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

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2. Joint CE and Three-Stage Turbo Receiver
   - Existing State-of-the-Art
   - Proposed Novel Scheme

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   - Simulation Results

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   - Concluding Remarks
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Coherent MIMO promises \textit{wonderland} of \textit{diversity} and/or \textit{multiplexing} gains

- Reaching MIMO promised land requires accurate MIMO CSI estimate

\textbf{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

\textbf{State-of-the-art}: semi-blind joint channel estimation and turbo detection-decoding

Non-coherent or \textit{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:
  \[ y(i) = H \ s(i) + v(i) \]

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

- **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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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.

\(l_{\text{in}}\) inner iterations, \(l_{\text{out}}\) outer iterations, \(l_{\text{ce}}\) CE iterations
Complexity and Performance

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

\[ C_{\text{ideal}} = l_{\text{out}} (C_{\text{RSC}} + l_{\text{in}} (C_{\text{ML}} + C_{\text{URC}})) \]

2. Existing powerful conventional scheme

\[ C_{\text{con}} = l_{\text{ce}} O(\tau^3) + l_{\text{ce}} C_{\text{ideal}} \]
\[ = l_{\text{ce}} O(\tau^3) + l_{\text{ce}} l_{\text{out}} (C_{\text{RSC}} + l_{\text{in}} (C_{\text{ML}} + C_{\text{URC}})) \]

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 \( O(\tau^3) \), 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 $L_p \in \mathbb{C}^{I_{in} \times (BPB \cdot \tau)}$, where $BPB = M_t \cdot BPS = M_t \cdot \log_2 L$
   - $n$th column of $L_p$ contains $I_{in}$ LLRs associated with $n$th bit

2. Sliding window with window size of BPB gleans through columns of $L_p$ to select $\tau^t_s$ 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 $\tau^t_s$ reaches the limit $\tau_{sel} \ll \tau$, stop; otherwise selection continues until all $\tau$ blocks are looked

3. $n$th bit is selected in either of following two cases
   - **Case 1**: soft decisions in $n$th column share similar values, i.e.
     \[
     \frac{|L_p^1(n) - L_p^2(n)| + \cdots + |L_p^{I_{in}-1}(n) - L_p^{I_{in}}(n)|}{|\text{mean of } n\text{th column}|} \in (0, T_h), \quad T_h \text{ is a given threshold}
     \]
   - **Case 2**: absolute values of soft decisions in $n$th 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
   \[ C_{\text{pro}} \leq l_{\text{out}} O(\tau_{\text{sel}}^3) + C_{\text{ideal}} \text{ or } C_{\text{pro}} \approx C_{\text{ideal}} \]
   - Dramatically lower complexity of LSCE, e.g. \( \tau = 1000 \) and \( \tau_{\text{sel}} = 100 \), \( O(\tau_{\text{sel}}^3) \) is 1000 times smaller than \( O(\tau^3) \)

3. With same \( l_{\text{in}} \) inner iterations and \( l_{\text{out}} \) 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** \( \text{CRLB}(\tau_{\text{sel}}) \)
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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: $G_{RSC} = [1, 0, 1]_2$, $G'_{RSC} = [1, 1, 1]_2$
5. URC generator polynomials: $G_{URC} = [1, 0]_2$, $G'_{URC} = [1, 1]_2$
6. Transmitted signal power normalised to unity, SNR defined as $\frac{1}{N_0}$
7. Number of initial training data blocks: 6, training overhead 0.6%
8. Blocks-of-bits selection limit set to $\tau_{sel} = 100$
9. All the results were averaged over 100 channel realisations
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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.

SNR = 5 dB

$f_d = 0.01$

3 inner iterations

5 outer iterations
**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.

![Graph showing BER performance comparison]
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

![Influence of Selection Threshold Diagram]

- 10^{-6}
- 10^{-5}
- 10^{-4}
- 10^{-3}
- 10^{-2}
- 10^{-1}
- 1

BER

SNR (dB)

Perfect CSI

Maximum Achievable Rate

Proposed semi-blind BBSB-SCE, $T_h=0.2$

Proposed semi-blind BBSB-SCE, $T_h=0.5$

Proposed semi-blind BBSB-SCE, $T_h=1.0$

Proposed semi-blind BBSB-SCE, $T_h=2.0$

Proposed semi-blind BBSB-SCE, $T_h=3.0$

Perfect CSI
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 $T_h = 1.0$. 

![Diagram showing MSE convergence performance with SNR (dB) and Mean Square Error (MSE) on the axes. The graph illustrates the performance of Iterative BBSB-SCE with 6 initial training blocks and CRLB for $\tau = 100$.](image-url)
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.
Introduction

Motivations

Joint CE and Three-Stage Turbo Receiver

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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