The Shannon limit in mobile cellular systems: How far off are we?

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Outline

- MIMO Testbed
  - WiMAX Measurements
    - IEEE 802.16-2004 (Section 8.3) with OFDM physical layer
    - feedback realization
    - achievable and measured throughput
  - HSDPA Measurements
    - signal generation and reception
    - feedback realization
    - achievable and measured throughput
- Comparisons HSDPA vs. WiMAX
- Conclusion
Evaluating MIMO radio communication

- theoretically
- by pure simulation
- by channel sounding
- utilizing a testbed
- utilizing a prototype
- using the final product

degree of realism effort
Data is created and evaluated in Matlab ...

**Number of Antennas:** 4x4  
**Bandwidth:** 5 MHz  
**Center Frequency:** 2.5 GHz
MIMO Testbed [T1,T2]

- **MIMO WiMAX 802.16-2004**
  OFDM physical layer
  - including channel coding and decoding
  - SISO and MIMO

- **MIMO HSDPA (TxAA, DTxAA)**
  CDMA physical layer
  - including channel coding and decoding
  - SISO and MIMO

- **MIMO LTE (new)**
Experimental MIMO Testbed: THE MOVIE
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Adaptive Modulation and Coding (AMC)

- **Encoding**
  - concatenated Reed-Solomon / convolutional code
  - puncturing depending on AMC information
  - optional block/convolutional turbo coding
  - Alternatively: LDPC coding

- **Adaptive symbol mapping**

- **Optional Alamouti space-time coding**
## Coding and Modulation

<table>
<thead>
<tr>
<th>AMC value</th>
<th>Modulation</th>
<th>RS Code Rate</th>
<th>CC Rate</th>
<th>Overall Code Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-PAM</td>
<td>1</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td>2</td>
<td>4-QAM</td>
<td>3/4</td>
<td>2/3</td>
<td>1/2</td>
</tr>
<tr>
<td>3</td>
<td>4-QAM</td>
<td>9/10</td>
<td>5/6</td>
<td>3/4</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>3/4</td>
<td>2/3</td>
<td>1/2</td>
</tr>
<tr>
<td>5</td>
<td>16-QAM</td>
<td>9/10</td>
<td>5/6</td>
<td>3/4</td>
</tr>
<tr>
<td>6</td>
<td>64-QAM</td>
<td>8/9</td>
<td>3/4</td>
<td>2/3</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>9/10</td>
<td>5/6</td>
<td>3/4</td>
</tr>
</tbody>
</table>
OFDM Frame Structure

- 3 OFDM symbols preamble
  1. Synchronization
  2. Channel estimation
  3. Control information

- Subcarrier distribution
  - 192 data subcarriers
  - 8 pilot subcarriers
  - 1 zero DC subcarrier
  - 55 guard band subcarriers
  - → 256 total
OFDM Modulation and Demodulation

Transmitter

Zero Padding

IFFT

Add CP

Channel

Receiver

Rem. Zeros

FFT

Rem. CP

200

256

256

264

320

200

256

256

264

320
Preliminary Measurement Setup [W2]

- **3 scenarios**
  1. NLOS, outdoor-to-indoor
  2. NLOS, outdoor-to-outdoor
  3. LOS, outdoor-to-indoor

- **Parameters**
  - 5 MHz channel bandwidth
  - Cyclic prefix 1/4
  - 192 carrier OFDM
  - Rx antenna distance \(1.2\lambda\)
  - Tx antenna distance: \(2.75\lambda\)
  - Tx antenna height: 16m
  Measurement distance: 50-100m
1. SIMO, 7 AMC schemes, 3 bit feedback
2. MIMO with Alamouti, 7 AMC schemes, 3 bit feedback
3. MIMO with spatial multiplexing, **same** coding scheme on both antennas, 3 bit feedback
4. MIMO with spatial multiplexing, **individual** coding schemes on both antennas, 6 bit feedback
Measured Channel Coefficients [W2]

Duration of measurements: ~200ms
One Receive Antenna: NLOS outdoor-to-outdoor [W2]
One Receive Antenna: NLOS outdoor-to-indoor [W2]

![Graph showing achievable throughput vs. transmit power for different antenna configurations.

- Dual Tx
- Single Tx (1)
- Single Tx (2)
- 1x1
- 2x1 Alamouti]
The measured scenarios behave asymmetric with respect to the transmit antenna.
If channel is known at the transmitter, antenna selection can improve the performance.
Alamouti looses (slightly) compared to single antenna transmission:
- more sensitive channel estimation errors
- 3dB less power for training
- Asymmetric scenario
Huge gap of >10dB between measured and achievable throughput!
Two Receive Antennas MRC: LOS outdoor-to-indoor

[Ref: W2]

![Graph showing achievable throughput vs. transmit power for different configurations.](image)
Two Receive Antennas: LOS outdoor-to-indoor [W2]
Two Receive Antennas: LOS outdoor-to-indoor [W2]
Two Receive Antennas: Conclusions [W2]

- Spatial multiplexing with 6 bit feedback outperforms spatial multiplexing with 3 bit feedback
  - The 6 bit feedback allows to exploit the asymmetric channels
- Alamouti is better than spatial multiplexing with 3 bit feedback due to transmit diversity
- Still, a huge gap of >10 dB between measured and achievable throughput is observed!

- **Enhancements**
  - Better channel coding
    - e.g. Low Density Parity Check (LDPC) codes
  - Enhanced channel estimation techniques
    - e.g. LMMSE channel estimation to exploit correlation between subcarriers
AWGN Performance of the Reed Solomon-Conv.Coder
AWGN Performance of LDPC codes

![Graph showing throughput vs. SNR for LDPC codes. The graph plots the throughput in Mbit/s on the y-axis and SNR in dB on the x-axis. Multiple lines with different colors represent different LDPC codes, illustrating their performance at various SNR levels.](image-url)
### SNR Gain of Improved Channel Estimators over the LS Estimator

#### [W1]

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>LMMSE</th>
<th>genie-driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x1 SISO</td>
<td>0.6 dB</td>
<td>1.2 dB</td>
</tr>
<tr>
<td>2x1 Alamouti</td>
<td>1.8 dB</td>
<td>2.9 dB</td>
</tr>
<tr>
<td>1x2 SIMO</td>
<td>0.5 dB</td>
<td>1.2 dB</td>
</tr>
<tr>
<td>2x2 Alamouti</td>
<td>1.9 dB</td>
<td>3.2 dB</td>
</tr>
<tr>
<td>2x2 Spatial Multiplexing (3 bit)</td>
<td>1.4 dB</td>
<td>2.4 dB</td>
</tr>
<tr>
<td>2x2 Spatial Multiplexing (6 bit)</td>
<td>1.1 dB</td>
<td>2.2 dB</td>
</tr>
</tbody>
</table>
Losses in WiMAX

SNR loss at 5 MBit/s [dB]

- 2x2 Alamouti
- 2x1 Alamouti
- 1x2 SIMO
- 1x1 SISO

LDPC  |  CTC  |  RS-CC
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Channel adaptation is performed by means of
- a Channel Quality Indicator (CQI) and
- a Precoding Control Indicator (PCI) when two transmit antennas are available
- Large number of possible transmit blocks require channel evaluation at the receiver
- Minireceiver estimates channel and noise and calculates the CQI and PCI
SINR Estimation in Minireceiver [H5]

\[
\text{SINR}_{\text{est}} = \frac{P_s}{\sigma_n^2 + P_{\text{ISI}} + P_{\text{INT}}}
\]

The post equalization SINR is given by

- the signal power \( P_s \)
- the noise at the output of the equalizer \( \sigma_n^2 \)
- the remaining inter-symbol interference \( P_{\text{ISI}} \)
- the interference caused by spatially multiplexed streams sharing the same scrambling and spreading codes \( P_{\text{INT}} \)

SINR is calculated for all possible precoding vectors and mapped to the supported CQI values. The precoding vector maximizing the transport block size is selected.
Verification of the SINR Estimation in the Simulation [H5]
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Two Measurement Campaigns: Alpine and Urban

\[ f_c = 2.5 \text{ GHz} \]
\[ B = 6.25 \text{ MHz} \]
\[ P_{\text{max}} = 36 \text{ dBm} \]
Two Measurement Campaigns: Alpine and Urban
Two Measurement Campaigns: Alpine and Urban

distance = 430 m

TX antenna  [C1,C2,C3,C4]  RX unit
Performance Comparisons

The graph illustrates the comparison of different performance metrics such as capacity, mutual information, achievable mutual information (MI), and measured throughput. The axes represent SNR (dB) and throughput. The graph highlights the feedback, design, and implementation loss at various SNR levels.
HSDPA vs WiMAX in Alpine Environment

Achievable Throughput vs. Achieved Throughput

Implementation loss
HSDPA vs WiMAX in Urban Environment

Achievable Throughput vs. Achieved Throughput

Implementation loss
HSDPA vs WiMAX in Alpine Environment
Mutual Information vs Achievable Throughput

SISO

2x2 MIMO

Design loss
HSDPA vs WiMAX in Urban Environment

Mutual Information vs Achievable Throughput

Design loss
HSDPA vs WiMAX in Alpine Environment
Capacity vs Mutual Information

Feedback loss
HSDPA vs WiMAX in Urban Environment
Capacity vs Mutual Information

Feedback loss
Conclusion

- WiMAX and HSDPA are ~10dB off from the Shannon Bound!

- Channel estimation loss
  - 2-3dB channel estimator
  - 6-9dB in HSDPA due to self-interference

- Coding loss
  - 5dB convolutional codes (WiMAX)
  - 2-3dB Turbo
  - 1-2dB LDPC

- CQI (PCI) indicators need to be selected optimally
  - 1-2dB loss depending on scenario
Thank you for your attention.

http://www.nt.tuwien.ac.at/
Testbed References


HSDPA References


WiMAX References


Comparisons


