MIMO-OFDM Precoder for Minimizing BER Upper Bound of MLD under Imperfect CSI

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Presentation Outline

• Introduction
  – Research background

• Literature Review
  – Precoder for minimizing BER upper bound under perfect CSI
  – Problem identification under imperfect CSI and research objective

• Proposed Precoding Method under Imperfect CSI
  – Criterion formulation and optimization
  – Computer simulation results

• Conclusions
  – Summary and suggestions for future work
Research Background

• Demands for future mobile communications (High Speed + High Reliability)

• Framework: MIMO-OFDM system with feedback channel

• Linear precoding criteria
  - Maximum Capacity
    - Adaptive Modulation Coding (AMC)
    - Waterfilling-based power allocation
  - Non-Capacity Based
    - Fixed modulation and coding
    - Phase and power optimization:
      - Satisfy QoS
      - Minimize transmit power
      - Minimize bit error rate (MBER)

Increase reliability (BER performance):
Focus of this research
Precoding

Transmitted signal replica of MIMO with QPSK and M=2 data streams

- Detection error: Received signal closer to another signal than transmitted one
- MBER precoding: Minimize detection error → Increase reliability
**MBER Precoder under Perfect CSI**

- Transmitter and receiver: Same CSI
- Procedures at transmitter

1. Calculate BER upper bound $J_e(F)$
2. Optimize $F$ to minimize $J_e(F)$

- Significant BER improvement over spatial multiplexing (nonprecoded) system

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Uncoded BER under Perfect CSI

- 2x2 MIMO-OFDM with QPSK
- Perfect CSI
- No AMC

- Eigenmode with Waterfilling Power Loading
- Eigenmode with MMSE Power Loading
- Spatial Multiplexing

Proposed MBER

Average BER vs. Average $E_b/N_0$ [dB]

6 dB
System Model under Imperfect CSI

- **CSI model**
  - Receiver: Channel Estimation Error
  - Transmitter: Channel Estimation Error + Quantization Error

- **Transmitter and receiver: Different CSI**
Problem and Proposed Solution

• Problem with conventional MBER precoder (designed by assuming perfect CSI)

\[ J_e(F) \]

Conventional cost function

CSI error \rightarrow \text{Large Degradation}

\[ F_0, F \]

Conventional optimal \quad \text{Calculated value}

• Proposed solution

\[ J_e'(F) \]

New cost function

CSI error \rightarrow \text{Small Degradation}

\[ F_0', F' \]

New optimal \quad \text{Calculated value}

New BER cost function: Robust to imperfect CSI
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MIMO-OFDM Transmitter

- System with $N_T$ transmit and $N_R$ receive antennas

$M \leq \min\{N_T, N_R\}$ data streams

$\text{Modulation signal vector } b(n,i)$

$\text{Baseband transmitted signal vector } s(n,i) = F(n)b(n,i)$

$k$-th antenna transmitted signal $x_k(p) = \text{IDFT}\{s_k(n,i)\}$
MIMO-OFDM Receiver

\[ r_l(p) = \sum_{k=1}^{N_T} \sum_{d=0}^{D} h_{lk,d}^T x_k(p-d) + n_l(p) \]

1 - th antenna received signal:

Baseband received signal vector:

\[ y(n,i) = \mathbf{H}(n) \mathbf{F}(n) \mathbf{b}(n,i) + \mathbf{z}(n,i) \]

\( h_{lk,d} \) d-th path impulse response between l-th and k-th antennas

\( x_k \) signal received antenna k

\( r_l(p) \) baseband signal received on antenna l

\( n_l(p) \) zero mean AWGN noise with variance \( \sigma_n^2 \)

\( y(n,i) \) output of the frequency domain channel estimation

\( \mathbf{H}(n) \) frequency response matrix, \( N_R \times N_T \)

\( \mathbf{F}(n) \) frequency response matrix, \( N_T \times 1 \)

\( \mathbf{b}(n,i) \) transmitted symbol

\( \mathbf{z}(n,i) \) noise vector, \( N_R \times 1 \)
CSI Error Model

- CSI at receiver: \( \hat{h}_{lk,d} = h_{lk,d} + \psi_{lk,d} \)  
  Estimation error

- CSI at transmitter: \( \hat{h}_{lk,d} = h_{lk,d} + \psi_{lk,d} + \nu_{lk,d} \)  
  Quantization error

- MMSE channel estimation

- Estimation error statistics:
  \[ \langle \psi_l \rangle = 0 \]
  \[ \langle \psi_l \psi_l^H \rangle \approx \sigma_n^2 \mathbf{I} \]

- Quantization error statistics:
  \[ \langle \nu_{lk,d} \rangle = 0 \]
  \[ \langle \nu_{l1,k1,1}^* \nu_{l2,k2,2} \rangle = \sigma_v^2 \delta_{l1,l2} \delta_{k1,k2} \delta_{d1,d2} \]
  \[ \sigma_v^2 / 2 = S_v^2 / 12 \]

- If \( \text{Re}\{h_{lk,d}\} \in [-1,1] \), then
  \[ B = \log_2 \left( \frac{2}{S_v} \right) \]
  No. of quantizing bit per path
Pairwise Error Probability (PEP)

- Detection error condition when $\sigma_v^2$ is small

$$\left\| y(n,i) - \hat{H}(n)F(n)b(n,i) \right\|^2 > \left\| y(n,i) - \hat{H}(n)F(n)c(n,i) \right\|^2$$

- PEP averaged with respect to CSI errors

$$P(\tilde{b} \rightarrow \tilde{c} | \hat{H}) = \int_0^\infty p(\varepsilon)d\varepsilon = \frac{1}{2}\text{erfc} \sqrt{\gamma(\tilde{b} \rightarrow \tilde{c})}$$

Joint p.d.f. between AWGN and CSI errors

$$\gamma(\tilde{b} \rightarrow \tilde{c}) = \left\| \hat{H}(n)F(n)[b(n,i) - c(n,i)] \right\|^2 / 4\sigma_e^2(F(n))$$

Error variance: $\sigma_e^2(F(n)) = N^{-1}\sigma_n^2 + \left[ F(n)b(n,i) \right]^H \Delta(n) [F(n)b(n,i)]$

Conventional

Proposed additional term

CSI errors: $\Delta(n) = \left\langle \Psi^H(n)\Psi(n) \right\rangle + \left\langle Y^H(n)Y(n) \right\rangle$

Estimation error

Quantization error
**BER Upper Bound Minimization**

- **BER upper bound cost function**

\[
J_e (\mathbf{F}(n)) = \sum_{i} \sum_{b \neq c} N_e (b \rightarrow \tilde{c}) P(\tilde{b} \rightarrow \tilde{c} | \hat{H})
\]

All pairs of \(b(n,i)\) and \(c(n,i)\)

No. of error bit when \(c(n,i)\) rather than \(b(n,i)\) is detected

- **Solution for optimal precoding matrix**

\[
\mathbf{F}_o (n) = \text{arg min}_{\mathbf{F}(n)} J_e (\mathbf{F}(n))
\]

Mathematically Untraceable

- **Optimization by the steepest descent algorithm**

\[
\mathbf{F}^{(q)} (n) = \mathbf{F}^{(q-1)} (n) - \mu \frac{\partial J_e (\mathbf{F}(n))}{\partial \mathbf{F}^* (n)} \mathbf{F}^{(q-1)} (n)
\]

Iteration index

Real positive constant

Gradient of \(J_e (\mathbf{F}(n))\)

subjected to

\[
\sum_{n=0}^{N-1} \left\langle \| \mathbf{F}(n) \mathbf{b}(n,i) \|^2 \right\rangle = \sum_{n=0}^{N-1} \text{tr} \left\{ \mathbf{F}(n) \mathbf{F}^H (n) \right\} = [P_0]
\]

Total average transmit power
## Simulation Conditions

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<tr>
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<tbody>
<tr>
<td><strong>Modulation</strong></td>
<td>QPSK</td>
</tr>
<tr>
<td><strong>Tx, Rx antenna (NT x NR)</strong></td>
<td>2 x 2</td>
</tr>
<tr>
<td><strong>Data stream M</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>OFDM packet format</strong></td>
<td>IEEE802.11a</td>
</tr>
<tr>
<td></td>
<td>(Preamble: 2 symbols, Data: 10 symbols)</td>
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<tr>
<td><strong>Total subcarrier</strong></td>
<td>64</td>
</tr>
<tr>
<td><strong>Effective subcarrier</strong></td>
<td>52 (Pilot:4, Data:48)</td>
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<td><strong>GI length</strong></td>
<td>16 points</td>
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<tr>
<td><strong>Channel model</strong></td>
<td>17 path exponential decay Rayleigh fading</td>
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<tr>
<td><strong>Maximum Doppler freq.</strong></td>
<td>0 Hz</td>
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<tr>
<td><strong>CSI at Rx</strong></td>
<td>MMSE channel estimation ((\lambda=1.0))</td>
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<tr>
<td><strong>CSI at Tx</strong></td>
<td>CSI from Rx + Quantization error ((\sigma_v^2=0.001-0.1))</td>
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<tr>
<td><strong>Signal detection</strong></td>
<td>MLD</td>
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Average BER Performance

2x2 MIMO-OFDM QPSK Modulation

Average BER vs. Average $E_b/N_0$ [dB]

- Perfect CSI
- Estimated CSI with $\sigma^2 = 0.03$ (3 bits/path)
- Spatial Multiplexing
- Conventional MBER
- Proposed MBER

2 dB Improvement
Robustness to Quantization Error

2x2 MIMO-OFDM with QPSK Modulation
Average BER = 10^{-3}
CSI at Tx = Quantized estimated CSI

Average $E_b/N_0$ [dB]

Quantization Error ($\sigma^2_v$)

Spatial Multiplexing

Conventional MBER

Proposed MBER

0.06 (2 bits/path)
Conclusions: Proposed MBER precoding technique under imperfect CSI

- Consider channel estimation and quantization errors as CSI imperfection
- Average PEP with respect to CSI errors
- Employ steepest descent algorithm for optimization
- Improve BER robustness to imperfect CSI

Future Works:

- Improvement of optimization and reduction of CSI amount
- Precoding technique for time-varying channel