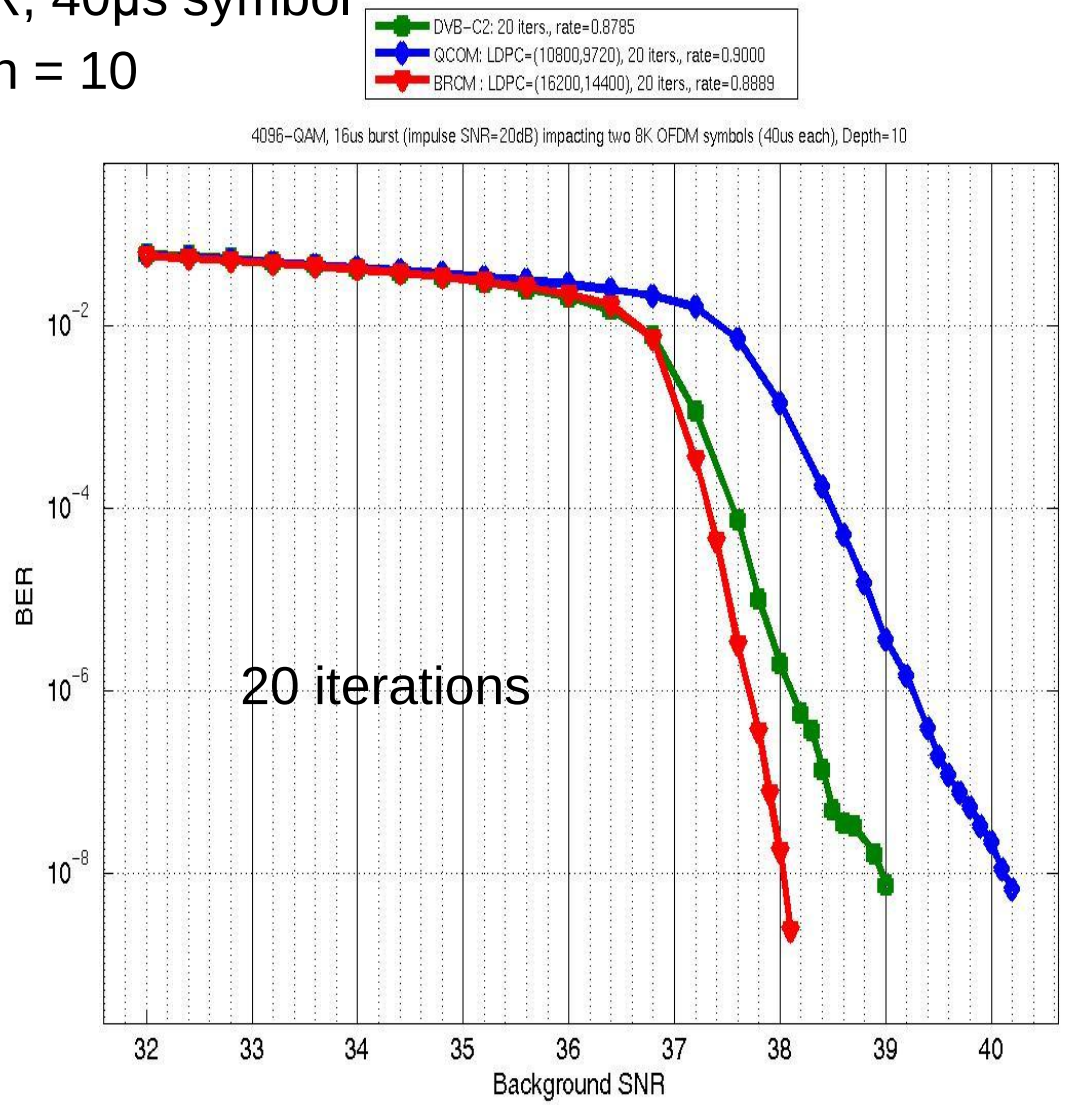




RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

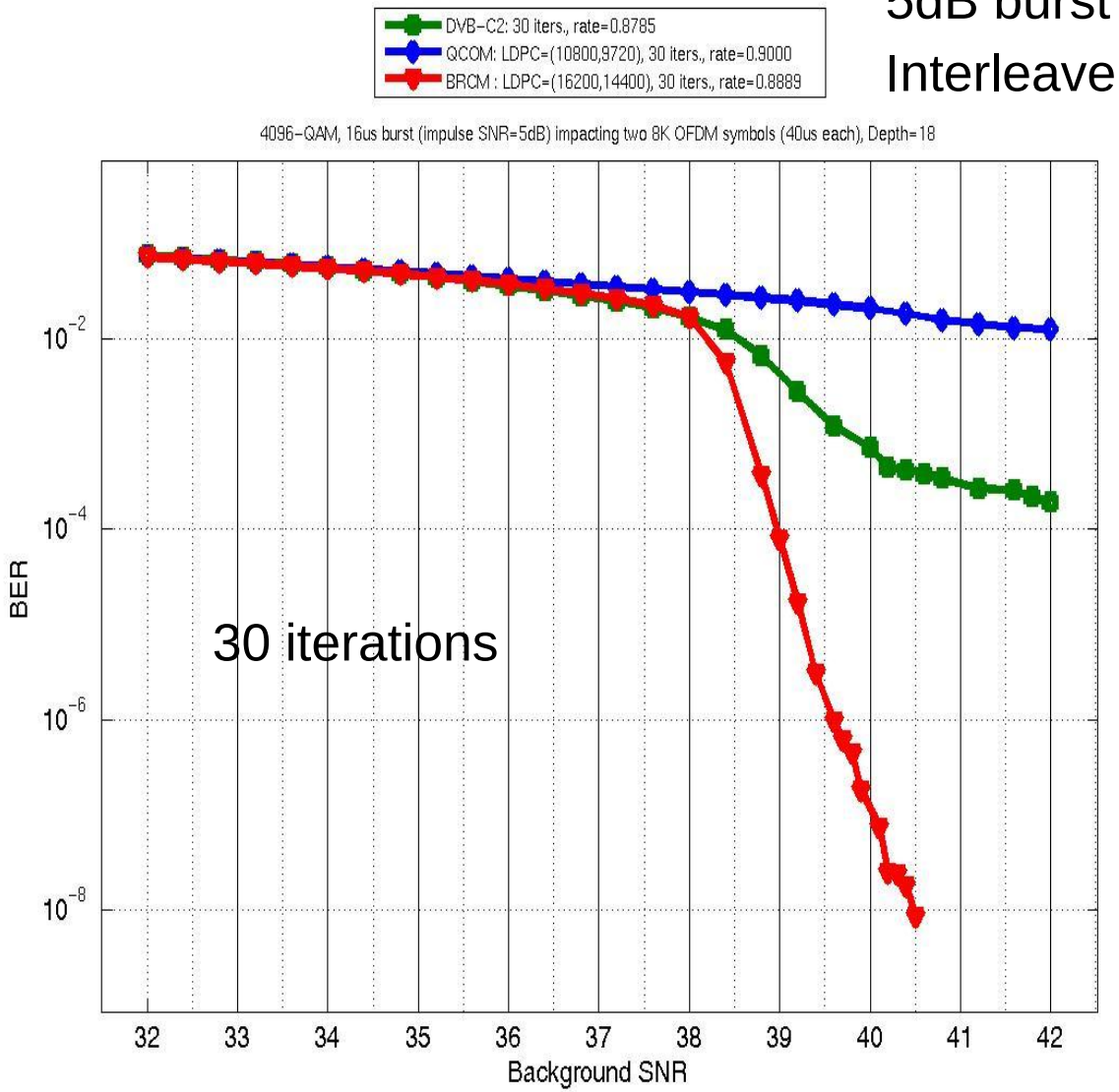
20dB burst SNR, 40µs symbol
Interleave depth = 10

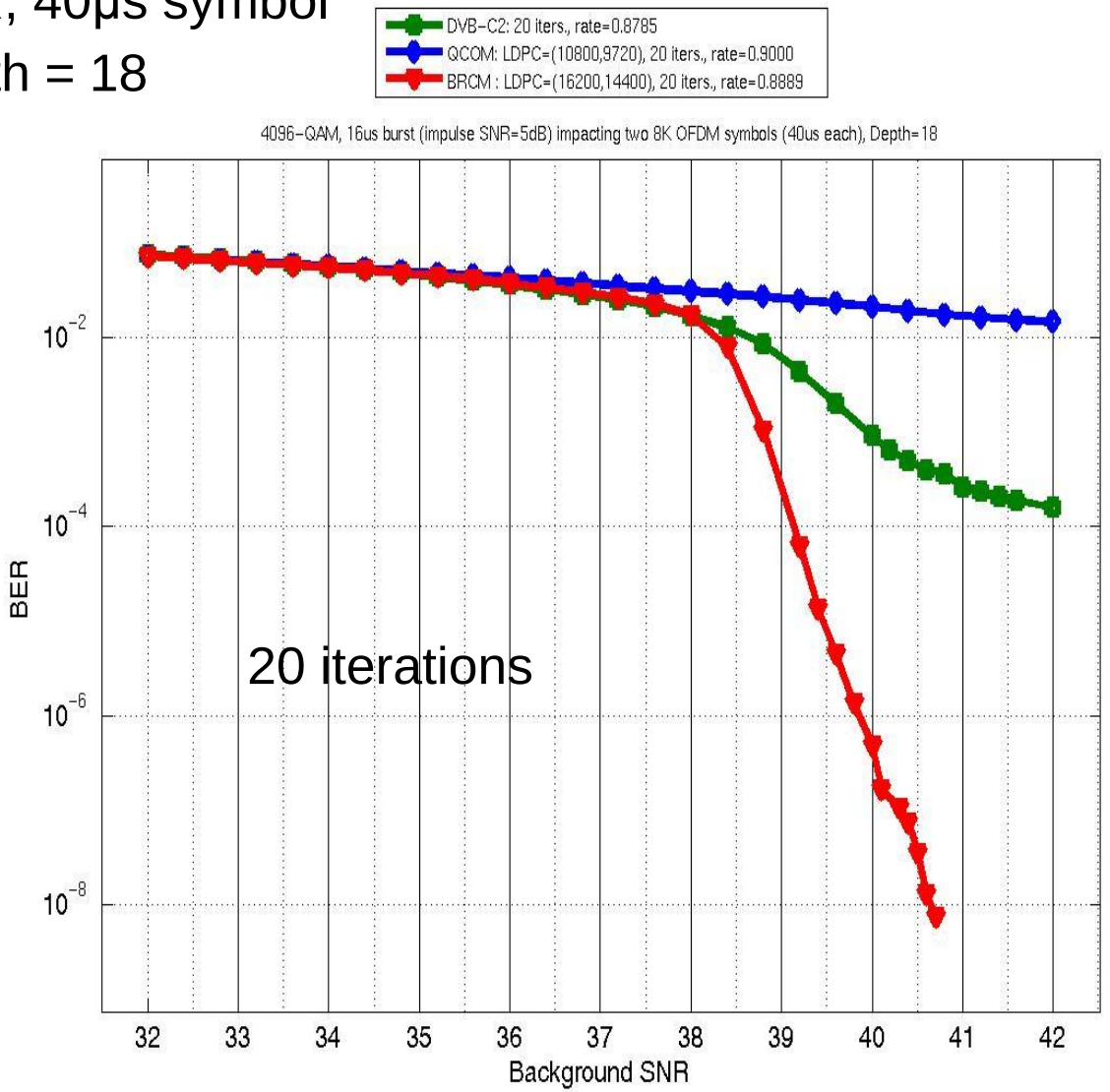




RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 40μs symbol
Interleave depth = 18

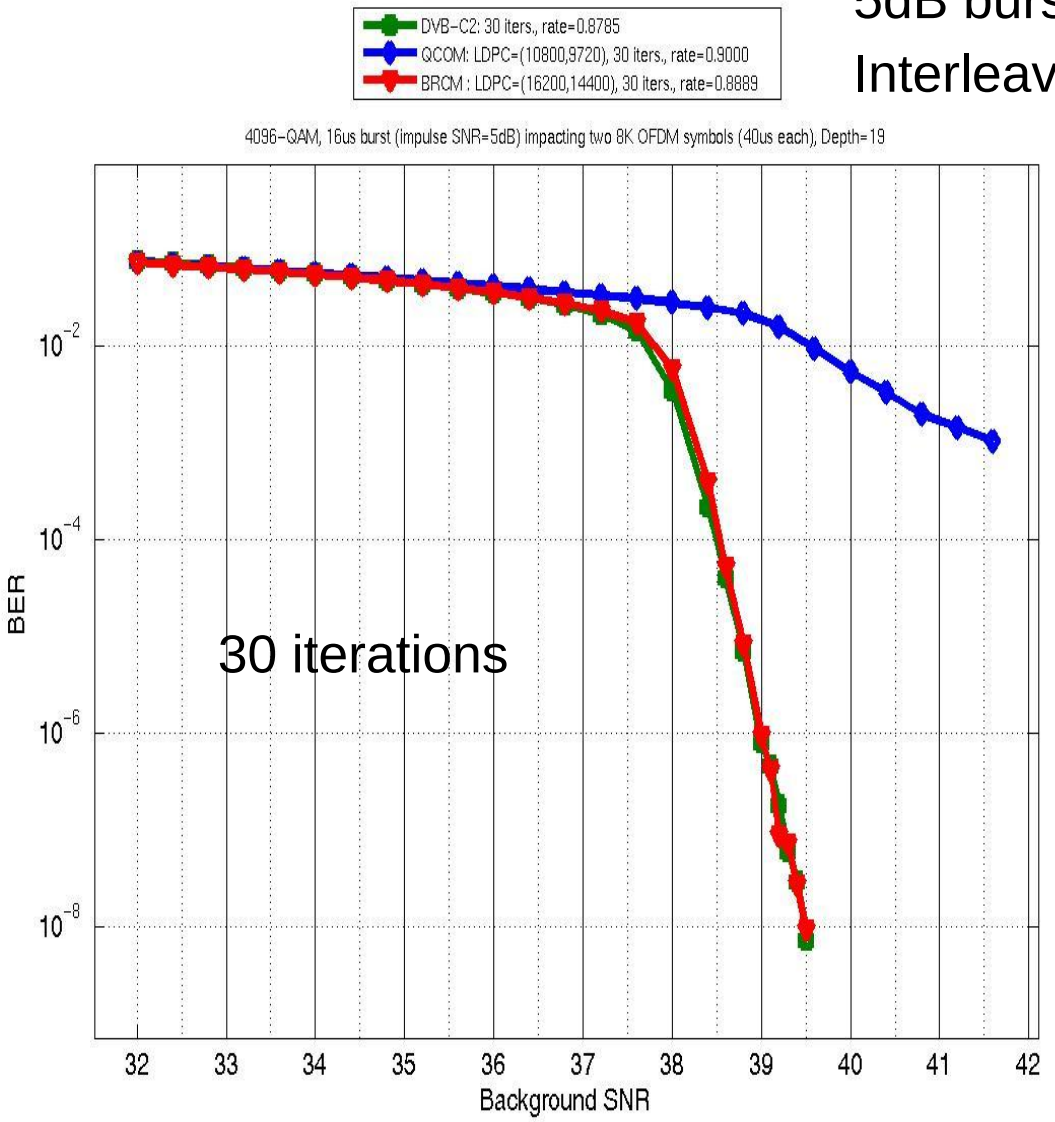


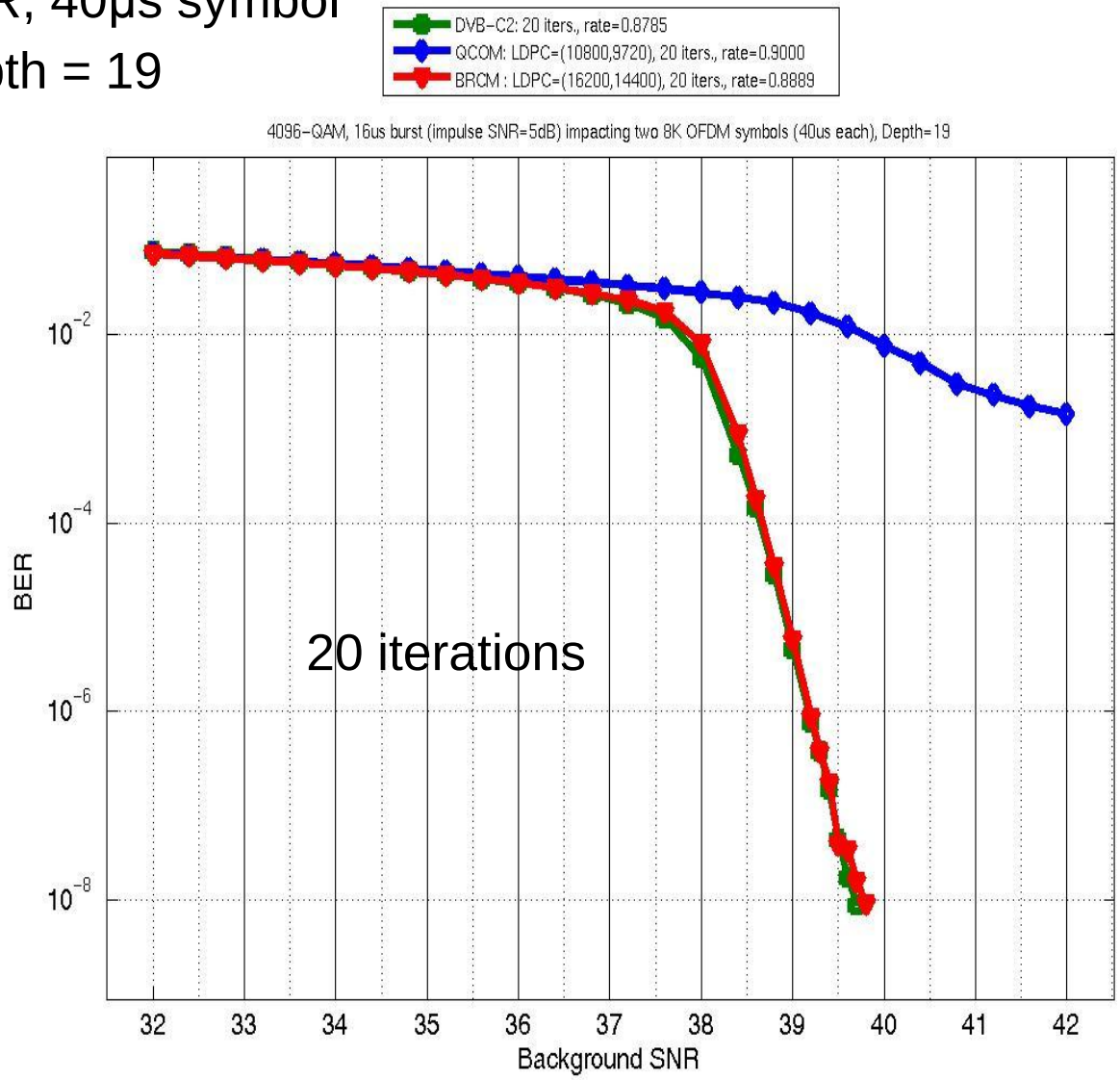


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 40μs symbol

Interleave depth = 19

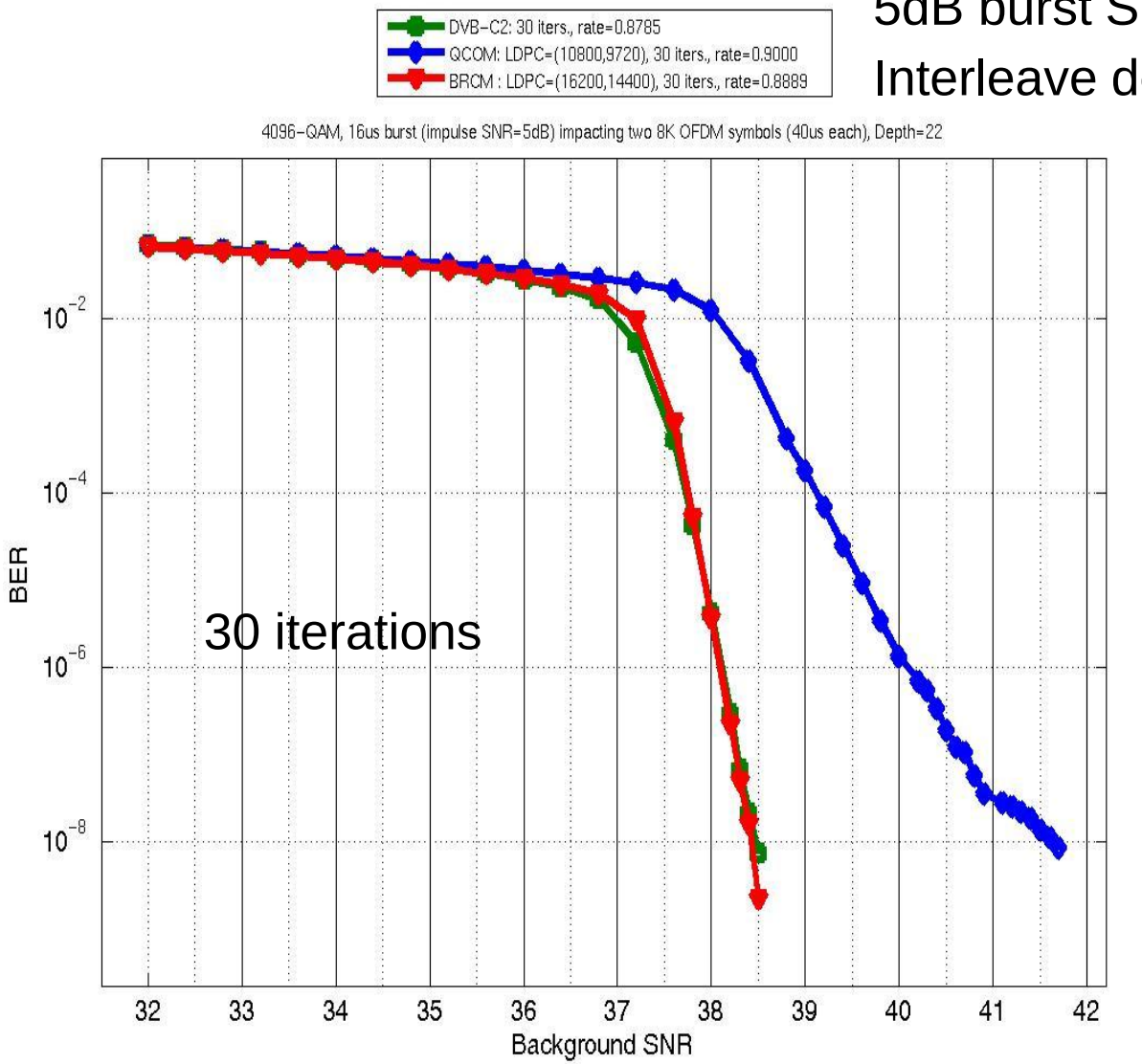


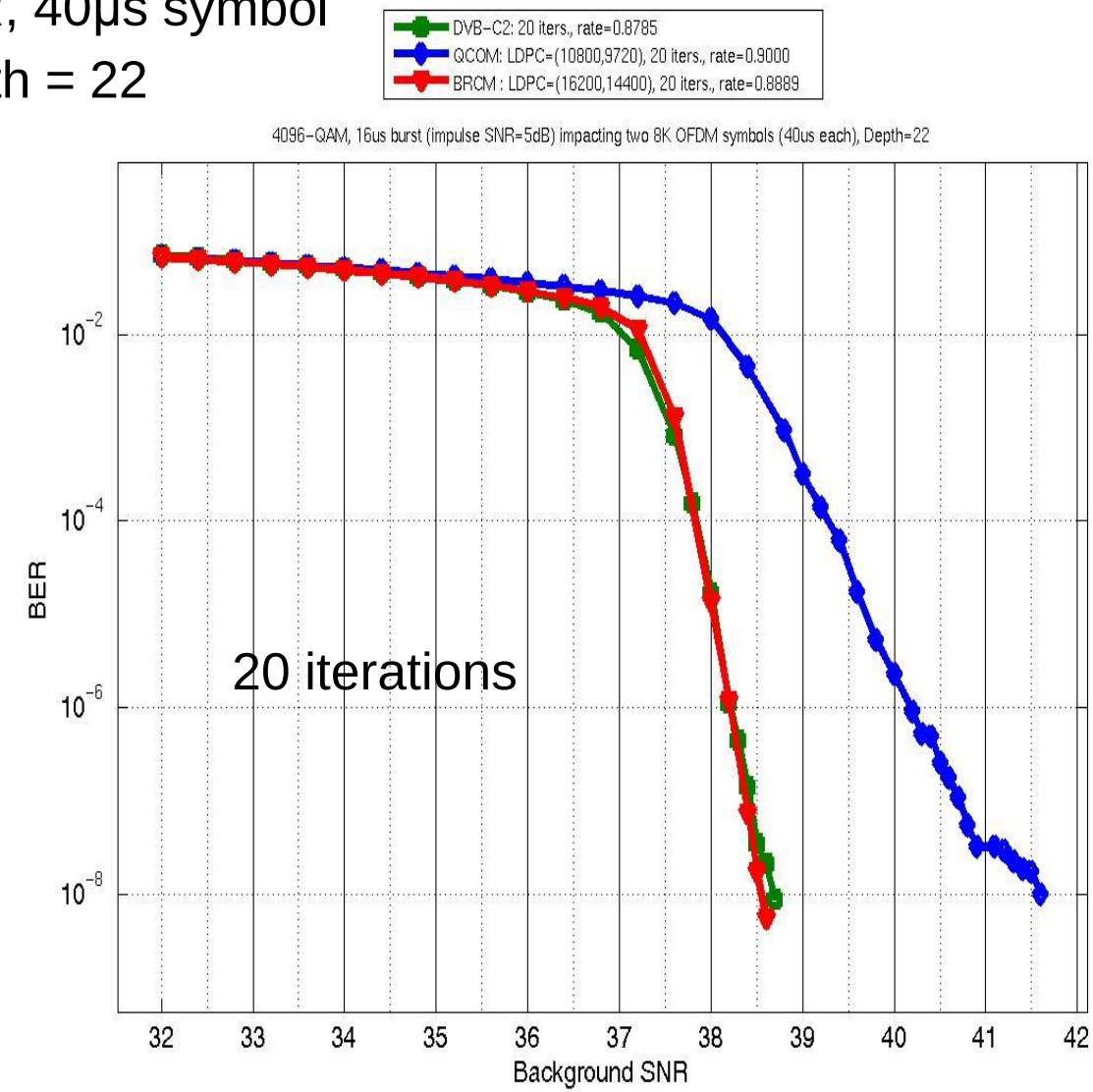


RATE 90% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 40μs symbol

Interleave depth = 22





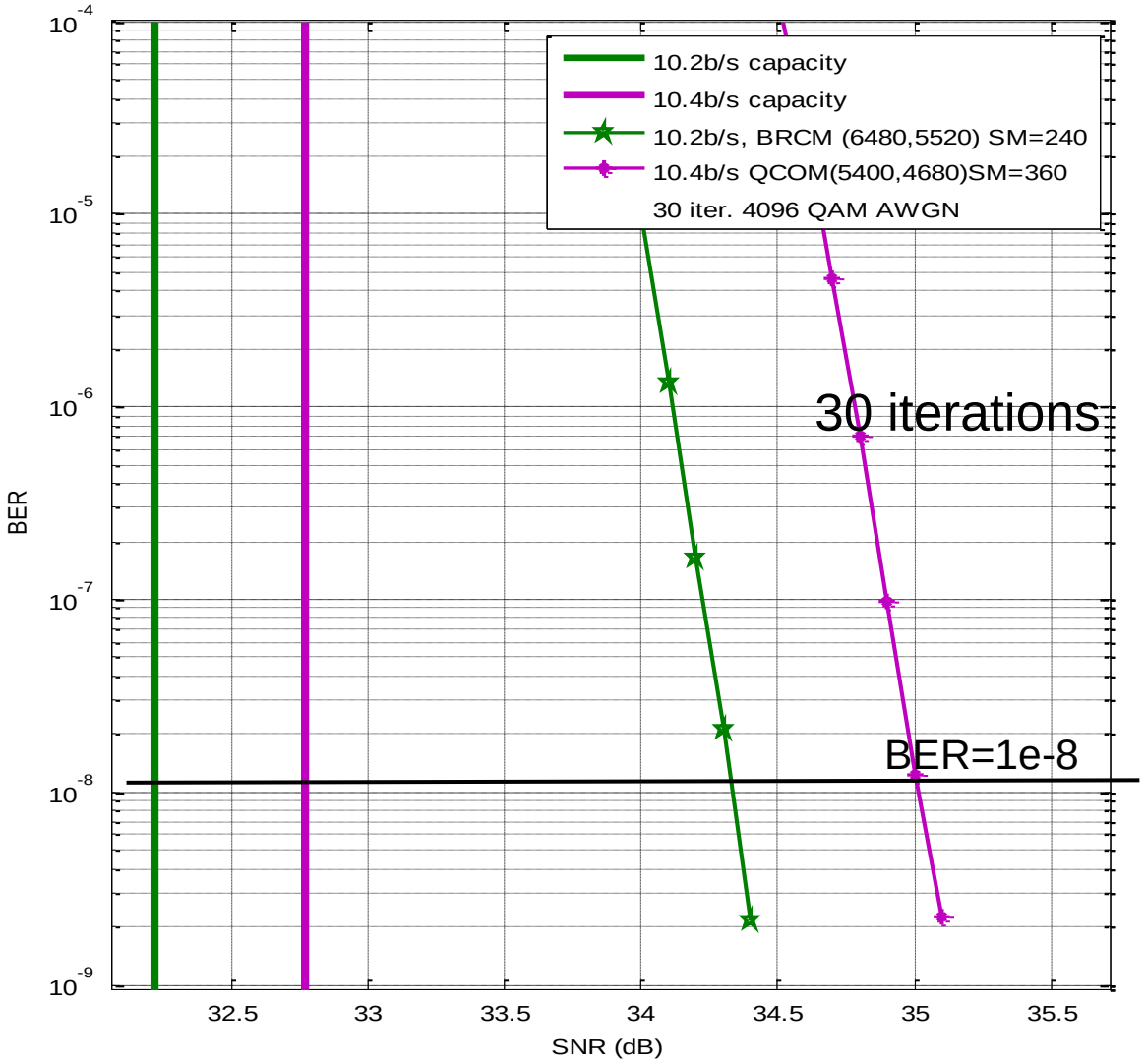
RATE 85% SHORT CODES - AWGN PERFORMANCE AND COMPLEXITY

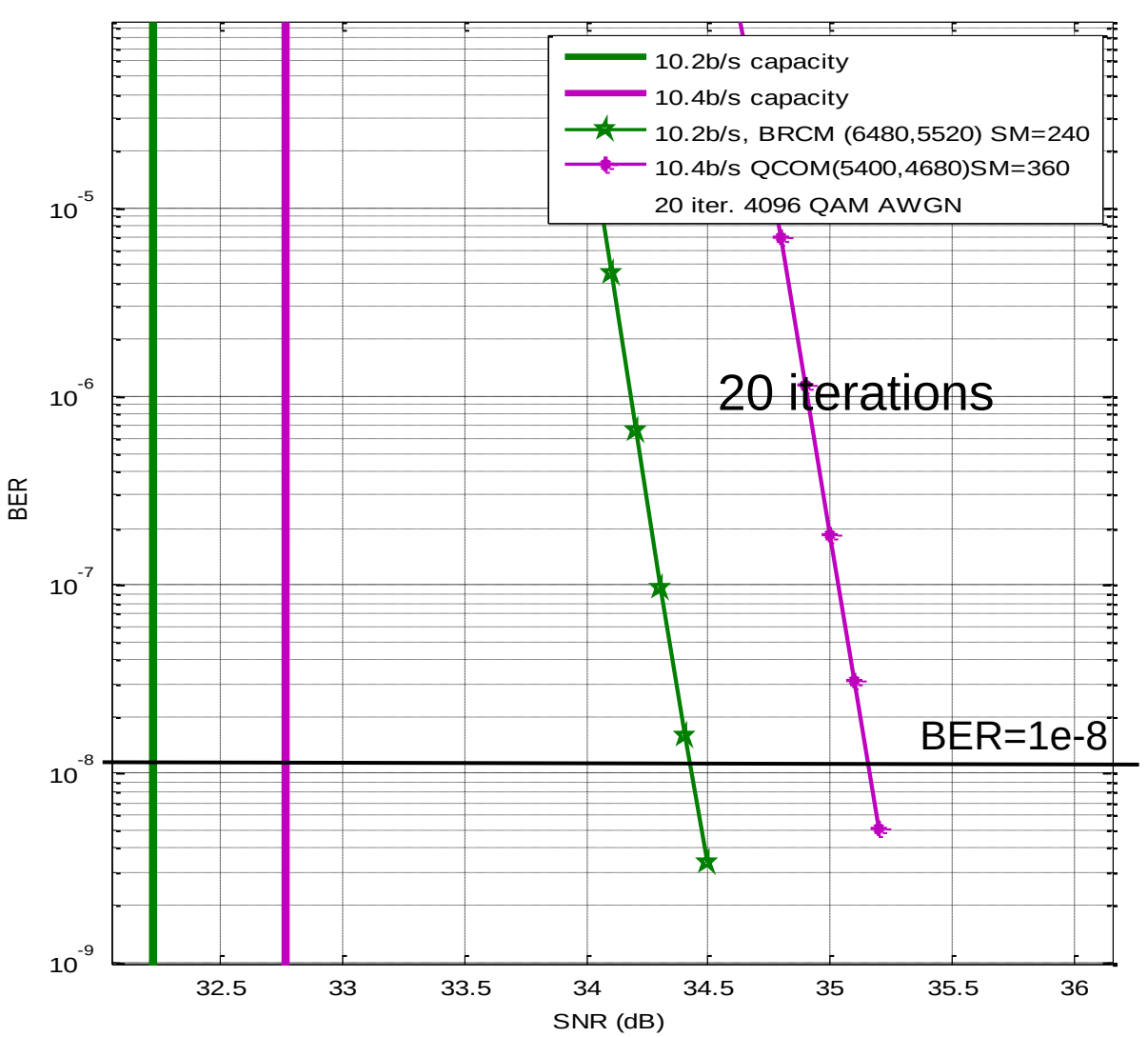
Code	Rate	Outer code	Inter-leave	4096QAM Capacity	K	N	I	SNR @WER=1e-6 (1024QAM)	Distance to capacity (1024QAM)	Spectral efficiency SNR gain compare to DVB C2	Eq/cb	Ed/cb
DVB-C2 8/9 based SM=360	0.8785	BCH	Twisted	33.21dB	14232	16200	20	35.53dB	2.32	.	0.1111	2.9999
							30	35.36dB	2.15	.		
BRCM SM=240	0.852	No	No	32.22dB	5520	6480	20	34.43dB	2.21	0.11	0.1481	3.5556
							30	34.33dB	2.11	0.05		
QCOM SM=360	0.867	No	No	32.77dB	4680	5400	20	35.16dB	2.39	-0.07	0.2667	3.6
							30	35.01dB	2.24	-0.09		

K: information size (bits) .N: codeword size (bits) I: number of maximum iterations

BRCM 6K 85% code is the closest to the Channel Capacity limit

85% CODES AWGN CHANNEL PERFORMANCE CURVES





RATE 85% CODES PERFORMANCE IN IMPULSE NOISE

Minimum depth and background SNR to achieve BER=1e-8 (4096QAM, 30 iterations)

	Burst duration	Burst SNR	BRCM 85.2%	QCOM 86.7%
20µs symbol (two affected)	16us	20dB	**8** 180µs@40dB	**10** 225µs@40.3dB
	16us	5dB	**16** 260µs@40.3dB	**19** 427.5µs@41.5dB
40µs symbol (two affected)	16us	20dB	**7** 297.5µs@38.6dB	**8** 340µs@40.4dB
	16us	5dB	**16** 680µs@38.7dB	**18** 765µs@40.1dB

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	Burst duration	Burst SNR	BRCM 85.2%	QCOM 86.7%
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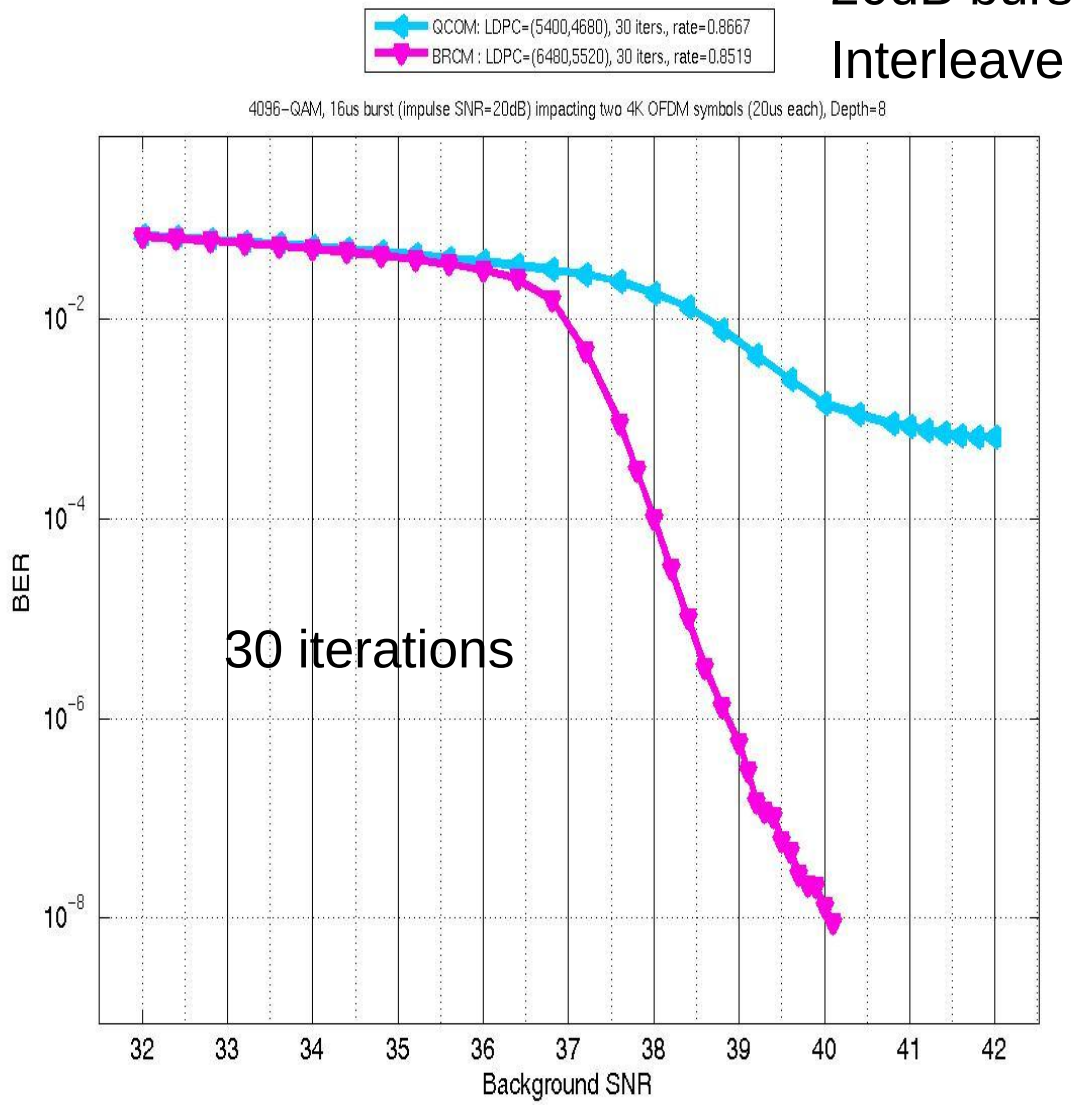
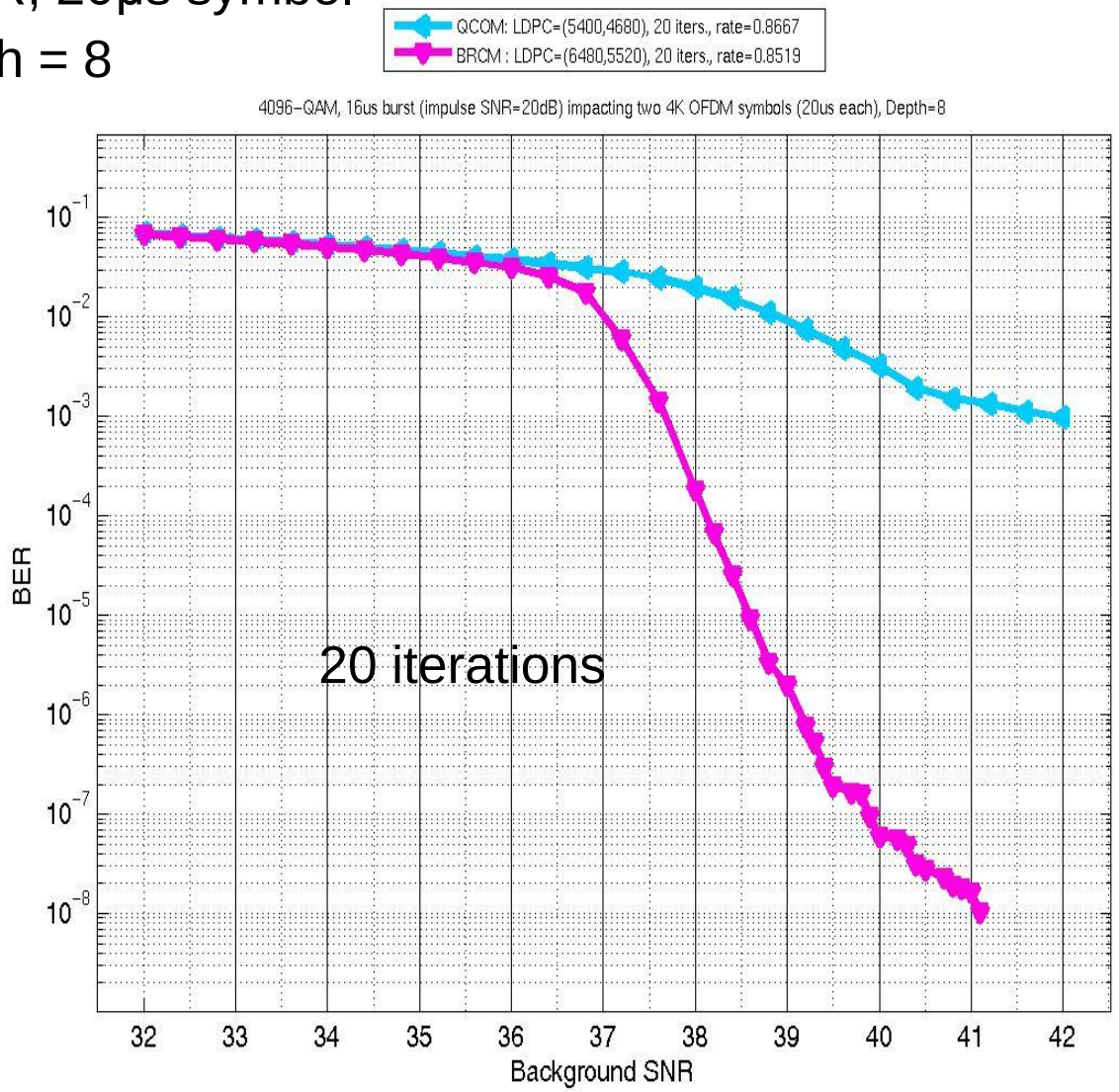
	16us	5dB	**16** 680µs@39dB	**18** 765µs@40.3dB

RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 20μs symbol
Interleave depth = 8

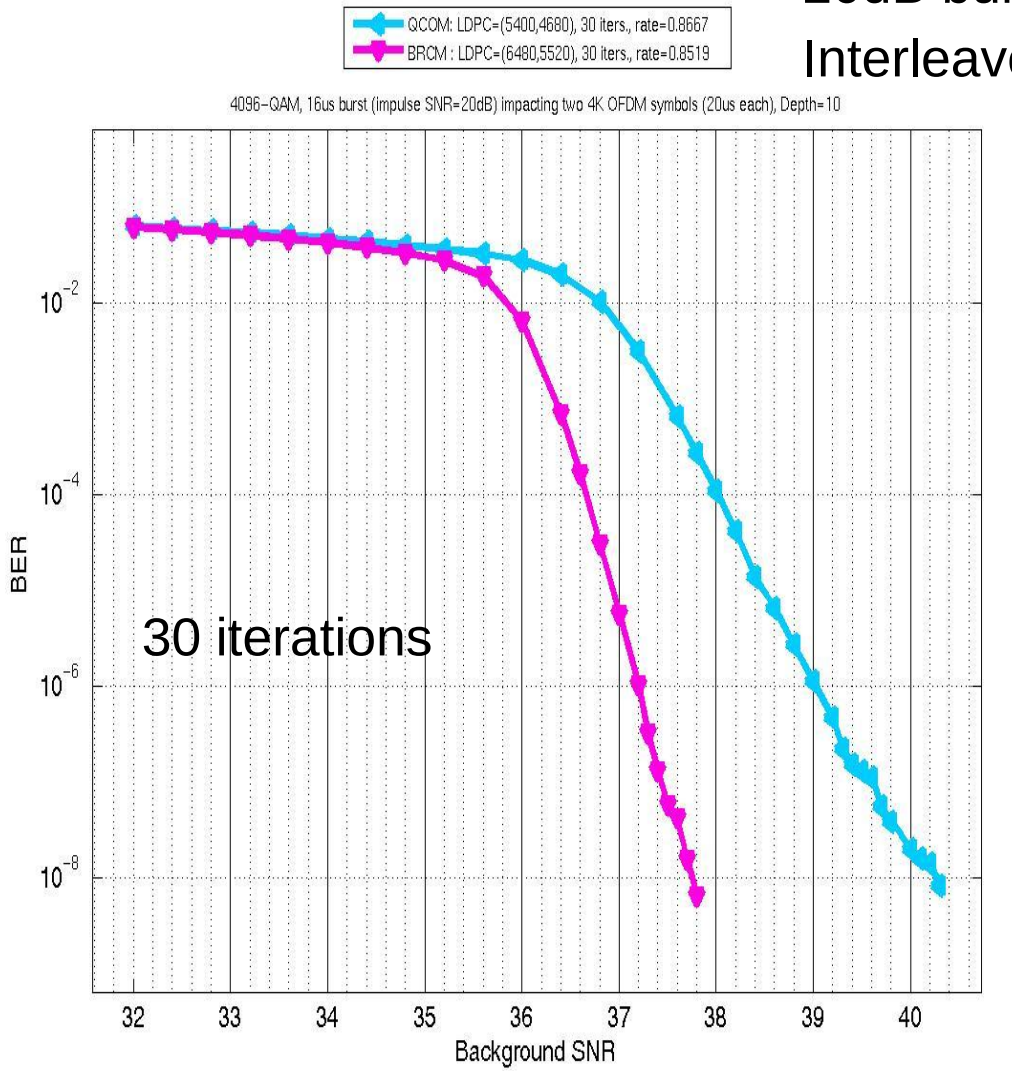


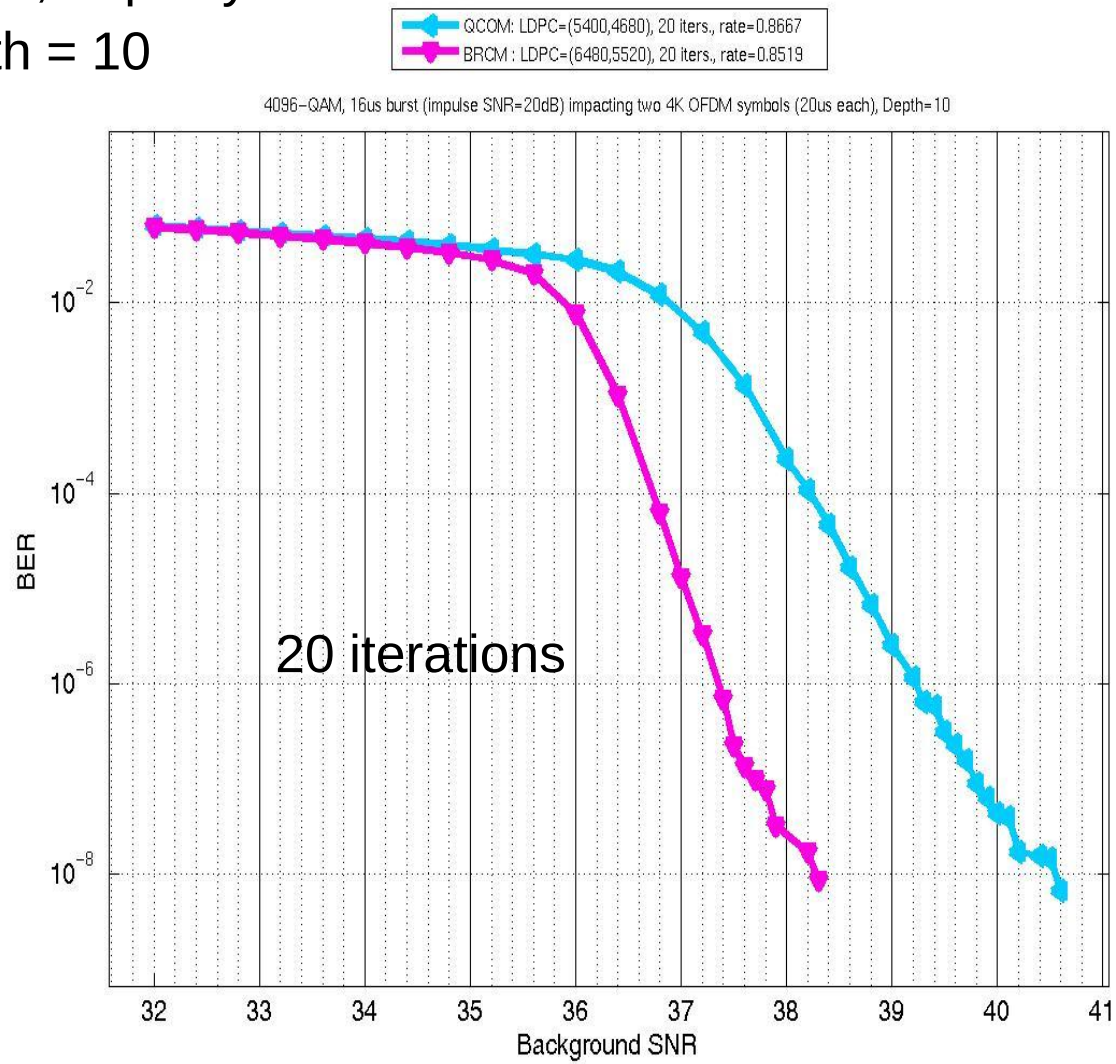


RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 20µs symbol

Interleave depth = 10

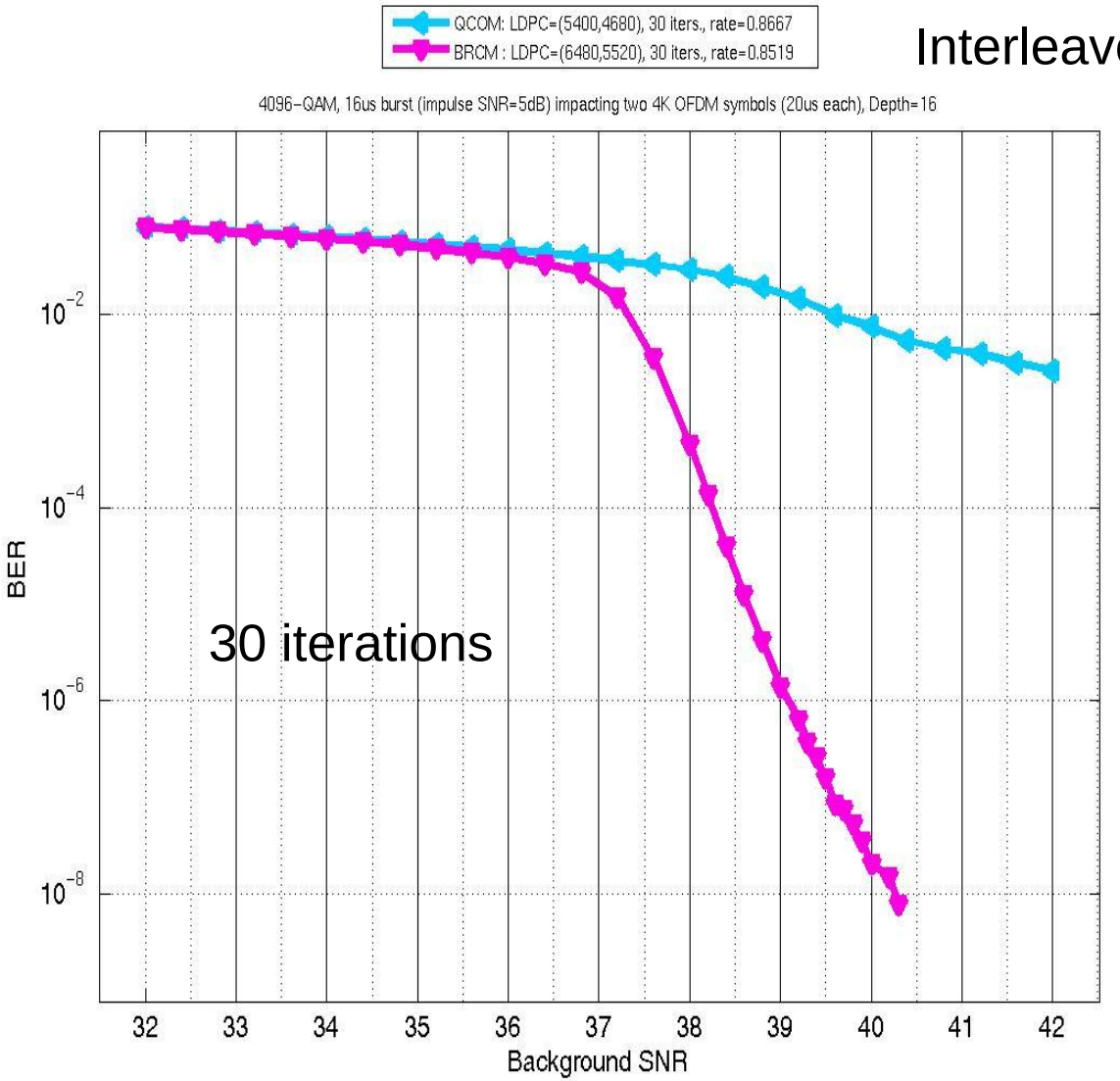


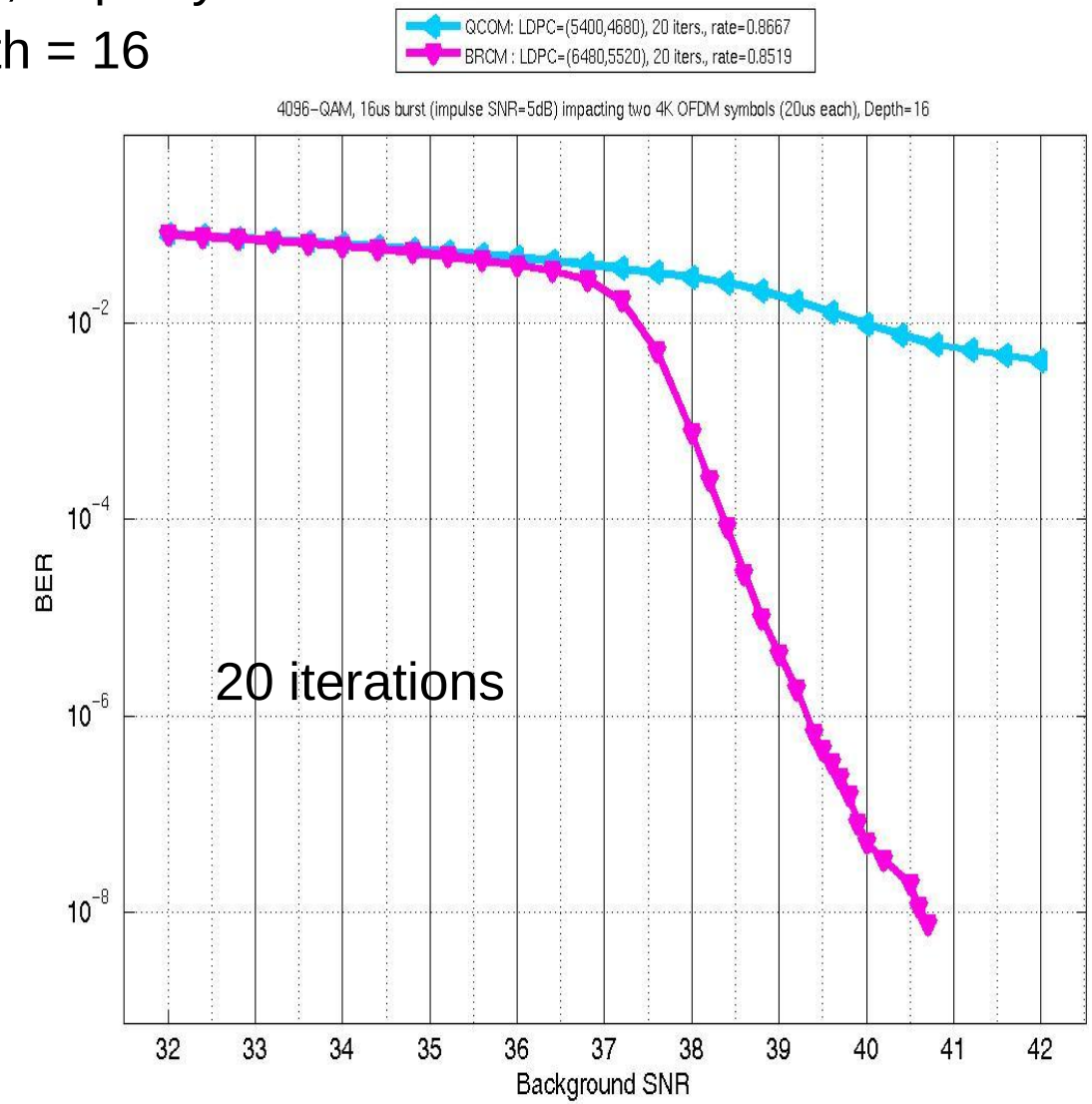


RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 20µs symbol

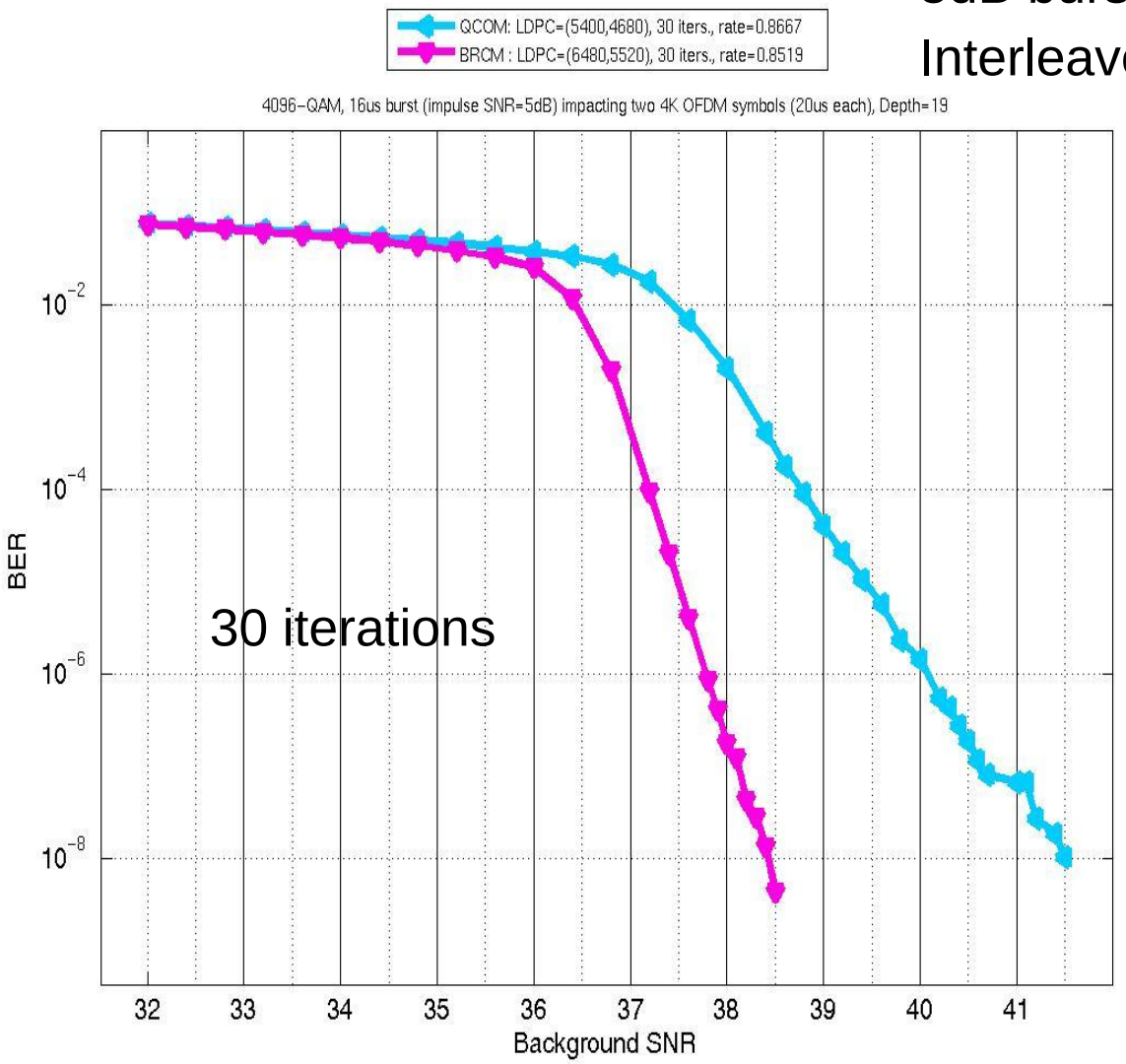
Interleave depth = 16

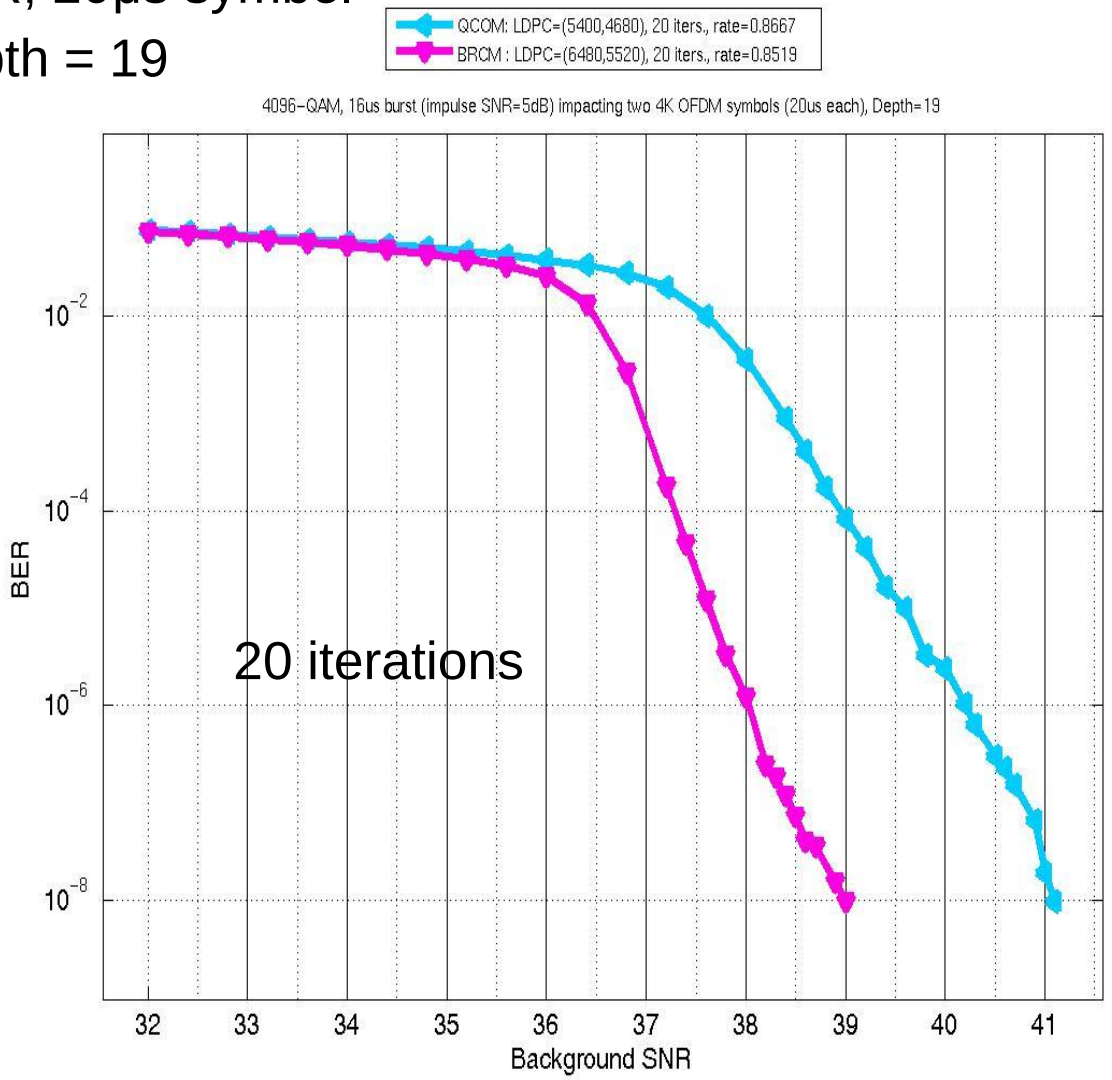




RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

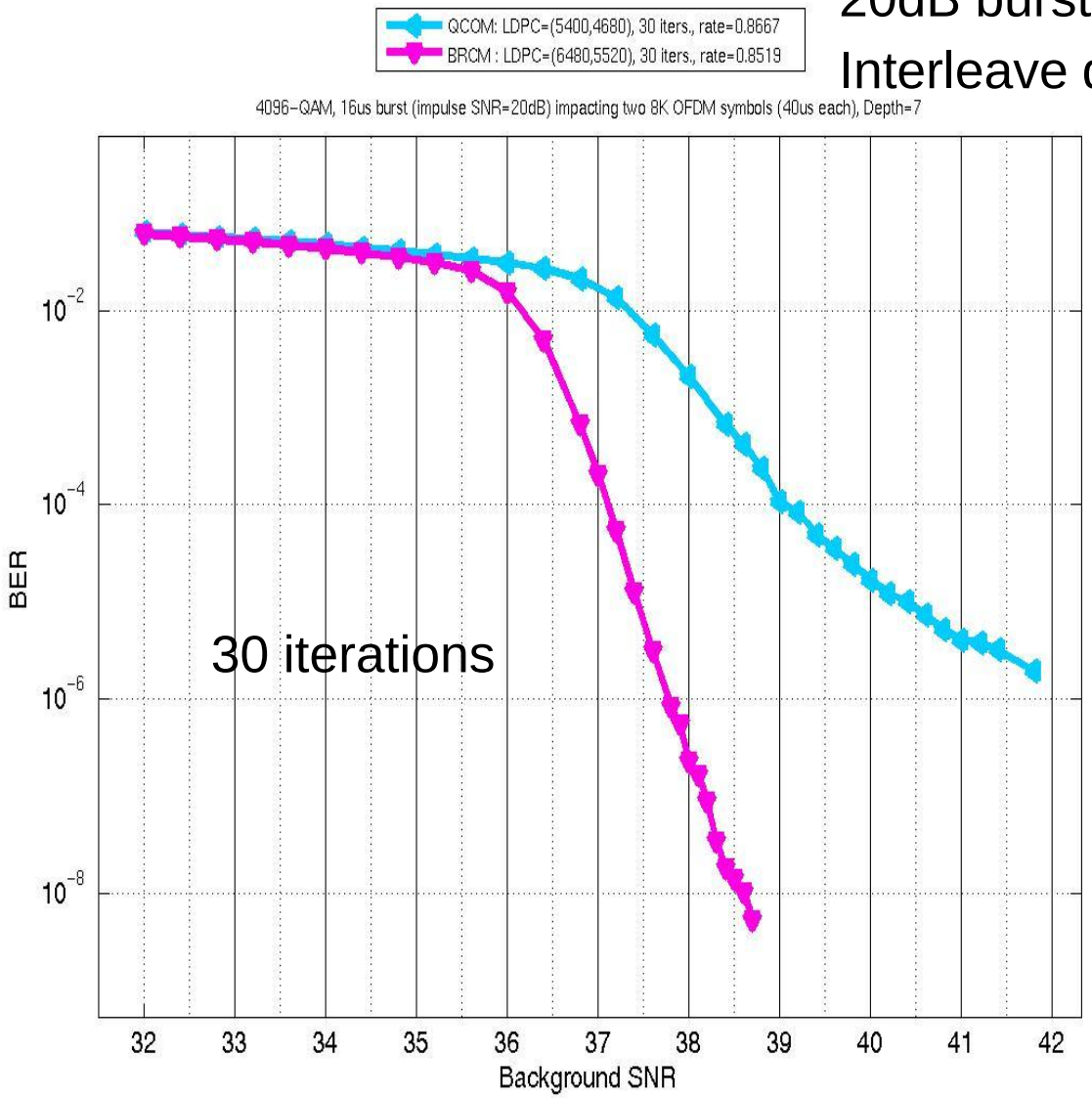
5dB burst SNR, 20µs symbol
Interleave depth = 19

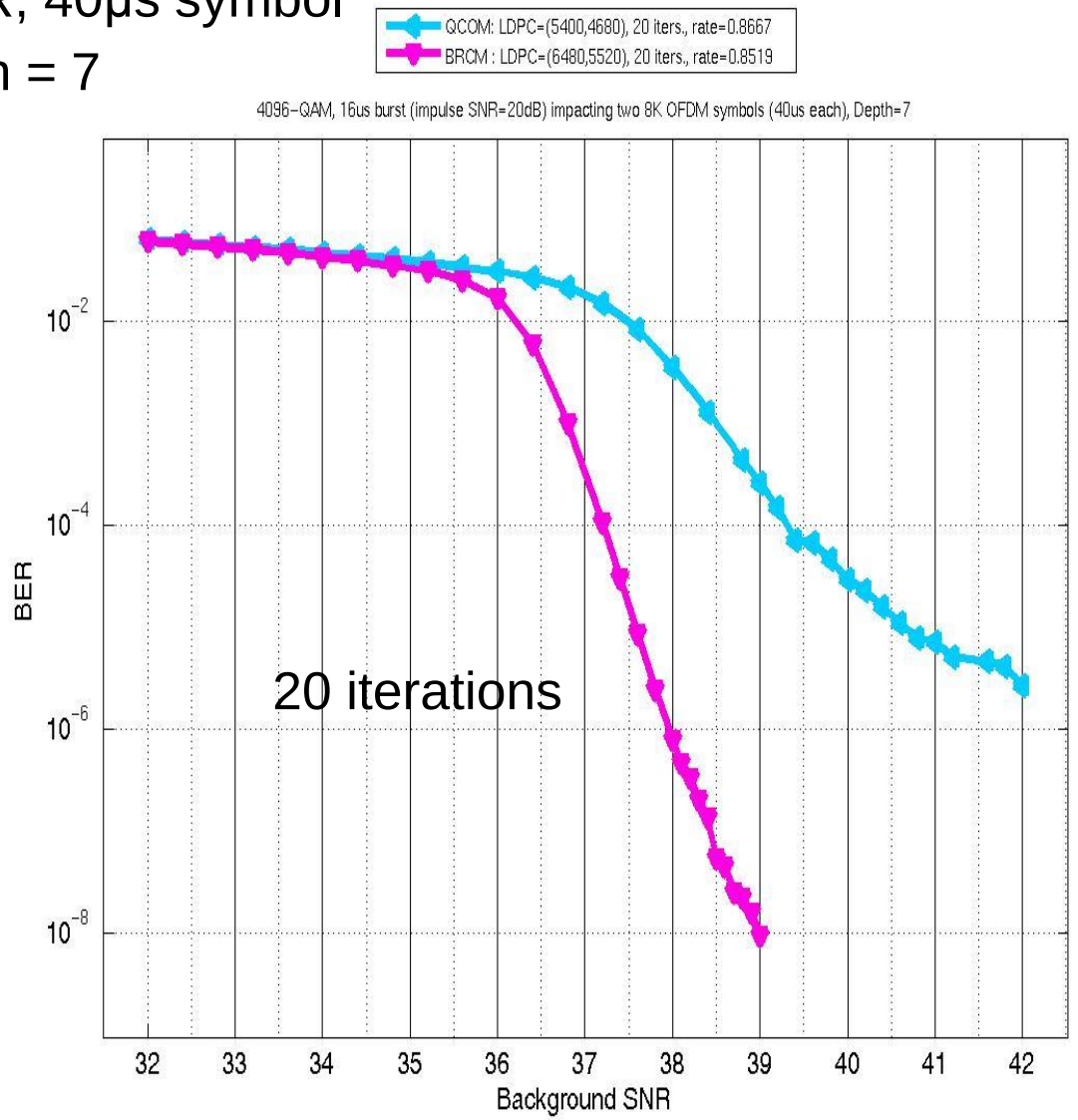




RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 40μs symbol
Interleave depth = 7

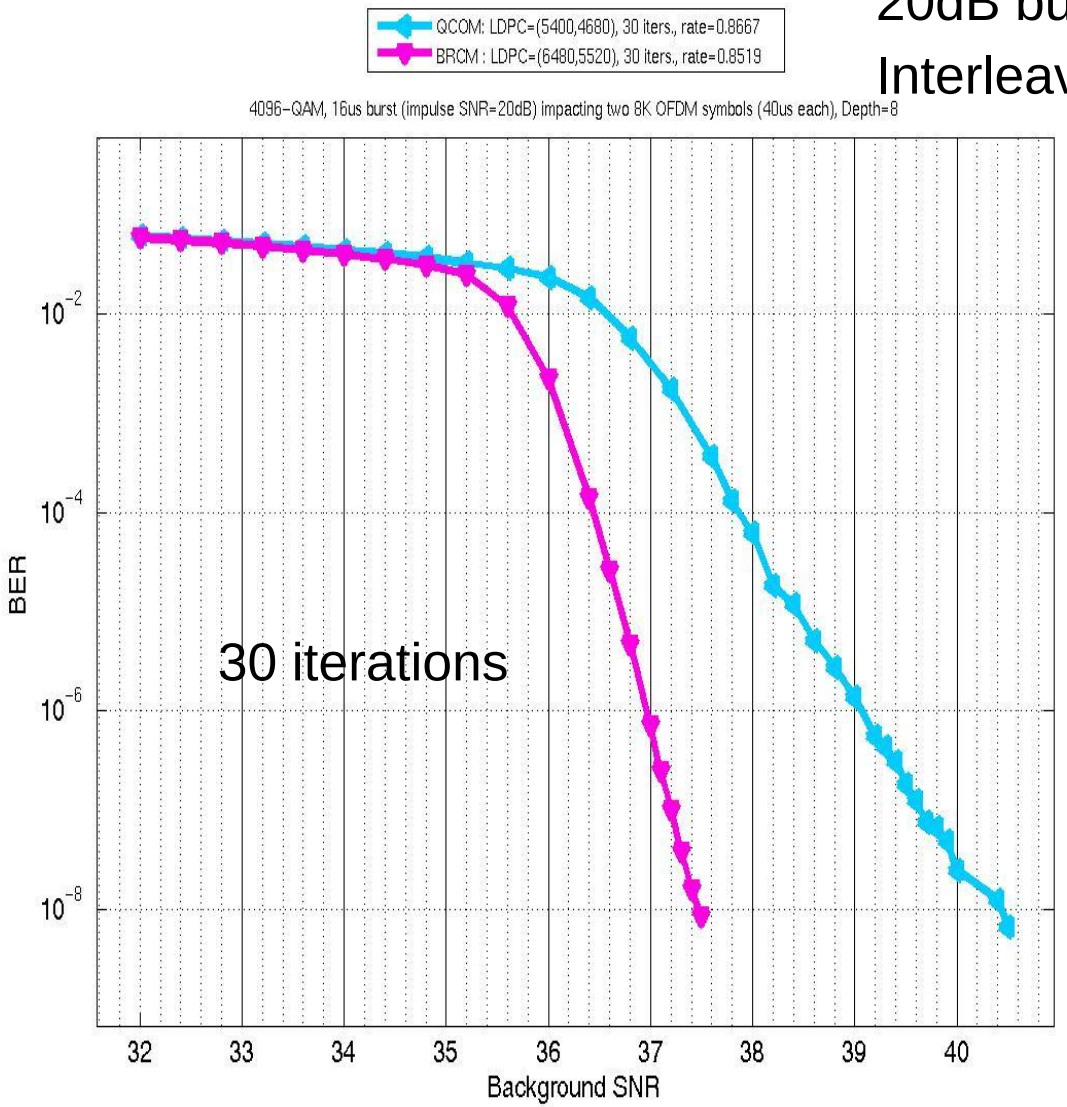


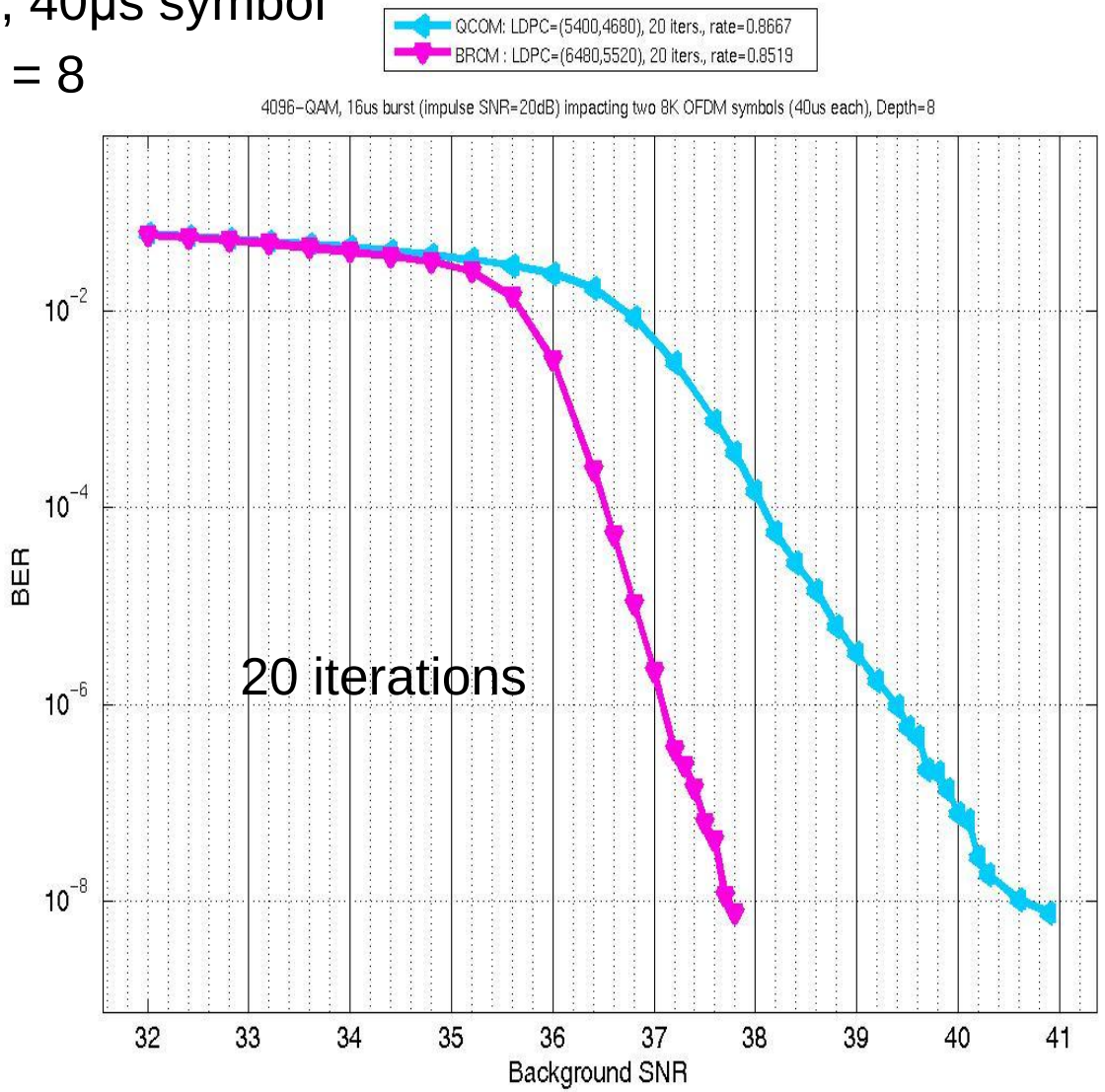


RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

20dB burst SNR, 40µs symbol

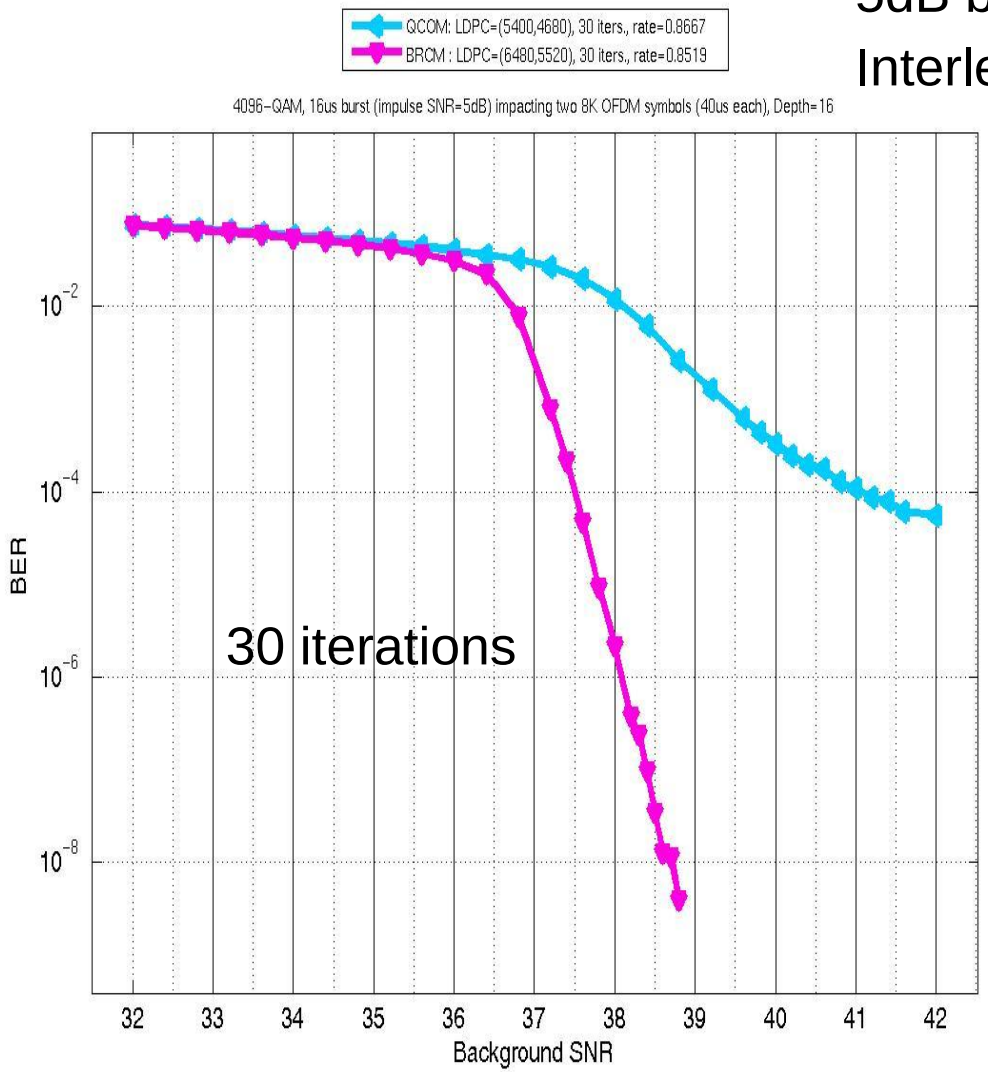
Interleave depth = 8

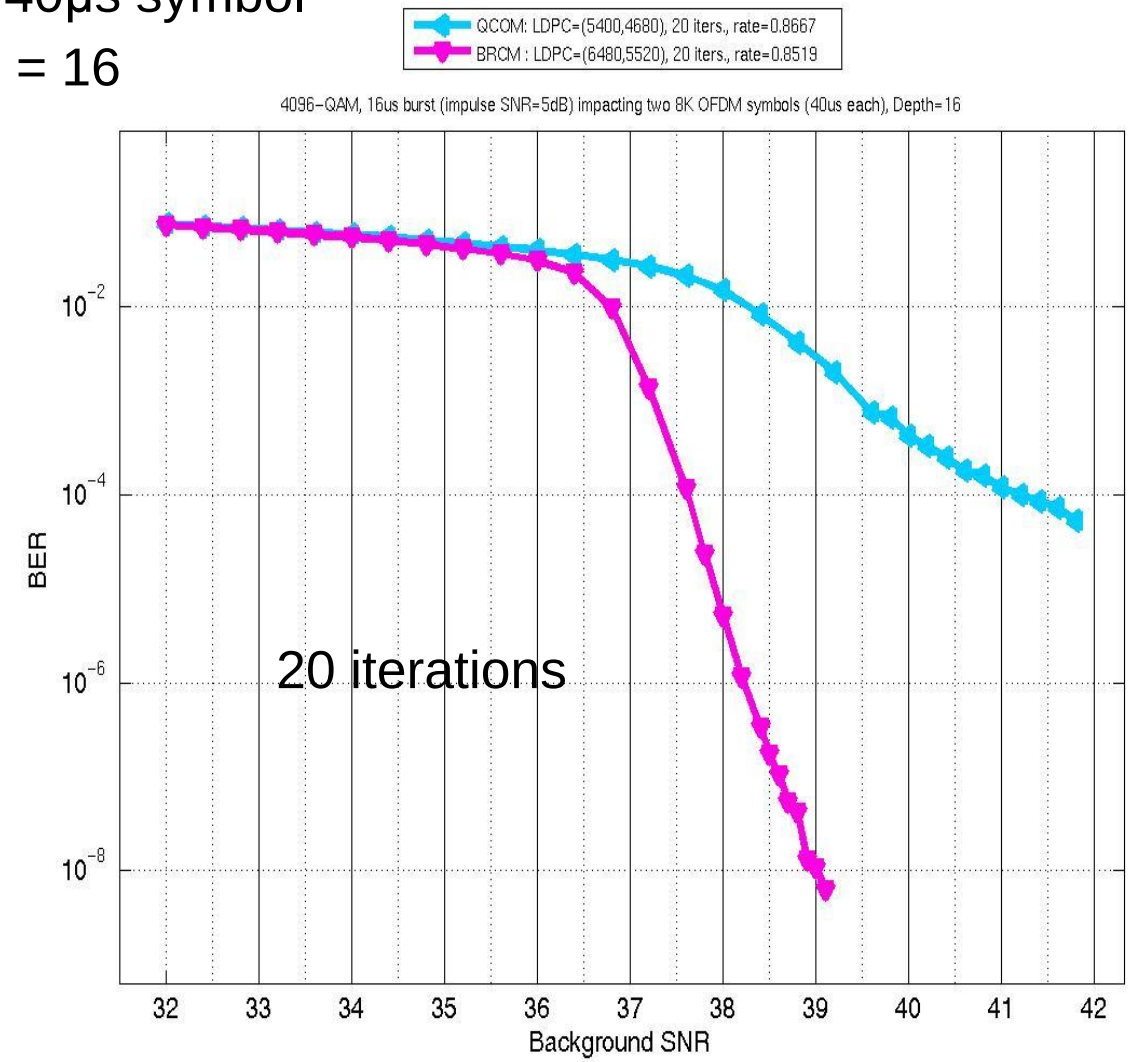




RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

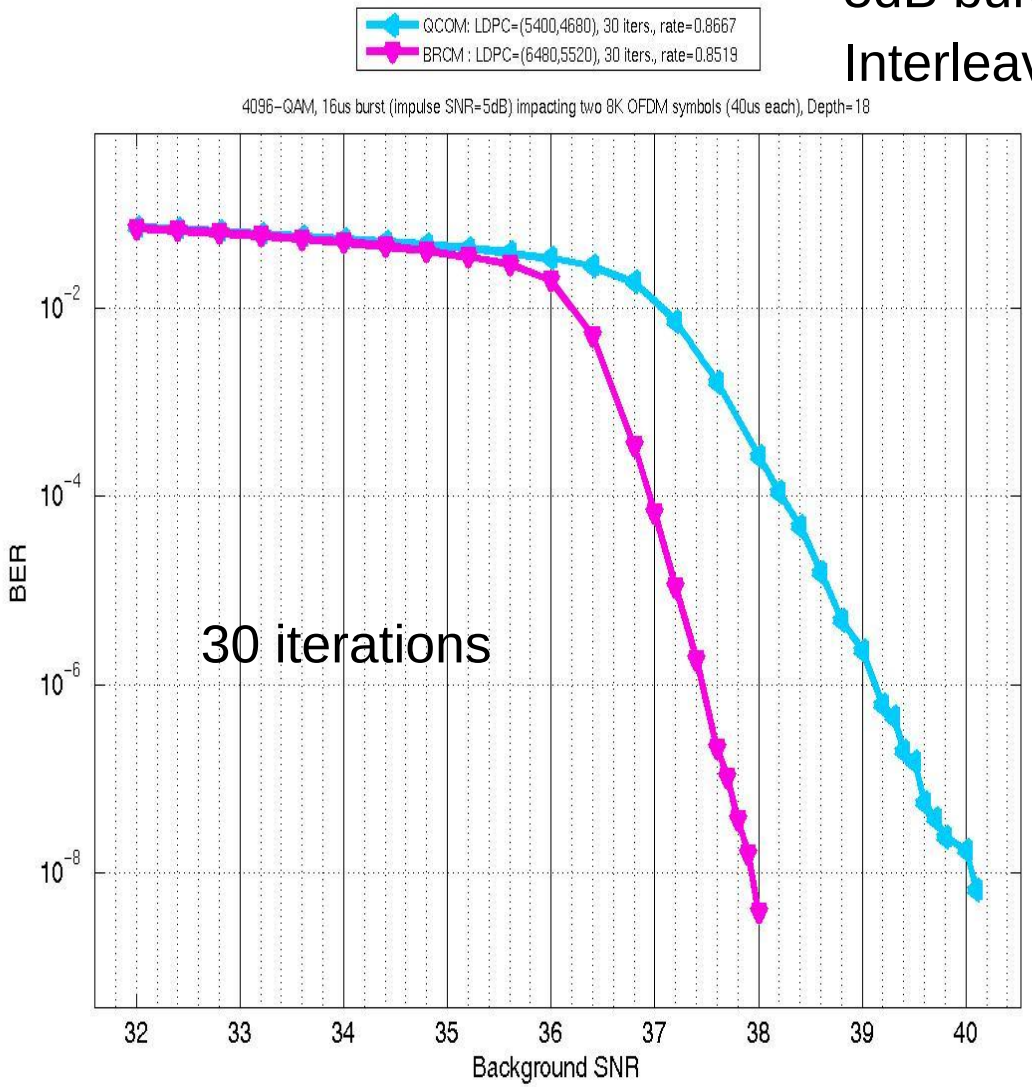
5dB burst SNR, 40µs symbol
Interleave depth = 16

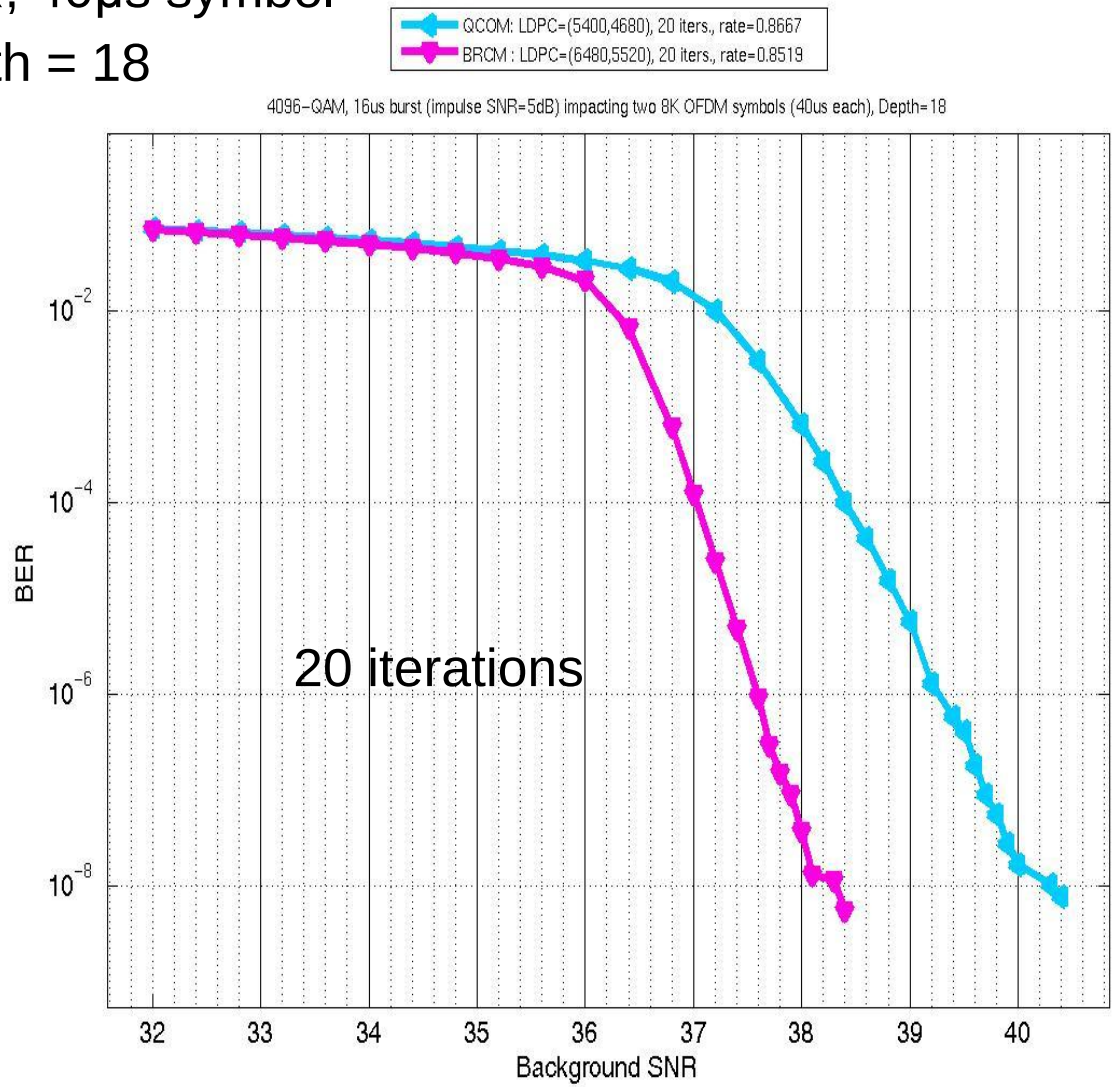




RATE 85% CODES PERFORMANCE CURVES IN IMPULSE NOISE

5dB burst SNR, 40µs symbol
Interleave depth = 18





CONCLUSIONS

- **Broadcom codes are structured to be lower complexity**
  - Broadcom provides a long LDPC code with the same codeword size, the same sub-matrix size, and the same code rate of DVB-C2 LDPC code *without* any outer coding and twisted interleaving that adds complexity
  - Broadcom short and long LDPC codes provide the lowest overall complexity
- **Broadcom codes are the closest to the Channel Capacity limit**
  - As a result when considering spectral efficiency, Broadcom codes perform better in the AWGN channel
- **Broadcom codes perform better in both moderate and strong impulse noise**
  - Lowest interleaver depth (i.e.latency) that meets the target BER of 1e-8
  - Lowest background AWGN SNR at the minimum interleaver depth that meets the target BER of 1e-8

Thank You