Outdoor WiMAX Throughput Measurements

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Outline

- WiMAX signal generation and reception
  - IEEE 802.16-2004 (Section 8.3) with OFDM physical layer
- Measurement setup
- Achievable and measured throughput
- Measurement results
- Enhancements
- Overall conclusions
TX Adaptive Modulation and Coding (AMC)

- **Encoding**
  - concatenated Reed-Solomon / convolutional code
  - puncturing depending on AMC information
  - optional block/convolutional Turbo coding

- **Adaptive symbol mapping** (2-PAM, 4-QAM, 16-QAM, 64-QAM)

- **Optional** Alamouti space-time coding
Receiver

- LS channel estimation
- max-log-MAP demapping

\[
LLR(b_k) \approx \max_{z|b_k=1} \left( -\frac{1}{2} \frac{||Hz - r||_2^2}{\sigma_v^2} \right) - \max_{z|b_k=0} \left( -\frac{1}{2} \frac{||Hz - r||_2^2}{\sigma_v^2} \right)
\]

- soft Viterbi decoding
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Measurement Setup

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

- Parameters
  - 2.503 GHz center frequency
  - 5 MHz channel bandwidth
  - Cyclic prefix 1/4
  - 256 carrier OFDM
  - TX antenna spacing 2.75 λ
Block Transmission
Measured Channel Coefficients at One Position

![Graph showing channel coefficients comparison between SISO and MIMO systems. The y-axis represents $\frac{|h_{1,1}|^2}{\sigma_n^2}$ in dB, and the x-axis represents the subcarrier index. The graph highlights a 3 dB difference between the two systems.]
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Achievable Throughput (1)

Mutual information of the transmitted and received symbol at subcarrier $k$, at transmitter attenuation $m$, and for channel realization $c$ is given by

$$ I_k^{(c,m)} = \log_2 \left\{ \det \left( I_{NR} + \frac{1}{\sigma^2_n} H_k^{(c,m)} H_k^{(c,m)H} \right) \right\} $$

Averaging over the channel realizations and summing over the subcarriers yields

$$ I_{\text{sum}}^{(m)} = \frac{1}{N_{\text{RXpos}}} \sum_{c=1}^{N_{\text{RXpos}}} \sum_{k=1}^{192} I_k^{(c,m)} $$
Achievable throughput

\[ D_{\text{achievable}}^{(m)} = \frac{1}{1 + G} \cdot \frac{1/T_s}{256} \cdot \frac{N_{\text{data}}}{N_{\text{OFDM}}} \cdot I_{\text{sum}}^{(m)} \]

- \( G \) ... cyclic prefix ratio
- \( T_s \) ... sampling time
- \( N_{\text{data}} \) ... number of OFDM data symbols per frame
- \( N_{\text{OFDM}} \) ... total number of OFDM symbols per frame
Evaluation of Measured Throughput

- Based on a “perfect” feedback method
  - Possible since all AMC schemes were transmitted over the same channel
- Best throughput at receive antenna position $c$

$$D_{best}^{(c,m)} = \max_{i \in I} R_i (1 - P_i^{(c,m)})$$

- Here, $P_i^{(c,m)} \in \{0, 1\}$ is a frame error indicator, $R_i$ is the data rate of the $i$-th AMC scheme
- The average throughput of one scenario at transmitter attenuation $m$ is given by

$$D_{best,avg}^{(m)} = \frac{1}{N_{RXpos}} \sum_{c=1}^{N_{RXpos}} D_{best}^{(c,m)}$$
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Two Receive Antennas: LOS outdoor-to-indoor

![Graph showing achievable throughput vs transmit power for dual Tx, single Tx (1), single Tx (2), 1x2, and 2x2 Alamouti.]
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WiMAX Reed-Solomon Convolutional Coding (AWGN Channel)
WiMAX Reed-Solomon Convolutional Coding (AWGN Channel)
WiMAX Convolutional Turbo Coding (AWGN Channel)
Low Density Parity Check Coding (AWGN Channel)

Throughput [Mbit/s] vs. SNR [dB]

LDPC
CTC
RS-CC
LS and LMMSE Channel Estimation

System model: \( \mathbf{r}(n_t) = \mathbf{T}(n_t) \mathbf{h}(n_t, n_{t'}) + \mathbf{v}(n_{t'}) \)

LS channel estimator: \( \hat{\mathbf{h}}^{\text{LS}} = (\mathbf{T}^H \mathbf{T})^{-1} \mathbf{T}^H \mathbf{r} = \frac{1}{4} \mathbf{T}^H \mathbf{r} \)

LMMSE channel estimator:

\[
\hat{\mathbf{h}}^{\text{LMMSE}} = \arg \min_{\hat{\mathbf{h}}} \mathbb{E} \left\{ \| \hat{\mathbf{h}} - \mathbf{h} \|^2_2 \right\} = \mathbf{R}_{hr} \mathbf{R}_{rr}^{-1} \mathbf{r}
\]

\[
\hat{\mathbf{h}}^{\text{LMMSE}} = \mathbf{R}_{hh} \mathbf{T}^H (\mathbf{TR}_{hh} \mathbf{T}^H + \mathbf{R}_{vv})^{-1} \mathbf{r} = \mathbf{R}_{hh} \left( \mathbf{R}_{hh} + \frac{\sigma_v^2}{4} \mathbf{I} \right)^{-1} \hat{\mathbf{h}}^{\text{LS}} = \mathbf{F} \hat{\mathbf{h}}^{\text{LS}}.
\]

The channel correlation matrix can be estimated as

\[
\mathbf{R}_{hh} = \mathbb{E} \{ \mathbf{h} \mathbf{h}^H \} \approx \hat{\mathbf{R}}_{hh} = \frac{1}{N_c} \sum_{i=1}^{N_c} \hat{\mathbf{h}}^{(i)} \hat{\mathbf{h}}^{(i)H} \quad N_c > N = 100
\]
Channel can be partitioned in the frequency domain:

\[ h = \begin{bmatrix} h_1^T, \ldots, h_M^T \end{bmatrix}^T \quad \text{with} \quad h_m = \begin{bmatrix} h_{L(m-1)+1}, \ldots, h_{L(m-1)+L} \end{bmatrix}^T \]

Estimate mean covariance matrix of size \( L \times L \):

\[
\hat{R}_{hh}^{(L)} = \mathbb{E} \{ h_m h_m^H \} \triangleq \frac{1}{MN_c} \sum_{i=1}^{N_c} \sum_{m=1}^{M} h_{m}^{(i)} h_{m}^{(i)H} \quad MN_c > L
\]

For \( L=10 \) we obtain

\[
M = \left[ \frac{N}{L} \right] = \left[ \frac{100}{10} \right] = 10 \quad \rightarrow \quad N_c \geq 1
\]

Now, calculate a filter matrix from the estimated covariance:

\[
F^{(L)} = \hat{R}_{hh}^{(L)} \left( \hat{R}_{hh}^{(L)} + \frac{\sigma_v^2}{4} I \right)^{-1}
\]
ALMMSE Channel Estimation

This filter can now be used to improve the accuracy of the LS channel estimate:

\[
\hat{h}_n^{\text{ALMMSE}} = \begin{cases} 
F_n^{(L)} \cdot \left[ \hat{h}_1^{\text{LS}}, \ldots, \hat{h}_L^{\text{LS}} \right]^T 
& n \leq \frac{L+1}{2} \\
F_{L+n-N}^{(L)} \cdot \left[ \hat{h}_{n-L-\left\lceil \frac{L-1}{2} \right\rceil}^{\text{LS}}, \ldots, \hat{h}_{n-L-\left\lfloor \frac{L-1}{2} \right\rfloor}^{\text{LS}} \right]^T 
& \text{otherwise} \\
F_{L+n-N}^{(L)} \cdot \left[ \hat{h}_{N-L-1}^{\text{LS}}, \ldots, \hat{h}_N^{\text{LS}} \right]^T 
& n \geq N - \frac{L-1}{2}
\end{cases}
\]
## SNR Gain of Improved Channel Estimators over the LS Estimator

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>LMMSE</th>
<th>genie-driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x1 SISO</td>
<td>0.6dB</td>
<td>1.2dB</td>
</tr>
<tr>
<td>2x1 Alamouti</td>
<td>1.8dB</td>
<td>2.9dB</td>
</tr>
<tr>
<td>1x2 SIMO</td>
<td>0.5dB</td>
<td>1.2dB</td>
</tr>
<tr>
<td>2x2 Alamouti</td>
<td>1.9dB</td>
<td>3.2dB</td>
</tr>
</tbody>
</table>
Conclusions and Outlook

- A huge SNR loss between the measured and the achievable data throughput is caused by
  - the inferior (convolutional) channel coding and
  - by too simple channel estimation techniques (like LS)
- Enhanced channel coding schemes yield up to 5dB SNR gain
- LMMSE channel estimation gains ~2 dB in the case of 2x2 Alamouti transmission
- Future work:
  - Evaluate new measurement data of MIMO WiMAX
  - Capacity analysis for MIMO High Speed Downlink Packet Access
Thank you for your attention.

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