

Performance Analysis of EPoC FEC for Passive Coax Plants

Christian Pietsch (Qualcomm)

Stefan Brueck (Qualcomm)

Introduction and Scope

- During the Victoria meeting it was agreed to specify two sets of LDPC codes (prodan_3bn_01_0513.pdf):
 - One code set for passive plants
 - One code set for active plants
- During the Geneva meeting codes were presented:
 - For active plants: `prodan_3bn_01b_0713.pdf`
 - For passive plants: `pietsch_3bn_01_0713.pdf`
- This presentation provides a more detailed performance analysis for the codes for passive plants. This includes AWGN performance and various burst noise scenarios.
- For reasons of self-containedness, this presentation contains the code description. The codes are the same as described in `pietsch_3bn_01_0713.pdf`.

Codes Parameters and Deployment Scenarios

CODES	Rate	Length
A	---	---
B	$R_B = 8/9$	16200
C	$R_C = 0.848$	5940
D	$R_D = 3/4$	1120
E	$R_E = 41/46$	16560
F	$R_F = 26/30$	10800
G	$R_G = 13/15$	5400
H	$R_H = 3/4$	960

DEPLOYMENT	Passive plant	Active plant
US, low band	E, F, G, H	B, C, D
DS, low band	E, F, G, H	---
US, high band	E, F, G, H	---
DS, high band	E, F, G, H	B

Code choice for passive plants:

- Typically, the code with the longest code words (E) will be preferred choice whenever possible, e.g. considering grant size, potential transmission windows, and latency requirements.
- For US transmissions, small grant sizes will entail the use of the shorter codes. Code E may be rarely used in some situations
- For DS transmissions, we will mostly see the use of code E. For TDD, shorter code words are necessary to increase efficiency for short transmission windows.

Code Description

- All LDPC codes for passive plants are quasi-cyclic and binary
- The matrix M to calculate the parity bits has nearly upper diagonal form for all 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
- 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 Codes E and F

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	46			
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	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	.	318	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	42	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	200	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	300	35				

Figure 8: Base code information bits: 41; (max) block length: 46. 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	28	29	30																	
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	1	1	1	1	1	0
183	90	.	.	160	295	.	.	268	240	182	127	.	187	.	.	179	288	.	167	14	327	96	.	215	359	.	.	273	344	261																	
183	0	.	.	276	291	.	.	58	308	348	286	.	4	93	.	171	.	.	171	.	.	207	54	190	352	309	34	223	84	62																	
.	0	61	.	.	184	160	212	235	.	.	.	256	.	39	191	236	303	324	.	.	.	292	.	83	132	189	224	251	142																		
.	.	61	122	351	.	344	51	.	.	267	122	.	284	341	94	335	.	.	256	194	270	.	240	127	351	234	.	202	228																		
.	.	.	122	175	104	.	206	42	.	91	.	198	329	266	.	.	.	284	269	73	192	.	93	1	.	220	197	44	.	266																	

Figure 4: Base code information bits: 26; (max) block length: 30. Lifting: ROTATION SPACE:NESTED CYCLIC:1: 360

Parity Matrices for Codes G and H

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

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	16	.	.	21	9	.	.	33	44	.	.	15	40	4	56	47
0	1	.	.	.	.	.	12	39	42	40	2	.	54	33	32	12
.	1	32	.	.	4	46	50	.	.	44	7	43	47	23	.	48
.	.	32	3	34	.	44	58	8	.	.	54	14	4	.	43	26
.	.	.	3	27	43	41	.	.	38	56	20	20	.	13	16	10

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

Edge Density, Parity Checks and Lifting Size

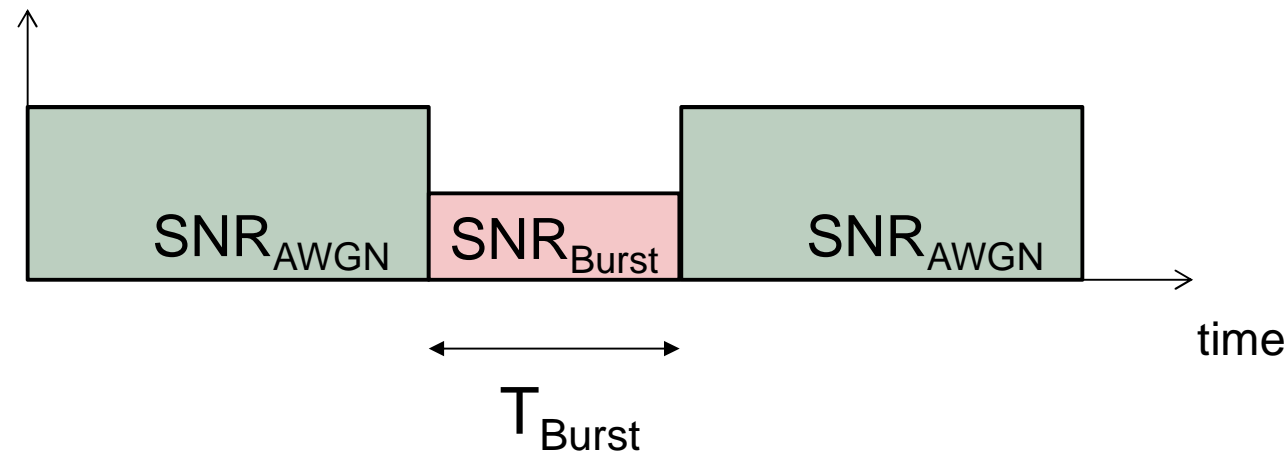
Base n	Base k	Rate	Lifting Z	Information Bits	Code word length	Parity checks	Based edges	Edge density
46	41	0.8913	360	14760	16560	2160	154	3.348
30	26	0.8667	360	9360	10800	1800	98	3.267
15	13	0.8667	360	4680	5400	1080 (1440)	54 (56)	3.6 (3.73)
16	12	0.75	60	720	960	300	53	3.3125

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 metric of interest is a bit error rate (BER) of $1\text{e-}8$
 - A BER of $1\text{e-}8$ corresponds roughly to a frame error rate of $1\text{e-}6$

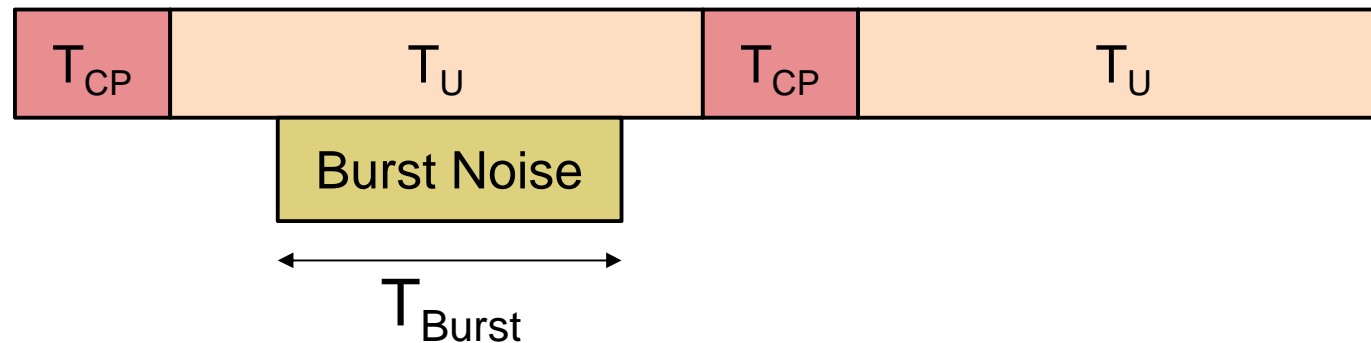
Burst Noise in OFDM

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



- 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

$$SNR = -10 \text{Log}_{10} \left(10^{\left(\frac{-SNR_{BE}}{10}\right)} + 10^{\left(\frac{-SNR_{AE}}{10}\right)} \right)$$

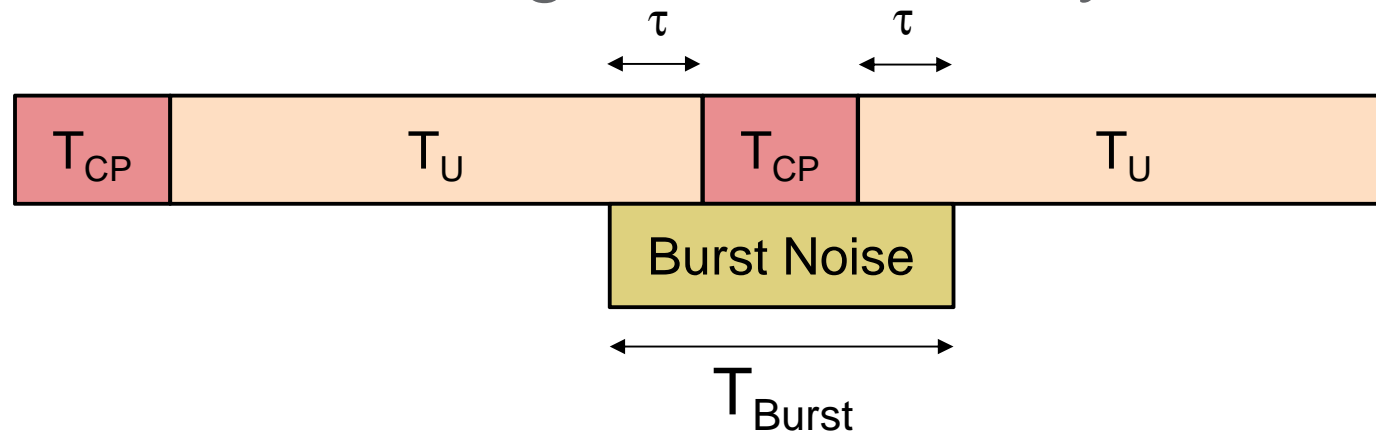
Burst Effective SNR: $SNR_{BE} = SNR_{Burst} - 10 \text{Log}_{10} \left(\frac{T_{Burst}}{T_U} \right)$

AWGN Effective SNR: $SNR_{AE} = SNR_{AWGN} - 10 \text{Log}_{10} \left(1 - \frac{T_{Burst}}{T_U} \right)$

- 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

$$SNR = -10 \text{Log}_{10} \left(10^{\left(\frac{-SNR_{BE}}{10}\right)} + 10^{\left(\frac{-SNR_{AE}}{10}\right)} \right)$$

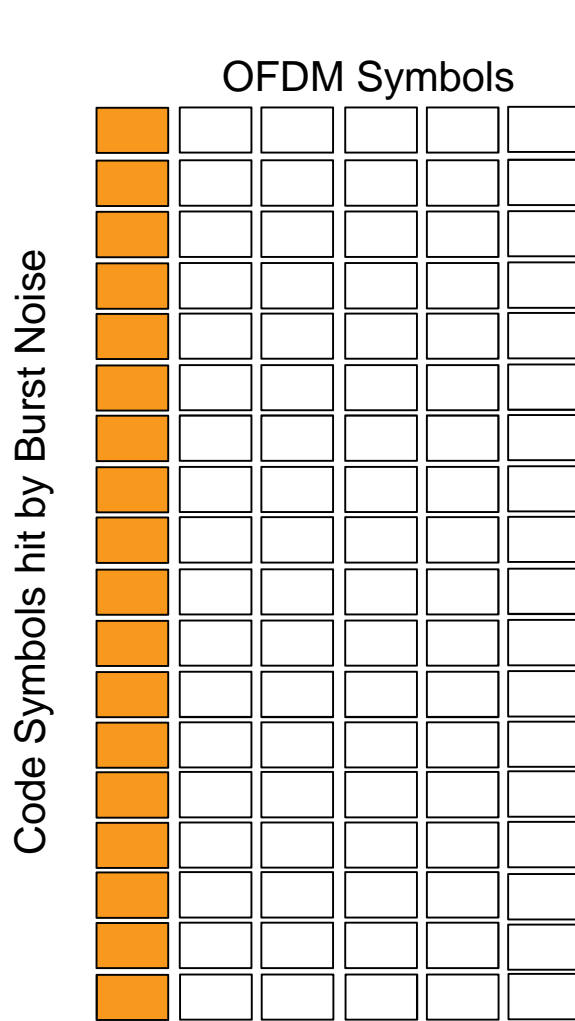
Burst Effective SNR: $SNR_{BE} = SNR_{Burst} - 10 \text{Log}_{10} \left(0.5 \left(\frac{T_{Burst} - T_{CP}}{T_U} \right) \right)$

AWGN Effective SNR: $SNR_{AE} = SNR_{AWGN} - 10 \text{Log}_{10} \left(1 - 0.5 \left(\frac{T_{Burst} - T_{CP}}{T_U} \right) \right)$

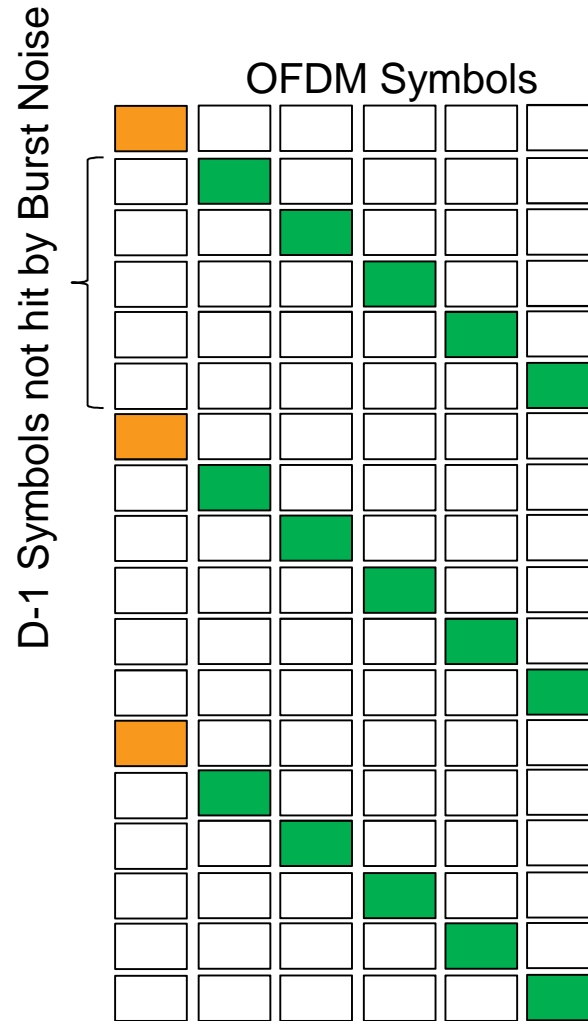
- Effective SNR in OFDM symbols not hit by burst noise

$$SNR = SNR_{AWGN}$$

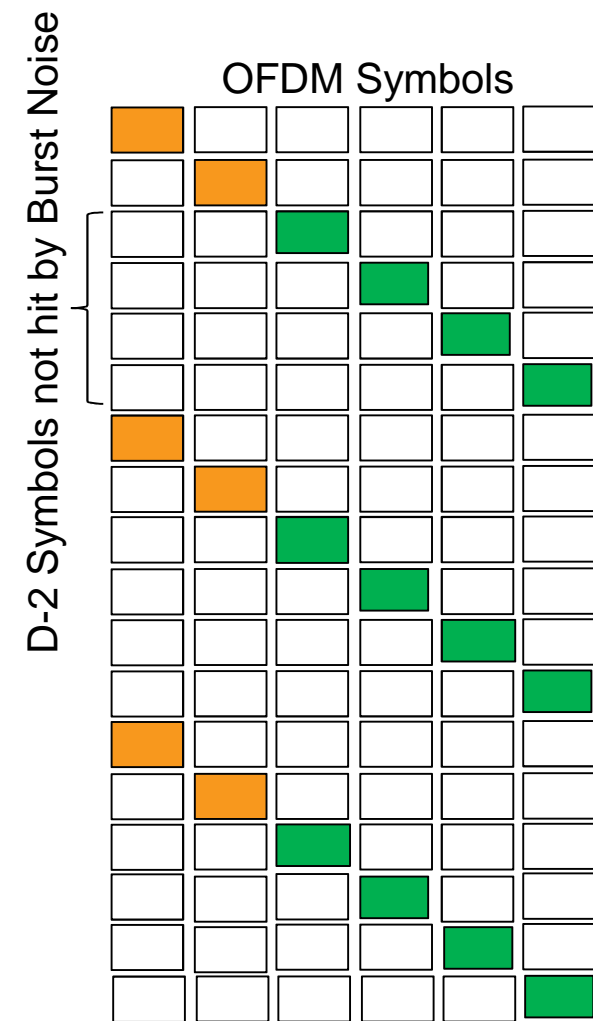
Frequency Domain View of Time Interleaving Depth D



Burst Noise
w/o Time Interleaving



Burst noise affecting one
OFDM symbol w/ Depth $D = 6$

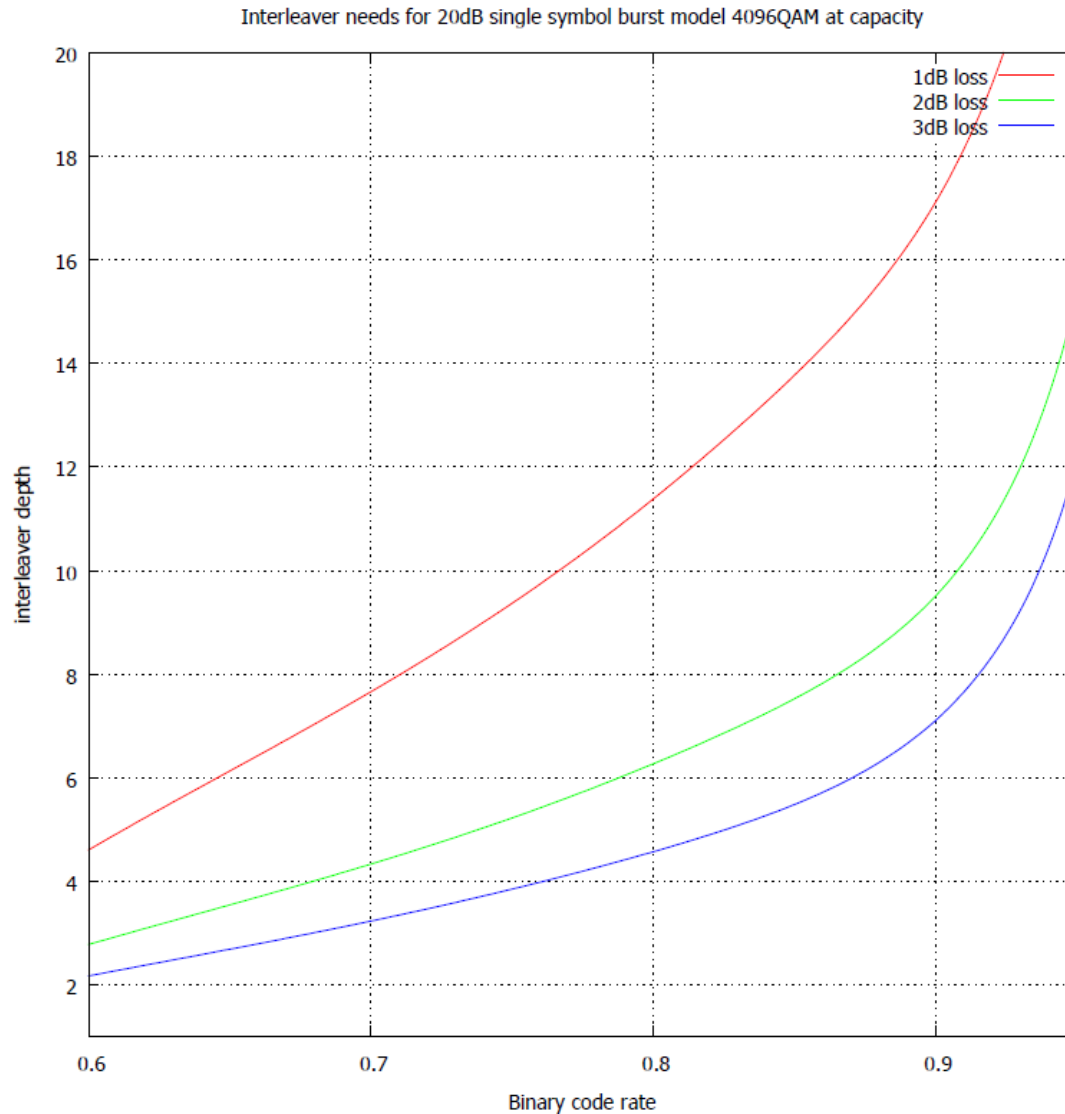


Burst noise affecting two
OFDM symbols w/ Depth $D = 6$

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 too 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. $D \sim 1 / (1 - R)$
 - See backup for analysis

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

Simulation Assumptions

■ Downstream

- 4096QAM
- OFDM symbol durations $T_U = 20 \mu\text{s}$ and $T_U = 40 \mu\text{s}$
- Cyclic prefix length $T_{CP} = 2.5 \mu\text{s}$
- Burst noise
 - a) $T_{\text{Burst}} = 16 \mu\text{s}$, $\text{SNR}_{\text{Burst}} = 20 \text{ dB}$ equally affecting two OFDM symbols

■ Upstream

- 1024QAM
- OFDM symbol durations $T_U = 20 \mu\text{s}$ and $T_U = 40 \mu\text{s}$
- Cyclic prefix length $T_{CP} = 2.5 \mu\text{s}$
- Burst noise
 - a) $T_{\text{Burst}} = 1 \mu\text{s}$, $\text{SNR}_{\text{Burst}} = 0 \text{ dB}$ affecting one OFDM symbol only
 - b) $T_{\text{Burst}} = 10 \mu\text{s}$, $\text{SNR}_{\text{Burst}} = 10 \text{ dB}$ equally affecting two OFDM symbols

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
- Simulation methodology according to [prodan_3bn_02_0313.pdf](#)

Required Interleaving Depths for Burst Noise – I/II

- The table shows the required time interleaving depths to achieve WER = $1e-6$ and BER = $1e-8$ and OFDM symbol duration $20 \mu\text{s}$
 - The simulation results in the following slides assume these interleaving depths

Interleaving Depths for $20 \mu\text{s}$ OFDM Symbol Duration

Burst Model / FEC	Long Code Length = 16560	Medium Code I Length = 10800	Medium Code II Length = 5400	Short Code Length = 960
Downstream Model a)	D = 17			
Upstream Model a)		D = 17	D = 17	D = 17
Upstream Model b)		D = 17	D = 17	D = 17

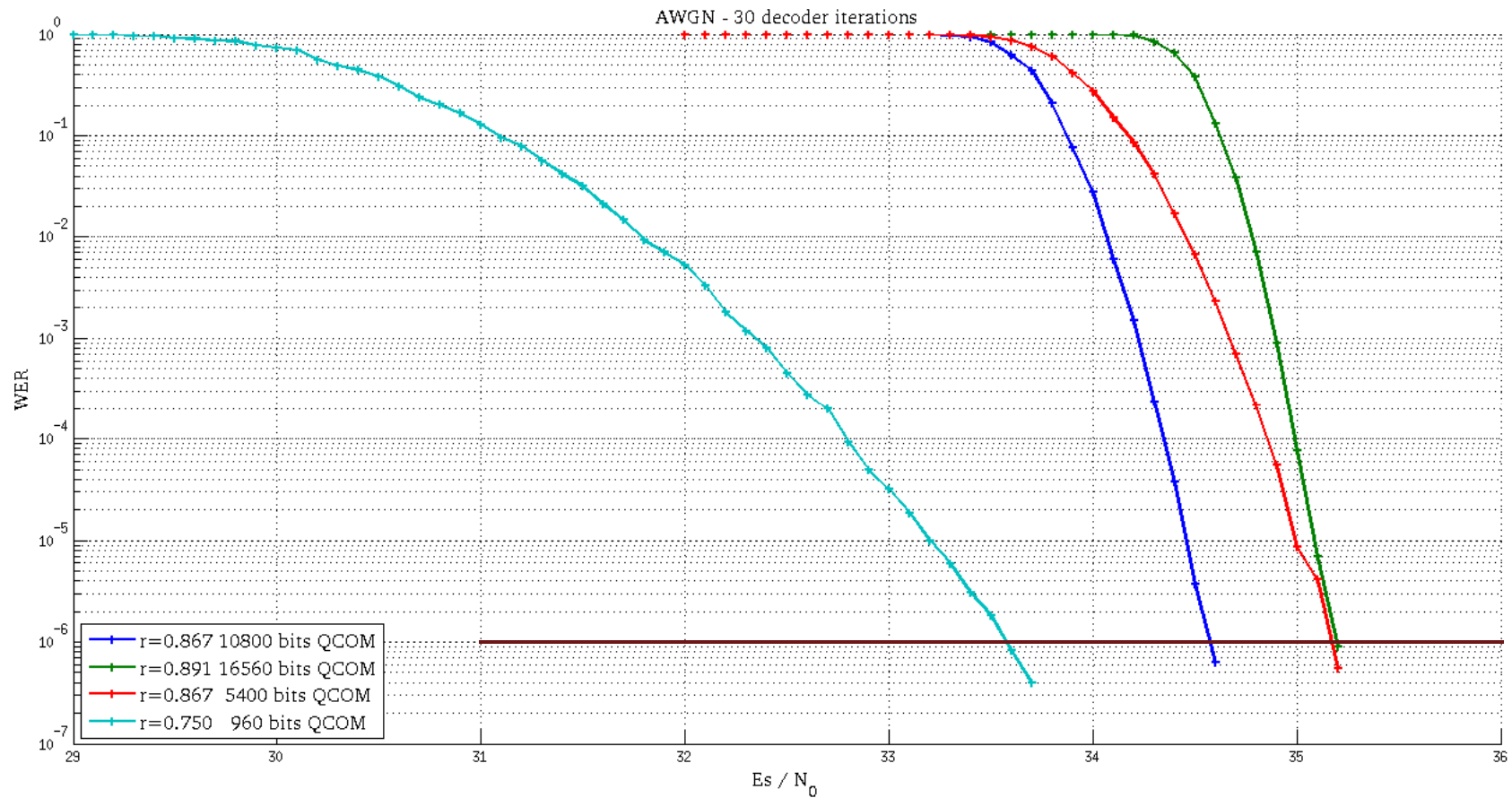
Required Interleaving Depths for Burst Noise – II/II

- The table shows the required time interleaving depths to achieve WER = $1e-6$ and BER = $1e-8$ and OFDM symbol duration $40 \mu\text{s}$
 - The simulation results in the following slides assume these interleaving depths

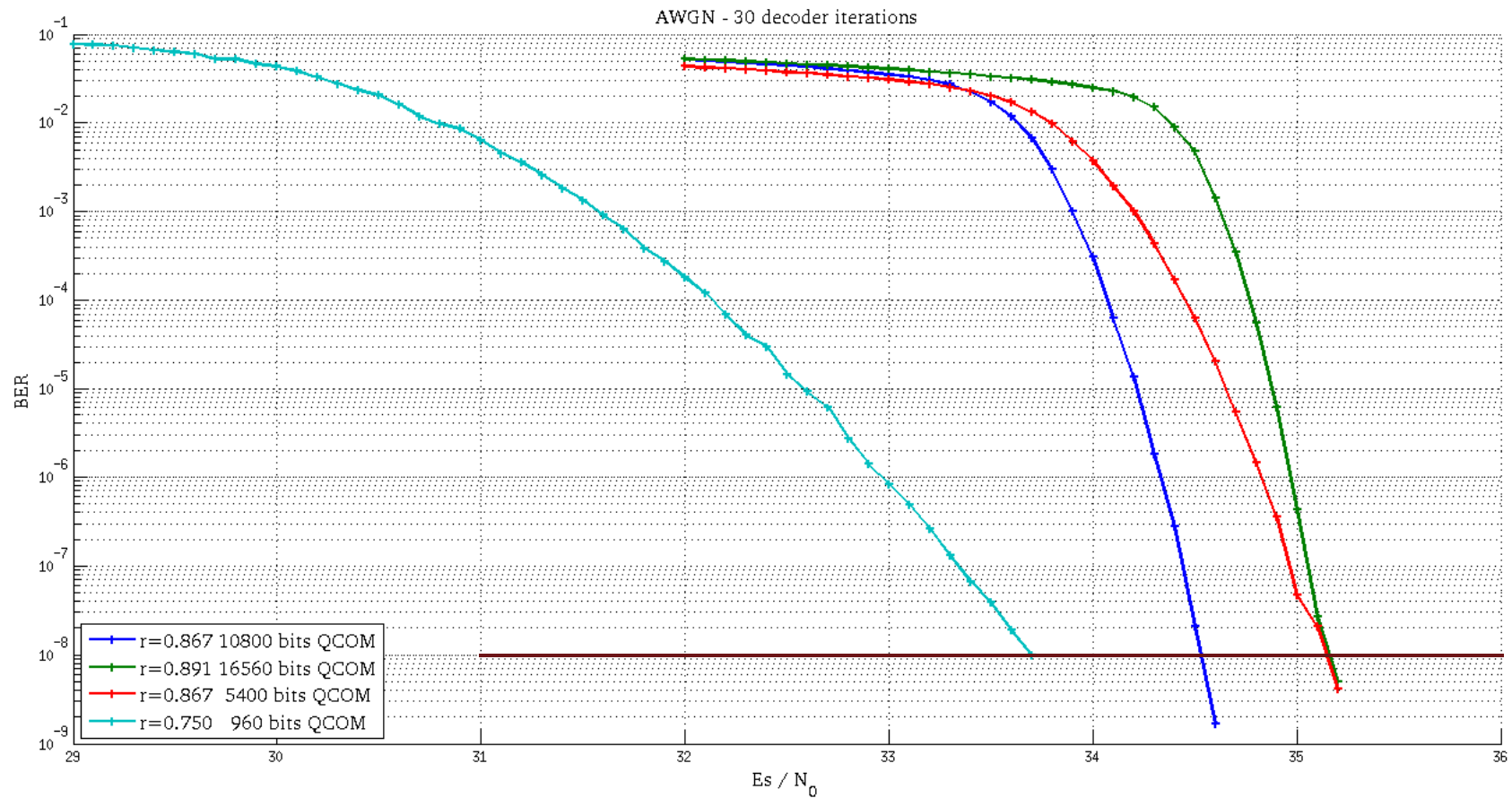
Interleaving Depths for $40 \mu\text{s}$ OFDM Symbol Duration

Burst Model / FEC	Long Code Length = 16560	Medium Code I Length = 10800	Medium Code II Length = 5400	Short Code Length = 960
Downstream Model a)	D = 9			
Upstream Model a)		D = 8	D = 8	D = 8
Upstream Model b)		D = 10		D = 8

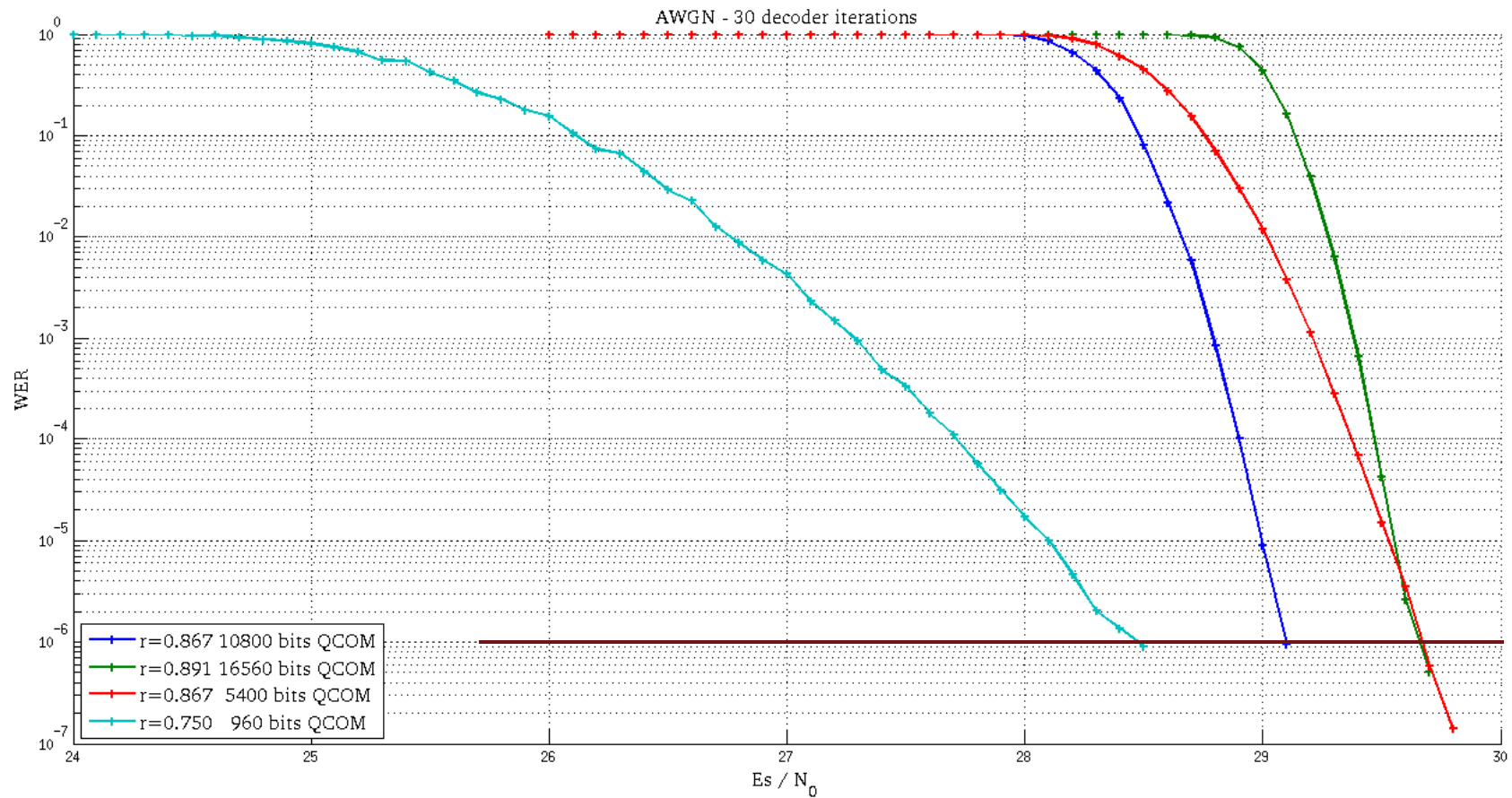
AWGN Performance for 4096QAM – WER



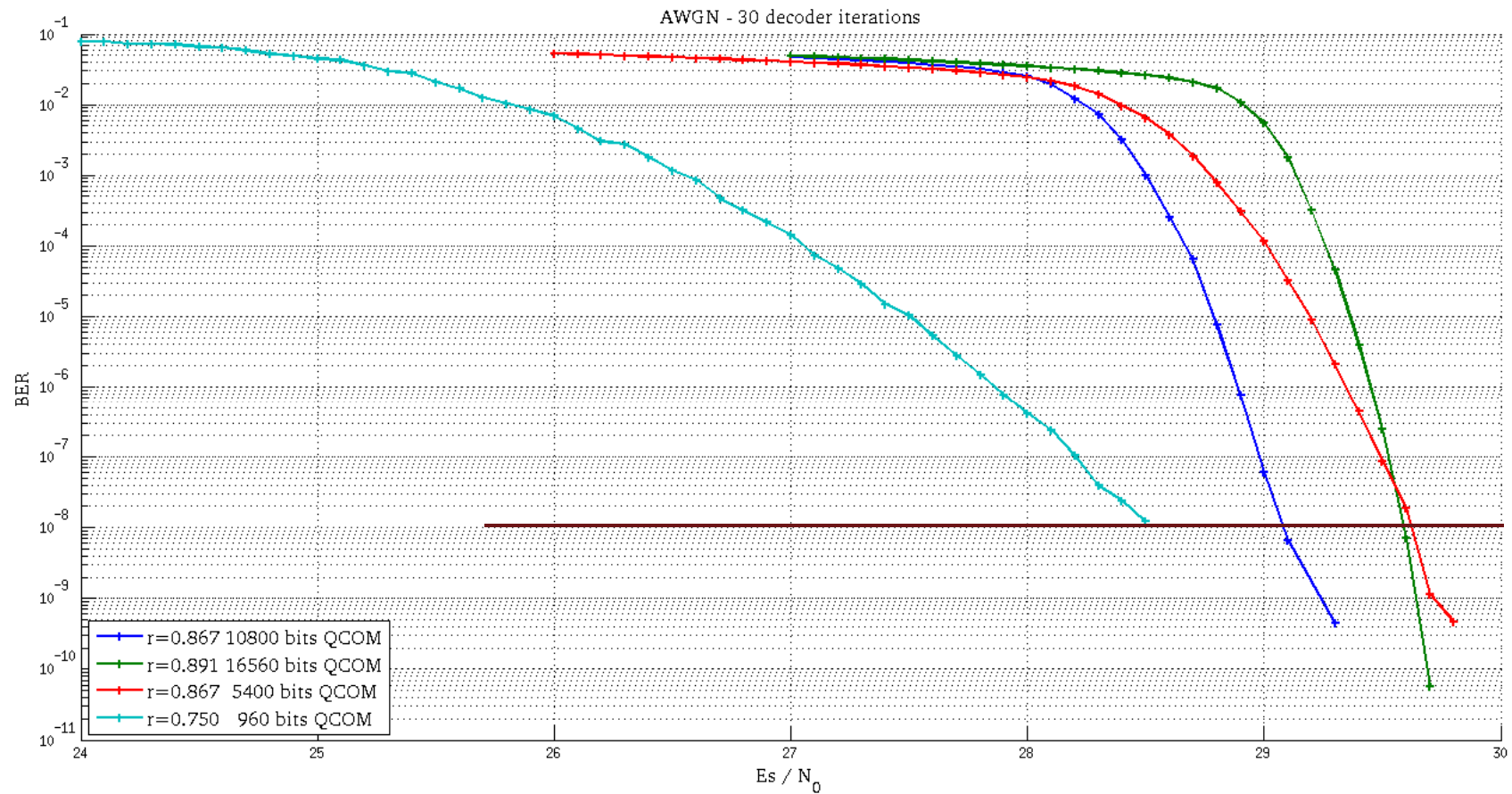
AWGN Performance for 4096QAM – BER



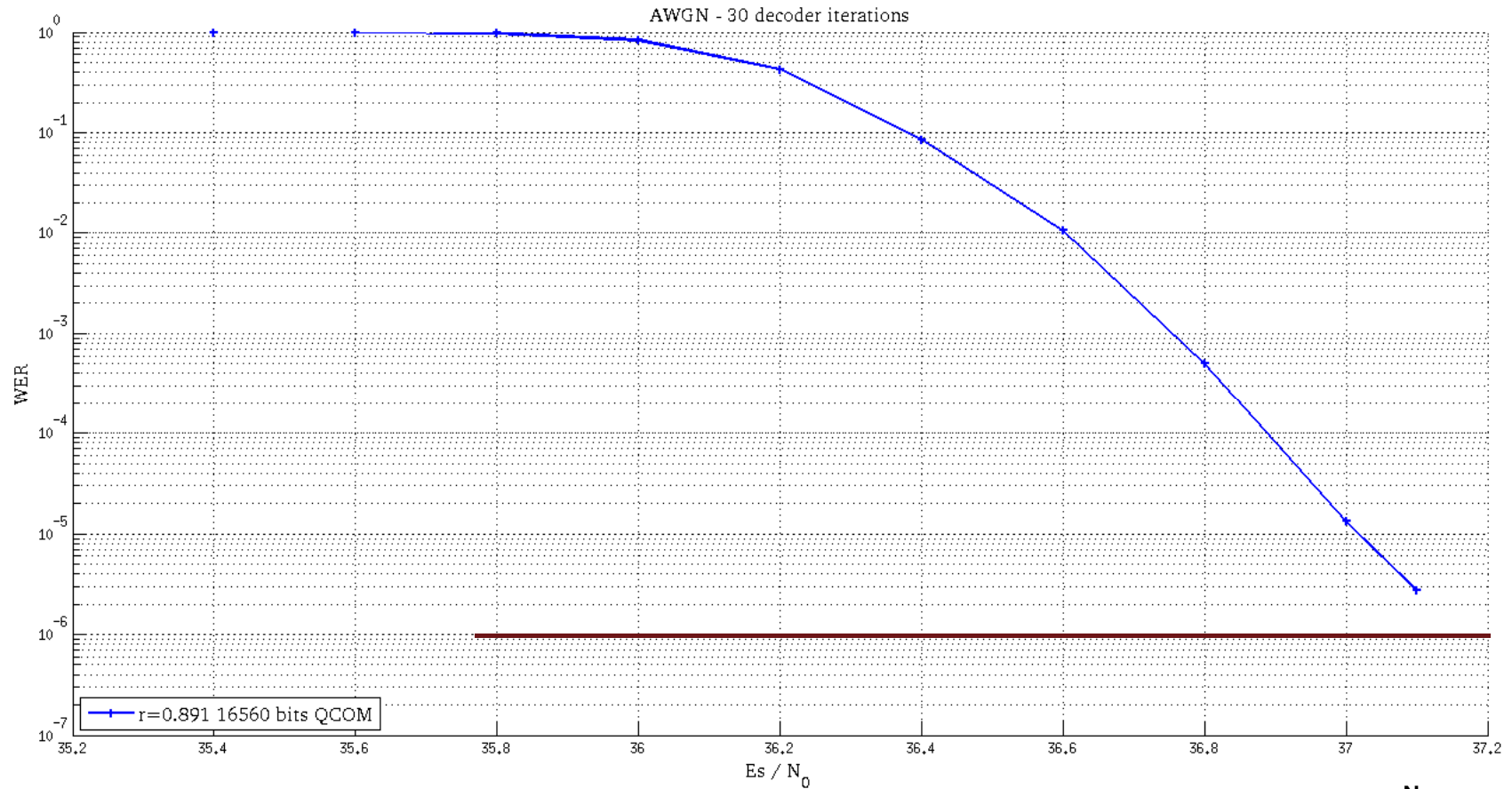
AWGN Performance for 1024QAM – WER



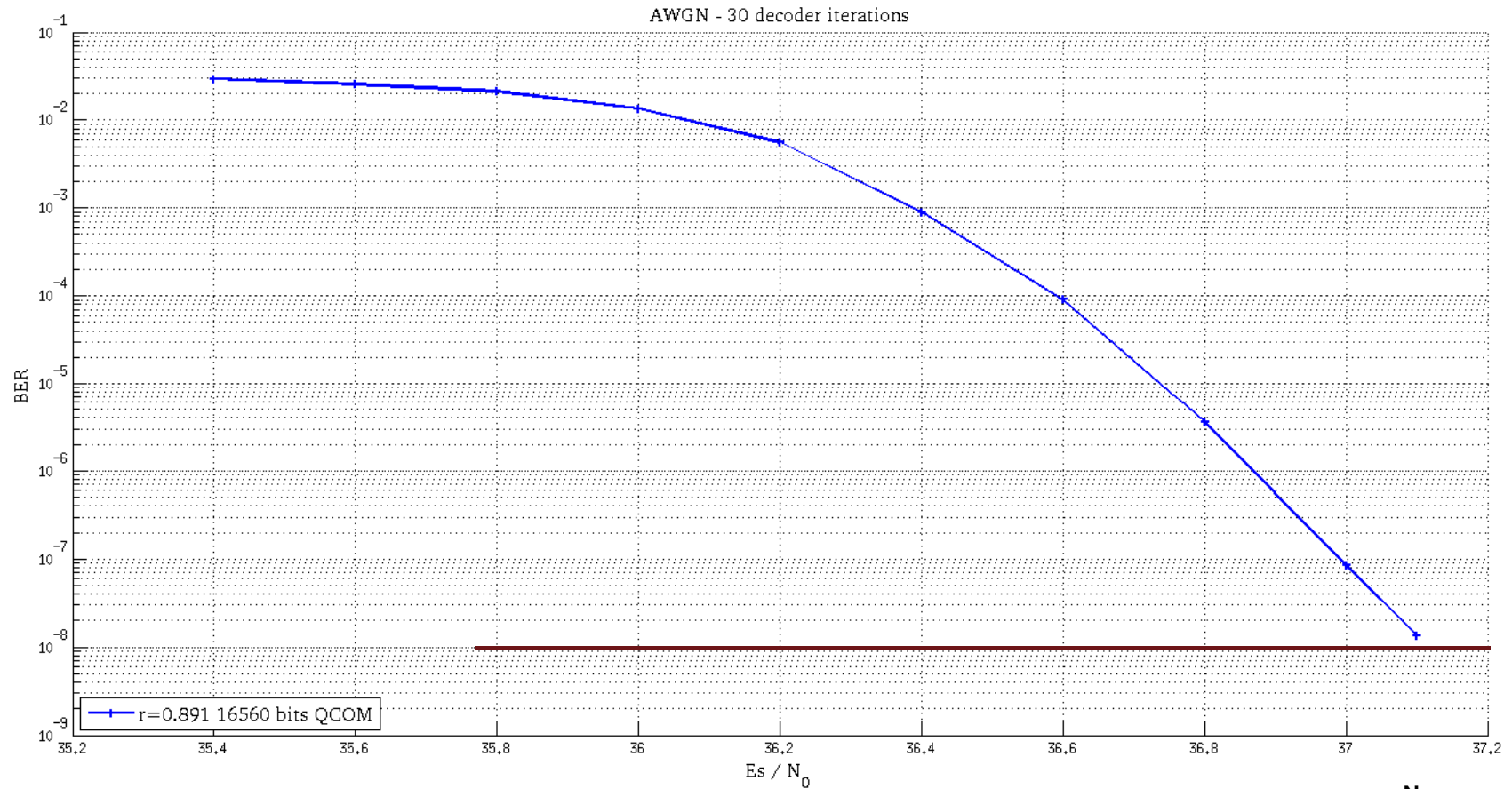
AWGN Performance for 1024QAM – BER



DS Burst Model a) – WER, 20 μ s Symbol Duration

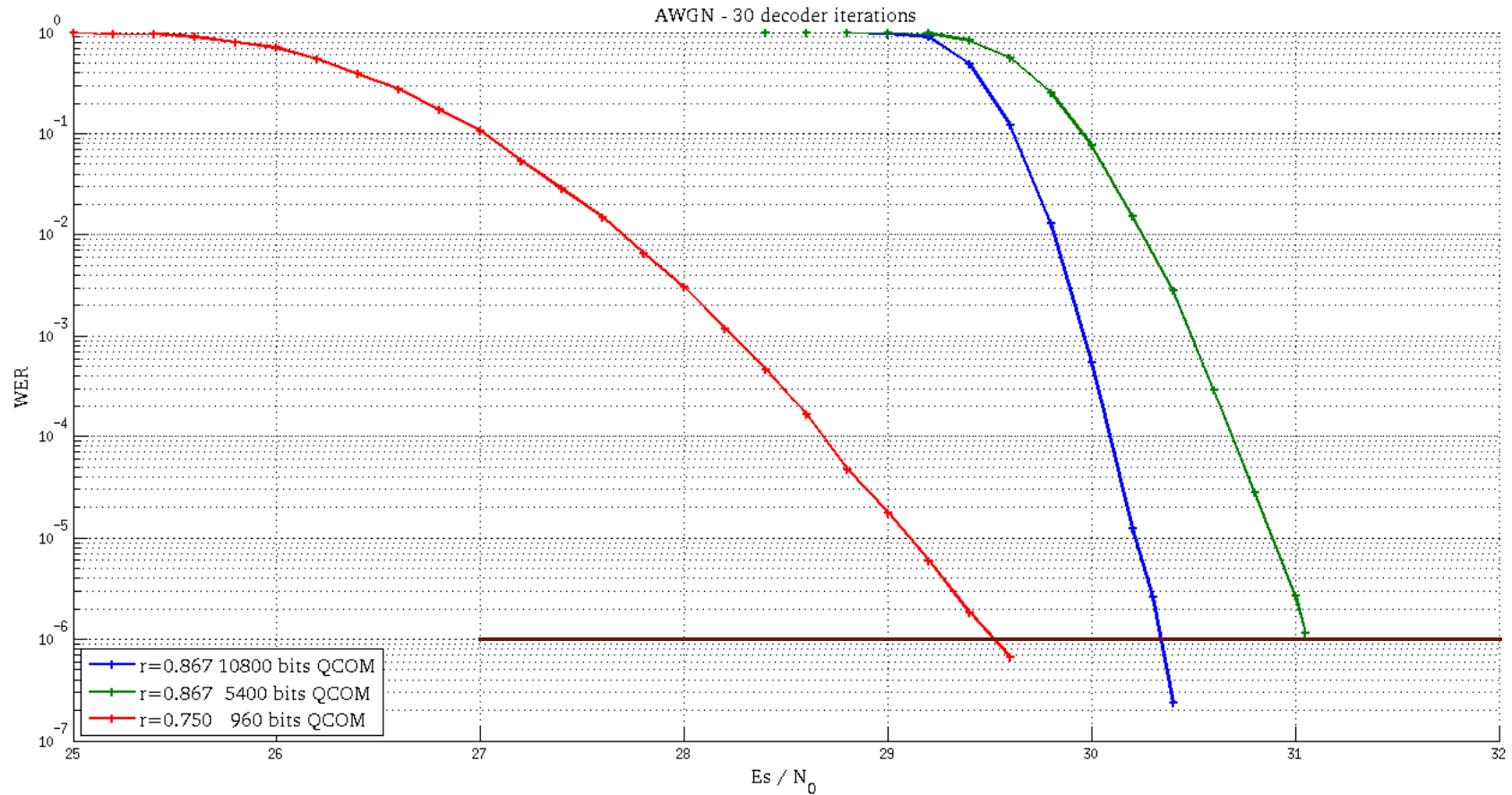


DS Burst Model a) – BER, 20 μ s Symbol Duration

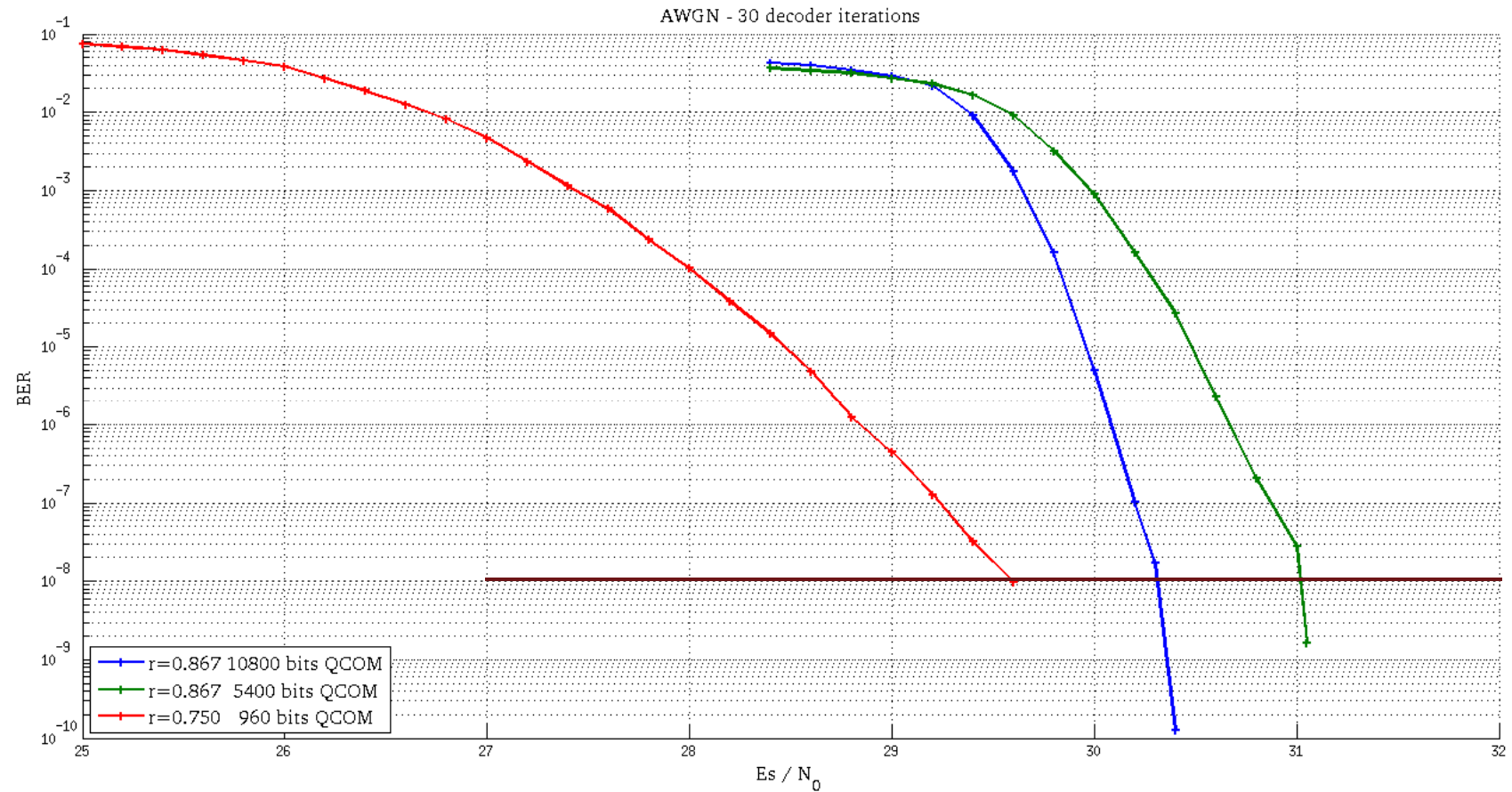


No error events yet
at 37.2 dB

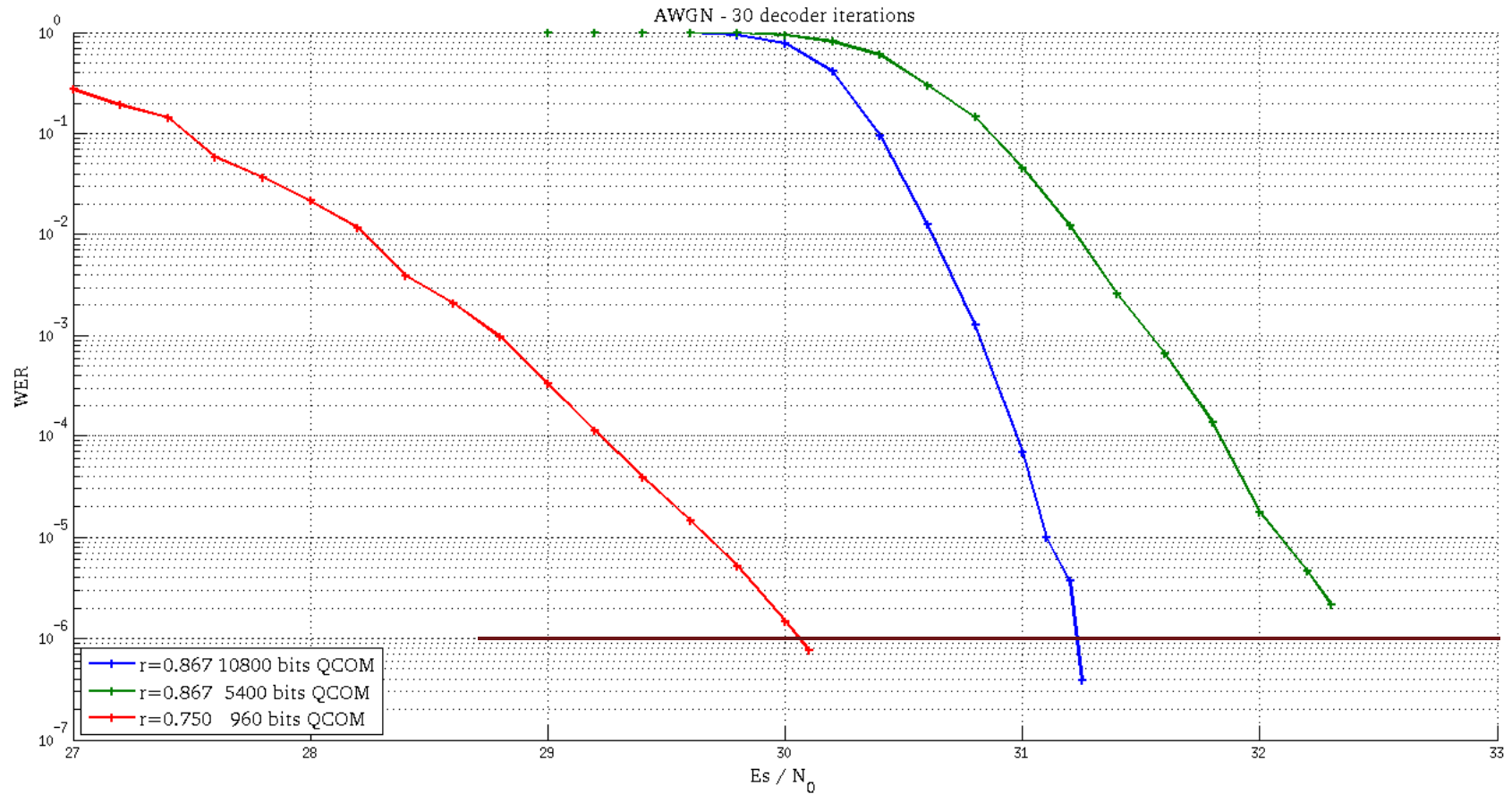
US Burst Model a) – WER, 20 μ s Symbol Duration



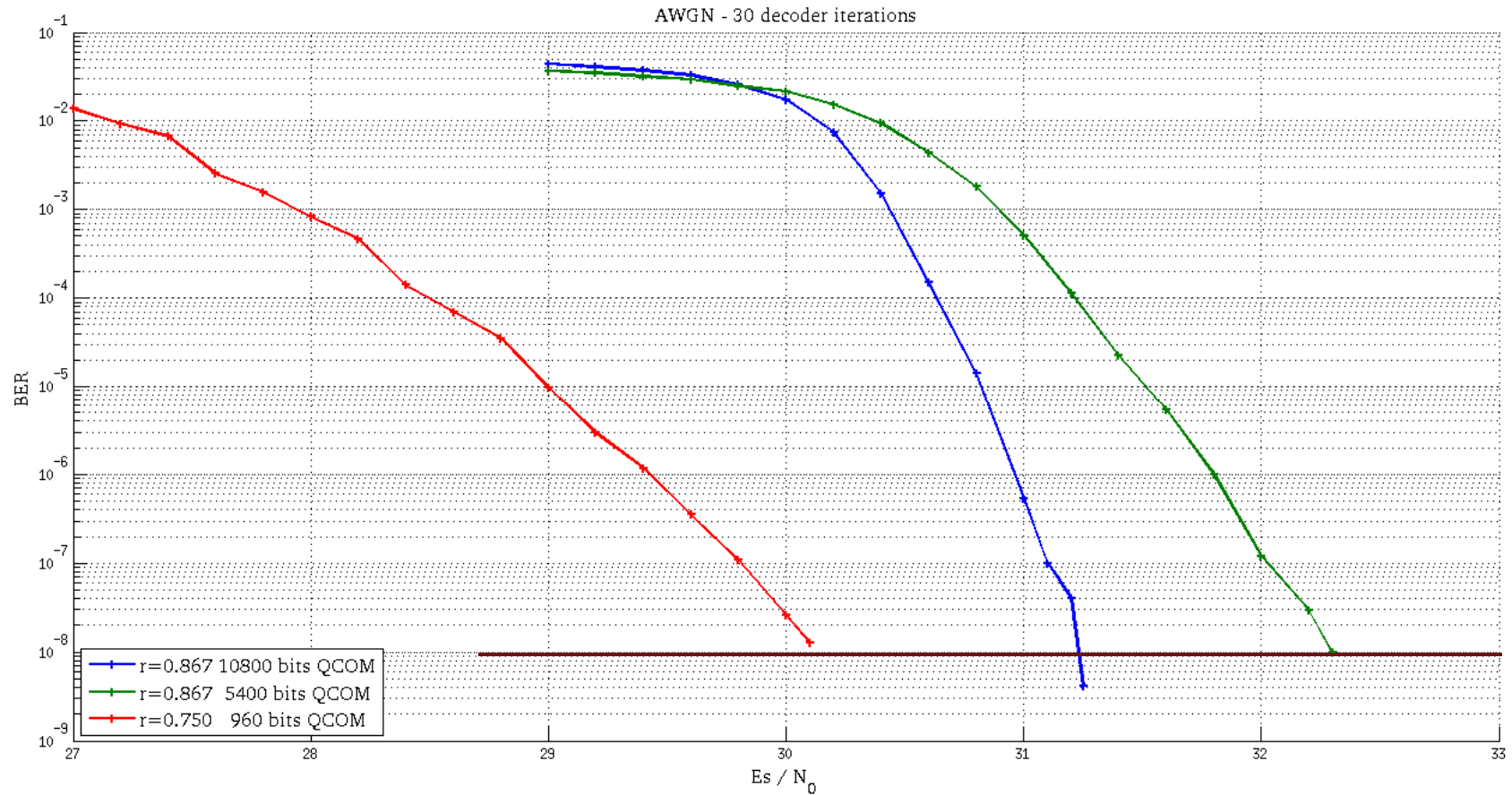
US Burst Model a) – BER, 20 μ s Symbol Duration



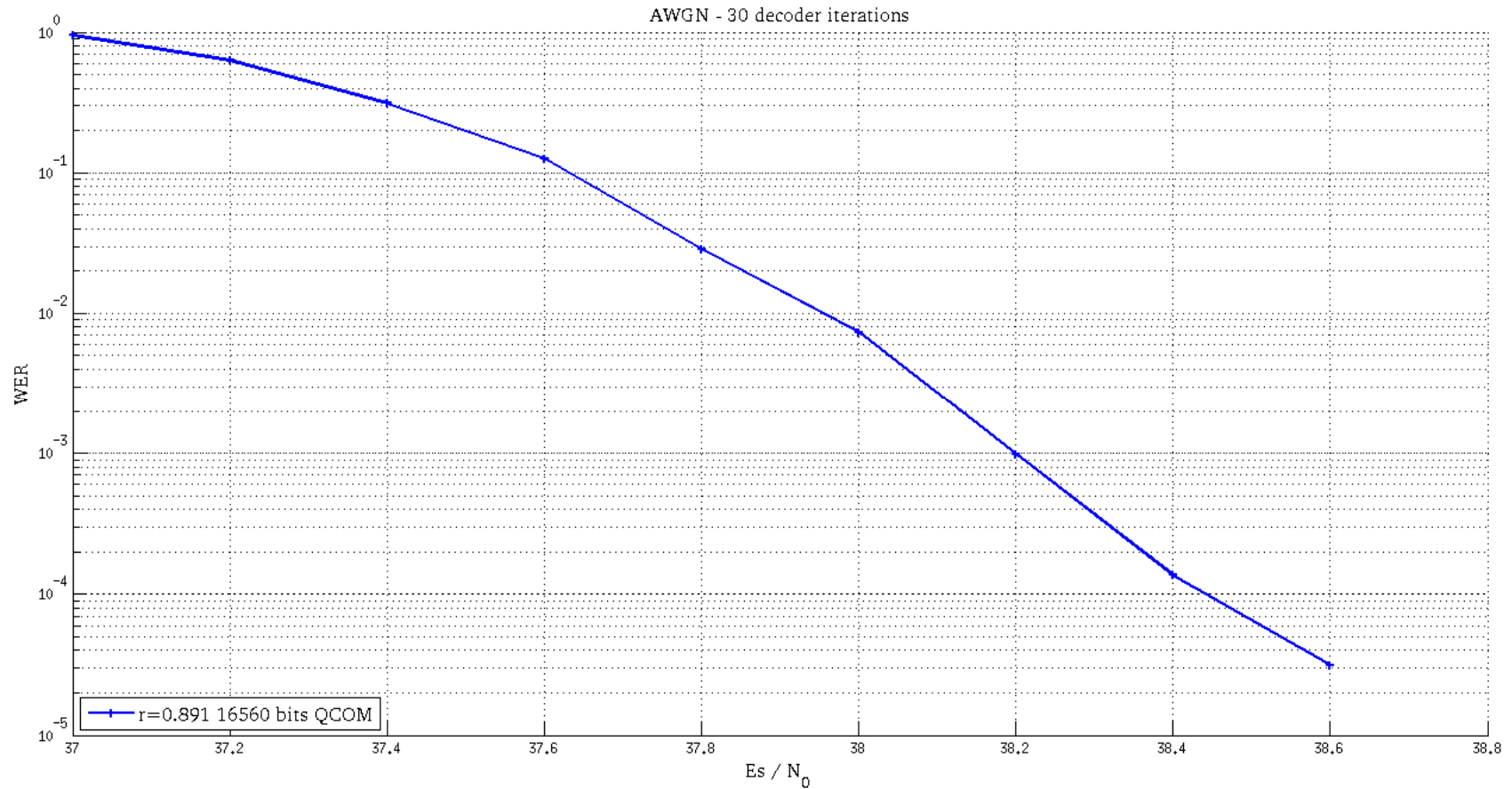
US Burst Model b) – WER, 20 μ s Symbol Duration



US Burst Model b) – BER, 20 μ s Symbol Duration

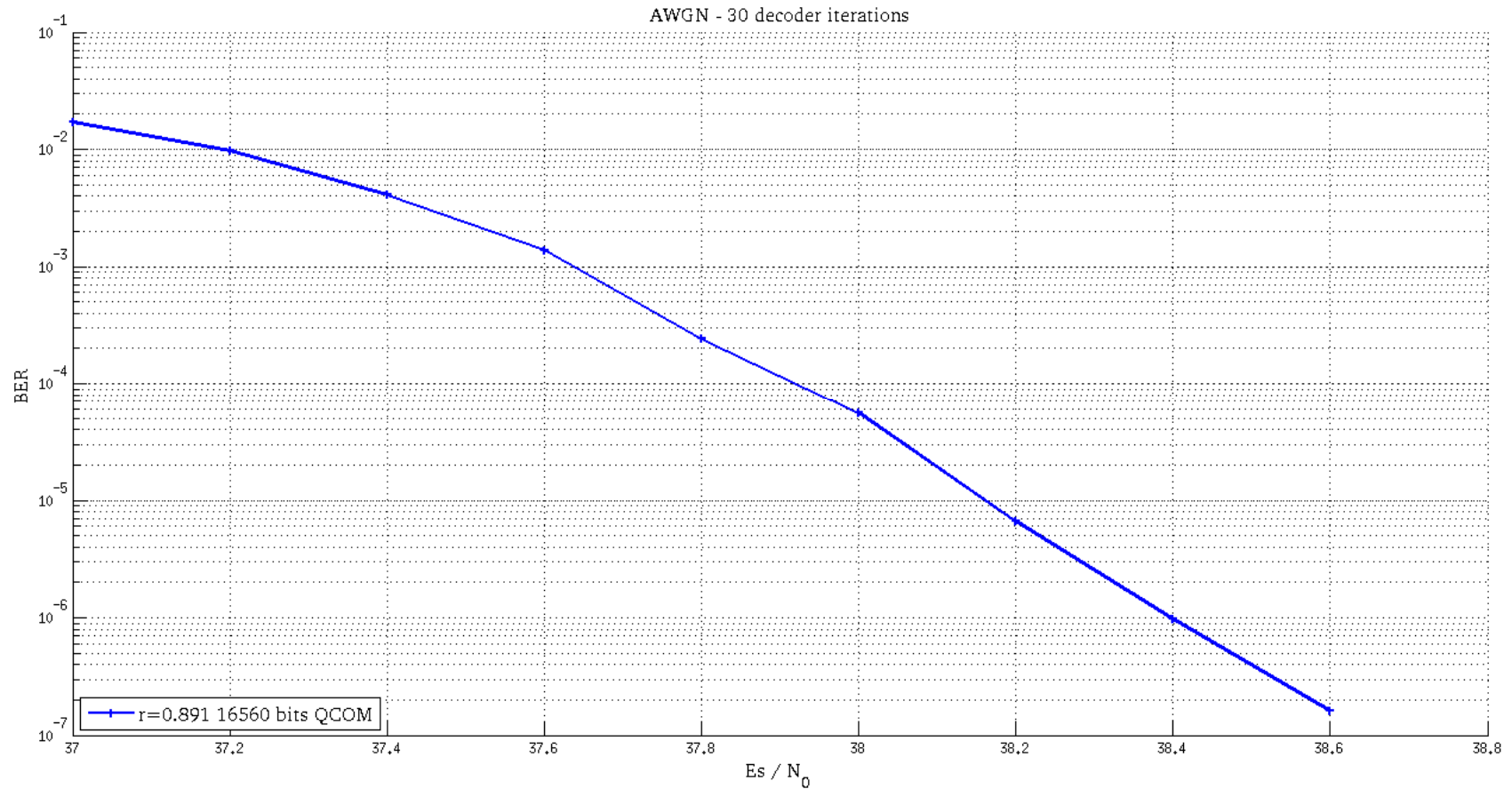


DS Burst Model a) – WER, 40 μ s Symbol Duration



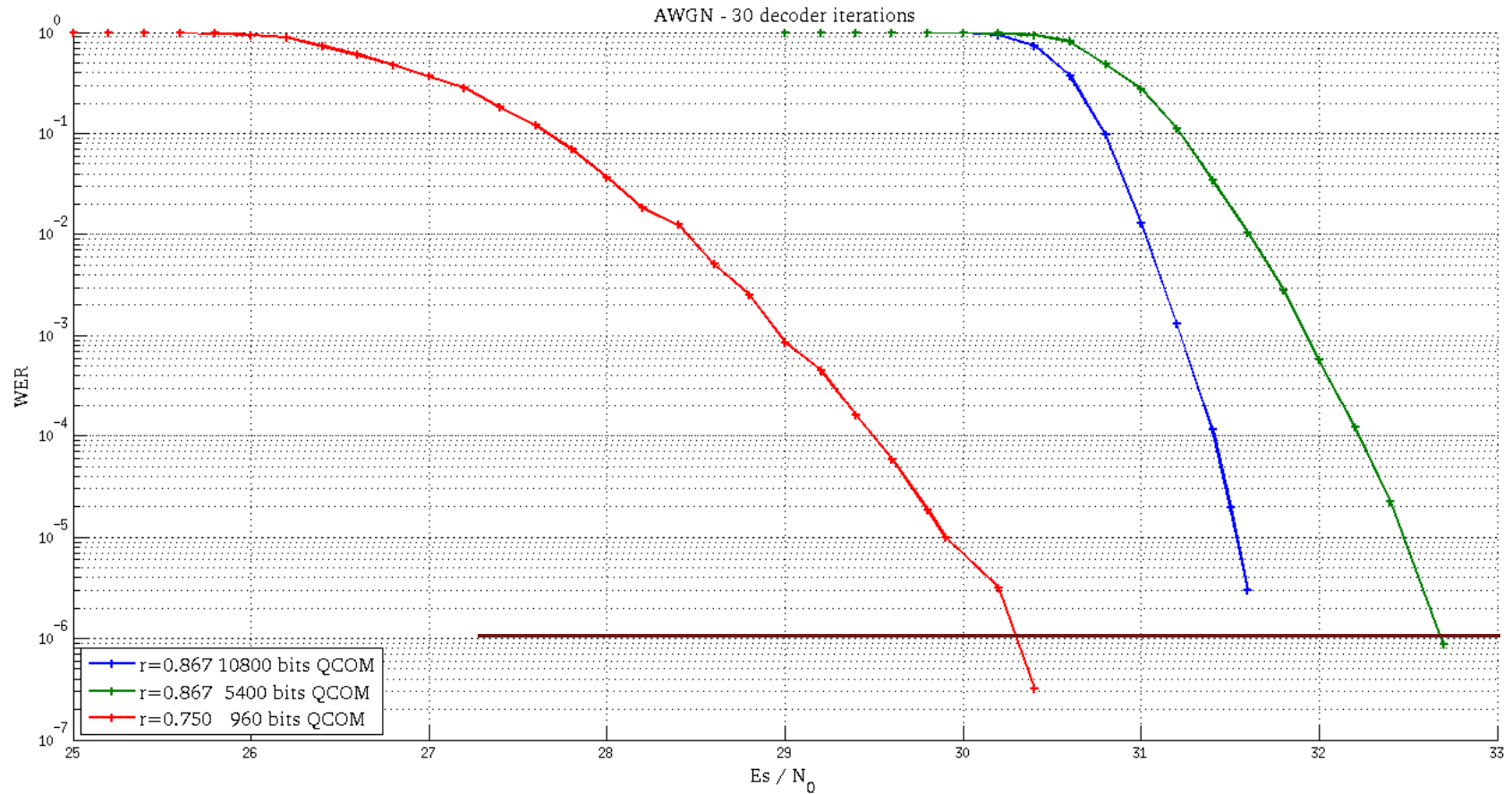
Simulation not yet completed

DS Burst Model a) – BER, 40 μ s Symbol Duration

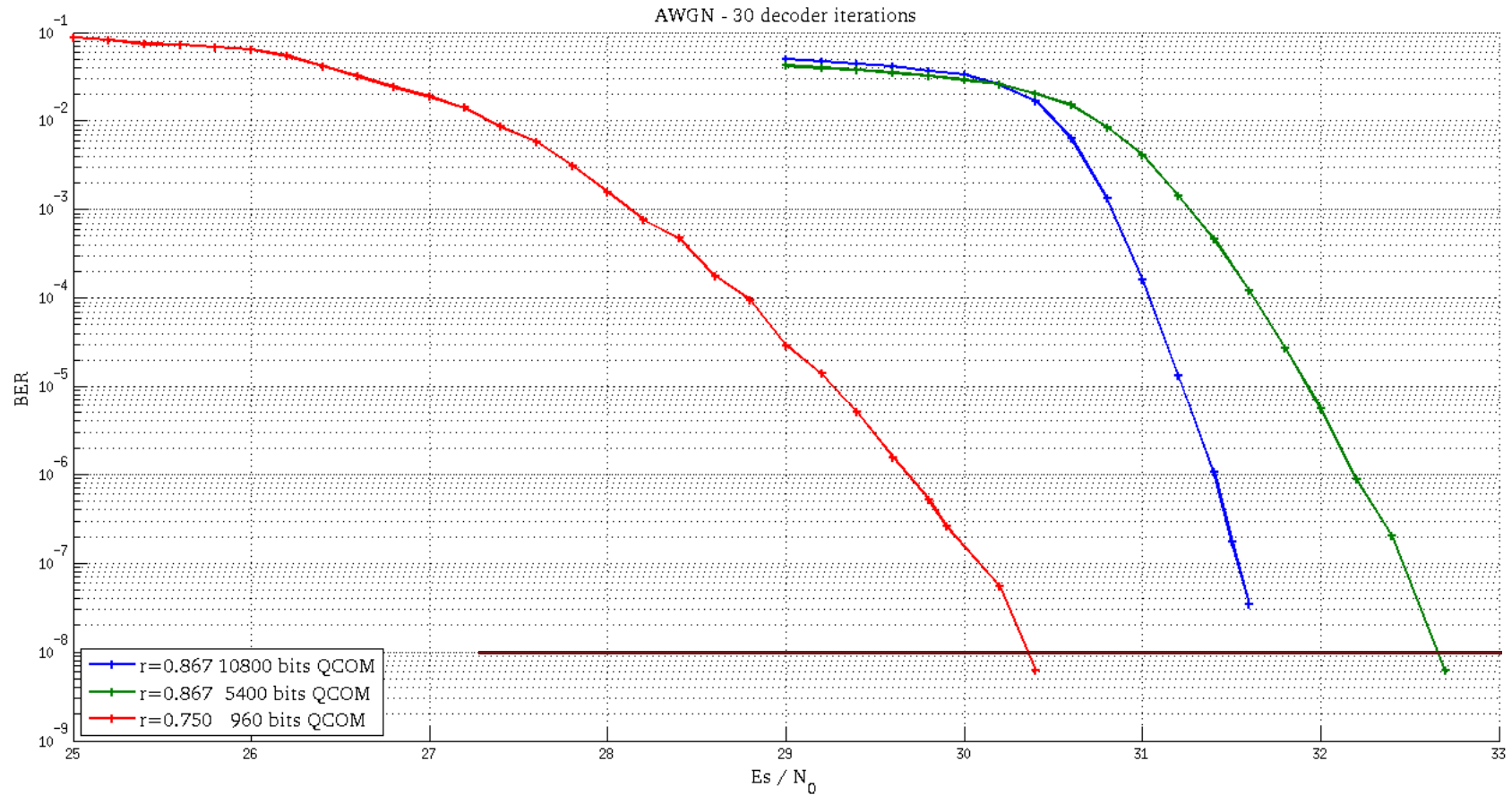


Simulation not yet completed

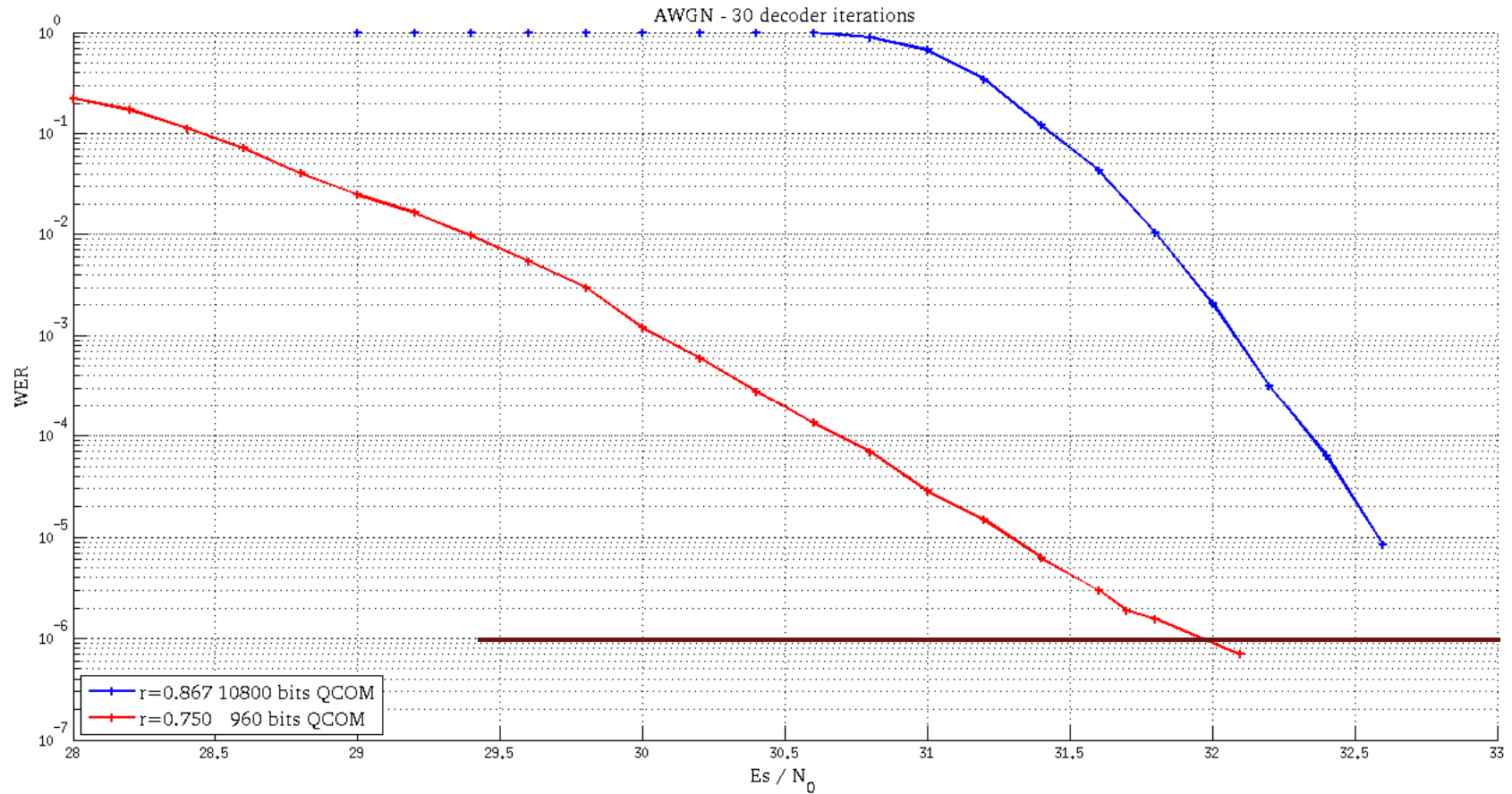
US Burst Model a) – WER, 40 μ s Symbol Duration



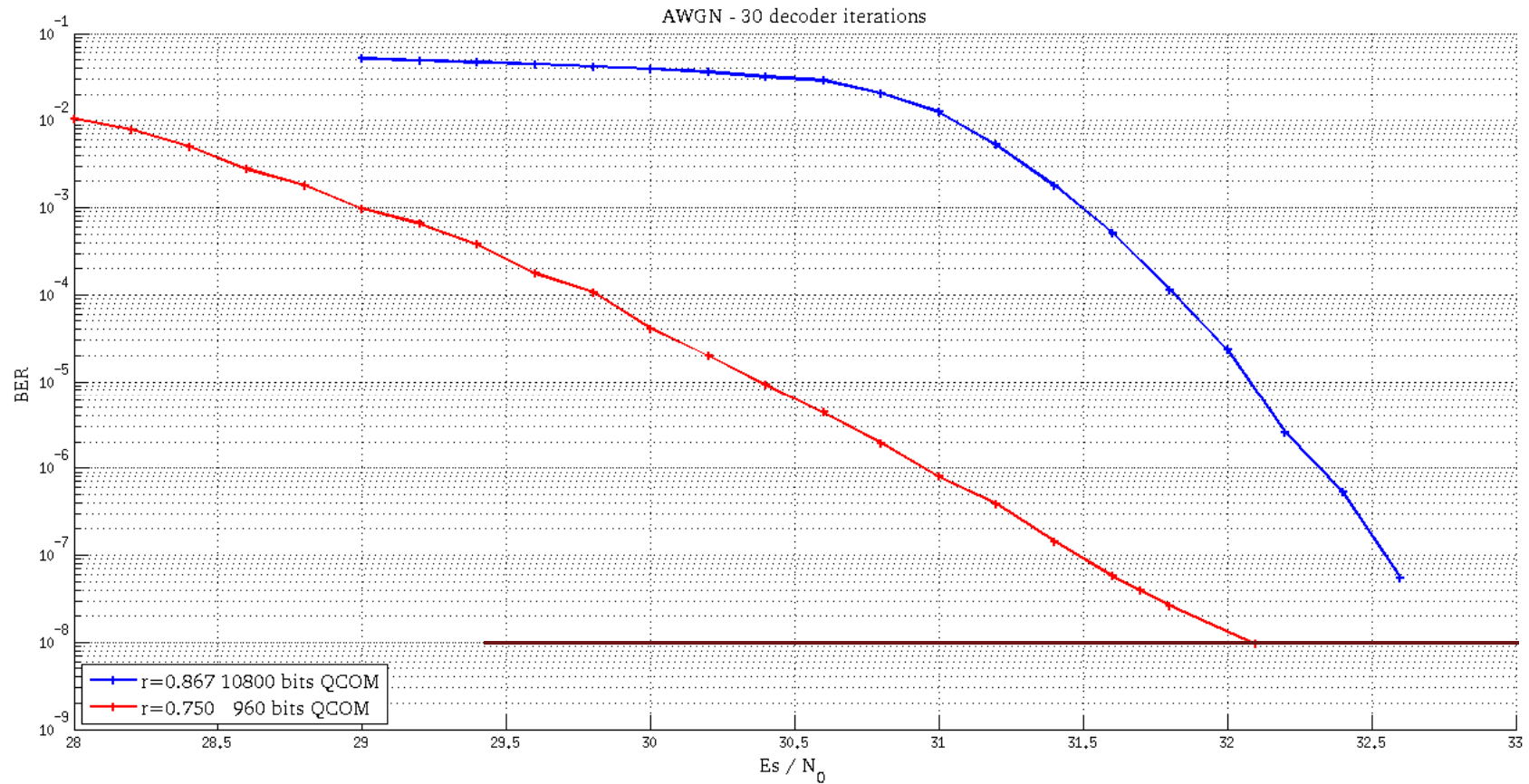
US Burst Model a) – BER, 40 μ s Symbol Duration



US Burst Model b) – WER, 40 μ s Symbol Duration



US Burst Model b) – BER, 40 μ s Symbol Duration



Discussion and Conclusions

- Performance results were presented for AWGN and burst noise scenarios
- Agreed performance metrics are shown to be met

Backup

Required Interleaving Depth and Code Rate

- The capacity C of a channel is given by $C = \log_2(1 + SNR)$ if the SNR is available for each coded bit
- In a bursty channel, roughly each D^{th} coded bit experiences a lower SNR_{Burst}
 - D is the time interleaving depth
- Assuming the other coded bits experience SNR_{clean} , then the capacity is given by $C' = \left(1 - \frac{1}{D}\right) \cdot \log_2(1 + SNR_{clean}) + \frac{1}{D} \cdot \log_2(1 + SNR_{Burst}) = \left(1 - \frac{1}{D}\right) \cdot C_{clean} + \frac{1}{D} \cdot C_{Burst}$
- To achieve the same capacity as above (i.e. $C = C'$), SNR_{clean} must be higher than SNR , i.e. $SNR_{clean} = \varepsilon \cdot SNR, \varepsilon > 1$
- This yields to the required interleaving depth $D = \frac{C_{Burst} - C_{Clean}}{C - C_{Clean}}$
 - ε can be interpreted as the loss in performance in the presence of burst noise
 - Clearly, the larger the interleaving depth D , the smaller the loss can be made
- The relation between loss and code rate has been plotted on slide 14

thank you