北京航空航天大學
BEIHANG UNIVERSITY

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Iterative Interference Mitigation and Channel Estimation for LDACS1

Qiaoyu Li[1], Jun Zhang[1], Jindong Xie[1],
Mohamad Mostafa[2], Michael Schnell[2]

[1] National Key Laboratory of CNS/ATM,
Beihang University (BUAA),
Beijing, China

[2] Institute of Communications and Navigation,
German Aerospace Center (DLR),
Oberpfaffenhofen, Germany

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1. Introduction

❑ **Problem**: Impulsive Interference towards LDACS1

- ➢ LDACS1 works between two DME signals, and is influenced by the impulsive interference from DME.
- ➢ Blanking Nonlinearity (BN) at receiver is simple and effective for interference mitigation, but introduces inter-carrier-interference (ICI) to the OFDM-based LDACS1.

❑ **Solution**: Iterative Receiver Design

- ➢ We use iterative decoding (ID) between the Soft-Input Soft-Output (SISO) demodulator and decoder to reduce the negative effect brought by ICI.
- ➢ Iterative channel state information (CSI) estimation is also carried out to further improve the performance.

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2. Brief Review of LDACS1

- **Service Coverage of LDACS1**
  - Air Traffic Services (ATS) and Airline Operational Communications (AOC)
- **FDD Air-Ground Cellular System**
  - Forward Link (FL): GS to AS
  - Reverse Link (RL): AS to GS
- **Inlay deployment of LDACS1**
  - LDACS1 locates between DME channels with approx. 500 KHz effective bandwidth (Figure 1).

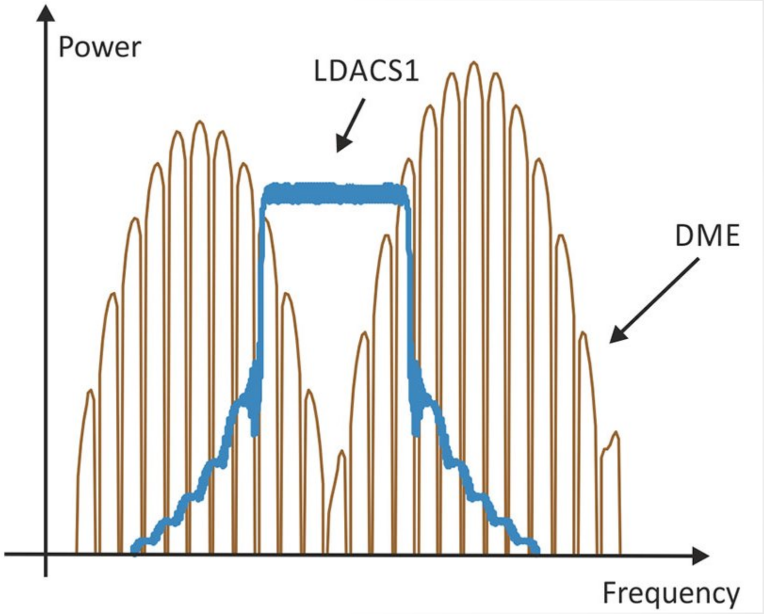

Figure 1. LDACS1 and DME Spectrum shapes. Inlay deployment.

2. Brief Review of LDACS1

❑ Frame Structure (Time & Freq.)

- ➢ Data, Random Access (RA), Braodcast (BC), Dedicated Control (DC), Common Control (CC)

- ➢ Example for Data/CC in FL (Figure 2)
  - ✓ 64-point FFT based OFDM
  - ✓ OFDM symbol duration: 120 μs
  - ✓ Subcarrier Spacing: approx. 10 KHz
  - ✓ Irregular pilot pattern & redundant synchronization time slot provide robustness against interference.

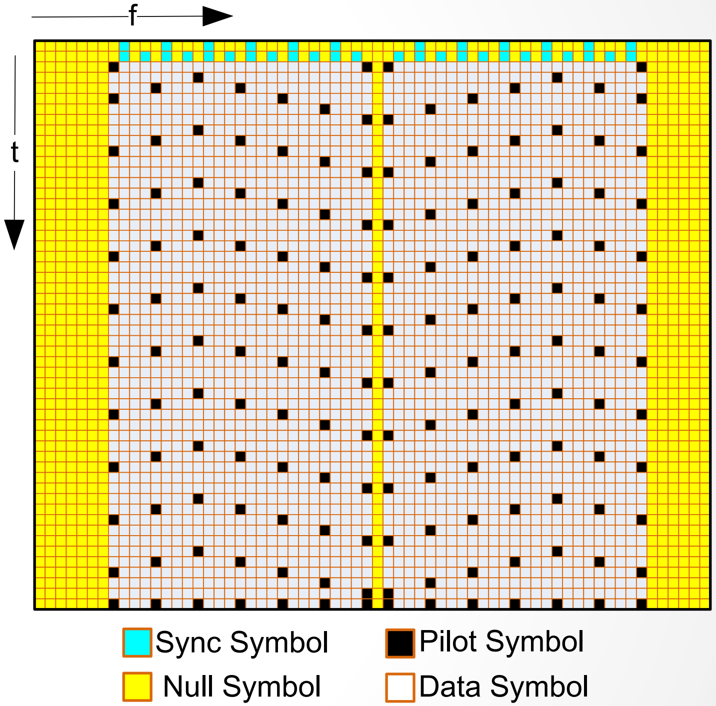

Figure 2. Structure of Data/CC Frame in FL.

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- **4. Proposed Transceiver Structure**
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  - 4.3. CSI Estimation
- **5. Numerical Results**
- **Concluding Remarks**

3. Interference Characterization of DME

- ☐ **DME Signal**
  - The most dominant interference towards LDACS1
- ☐ **Combination of two Gaussian pulses:**
  - $i(t) = e^{-\frac{\alpha t^2}{2}} + e^{-\frac{\alpha(t-\Delta t)^2}{2}}$
    - ✓ α: impulse width; Δt =30 μs or 36 μs.
    - ✓ 50% pulse width=3.5 μs → ***impulsive*** compared to LDACS1 (120 μs duration of one OFDM symbol).
- ☐ **Transmission rate (No. pulse pairs per second, ppps)**
  - From 30 ppps to 2700 ppps depending on different modes.

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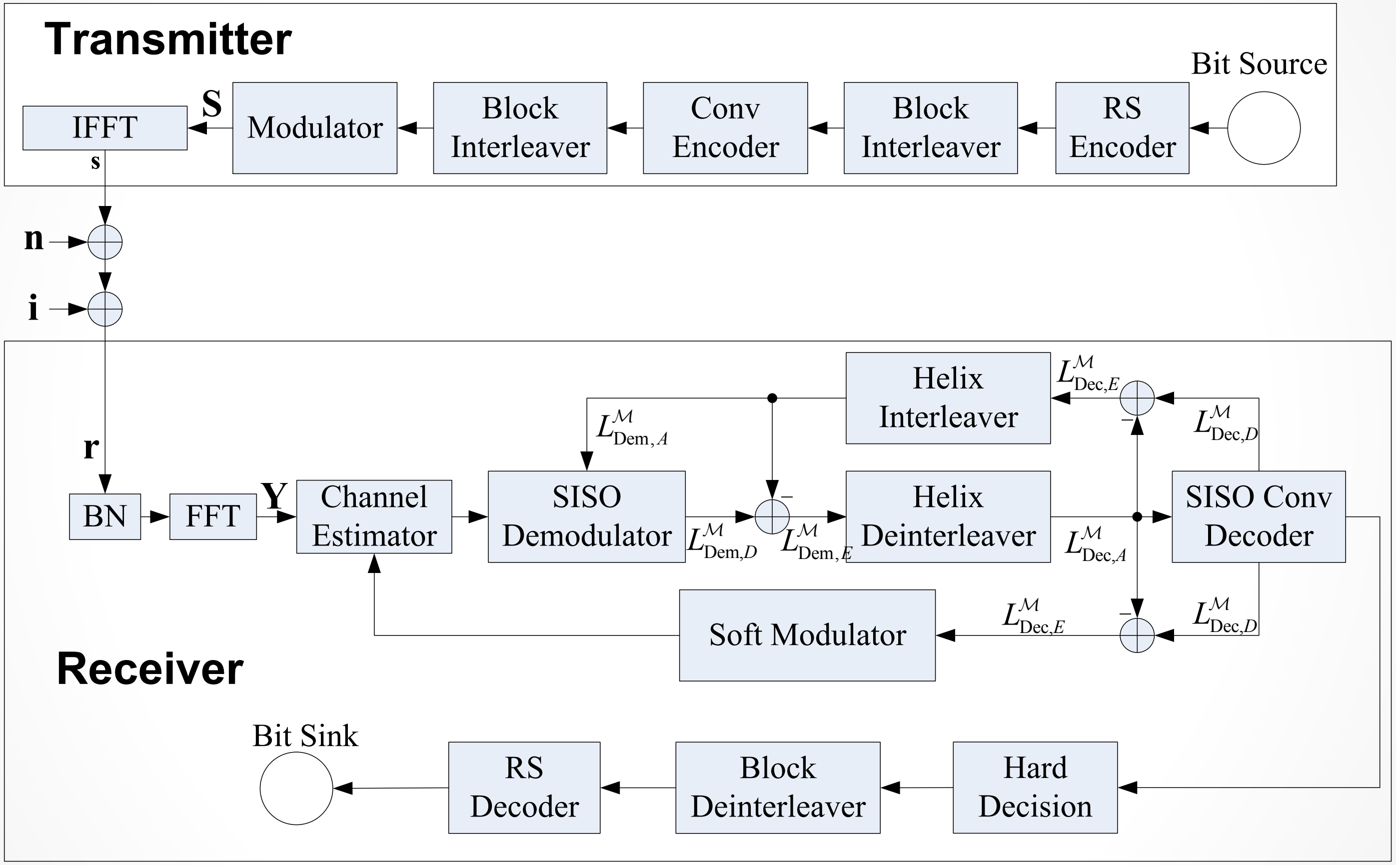
4. Proposed Transceiver Structure



Transmitter

Bit Source

RS Encoder

Block Interleaver

Conv Encoder

Block Interleaver

Modulator

$\mathbf{S}$

IFFT

$\mathbf{s}$

$\mathbf{n}$

$\mathbf{i}$

$\mathbf{r}$

Receiver

BN

FFT

$\mathbf{Y}$

Channel Estimator

SISO Demodulator

$L^{\mathcal{M}}_{\text{Dem},A}$

$L^{\mathcal{M}}_{\text{Dem},D}$

$L^{\mathcal{M}}_{\text{Dem},E}$

Helix Interleaver

Helix Deinterleaver

$L^{\mathcal{M}}_{\text{Dec},E}$

$L^{\mathcal{M}}_{\text{Dec},D}$

$L^{\mathcal{M}}_{\text{Dec},A}$

SISO Conv Decoder

Soft Modulator

Hard Decision

Block Deinterleaver

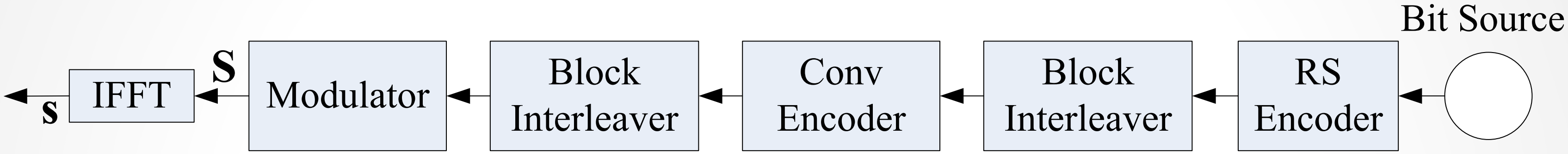
RS Decoder

Bit Sink

Figure 3. Transceiver Structure

4. Proposed Transceiver Structure

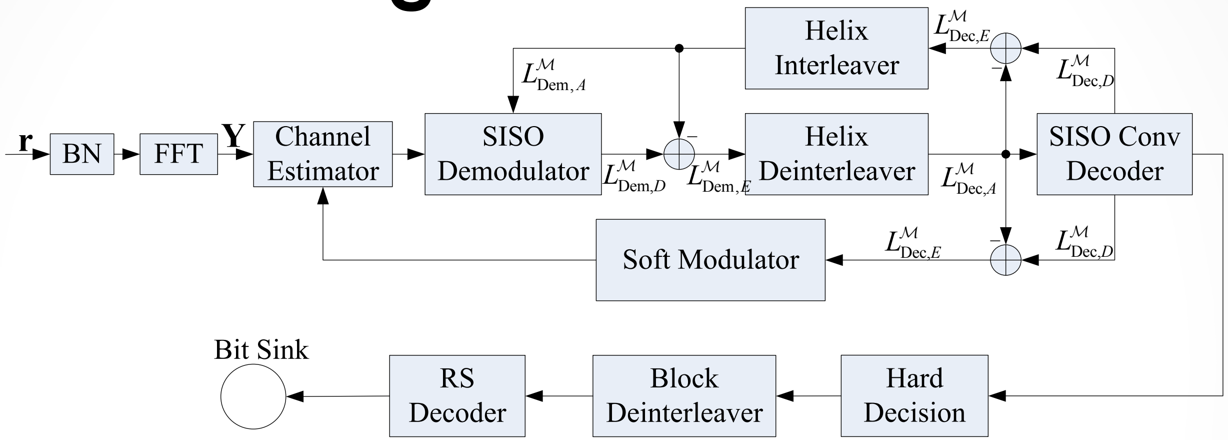
❑Transmitter



- **RS and Convolutional Encoding**
- **Constellation Modulation**
  - ✓ Coded and interleaved bits $[b_1, b_2, \dots, b_M]$ → Cons. Modul. → 2^M-ary symbol $S \in \mathcal{S}$ ($b_l \in \{0,1\}$ and $\mathcal{S}$ means symbol alphabet).
- **OFDM Modulation: 64-point IFFT**
  - ✓ $\mathrm{S} = [S_1, S_2, \dots, S_{64}]^T$ → $\mathrm{s} = \mathcal{F}^{-1} \cdot \mathrm{S}$ ($\mathcal{F}^{-1}$: IFFT matrix)
- **AWGN and impulsive noise at the receiver**
  - ✓ $[r_1, r_2, \dots, r_{64}]^T = \mathbf{r} = \mathbf{s} + \mathbf{n} + \mathbf{i}$
  - ✓ $\mathbf{n}=[n_1, n_2, \dots, n_{64}]^T$: AWGN with noise variance N_0;
  - ✓ $\mathbf{i}=[i_1, i_2, \dots, i_{64}]^T$: impulsive noise.

4. Proposed Transceiver Structure

❑ Receiver Design



- ➢ **Main Components**
  - ✓ Blanking Nonlinearity
  - ✓ SISO Demodulation and Decoding
  - ✓ Channel Estimation
- ➢ **Two Loops**
  - ✓ Inner Loop: Iterative Demodulation and Decoding
  - ✓ Outer Loop: Iterative CSI Estimation

Contents

4.1. Blanking Nonlinearity

- **Signals with amplitude greater than $\boldsymbol{T_{BN}}$ is blanked:**

$$y_l = f(r_l) = \begin{cases} r_l, & \text{if } |r_l| < T_{BN} \\ 0, & \text{else} \end{cases}, \; l = 1,2,\ldots,64,$$

which is optimal in terms of maximizing SINR.

- **BN introduces ICI in frequency domain**
  - BN: multiplication to $\mathbf{r}$ with rectangular windows.
  - Recall: OFDM = convolution between Si-function and Dirac function at the initial sampling index.
  - Reduced window length by BN → wider Si-function → non-zero values at all sample indices → ICI

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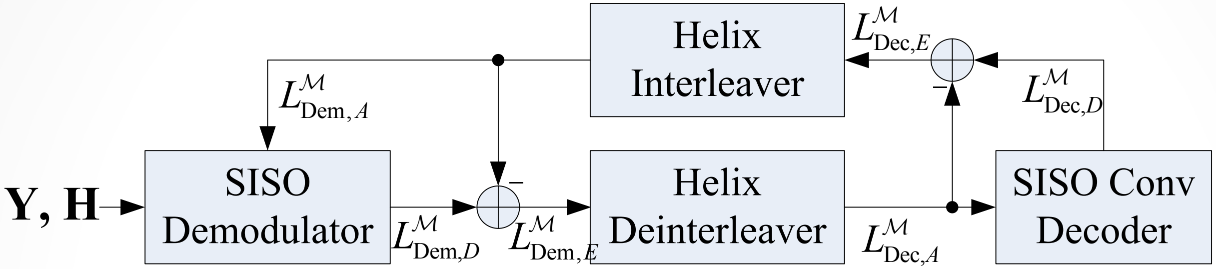
4.2. Iterative Demodulation and Decoding

❑Assumptions & definitions for derivation

- CSI available at demodulator
- $H_{n,l}$, $S_{n,l}$, and $Y_{n,l}$:
  - ✓ CSI, received symbol after FFT, and transmitted symbol, at the nth OFDM symbol and the lth subcarrier.
- $S_{n,l}^{\mathcal{M}}$: the $\mathcal{M}$th MSB of symbol $S_{n,l}$, $\mathcal{M} = 1, \ldots, M$.
- $S_{\mathcal{M}}^{+} = \{S \in \mathcal{S} | S^{M} = 1\}$, $S_{\mathcal{M}}^{-} = \{S \in \mathcal{S} | S^{M} = 0\}$

4.2. Iterative Demodulation and Decoding



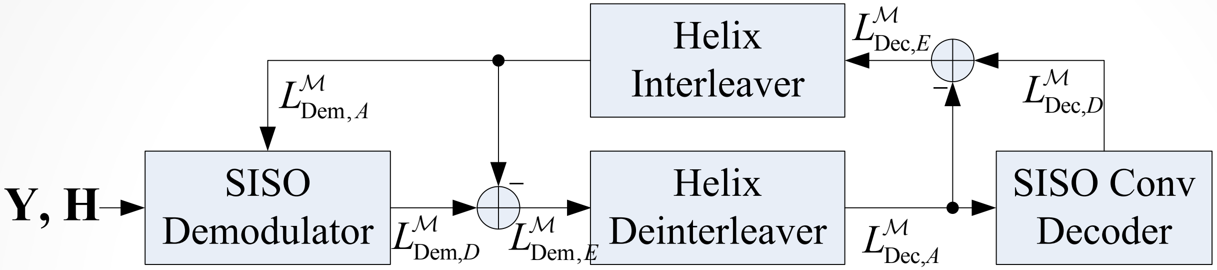
- ☐ **MAP demodulation of $S^{\mathcal{M}}_{n,l}$ → LLR of $S^{\mathcal{M}}_{n,l}$**
  - ➢ $L^{\mathcal{M}}_{Dem,D} = \log \frac{\Pr[S^{\mathcal{M}}_{n,l}=1|Y_{n,l}]}{\Pr[S^{\mathcal{M}}_{n,l}=0|Y_{n,l}]}$

$$= \log \frac{\Pr[S^{\mathcal{M}}_{n,l}=1]}{\Pr[S^{\mathcal{M}}_{n,l}=0]} + \log \frac{\sum_{S\in S^{+}_{\mathcal{M}}} p[Y_{n,l}|S] \prod_{\substack{M'=1 \\ M'\neq\mathcal{M}}}^{\mathcal{M}} \Pr[S^{M'}_{n,l}]}{\sum_{S\in S^{-}_{\mathcal{M}}} p[Y_{n,l}|S] \prod_{\substack{M'=1 \\ M'\neq\mathcal{M}}}^{\mathcal{M}} \Pr[S^{M'}_{n,l}]}$$

$$\triangleq \boldsymbol{L^{\mathcal{M}}_{Dem,A}} + \boldsymbol{L^{\mathcal{M}}_{Dem,E}}$$

✓ Likelihood function: $p[Y_{n,l}|S] = \frac{1}{\pi N_0} e^{-\frac{\left|Y_{n,l}-H_{n,l}S\right|^2}{N_0}}$

4.2. Iterative Demodulation and Decoding



- **Channel Decoding:**
  - Take deinterleaved $\boldsymbol{L^{\mathcal{M}}_{Dem,E}}$ as a priori information for decoding: $\boldsymbol{L^{\mathcal{M}}_{Dec,A}}$
  - SISO MAP convolutional decoding algorithm→$L^{\mathcal{M}}_{Dec,D}$
  - Output: $\boldsymbol{L^{\mathcal{M}}_{Dec,E}} = L^{\mathcal{M}}_{Dec,D} - \boldsymbol{L^{\mathcal{M}}_{Dec,A}}$
- **Feedback**
  - Demodulator takes the interleaved $\boldsymbol{L^{\mathcal{M}}_{Dec,E}}$ as a priori information for demodulation.

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- **Concluding Remarks**

4.3. CSI Estimation

❑ Initial Outer Iteration (no feed back for decoding)

- ➢ Linear interpolation along the time index, and another one along the frequency index:
  - ✓ d_t: distance between two adjacent pilot tones along time index
  - ✓ CSI estimation in between (time index):
  - ✓ $\widetilde{H}_{p+i,l} = \frac{d_t - i}{d_t}\widetilde{H}_{p,l} + \frac{i}{d_t}\widetilde{H}_{p+d_t,l},\ i = 1, \ldots, d_t - 1$
  - ✓ CSI estimation along frequency index: similar procedure

4.3. CSI Estimation

❑ Subsequent Outer Iterations

- $E\{S_{n,l}\}$ and $E\{|S_{n,l}|^2\}$ can be obtained using $\boldsymbol{L}_{\mathbf{Dec,E}}^{\boldsymbol{\mathcal{M}}}$ (for details see the Appendix in this slide).

- Hard estimation of $S_{n,l}$ can be found as
  - ✓ $\hat{S}_{n,l} = \arg\min_{S\in\mathcal{S}} \left| E\{S_{n,l}\} - S \right|^2$

- Given $S_{n,l}$, the ideal estimate of $H_{n,l}$ can be given by $Y_{n,l}/S_{n,l} = Y_{n,l}S_{n,l}^{*}/\left|S_{n,l}\right|^2$, so the practical estimate can be given by
  - ✓ $\tilde{H}_{n,l} \approx Y_{n,l}\left[E\{S_{n,l}\}\right]^{*}/E\{|S_{n,l}|^2\}$

4.3. CSI Estimation

❑Wiener Filter

- The enhanced CSI estimate

$$\widehat{H}_{n,l} = \sum_{n'=1}^{N_T} \sum_{l'=1}^{64} \Omega_{n',l',n,l} \widetilde{H}_{n',l'}$$

✓N_T: number of OFDM symbols in a data frame.

✓$\Omega_{n',l',n,l}$: 2-D Wiener filtering coefficient[r1].

[r1] F. Sanzi, S. Jelting, and J. Speidel, "A Comparative Study of Iterative Channel Estimators for Mobile OFDM Systems," IEEE Transactions on Wireless Communications, pp. 849-859, September 2003.

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5. Numerical Results

☐ Simulations

- ➢ BER over SNR
- ➢ Extrinsic Information Transfer (EXIT) Chart

☐ Parameters

- ➢ Framing: Data frame in the FL
- ➢ Constellation Modulation: 4-QAM
- ➢ Channel: Aeronautical En-route multi-path channel[r2] with additional DME interference[r3].
- ➢ BN threshold T_{BN} is adaptively optimized [r4].

- ✓ [r2] M. Sajatovic, et al, February 2009, "L-DACS1 System Definition Proposal: Deliverable D2", Edition 1.0.
- ✓ [r3] U. Epple, M. Schnell, "Overview of Interference Situation and Mitigation Techniques for LDACS1", DASC 2011.
- ✓ [r4] U. Epple, M. Schnell, "Adaptive Threshold Optimization for a Blanking Nonlinearity in OFDM Receivers", GLOBECOM 2012

5.1 BER Simulations

- ☐ **Performance of inner loop with Perfect CSI. 10 inner iterations are considered.**
- ☐ **Constellation mapping rules**
  - ✓ Affects performance of iterative demodulation and decoding directly in AWGN [r5, r6, r7].
  - ✓ For 4-QAM, only ***Gray*** and ***Binary*** mappings are encountered.
- ☐ **Observations**
  - ✓ Gray is worse than Binary after iterations, and Gray achieves marginal iterative gain.
  - ✓ Gray → base line of non-iterative receiver
  - ✓ Binary over 10 iterations → performance of iterative receiver
  - ✓ 2 dB of SNR gain at BER = 10^{-6}

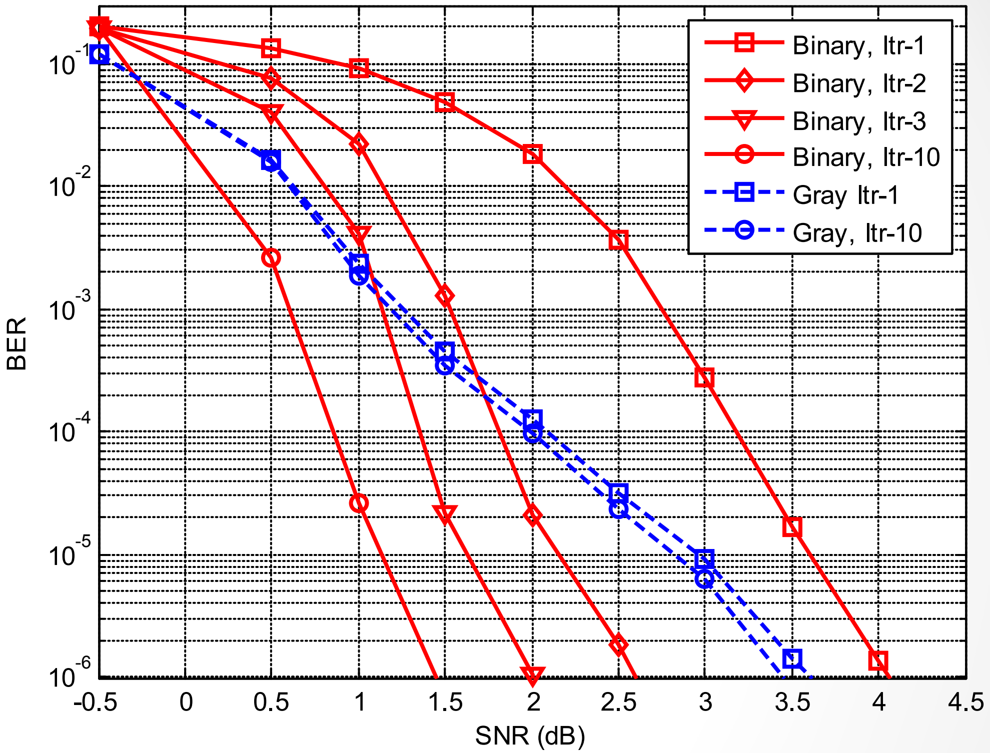

Figure 4. Inner loop BER with perfect CSI

- ✓ [r5] A. Chindapol and J. A. Ritcey, “Design, Analysis, and Performance Evaluation for BICM-ID with Square QAM Constellations in Rayleigh Fading Channels,” IEEE JSAC 2001.
- ✓ [r6] X. Li, et al, “Bit-interleaved coded modulation with iterative decoding and 8PSK signaling,” IEEE TCOM 2002.
- ✓ [r7] Q. Li, et al, “Performance Analysis and System Design for Hierarchical Modulated BICM-ID”, IEEE TWC 2014.

5.1 BER Simulations

- ☐ **Performance of outer loop with estimated CSI. 10 inner iterations are considered. And only Binary mapping is taken into account.**
- ☐ **BER with perfect CSI over 10 inner iterations is used as benchmark.**
- ☐ **Observations**

✓ Initial CSI estimate yields unacceptable BER.

✓ Strong BER improvement achieved after 10 outer itr., which approaches perfect CSI benchmark.

✓ Reason: reliability of CSI estimate and data detection improves through iterations, as more information can be deployed

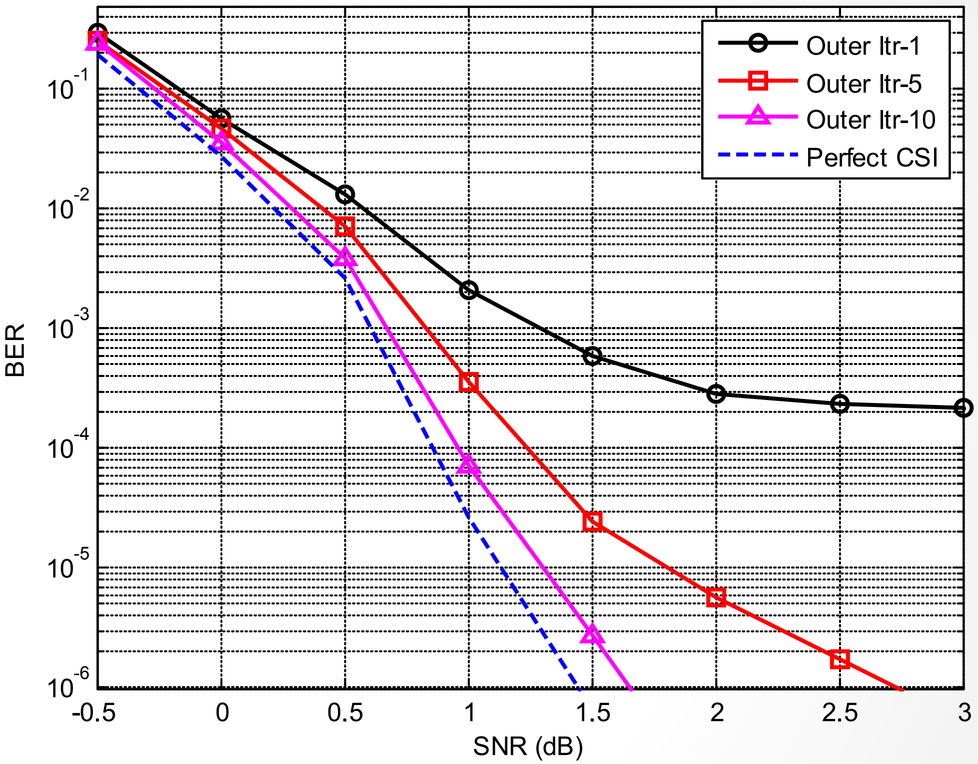

Figure 5. Outer loop BER with iteratively estimated CSI

5.2 EXIT Chart Analysis

❑ EXIT Chart:

- ✓ Scheme to analyze convergence behavior of iterative demodulation and decoding
- ✓ Generally, the greater the output mutual information, the better the BER

❑ Observations (SNR=1 dB)

- ✓ EXIT chart for Gray is generally horizontal → marginal iterative gain can be collected.
- ✓ EXIT chart for Binary mapping has obvious slope → creates open tunnel between dem. And dec. curves → performance gradually improves with iterations.
- ✓ Confirms BER simulations

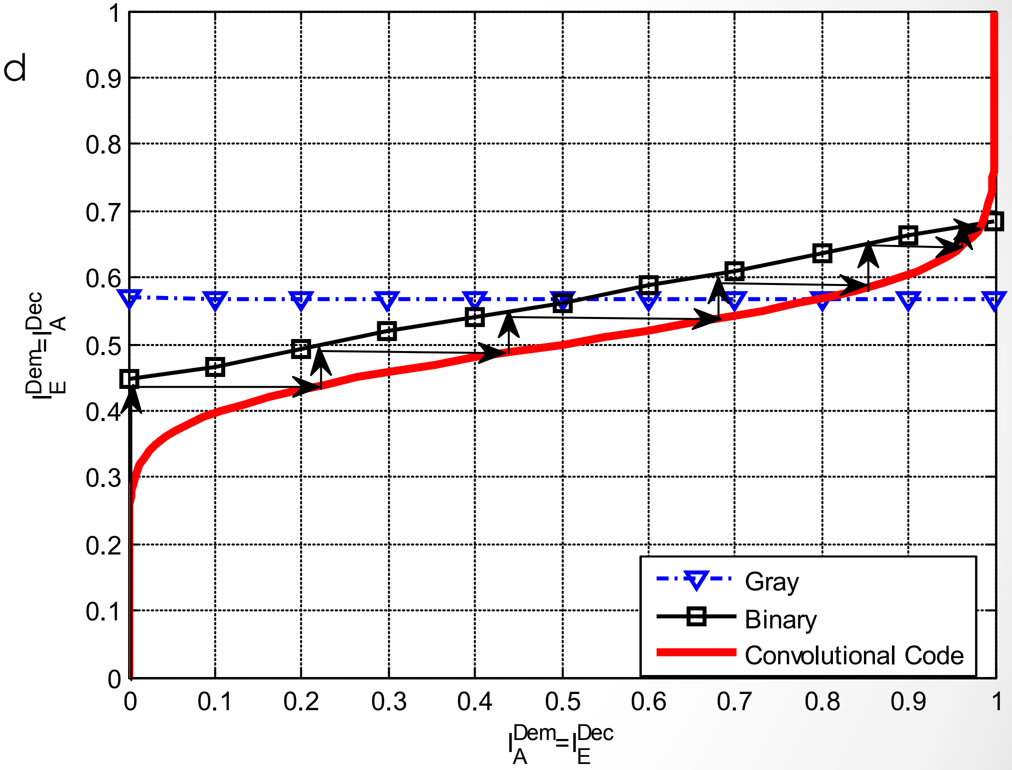

Figure 6. EXIT Chart Analysis

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Concluding Remarks

- **Iterative receiver design for LDACS1 under impulsive interference**
  - Using BN, impulsive noise is blanked to maximize SINR, but introduces ICI in frequency domain.
  - Iterative demodulation and decoding is carried out to reduce the negative effect brought by such ICI.
  - Iterative CSI estimation → further performance improvement.
  - Numerical results (BER & EXIT Chart) show that the proposed iterative receiver can effectively compensate the ICI, and improves CSI estimation.

Iterative Interference Mitigation and Channel Estimation for LDACS1

Thanks for your attention!

Appendix

- ❑ **Calculation of $E\{S_{n,l}\}$ and $E\{|S_{n,l}|^2\}$:**

  - ➢ $E\{S_{n,l}\} = \sum_{S\in\mathcal{S}} S \prod_{\mathcal{M}=1}^{M} \frac{1}{2}\left[1+\tanh\left(\frac{L_{Dec,E}^{\mathcal{M}}}{2}\right)s^{\mathcal{M}}\right]$

  - ➢ $E\{|S_{n,l}|^2\} = \sum_{S\in\mathcal{S}} |S|^2 \prod_{\mathcal{M}=1}^{M} \frac{1}{2}\left[1+\tanh\left(\frac{L_{Dec,E}^{\mathcal{M}}}{2}\right)s^{\mathcal{M}}\right]$