



Designing practical diversity schemes for next generation broadcasting applications

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Subject and outline

- **Signal space diversity and its implementation into a practical application**
- **Adopted lately in the second generation of terrestrial digital video broadcasting standard DVB-T2**
- **Real world scenarios => modifications to the original idea**
- **Construction of a multi-block STBC with signal space diversity**

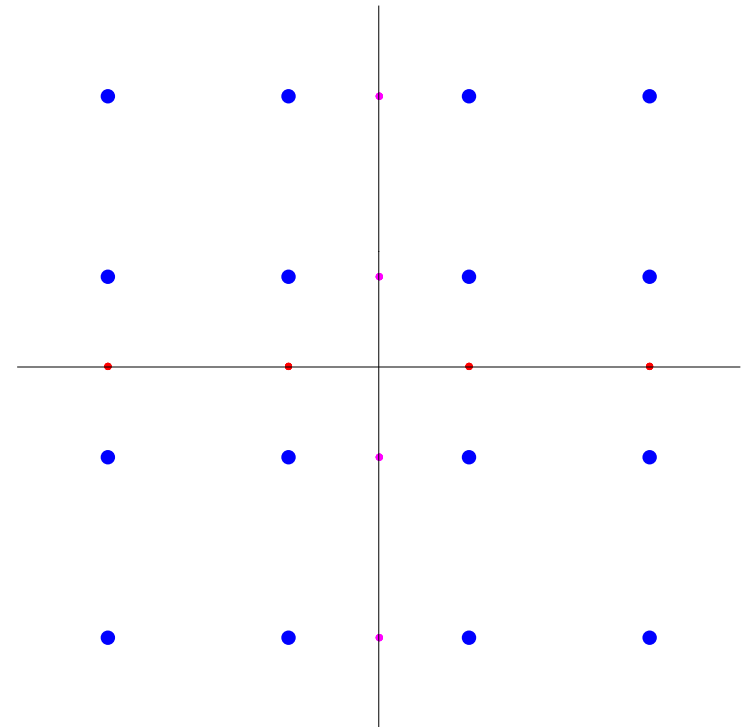


Part I

Motivation

Illustration example

- QAM with Gray mapping can be detected as 2 independent PAM
- Severe fading = possible loss of information on all transmitted bits
- Diversity techniques should be investigated



Signal Space Diversity (SSD): Goal, proposal and means

■ Goal

- Doubling the diversity order

■ Proposal

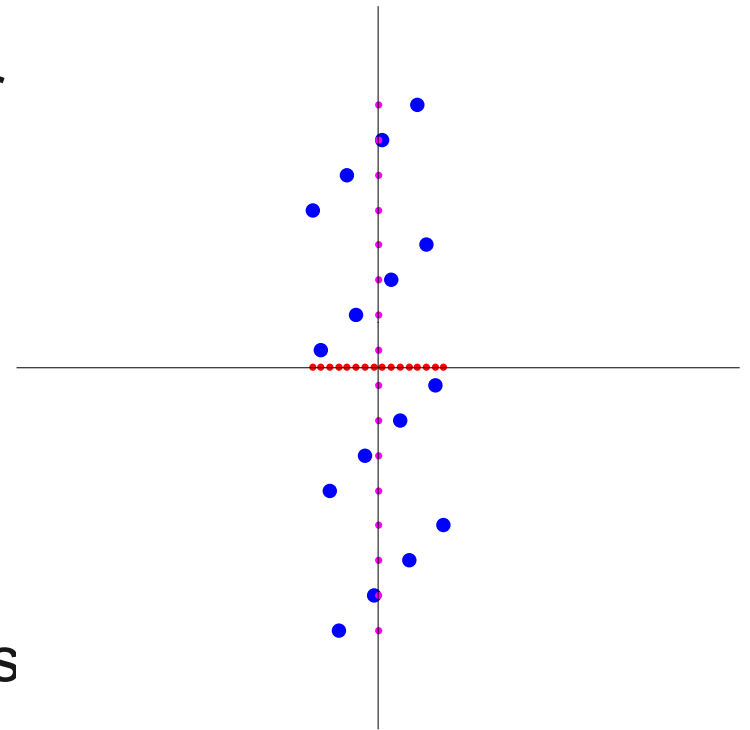
- Correlate the I and Q carried information
- Make the transmitted signal fade independently over the I and Q component axes

■ Means

- I and Q correlation => Rotation of the constellation
- Independent I-Q fading => Component interleaving

Signal Space Diversity (SSD)

- Gray mapped QAM schemes no longer considered as 2 independent PAMs.
- Signal points uniquely identifiable in I and Q component axis separately.
- Distances to origin unvaried
 - BER over Gaussian channel unchanged
- Demapper: 2^m instead of $2 \times 2^{m/2}$ metrics computation for rotated QAM
- Rotation angle ?



Choice of the rotation angle [Giraud 97, Boutros 98]

Pairwise error probability

- Fading
 - Find rotation angle that maximizes:
 - Fading channels: **maximise**
- $$P(v \rightarrow \hat{v}) \leq \frac{1}{\prod_{n \in N} \frac{E_s}{4N_0} |v_n - \hat{v}_n|^2} = \frac{1}{\prod_{n \in N} \prod_{\substack{k=I, Q \\ x_k; \hat{x}_k}} \frac{E_s}{4N_0} |x_k - \hat{x}_k|^2}$$
- $$\min \left\{ |x_I - \hat{x}_I|^2 \cdot |x_Q - \hat{x}_Q|^2 \right\}$$

➔ Improve uncoded performance at very high SNR for fading channels

Giraud => $\Pi/8 = 22.5^\circ$

Boutros, Viterbo => 31.7°

X. Giraud, E. Boutillon, and J. C. Belfiore, "Algebraic tools to build modulation schemes for fading channels," *IEEE Trans. Commun.*, vol. 43, no. 3, pp. 938–952, May 1997

J. Boutros and E. Viterbo, "Signal space diversity: A power- and bandwidth-efficient diversity technique for the Rayleigh fading channel," *IEEE Trans. Inform. Theory*, vol. 44, no. 4, pp. 1453–1467, July 1998.

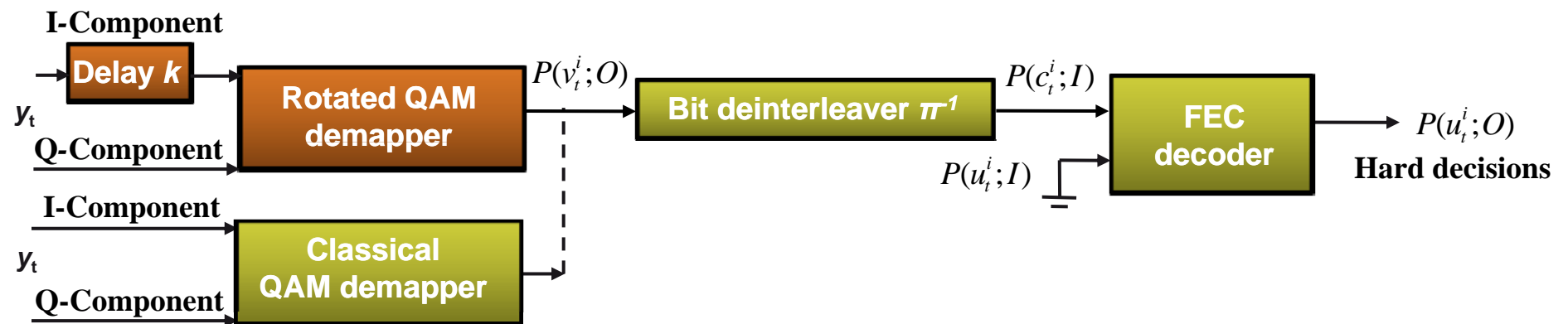
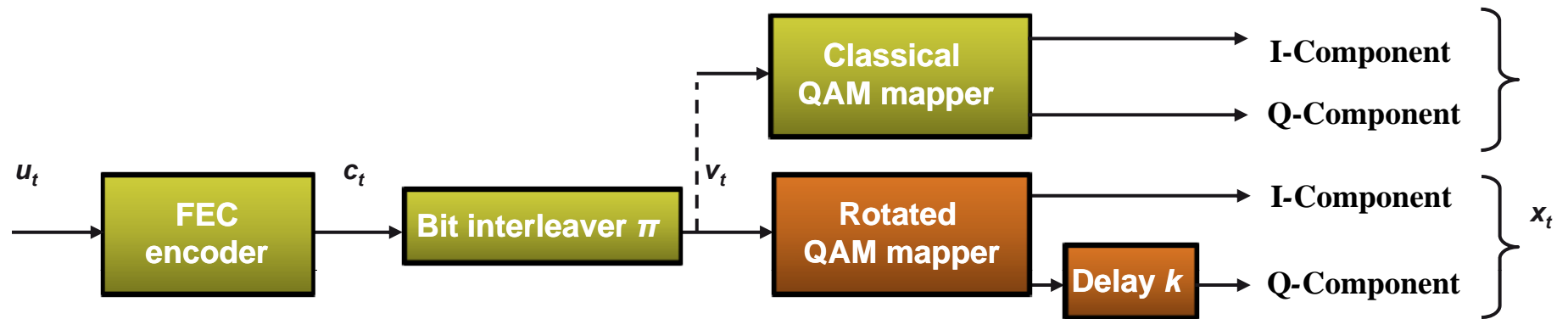
Signal Space Diversity: I-Q interleaving

- Initially introduced for TCM (wo rotation) [Al-Semari, 1996]
- Simplified when adapted to the fading channel model
- Could be reduced to a simple delay k of Q wrt I for memoryless fading channels (without rotation [Chindapol, 01])
 - **Correlated channels** $\Rightarrow k > \text{correlation length}$
 - **Block fading** \Rightarrow a delay multiplexer can be introduced depending on the model
 - **Flat fading channels** $\Rightarrow k = 1$ symbol period satisfies constraints
- Additional latency dependent on the delay value k

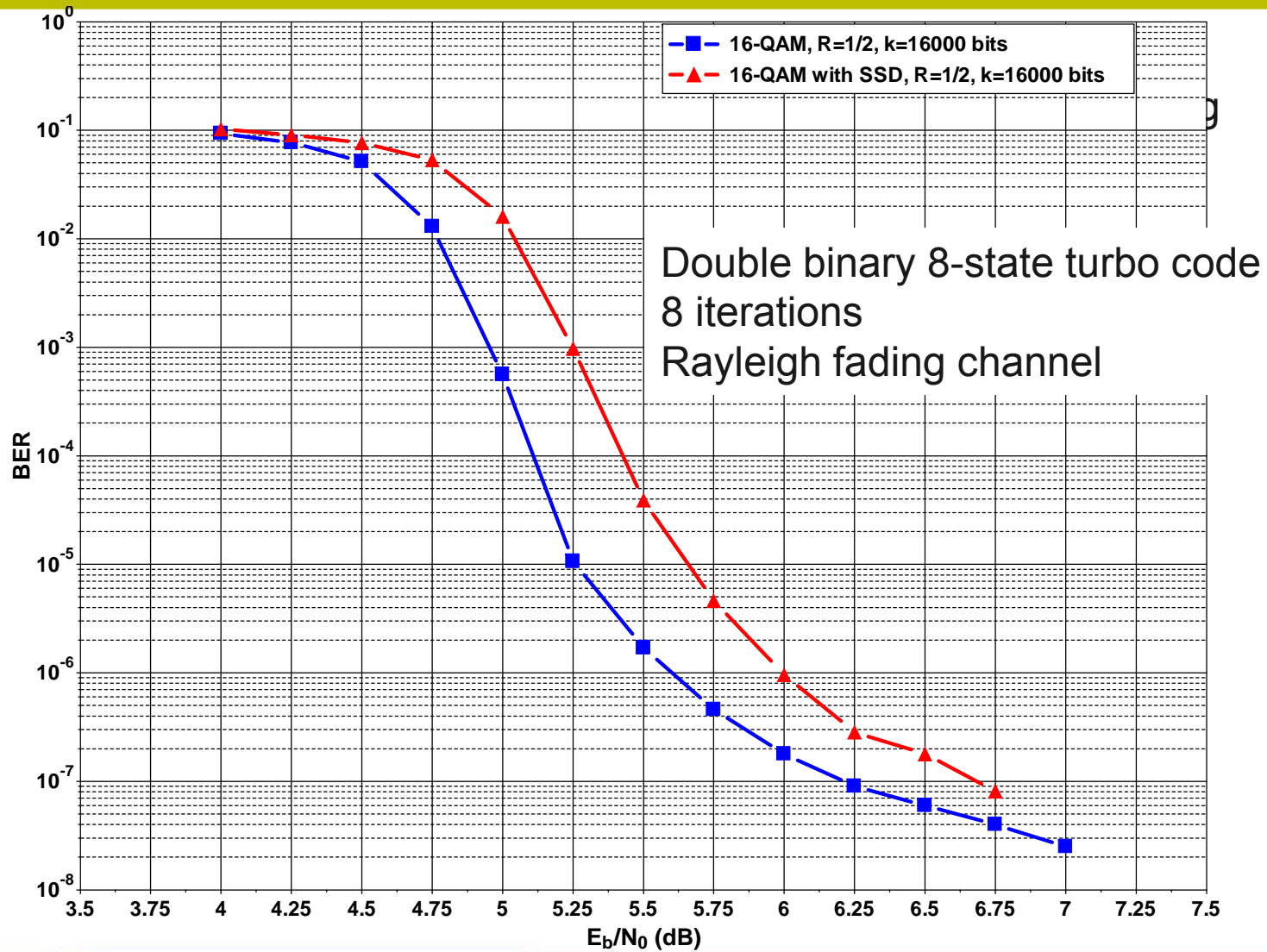
S. A. Al-Semari and T. E. Fuja, "I-Q TCM: reliable communication over the Rayleigh fading channel close to the cutoff rate," *IEEE Transactions on Information Theory*, vol. 43, no. 1, pp. 250-262, 1997.

Chindapol and J. Ritcey, "Design, analysis, and performance evaluation for BICM-ID with square QAM constellations in Rayleigh fading channels," *IEEE J. Select. Areas Commun.*, vol. 19, no. 5, pp. 944-957, May 2001

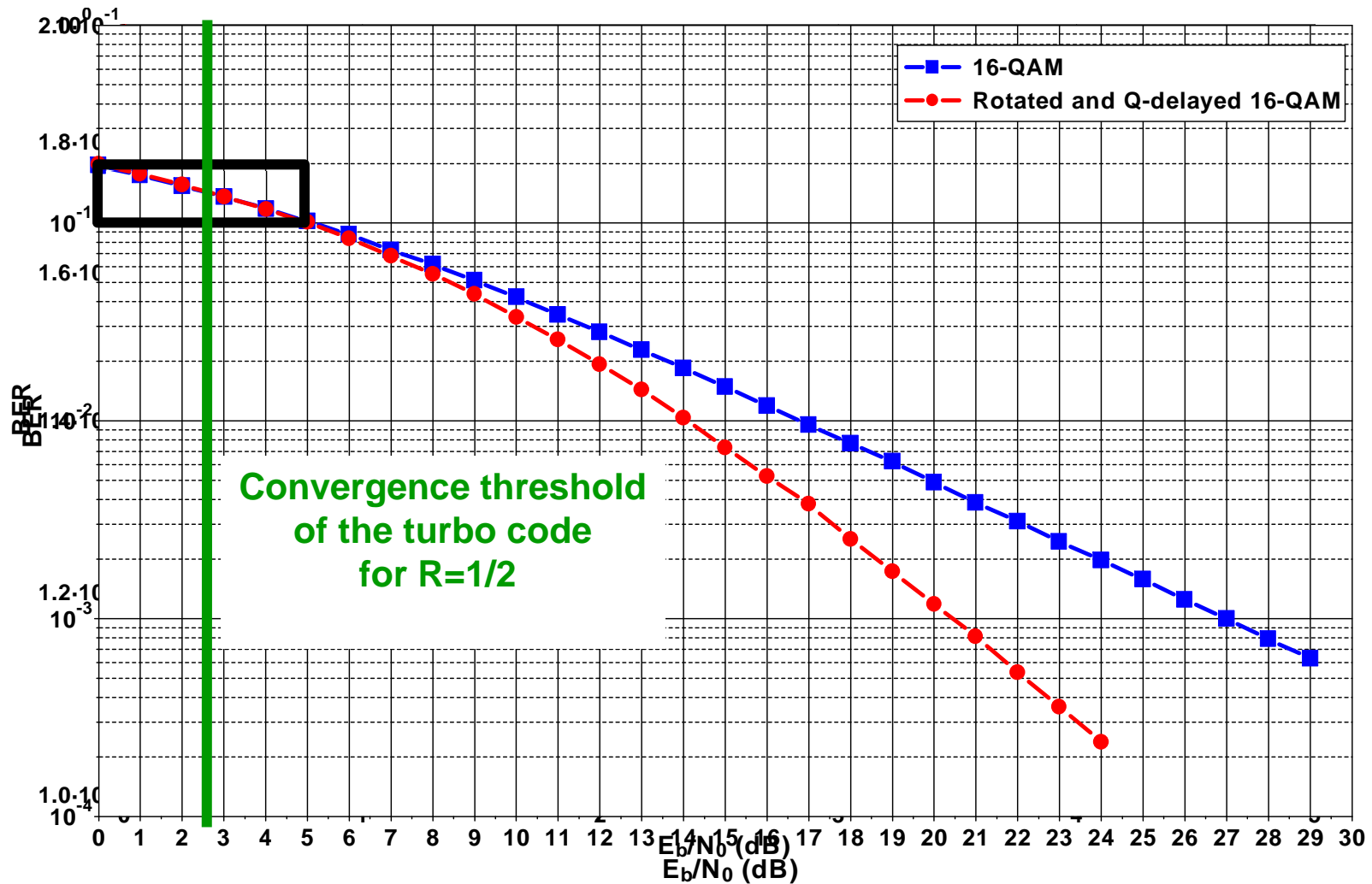
System description



BER performance for coded system



Uncoded BER performance

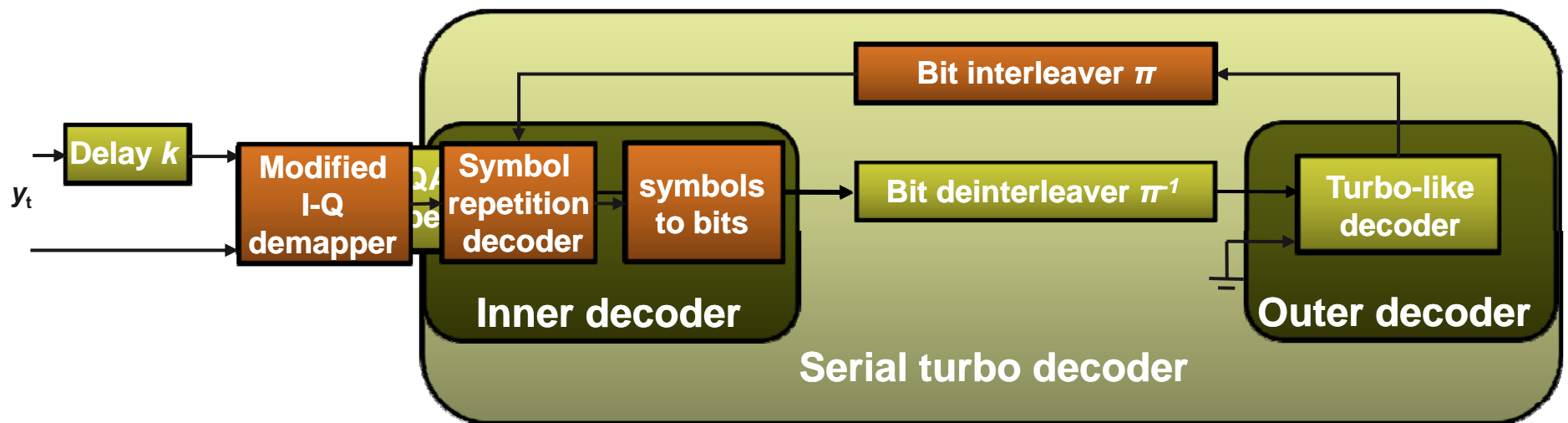
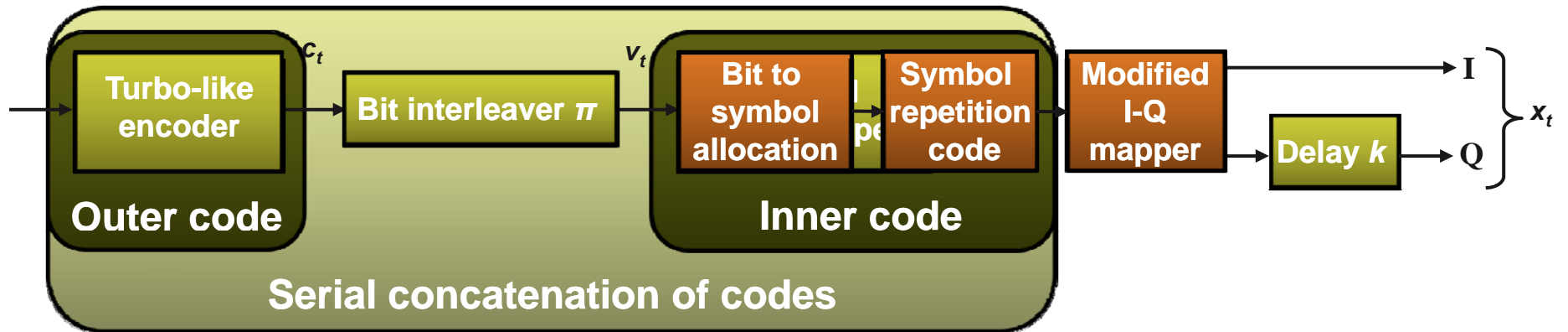




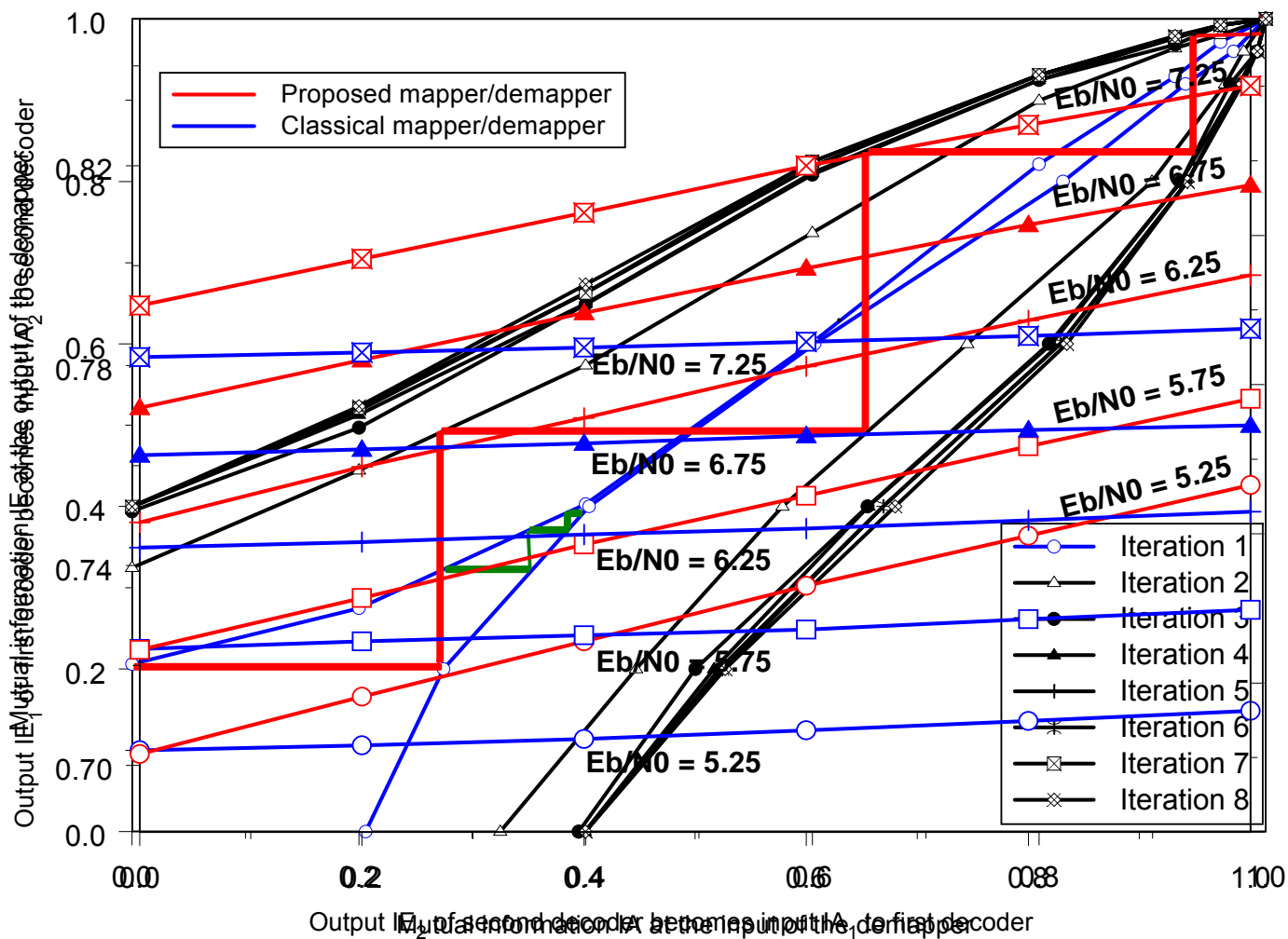
Part II

Iterative decoding and demodulation with SSD

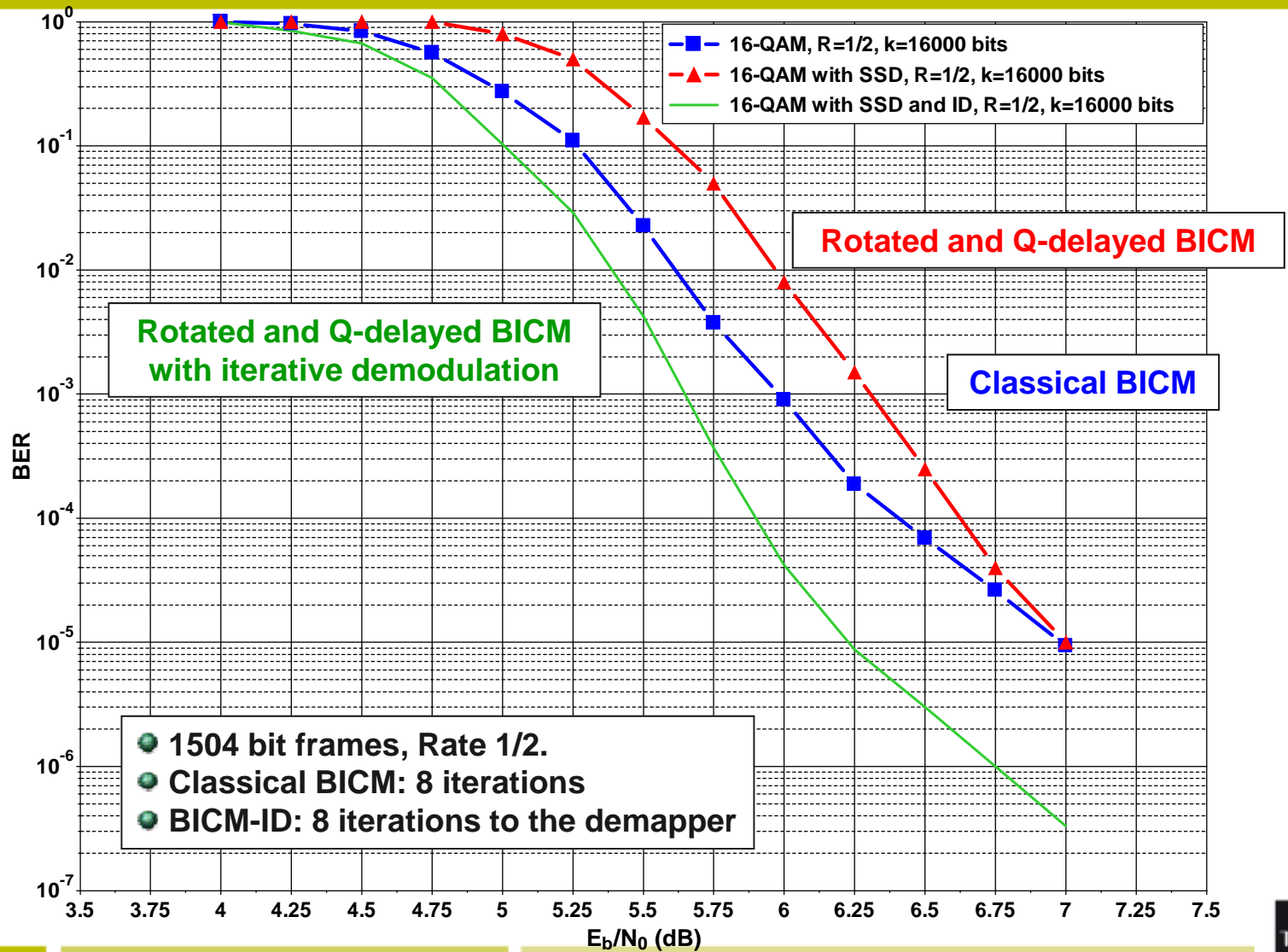
Signal Space Diversity and iterative decoding and demodulation



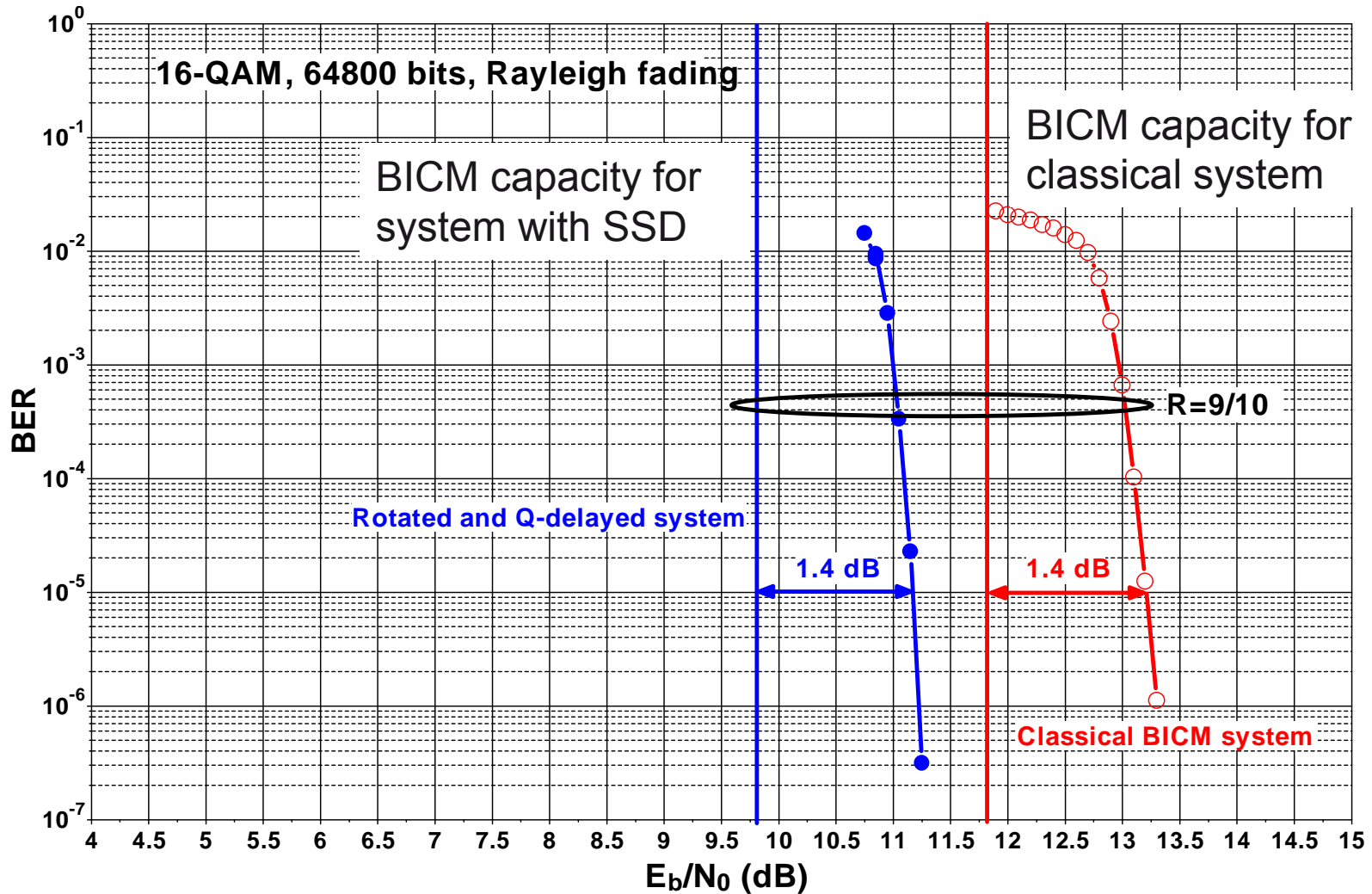
EXIT chart comparison of the proposed decoder



Turbo BICM-ID with signal space diversity: FER results



Gap to capacity





Part III

Second generation of Digital Video Broadcasting - Terrestrial DVB-T2

Standardisation constraints

- **Broadcasting channel models are not necessarily Rayleigh i.i.d**
- **New techniques should provide a gain in a broadcast scenario**
 - Especially over Single Frequency Networks (SFN)
- **Iterative decoding and demodulation at the receiver cannot be made mandatory**

Single Frequency Network (SFN)



Antenna 2



$$P_{a1} \approx P_{a2}$$
$$F_{a1} = F_{a2}$$
$$AOA1 \neq AOA2$$

⇒ Severe fading
⇒ Erasure events

P_{a2}



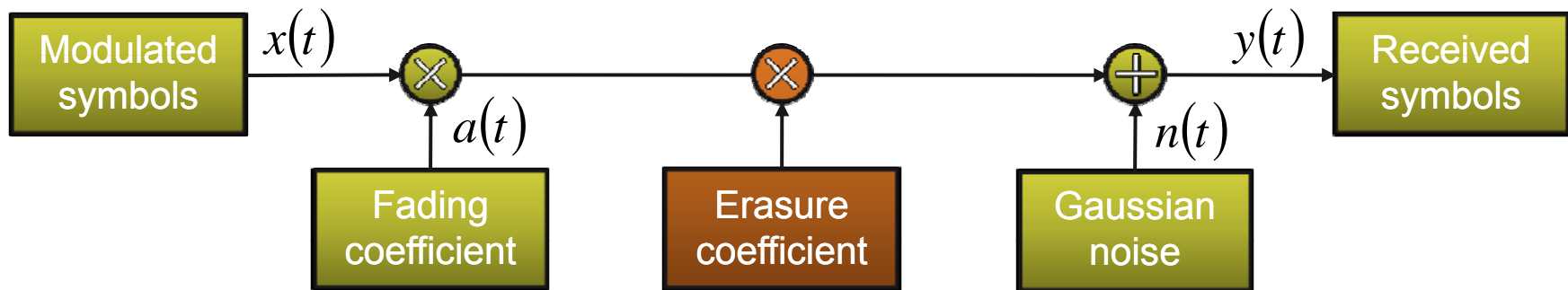
P_{a1}



Antenna 1



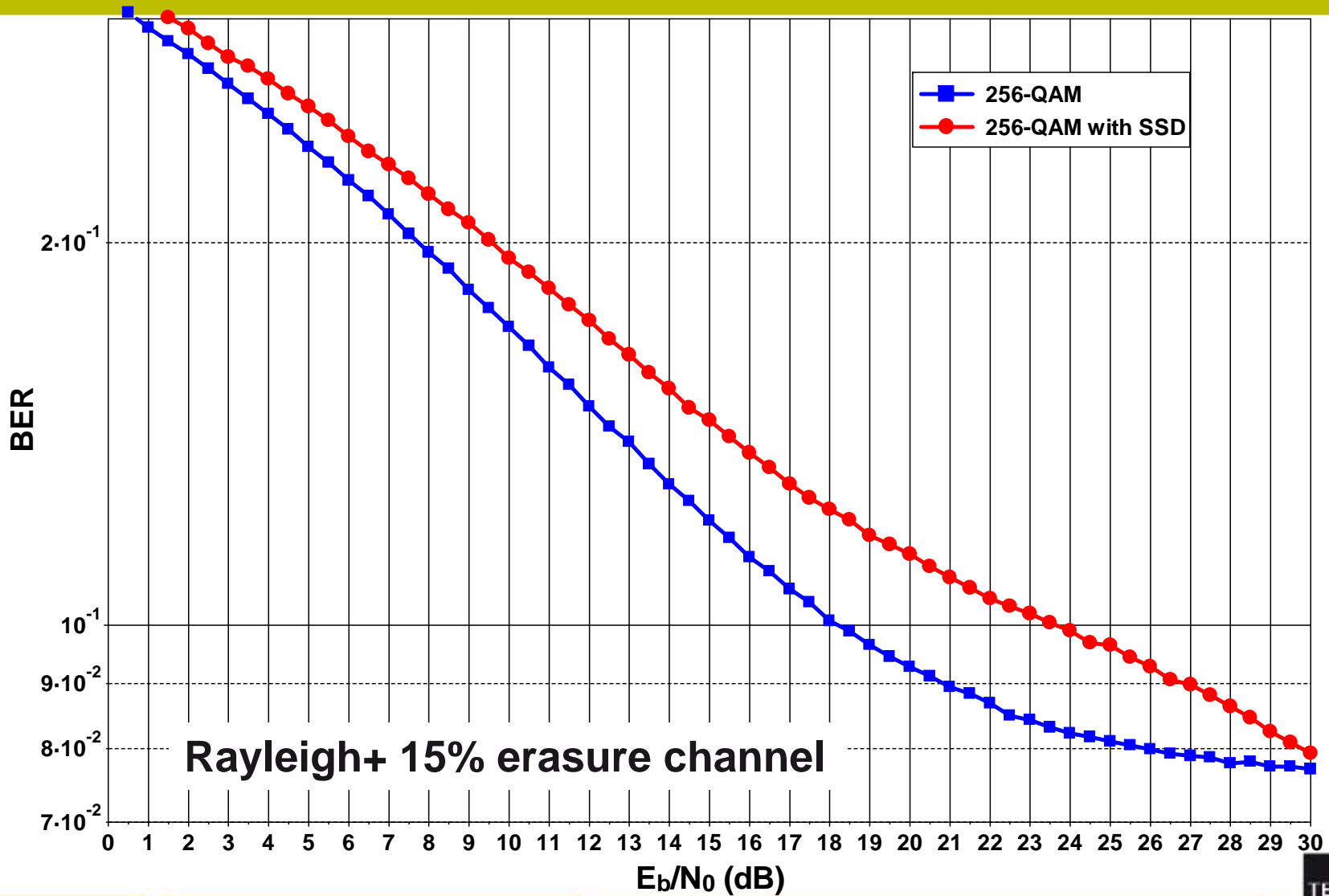
DVB-T2 faded erasure channel model



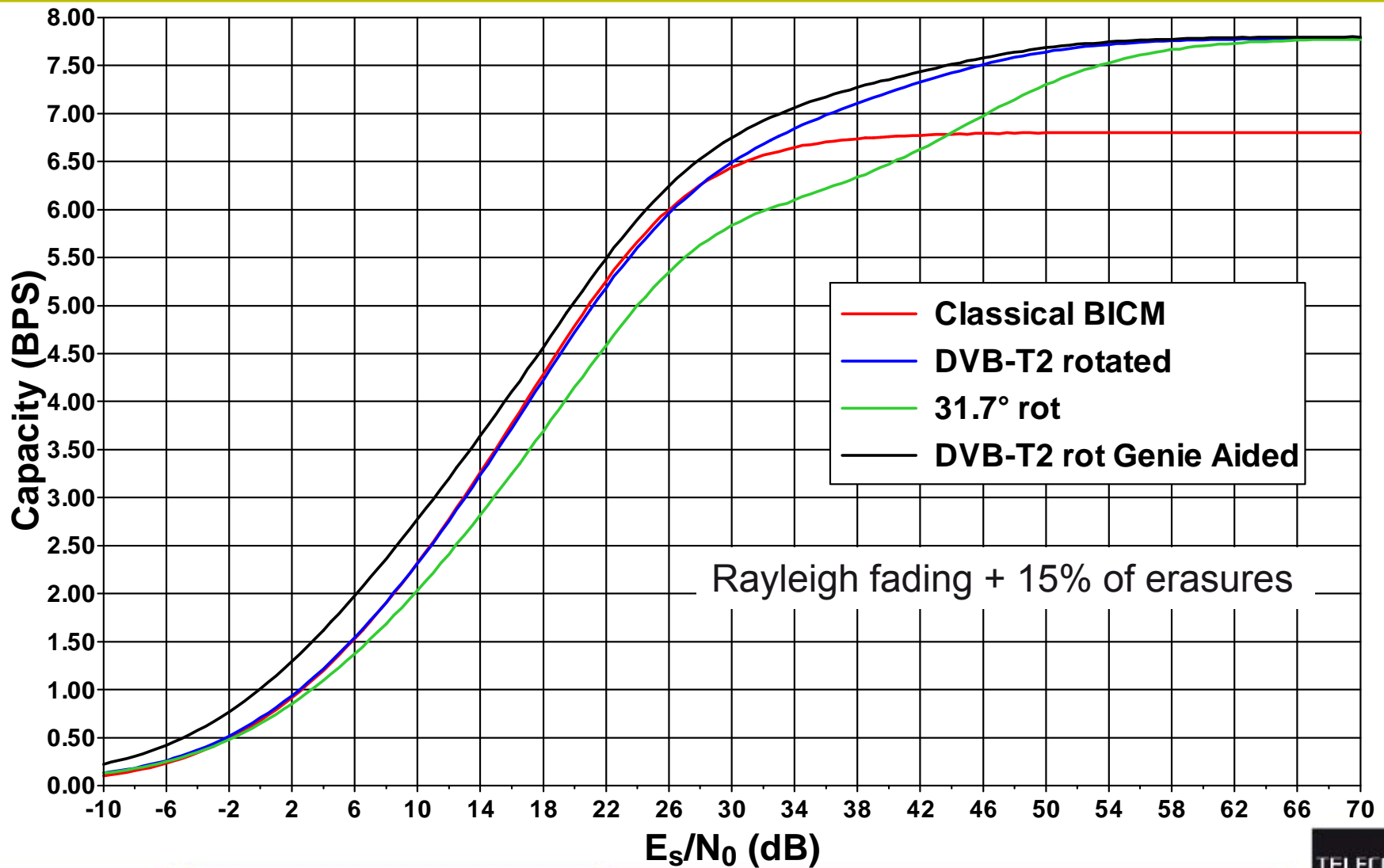
- $e(t)$: a random process taking a value of 0 with a probability of P_e and a value of 1 otherwise
- Uncorrelated erasure events
- Perfect CSI
- 15% of erasures have been used as a worst case scenario

Bound on the code rate for reliable transmission: $R < 1 - P_e$

Uncoded performance over a faded erasure channel



Capacity comparison for 256-QAM



Modification of the rotation angle

■ Observations

- Performance gain of signal space diversity is rotation angle dependent

■ Reasons

- Optimum rotation angle is channel model dependent

■ Motivations

- Gain for signal space diversity in all channel model scenarios

Choice of the rotation angle

Pairwise error probability

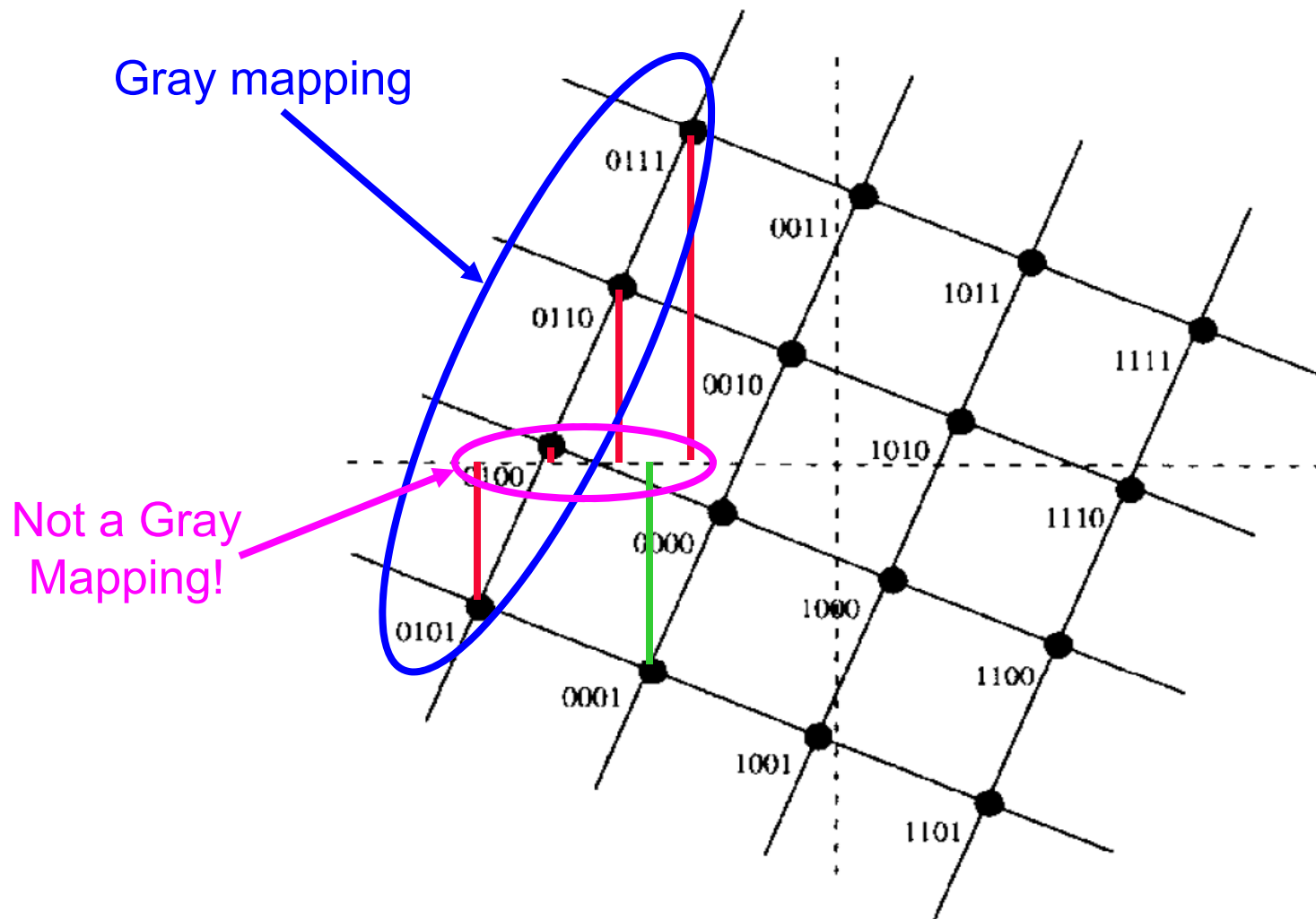
$$P(v \rightarrow \hat{v}) \leq \frac{1}{\prod_{n \in N} \frac{E_s}{4N_0} |v_n - \hat{v}_n|^2} = \frac{1}{\prod_{n \in N} \prod_{\substack{k=I,Q \\ x_k, \hat{x}_k}} \frac{E_s}{4N_0} |x_k - \hat{x}_k|^2}$$

- Fading
- Find rotation angle that maximizes:

- Fading channels: **maximise** $\min \left\{ |x_I - \hat{x}_I|^2 \cdot \cancel{|x_Q - \hat{x}_Q|^2} \right\}$

➔ Erasure event on one component => optimize 1D distance

Hamming distance problem: illustration example



New rotation angle design criteria

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3 additional design criteria

Min 1-D distance: design measure suitable for high erasure ratio channels at high SNR

The average Hamming distance between two neighbours of the constellation after projection over a 1D axis.

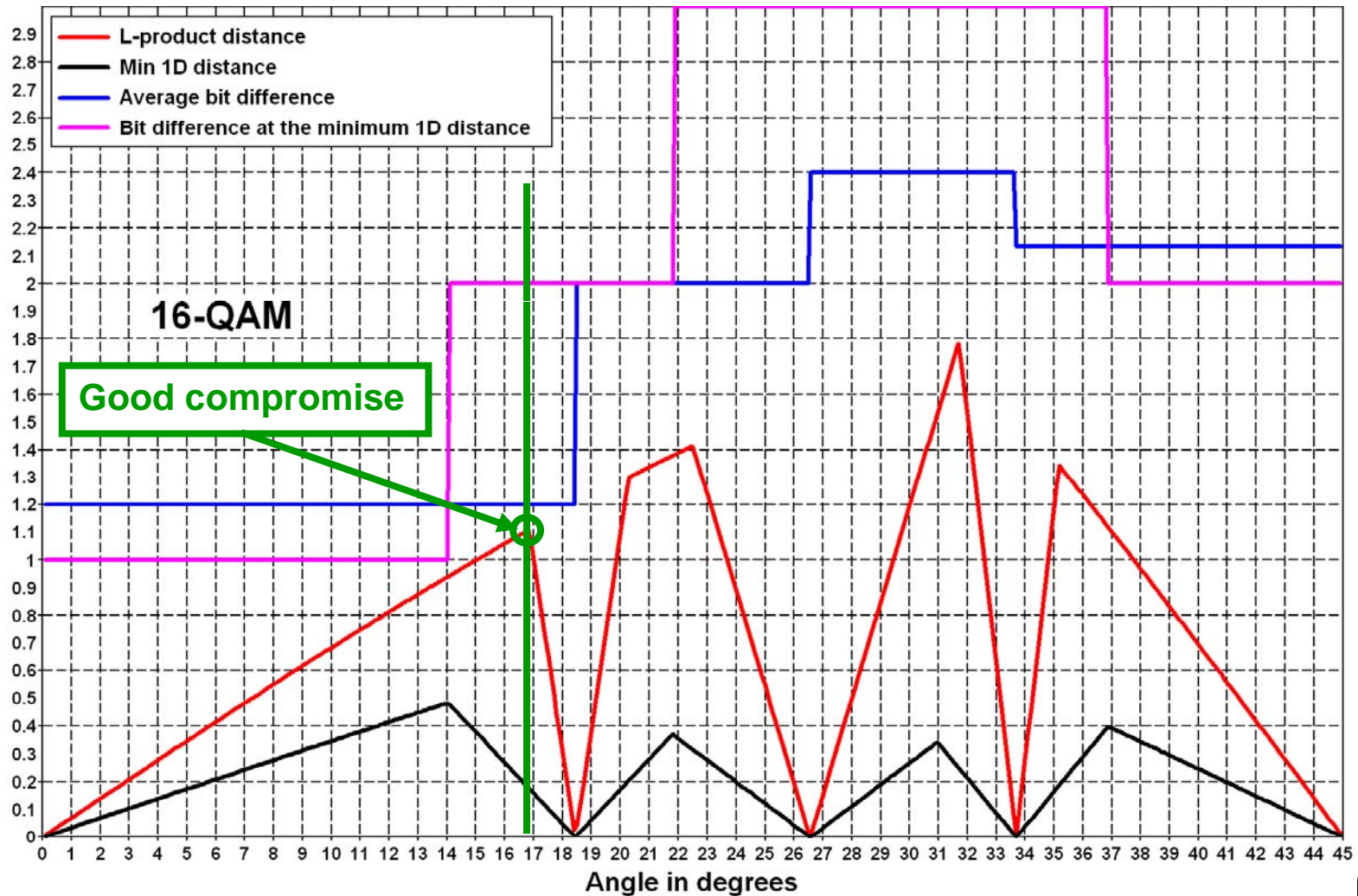
The minimum Hamming distance between two neighbours at the minimum 1D distance.

Observations

Performance of SSD seem to be explained by the interaction of the 4 design criteria

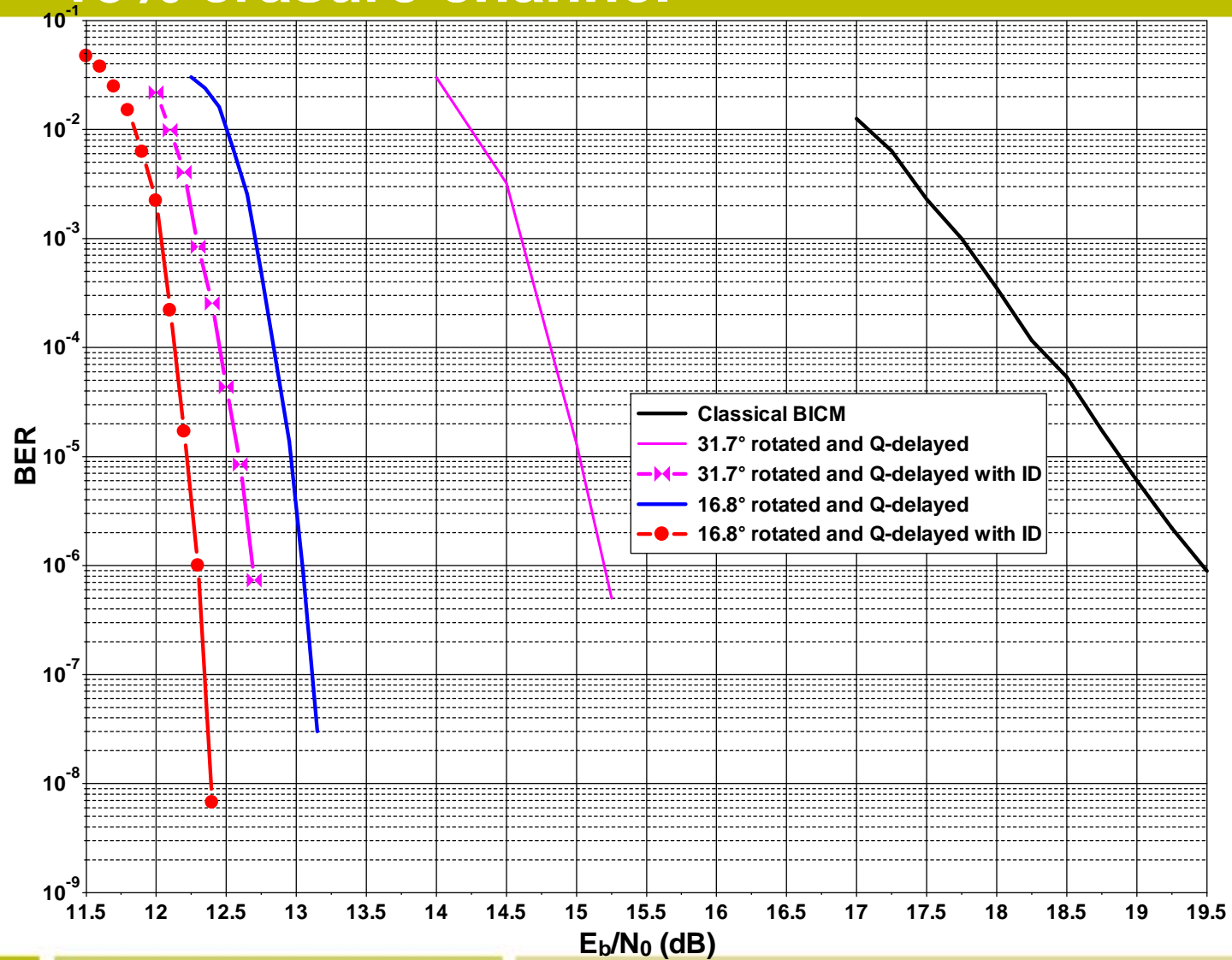
Application to 16-QAM

26



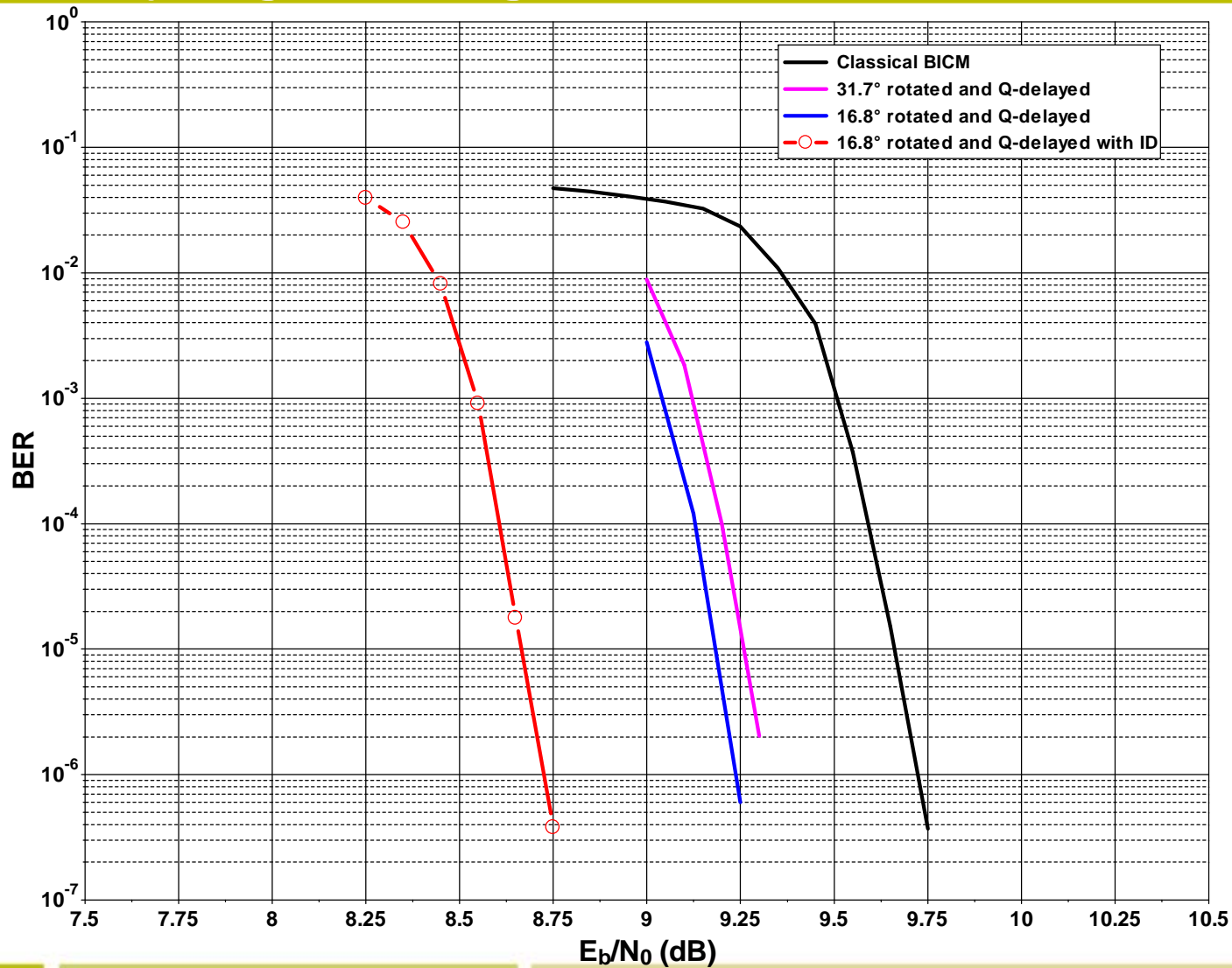
LDPC coded performance of 16-QAM over a 15% erasure channel

27

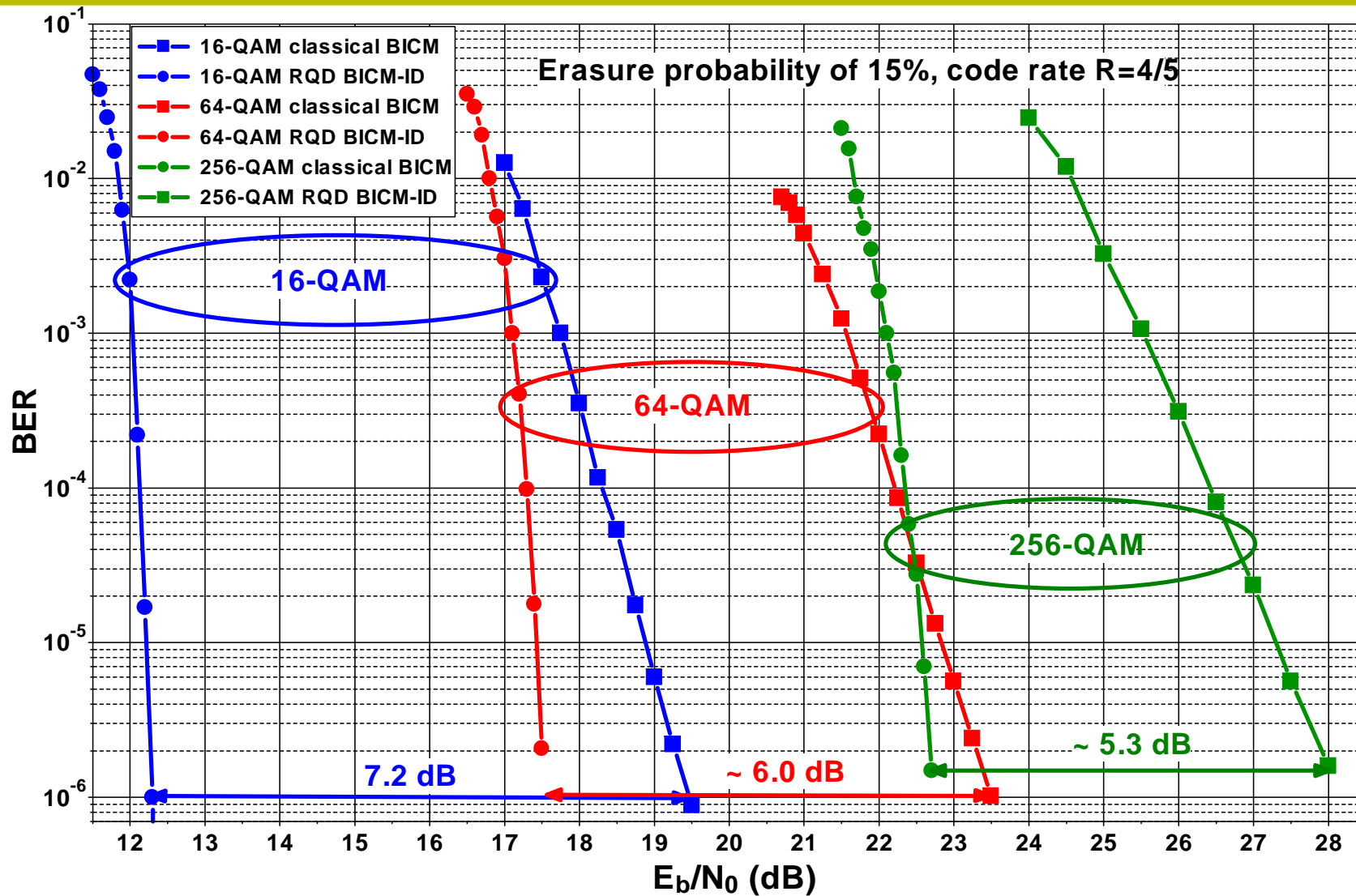


LDPC coded performance of 16-QAM over a Rayleigh fading channel with no erasure

28



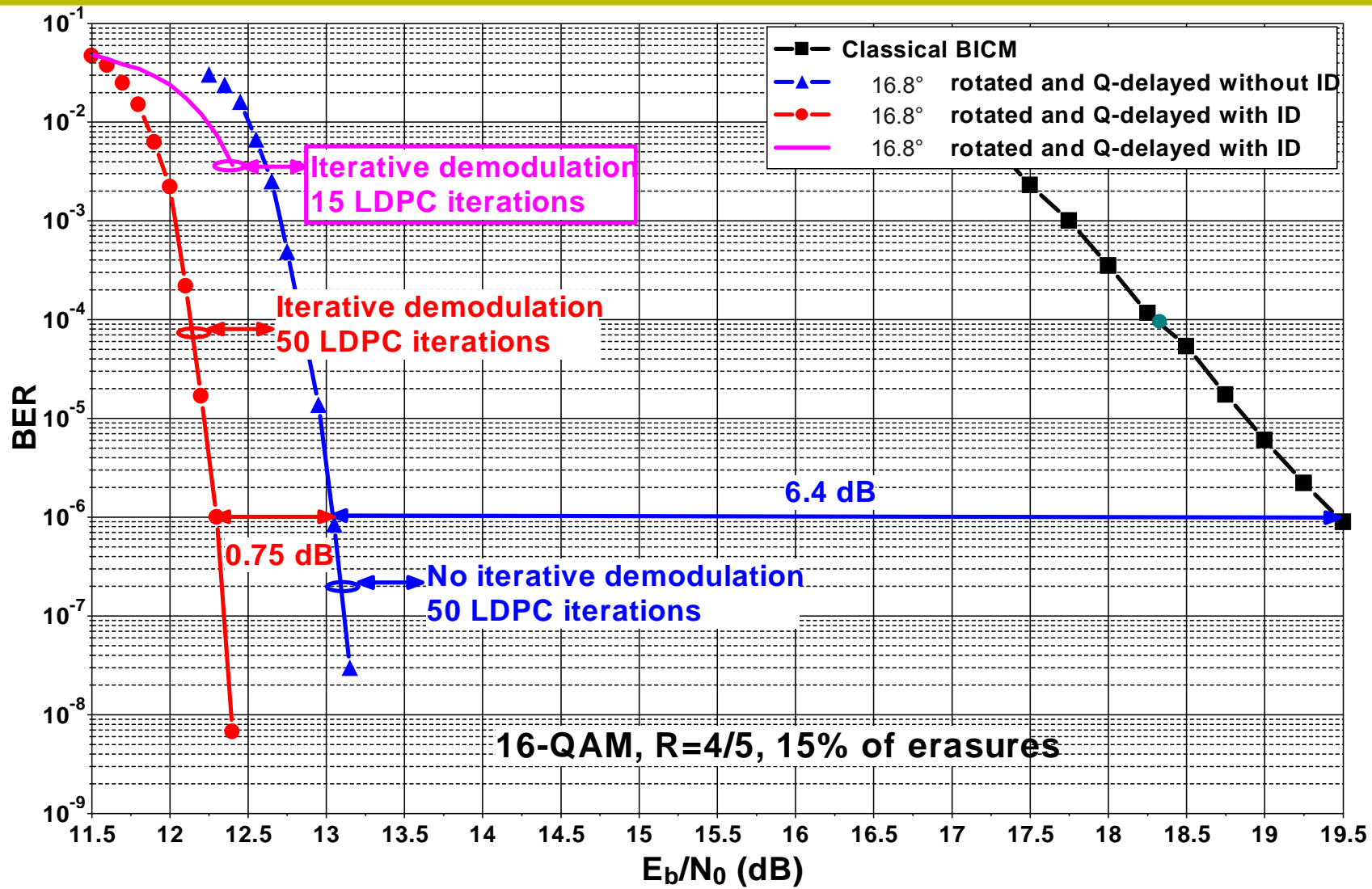
Summary of performance results



Performance with OFDM

	Gain of SSD at 10^{-7} of BER on a Rayleigh multipath channel P1	Gain of SSD at 10^{-7} of BER on a 0dB echo channel
QPSK R=1/2	0.7 dB	0.6 dB
QPSK R=3/5	1.2 dB	1.0 dB
QPSK R=2/3	1.2 dB	1.3 dB
QPSK R=3/4	1.7 dB	2.1 dB
QPSK R=4/5	2.0 dB	3.0 dB
QPSK R=5/6	2.3 dB	3.8 dB
16QAM R=1/2	0.4 dB	0.5 dB
16QAM R=3/5	0.5 dB	0.7 dB
16QAM R=2/3	0.6 dB	0.7 dB
16QAM R=3/4	0.8 dB	1.2 dB
16QAM R=4/5	1.1 dB	1.7 dB
16QAM R=5/6	1.2 dB	2.2 dB

Iterative demapping: another point of view





Part IV

Reduced complexity high diversity STBC

Introduction

- **SSD => double diversity for STBC**
- **Multi-block MIMO => Multiple STBC matrices**
- **Diversity order of 8**
- **Complexity of $O(M^4)$**
- **Designed to suit fading channels with erasures**

Multi-block STBC

$$\mathbf{X} = \begin{bmatrix} a(I_1 + jQ_7) + b(I_2 + jQ_8) & -c(I_3 - jQ_5) - d(I_4 - jQ_6) & a(I_5 + jQ_3) + b(I_6 + jQ_4) & -c(I_7 - jQ_1) - d(I_8 - jQ_2) \\ a(I_3 + jQ_5) + b(I_4 + jQ_6) & c(I_1 - jQ_7) + d(I_2 - jQ_8) & a(I_7 + jQ_1) + b(I_8 + jQ_2) & c(I_5 - jQ_3) + d(I_6 - jQ_4) \end{bmatrix}$$

$\underbrace{\hspace{15em}}_H$
 $\underbrace{\hspace{15em}}_{H'}$

- **Quasi-static code => channel constant over 2 consecutive periods**
- **Signal space diversity**
 - => x_1 benefits from 2 MIMO channel matrices H and H'
 - => I,Q components are sent over different antennas and different time instances
- **Parameters a, b, c, d have to be optimised to guarantee full diversity in various channel scenarios**

Classical ML detection

$$\begin{aligned}
 D(s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8) = & \left| r_1^1 - \left(h_{11} [a(I_1 + jQ_7) + b(I_2 + jQ_8)] + h_{12} [a(I_3 + jQ_5) + b(I_4 + jQ_6)] \right) \right|^2 \\
 & + \left| r_2^1 - \left(h_{11} [-c(I_3 - jQ_5) - d(I_4 - jQ_6)] + h_{12} [c(I_1 - jQ_7) + d(I_2 - jQ_8)] \right) \right|^2 \\
 & + \left| r_3^1 - \left(h'_{11} [a(I_5 + jQ_3) + b(I_6 + jQ_4)] + h'_{12} [a(I_7 + jQ_1) + b(I_8 + jQ_2)] \right) \right|^2 \\
 & + \left| r_4^1 - \left(h'_{11} [-c(I_7 - jQ_1) - d(I_8 - jQ_2)] + h'_{12} [c(I_5 - jQ_3) + d(I_6 - jQ_4)] \right) \right|^2 \\
 & + \left| r_1^2 - \left(h_{21} [a(I_1 + jQ_7) + b(I_2 + jQ_8)] + h_{22} [a(I_3 + jQ_5) + b(I_4 + jQ_6)] \right) \right|^2 \\
 & + \left| r_2^2 - \left(h_{21} [-c(I_3 - jQ_5) - d(I_4 - jQ_6)] + h_{22} [c(I_1 - jQ_7) + d(I_2 - jQ_8)] \right) \right|^2 \\
 & + \left| r_3^2 - \left(h'_{21} [a(I_5 + jQ_3) + b(I_6 + jQ_4)] + h'_{22} [a(I_7 + jQ_1) + b(I_8 + jQ_2)] \right) \right|^2 \\
 & + \left| r_4^2 - \left(h'_{21} [-c(I_7 - jQ_1) - d(I_8 - jQ_2)] + h'_{22} [c(I_5 - jQ_3) + d(I_6 - jQ_4)] \right) \right|^2
 \end{aligned}$$

- **ML Complexity should be proportional to M^8 !**
 - QPSK => $4^8 = 65536$ distances
- **Proposed matrix X has however a particular form**

Reduced complexity detection inspired by [Sari, 2008]

Compute y signals

$$y_1^1 = r_1^1 - b[h_{11}(I_2 + jQ_8) + h_{12}(I_4 + jQ_6)] = a[h_{11}(I_1 + jQ_7) + h_{12}(I_3 + jQ_5)] + n_1^1$$

$$y_2^1 = r_2^1 - d[h_{12}(I_2 - jQ_8) - h_{11}(I_4 - jQ_6)] = c[h_{12}(I_1 - jQ_7) - h_{11}(I_3 - jQ_5)] + n_2^1$$

$$y_3^1 = r_3^1 - b[h'_{11}(I_6 + jQ_4) + h'_{12}(I_8 + jQ_2)] = a[h'_{11}(I_5 + jQ_3) + h'_{12}(I_7 + jQ_1)] + n_3^1$$

$$y_4^1 = r_4^1 - d[h'_{12}(I_6 - jQ_4) - h'_{11}(I_8 - jQ_2)] = c[h'_{12}(I_5 - jQ_3) - h'_{11}(I_7 - jQ_1)] + n_4^1$$

Depends only on even symbols => conditioned detection

$$y_1^2 = r_1^2 - b[h_{21}(I_2 + jQ_8) + h_{22}(I_4 + jQ_6)] = a[h_{21}(I_1 + jQ_7) + h_{22}(I_3 + jQ_5)] + n_1^2$$

$$y_2^2 = r_2^2 - d[h_{22}(I_2 - jQ_8) - h_{21}(I_4 - jQ_6)] = c[h_{22}(I_1 - jQ_7) - h_{21}(I_3 - jQ_5)] + n_2^2$$

$$y_3^2 = r_3^2 - b[h'_{21}(I_6 + jQ_4) + h'_{22}(I_8 + jQ_2)] = a[h'_{21}(I_5 + jQ_3) + h'_{22}(I_7 + jQ_1)] + n_3^2$$

$$y_4^2 = r_4^2 - d[h'_{22}(I_6 - jQ_4) - h'_{21}(I_8 - jQ_2)] = c[h'_{22}(I_5 - jQ_3) - h'_{21}(I_7 - jQ_1)] + n_4^2$$

S. Sezginer and H. Sari, "Recent results in space-time code design", Wireless World Research Forum Meeting 20, Ottawa, April 2008

Reduced complexity detection

- For all possible values of even symbols (M^4 possibilities) compute

$$Z_1 = \frac{h_{11}^* y_1^1 + h_{21}^* y_1^2}{a} + \frac{h_{12} y_2^{1*} + h_{22} y_2^{2*}}{c^*}$$

$$Z_2 = \frac{h_{12}^* y_1^1 + h_{22}^* y_1^2}{a} - \frac{h_{11} y_2^{1*} + h_{21} y_2^{2*}}{c^*}$$

$$Z_3 = \frac{h_{11}'^* y_3^1 + h_{21}'^* y_3^2}{a} + \frac{h_{12}' y_4^{1*} + h_{22}' y_4^{2*}}{c^*}$$

$$Z_4 = \frac{h_{12}'^* y_3^1 + h_{22}'^* y_3^2}{a} - \frac{h_{11}' y_4^{1*} + h_{21}' y_4^{2*}}{c^*}$$

Reduced complexity detection

$$\text{Re}\{Z_1\} + j \text{Im}\{Z_4\} = \underbrace{\left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right)}_{\text{Diversity 8}} I_1 + j \underbrace{\left(|h'_{11}|^2 + |h'_{12}|^2 + |h'_{21}|^2 + |h'_{22}|^2\right)}_{\text{Linear complexity with M}} Q_1 + \text{Re}\{N_1\} + j \text{Im}\{N_4\}$$

Similar detection can be applied to all odd symbols

$$\text{Re}\{Z_2\} + j \text{Im}\{Z_3\} = \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) I_3 + j \left(|h'_{11}|^2 + |h'_{12}|^2 + |h'_{21}|^2 + |h'_{22}|^2\right) Q_3 + \text{Re}\{N_2\} + j \text{Im}\{N_3\}$$

$$\text{Re}\{Z_3\} + j \text{Im}\{Z_2\} = \left(|h'_{11}|^2 + |h'_{12}|^2 + |h'_{21}|^2 + |h'_{22}|^2\right) I_5 + j \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) Q_5 + \text{Re}\{N_3\} + j \text{Im}\{N_2\}$$

$$\text{Re}\{Z_4\} + j \text{Im}\{Z_1\} = \left(|h'_{11}|^2 + |h'_{12}|^2 + |h'_{21}|^2 + |h'_{22}|^2\right) I_7 + j \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) Q_7 + \text{Re}\{N_4\} + j \text{Im}\{N_1\}$$

Optimization of parameters a, b, c, d

- **Detector computes**

$$Z_1 = \frac{h_{11}^* y_1^1 + h_{21}^* y_1^2}{a} + \frac{h_{12} y_2^{1*} + h_{22} y_2^{2*}}{c^*}$$

- **Parameters a and c chosen as real numbers => avoid complex division at receiver**

$$a = c = \frac{1}{\sqrt{2}}$$

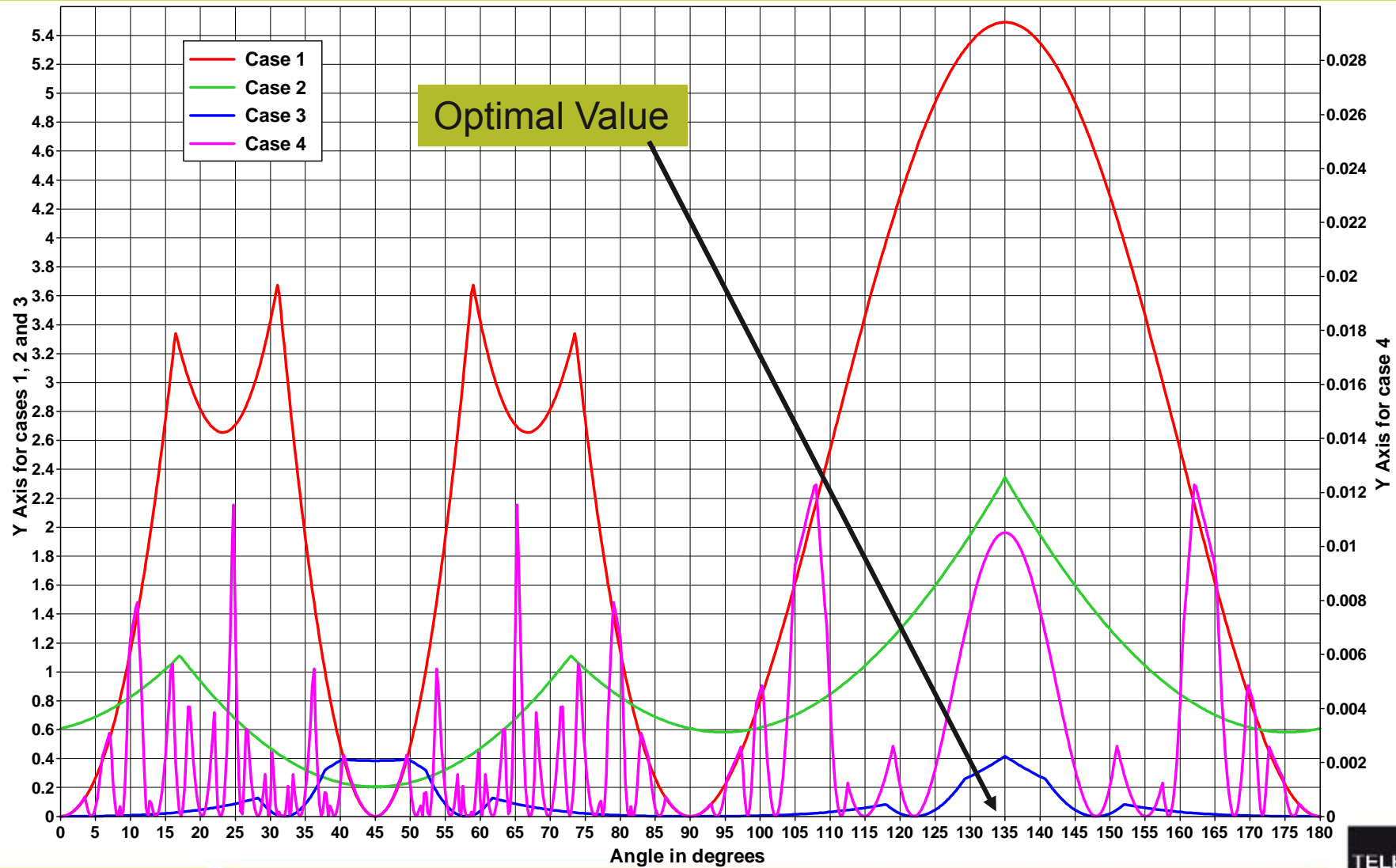
- **Parameters b and d have to be optimized to guarantee full diversity for all transmitted 8 symbols**

- **Criteria for optimization in different fading and erasure event scenarios have been derived**

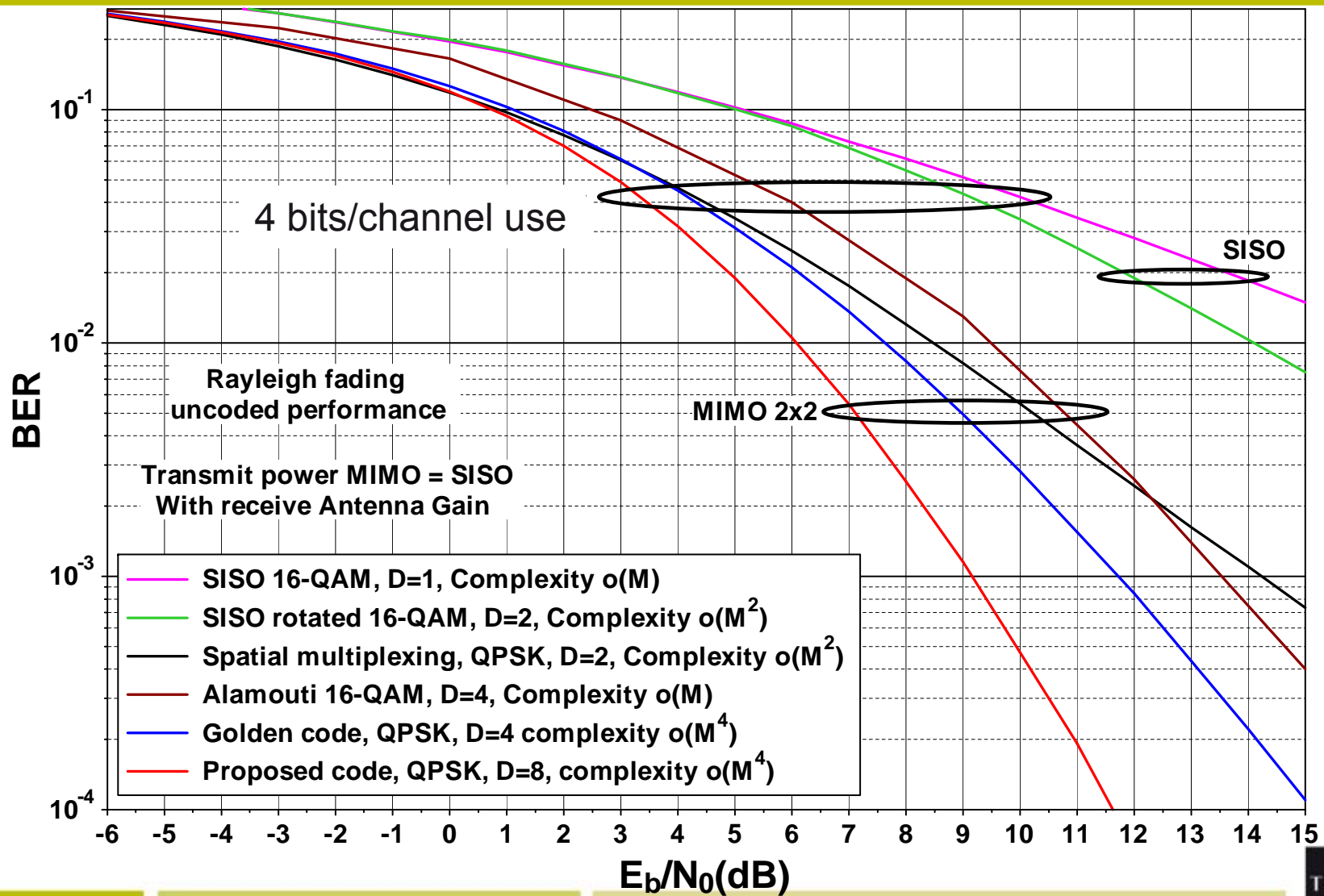
- Based on the determinant criteria

$$b = \frac{e^{j\varphi_1}}{\sqrt{2}} \quad d = b \cdot e^{j\varphi_2} \quad \varphi_2 = -90^\circ$$

Optimization results



Performance results



Conclusion

- **Design of signal space diversity showing an important improvement in performance over fading and erasure channels**
- **Gain increases with coding rates and erasure ratios**
- **Proposal of iterative demapping to improve performance or reduce complexity (in number of iterations)**
- **Low additional complexity**
- **Adopted in DVB-T2**
- **Construction of a high diversity STBC with the possibility of a reduced complexity detection**