Iterative Detection for Multi-User MIMO Systems

Joseph C. Liberti, Ph.D.
Carol C. Martin
John C. Koshy, Ph.D.
Timothy R. Hoerning

Mar 16, 2004

Advanced Wireless Signal Processing Research
Telcordia Technologies
Red Bank, New Jersey

Copyright 2004, Telcordia Technologies, Inc.

Prepared through collaborative participation in the Communications and Networks Consortium sponsored by the U. S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-2-0011. The U. S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

An SAIC Company
Outline

• MIMO Review
  – Motivation
• Spring 2002 Measurements
  – OFDM STTC Waveform Spec
  – ML vs LST Results
• Waveforms for Space-Time Bit Interleaved Coded Modulation
  – Motivation
  – Designing for Iterative Detection
• Spring 2003 Multi-User MIMO Measurements
  – Channel Characterization
MIMO Capacity Relative to Beamformed Systems

How does it compare with more traditional smart antenna techniques?
The capacity of a MIMO link is:

$$C = \log_2 \left( \det \left( I_{N_r} + \rho H H^H \right) \right) = \sum_{n=0}^{N_t-1} \log_2 \left( 1 + \rho \lambda_n \right) \rightarrow N_t \log_2 \left( 1 + \rho N_r \right)$$

Compare this with the capacity of a traditional smart antenna link:

$$C = \log_2 \left( 1 + \rho N_t N_r \right)$$

By creating multiple parallel channels out of the multipath environment, we can obtain link efficiency that far exceeds what we can get by simply using the antenna elements for traditional beamforming. However, this plot is overly optimistic because:

- It assumes the channel is full rank
- It assumes all paths have the same gain

$\rho =$ SNR Per Tx antenna Per Rx antenna
Telcordia’s MIMO Experiments

- 2000: 6x8 OFDM MIMO experiment, supported by ARL
- 2001: Mobile 6x8 OFDM MIMO experiments supported by DARPA
- 2002: Demonstration of ML-detection of Space-Time Trellis Coded (STTC) OFDM MIMO over-the-air and shows improved performance relative to Layered Space Time approach (ARL).
- 2003: Demonstration of Turbo MIMO approach with soft cancellation over-the-air in joint measurements with ARL
Spring 2002 Measurements

- Demonstrated OFDM MIMO using 4 transmitters
- Encoding and detection methods:
  - Space Time Trellis Code
  - Vector Viterbi Receiver
  - Dynamic Grouping
- Measurements through foliage and building-obstructed environments.
- Using over-the-air data, demonstrated relative performance of:
  - Layered Space Time Processing
  - Maximum Likelihood Processing
  - Dynamic Grouping with ML on Sub Groups
- Explore real-world training/sync/channel estimation
Complexity versus SNR Comparison

- BER=1e-2
- BER=1e-3

ML-JD

Threshold Based Adaptive Hybrid

Metric Based Adaptive Hybrid

2 Groups of 3 Adaptive

2 Groups of 3 Fixed

Symbol-wise LST

Stream-wise LST

log10(Relative Complexity)

SNR per Rx antenna per Tx antenna
Lower Complexity Methods

Tarokh, Naguib, Seshadri, and Calderbank proposed a technique in [Tar99a] in which transmitters are grouped, with Space-Time Coding performed on groups of antennas.

The complexity of this approach is exponential in the number of antennas per group, linear in the number of groups. Therefore, the simulation shown at right, with $N_t=6$, $N_r=6$, we obtain performance somewhere between LST and ML-JD at complexity comparable to ML-JD with $N_t=3$, $N_r=6$.

Simulation for $N_t=6$, $N_r=6$, with two groups of three transmitters.
Threshold based technique outperforms the metric-based technique. 
- Threshold based allows a single group of $N_t$ antennas (same as full ML-JD), which results in higher complexity.
- Since metric uses pair-wise projections, it can not produce a single group.
MIMO Testbed Hardware

The transmitter and receiver are shown during measurements at the RVR site.

- **Transmitter**
  - OFDM Tx #1
  - OFDM Tx #2
  - OFDM Tx #3
  - OFDM Tx #4
  - OFDM Tx #5
  - OFDM Tx #6
  - Controller
  - Cesium Reference
  - GPS Timing Reference

- **Receiver**
  - GPS Timing Reference
  - Communications Test Van

**Specifications**
- **RF Frequency:** 1780-2000 MHz
- **Transmit Channel:** 1-6 Antennas
- **Waveform:** 192-OFDM 1.0 MHz
- **Receiver Channels:** 8 Coherent
- **Rx Sampling Rate:** 21.3333 Msps
- **A/D Conversion:** At 5.3333 MHz IF
- **A/D RF Bandwidth:** 1.3 MHz
- **Array Geometry:** Circular
- **Mast Height:** 13-46 ft.
- **Capture Length:** 0.5 Seconds at 5.3333 Msps
- **Processors:** 16 x 200 MHz C6201
## Spring 2002 OFDM STTC MIMO Measurements

### OFDM and STTC

<table>
<thead>
<tr>
<th>Ant 1</th>
<th>Ant 2</th>
<th>Ant 3</th>
<th>Ant 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>M2</td>
<td>M3</td>
<td>M4</td>
</tr>
<tr>
<td>T1</td>
<td>T2</td>
<td>T3</td>
<td>T4</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
</tbody>
</table>

### TDMA

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>5.00ms</th>
<th>10.00ms</th>
</tr>
</thead>
</table>

### MLJD STTC

<table>
<thead>
<tr>
<th>M-sequences</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>5x511</td>
<td>BPSK</td>
</tr>
</tbody>
</table>

### "Dynamically" grouped STTC

<table>
<thead>
<tr>
<th>Tones</th>
<th>M-sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>a</td>
</tr>
<tr>
<td>T2</td>
<td>a</td>
</tr>
<tr>
<td>T3</td>
<td>a</td>
</tr>
<tr>
<td>T4</td>
<td>a</td>
</tr>
</tbody>
</table>

### 61 OFDM Bursts

<table>
<thead>
<tr>
<th>Overlap region (18.75 µs)</th>
</tr>
</thead>
</table>

### IFFT samples from OFDM spectrum (192 µs)

<table>
<thead>
<tr>
<th>Copy of samples from the beginning of IFFT (18.75 µs)</th>
</tr>
</thead>
</table>

### 1 MHz

<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subcarriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
</tr>
</tbody>
</table>
Spring 2002 Measurement Locations

- 578 total measurements
  - 3 experimental deployments
  - 17 – 40 different SNRs for each measurement configuration
  - 3 different carrier frequencies
  - Movement of transmitter to average over a local area

<table>
<thead>
<tr>
<th>RX Height</th>
<th>TX Move</th>
<th>Freq (MHz)</th>
<th># of Measurements (each with different transmitter power level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (12.3ft)</td>
<td>0</td>
<td>fc-2 MHz</td>
<td>17 40 26</td>
</tr>
<tr>
<td>Low (12.3ft)</td>
<td>0</td>
<td>fc+2 MHz</td>
<td>17 40 26</td>
</tr>
<tr>
<td>Low (12.3ft)</td>
<td>+6in</td>
<td>fc</td>
<td>17 40 26</td>
</tr>
<tr>
<td>Low (12.3ft)</td>
<td>+6in</td>
<td>fc-2 MHz</td>
<td>17 22</td>
</tr>
<tr>
<td>Low (12.3ft)</td>
<td>+6in</td>
<td>fc+2 MHz</td>
<td>17 22</td>
</tr>
<tr>
<td>High (41.2ft)</td>
<td>0</td>
<td>fc</td>
<td>17 40 22</td>
</tr>
<tr>
<td>High (41.2ft)</td>
<td>+6in</td>
<td>fc</td>
<td>17 40 22</td>
</tr>
</tbody>
</table>
Next Steps

- In previous measurements:
  - Demonstrated value of ML detection when the number of receive antennas is limited
  - Demonstrated dynamic grouping
- Next steps
  - Design for FH compatible environments
  - Derive computationally tractable receivers
  - Achieve better channel estimation, coding gain
  - Design techniques appropriate for FH channels

Iterative MIMO Receivers

- Iterative Detection
  - Iterative channel estimation
  - Double encoding + interleaving
  - Computation of LLRs
  - Sphere detection
Space-Time Bit-Interleaved Coded Modulation

Ref: Stefanov and Duman, JSAC 2001
Tonello, VTC 2000 Fall

$Le(x)$ Extrinsic LLRs
Iterative MIMO Waveform used for Summer 2003 (ST-BICOM)

- The following transmitter-receiver pair incorporates concepts from ST-BICM, but adds:
  - OFDM
  - Soft Cancellation
- System achieves information spectral efficiency of 10.3 bps/Hz using 6x8 system.
Iterative MIMO Receiver used for Summer 2003 (ST-BICOM)

- RF/ADC/DDR
- OFDM Dem
- Channel Estimation
- Split Pilot Carriers and Info
- Soft Cancellation
- LLR Calculation
- De-Interleaver
- Soft-Input Soft-Output Turbo Decoder
- Initialize Soft Canceller Values to 0
- LLR Calculation
- Interleaver
- Compute Hard Decisions At Iteration = Nmax
- S/P
- Soft Sym Mapper
- Soft Sym Mapper
Multi-User MIMO Iterative Detector

1. **RF/ADC/DDR** \(\rightarrow\) **OFDM Dem**
2. **Distribution**
3. **Split Pilot Carriers and Info**
4. **Channel Estimation**
5. **Soft Cancellation**
6. **LLR Calculation**
7. **P/S**
8. **De-Inter-leaver**
9. **Soft-Input Soft-Output Turbo Decoder**
10. **Inter-leaver**

**Initialization:**
- Initialize Soft Canceller Values to 0

**Iteration:**
- Iter = 0
- \(w_1\) \(\rightarrow\) LLR Calculation
- \(w_6\) \(\rightarrow\) LLR Calculation

**MIMO User 1:**
- MIMO User 1 Path

**MIMO User 2:**
- MIMO User 2 Path

**Soft Sym Mapper**
- ...
6 x 8, 16-QAM, Rate ½ Turbo (Simulation)

**With Soft-Cancellation**

<table>
<thead>
<tr>
<th>Capacity (bps/Hz)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.4</td>
</tr>
<tr>
<td>12</td>
<td>5.0</td>
</tr>
</tbody>
</table>

No overhead → 1.5 dB within capacity @ 12 bps/Hz
With overhead → 3 dB within capacity @ 10 bps/Hz
Summer 2003 Multi-User MIMO Experiments

Key:

- Receiver (Van)
- Transmitter # 1 (3 element array - mobile)
- Transmitter # 2 (3 element array - fixed)

Telcordia Navesink Campus

1. 3-Element MIMO Transmitter #1 (Mobile)
2. 8-Element MIMO Receiver
3. Building 2
4. Building 1
5. Building 3
6. Telcordia Navesink Campus
2-User Experimental Case Using Multi-User MIMO Iterative Detector

3 Transmitters on Each MIMO Tx, 8 Antennas on the Receiver

Low SNR User has an average SNR that is 6 dB below the higher level user.

The average SNR for each 3x Node is shown as the overall SNR is varied. The relative levels of the two users are approximately fixed.
MIMO Channel Characterization

Illustrated LOS Link

Illustrated NLOS Link

Key:
- North
- Receiver (Van)
- Transmitter (6 element array - Pickup)
- Transmitter location number (color denotes data was taken over a few days)

NOT TO SCALE

Tela Technologies
Performance from Experience
Iterative channel estimation (MIMO Case)

- Initial channel estimates are performed using pilot symbols.
- Channel estimates are improved during periods with no pilot symbols by using tentative decisions from the turbo decoder.
Summary

- Presented Spring 2002 measurement results which demonstrated improvements using ML detection over null-and-cancel methods when the number of receive antennas is limited.
- Developed waveforms that extend Space-Time Bit Interleaved Coded Modulation (ST-BICM) to include OFDM with soft cancellation.
- Implemented a measurement campaign in Summer 2003 using the ST-BICOM-SC waveform/receiver to demonstrate high spectral efficiency coupled with low-Eb/No tolerance.

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.