Forward error correction for next-generation high-speed optical networks

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Overview

- Motivation
- Introduction to FEC codes
- FEC codes in Optical Communication
- Implementation of a State of the Art FEC code
- Next Generation of FEC codes for Optical Communication
- Final Comments

Motivation

Motivation

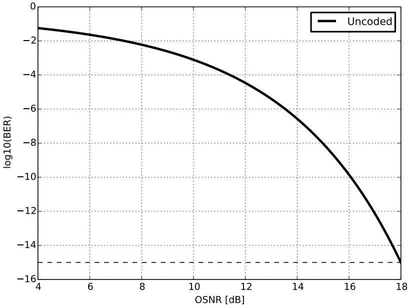
Network operators have to manage the increasing capacity requirements on their optical transport networks due to:

- high-speed data services
- 3G/4G smartphone services
- Internet video services

To support these new services, network speeds have increased from 10 Gbps to 40 Gbps and is currently increasing to $>$100 Gbps per wavelength.

The OSNR Limit

One of the fundamental limits in designing optical transport networks is the Optical Signal to Noise Ratio (OSNR)



- Optical transceivers must operate above their OSNR limit to warranty error-free operation
- The longer the fiber link, the lower the OSNR. Therefore, the OSNR limit determines how far the optical signal can travel before regeneration

The OSNR limits can be lowered by using Forward Error Correcting (FEC) codes. The later is possible because FEC dramatically lowers the BER

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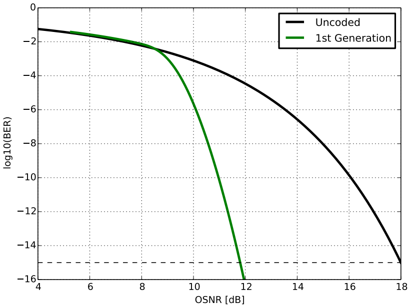

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Benefits of FEC Codes

FEC provides the following benefits for fiber optic communications links:

- Improves performance of an existing link between two points
- Increases the maximum span of the link in systems without repeaters
- Increases the distance between repeaters in optically amplified systems or relaxes the specifications of the optical components or fiber
- Improves the overall quality of the link by diagnosing degradation and link problems earlier

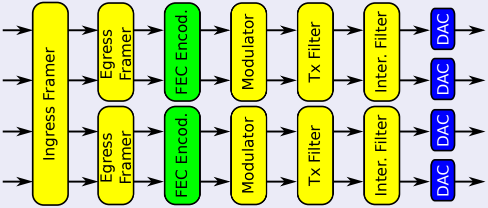
Introduction to FEC codes

What is FEC?

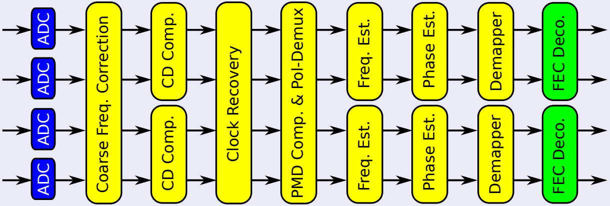
- Forward error correction (FEC) is a digital signal processing technique used to enhance data reliability over unreliable or noisy communication channels
- It introduces redundant data (parity), prior to data transmission or storage. This redundant data provides the receiver with the ability to correct errors without retransmission
- The simplest FEC code is the triple repetition code which transmits each bit 3 times. I.e., bits 1 and 0 are transmitted as 111 and 000, respectively (where 000 and 111 are called codewords). In the receiver, the majority vote strategy is used. I.e., 111, 011, 101, and 110 are decoded as 1. Note that this code can correct up to one error per codeword

Where is FEC within the Transceiver?

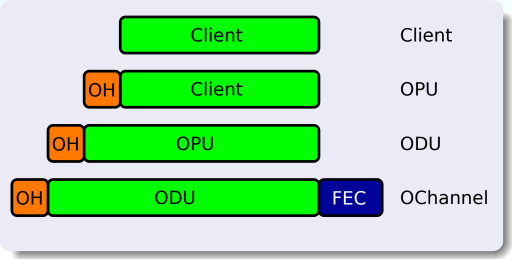
Transmitter



Receiver

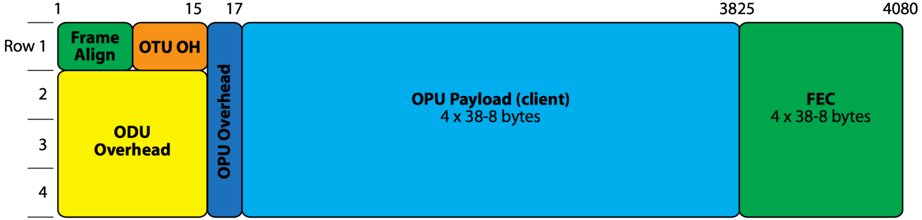


Where is FEC within the OTN Frame?



Optical Payload Unit (OPU),
Optical Data Unit (ODU),
Optical Transport Unit (OTU),
These overheads provide path and section performance monitoring, alarm indication, communication, and protection switching capabilities.

Forward Error Correction (FEC) provides an OSNR improvement



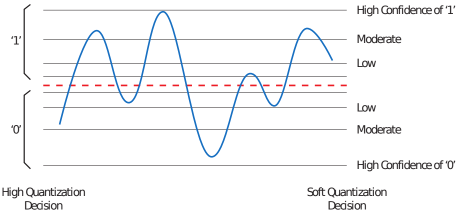
Classification and Parameters

- Codes can be classified in:
  - Block codes (work on blocks/packets) and Convolutional codes (work with a continuous stream of symbols/bits)
  - Linear codes and non-linear codes
- Here we will focus on linear block codes. However, a similar analysis is valid for non-linear block codes and convolutional codes
- The main parameters of a linear block code are:
  - **Length**, denoted N, is number of bits per codeword
  - **Dimension**, denoted K, is number of information bits per codeword
  - **Parity**, denoted P, is number of parity bits per codeword, P=N-K
  - **Code rate**, denoted R, is defined as K/N
  - **Overhead**, denoted OH, is defined as P/K = (N-K)/K

Decoding Algorithms

The decoding algorithm can be classified in:

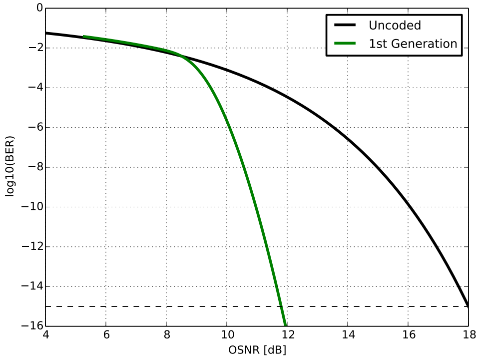
- **Hard decoding** (the input of the decoder are bits or symbols)
- **Soft decoding** (the input of the decoder are the probabilities of each bit or symbol)



- Soft decoding provides better performance than hard decoding at the expense of a much higher implementation complexity
- To achieve Shannon capacity on a general channel, soft decoding is necessary

FEC codes in Optical Communication

FECs in Optical Communication

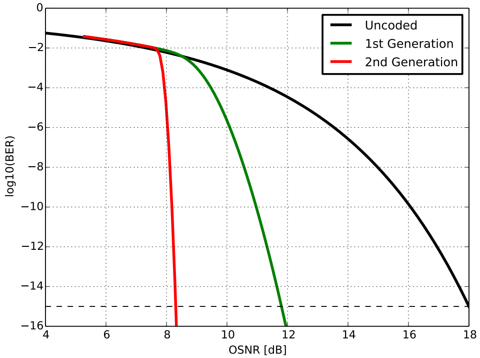


1st Generation

Hard decision cyclic and algebraic codes such as RS and BCH.

- Net coding gain ≈ 5.8 dB
- Overhead ≈ 6.5 %
- Throughput ≈ 10Gb/s

FECs in Optical Communication



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2nd Generation

Hard decision concatenated codes such as RS+BCH and RS+RS.

- Net coding gain ≈ 6 to 10 dB dB
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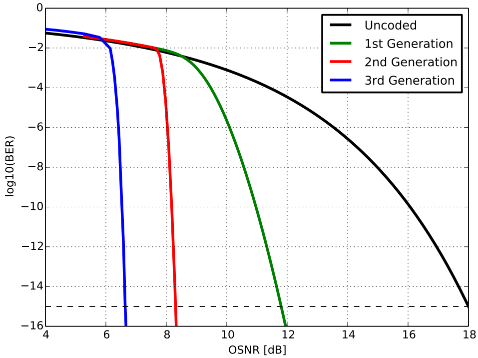
- Throughput ≈ 40Gb/s

FECs in Optical Communication



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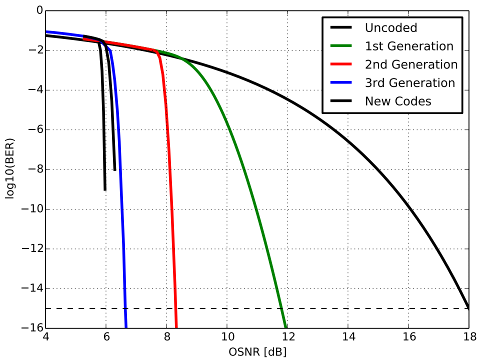
3rd Generation (today)

Soft decision and iterative decoding codes such as Turbo Codes and LDPC codes.

- Net coding gain ≈ 10 to 11.5 dB
- Overhead ≈ 15 % to 25 %
- Throughput ≈ 100Gb/s to 200Gb/s

FECs in Optical Communication



- In the road to the 4th generation, codes with a net coding gain of 12 dB and overhead of 25 % are already designed

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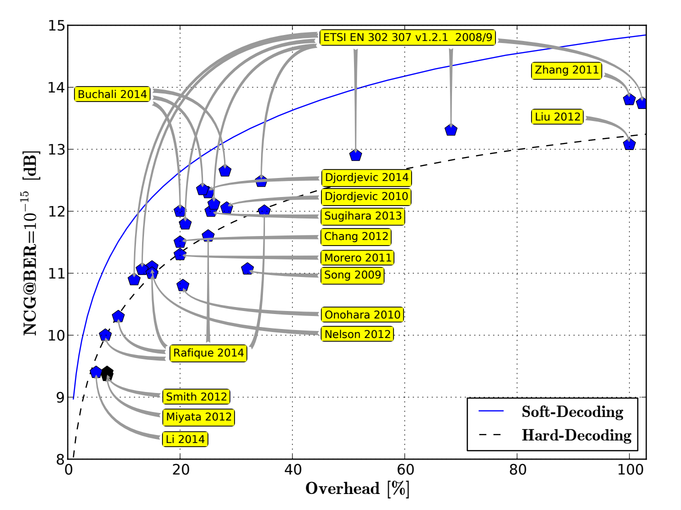
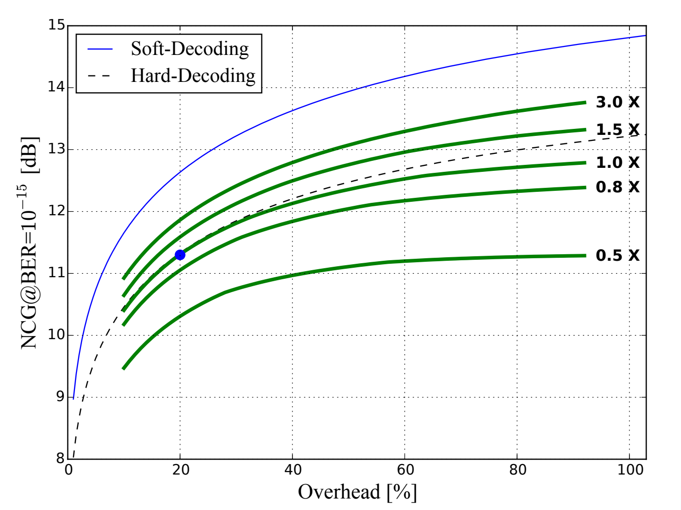
Published FEC Codes



Coding Gain vs. Overhead vs. Complexity



Implementation of a State of the Art FEC code

Challenges

Complexity

The high coding gain and throughput required in optical communication can only be satisfied with complex FEC codes

- For instance, LDPC codes have high interconnection density. This represents an obstacle to the use of long codes, which is required to achieve a near Shannon limit performance

Very low BER

The iterative Soft-FEC codes, required to achieve near Shannon limint performance, suffer from a performance degradation that is only observed at low BER (typically $< 10^{-15}$). This effect is known as **Error-Floor**.

Performance verification at very lor BER

There are not analytic methods to accurately estimate the performance at low BER of iterative Soft-FEC codes. Therefore, high speed FPGA emulation is required.

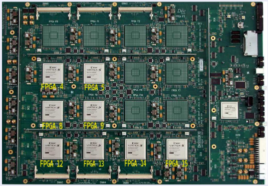
Performance Analysis Based on FPGA Emulation

FPGA Boards used are:

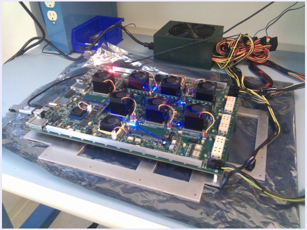
- One board with 8 FPGAs Virtex 5 in which a throughput of 4.9 Gb/s was achieved
- One board with 7 FPGAs Virtex 6 in which a throughput of 10 Gb/s was achieved
- The FPGA emulation comprises the following main blocks:
  - A Gaussian noise generator
  - An encoder/decoder LDPC
  - An error pattern capture block and BER estimator

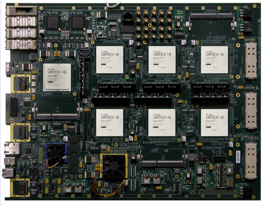
FPGA Boards

Virtex 5

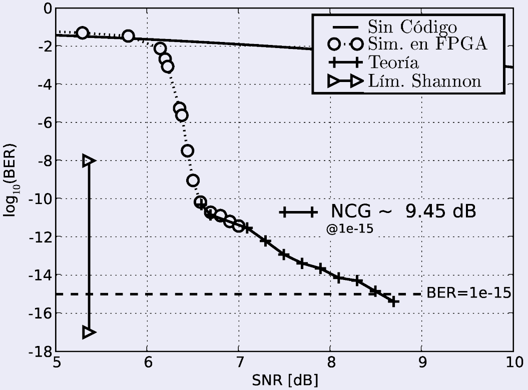


Virtex 6





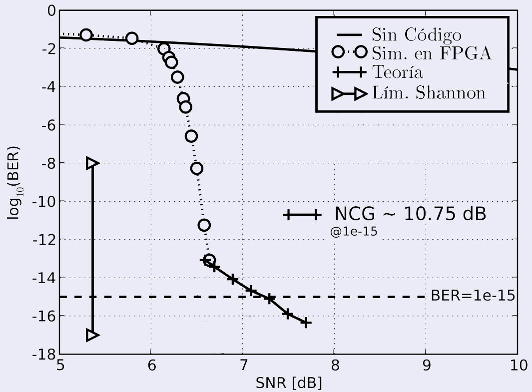
Emulated Performance



Code $\mathcal{C}_1$

The code was not optimized

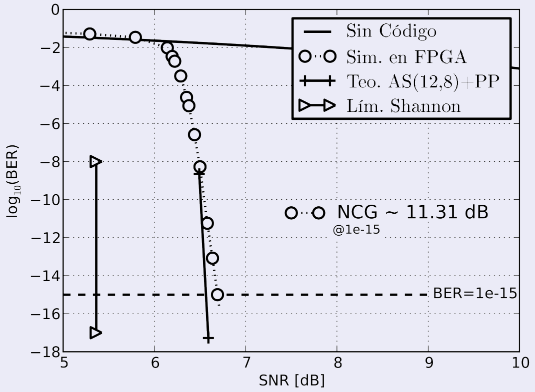
Emulated Performance



Code $\mathcal{C}_2$

The parity check matrix of the code was optimized to reduce the error-floor

Emulated Performance

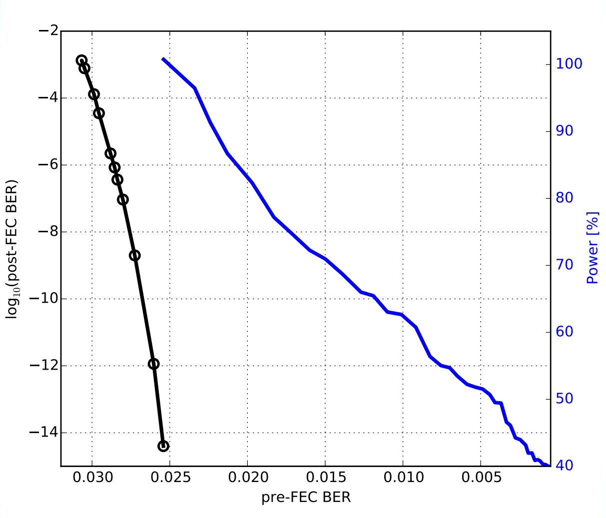


Code $\mathcal{C}_2$

The parity check matrix of the code was optimized to reduce the error-floor

A post-processing algorithm was added to the decoder

Performance Verification in the Lab



Comments

- A Soft-FEC LDPC code was designed and implemented in CMOS technology
  - Net coding gain > 11.3 dB at BER$=10^{-15}$
  - Throughput $= 256$ Gb/s
- A post-processing algorithm was used to reduce the error-floor
- This code was included as part of a 200Gb/s coherent optical transceiver that will be used in several networks around the word including: submarine ($>$10000 Km), long houl metro ($\approx$3000 Km), pluggable metro (80 to 1000 Km), and data center ($<$80 Km)

Next Generation of FEC codes for Optical Communication

4th Generation

The 4th Generation FEC Codes

ClariPhy Argentina

Performance

Soft decision and iterative decoding coded modulation schemes

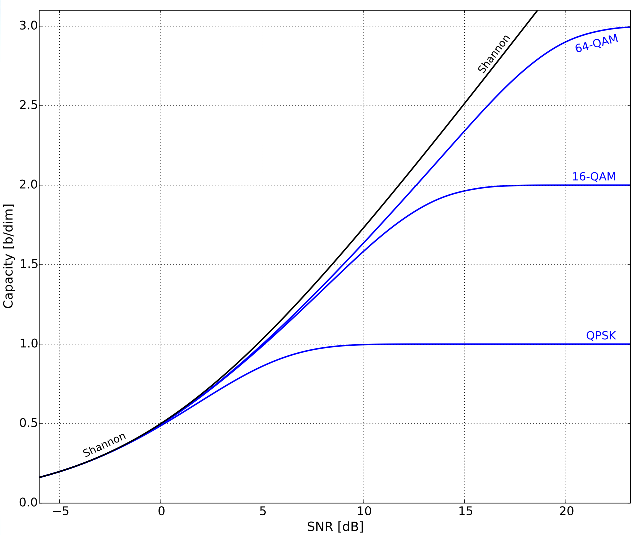
- Gap to Shannon capacity < 2.5 dB
- Overhead $\approx 15\,\%$ to $60\,\%$

Flexibility

A configurable number of bits per Hz/s is a key characteristic for the next generation of optical transceivers

- Throughput between 400Gb/s and 1Tb/s
- Several modulation formats: QPSK, QAM8, QAM16, QAM64, etc

Channel Capacity



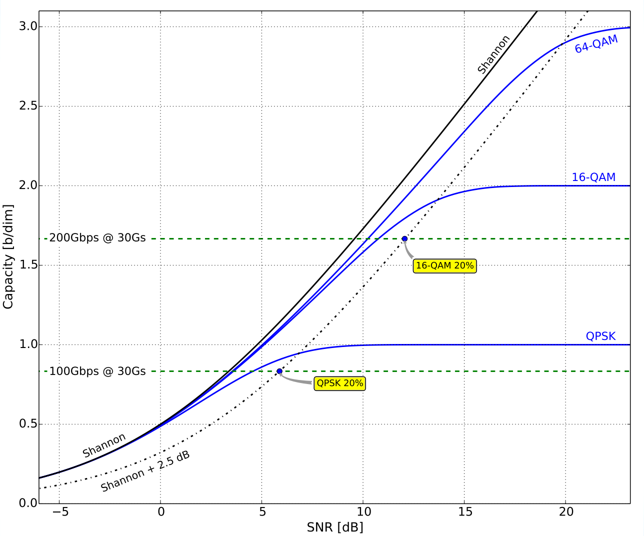
In the low-SNR regime an equiprobable binary alphabet is nearly optimal

In the high-SNR regime, the capacity of equiprobable PAM constellations asymptotically approaches a straight line parallel to the capacity of the AWGN channel.

The asymptotic loss of (1.53 dB) is due to using a uniform rather than a Gaussian distribution over the signal set

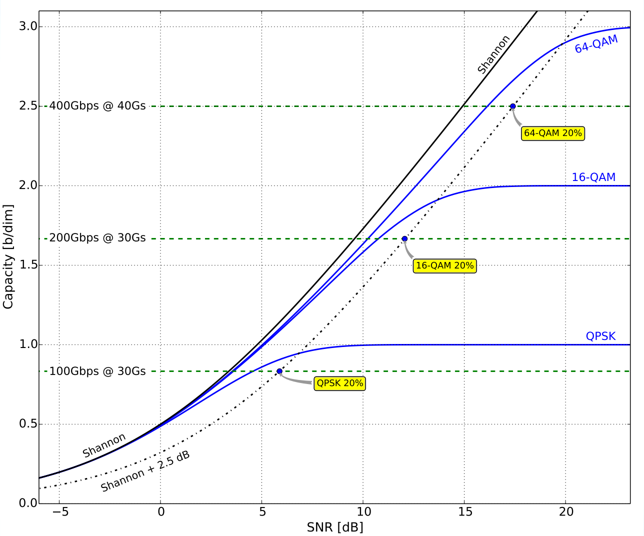
To obtain the remaining 1.53 dB, constellation-shaping techniques that produce a Gaussian-like distribution over an PAM constellation are required

Channel Capacity



3G state of the Art

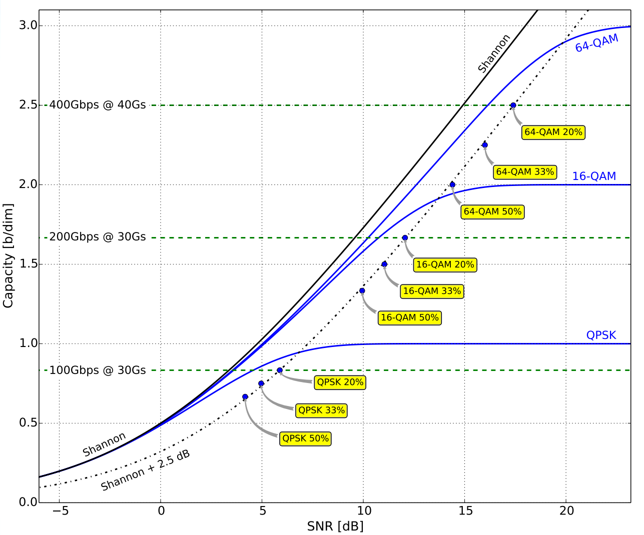
Channel Capacity



4G new features:

400Gb/s based on 64 QAM

Channel Capacity



4G new features:

400Gb/s based on 64 QAM

Spectral flexibility based on programmable overhead

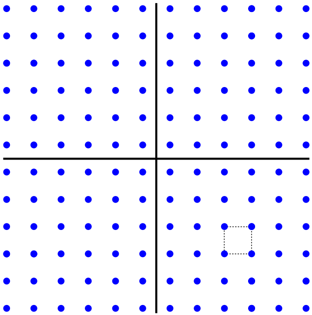
Reducing the Gap to Capacity

The performance of estate of the art commercial FEC codes is about 2.5 dB from Shannon capacity, where ideal DSP compensation is assumed

- **Powerful FEC codes:** new CMOS technology ($\leq$16nm) will allow to implemented more complex FEC codes. A gain improvement up to 1 dB may be possible
- **Coded Modulation:** however, in order to achieve further improvements in the gap to capacity, the combination of coding and modulation will be required.
- **Iterative Graph Based Receivers:** additionally, even further improvements in performance are possible combining coding, modulation and DSP.

The Road to Coded Modulation

Coded Modulation is the natural evolution of the classical constellation schemes to higher dimensions and better distance properties



Campopiano and Glazer Constellations

- Rectangular constellations
  - Even integer number of bits per symbol
  - This constellations can be represented by two independent PAM channels
- Cross constellations
  - Odd integer number of bits per symbol
  - It is slightly more efficient than the square constellation, by a factor of 31/32 or 0.14 dB, because it is more like a circle
- The later suggests that the cross would be the better shape even for *n* even. This motivates the so called "**Generalized Campopiano and Glazer Constellations**"

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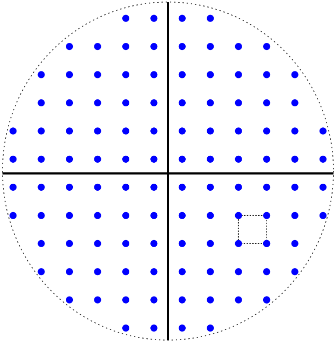

Constellations based on a square lattice

From an infinite array of points closely packed in a regular array or lattice, select a closely packed subset of 2^b points as a signal constellation.

- The $n = 4$ cross constellation is as good as the conventional 4×4 square constellation
- The $n = 6$ cross constellations is 0,1 dB better than the 8×8 square constellation
- The best enclosing boundary would be a circle, the geometrical figure of least average energy for a given area. Note that the $n = 6$ circular constellation outperform the $n = 6$ cross constellation by 0.1 dB

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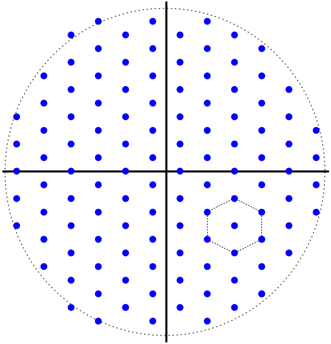

Const. based on a hexagonal lattice

The densest lattice in two dimensions is the hexagonal lattice. Therefore, constellations using points from a hexagonal lattice ought to be the most efficient

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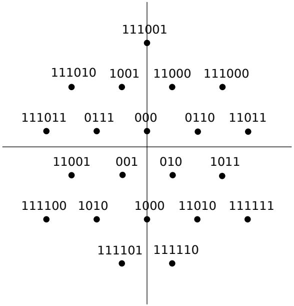

Source Coded Constellations

Attainment of the channel capacity bound requires that the signal points have a Gaussian probability distribution.

The data bits are divided into words of nonuniform length according to a prefix code, and then to map the prefix code words into signals points.

- The figure shows a set of prefix code words and a mapping onto the hexagonal lattice that yields an average energy of $S = 7{,}02$ while transmitting an average of 4 bits/symbol
  - an improvement of close 1 dB over the best $n = 4$ uniform code known

The Road to Coded Modulation

Coded Modulation is the natural evolution of the classical constellation schemes to higher dimensions and better distance properties

N	Gain	dB
2	1,05	0,20
4	1,11	0,45
8	1,18	0,73
16	1,25	0,98
24	1,29	1,10
32	1,31	1,17
48	1,34	1,26
64	1,35	1,31
∞	$\pi e/6$	1,53

Energy saving possible in N dimensions, based on the difference between average energy of and N-sphere versus an N-cube of the same volume

High-Dimensional Constellations

A small gain of 0.2 dB is possible by going from one-dimensional PAM to two-dimensional QAM and choosing points on a two-dimensional rectangular lattice from within a circular rather than a square boundary

In the same way, by going to a higher number N of dimensions and choosing points on an N-dimensional rectangular lattice from within an N-sphere rather than an N-cube, further modest saving are possible.

For large N the probabilities of points in any two dimensions become nonuniform and ultimately Gaussian

The Road to Coded Modulation

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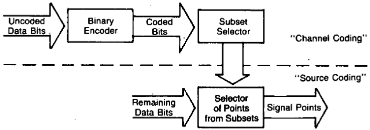
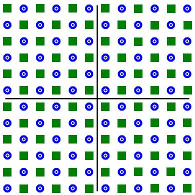


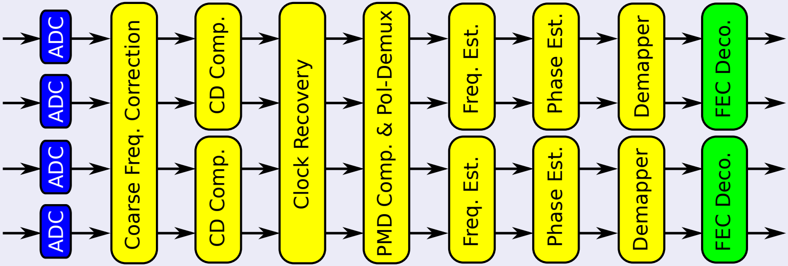


Coded Modulation: Basic Idea

- Coded Modulation is the introduction of interdependencies between sequences of signal points such that not all sequences are possible
- Due to the later, the minimum distance d_{min} in the N-dimensional space between two possible sequences can be greater than the minimum distance d_0 in the 2-dimensional space
- Therefore, the use of maximum likelihood sequence detection at the receiver yields a "coding gain" of a factor of d_{min}^2/d_0^2
- Coded modulation can be based on **block codes** or **trellis codes**

Iterative Graph Based Receivers

Combining Coding and DSP



[1] M. A. Castrillon, D. A. Morero, O. E. Agazzi and M. R. Hueda, "Performance of joint iterative detection and decoding in coherent optical channels," 2015 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, 2015, pp. 1-3.

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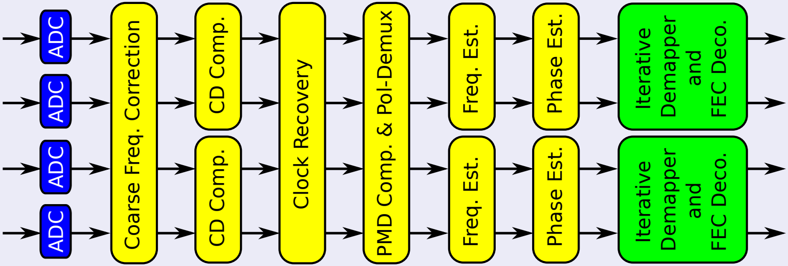

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Iterative Graph Based Receivers

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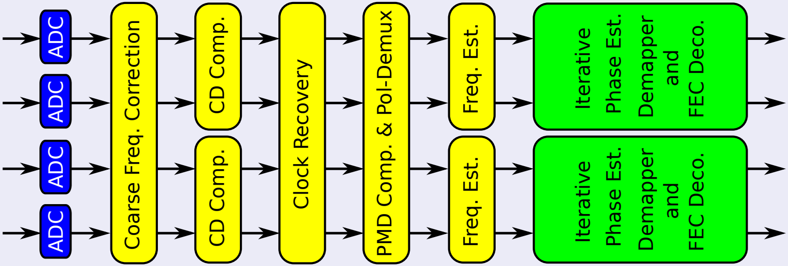

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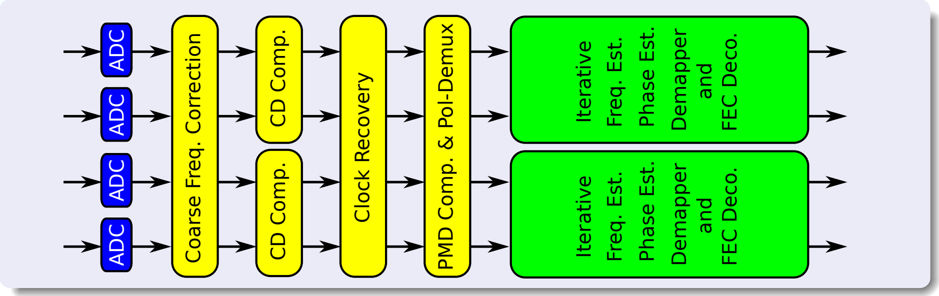

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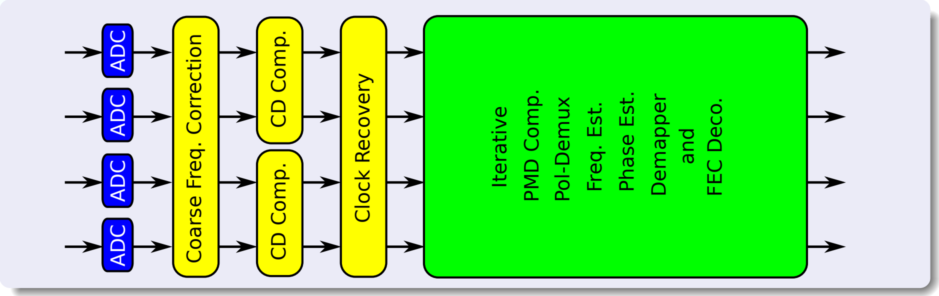
[3] M. A. Castrillon, D. A. Morero and M. R. Hueda, "Joint iterative detection and decoding using spatially coupled LDPC codes," 2016 IEEE Photonics Conference (IPC), Waikoloa, HI, 2016, pp. 305-306.

Iterative Graph Based Receivers

Combining Coding and DSP



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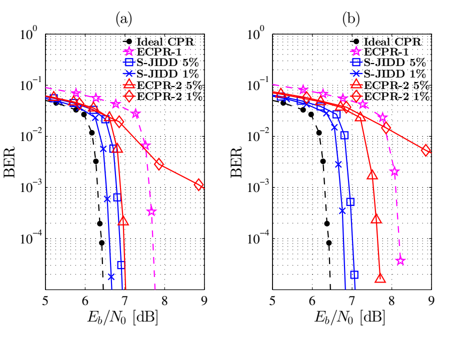

Performance comparison between two state of the art Carrier Phase Recoveries (ECPR-1 and ECPR-2) and the proposed Join Iterative Demapper and Decoder (JIDD) with integrated carrier phase recovery.

(a) Linewidth = 500KHz
(b) Linewidth = 5MHz

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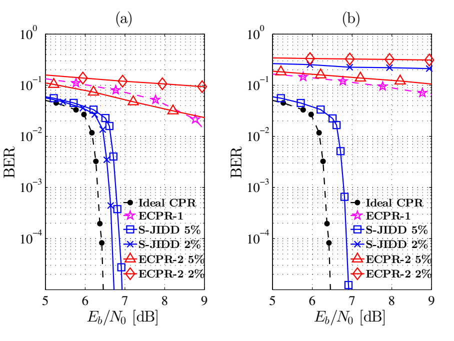

Performance comparison between two state of the art Carrier Phase Recoveries (ECPR-1 and ECPR-2) and the proposed Join Iterative Demapper and Decoder (JIDD) with integrated carrier phase recovery.

Linewidth = 500KHz
Frequency fluctuation:
(a) ±200MHz @35KHz
(b) ±500MHz @35KHz

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Final Comments

Final Comments

- Next generation FEC codes will achieve a gap to capacity below 2.5 dB under an AWGN channel model and they will provide spectral flexibility by supporting a wide range of overheads and modulations formats (similar to what have happened in wireless communication)
  - Soft-FEC such as LDPC codes will be the main strategy
  - Coded modulation scheme will be necessary in high order modulation
- However, DSP algorithms are still far from capacity
- Joind decoding and DSP processing is required to achieve the ultimate near Shannon limit performance
  - Iterative graph based joint decoding and DSP processing provide a good trade off between performance and complexity