WIRELESS WORLD
RESEARCH FORUM

Error Control Coding Options for Next Generation Wireless Systems

Joint WG4/5 White Paper

- Table of Content –

WWRF 17, November 15-17, Heidelberg

Editors: T. Lestable*, M. Ran +

* Samsung Electronics UK

+ H.I.T - Holon Institute of Technology, Israel

Contributors

Name	Affiliation
Thierry Lestable	Samsung Electronics Research Institute, UK. Advanced Technology & Standard Group. Thierry.lestable@samsung.com
Moshe Ran	Horon Institute of Technology (H.I.T), Israel ranmoshe@bezeqint.net
Gerhard Bauch	DoCoMo Eurolabs, Germany bauch@docomolab-euro.com
David Declercq	ENSEA/ETIS, France Declercq@ensea.fr
Jossy Sayir	FTW, Austria Jossy.sayir@FTW.at
Marcos .B.S Tavares	TUD Vodafone Chair, Germany tavares@ifn.et.tu-dresden.de

- **11 Specialists**
- **8 Organizations**
- **6 Countries**

Marie-Helene Hamon	France Telecom R&D, France mhelene.hamon@orange-ft.com
Carlos De Segovia	France Telecom R&D, France carlos.desegovia@orange-ft.com
Isabelle Siaud	France Telecom R&D, France Isabelle.siaud@orange-ft.com
Xiangming Li	DoCoMo Beijing Labs, China lixm@docomolabs-beijing.com.cn
Frank Kienle	University of Kaiserslautern, Microelectronic Systems Design Research Group, kienle@eit.uni-kl.de

Outlines

- Abstract
- Table of Content for the White Paper
- Latest Presentation given during Call for Contribution in Shangai
  - Introduction
  - General Code Types
  - LDPC Codes
  - Short Packet Length
- Assignment of Chapter Editors
- References

Abstract

WIRELESS WORLD RESEARCH FORUM

- *Abstract* – The objective of this White Paper (WP) is twofold: first we would like to identify current state of advanced channel coding technologies, by assessing their respective performance, computational complexity, implementation solutions, and thus comparing them relying on their maturity. Then identifying for all of them new and promising research directions would be the second and complementary target of this WP.

  The outstanding near-capacity performances of advanced channel coding schemes have attracted for more than 10 years the interest of the overall information theory community and their industry partners. The maturity of both the theoretical framework and the technology has given birth to many different design and analysis tools, together with outperforming applications, and new business opportunities (Flarion, Digital Foutain).

After some years of an unshared reign from the technology supporting the Turbo-Codes (PCCC, SCCC and TPC), we are now entering an era of fierce competition where many different iterative decoding solutions are available, with their respective performance and complexity.

It becomes thus crucial and highly interesting to give a fair state of art of such leading-edge solutions, and then to sketch their pros and cons, in terms of both theoretical advances and implementations aspects.

Table of Content [1/2]

WIRELESS WORLD RESEARCH FORUM

Table of Content [2/2]

WIRELESS WORLD RESEARCH FORUM

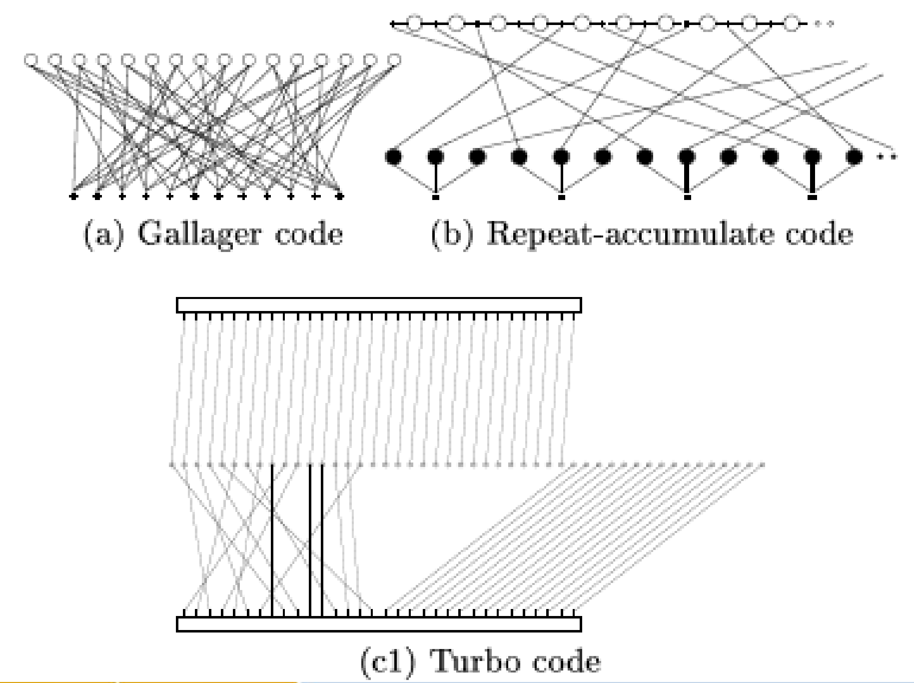
-

Introduction

- Sparsity

Sparsity

- Generalized Parity-Check Matrices



- 9 open questions
  - Are State variable going to be present in the best codes?
  - How many weight-two columns can a Gallager code of Rate R have, and still remain a ‘good’ code?
  - Are there optimization methods that optimize block error probability instead of bit-error probability?
  - Are there any advantages in terms of code strength to making the code by parallel concatenation of two or more codes? …

D. McKay, “Relationships between Sparse Graph Codes”, Information-Based Induction Science, IBIS 2000, July 17-18 2000, Shizuoka, Japan

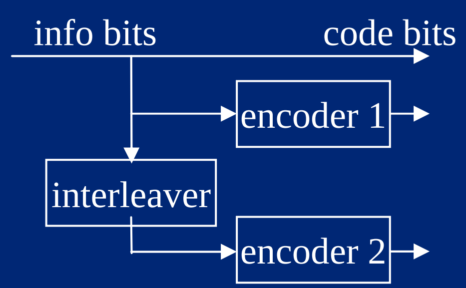
General Code Types

- Turbo-PCCC
- Turbo-SCCC
- LDPC Codes
- RA…

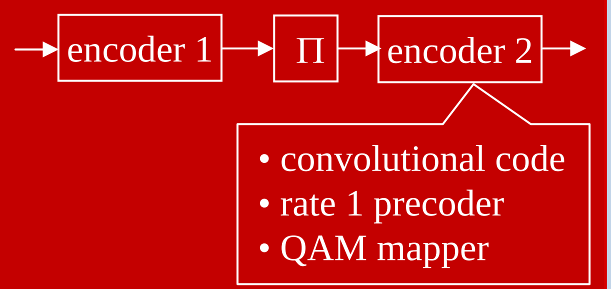
Forward Error Control (FEC) Coding with Iterative ("Turbo") Detection

Goals:
- Close to capacity performance for high power and bandwidth efficiency.
- Reasonable encoding and detection complexity.
- High flexibility for code rate adaptation to channel quality and QoS requirements.

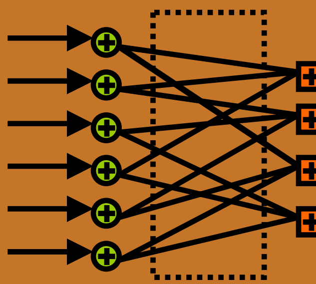
Parallel Concatenation (Turbo Codes)

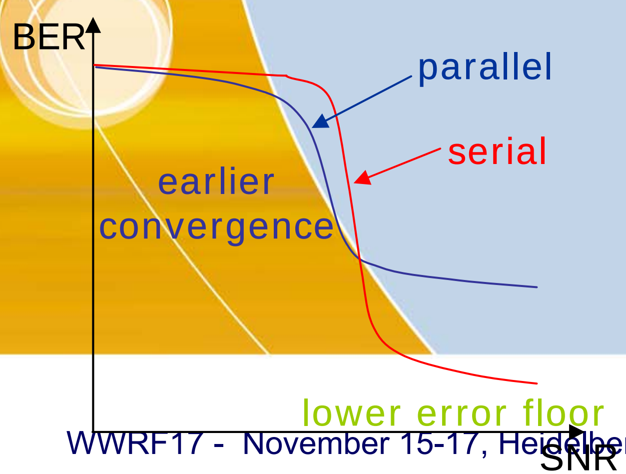


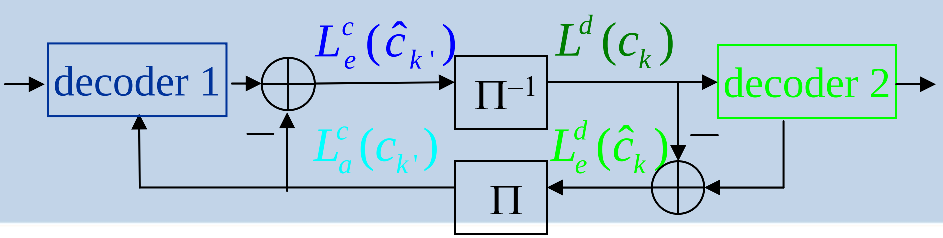
Serial Concatenation



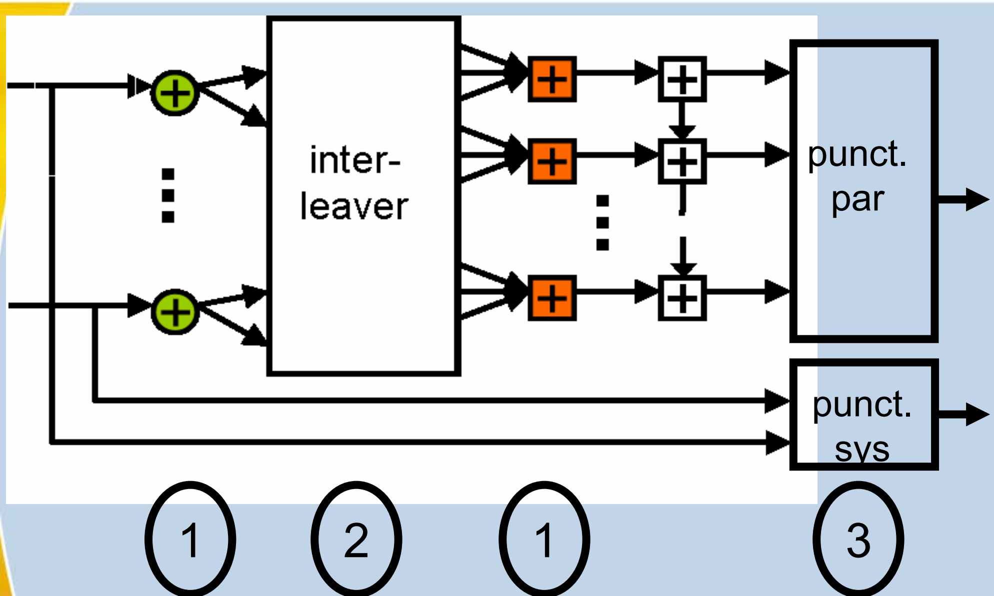
LDPC Codes







Design Approach for Rate Comp. RA Code



Mother Code

1 Degree distrib.

2 Interleaver

3 (Code doping)

Rate Compatibility

3 Puncturing

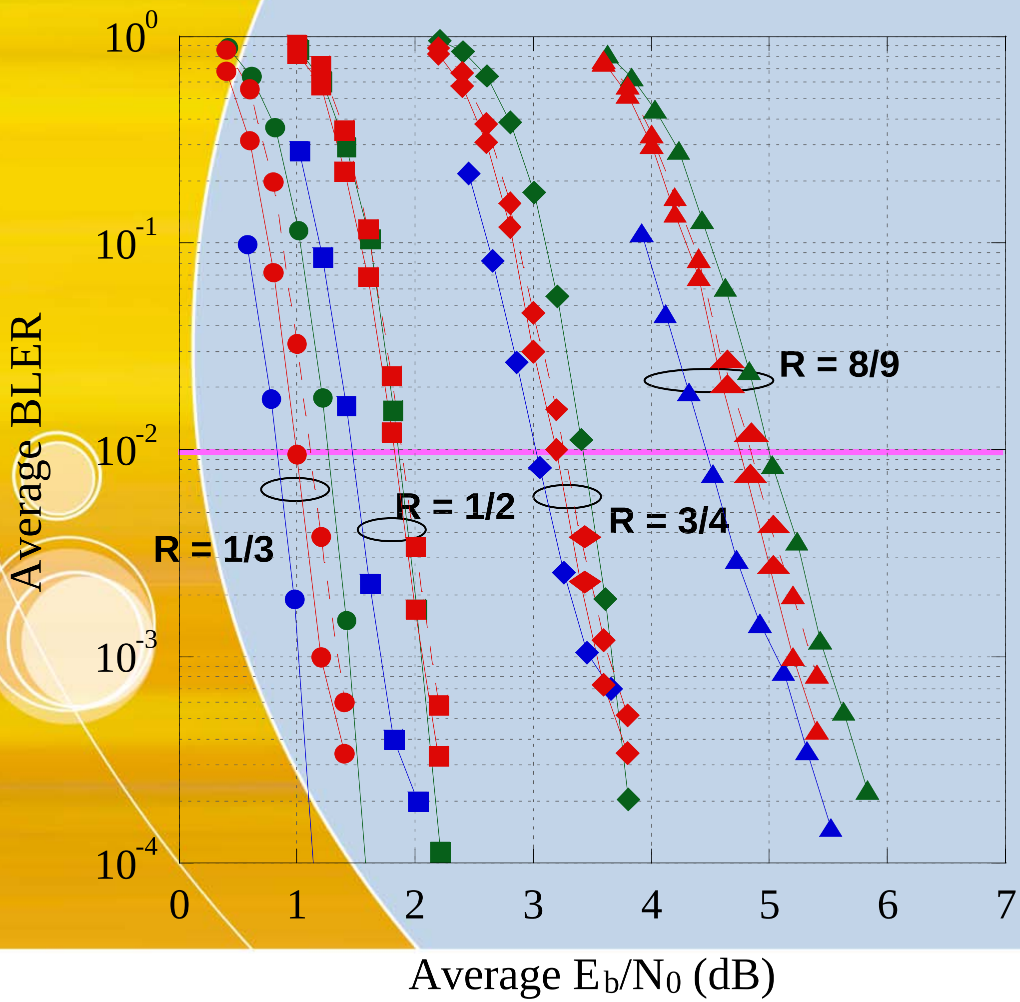
Advantages:

- Repeat-accumulate (RA) structure allows low-complexity encoding.
- Regular puncturing requires low memory for storing punturing pattern.
- RA structure allows for different decoding strategies: message passing (highly parallel) and mixed trellis-based/message passing decoding (less iterations).

Problems:

- Interleaver not algebraic ⇒ high memory requirement
- Performance degradation at high rates

BLER comparison of rate compatible codes



- **AWGN channel**
- **QPSK**
- **Sub-optimum decoding**
  - **- PCCC, SCCC: Norm. Max-Log.**
  - **- RA: Box-plus with correct. term**
- **Information length**
  - **- PCCC, SCCC: 996 w/o tail bits**
  - **- RA: 1000**
- **Regular Puncturing for SCCC**

Degradation to PCCC(at 10^{-2} BLER)

- SCCC : 0.4 dB – 0.6 dB

- RA : 0.2 dB – 0.5 dB

Decoder Complexity

Decoder complexity
- SCCC, PCCC : Max log with correction term
- RA : Box plus with correction term
- Required Operation per iteration per info. bit

	PCCC	SCCC	RA
Addition (1)	198	128.5	120
Comparison (1)	60	35	140
Multiplication (10)	2	2.5	
Total	278	187	260

LDPC Codes

- LDPC Convolutional Codes
- Non-Binary LDPC Codes

Motivation for LDPC Convolutional Codes

→ **LDPC Convolutional Codes are not limited to a fixed Block Length** as LDPC Block Codes, i.e. a single Code can be used for several Block Lengths

→ **Low-Complexity Encoding** using Shift-Registers

→ **Continuous Decoding** using Pipeline-Decoder

→ **VLSI Implementation** of the Decoder is facilitated due to **Convolutional Structure** of the underlying Graph

→ **For a given Complexity, LDPC Convolutional Codes have better Performance than LDPC Block Codes**

General Definition of LDPC Convolutional Codes

A (m_s,J,K) regular time-varying LDPC Convolutional Code is a Set of Sequences ***v*** satisfying the equation $\boldsymbol{v}\boldsymbol{H}^T = 0$, where

$$H^T = \begin{bmatrix} H_0^T(0) & \cdots & H_{m_s}^T(m_s) & & \\ & \ddots & & \ddots & \\ & & H_0^T(t) & \cdots & H_{m_s}^T(t+m_s) \\ & & \ddots & & \ddots \end{bmatrix}$$

For a LDPC Convolutional Code of rate ***R = b/c***, ***b<c***, the elements $H_i^T(t)$, $i=0,1,\ldots,m_s$, are binary ***cx(c-b)*** sub-matrices defined as:

$$H_i^T(i) = \begin{bmatrix} h_i^{(1,1)}(t) & \cdots & h_i^{(1,c-b)}(t) \\ \vdots & & \vdots \\ h_i^{(c-1,1)}(t) & \cdots & h_i^{(c,c-b)}(t) \end{bmatrix}$$

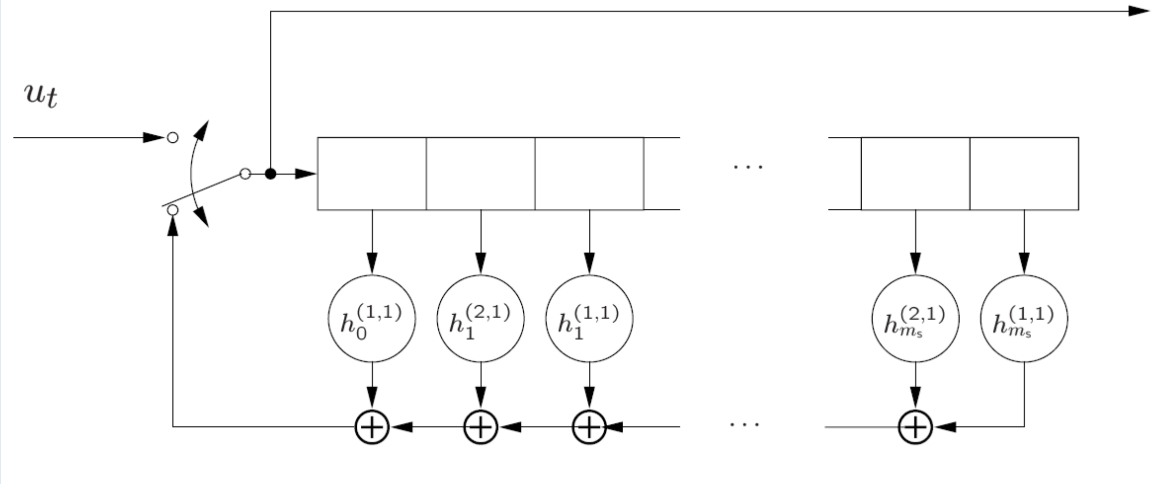
The value m_s is called the syndrome former memory and the associated constraint length is defined as $v_s = (m_s+1)c$.

Encoding of LDPC Convolutional Codes

A systematic encoder for a rate ***R = b/c*** convolutional code can be obtained from:

$$v_t H_0^T(t) + v_{t-1} H_1^T(t) + \cdots + v_{t-m_s} H_{m_s}^T(t) = 0$$

Shift-Register Implementation for ***R = 1/2***:

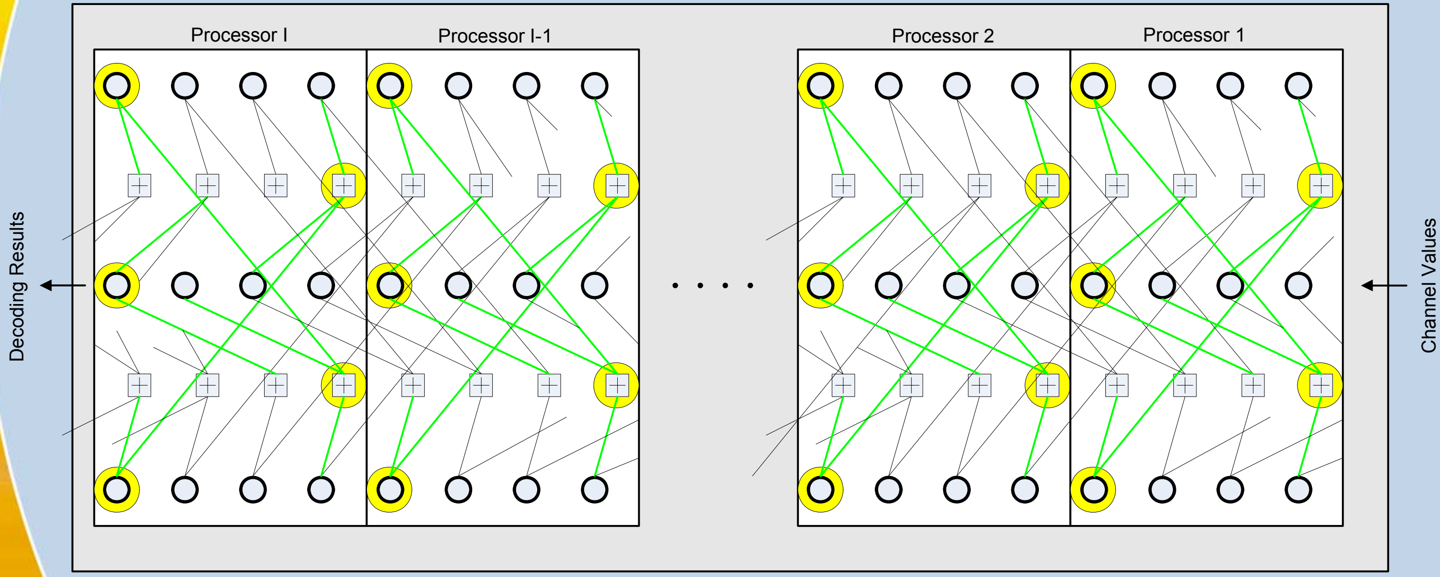


- The Tap Weights $h_i^{(\cdot,\cdot)}$ can vary on time or not, depending on the code (time-varying or time-invariant code)
- Each Time ***K-1*** Taps are active → Complexity independent of m_s

Decoding of LDPC Convolutional Codes

Pipeline-Decoder:

$$H(D)=\begin{bmatrix} 1 & D & D^3 \\ D^3 & D^2 & 1 \end{bmatrix}$$



Decoding Window, Size = $I(m_s+1)$

- Continuous Decoder that operates on a Finite Window, sliding along the received sequence
- Identical, Independent Processors perform I Iterations in parallel

Non binary LDPC codes are good candidates for small packet lengths

Binary LDPC codes for small packet length

→ Even with good construction methods (PEG, quasi-cyclic, etc), binary LDPC codes start to show their weakness when the codeword becomes small (500<N<3000).

- ❖ LDPC codes with good convergence (asymptotic performance) are highly irregular = the LDPC code is strongly connected.
- ❖ Strongly connected LDPC codes have a lot of Stopping/Trapping sets = bad error floor region performance.

→ There is a necessary “tradeoff” between good convergence and low error floor with binary LDPC codes.

Non binary LDPC codes are good candidates for small packet lengths

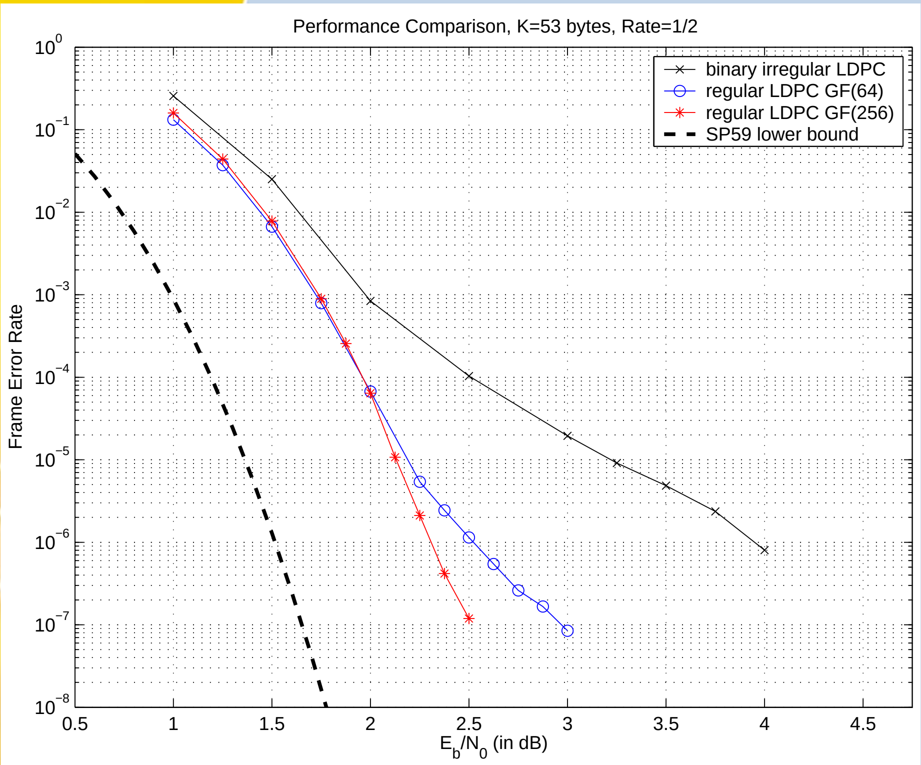
Non Binary LDPC codes for small packet length

→ Ultra-sparse LDPC codes are defined as strictly regular LDPC codes with minimum symbol variable node degree d_v=2. With non binary ultra-sparse LDPC codes over GF(q)

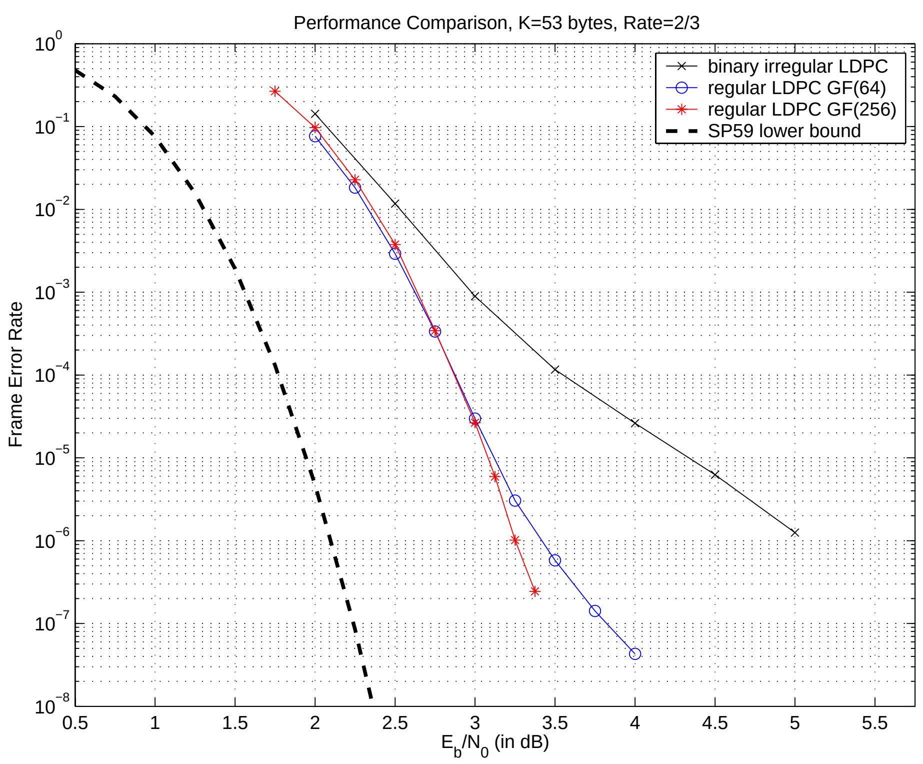
- ❖ The girth of the Tanner graph is excellent and the BP decoder operates close to MLD (less stopping sets).
- ❖ Increasing q lead to codes whose binary image has increasing average density = codes with good minimum distance (although asymptotically bad).
- ❖ The “tradeoff” between good convergence and low error floor is solved by considering non binary LDPC codes over high order Galois Fields.

Small codeword length performance of optimized ultra-sparse GF(q) LDPC codes

Rate=0.5 N=848 bits (ATM size)



Rate=0.66 N=848 bits (ATM size)



* **C. Poulliat, M.P. Fossorier and D. Declercq "Using binary image of LDPC codes over GF(q) to improve overall performance", ISTC'06, April 2006, Munich, Germany.**

Decoding Algorithms for non binary LDPC codes

Brute force Belief Propagation is too complex

→ The complexity of a check node processing has complexity $O(q^2)$, which is not feasible for high order fields ($q>32$).

- ❖ Computing the check node in the Fourier domain with $\log_2(q)$-dimensional FFT reduces the complexity to $O(q\log_2(q))$,
- ❖ Using (q-1) log-density-ratios (LDR) to define the message on the edges of the Tanner graph allows to consider only additions in BP-like decoders.
- ❖ Generalizing Min-Sum decoders to non-binary codes can further reduce the decoding complexity without sacrifying much performance (Extended min-sum = EMS).

* D. Declercq and M.P. Fossorier, "Extended MinSum Algorithm for Decoding LDPC Codes over GF(q)", ISIT'05, April 2006, Munich, Germany.

Short Packet Length

- Soft Decision Decoders

Motivation for Soft Decision Decoders (SDD) for Short Packet Lengths over wireless channels

WIRELESS WORLD RESEARCH FORUM

Motivation

→ **short messages with few bytes (e.g., less than 64 bytes) are commonly used in PHY headers, control messages of MAC protocols in many multi-user systems**

→**Very good codes (e.g. LDPC, Repeat Accumulate, Turbo codes, Turbo-product…) for <u>long messages</u> are well known**

→Focus on

- **iterative algebraic SDD of binary and non-binary (e.g., Reed-Solomon) codes**
- **Adaptive algorithms that reduce complexity when SNR is increased (as in all practical wireless channels)**
- **bound meeting performance, optimal Vs. suboptimal**

Basics of Iterative SDD decoders

WIRELESS WORLD RESEARCH FORUM

- Maximum-Likelihood (ML) decoding of linear codes is NP-hard

open problem:

find polynomial-time decoding algorithm with "near ML" for good codes with large minimum distance

- ML of binary codes over AWGN maximizes

$$\log P(\underline{r} \mid \underline{c}), \quad \underline{r} = (r_0, \cdots r_{n-1}) \text{ SD recieved sequence,}$$

$$\underline{c} = (c_0, \cdots, c_{n-1}) \text{ transmitted binary codeword}$$

Or minimizing $d_E^2(\underline{r}, \underline{x}), \quad \text{where } x_i = (-1)^{c_i}$

Or maximizing $M(\underline{r}, \underline{c}) = \sum_{i=0}^{n-1} r_i \cdot x_i$

Iterative SDD decoders schemes

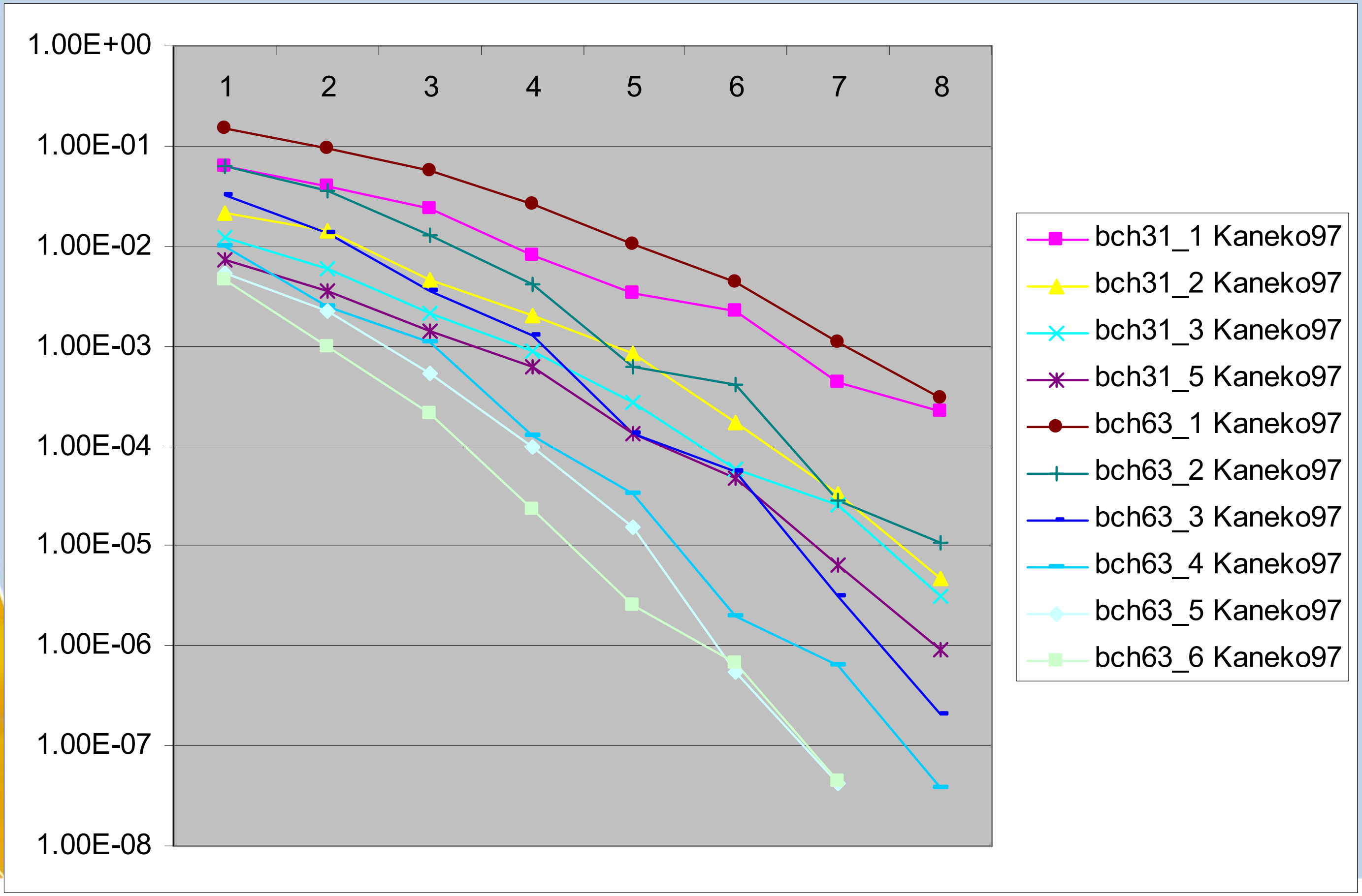
Binary codes

- Generalized min. distance (GMD) [Forney 66]
- Chase II [72]
- Reduced list syndrome decoder (RLSD) [Snyders91]
- KNIH [94]
- Constrained Designs [Ran95]
- Ordered Statistic Decoding (OSD) [Fossorier95]
- KNH [97]

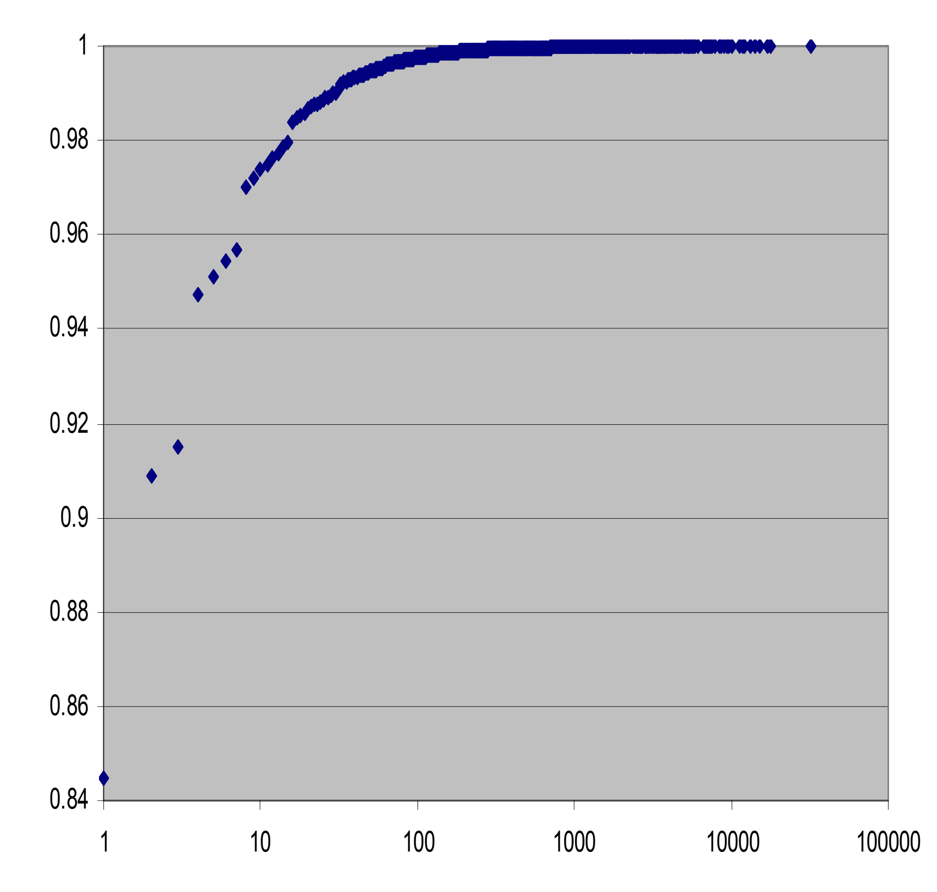
Non-Binary

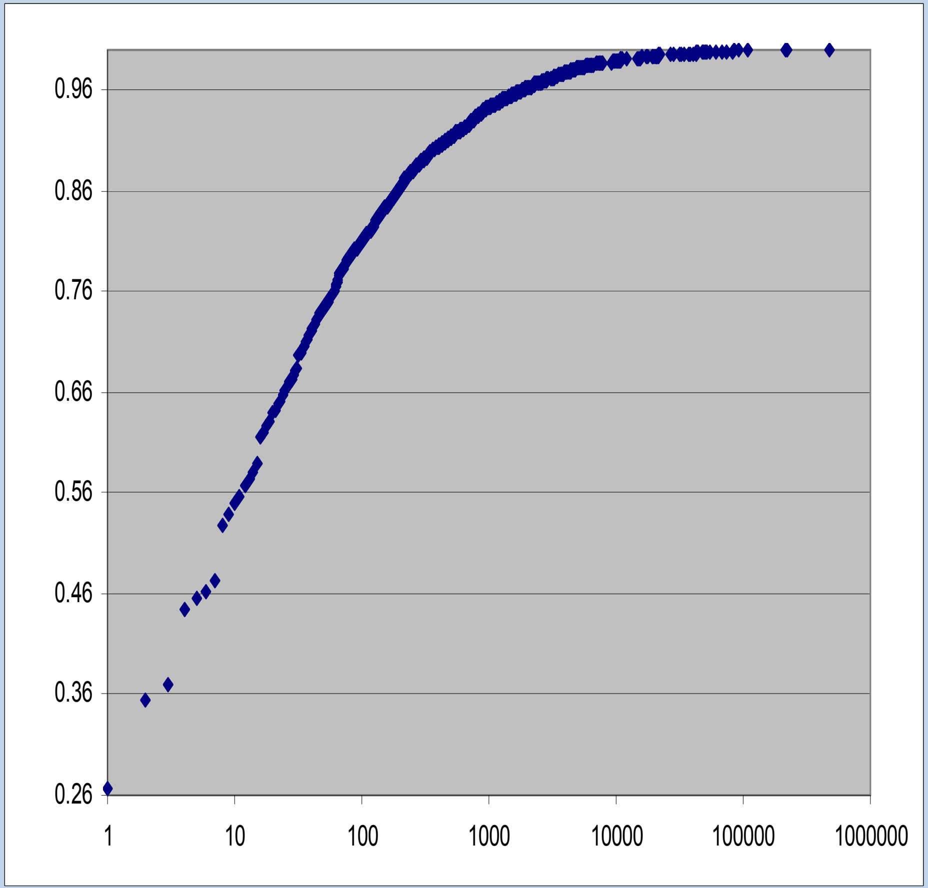
- GMD
- Chase II – GMD
- Koetter-Vardy (KV, 2003)
- Jiang-Narayanan (JN, 2004)
- Al-Khamy-McEliece (KM,2006)

ML-SDD decoders for short BCH based on KNH97



Complexity of ML-SDD for BCH[63, t=6] at
(1) Eb/N0=5dB (2) Eb/N0=3dB





Complexity analysis of algebraic soft-decoders

- Main drawback of all algebraic soft decoders is the Worst case complexities at low SNR e.g., for KNH and KNIH decoders for BCH[128,64,22] t=10

SNR [dB]	5.0	5.5	6.0	6.5	7.0
N_{max}	2097152	32768	1024	5	1

KNH improves 10 times at SNR ~5dB over KNIH

N_{max} = *max. number of operations of BCH HD decoder*

Soft Syndrome Decoder approach

* J. Snyders, "Reduced list of error patterns for Maximum likelihood soft decoding," IEEE Trans. Inform. Theory vol. IT-37 pp.1194-1200 July 1991

- Let $H=(\underline{h}_1,\underline{h}_2,\cdots,\underline{h}_n)$ be a check matrix of $[n,k,d]$ binary linear block code C of length n, dimension k and min. distance d
- Codewords $\underline{x}=(x_1,x_2,\cdots,x_n)$ at channel input are transmitted with equal probabilities over AWGN channel. Assume $\underline{y}=(y_1,y_2,\cdots,y_n)$ $x_i=(-1)^{c_i},\quad c_i\in\{0,1\}$
- Received sequence

  where y_i received signal when x_i was transmitted
- The reliability α_i matched to the AWGN channel is the bit-log-likelihood ratio

$$\alpha_i = K\cdot\ln\frac{p(y_i\,|\,c_i=1)}{p(y_i\,|\,c_i=0)}\qquad i=1,2,\cdots,n$$

$|\alpha_i|=\rho(\underline{h}_i)$ indicates reliability of received y_i (weight of location i)

K arbitrary positive const.

$p(y_i\,|\,x_i)$ probabilty of receiving y_i when transmitting x_i

Note that $\underline{\alpha}=(\alpha_1,\alpha_2,\cdots\alpha_n)$ is generated by SDD from received sequence $\underline{y}=(y_1,y_2,\cdots,y_n)$

Soft Syndrome Decoder approach: elimination rules to reduce complexity

- Eliminations is based on a set of $r < n\text{-}k$ linearly independent columns of H
- Let

$$\Omega_j = \{\underline{v}_1, \underline{v}_2, \cdots, \underline{v}_j\},\ j \le n-k$$

Be a set of linearly independent columns of H sorted in increasing weights

Elimination rule 1 If

(a) $\underline{z} = \underline{v}_1 \Rightarrow$ single error occured at location j=1

(b) $\underline{z} = \underline{v}_2 \Rightarrow$ single error occured at location j=2

(c) $\underline{z} = \underline{v}_1 + \underline{v}_2 \Rightarrow$ Need to compare the single (possible) error at $z = \underline{h}_i$ with double error occured at locations j=1,2

Soft Syndrome Decoder approach: elimination rules to reduce complexity

Elimination rule 2: Let $\underline{z} = \underline{h}$

$$\rho(\underline{h}) < \rho(\underline{v}_j) \text{ for an } \underline{h} \in \{\underline{h}_1, \underline{h}_2, \cdots, \underline{h}_n\} \text{ implies } \underline{h} \in Ls\left(\Omega_{j-1}\right)$$

That is – the “single” should be compared to “duets”, “triplets” etc. only in the subspace spanned by the j-1 “least reliable” columns of H

Notes:

- many cases are eliminated by this rule.
- obviously if the “single” is e.g., $z = \underline{v}_5$ then all pairs as

$\underline{v}_i + \underline{v}_j$, i or j are greater than 5 are eliminated

Soft Syndrome Decoder approach methods for efficient search

- Sorting stage: re-order the columns

$\underline{h}_i$ in an increasing order of reliabilities

- for each case $\underline{z} = \underline{h}_i$ compare the "single" error at location i with weight $\rho_i = \rho(\underline{h}_i)$ with all possible "duet" errors expressed by the pairs $\underline{z} = \underline{h}_{i_1} + \underline{h}_{i_2}$ such that $\rho_{i_1} < \rho_i, \quad \rho_{i_2} < \rho_i$

  replace the "single" with the "duet" if $\rho(\underline{h}_{i_1}) + \rho(\underline{h}_{i_2}) < \rho(\underline{h}_i)$

- Compare the "duets" with the "triplets" by splitting columns of "duets"

$$h_{i_1} \rightarrow \underline{v}_i + \underline{v}_j \quad \text{if } \rho(\underline{v}_i) + \rho(\underline{v}_j) < \rho(\underline{h}_{i_1})$$

- Continue with L-patterns with cardinality up to n-k

Example 1: Apply ML soft syndrome decoding for the [7,4,3] binary Hamming code, apply when possible eliminations rules

Given

$$H = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} = [\underline{h}_1, \underline{h}_2, \underline{h}_3, \underline{h}_4, \underline{h}_5, \underline{h}_6, \underline{h}_7]$$

$$\underline{\alpha} = [+0.5, -1, +2, -4, +7, +11, +15]$$

$$\underline{y}^H = [0,1,0,1,0,0,0]$$

$$\underline{z} = H\left[\underline{y}^H\right]^T = \underline{h}_2 + \underline{h}_4 = \underline{h}_6 = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$$

"single" $\underline{z} = \underline{h}_6 \rightarrow \quad \rho_6 = 11$

"duet" 1*: $\underline{h}_6 = \underline{h}_1 + \underline{h}_7 \rightarrow \rho_1 + \rho_7 = 15.5$
(*eliminated by the "single" (rule 2))

"duet" 2: $\underline{h}_6 = \underline{h}_2 + \underline{h}_4 \rightarrow \rho_2 + \rho_4 = 5$

"duet" 3*: $\underline{h}_6 = \underline{h}_3 + \underline{h}_5 \rightarrow \rho_3 + \rho_5 = 9$
(*eliminated by "duet" 2)

"triplet" 1*: $\underline{h}_6 = \underline{h}_1 + (\underline{h}_2 + \underline{h}_5) \rightarrow \rho_1 + \rho_2 + \rho_5 = 8.5$
(*eliminated by "duet" 2)

"triplet" 2*: $\underline{h}_6 = \underline{h}_1 + (\underline{h}_3 + \underline{h}_4) \rightarrow \rho_1 + \rho_3 + \rho_4 = 6.5$
(*eliminated by "duet" 2)

"triplet" 3*: $h_6 = \underline{h}_2 + (\underline{h}_3 + \underline{h}_7) \rightarrow \rho_2 + \rho_3 + \rho_7 = 10$
(*eliminated by "single" and "duet" 2)

"triplet"4*: $h_6 = (\underline{h}_4 + \underline{h}_7) + \underline{h}_5 \rightarrow \rho_4 + \rho_7 + \rho_5 = 26$
(*eliminated by "single" and "duet" 2)

Since the single has weight 11 and "duet" 2 is the only survivor to be considered, the ML selection should be: choose "duet" 2. Hence $\underline{e} = [0,1,0,1,0,0,0]$

$$\hat{c} = \underline{y}^H + \underline{e} = \underline{0}$$

Example 2: Apply ML soft syndrome decoding for the [7,4,3] binary Hamming code, apply when possible eliminations rules

Given

$$H = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} = [\underline{h}_1, \underline{h}_2, \underline{h}_3, \underline{h}_4, \underline{h}_5, \underline{h}_6, \underline{h}_7]$$

$$\underline{\alpha} = [+0.5, -1, +0.4, -6.4, +7, +11, +15]$$

$$\underline{y}^H = [0,1,0,1,0,0,0]$$

$$\underline{z} = H\left[\underline{y}^H\right]^T = \underline{h}_2 + \underline{h}_4 = \underline{h}_6 = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$$

"single" $\underline{z} = \underline{h}_6 \rightarrow \quad \rho_6 = 11$

In this case the $\underline{h}_i$ are NOT sorted

Now the "duet" 2

$\underline{h}_6 = \underline{h}_2 + \underline{h}_4 \rightarrow \rho_2 + \rho_4 = 7.4$

but "triplet" 3 is

$\underline{h}_6 = \underline{h}_1 + \underline{h}_3 + \underline{h}_4 \rightarrow \rho_1 + \rho_3 + \rho_4 = 7.3$

Since the single has weight 11 and "duet" 2 has weight 7.4 but the triplet 2 has weight 7.3. Thus

$$\underline{e} = [1,0,1,1,0,0,0]$$

$$\hat{c} = \underline{y}^H + \underline{e} = [1,1,1,0,0,0,0]$$

Conclusion

- Call For Contribution

Call for Contribution

- 8 Organizations / 11 Contributors
  - Samsung Electronics UK
  - H.I.T - Holon Institute of Technology
  - DoCoMo, Eurolabs & Beijing
  - France Telecom R&D
  - ENSEA/ETIS
  - FTW
  - TU Dresden, Vodafone Chair
  - University of Kaiserslauten
  - ...

- Scope of White Paper widened
- Table of Content
  - Stabilized
  - Still living doc.
- Comparison
  - Performance
  - Complexity
  - HW inputs
- Future Research directions
- Reviewing starts on 11th of September

Assignment Chapter Editors

- I – Introduction [M. Ran & T. Lestable]
- II – Codes Types [G. Bauch]
- IV – Decoding [M. Ran]
- V – Architecture & HW requirements [F. Kienle]
- VI – Standardization Overview [M-H. Hamon & T. Lestable]
- VII – Extensions : Turbo-Principle [T. Lestable]
- VII – Conclusions [M. Ran & T. Lestable]

WINNER

WIRELESS WORLD
RESEARCH FORUM

Thank you…

Any Question ?

Thierry.Lestable@samsung.com

References

Non binary LDPC codes references

WIRELESS WORLD
RESEARCH FORUM

- [1] M. Davey and D.J.C. MacKay, « Low Density Parity Check Codes over GF(q) » , *IEEE Commun. Lett.*, vol. 2, pp. 165-167, June 1998.
- [2] X.-Y. Hu and E. Eleftheriou, « Binary Representation of Cycle Tanner-Graph GF(2^q) Codes », *The Proc. IEEE Intern. Conf. on Commun.*, Paris, France, pp. 528-532, June 2004.
- [3] D.J.C. MacKay and M. Davey, « Evaluation of Gallager Codes for Short Block Length and High Rate Applications, », *The Proc. IMA Workshop on Codes, Systems and Graphical Models*, 1999.
- [4] H. Song and J.R. Cruz, « Reduced-Complexity Decoding of Q-ary LDPC Codes for Magnetic Recording,», *IEEE Trans. Magn.* , vol. 39, pp. 1081-1087, Mar. 2003.
- [5] L. Barnault and D. Declercq, « Fast Decoding Algorithm for LDPC over GF(2^q), », *The Proc. 2003 Inform. Theory Workshop*, Paris, France, pp. 70-73, Mar. 2003,
- [6] H. Wymeersch, H. Steendam and M. Moeneclaey, « Log-Domain Decoding of LDPC Codes over GF(q), », *The Proc. IEEE Intern. Conf. on Commun.*, Paris, France, June 2004, pp. 772-776.
- [7] C. Poulliat, M.P. Fossorier and D. Declercq “Using binary image of LDPC codes over GF(q) to improve overall performance”, ISTC’06, April 2006, Munich, Germany.
- [8] D. Declercq and M.P. Fossorier, “Decoding algorithms for LDPC codes over GF(q)”, *submitted to IEEE Trans. On Commun., April 2005.*

LDPC Convolutional Codes References

1. A. Jiménez Felström and K. Sh. Zigangirov, "Time-Varying Periodic Convolutional Codes With Low-Density Parity-Check Matrix", IEEE Trans. Info. Theory, Vol. 45, No. 6, September 1999.
2. R. M. Tanner et al, "LDPC Block and Convolutional Codes Based on Circulant Matrices", IEEE Trans. Info. Theory, Vol. 50, No. 12, December 2004.

Short Packet length References [1/2]

[Ber78] E.R. Berlekamp, R. McEliece, and H. Van Tilborg, *On the inherent intractability of certain coding problems*, IEEE Trans. Inf. Theory, Vol.3, pp384-386, May 1978

[Cha72] D. Chase, *A class of algorithms for decoding of block with channel measurement information*, IEEE Trans. Inf. Theory, vol. 41, no.1 pp170-182, Jan 1972

[For66] G.D. Forney, Generalized minimum distance decoding, IEEE Trans. Inf. Theory, vol. 12, no.2 pp125-131, April 1966

[Fos95] M. Fosserier and S. Lin, Soft Decision Decoding of linear block codes based on ordered statistics, IEEE Trans. Inf. Theory, vol. IT-18, no.5 pp1379-1396, Sep 1995

[Jia04] J. Jiang and K. Narayanan , *Iterative soft decision of Reed-Solomon Codes*, IEEE Trans. Commun. Lett., Vol.8, pp244-246, April 2004

[Kan94] T. Kaneko, T. Nishijima H. Inazumi and S. Hirasawa, *An efficient Maximum Likelihood decoding algorithm for linear codes with algebraic decoder,* IEEE Trans. Inf. Theory, Vol.43, pp1314-1319, July 1997

[Kan97] T. Kaneko, T. Nishijima and S. Hirasawa, *An improvement of Soft-Decision Maximum Likelihood decoding algorithm using Hard-Decision Bounded distance Decoding,* IEEE Trans. Inf. Theory, Vol.43, pp1314-1319, July 1997

Short Packet length References [2/2]

[Kha06] M. El-Khamy and R.J. McEliece, *Iterative Algebraic Soft-Decision List Decoding of Reed-Solomon Codes*, IEEE J. Selected Areas in Communications Vol. 24, No. 3 March 2006

[Kot03] R. Kotter and A. Vardy , *Algebraic soft-decision decoding of Reed-Solomon codes*, IEEE Trans. Inf. Theory, Vol.49, no.11, pp2809-2825, Nov. 2003

[Lin04] S. Lin and D.J. Costello, *Error Control Coding*, 2Ed , Chapter 10, Pearson Education 2004

[Sny91] J. Snyders , *Reduced lists of error pattern for maximum likelihood soft decoding*, IEEE Trans. Inf. Theory, Vol.37, no.4, pp1194-1200, July 1991

[Ran95] M. Ran and J. Snyders, *Constrained designs for maximum likelihood soft decoding of RM (2,m) and the extended Golay codes, IEEE Trans. on Communications COM-43, No.2/3/4, pp.812-820, February/March/April 1995*