The Performance of 3G and 4G Cellular Systems

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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
MIMO Testbed [T1,T2]

Data is created and evaluated in Matlab ...

Number of Antennas: 4x4 → 12x4
Bandwidth: 5 MHz → 20 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)**
  - also MU, multi BS
Outline

- MIMO Testbed
- WiMAX in Brief
  - Losses in WiMAX
- HSDPA in Brief
  - signal generation and reception
- LTE in Brief
- Comparisons HSDPA vs. WiMAX
- Further Comparisons to LTE
- Conclusion
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**
Adaptive Modulation and Coding (AMC)

<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>

3bit feedback
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
**Losses**

- WiMAX does not reach Shannon bound because of
  - Channel estimation losses
  - Coding losses

- 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>
AWGN Performance of the Reed Solomon-Conv.Coder
AWGN Performance of LDPC codes

![Graph showing throughput versus SNR for LDPC codes.](image)
Losses in WiMAX

The graph shows SNR loss at 5 MBit/s [dB] for different modulation schemes and conditions.

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

The modulation schemes are:
- **LDPC**
- **CTC**
- **RS-CC**
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HSDPA Overview:
Adaptive Modulation and Coding (AMC)

- Channel adaptation is performed by means of
  - a Channel Quality Indicator (CQI) and
  - a Precoding Control Indicator (PCI) when two transmit antennas are available

CQI: 30 values=5bit/15 values=4bit for DTxAA
PCI: 2 bit/4bit for DTxAA
**Significantly more Feedback**

- HSDPA Parameters: CQI, PCI

- Measurement not possible with quasi-static assumption
  - Mini receiver solution (computes the post equalization SINR)

- HDSPA Losses:
  - channel estimation,
  - successive interference cancellation required due to non-orthogonal synch codes
  - High self interference
SINR Estimation in Minireceiver [H5,C6,C9]

$$\text{SINR}_{\text{est}} = \frac{P_s}{\sigma_{n'}^2 + P_{\text{ISI}} + P_{\text{INT}}}$$

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,C9]
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Similar to WiMAX, LTE is an OFDM system

- It offers AMC by
  - CQI (15 values = 4 bit / 31 values = 5 bit)
  - PMI (15 values = 4 bit)
  - RI (2 bit)
  - → Minireceiver required again
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Two Measurement Campaigns: Alpine and Urban

$\nu_c = 2.5 \text{ GHz}$

$B = 6.25 \text{ MHz}$

$P_{\text{max}} = 36 \text{ dBm}$

[W4, W5, C9]
Two Measurement Campaigns: Alpine and Urban

control link  RX unit  distance = $4.7\text{km}$  TX antenna  TX unit

GPS

RX unit  XYΦ table  antennas
Two Measurement Campaigns: Alpine and Urban

$[C1, C2, C3, C4, C5, C6, C7, C8, C9]$

TX antenna

distance $= 430 m$

RX unit
**Channel Capacities**

Capacity (Shannon, Foschini&Gans, Telatar)

\[
C(P_{Tx}) = \max_{\sum \text{tr}\{R_k\} \leq K} \frac{B}{K} \sum_{k=1}^{K} \log_2 \det \left( I + \frac{P_{Tx}}{\sigma_n^2 N_T} H_k R_k H_k^H \right)
\]

Mutual Information (constrained capacity)

\[
I(P_{Tx}) = \frac{B}{K} \sum_{k=1}^{K} \log_2 \det \left( I + \frac{P_{Tx}}{\sigma_n^2 N_T} H_k H_k^H \right)
\]

Achievable Mutual Information (constrained by Standard)

\[
I_a(P_{Tx}) = \max_{W \in \mathcal{W}} \frac{\beta B}{K} \sum_{k=1}^{K} \log_2 \det \left( I + \frac{\alpha P_{Tx}}{\sigma_n^2 N_T} H_k W W^H H_k^H \right)
\]
Throughput Losses

- **Channel State Information (CSI) Loss:**

  \[ L_{\text{CSI}}(P_{\text{Tx}}) = C(P_{\text{Tx}}) - I(P_{\text{Tx}}); \quad L_{\text{CSI}}%(P_{\text{Tx}}) = 100 \cdot \frac{C(P_{\text{Tx}}) - I(P_{\text{Tx}})}{C(P_{\text{Tx}})} \]

- **Design Loss**

  \[ L_d(P_{\text{Tx}}) = I(P_{\text{Tx}}) - I_a(P_{\text{Tx}}); \quad L_d%(P_{\text{Tx}}) = 100 \cdot \frac{I(P_{\text{Tx}}) - I_a(P_{\text{Tx}})}{C(P_{\text{Tx}})} \]

- **Implementation Loss**

  \[ L_i(P_{\text{Tx}}) = I_a(P_{\text{Tx}}) - D_m(P_{\text{Tx}}); \quad L_i%(P_{\text{Tx}}) = 100 \cdot \frac{I_a(P_{\text{Tx}}) - D_m(P_{\text{Tx}})}{C(P_{\text{Tx}})} \]
Channel State Information loss

Design loss

Implementation loss
Performance Comparisons

- ~10 dB loss
- ~10 dB loss
- ~60% loss

Charts showing performance metrics for different transmit powers and average received SISO SNRs.
Absolute Losses [C6,C9]

Fig. 2. Throughput losses of the SISO WiMAX and the SISO HSDPA systems in the alpine (ID “2008-09-23”) and the urban environments (ID “2009-01-15c”).

Fig. 3. Throughput losses of the MIMO WiMAX and the MIMO HSDPA systems in the alpine (ID “2008-09-23”) and the urban environments (ID “2009-01-15c”).
Relative Losses [C8,C9]

- WiMAX
- HSDPA
Relative Losses: WiMAX [C8,C9]

No difference between Urban and Alpine
Relative Losses HSDPA [C8,C9]

Difference between Urban and Alpine due to RMS Delay spread
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You can find below the links to each one of the LTE simulators:

- **LTE Downlink Link Level Simulator**
- **LTE Downlink System Level Simulator**
- **LTE Uplink Link Level Simulator**

Now Available:
- **LTE-Advanced Downlink Link Level Simulator**

Since 2009 >25,000 downloads
2x2 LTE OL Measurement with 10MHz Bandwidth

- Crosspolarized antennas

![Graph showing throughput vs. average SISO SNR (dB)]
2x2 LTE OL Measurement with 10MHz Bandwidth
4x4 LTE OL Measurement with 10MHz Bandwidth

![Graph showing throughput (Mbit/s) vs. Average SISO SNR (dB)]

- Channel capacity
- Mutual information
- Achieved mutual information
- Measured throughput

*95% confidence intervals*
4x4 LTE OL Measurement with 10MHz Bandwidth

- 4x4 MIMO [L13,L14]
Maximum OLSM Throughput 10MHz Bandwidth

- 2x2 LTE
  - 41%

- 4x4 LTE
  - 36%

- 8x8 LTE
  - 31% (predicted)
### Conclusion

- **WiMAX and HSDPA** are ~10dB off from the Shannon Bound! Less than half of the potential throughput is achieved.

- **Channel estimation loss**: an overemphasized loss!
  - Channel knowledge at transmitter is mostly irrelevant

- **Design loss**: a political loss!
  - Standards have not been treated scientifically yet

- **Implementation loss**: an unavoidable loss!
  - Need of accurate implementation models as design loss depends on them!

- **LTE is not expected to be much better**!

- **In particular LTE MIMO** is not efficient!
**Improvements**

- Gain 25% throughput by using the entire spectrum
  Synchronise base stations!

- Gain 13% throughput by switching to differential encoding → no pilots

- Gain a lot % throughput by utilising MIMO the right way:
  Does anybody know how???
Thank you for your attention.

http://www.nt.tuwien.ac.at/
With help from...
Available now!
**Testbed References**


HSDPA References


WiMAX References


Comparisons


Comparisons


LTE


