PhD Defence, July 10th, 2017

The Physical Layer for Low Power Wide Area Networks: A Study of Combined Modulation and Coding Associated with an Iterative Receiver

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under the supervision of

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Vincent Berg

General Context

Internet-of-Things

Internet-of-Things (IoT)

"Global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies." [1]

=

Global infrastructure interconnecting things based on existing and evolving communication technologies

- things: sensors, actuators, but also vehicles, buildings
- existing [...] communication technologies: legacy networks are used
- evolving communication technologies: new networks must be deployed
- Estimated 10% of the IoT connections are done using Low Power Wide Area (LPWA) networks [2]

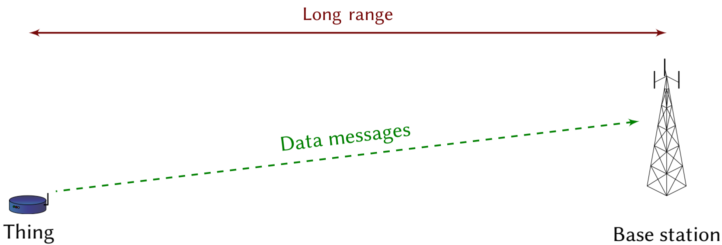
[1] International Telecommunication Union (ITU-T), *Overview of the Internet-of-Things*, 2012

[2] Rebbeck, Mackenzie, and Afonso, *Low-powered wireless solutions have the potential to increase the M2M market by over 3 billion connections*, 2014

General Context

Low Power Wide Area Networks

- LPWA Physical Layer requirements [3]



- **Long range** communication

[3] Machina Research, *LPWA Technologies - Unlock New IoT Market Potential*, 2014

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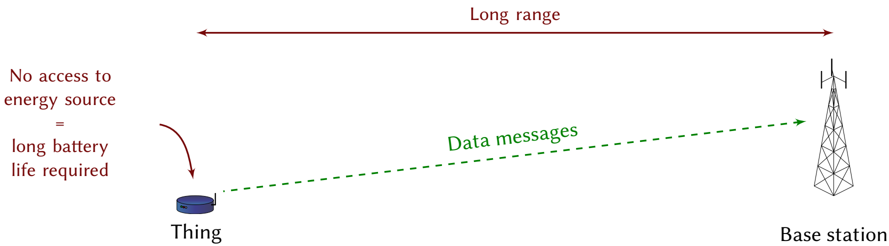

- **Long range** communication
- **Low energy consumption**: minimize the constraint on the power amplifier

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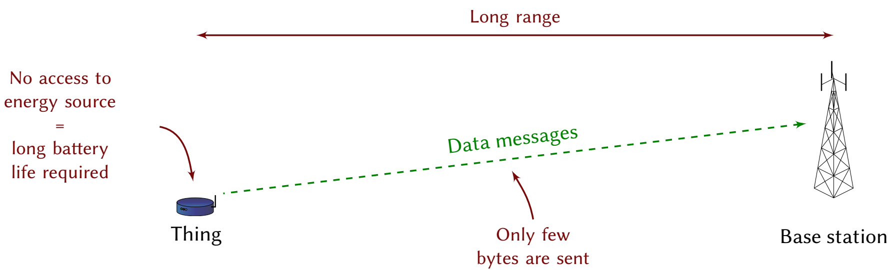

  - **Long range** communication
  - **Low energy consumption**: minimize the constraint on the power amplifier
- **Low data rate** is assumed

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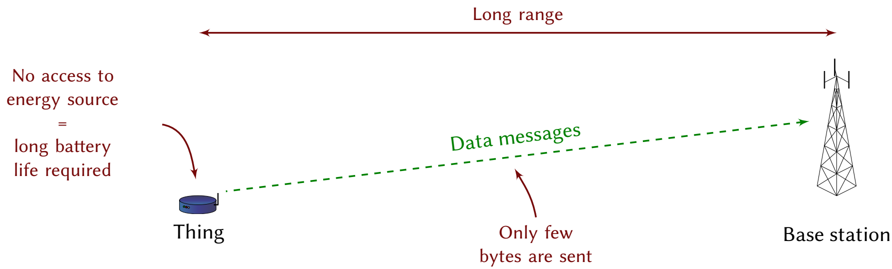

  - **Long range** communication
  - **Low energy consumption**: minimize the constraint on the power amplifier
- **Low data rate** is assumed
- Example of LPWA applications:
  - Water metering: water consumption is transmitted to the water provider
  - Parking sensors: detect available parking spots and inform customers

[3] Machina Research, *LPWA Technologies - Unlock New IoT Market Potential*, 2014

General Context

This work

- Analyze the problem of LPWA transmission and identify strategies
- Propose an innovative solution
- Study and optimize the scheme
- Confront its performance to the existing LPWA environnement and powerful solutions

Contents

Contents

Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

- How to achieve long range communication?

Friis Equation (free path loss)

$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

d: distance between TX and RX

Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

- How to achieve long range communication?

Friis Equation (free path loss)

Increase power at TX ?
Regulation problem

$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

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Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

- How to achieve long range communication?

Friis Equation (free path loss)

Increase antenna gains ?
Scaling problem

$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

d: distance between TX and RX

Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

- How to achieve long range communication?

Friis Equation (free path loss)

$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

Increase wavelength ?
(= reduce carrier frequency)
Regulation problem

d: distance between TX and RX

Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

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Friis Equation (free path loss)

$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

Reduce required power at RX ?

d: distance between TX and RX

Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

- How to achieve long range communication?

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$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

Reduce required power at RX ?

d: distance between TX and RX

- Required power at RX is characterized by the sensitivity (P_{req}):

Sensitivity of a Receiver (P_{req})

Level of received signal power P_r required for a specific Quality of Service (QoS)

Low Sensitivity, Strategies and Existing Solutions

Long Range and Sensitivity

- How to achieve long range communication?

Friis Equation (free path loss)

$$d^2 = \frac{P_t G_t G_r}{P_r} \left(\frac{\lambda_w}{4\pi} \right)^2$$

Reduce required power at RX ?

d: distance between TX and RX

- Required power at RX is characterized by the sensitivity (P_{req}):

Sensitivity of a Receiver (P_{req})

Level of received signal power P_r required for a specific Quality of Service (QoS)

- Long range can be achieved by ensuring a low level of sensitivity

Low Sensitivity, Strategies and Existing Solutions

Main strategies

Power of a signal (sensitivity)

$$P_{\text{req}} = \underbrace{E_{b\ \text{req}}}_{\text{Energy per bit required}} \cdot \underbrace{R}_{\text{Data Rate}}$$

- Reduce the sensitivity:
  - Reduce the data rate ➡ mandatory for long range solutions
  - Reduce E_b (intrinsic to the technique selected)

Low Sensitivity, Strategies and Existing Solutions

Main strategies

Power of a signal (sensitivity)

$$P_{\text{req}} = E_{b\ \text{req}} \cdot R$$

Energy per bit required

Data Rate

- Reduce the sensitivity:
  - Reduce the data rate ➡ mandatory for long range solutions
  - Reduce E_b (intrinsic to the technique selected)
- Commonly used metric for receivers: the Signal-to-Noise Ratio (SNR)

Signal-to-Noise Ratio

Signal Power

Spectral efficiency (bits/s/Hz)

$$\text{SNR} = \frac{P}{N_0 B} = \frac{E_b}{N_0} \times \frac{R}{B} = \frac{E_b}{N_0}\eta$$

Noise Spectral Density

Bandwidth

Ratio: SNR per bit

Low Sensitivity, Strategies and Existing Solutions

Main strategies

Sensitivity (in dBm, at 15°C)

$$P_{\text{req}}^{\text{dBm}} = (\text{SNR})_{\text{min}}^{\text{dB}} + 10\log_{10}(B) - 174$$

- Two main strategies:
  - Reduce the bandwidth B (narrow band signaling)
  - Reduce the required SNR

Low Sensitivity, Strategies and Existing Solutions

Main strategies

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Main strategies

Sensitivity (in dBm, at 15°C)

$$P_{\text{req}}^{\text{dBm}} = (\text{SNR})_{\text{min}}^{\text{dB}} + 10\log_{10}(B) - 174$$

- Two main strategies:
  - Reduce the bandwidth B (narrow band signaling)
  - Reduce the required SNR
- $\text{SNR} = \dfrac{E_b}{N_0} \cdot \eta$
  - Reduce the spectral efficiency η
  - Reduce the E_b/N_0 required for the QoS
  - Reduce both

Low Sensitivity, Strategies and Existing Solutions

Main strategies: Reduce the spectral efficiency

- Reduce the spectral efficiency η: repetition factor
  - Information bits are repeated λ times
  - Receiver recombines the repetitions

Low Sensitivity, Strategies and Existing Solutions

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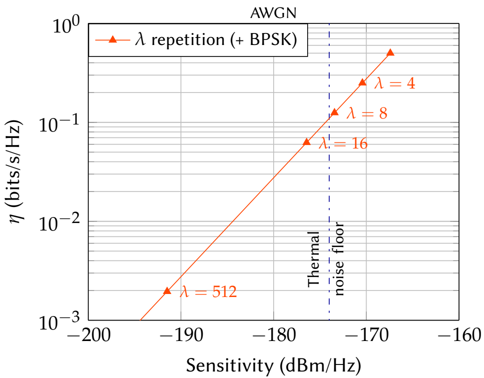

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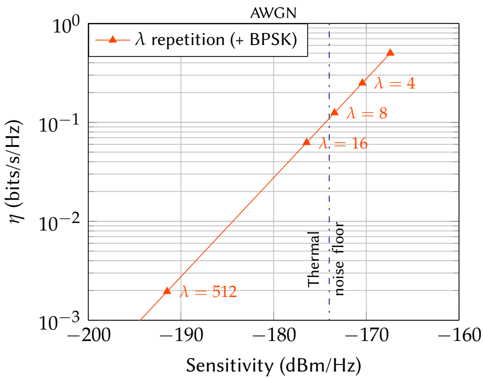
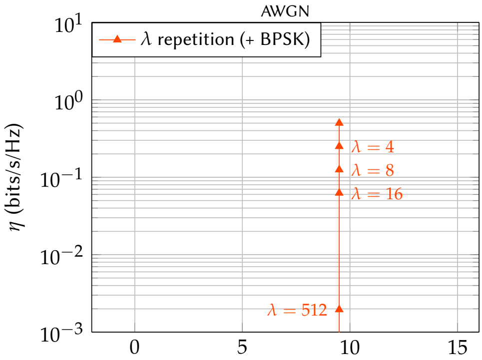




E_b/N_0 (dB) $= P_{\mathrm{req(dBm)}} - 10\log_{10}(\eta) + 174$

Low Sensitivity, Strategies and Existing Solutions

Main strategies: Reduce both η and E_b/N_0

- Reduce both η and E_b/N_0: M-ary orthogonal modulation
- Principle:
  - M: size of the alphabet
  - Distinct elements of the alphabet are orthogonal to each other
  - Scalar product between two symbols $\boldsymbol{s}_i$ and $\boldsymbol{s}_k$ of the alphabet:

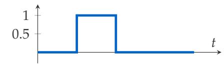
$$\langle \boldsymbol{s}_i,\ \boldsymbol{s}_k \rangle = 0$$

  - Groups of $\log_2(M)$ bits have a unique association to one symbol from the alphabet

Low Sensitivity, Strategies and Existing Solutions

Main strategies: Reduce both η and E_b/N_0

- Reduce both η and E_b/N_0: M-ary orthogonal modulation
- Example
  - Pulse Position Modulation (PPM): time localization
  - Alphabet for $M = 4$:

Binary information word	PPM symbol	Analog PPM symbol
0 0	1 0 0 0	
0 1	0 1 0 0	
1 1	0 0 1 0	
1 0	0 0 0 1	

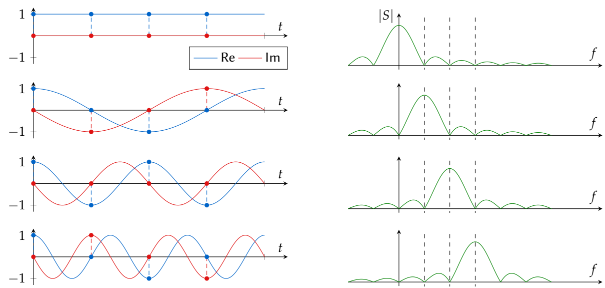
Low Sensitivity, Strategies and Existing Solutions

Main strategies: Reduce both η and E_b/N_0

- Reduce both η and E_b/N_0: M-ary orthogonal modulation
- Example
  - Frequency Shift Keying (FSK): frequency localization
  - Alphabet for $M = 4$:

Binary information word	FSK symbol (time domain)
0 0	1 1 1 1
0 1	1 $-j$ -1 j
1 1	1 -1 1 -1
1 0	1 j -1 $-j$

Analog FSK symbol (time domain) | Analog FSK symbol (frequency domain)

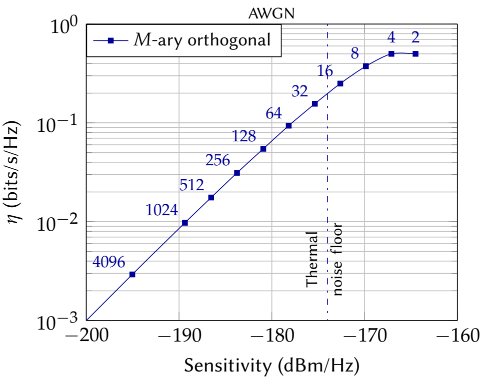


  - Instantaneous power of the signal equal to 1: constant envelope

Low Sensitivity, Strategies and Existing Solutions

Main strategies: Reduce both η and E_b/N_0

- Reduce both η and E_b/N_0: M-ary orthogonal modulation
- Performance



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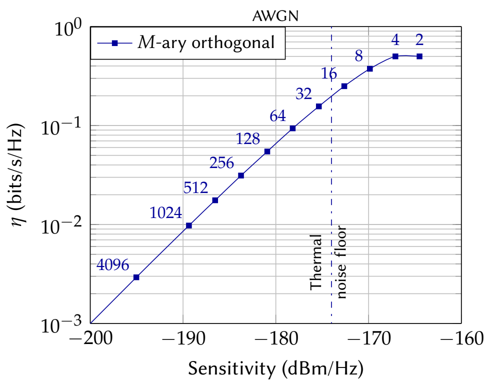
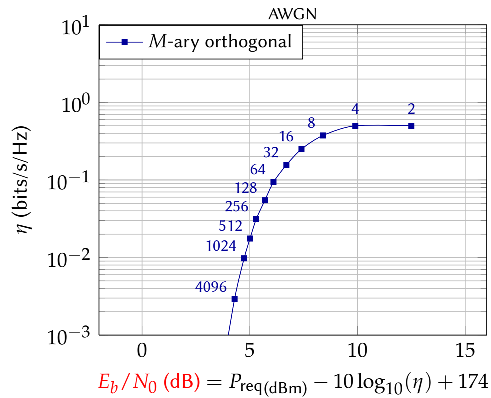




Low Sensitivity, Strategies and Existing Solutions

Main strategies

- These techniques allow for low levels of sensitivity
- Are they efficient regarding the limits of the information theory ?

Low Sensitivity, Strategies and Existing Solutions

Maximum Achievable Spectral Efficiency

Shannon Theorem

The maximum achievable data rate (the capacity) over Additive White Gaussian Noise (AWGN) for an arbitrarily small level of error is given by [4]:

$$C = B \cdot \log_2 (1 + \mathrm{SNR})$$

- Reaching the limit = efficient use the resource

Maximum Achievable Spectral Efficiency

$$\eta_{\mathrm{max}} = \frac{C}{B} = \log_2 (1 + \mathrm{SNR})$$

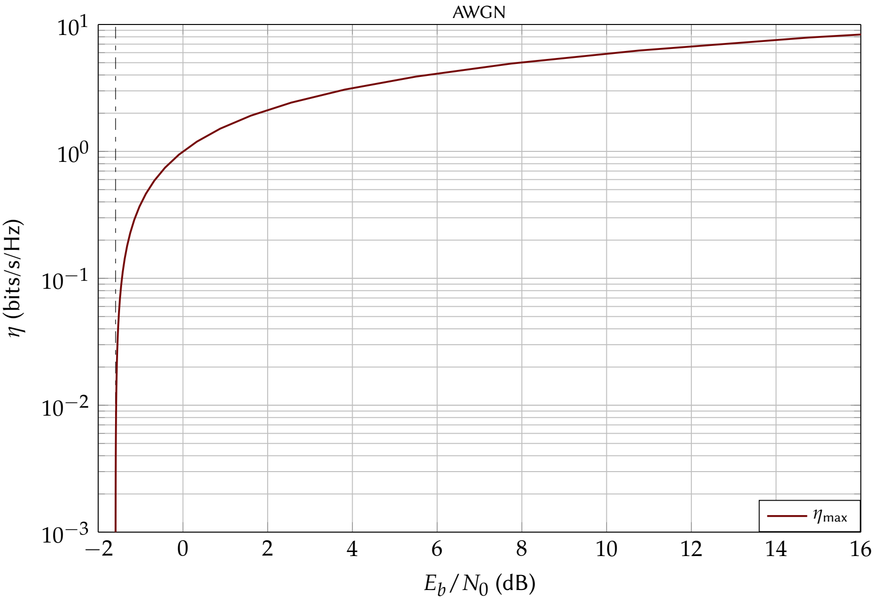
- Expressed in E_b/N_0, the limit is

$$\left(\frac{E_b}{N_0}\right)_{\mathrm{min}} = \frac{2^{\eta} - 1}{\eta} \xrightarrow[\eta \to 0]{} -1.59\mathrm{dB}$$

[4] Shannon, "A mathematical theory of communication", 1948

Low Sensitivity, Strategies and Existing Solutions

Maximum Achievable Spectral Efficiency



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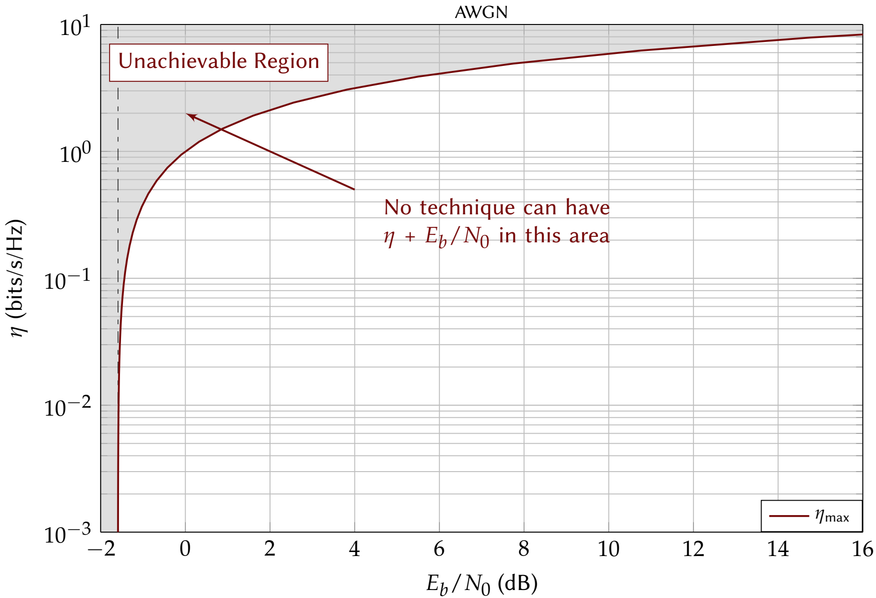

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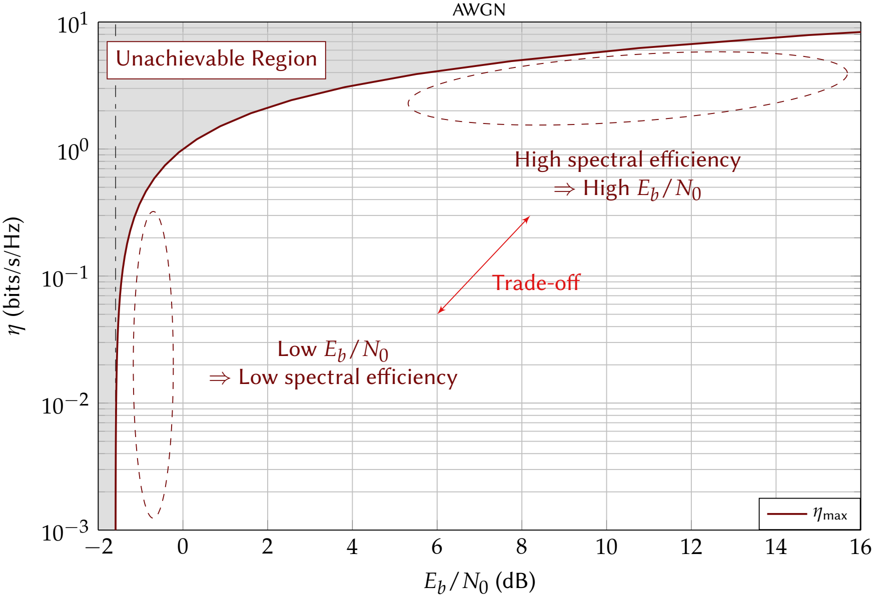

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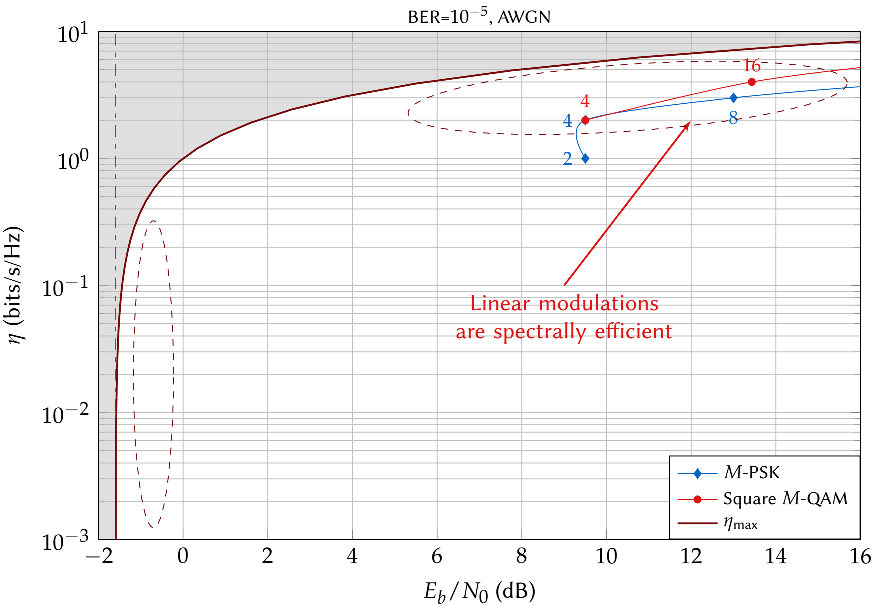

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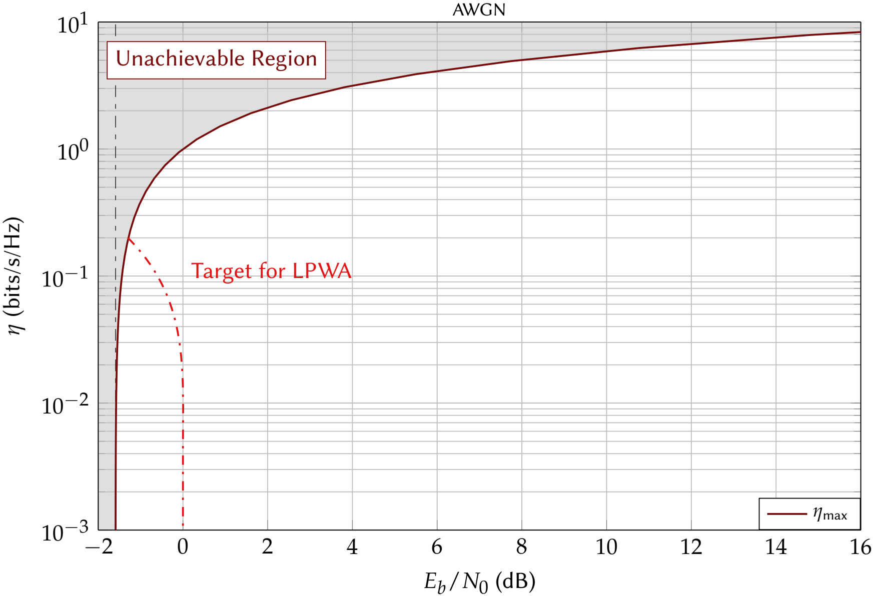

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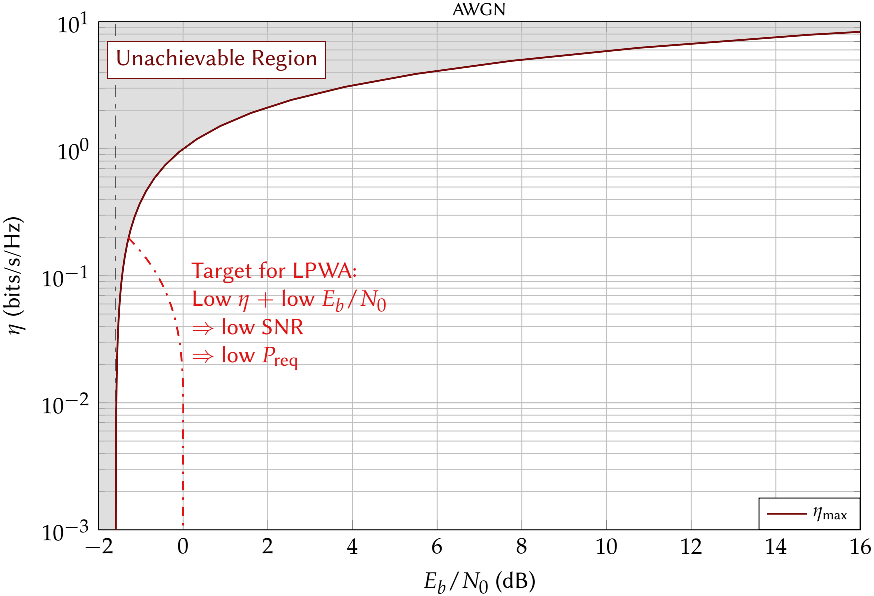

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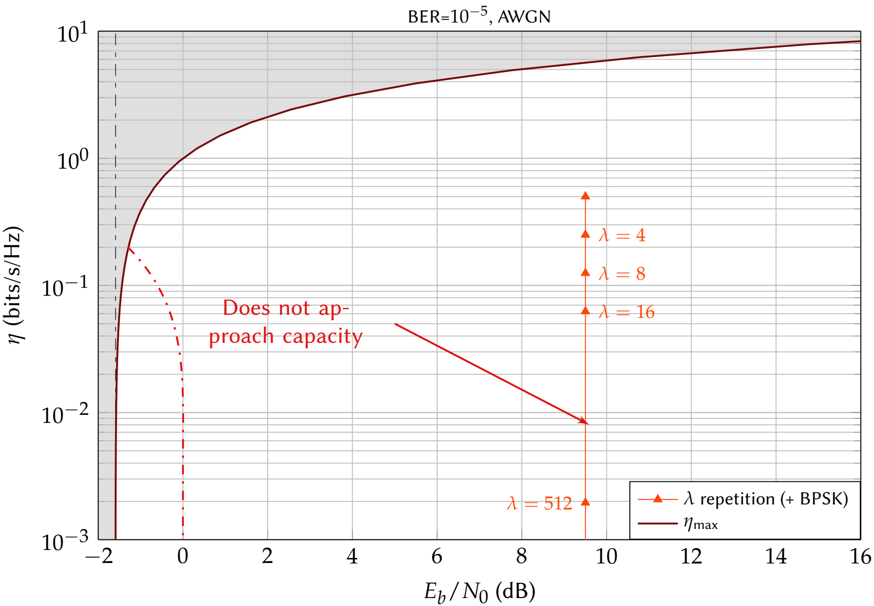

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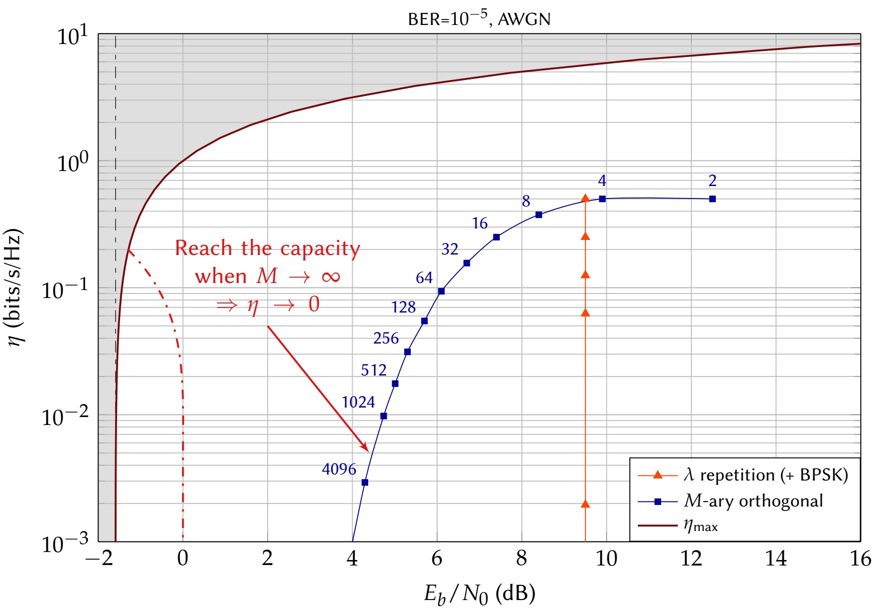
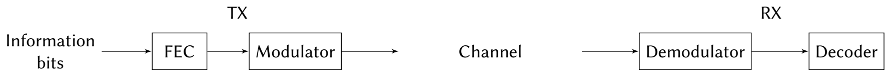


Low Sensitivity, Strategies and Existing Solutions

Forward Error Correction

- Are they efficient regarding the limits of the information theory ? NO
- Additional gain in E_b/N_0 can be obtained using Forward Error Correction (FEC)



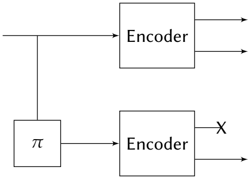
- Principle:
  - Redundancy is added at the transmitter side (reduces η)
  - The receiver uses this redundancy to reduce the E_b/N_0 required for the QoS
- Various families: block codes, convolutional codes, ...
- Some families can even reach the capacity (LDPC, Polar Codes [5])

[5] Arikan, "Channel Polarization: A Method for Constructing Capacity-Achieving Codes for Symmetric Binary-Input Memoryless Channels", 2009

Low Sensitivity, Strategies and Existing Solutions

Forward Error Correction: Turbo Codes

- Turbo Code [6] is a powerful FEC scheme
- Principle (TX):



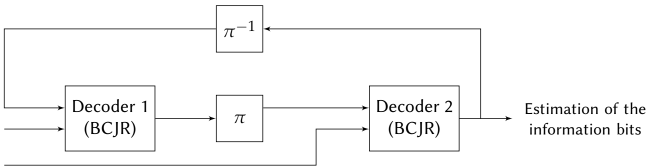
  - Two interleaved versions of the message are encoded and sent

[6] Berrou, Glavieux, and Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo-codes", 1993

Low Sensitivity, Strategies and Existing Solutions

Forward Error Correction: Turbo Codes

- Turbo Code [6] is a powerful FEC scheme
- Principle (RX):



  - Probabilistic decoding
  - Two decoders use the Bahl, Cocke, Jelinek and Rajiv (BCJR) algorithm [7]
  - Iterative decoding: exchange of information between the two decoders

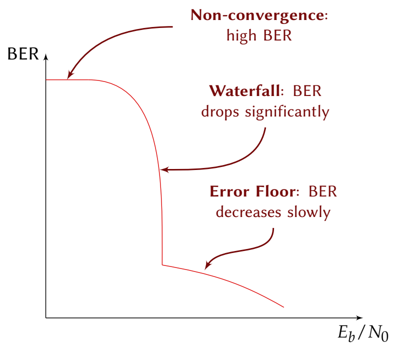
[6] Berrou, Glavieux, and Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo-codes", 1993

[7] Bahl et al., "Optimal decoding of linear codes for minimizing symbol error rate (Corresp.)", 1974

Low Sensitivity, Strategies and Existing Solutions

Forward Error Correction: Turbo Codes

- Turbo Code [6] is a powerful FEC scheme
- Typical Bit Error Rate (BER) performance:



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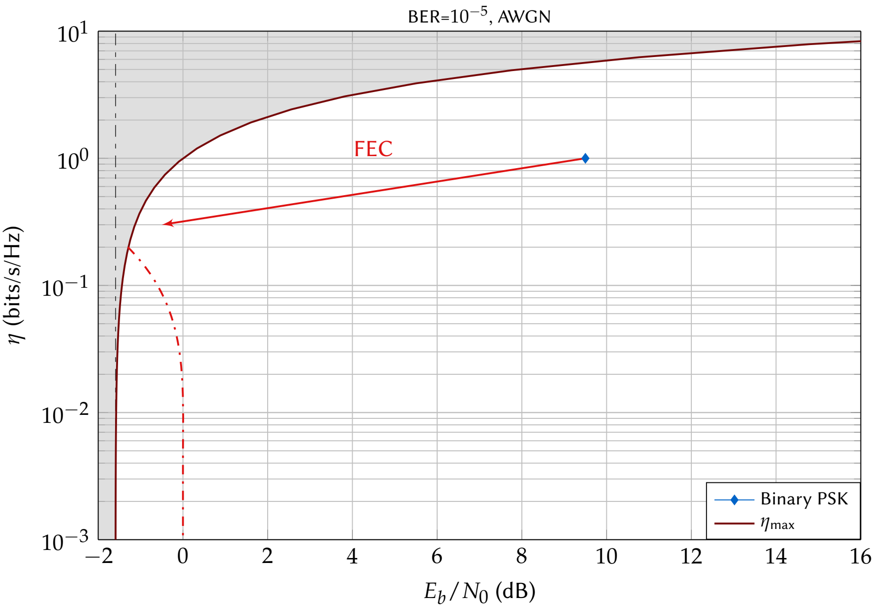
Low Sensitivity, Strategies and Existing Solutions

Forward Error Correction



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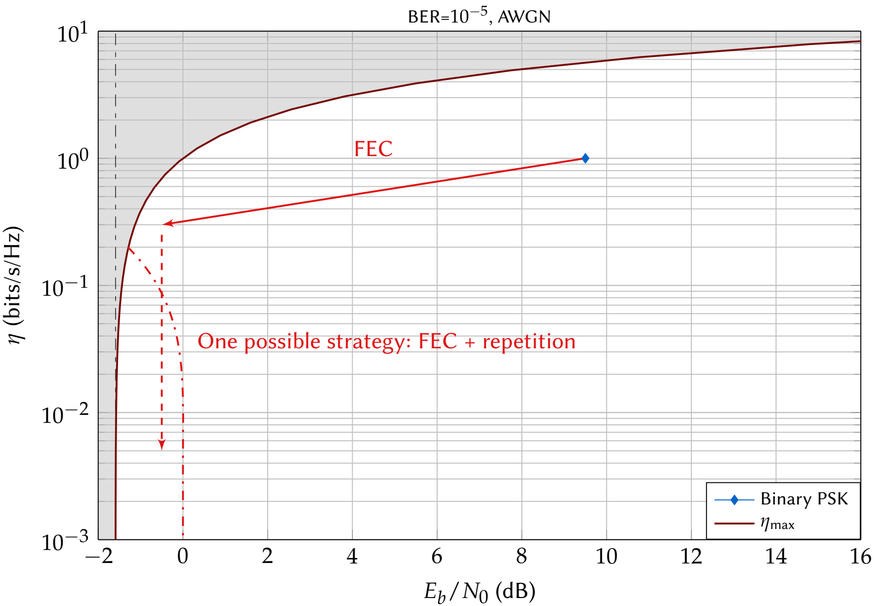


Low Sensitivity, Strategies and Existing Solutions

Existing Solutions

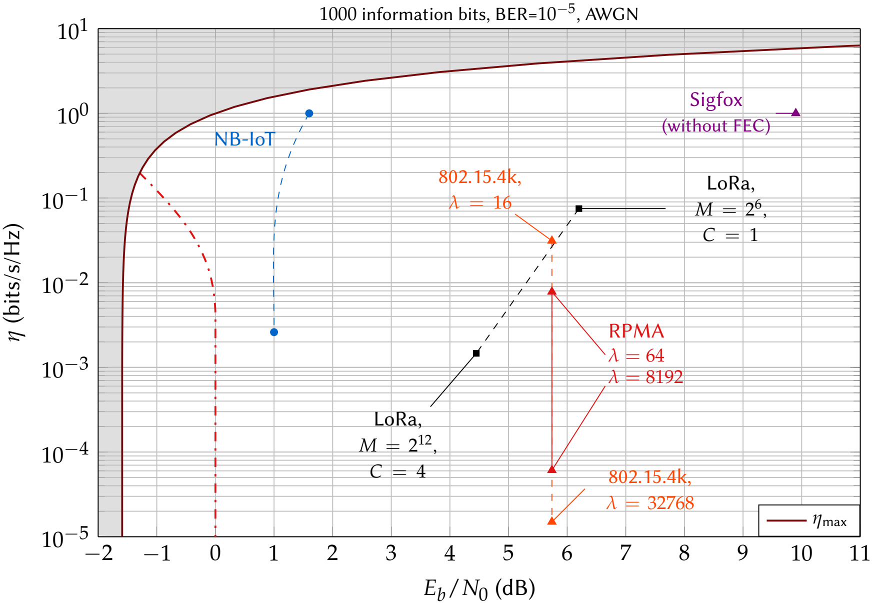
- What are the strategies selected by the existing solutions ?
- The solutions mix fundamental techniques (modulation or FEC)

PHY-layer	Modulation	FEC
Sigfox	DBPSK	?
LoRa based	Orthogonal	Hamming
802.15.4k, RPMA	DBPSK	CC [171 133] + repetition
NB-IoT based	BPSK/QPSK	TC [13 15] + repetition

- Large number of possible configurations, resulting in various levels of η
- Performance over AWGN for small information block size (1000 bits or 125 bytes)

Low Sensitivity, Strategies and Existing Solutions

Existing Solutions



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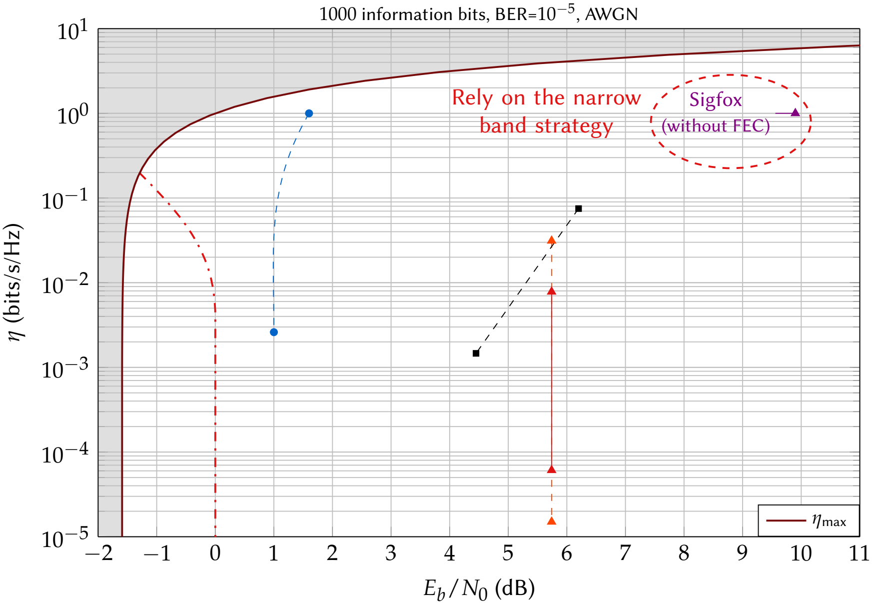

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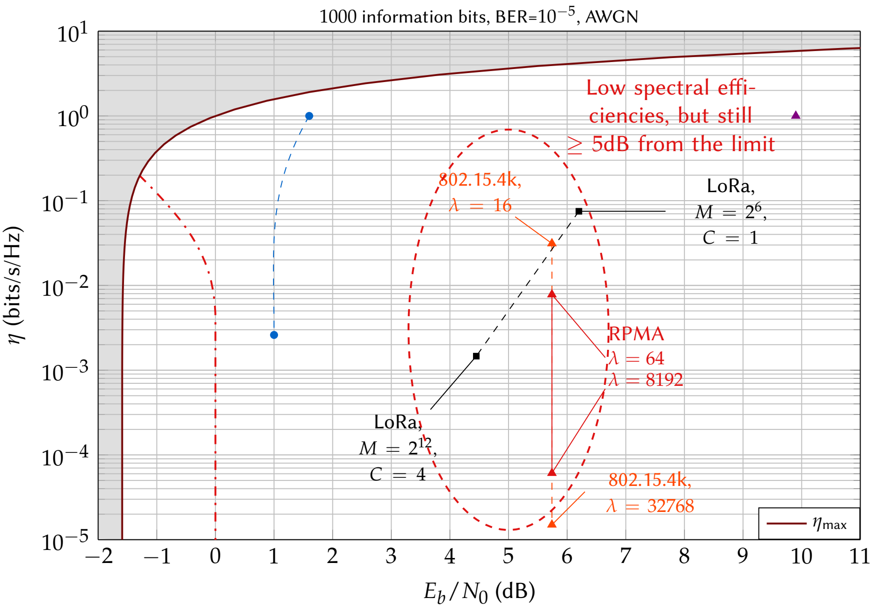

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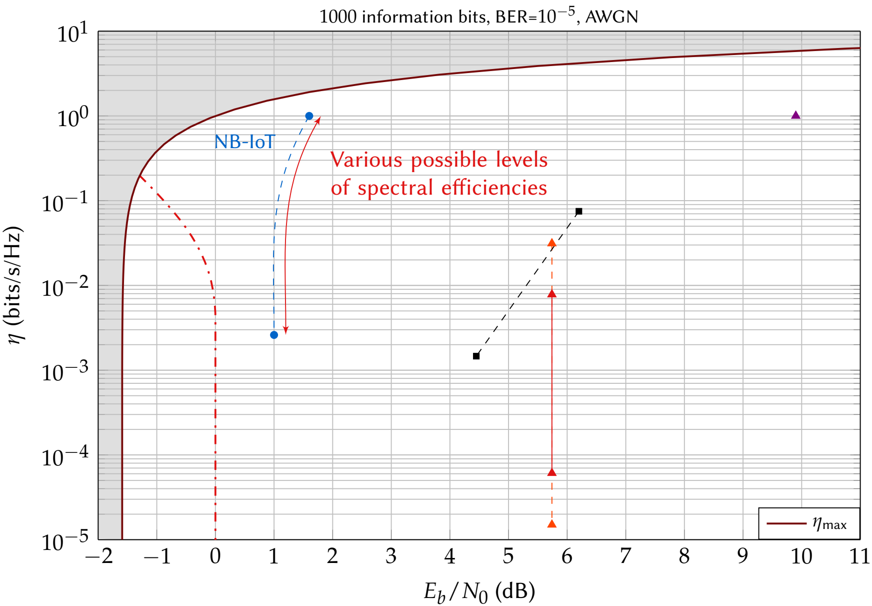

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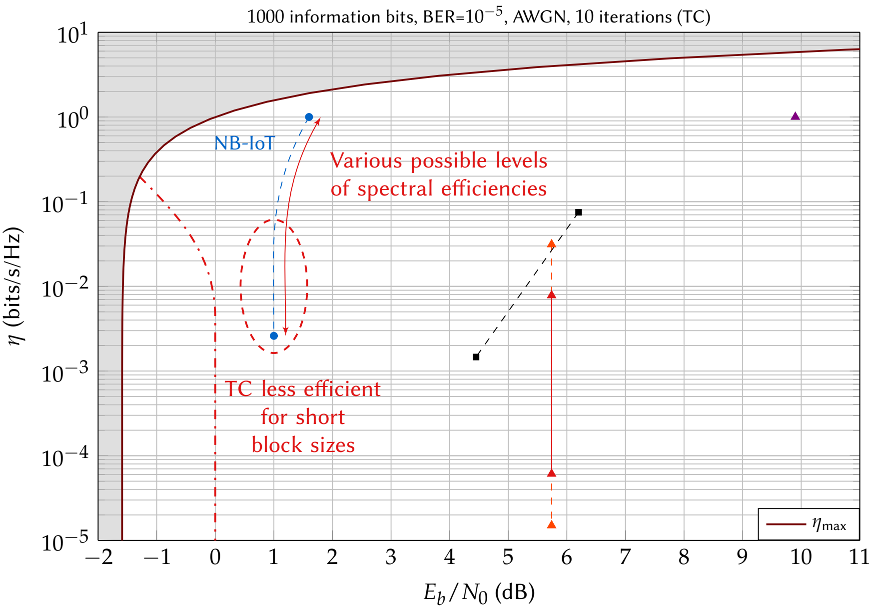

Low Sensitivity, Strategies and Existing Solutions

Conclusion

- LPWA requirements:
  - **Long range**: requires low levels of sensitivity
  - **Low energy consumption**: minimize the variations of the envelope
- **Low data rate** is assumed (+ short block sizes)
- Target area: low η + low E_b/N_0
- Best technique so far: use a TC + repetition (NB-IoT)
  - Offers a large range of spectral efficiency i.e. more applications
  - Short block size: reduce the performance

Low Sensitivity, Strategies and Existing Solutions

Conclusion

- Alternative to the strategy FEC + repetition: use ultra low rate FEC
- Example: Turbo-Hadamard [7]
  - Based on the combination of a binary orthogonal block code (Hadamard codes) and a convolutional code
  - Uses a turbo receiver
  - Very low E_b / N_0

[7] Ping, Leung, and Wu, "Low-rate turbo-Hadamard codes", 2003

Low Sensitivity, Strategies and Existing Solutions

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Our work

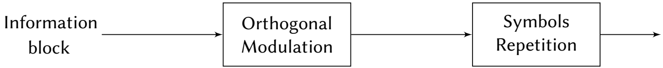
We propose an extension of the initial scheme Turbo-Hadamard: **Coplanar Turbo-FSK**

[7] Ping, Leung, and Wu, "Low-rate turbo-Hadamard codes", 2003

Contents

Coplanar Turbo-FSK

Origins



Coplanar Turbo-FSK

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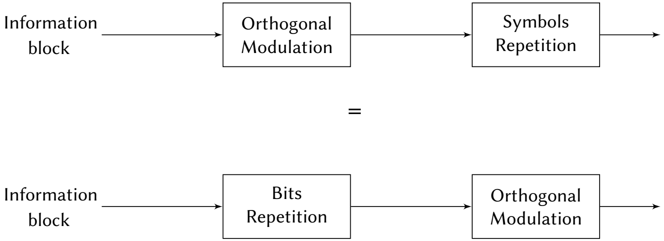

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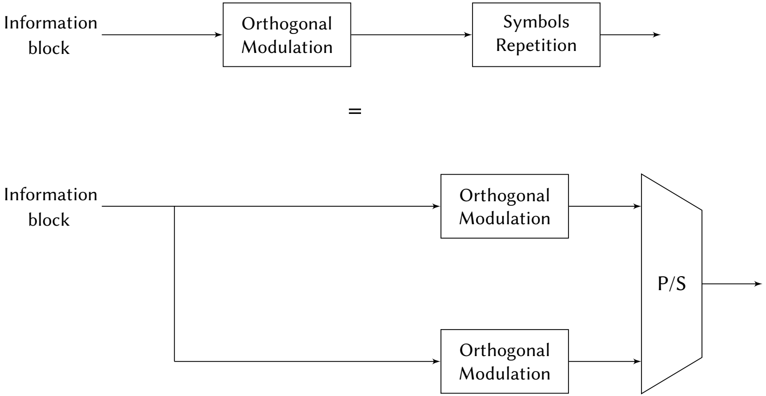
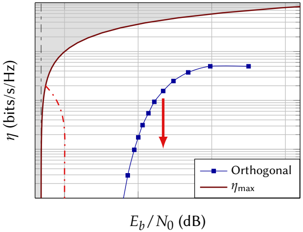
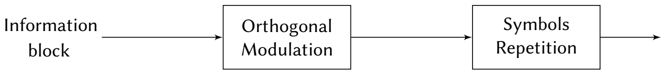


Coplanar Turbo-FSK

Origins





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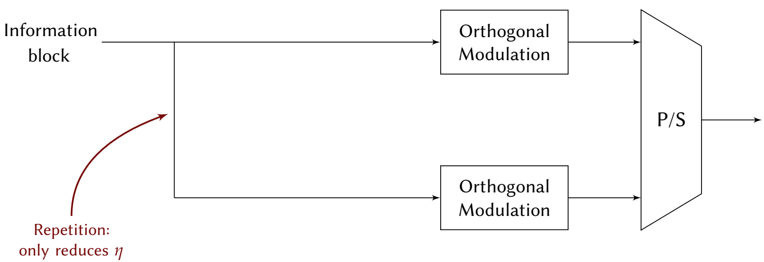

Coplanar Turbo-FSK

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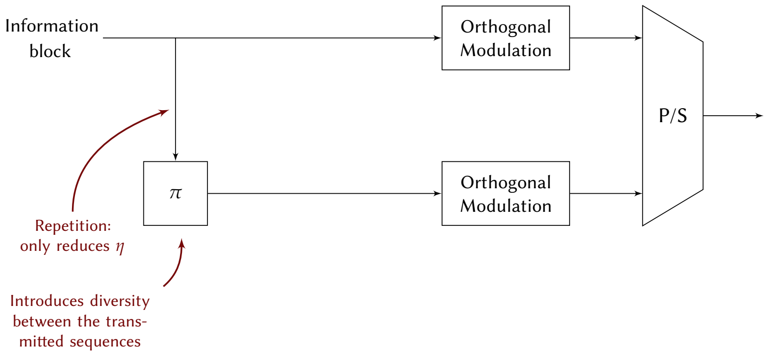
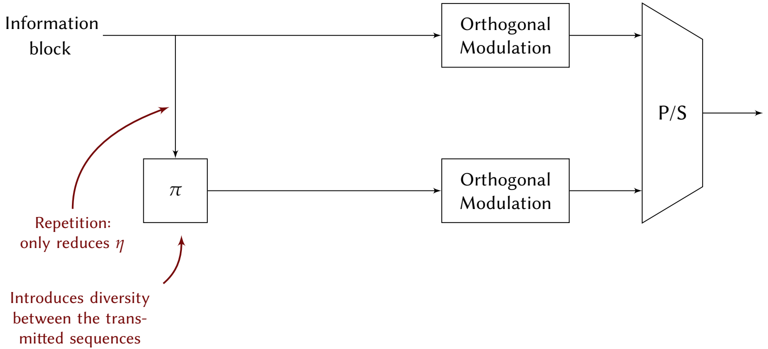


Coplanar Turbo-FSK

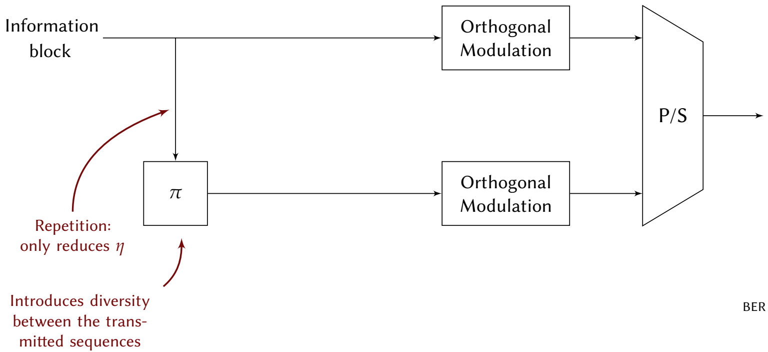
Origins



<u>Receiver</u>: can use diversity to improve E_b/N_0 (turbo receiver)

Coplanar Turbo-FSK

Origins



<u>Receiver</u>:
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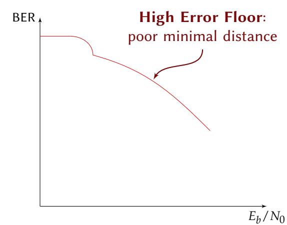
<u>Problem</u>:
poor performance



Coplanar Turbo-FSK

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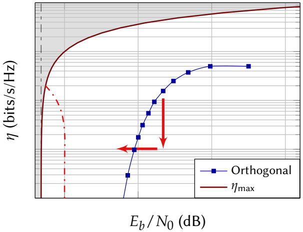
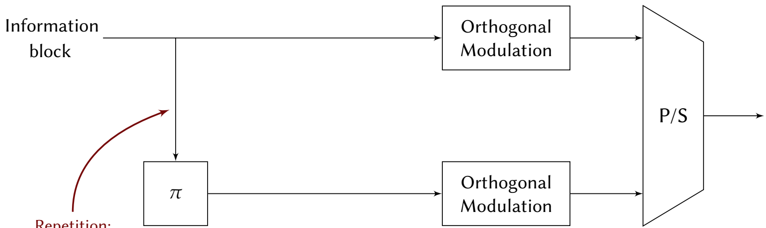


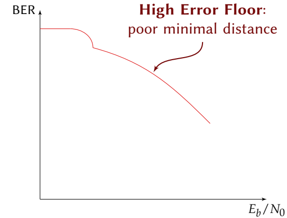


Repetition:
only reduces η

Introduces diversity between the transmitted sequences

Receiver:
can use diversity to improve E_b/N_0 (turbo receiver)

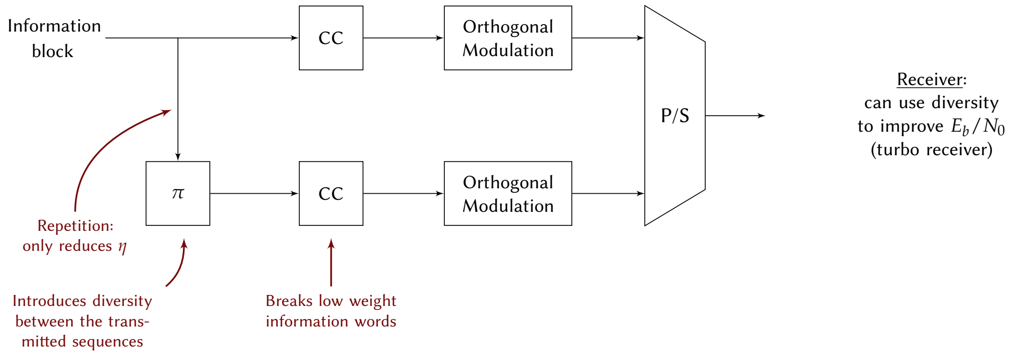
Problem:
poor performance



High Error Floor:
poor minimal distance

Coplanar Turbo-FSK

Origins



Coplanar Turbo-FSK

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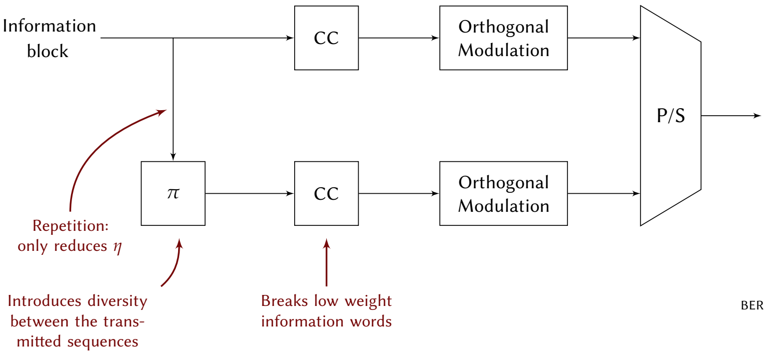

<u>Receiver</u>:
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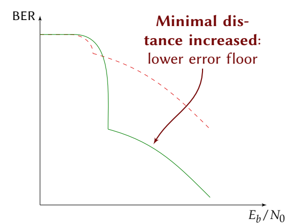
<u>Performance</u>:



Coplanar Turbo-FSK

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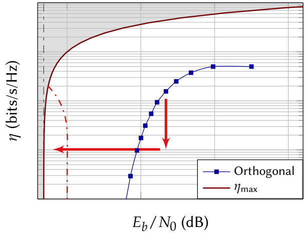

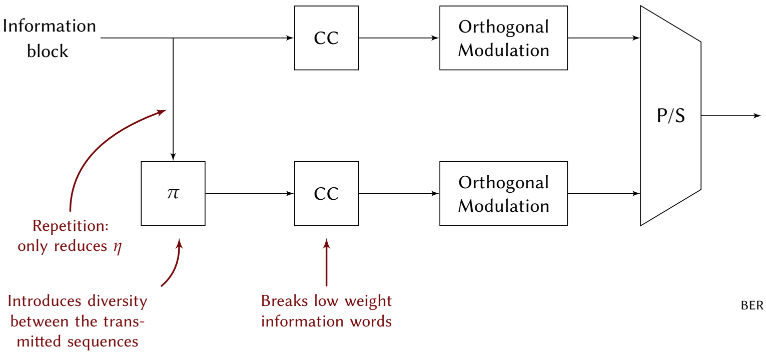

Receiver: can use diversity to improve E_b/N_0 (turbo receiver)

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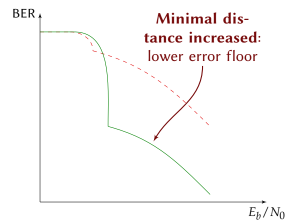

Coplanar Turbo-FSK

Origins

- Turbo-Hadamard FEC scheme [8]:
  - Uses binary Hadamard codes as orthogonal alphabet
  - More than two encoders can/should be used
  - Various possible choices for the convolutive part
- Low rate, high performance

[8] Ping, Leung, and Wu, "Low-rate turbo-Hadamard codes", 2003

Coplanar Turbo-FSK

Origins

- Turbo-Hadamard FEC scheme [8]:
  - Uses binary Hadamard codes as orthogonal alphabet
  - More than two encoders can/should be used
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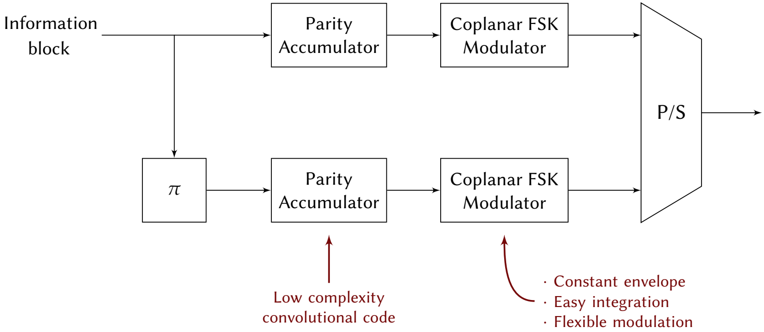
Our proposition

Coplanar Turbo-FSK: a modulation scheme inspired by the Turbo Hadamard FEC

[8] Ping, Leung, and Wu, "Low-rate turbo-Hadamard codes", 2003

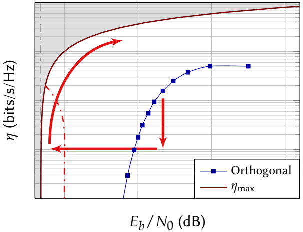
Coplanar Turbo-FSK

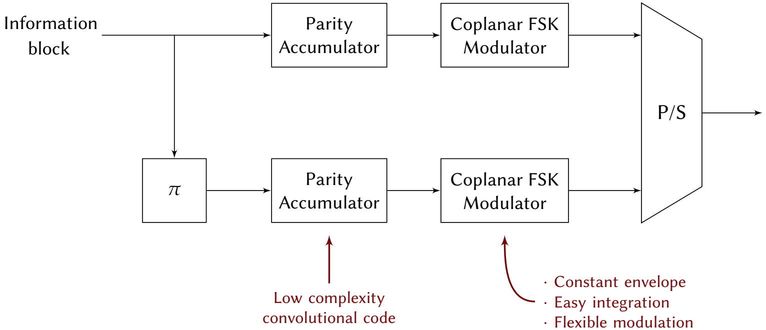
Origins



Coplanar Turbo-FSK

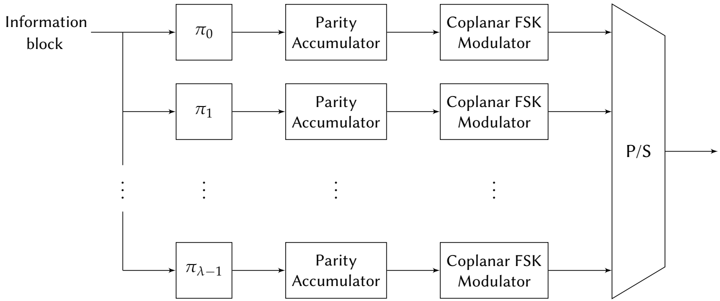
Origins





Coplanar Turbo-FSK

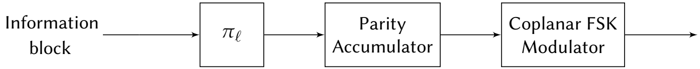
Transmitter Overview



- λ stages = the Q bits are encoded λ times
- Each stage performs the same operations

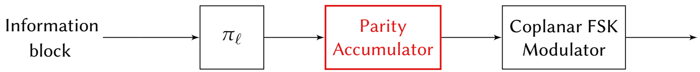
Coplanar Turbo-FSK

Transmitter Overview

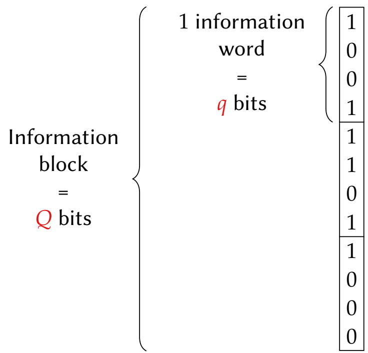


Coplanar Turbo-FSK

Encoder

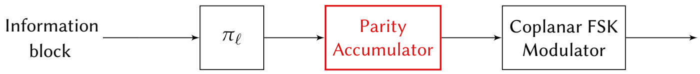


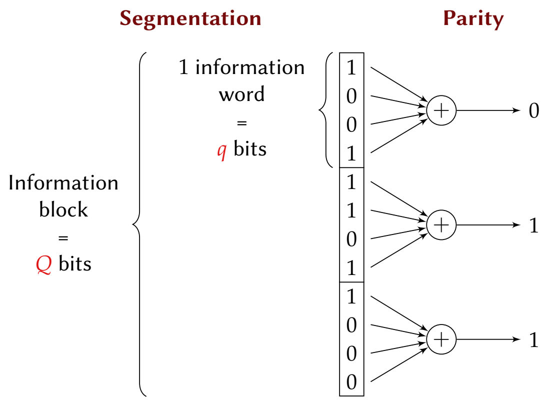
Segmentation



Coplanar Turbo-FSK

Encoder





Coplanar Turbo-FSK

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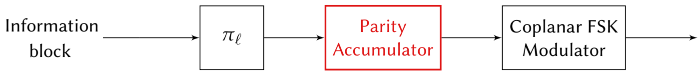

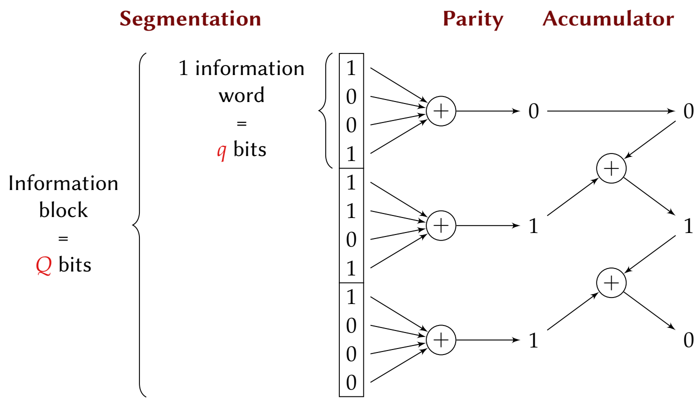

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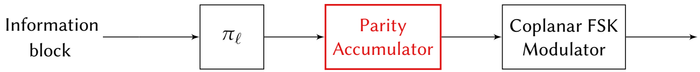

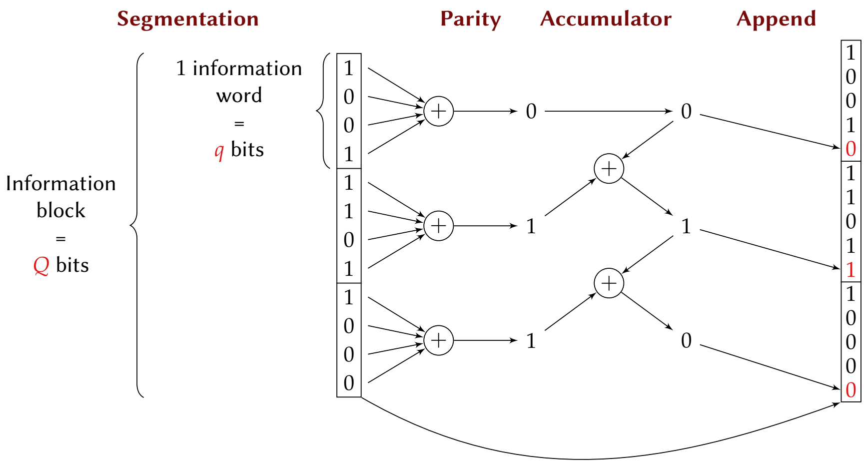

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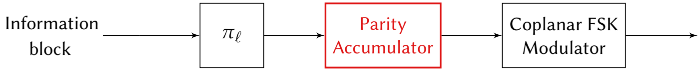
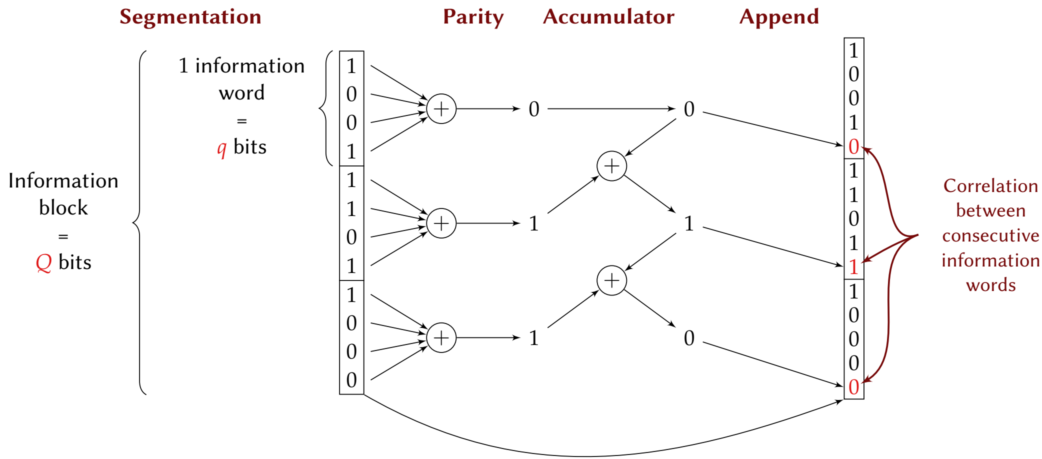
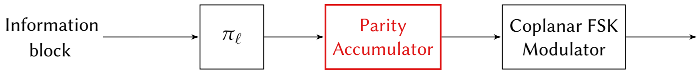
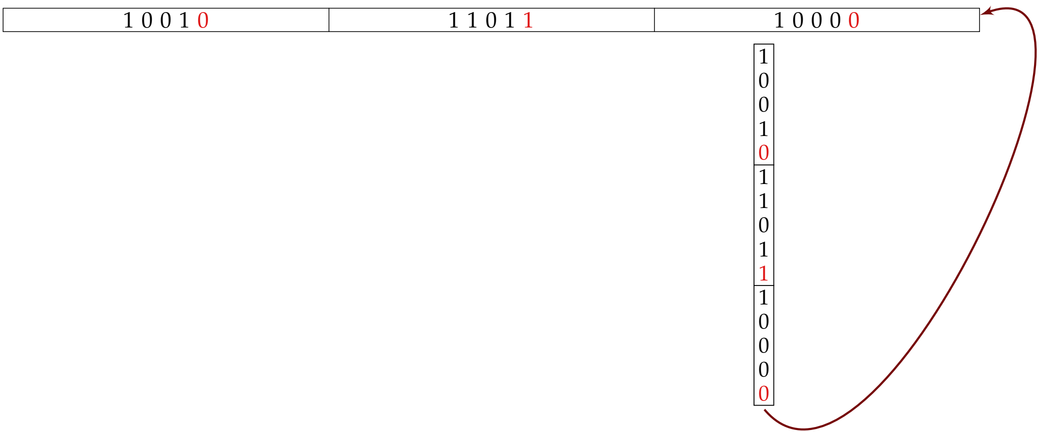




Coplanar Turbo-FSK

Trellis





Coplanar Turbo-FSK

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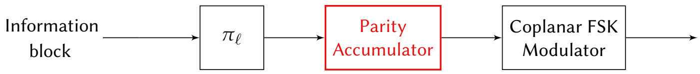

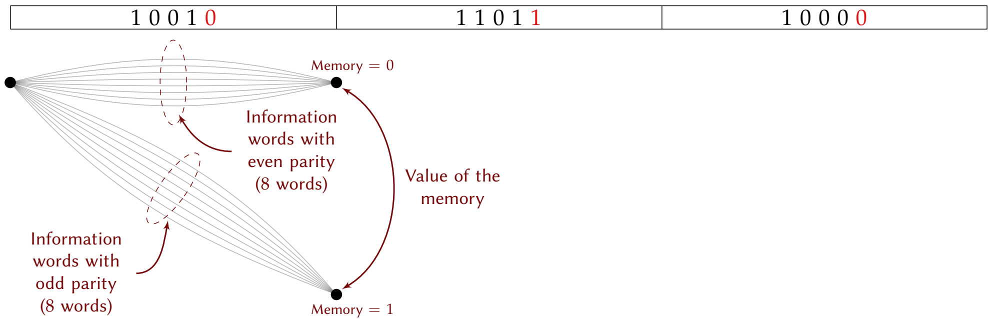

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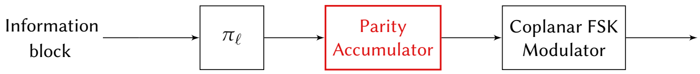

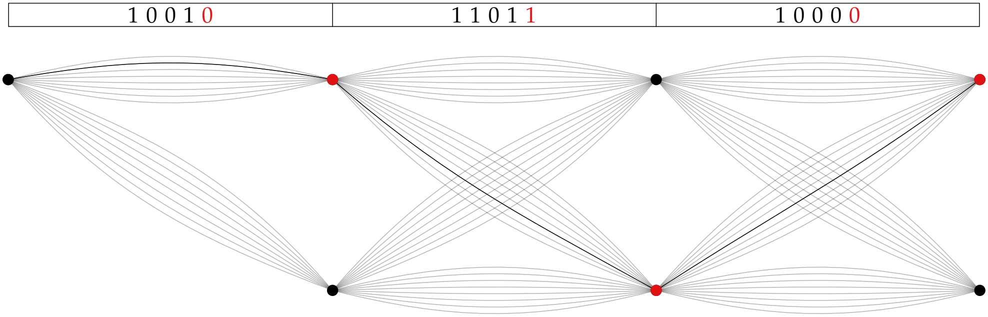

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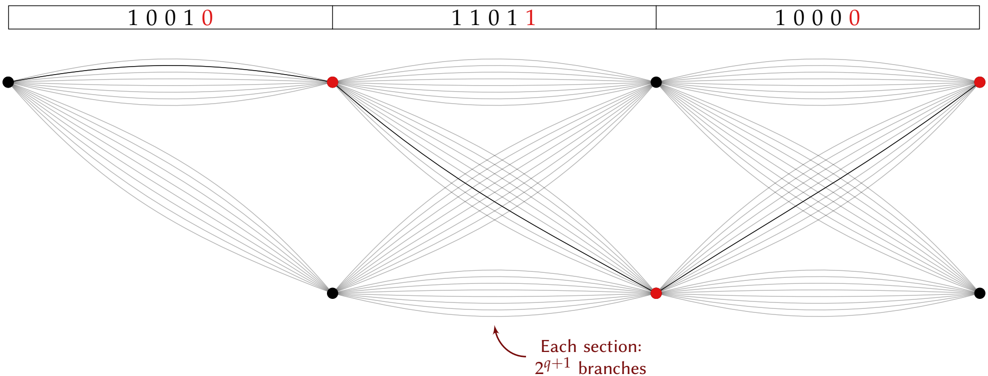
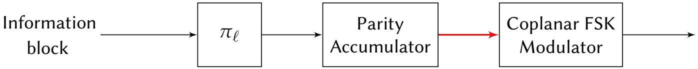
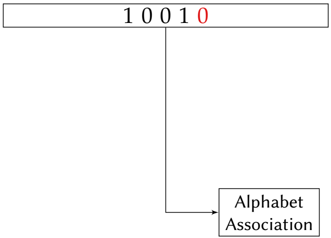
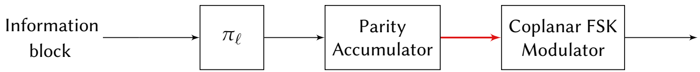


Coplanar Turbo-FSK

Modulation: Alphabet Association







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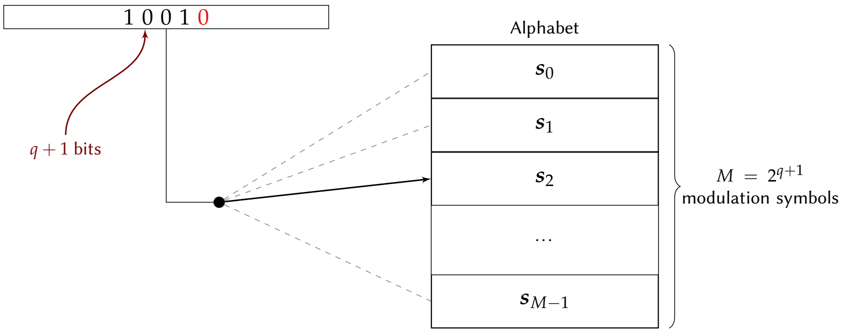

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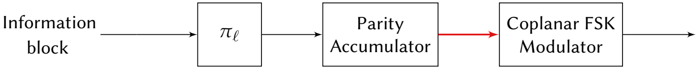
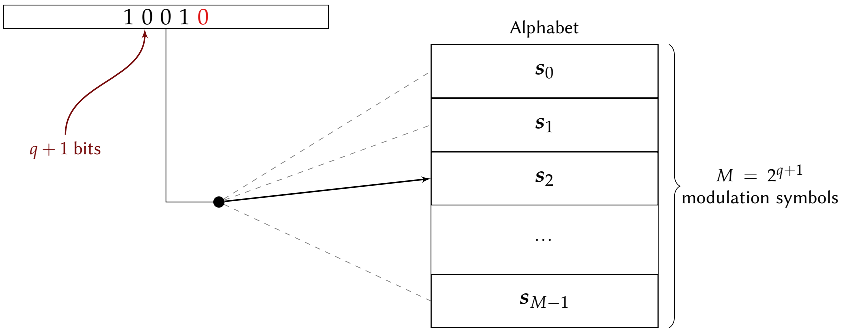
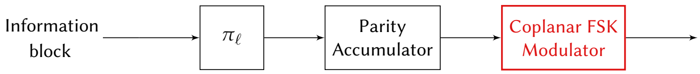




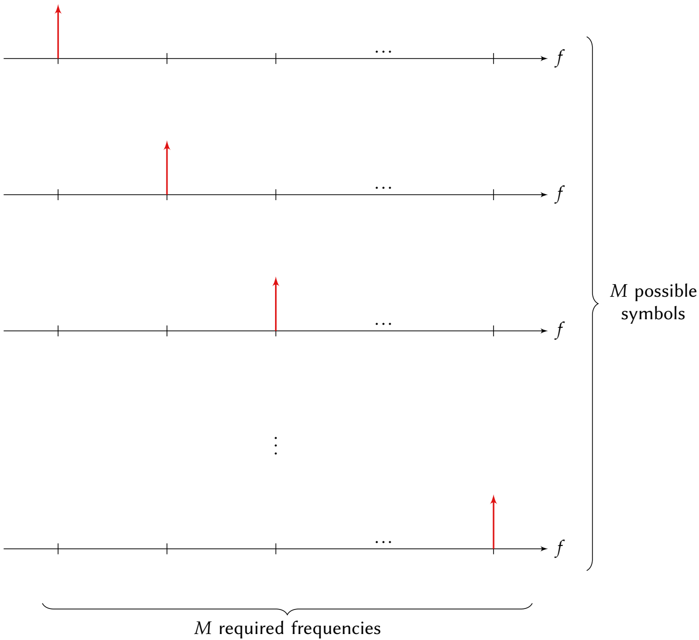
- How is the alphabet constructed ? Coplanar FSK

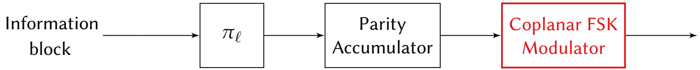


Coplanar Turbo-FSK

Modulation: Alphabet Design

- Orthogonal case: FSK



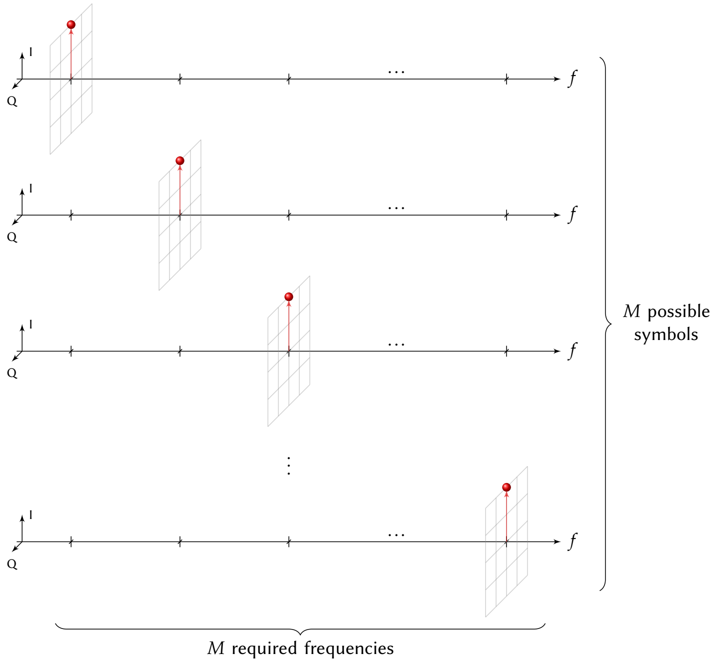


Coplanar Turbo-FSK

Modulation: Alphabet Design

- Orthogonal case: FSK
- At each frequency: a complex plane with one possible point
- $\log_2(M)$ bits in M dimensions:

$$\eta = \frac{\log_2(M)}{M}$$

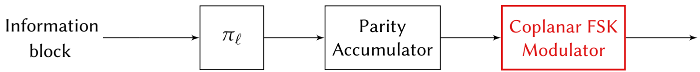


Information block → π_ℓ → Parity Accumulator → Coplanar FSK Modulator →

Coplanar Turbo-FSK

Modulation: Alphabet Design

- Coplanar FSK:
  - Allow N_L points ($N_L \geq 1$) for each frequency
  - Coplanar values are roots of the unity
  - Only subsets of the alphabet are orthogonal

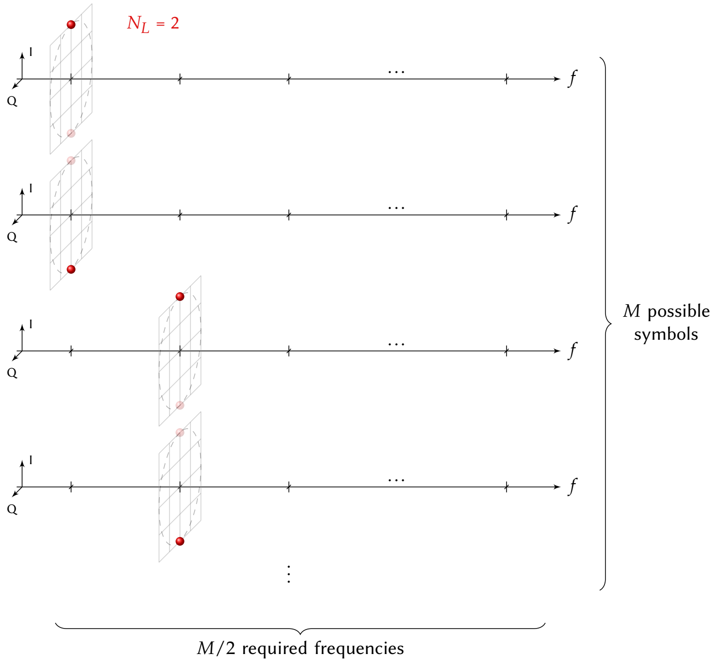


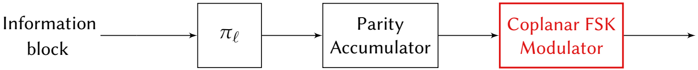
Coplanar Turbo-FSK

Modulation: Alphabet Design

- Coplanar FSK:
  - Allow N_L points ($N_L \geq 1$) for each frequency
  - Coplanar values are roots of the unity
  - Only subsets of the alphabet are orthogonal
- Example: 2 points
- Subsets of 2 symbols are orthogonal
- $\log_2(M)$ bits in $M/2$ dimensions:

$$\eta = \frac{2\log_2(M)}{M}$$



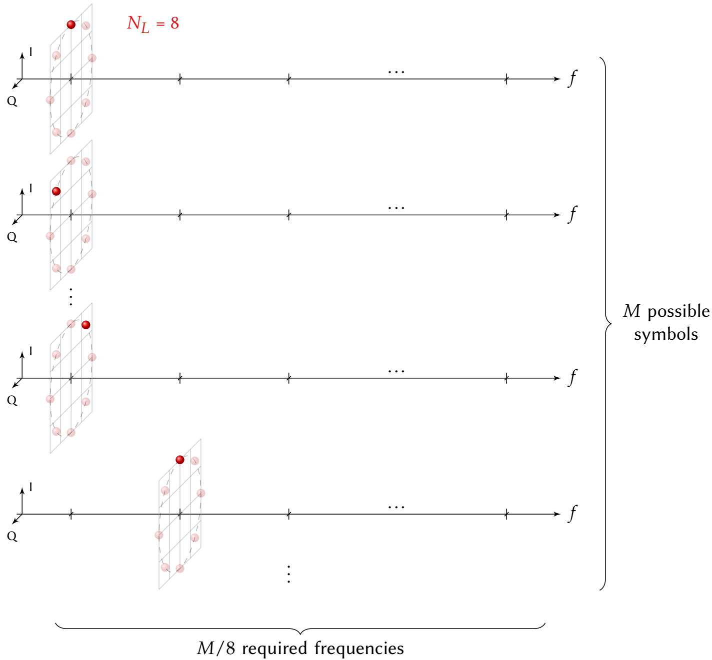


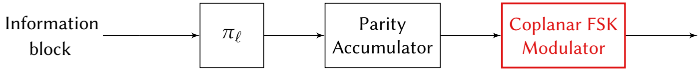
Coplanar Turbo-FSK

Modulation: Alphabet Design

- Coplanar FSK:
  - Allow N_L points ($N_L \geq 1$) for each frequency
  - Coplanar values are roots of the unity
  - Only subsets of the alphabet are orthogonal
- Example: 8 points
- Subsets of 8 symbols are orthogonal
- $\log_2(M)$ bits in $M/8$ dimensions:

$$\eta = \frac{8\log_2(M)}{M}$$

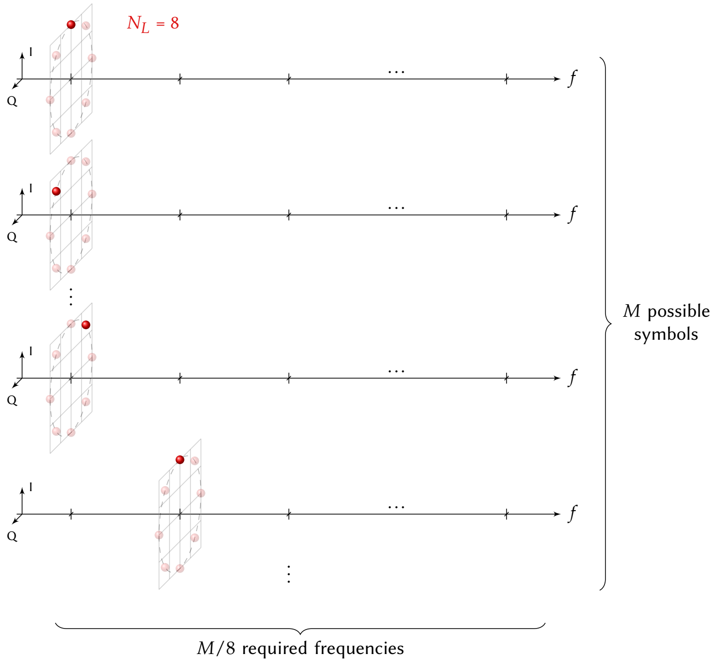




Coplanar Turbo-FSK

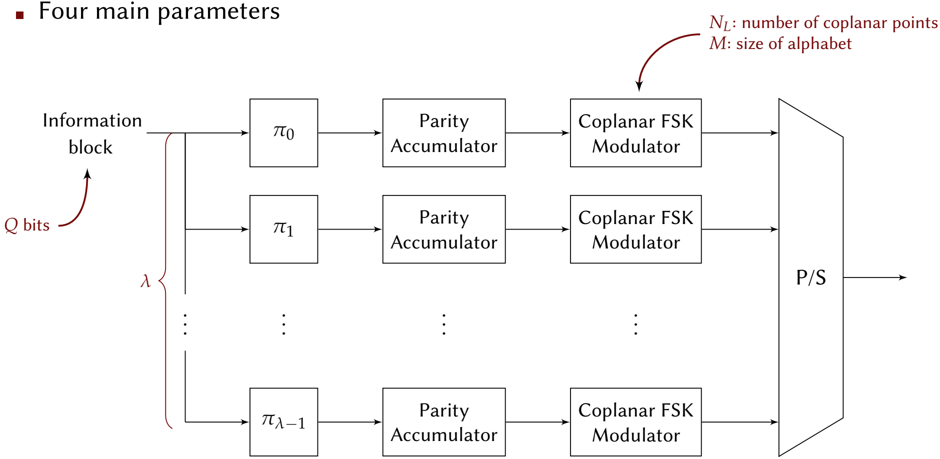
Modulation: Alphabet Design

- Coplanar FSK:
  - Allow N_L points ($N_L \geq 1$) for each frequency
  - Coplanar values are roots of the unity
  - Only subsets of the alphabet are orthogonal
- Distance between the points is smaller
- May lead to performance loss
- This is a constant envelope modulation



Coplanar Turbo-FSK

- Four main parameters



Spectral Efficiency: $\eta = \dfrac{Q}{\left(\dfrac{Q}{q}+1\right)\cdot\dfrac{M}{N_L}\cdot\lambda}$ with $q = \log_2(M) - 1$

Coplanar Turbo-FSK

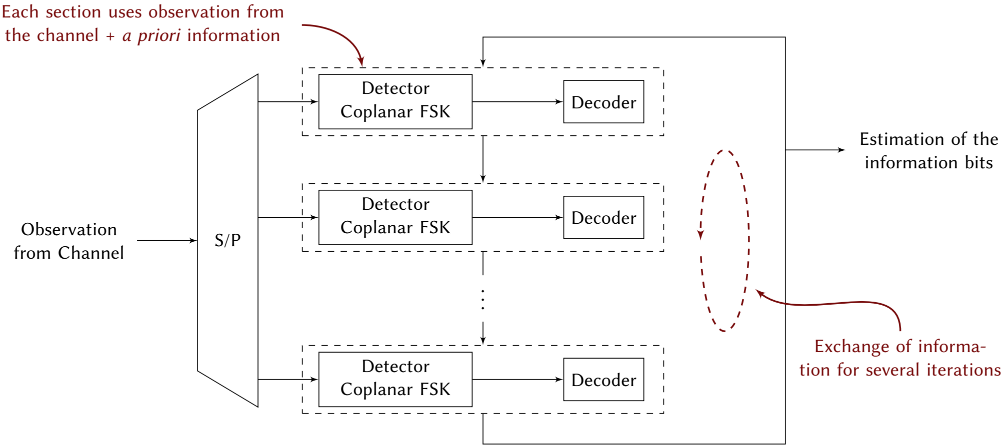
Turbo Receiver

- λ versions of the information block were sent ➡ architecture with λ decoders is required

Coplanar Turbo-FSK

Turbo Receiver

- λ versions of the information block were sent ➡ architecture with λ decoders is required
- Turbo receiver: combines detection of the symbols and iterative decoding



Coplanar Turbo-FSK

Conclusion

- Coplanar Turbo-FSK is our patented modulation scheme [9], inspired from Turbo Hadamard
  - Denomination Turbo-FSK: when FSK alphabet is considered

- Four main parameters:
  - Q: information block size
  - λ: number of repetitions
  - N_L: number of coplanar points
  - M: size of the modulation alphabet

- It is a combination of orthogonal modulation, convolutional code and a turbo receiver

- The Coplanar FSK modulation allows for a constant envelope and flexibility in spectral efficiency

[9] Roth et al., "Transmission/Reception System Based on the Use of a Joint Orthogonal and Linear Modulation", 2017

Coplanar Turbo-FSK

Conclusion

- What is the best strategy for the turbo receiver ?
- Turbo-FSK: what parameters give the lowest E_b/N_0?
- Coplanar Turbo-FSK: what is the optimum combination of parameters ?

Contents

Analysis

- What is the best strategy for the turbo receiver ?
- Turbo-FSK: what parameters give the lowest E_b/N_0?
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Analysis

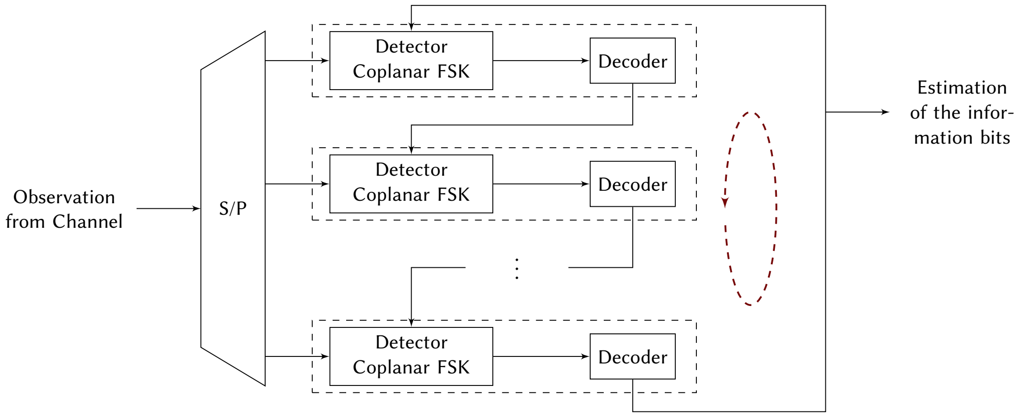
Receiver's Strategy

- At the transmitter: encoding and modulation are strongly dependent

Analysis

Receiver's Strategy

- At the transmitter: encoding and modulation are strongly dependent
- Coupled strategy: *a priori* information from the other decoders is reused at the demodulation level



Analysis

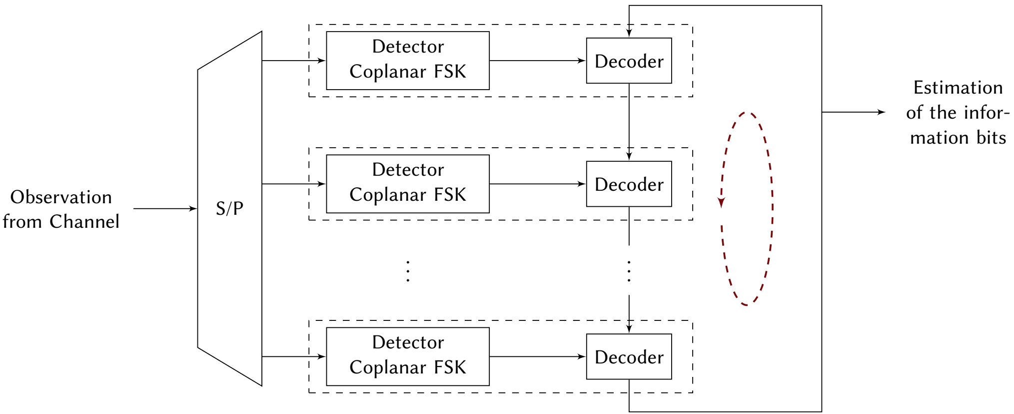
Receiver's Strategy

- Complexity can be reduced by considering another strategy

Analysis

Receiver's Strategy

- Complexity can be reduced by considering another strategy
- Uncoupled strategy: demodulation and decoding are uncoupled and are treated independantly



Analysis

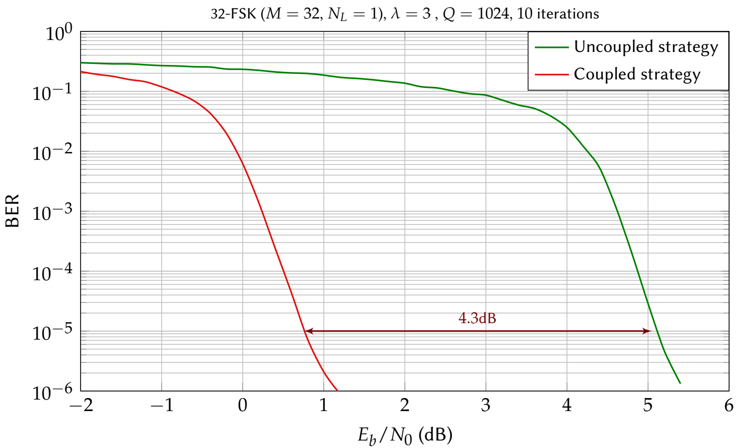
Receiver's Strategy

- Impact of the selected strategy on the performance ?

Analysis

Receiver's Strategy

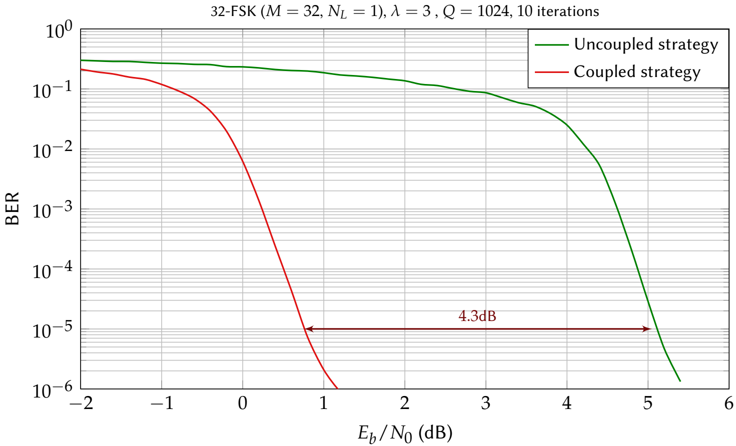
- Impact of the selected strategy on the performance ?
- BER performance for the two decoders



Analysis

Receiver's Strategy

- Impact of the selected strategy on the performance ?
- BER performance for the two decoders

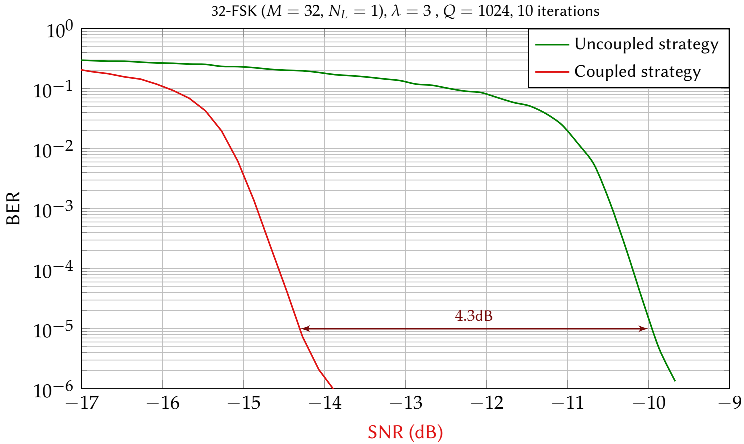


- The reduction of complexity of the uncoupled strategy is not worth the performance loss

Analysis

Receiver's Strategy

- Impact of the selected strategy on the performance ?
- BER performance for the two decoders



- Very low levels of SNR are reached

Analysis

- What is the best strategy for the turbo receiver ?
- Turbo-FSK: what parameters give the lowest E_b/N_0?
- Coplanar Turbo-FSK: what is the optimum combination of parameters ?

Analysis

Turbo-FSK

- Turbo-FSK: orthogonal alphabet
- 3 parameters λ, Q and M (N_L is set to 1)

- Asymptotic analysis is considered (i.e. for infinite size of Q)
- Parameter Q discarded: only 2 parameters

Analysis

Turbo-FSK: Optimization

Optimization

Objective: find couple of M and λ which minimizes the E_b/N_0

- Evaluation of the performance of the receiver

[10] S. ten Brink, "Convergence behavior of iteratively decoded parallel concatenated codes", 2001

Analysis

Turbo-FSK: Optimization

Optimization

Objective: find couple of M and λ which minimizes the E_b/N_0

- Evaluation of the performance of the receiver

- EXIT Chart [10]: semi-analytical tool for iterative processes
- The threshold of the receiver can be estimated using the EXIT chart

Threshold of the Receiver

Minimum E_b/N_0 **required** for the receiver to be able to correct erroneous codewords assuming **perfect independence** between the multiple transmitted versions

- Adaptation of the EXIT chart to FSK signaling

[10] S. ten Brink, "Convergence behavior of iteratively decoded parallel concatenated codes", 2001

Analysis

Turbo-FSK: Optimization

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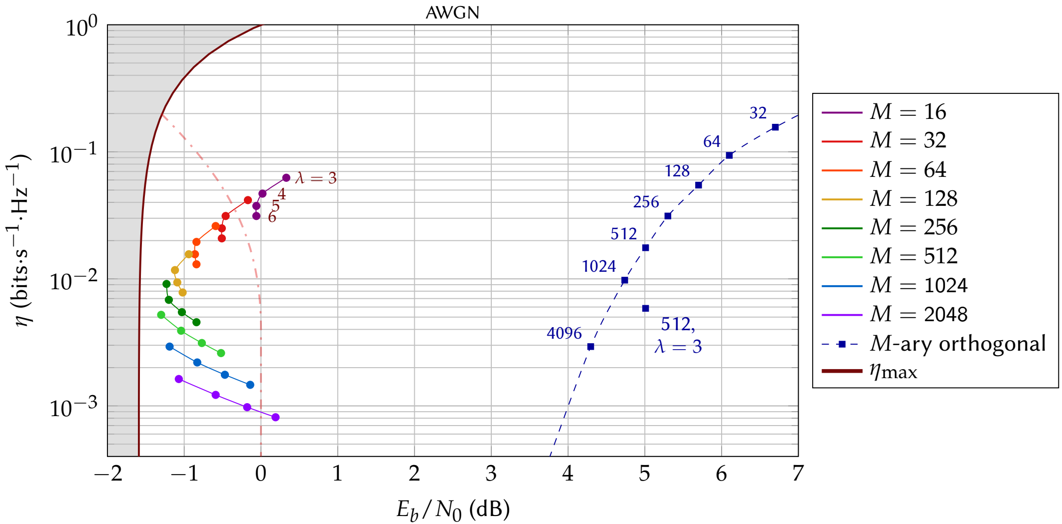

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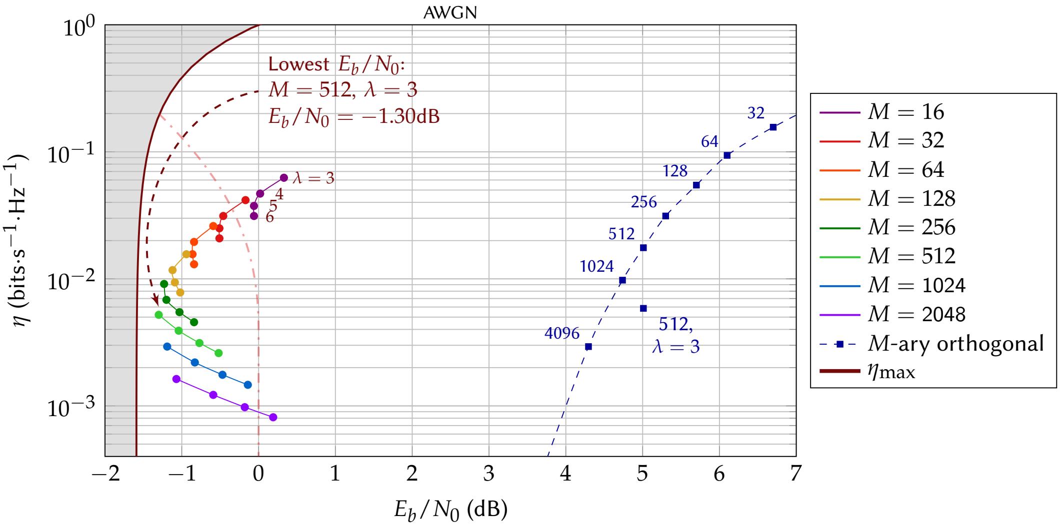

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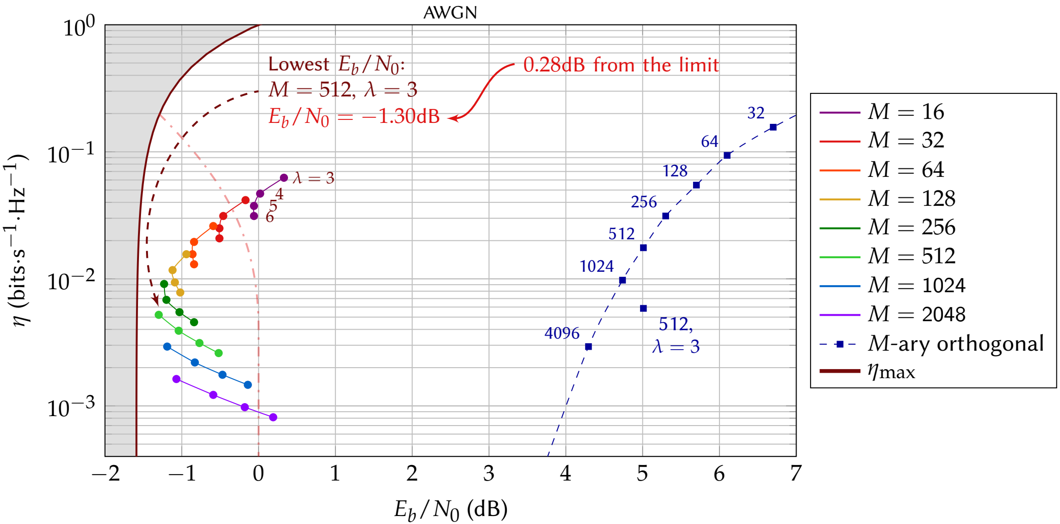

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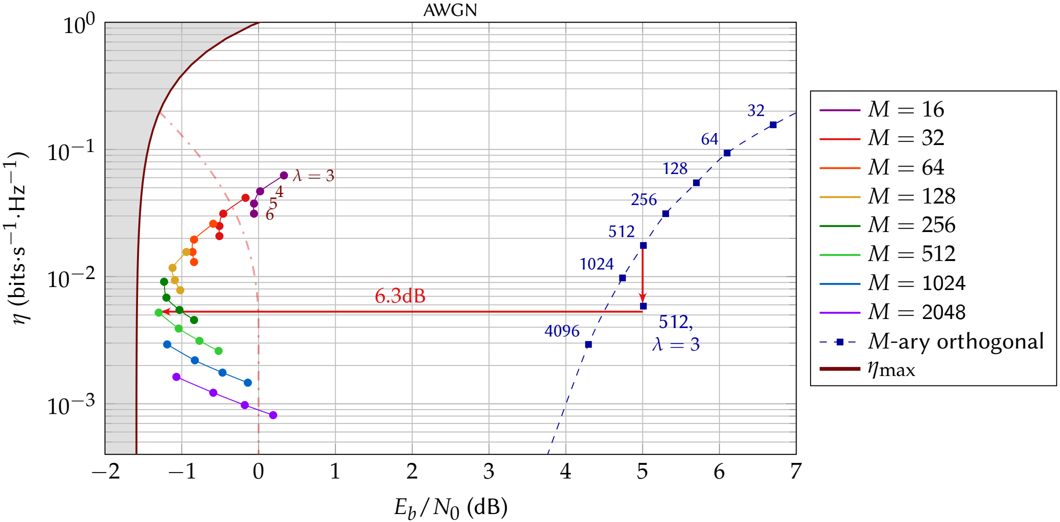

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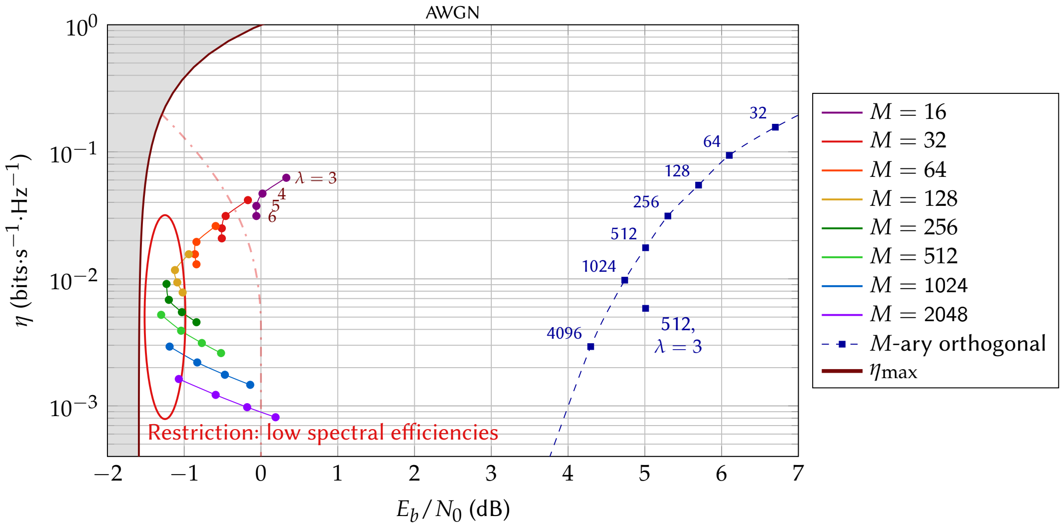

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Analysis

Coplanar Turbo-FSK

- Coplanar Turbo-FSK: extra parameters

Analysis

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- Coplanar Turbo-FSK: extra parameters

- Choice of mapping:
  - Only subsets of the alphabet are orthogonal
  - Distance between symbols $\neq$ constant
  - The choice of association binary words $\Leftrightarrow$ symbols from the alphabet (mapping) has consequences
  - $M!$ possible mappings

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  - Best performance (with exceptions): roots of unity (+ constant envelope)

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Coplanar Turbo-FSK

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Analysis

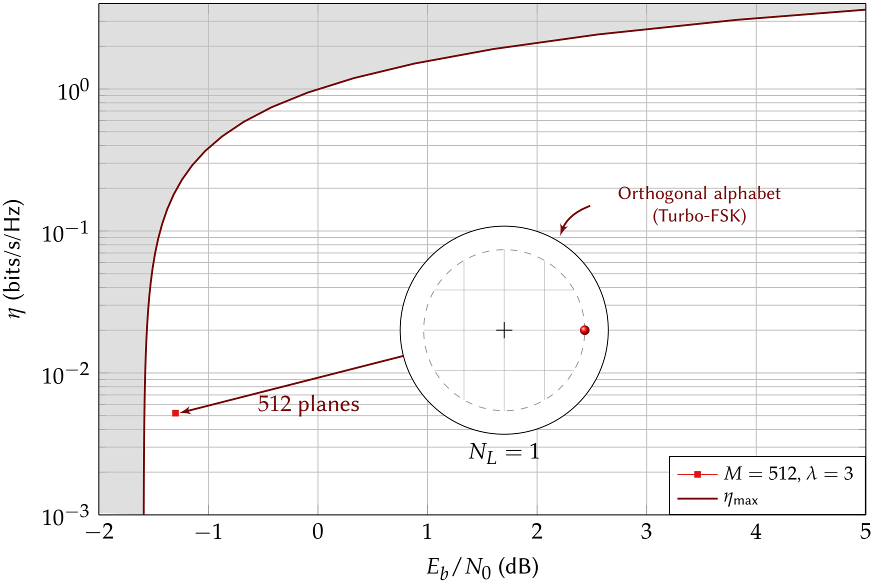
Coplanar Turbo-FSK

- Optimization is cumbersome (very large number of parameter's combination)

- Evaluation of the asymptotic performance for a given value of M and λ
- The best parameter's couple of the orthogonal case ($M = 512$ and $\lambda = 3$) is selected
- Only N_L varies
- Computation of the thresholds using the EXIT chart

Analysis

Coplanar Turbo-FSK



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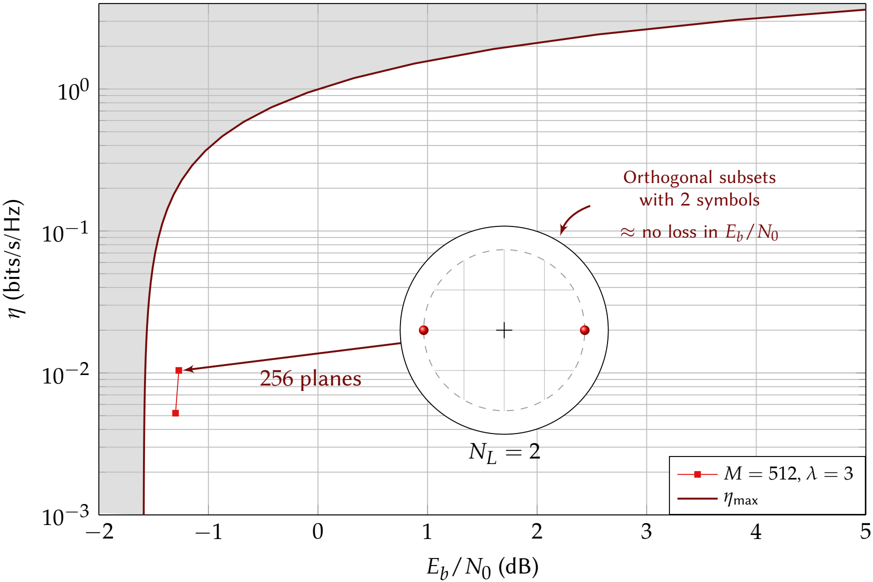

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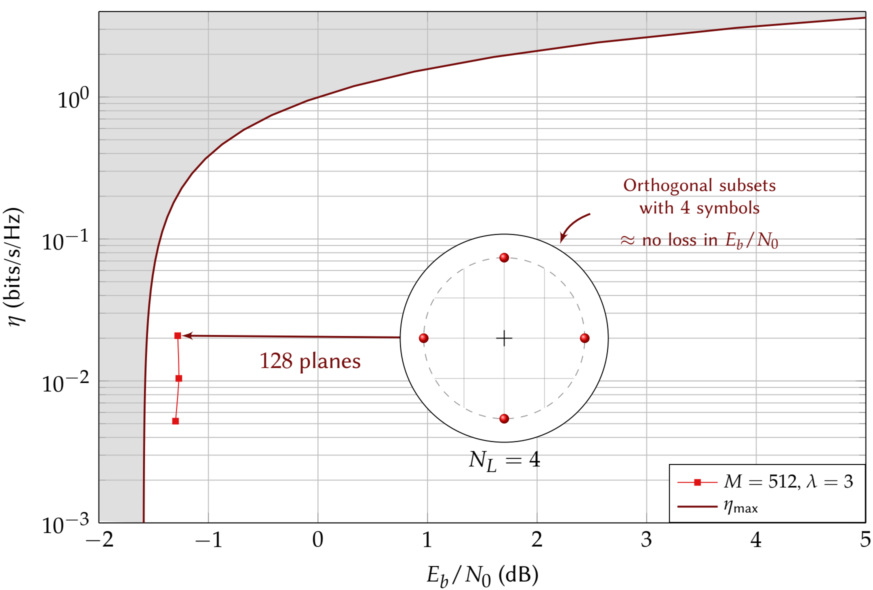

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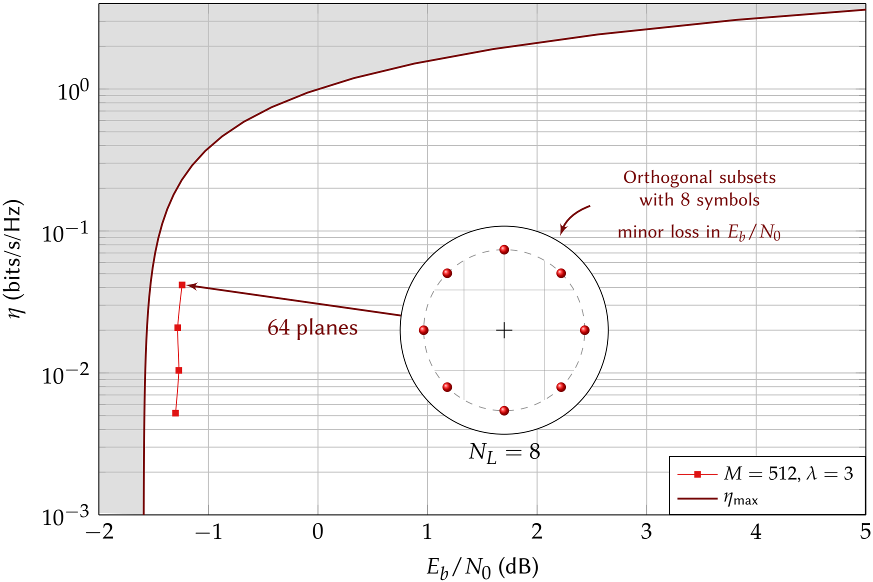

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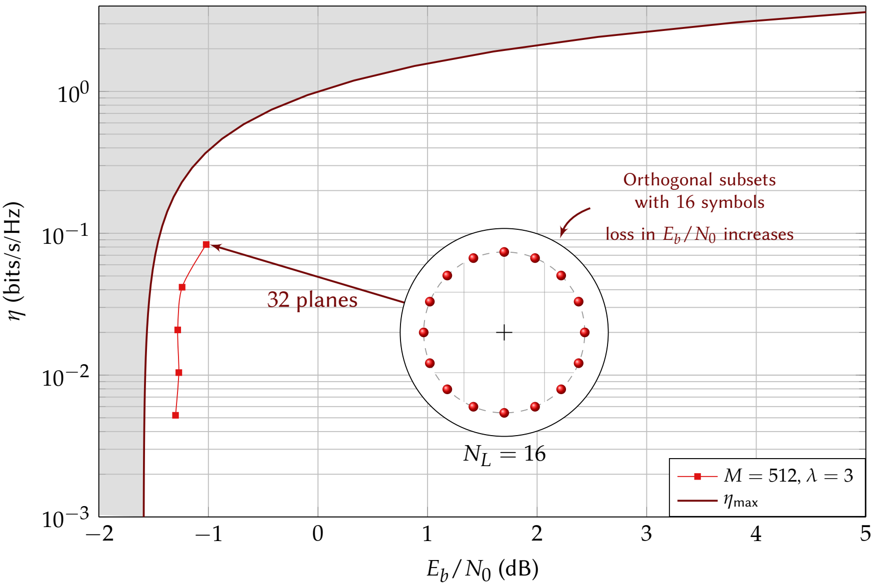

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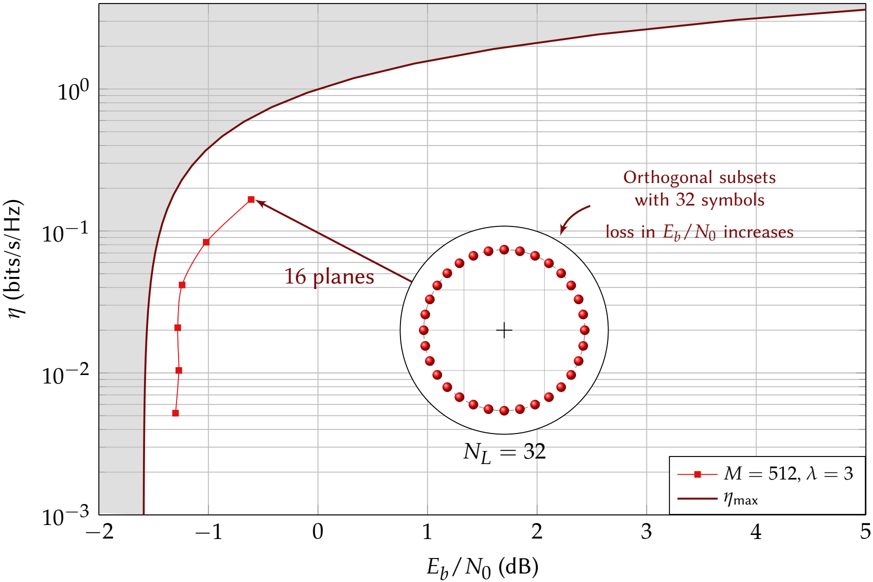

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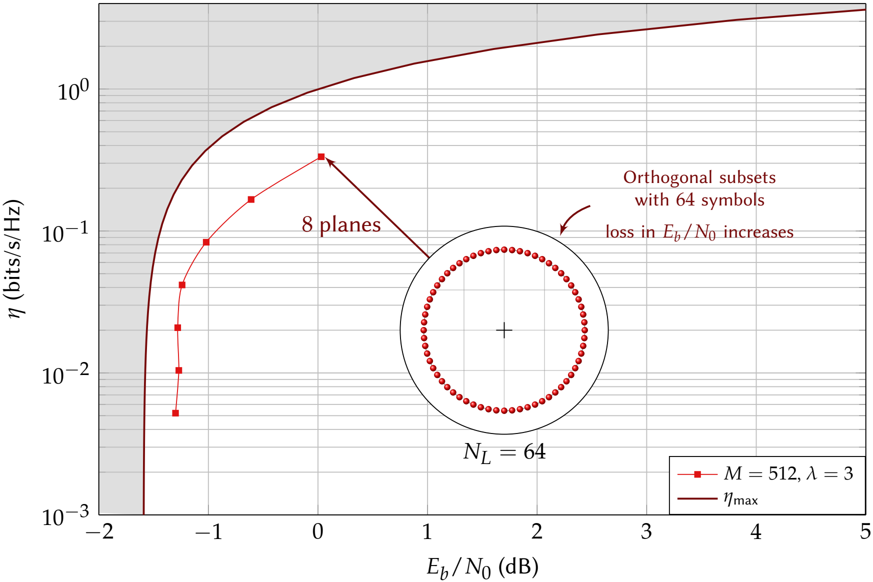

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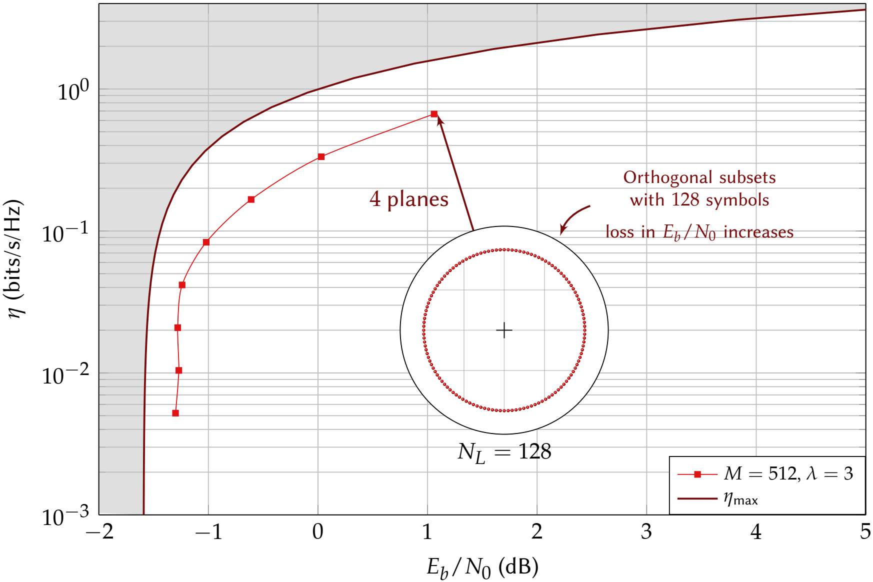

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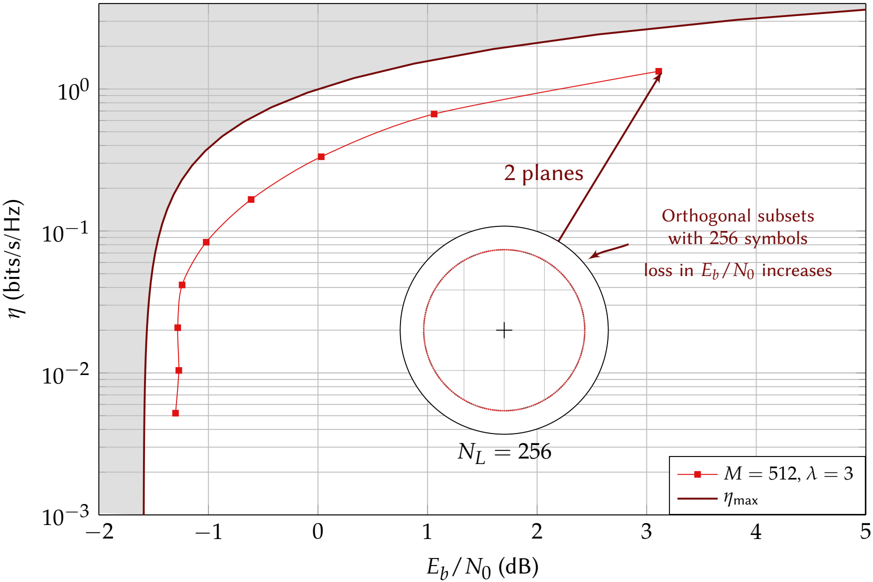

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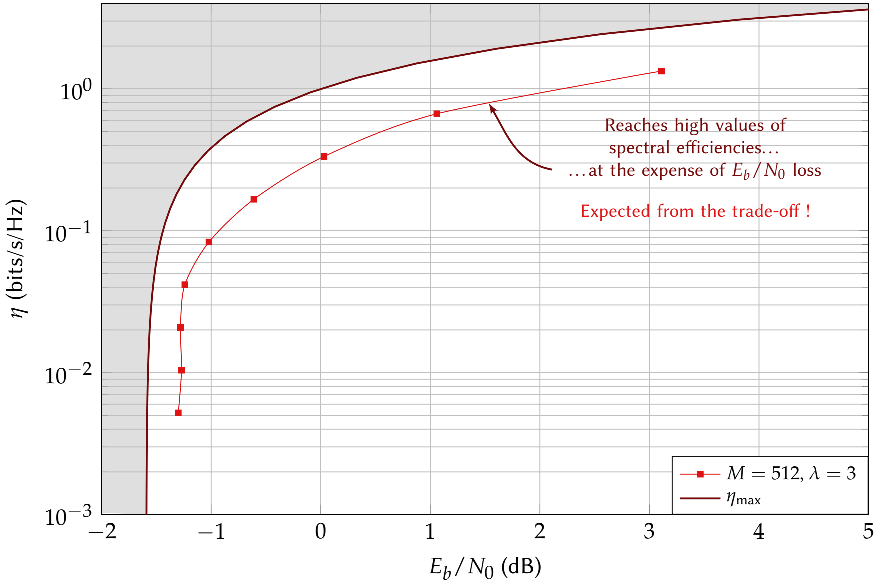

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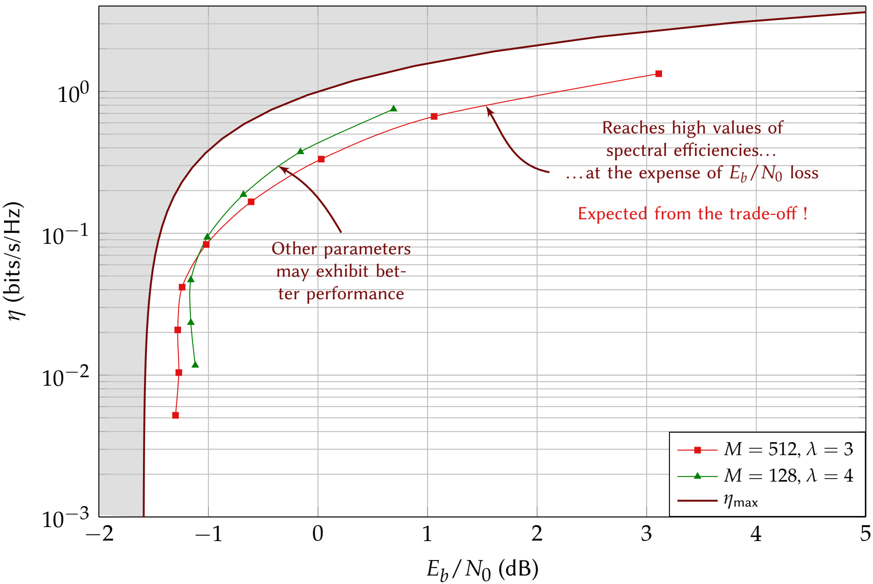

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  - …at the expense of some performance loss for large values of N_L

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- Only asymptotic performance was considered

Analysis

Conclusion

- Performance of the Turbo-FSK in the LPWA context (short block sizes) ?
- Further integration to existing technologies ?

Contents

Application to Low Power Wide Area Networks

- Performance of the Turbo-FSK in the LPWA context (short block sizes) ?
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Application to Low Power Wide Area Networks

Comparison to Existing Solutions

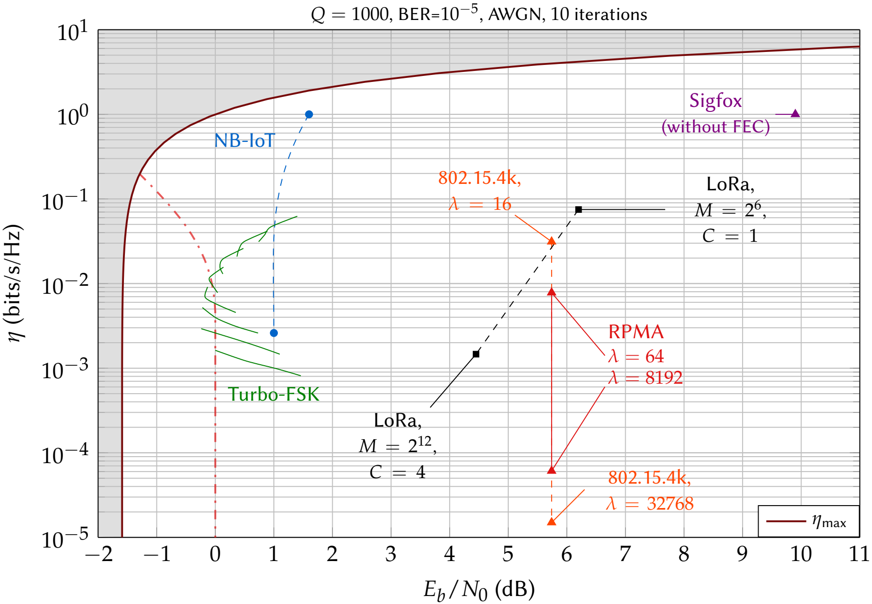
- Existing solutions presented previously:

PHY-layer	Modulation	FEC
Sigfox	DBPSK	?
LoRa based	Orthogonal	Hamming
802.15.4k, RPMA	DBPSK	CC [171 133] + repetition
NB-IoT based	BPSK/QPSK	TC [13 15] + repetition

- The Turbo-FSK is considered (orthogonal alphabet)
- AWGN and an information block size $Q = 1000$ are considered
- Averaged over random interleavers

Application to Low Power Wide Area Networks

Comparison to Existing Solutions



Application to Low Power Wide Area Networks

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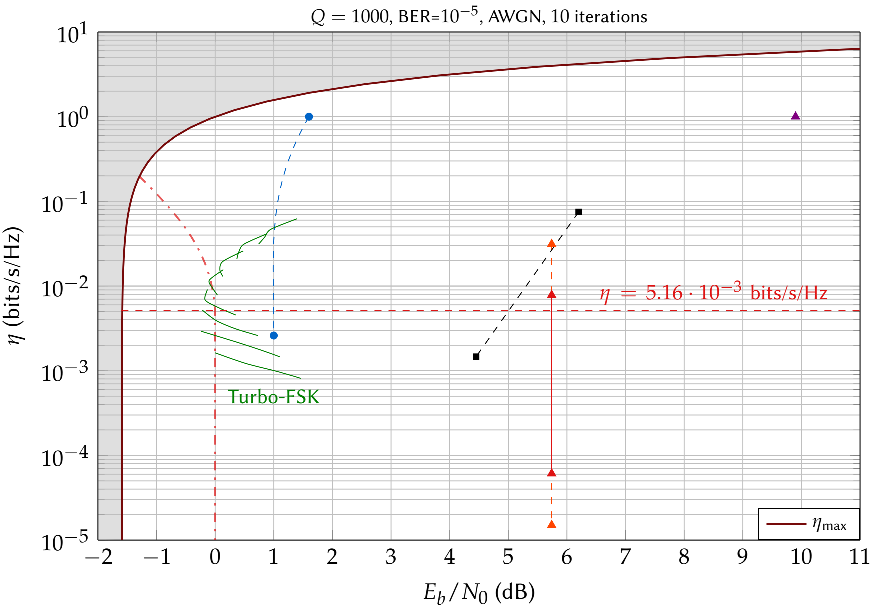

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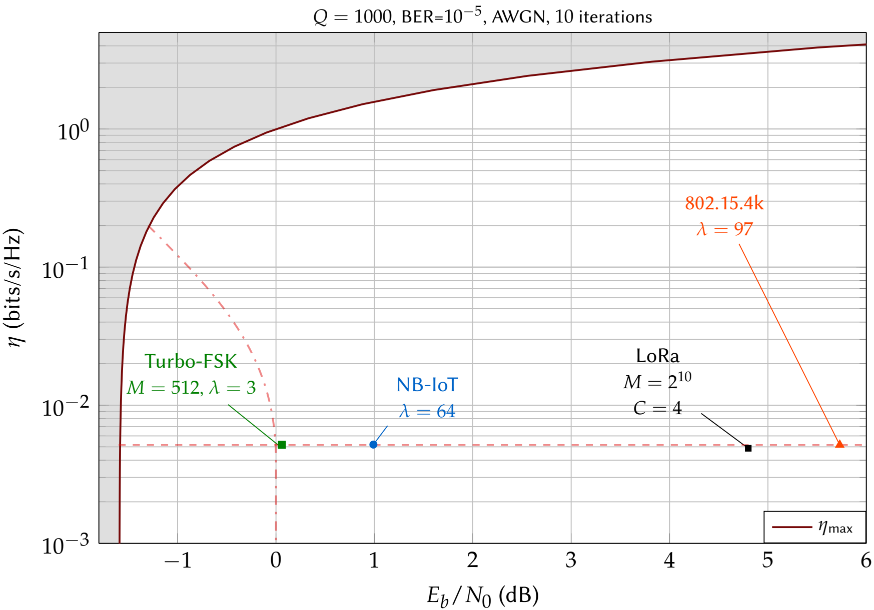

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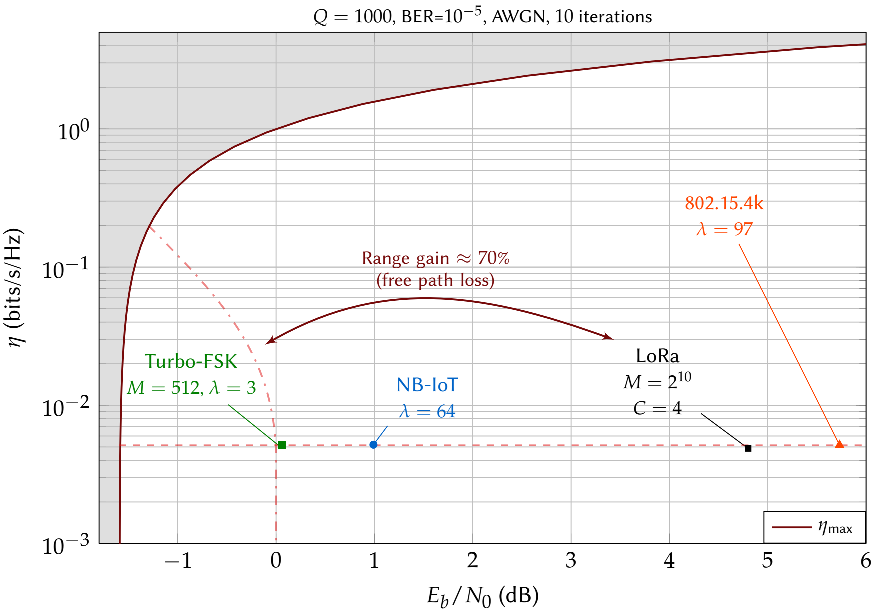

Application to Low Power Wide Area Networks

Comparison to Existing Solutions

- Turbo-FSK satisfies the LPWA requirements:
  - Long range, low data rate: can reach low levels of SNR, even for short packet sizes
  - Low consumption: low complexity transmitter (+ constant envelope)
- Offers a gain versus existing solutions
- Implementation on low cost platform has been demonstrated possible [11]

[11] Estavoyer, Roth, Doré, and Berg, "Implementation and Analysis of a Turbo-FSK Transceiver for a New Low Power Wide Area Physical Layer", 2016

Application to Low Power Wide Area Networks

- Performance of the Turbo-FSK in the LPWA context (short block sizes) ?
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Application to Low Power Wide Area Networks

Integration in an OFDM framework

- Previous comparison: standalone version of Turbo-FSK
- Coexistence with existing cellular networks
- Current generation of cellular network (LTE) + NB-IoT: Orthogonal Frequency Division Multiplexing (OFDM)

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- Can the Coplanar Turbo-FSK scheme be integrated in such a framework ?
- Performance using this implementation ?

Application to Low Power Wide Area Networks

Integration in an OFDM framework

- OFDM: frequency multiplexing
- Complex symbols are mapped on the N_A active carriers

Application to Low Power Wide Area Networks

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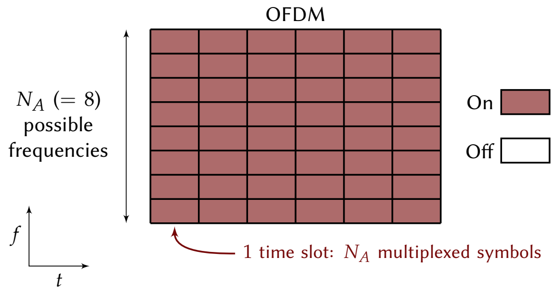
- Typical time-frequency allocation:



Application to Low Power Wide Area Networks

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- FSK signaling: only one frequency of the N_A active carriers is excited
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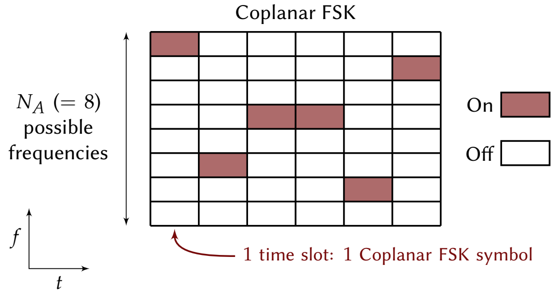

- Integration of FSK signal is possible

Application to Low Power Wide Area Networks

Integration in an OFDM framework: System compared

- Performance using this implementation ?

- Comparison of 3 systems:
  - **TC-OFDM**:
    QPSK symbols + TC [13 15] + repetition
  - **TC-SC-FDMA**:
    QPSK with precoding + TC [13 15] + repetition
  - **Coplanar Turbo-FSK**

- Performance in terms of:
  - Variation of the envelope
  - Packet Error Rate (PER) under multipath Rayleigh fading channel

- OFDM framework:
  $\Delta f = 15$kHz, 128-FFT, Cyclic prefix: 9 samples, $N_A = 16$ active carriers

Application to Low Power Wide Area Networks

Integration in an OFDM framework: Envelope variations

- Variations of the envelope: characterized by the Instantaneous-to-Average Power Ratio (IAPR)
- Considers all the samples that will be amplified, not just the maximum

Application to Low Power Wide Area Networks

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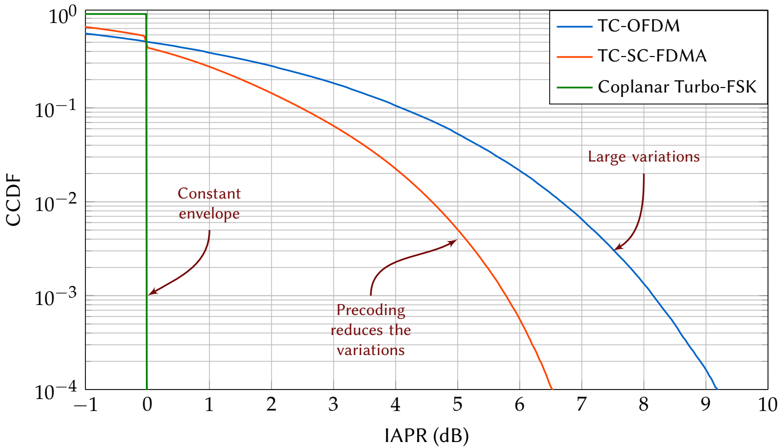

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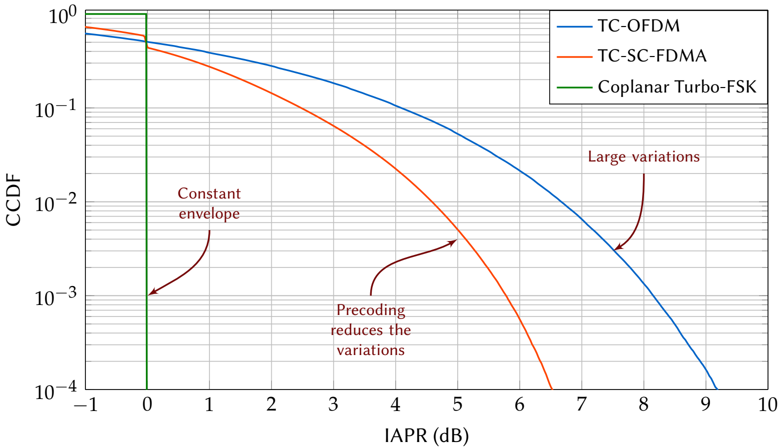

- Coplanar Turbo-FSK minimizes the constraint on the power amplifier

Application to Low Power Wide Area Networks

Integration in an OFDM framework: Scenarios

- Performance under multipath Rayleigh slow fading
- Two considered scenarios:

PHY-layer	TC-OFDM/ TC-SC-FDMA	Turbo-FSK
N_L	-	1
λ	17.76	5
R	8.24kbps	

TC-OFDM/ TC-SC-FDMA	Coplanar Turbo-FSK
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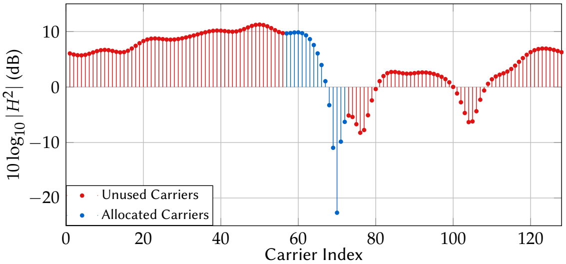
- ETU profile (frequency selectivity): Delay spread $\tau = 5\mu s$



Application to Low Power Wide Area Networks

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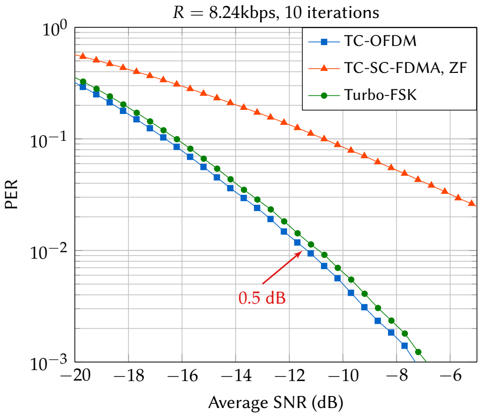

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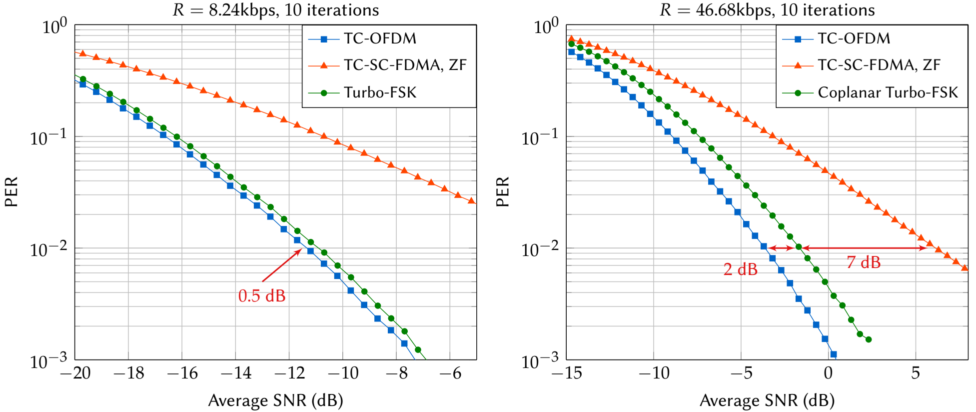

- Low rate: outperforms TC-SC-FDMA and comparable to TC-OFDM
- High rate: performance loss due to the use of a large size of N_L

Application to Low Power Wide Area Networks

Integration in an OFDM framework: Conclusion

- Can the Coplanar Turbo-FSK scheme be integrated in such a framework ?
  - Integration in OFDM framework is possible and straightforward due to FSK signaling
- Performance using this implementation ?
  - Coplanar Turbo-FSK has performance close to TC-OFDM…
  - …while having a constant envelope
  - Performance loss increases for higher values of N_L

Application to Low Power Wide Area Networks

Conclusion

- Turbo-FSK offers a gain in performance compared to existing solutions
- Coplanar Turbo-FSK can coexist with current standards and be used as an additionnal mode for LPWA transmission
  - Offers a trade-off between performance and constant envelope

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  - Higher levels of spectral efficiency are obtained at the expense of a loss in E_b/N_0
- Coplanar Turbo-FSK is a low power constant envelope alternative to very powerful solutions
  - The scheme offers a gain versus existing solutions
  - It can coexist with current systems

Conclusion

Perspectives

- The use of another orthogonal modulation (Zadoff-Chu CAZAC sequences) has been considered for Coplanar Turbo-FSK, and showed promising performance
  - Extension of the scheme to other orthogonal modulations and/or other coplanar distribution could be considered

[12] Polyanskiy, Poor, and Verdu, “Channel Coding Rate in the Finite Blocklength Regime”, 2010

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- Tighter bounds should be considered for short block size [12]

[12] Polyanskiy, Poor, and Verdu, “Channel Coding Rate in the Finite Blocklength Regime”, 2010

Published Work

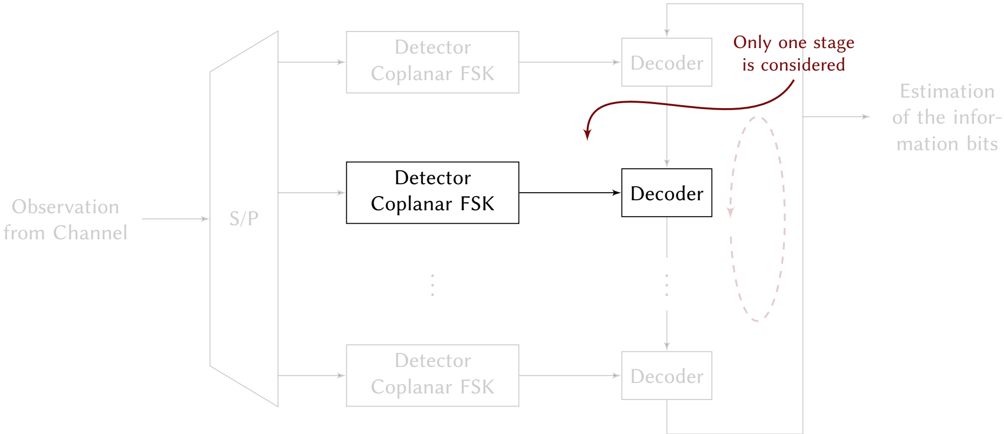
- **Patents** (1)
  - **"Transmission/Reception System Based on the Use of a Joint Orthogonal and Linear Modulation"**, 2017
- **International Journals** (3)
  - **"Turbo-FSK, a physical layer for low-power wide-area networks: Analysis and optimization"**
    Elsevier Comptes Rendus Physique, 2017
  - **"Coplanar Turbo-FSK: A Flexible Physical Layer for IoT"**
    To be submitted, 2017
  - **"Contenders for Low Power Wide Area Networks"**
    To be submitted, 2017
- **Conferences** (6)
  - **"Turbo-FSK: A New Uplink Scheme for Low Power Wide Area Networks"**
    2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Stockholm, Sweden, 2015
  - **"Turbo-FSK : une nouvelle technique de communication montante pour les réseaux longue portée basse consommation"**
    Colloque Gretsi, Lyon, France, 2015
  - **"Nouvelle technique de communication pour les réseaux longue portée basse consommation : optimisation et comparaison"**
    Journées scientifiques de l'URSI 2016, Rennes, France, 2016
  - **"A Comparison of Physical Layers for Low Power Wide Area Networks"**
    11th EAI International Conference on Cognitive Radio Oriented Wireless Networks (Crowncom), Grenoble, France, 2016
  - **"EXIT Chart Optimization of Turbo-FSK: Application to Low Power Wide Area Networks"**
    9th International Symposium on Turbo Codes & Iterative Information Processing 2016 (ISTC'16), Brest, France, Sept. 2016
  - **"Implementation and Analysis of a Turbo-FSK Transceiver for a New Low Power Wide Area Physical Layer"**
    2016 International Symposium on Wireless Communication Systems (ISWCS): Special sessions (ISWCS'2016 - Special sessions), Poznan, Poland, 2016

APPENDICES

Contents

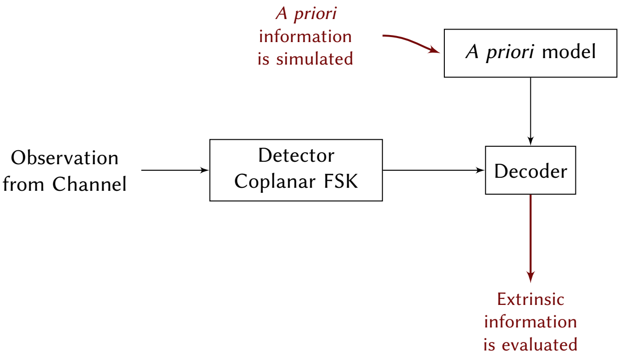
The EXIT Chart

Computation



The EXIT Chart

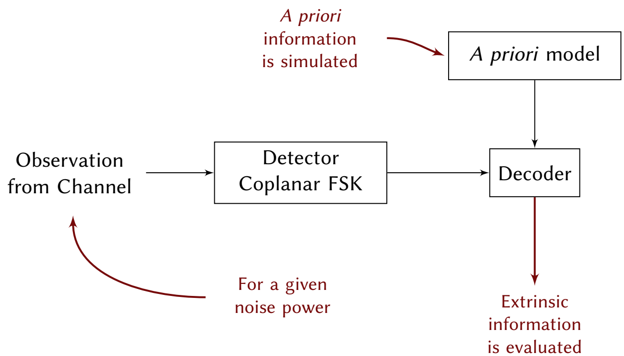
Computation



- Evaluates the response of the receiver to a specific level of *a priori* information

The EXIT Chart

Computation

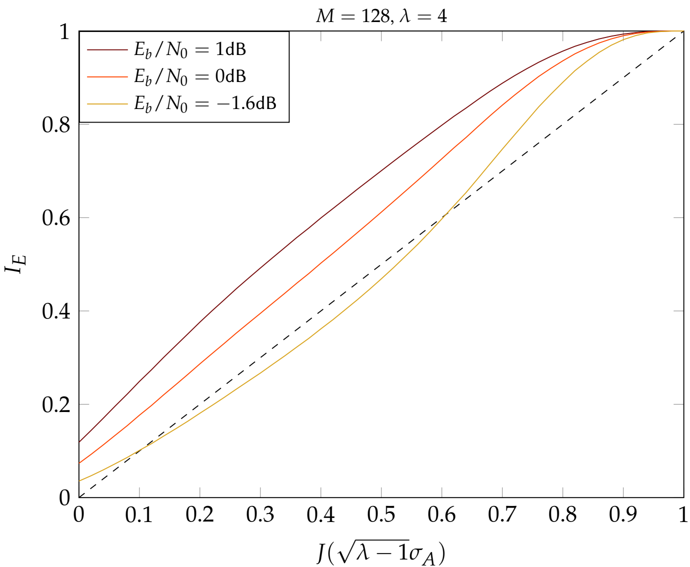


- Evaluates the response of the receiver to a specific level of *a priori* information
- For a given value of noise power (i.e. a given E_b/N_0)

The EXIT Chart

Interpretation

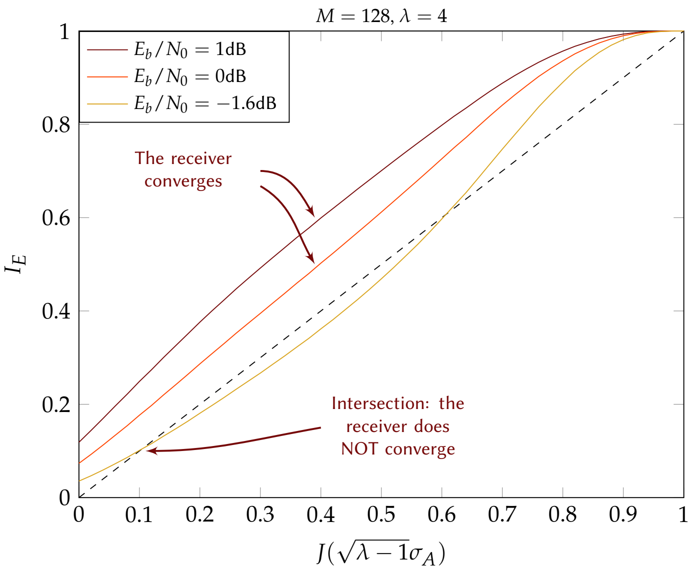
- Intersection with the diagonal indicates if the receiver converges



The EXIT Chart

Interpretation

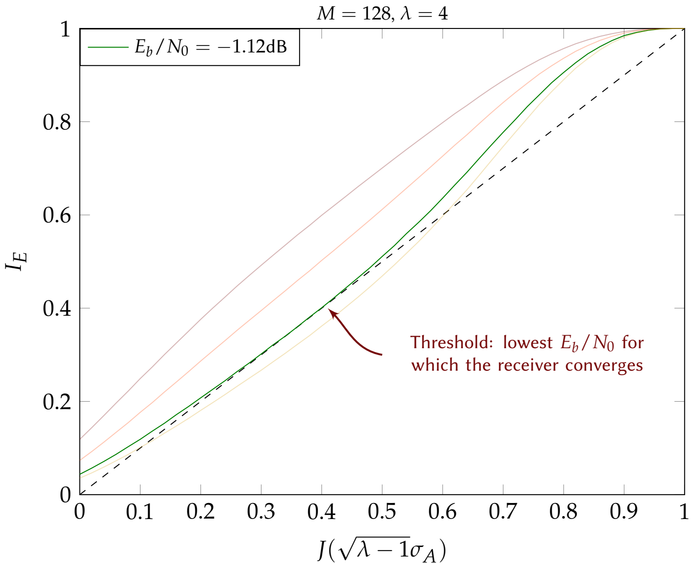
- Intersection with the diagonal indicates if the receiver converges



The EXIT Chart

Threshold

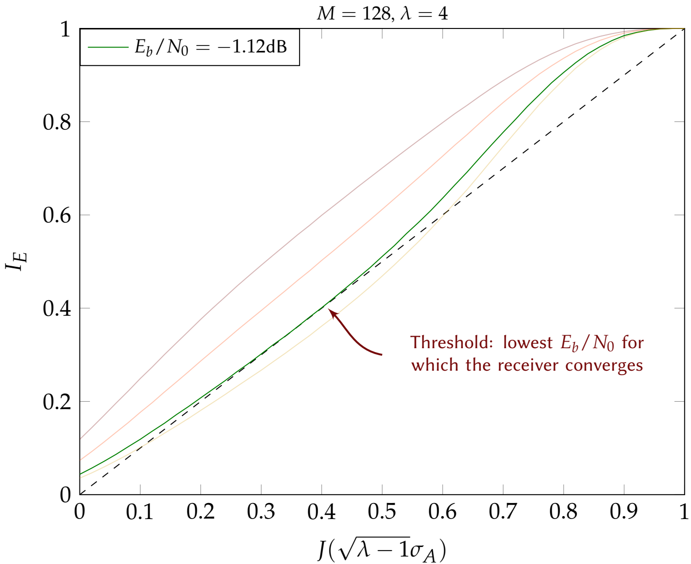
- Threshold of the receiver can be estimated

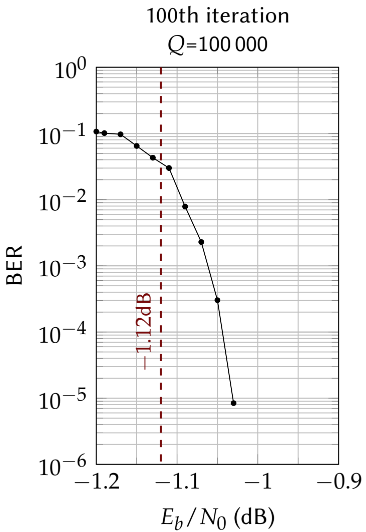


The EXIT Chart

Threshold

- Threshold of the receiver can be estimated, and accurately predicts the performance





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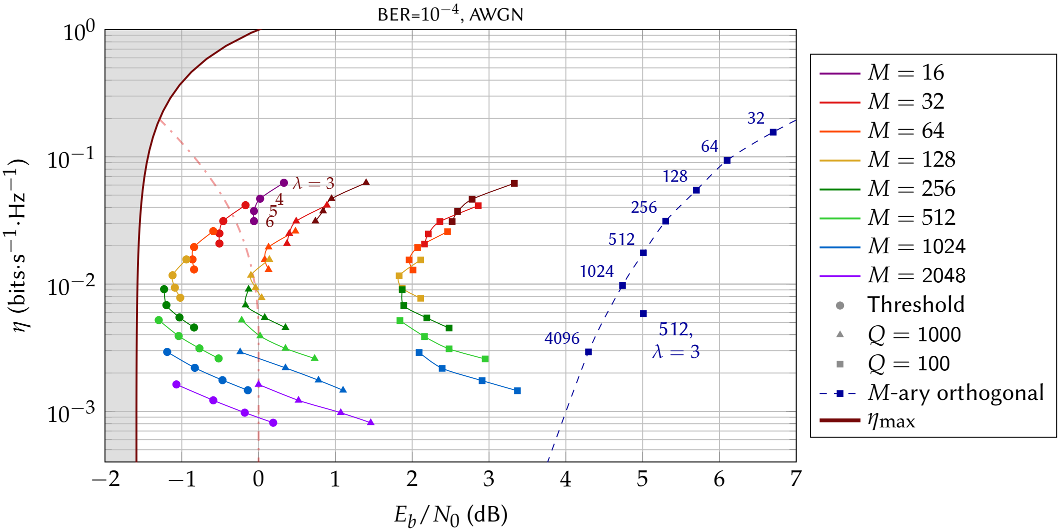
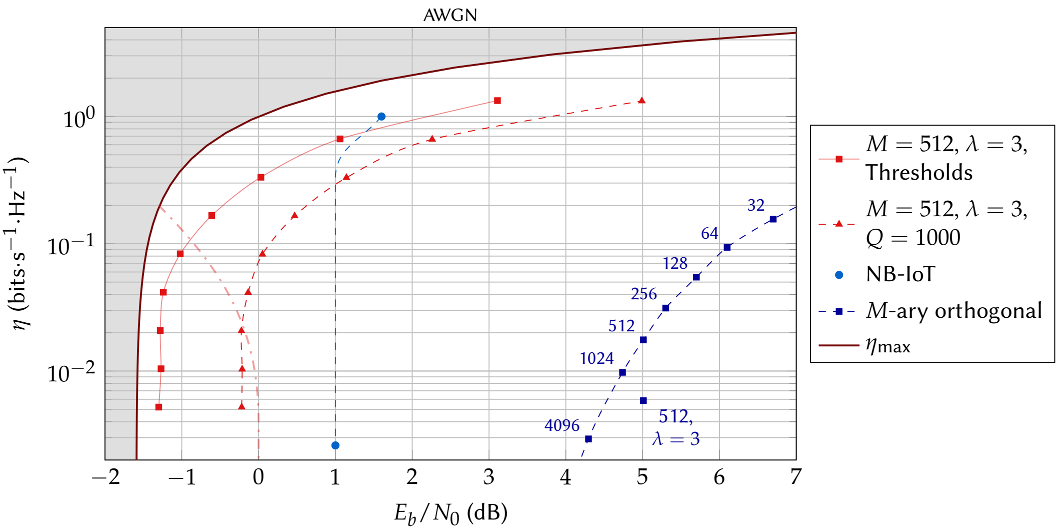
Short Block Sizes

Turbo-FSK: Performance with Short Block Sizes



Short Block Sizes

Coplanar Turbo-FSK: Performance with Short Block Sizes



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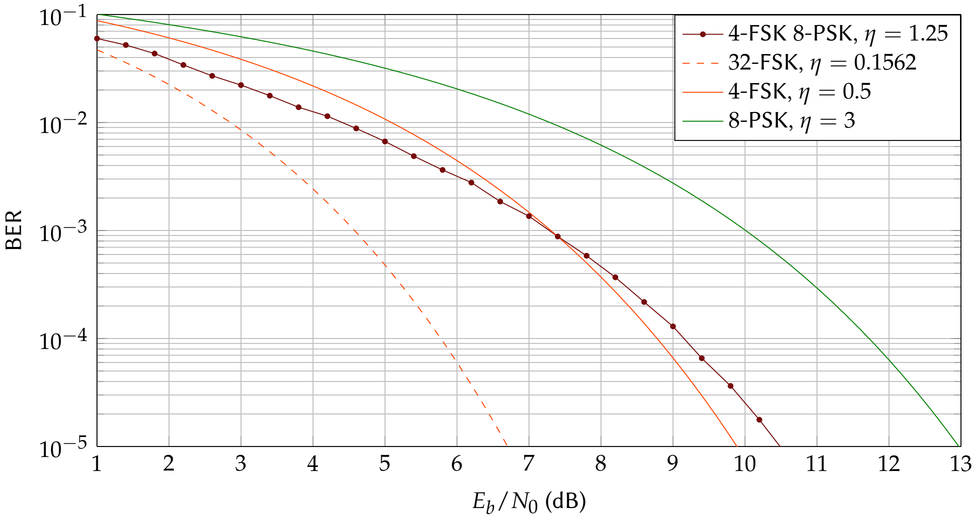
Coplanar FSK

BER Performance



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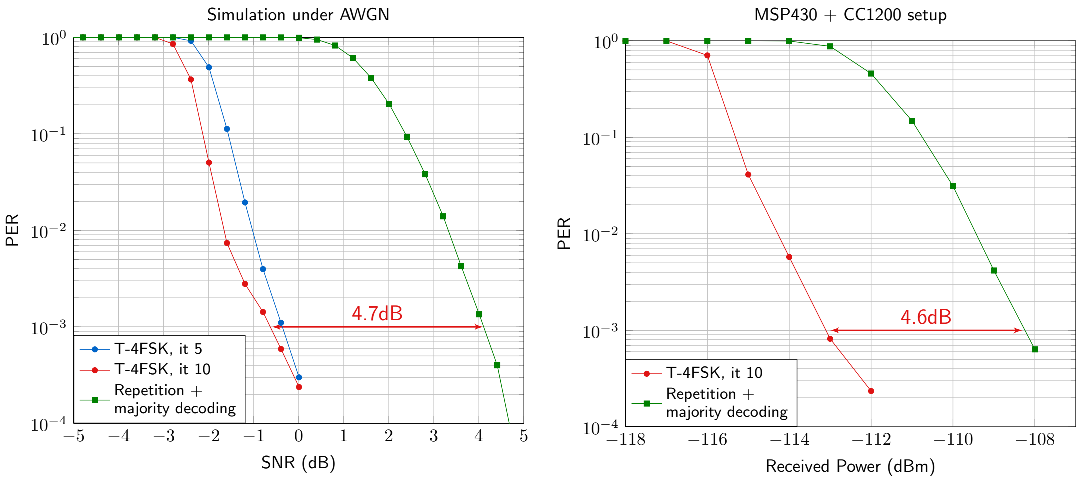
Implementation (Turbo-FSK)

Packet-Error Rate measurements

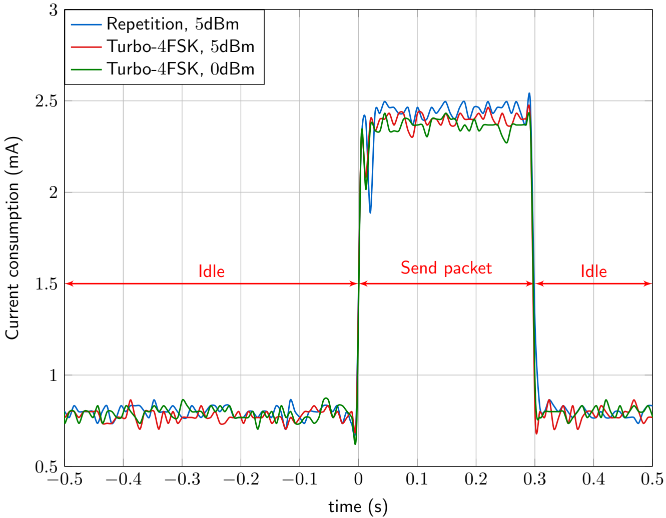


- Gain predicted by simulation is observed under controlled environnement

Implementation (Turbo-FSK)

TX Power consumption measurements: MSP430

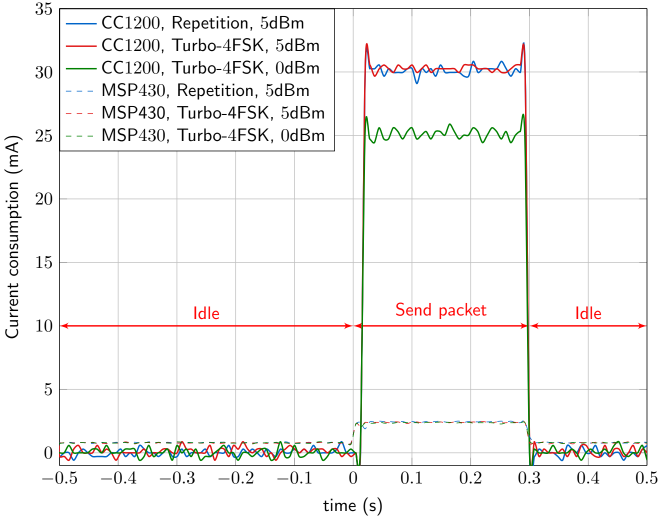
- Using the Turbo-4FSK encoder: increase complexity
  - What is the impact on the consumption of the MSP430 (μ-controller) ?



Implementation (Turbo-FSK)

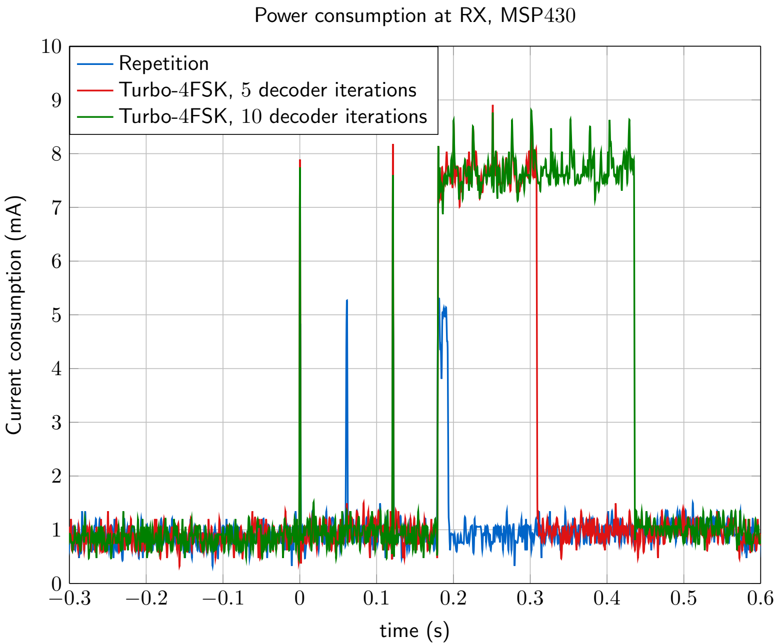
TX Power consumption measurements: TX power reduction

- PER performance: $\sim$ 5dB of performance gain
  - TX transmit power can be reduced by 5dBm for the same PER performance
  - What is the impact on the consumption of the CC1200 (RF chip) ?



Implementation (Turbo-FSK)

RX Power consumption measurements: TX power reduction

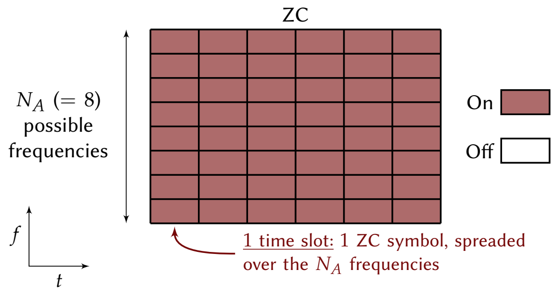


Contents

Turbo-ZC

Zadoff-Chu Sequences

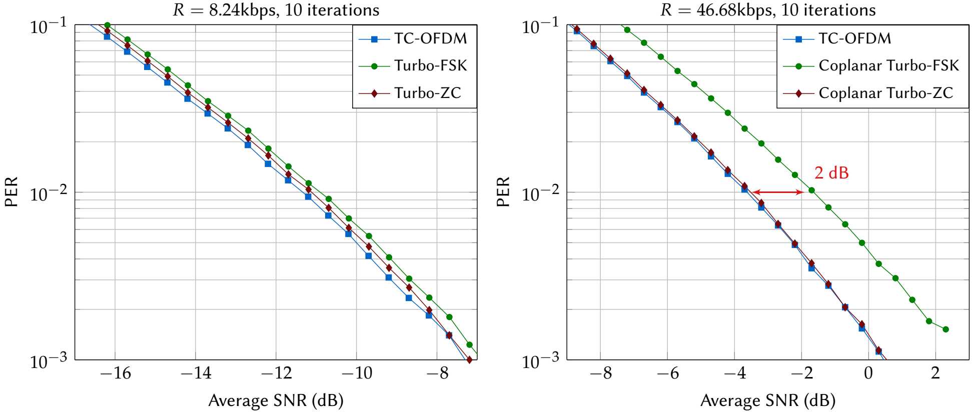
- Zadoff-Chu (ZC) Sequences: can form an orthogonal alphabet (Constant Amplitude Zero Autocorrelation sequences)
- Information is in the delay of the sequence
- Coplanar ZC: sequence is multiplied by a complex value
- Typical time-frequency allocation:



- Construction of the ZC sequence in the frequency domain
- Integration in the OFDM framework is possible

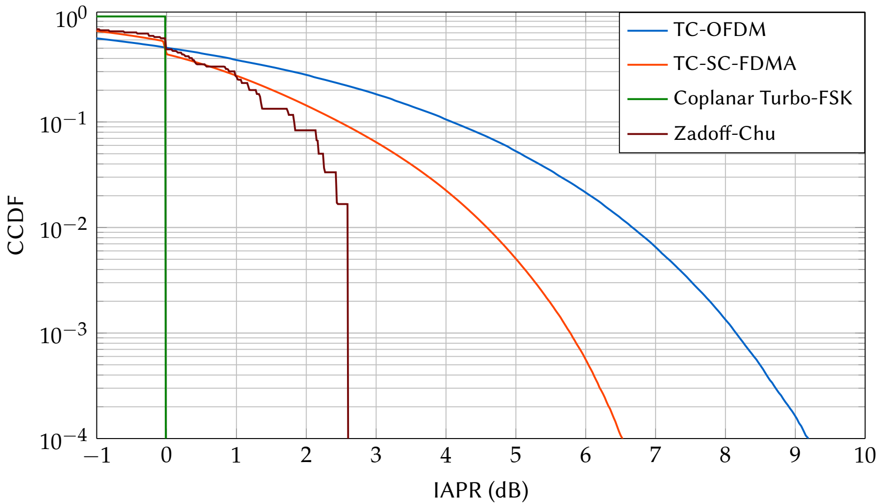
Turbo-ZC

Performance under Static Rayleigh Slow Fading Channel



Turbo-ZC

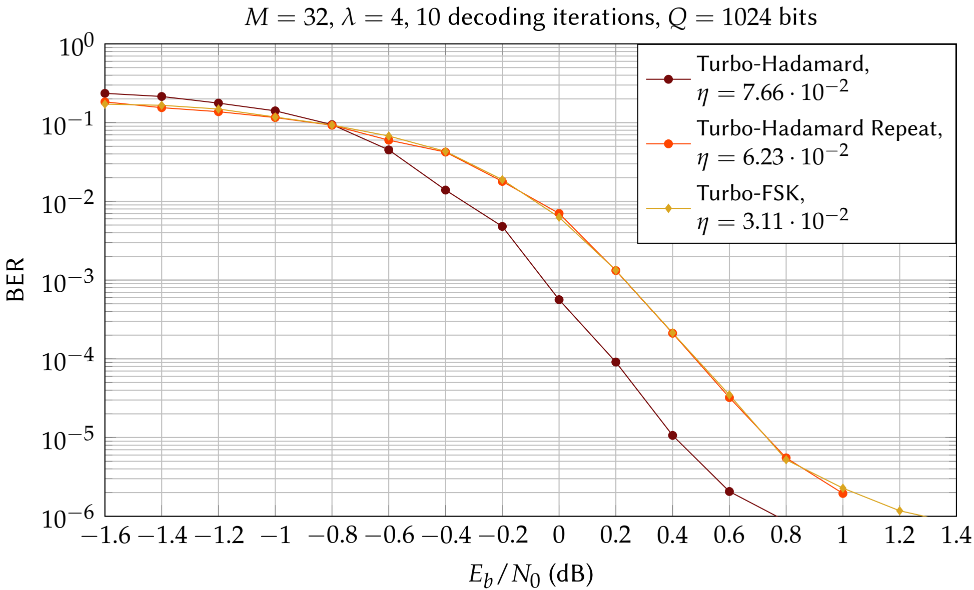
PAPR



Contents

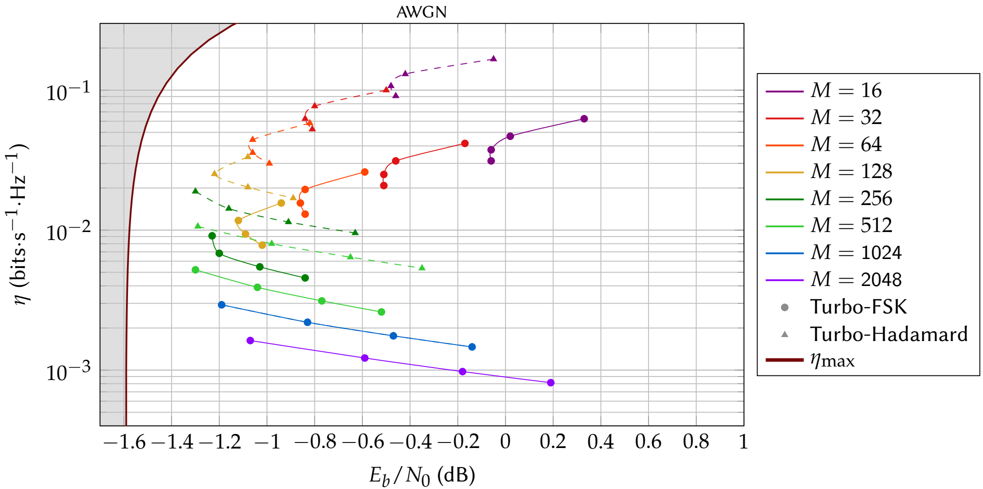
Turbo-Hadamard

BER Performance



Turbo-Hadamard

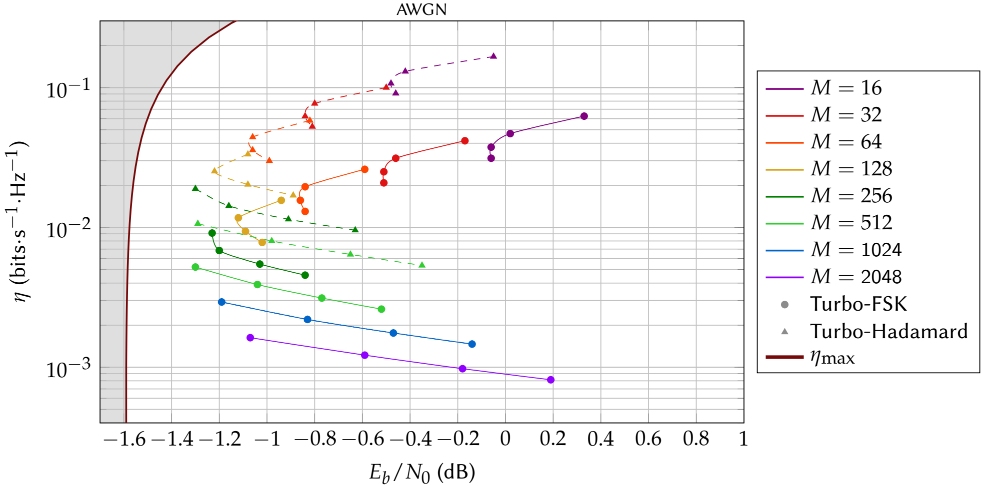
Thresholds



- Turbo-Hadamard is systematic (lower E_b/N_0 + higher spectral efficiency)
- Bi-orthogonal alphabet: even higher spectral efficiency

Turbo-Hadamard

Thresholds



- Turbo-Hadamard is based on binary codes, integration is OFDM framework leads to high IAPR
- Applicable for single carrier modulation (BPSK + Turbo-Hadamard), but higher η

Contents

Receiver's Strategy

Strategies

- Uncoupled strategy: the detector computes the LLR (probabilistic demodulation)

$$L(b) = \log \frac{p\left(r \mid b=+1\right)}{p\left(r \mid b=-1\right)} = \log \sum_{i \in \mathcal{B}_1^n} p\left(\boldsymbol{r} \,\middle|\, \boldsymbol{s}^i\right) - \log \sum_{i \in \mathcal{B}_{-1}^n} p\left(\boldsymbol{r} \,\middle|\, \boldsymbol{s}^i\right).$$

Likelihood of a codeword from the alphabet

Computes **likelihood** of the M codewords and deduces **LLR** of the **encoded bits**

LLR are fed to the decoder

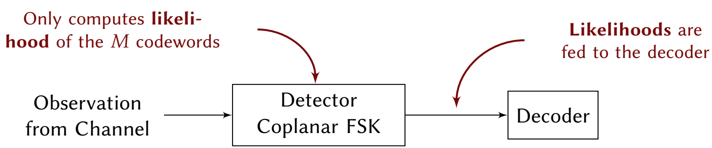
Observation from Channel → Detector Coplanar FSK → Decoder

Receiver's Strategy

Strategies

- Coupled strategy: the detector feeds codeword likelihoods

$$p\left(\boldsymbol{r} \,\middle|\, \boldsymbol{s}^i\right)$$

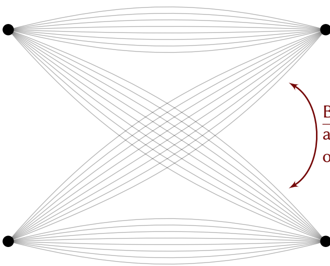


Receiver's Strategy

Trellis Metric

- BCJR: associates the metric (LLR or likelihoods) to the M branches of the trellis

Uncoupled strategy

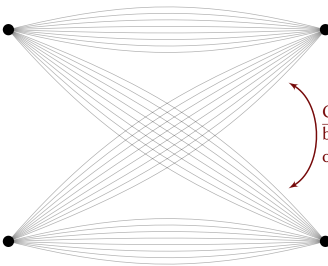


Binary metric: branches are mapped by non-orthogonal codewords

Metric:
$p\left(\boldsymbol{r} \,\middle|\, \boldsymbol{c}^i\right) = \sum L(b_k) c_k^i$

Codewords $\boldsymbol{c}^i$: 00000, 00001, …

Coupled strategy



Orthogonal metric: branches are mapped by orthogonal codewords

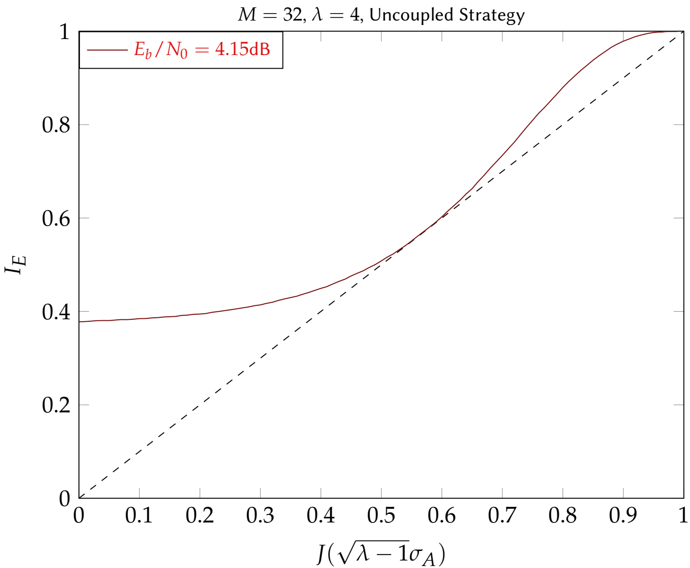
Metric:
$p\left(\boldsymbol{r} \,\middle|\, \boldsymbol{s}^i\right)$

Codewords: from FSK alphabet

Receiver's Strategy

Performance

- EXIT chart: threshold following the uncoupled strategy



Receiver's Strategy

Performance

- EXIT chart: threshold following the coupled strategy of Turbo-FSK