Near-Capacity Joint Channel Estimation and Three-Stage Turbo Detection for MIMO Systems

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Outline

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Background

- Coherent MIMO promises **wonderland** of **diversity** and/or **multiplexing** gains
  - Reaching MIMO promised land requires accurate MIMO CSI estimate
- **Challenge**: acquisition of accurate MIMO CSI
  - Without sacrificing system throughput too much
  - Avoiding significant increase in computational complexity
- Training based or pure blind methods cannot meet these needs
- **State-of-the-art**: semi-blind joint channel estimation and turbo detection-decoding
- Non-coherent or **differential** MIMO does not require CSI but suffers from 3 dB penalty in SNR and less design freedom

Our Contributions

- Existing joint channel estimation and turbo detection-decoding
  1. Add **iterative loop** between channel estimator and turbo detector-decoder, and significantly increase complexity
  2. Using **entire frame** of soft or hard detected bits for channel estimate and high complexity of channel estimation
  3. **Cannot reach** optimal performance lower bound of ML turbo detector-decoder associated with perfect CSI
- Our joint channel estimation and turbo detection-decoding
  1. Channel estimation **naturally embedded** in original turbo detector-decoder loop
  2. Only **select** sufficient number of high-quality detected bit blocks for DD channel estimate
  3. Approach **optimal** BER performance lower bound of ML turbo detector-decoder associated with perfect CSI

MIMO Model

- **Transmitter**: two-stage outer RSC encoder and inner URC encoder, followed by MIMO L-QAM modulator
- Standard $M_r \times M_t$ flat fading **MIMO**:

$$\boldsymbol{y}(i) = \boldsymbol{H}\,\boldsymbol{s}(i) + \boldsymbol{v}(i)$$

  1. Channel matrix $\boldsymbol{H} = \left[h_{k,l}\right] \in \mathbb{C}^{M_r \times M_t}$ with $h_{k,l} \sim \mathcal{CN}(0, 1)$
  2. AWGN vector $\boldsymbol{v}(k)$ whose elements obey $\mathcal{CN}(0, N_{\text{o}})$

- **Receiver**:
  1. Minimum training overhead $\approx M_t$ for initial training based channel estimate
  2. Three-stage turbo ML-detector/decoder consists of inner URC decoder/ML detector unit, and outer RSC decoder
  3. Soft decision based channel estimator for refining/updating decision-directed channel estimate

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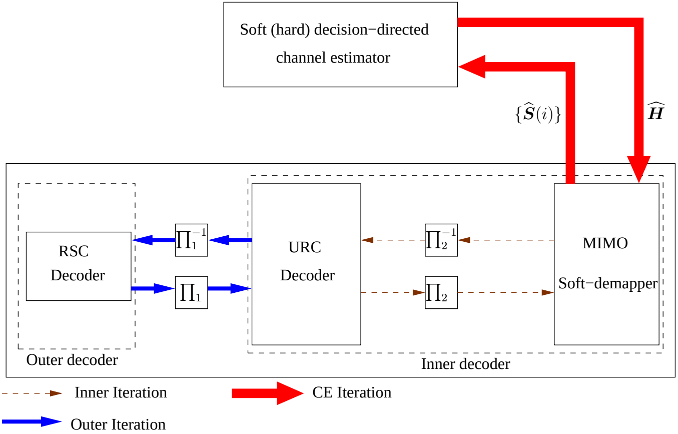
Existing Scheme



- As entire frame of detected bits are used for channel estimate, to benefit from error correcting capability of turbo detection/decoding, channel estimate update takes place after convergence of three-stage turbo detector/decoder
- I_{in} inner iterations, I_{out} outer iterations, I_{ce} CE iterations

Complexity and Performance

- Idealised three-stage turbo ML-detector-decoder associated with perfect CSI

$$C_{\text{ideal}} = I_{\text{out}}\left(C_{\text{RSC}} + I_{\text{in}}\left(C_{\text{ML}} + C_{\text{URC}}\right)\right)$$

- Existing powerful conventional scheme

$$\begin{aligned} C_{\text{con}} &= I_{\text{ce}} O\left(\tau^3\right) + I_{\text{ce}} C_{\text{ideal}} \\ &= I_{\text{ce}} O\left(\tau^3\right) + I_{\text{ce}} I_{\text{out}}\left(C_{\text{RSC}} + I_{\text{in}}\left(C_{\text{ML}} + C_{\text{URC}}\right)\right) \end{aligned}$$

1. An interleaved frame of turbo code contains tens of thousands of bits, and a frame: $\tau =$ thousands of symbols
2. Decision-directed LSCE has high complexity of $O\left(\tau^3\right)$, and complexity “amplifies” dramatically by channel estimation loop
3. Cannot approach optimal BER performance lower-bound of idealised three-stage turbo ML-detector-decoder

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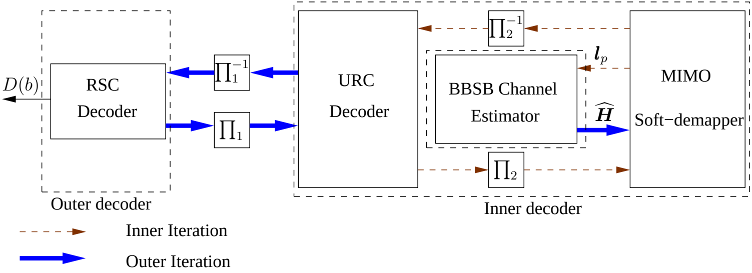
Structure



- Only select sufficient number of **high-quality** soft decision bit blocks for DD LSCE
- Channel estimate update occurs **concurrently** with original outer turbo iteration
- Approach optimal BER **lower-bound** of idealised three-stage turbo ML-detector-decoder associated with perfect CSI

Block-of-Bits Selection

1. MIMO soft-demapper produces *a posteriori* information matrix $\boldsymbol{L}_p \in \mathbb{C}^{I_{\text{in}} \times (\text{BPB} \cdot \tau)}$, where $\text{BPB} = M_t \cdot \text{BPS} = M_t \cdot \log_2 L$
   - nth column of $\boldsymbol{L}_p$ contains I_{in} LLRs associated with nth bit
2. Sliding window with window size of BPB gleans through columns of $\boldsymbol{L}_p$ to select τ_s^t **high-quality** soft symbol vectors for channel estimation
   - If BPB consecutive bits are all high-quality, corresponding information block or soft symbol vector is selected for CE
   - Any stage if τ_s^t reaches the **limit** $\tau_{\text{sel}}(\ll \tau)$, stop; otherwise selection continues until all τ blocks are looked
3. nth bit is selected in either of following two cases

   Case 1: soft decisions in nth column share similar values, i.e.

$$\frac{|L_p^1(n) - L_p^2(n)| + \cdots + |L_p^{I_{\text{in}}-1}(n) - L_p^{I_{\text{in}}}(n)|}{|\text{mean of } n\text{th column}|} \in (0,\ T_h)\,,\ \ T_h \text{ is a given threshold}$$

   Case 2: absolute values of soft decisions in nth column are in monotonically ascending order and share same polarity

Benefits

1. As only high-quality blocks of detected bits are used, no need to wait for three-stage turbo detector/decoder to converge
   - Channel estimate update occurs **concurrently** with original outer turbo iteration
2. Complexity of proposed scheme

$$C_{\text{pro}} \leq I_{\text{out}} \text{O}\left(\tau_{\text{sel}}^3\right) + C_{\text{ideal}} \text{ or } C_{\text{pro}} \approx C_{\text{ideal}}$$

   - Dramatically lower complexity of LSCE, e.g. $\tau = 1000$ and $\tau_{\text{sel}} = 100$, $\text{O}\left(\tau_{\text{sel}}^3\right)$ is 1000 times smaller than $\text{O}\left(\tau^3\right)$
3. With same I_{in} inner iterations and I_{out} outer iterations,
   - Reach **optimal** BER lower-bound of **idealised** three-stage turbo ML-detector/decoder associated with **perfect** CSI
   - MSE of soft DD channel estimator approach **Cramér-Rao lower bound** CRLB(τ_{sel})

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Simulation System

1. Quasi-static Rayleigh fading MIMO: $M_t = 4$, $M_r = 4$ and 16-QAM
2. Channel taps are static within frame and faded between frames at normalised Doppler frequency $f_d = 0.01$
3. Interleaver length of $16,000$ bits, $\tau = 1000$ symbol vectors
4. RSC generator polynomials: $G_{RSC} = [1, 0, 1]_2$, $G^r_{RSC} = [1, 1, 1]_2$
5. URC generator polynomials: $G_{URC} = [1, 0]_2$, $G^r_{URC} = [1, 1]_2$
6. Transmitted signal power normalised to unity, SNR defined as $\frac{1}{N_o}$
7. Number of initial training data blocks: 6, training overhead 0.6%
8. Blocks-of-bits selection limit set to $\tau_{\text{sel}} = 100$
9. All the results were averaged over 100 channel realisations

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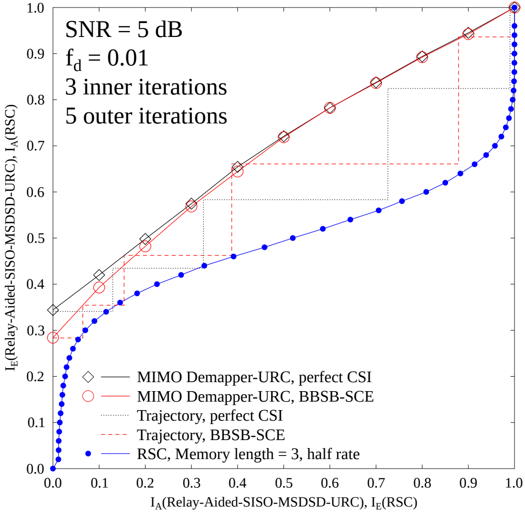
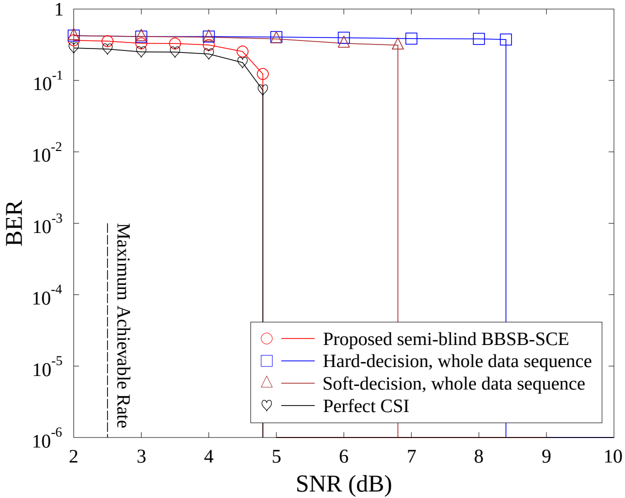
EXIT Chart Analysis

- **EXIT chart** analysis of our proposed semi-blind joint BBSB-SCE and three-stage turbo receiver with the block-of-bits selection threshold of $T_h = 1.0$, in comparison to the perfect-CSI scenario



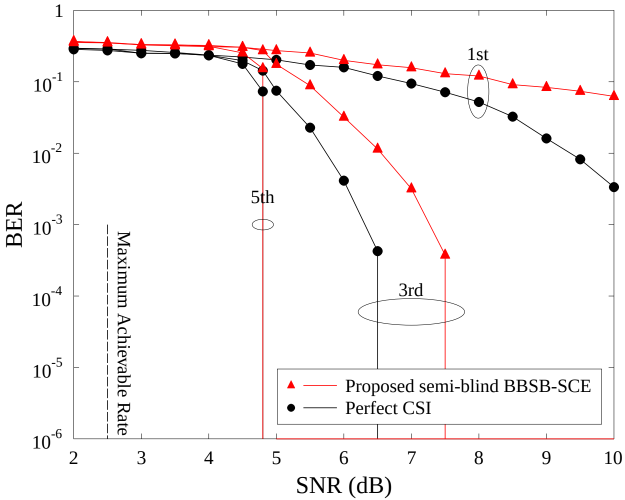
BER Performance comparison

- **BER** comparison: the proposed joint BBSB-SCE and three-stage turbo receiver with a block-of-bits selection threshold of $T_h = 1.0$, the perfect CSI scenario as well as the conventional joint CE and three-stage turbo receivers employing the entire detected data sequence for the soft-decision and hard-decision aided channel estimators, respectively



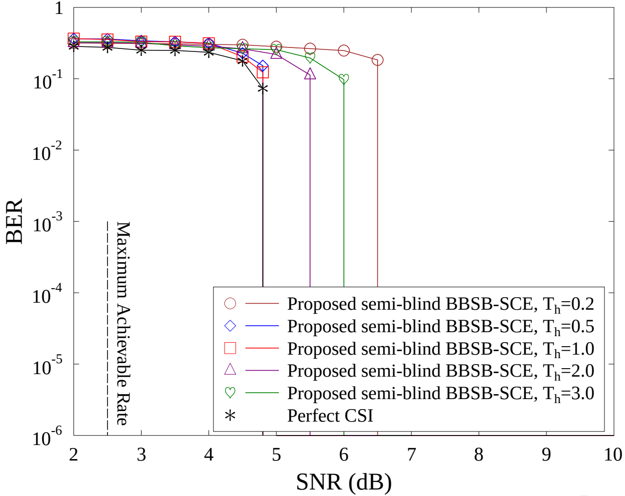
BER Convergence Performance

- BER **convergence** performance of the proposed joint BBSB-SCE and three-stage turbo receiver with a block-of-bits selection threshold of $T_h = 1.0$, in comparison to the perfect-CSI case



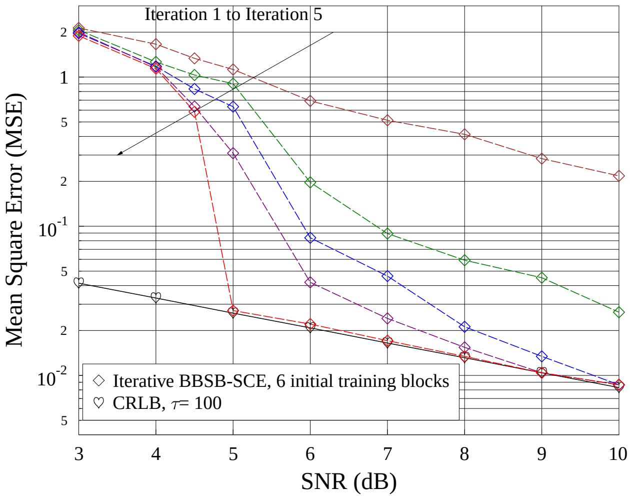
Influence of Selection Threshold

- Effects of the block-of-bits **selection threshold** T_h on the BER performance of our proposed semi-blind joint BBSB-SCE and three-stage turbo receiver
- $T_h \in [0.5,\ 1.0]$ appropriate for this example, and as long as the threshold is not chosen to be too small or too large, the scheme is not sensitive to the value of T_h used



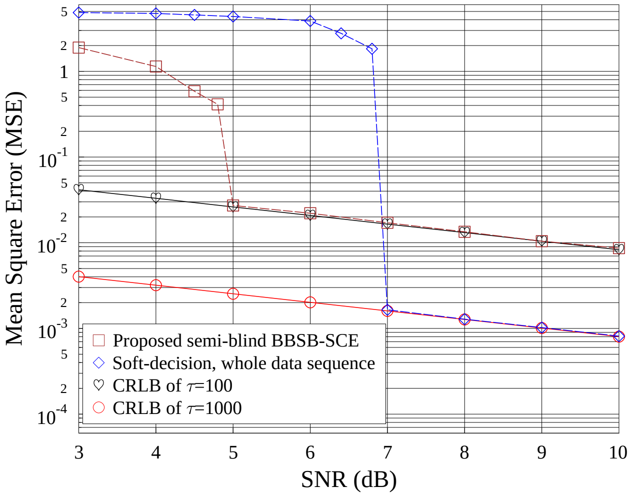
MSE Convergence Performance

- **MSE** convergence performance of the channel estimator in our proposed semi-blind joint BBSB-SCE and three-stage turbo receiver using a block-of-bits selection threshold of $T_h = 1.0$



MSE Performance Comparison

- MSE performance comparison: **proposed** joint BBSB-SCE and three-stage turbo receiver, which selects $\tau_s^t \leq 100$ high-quality soft detected symbol vectors for channel estimator, and **conventional** joint CE and three-stage turbo receiver, which uses all $\tau = 1000$ soft detected symbol vectors for channel estimator



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Summary

- Propose a new semi-blind joint block-of-bits selection based soft channel estimation and three-stage turbo detector-decoder
  1. Our BBSB-SCE naturally embedded in original three-stage demapping/decoding turbo loop
  2. Complexity of our channel estimator is several orders of magnitude lower than the existing methods
  3. Complexity of our scheme is similar to idealised three-stage turbo ML-detector/decoder associated with perfect CSI
- Our novel scheme is capable of reaching near-capacity MIMO promised land associated with perfect CSI
  1. BER of our scheme attains optimal ML bound of idealised three-stage turbo receiver furnished with perfect CSI
  2. Mean square error of our BBSB soft channel estimator reaches Cramér-Rao lower bound