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

Peichang Zhang\textsuperscript{a}, Sheng Chen\textsuperscript{a,b} and Lajos Hanzo\textsuperscript{a}

\textsuperscript{a}Communications, Signal Processing and Control Group
Electronics and Computer Science
University of Southampton, Southampton SO17 1BJ, UK
E-mails: \{pz3g09, sqc, lh\}@ecs.soton.ac.uk

\textsuperscript{b}King Abdulaziz University, Jeddah 21589, Saudi Arabia

2013 IEEE Wireless Communications and Networking Conference
Shanghai, China, April 7-10 2013
1 Introduction
   • Motivations

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

3 Simulation Example
   • Simulation Settings
   • Simulation Results

4 Conclusions
   • Concluding Remarks
Introduction

Motivations

Joint CE and Three-Stage Turbo Receiver

Existing State-of-the-Art

Proposed Novel Scheme

Simulation Example

Simulation Settings

Simulation Results

Conclusions

Concluding Remarks
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:

  $$y(i) = H s(i) + v(i)$$

  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 $\mathcal{CN}(0, N_0)$

- **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
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.

- $l_{in}$ inner iterations, $l_{out}$ outer iterations, $l_{ce}$ CE iterations
Complexity and Performance

- Idealised three-stage turbo ML-detector-decoder associated with perfect CSI
  \[ C_{\text{ideal}} = l_{\text{out}}(C_{\text{RSC}} + l_{\text{in}}(C_{\text{ML}} + C_{\text{URC}})) \]

- 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
Outline

1. Introduction
   - Motivations

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

3. Simulation Example
   - Simulation Settings
   - Simulation Results

4. Conclusions
   - Concluding Remarks
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 \textit{a posteriori} information matrix $L_p \in \mathbb{C}^{I_{\text{in}} \times (\text{BPB}\cdot \tau)}$, where $\text{BPB} = M_t \cdot \text{BPS} = M_t \cdot \log_2 L$

   - $n$th column of $L_p$ contains $I_{\text{in}}$ LLRs associated with $n$th bit

2. Sliding window with window size of BPB gleans through columns of $L_p$ to select $\tau_s^t$ 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 $\tau_s^t$ 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
   
   \textit{Case 1:} soft decisions in $n$th column share similar values, i.e.

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

   \textit{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
   \[ C_{\text{pro}} \leq l_{\text{out}} O\left(\tau_{\text{sel}}^3\right) + C_{\text{ideal}} \text{ or } C_{\text{pro}} \approx C_{\text{ideal}} \]
   - Dramatically lower complexity of LSCE, e.g. \( \tau = 1000 \) and \( \tau_{\text{sel}} = 100 \), \( O\left(\tau_{\text{sel}}^3\right) \) is 1000 times smaller than \( O\left(\tau^3\right) \)

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* \( \text{CRLB}(\tau_{\text{sel}}) \)
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
Outline

1. Introduction
   - Motivations

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

3. Simulation Example
   - Simulation Settings
   - Simulation Results

4. Conclusions
   - Concluding Remarks
**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.

SNR = 5 dB

$f_d = 0.01$

3 inner iterations

5 outer iterations

MIMO Demapper-URC, perfect CSI

MIMO Demapper-URC, BBSB-SCE

Trajectory, perfect CSI

Trajectory, BBSB-SCE

RSC, Memory length = 3, half rate
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 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 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 $T_h = 1.0$.

![Graph showing MSE convergence performance](image.png)

- Iterative BBSB-SCE, 6 initial training blocks
- CRLB, $\tau = 100$
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.
Outline

1. Introduction
   - Motivations

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

3. Simulation Example
   - Simulation Settings
   - Simulation Results

4. Conclusions
   - Concluding Remarks
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