Iterative Detection for Multi-User MIMO Systems

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Abstract  Multi-input multi-output (MIMO) systems can serve as the building blocks for spectrally efficient mobile multi-user tactical wireless systems; however, care must be taken to translate high per-link spectral efficiency into high network throughput. Mobile tactical networks generally have several features that complicate achievement of high multi-user MIMO spectral efficiency, including non-centralized, infrastructure-free operation, and operation when all nodes are mobile, as well as requirements to minimize probability of interception and susceptibility to jamming. The paper presents results from both simulations and an extensive over-the-air measurement campaign, which illustrate the key features needed for spectrally efficient multi-user MIMO systems.

High MIMO network throughput can be achieved by combining efficient MAC (taking into account MIMO signal processing resources) and transmitter stream control, as well as high performance MIMO signal processing and waveforms that minimize per-link signal-to-interference-and-noise ratio (SINR) requirements leading to effective spectral reuse. Iterative detection schemes provide such high spectral efficiency at low SINRs, achieving performance that approaches the Shannon bound, and provide scalable complexity. These methods are also well suited to operation in multi-user environments, supporting both interference-mitigation and joint detection approaches.

The paper provides analysis and experimental results for waveforms and receiver signal processing for Space-Time Bit Interleaved Coded Modulation using multi-carrier waveforms. Results and parameter trades are presented for variations of this approach using List Sphere Detection and Soft-Symbol Cancellation as well as structures based on convolutional codes and turbo codes.

In June–September 2003, these waveforms and iterative detection methods were demonstrated over the air using a 6-element transmitter and 8-element receiver system as well as configurations using two 3-element MIMO transmitters with an 8-element receiver. The measurements provide over-the-air performance results in a variety of channel configurations and provide data on real-world multi-user MIMO radio channels.
Report Documentation Page

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Outline

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  – 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:

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

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

\[ C = \log_2 (1 + \rho N_t N_r) \]

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

\( \rho = \text{SNR Per Tx antenna Per Rx antenna} \)
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

- ML-JD
- Metric Based Adaptive Hybrid
- Threshold Based Adaptive Hybrid
- 2 Groups of 3 Adaptive
- 2 Groups of 3 Fixed
- Symbol-wise LST
- Stream-wise LST

- BER=1e-2
- BER=1e-3
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**: Shows the setup with multiple antennas and associated electronics.
- **Receiver**: Includes details about GPS timing and reference sources.

**Hardware 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

**Diagram Details**:
- **Masthead Electronics Unit**
- **IF Processing Unit**
- **Communications Test Van**

**Key Components**:
- **Controller**
- **GPS Timing Reference**
- **Calibration Input**
- **300 MHz IF Channels**
- **1550-1690 MHz LO**
- **1850-1990 MHz LO**
- **230 MHz**

**Imagery**:
- Transmitter and receiver images showing the practical setup at the RVR site.
Spring 2002 OFDM STTC MIMO Measurements

STTC OFDM and Dist. Network

5x511-len BPSK M-sequences

MLJD STTC

Tones

MLJD

TDMA

“Dynamically” grouped STTC

LST

5.11 ms

4.65 ms

5.00 ms

10.00 ms

STTC

M1 T1

M2 T2

M3 T3

M4 T4

a a a a a a a a a a a a a a

a a a a a b b b b b b b b b

a a b b b a a a a b b b c c c c

a b a b c a b c a b c a b c d

5.00 ms

10.00 ms

61 OFDM Bursts

Time

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ...

61 OFDM Bursts

Overlap region (18.75 µs)

First OFDM Burst

Last OFDM Burst

Copy of samples from the end of IFFT (48 µs)

IFFT samples from OFDM spectrum (192 µs)

Copy of samples from the beginning of IFFT (18.75 µs)

1 MHz

192 Subcarriers

Freq

240 µs
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>
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<tr>
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<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, 40, 22</td>
</tr>
<tr>
<td>Low (12.3ft)</td>
<td>+6in</td>
<td>fc+2 MHz</td>
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<tr>
<td>High (41.21ft)</td>
<td>0</td>
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<td>17, 40, 22</td>
</tr>
<tr>
<td>High (41.21ft)</td>
<td>+6in</td>
<td>fc</td>
<td>17, 40, 22</td>
</tr>
</tbody>
</table>

- Performance from Experience
Spring 2002 OFDM STTC MIMO Measurement Results

Using 8 Receive Antennas

Using 4 Receive Antennas

Using 3 Receive Antennas

Using 2 Receive Antennas

“Canyon Measurements”
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
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)
Multi-User MIMO Iterative Detector
6 x 8, 16-QAM, Rate ½ Turbo (Simulation)

With Soft-Cancellation

No overhead → 1.5 dB within capacity @ 12 bps/Hz
With overhead → 3 dB within capacity @ 10 bps/Hz

Capacity (bps/Hz) SNR (dB)
10  3.4
12  5.0
Summer 2003 Multi-User MIMO Experiments

Key:

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

North

Building 1
Building 2
Building 3
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:
- Receiver (Van)
- Transmitter (6 element array - Pickup)
- Transmitter location number (color denotes data was taken over a few days)

NOT TO SCALE

North

Transmitter location number

Telco 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.

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