Two-Dimensional Pilot Symbol Aided Channel Estimation for a Broadband MC-CDMA System with High Mobility

of the DoCoMo - DLR Project
“Broadband Air Interface for 4G Mobile Radio Systems”

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COST 289, 3rd MCM, October 30-31, 2003

Outline

- System model
- System parameters to determine the choice of reference symbols
- Pilot symbol aided channel estimation
- MIMO channel estimation
- MIMO techniques
- Simulation results
- Conclusions
System Parameters to Determine the Choice of Reference Symbols

- All channel estimation algorithms need reference symbols: pilot symbols, training sequences, previously decided symbols.
- Choice of reference symbols depend on:
  - the time- and frequency-selective fading of the channel,
  - the subcarrier spacing,
  - the package duration,
  - the total bandwidth.

Example:

- Doppler frequencies: 20 - 1500 Hz (@ 5 GHz)
- time delays: 0.163 - 1.36 µs
- subcarrier spacing: 131.836 kHz
- package duration: ≈ 0.6 ms (64 OFDM Symbols)
- total bandwidth: 101.5 MHz
- Coherence bandwidth: 380 – 960 kHz
- Coherence time: 0.12 - 9 ms

⇒ Pilot symbols as reference symbols.
Pilot Aided Channel Estimation (PACE) by Wiener Filtering

- Arbitrary regular grid, starting point (1,1)
  - Pilot distance in frequency direction: $N_l$
  - Pilot distance between OFDM Symbols: $N_s$
  - Pilot offset: $N_o$

- 2 × oversampling
  - Pilot distance in frequency direction: $N_l \approx \frac{1}{2 \tau_{\text{max}} \Delta F}$
  - Pilot distance between OFDM Symbols: $N_s \approx \frac{1}{4 f_{\text{max}} T_s}$

- Empty symbols
  - Frequency interleaver requires constant number of data symbols per OFDM Symbol

PACE by Wiener Filtering

- Pilot symbols yield initial estimates for the channel transfer function at pilot symbol positions: divide received pilot symbols by the originally transmitted pilot symbols

- Filtering pilot symbols yields final estimates for the complete channel transfer function

- Filter design:
  - knowledge of the Doppler and time delay power spectral densities (PSDs)
    - optimal 2D FIR Wiener filter
  - separable Doppler and time delay PSDs
    - two cascaded 1-D FIR Wiener filters perform similar to 2D FIR Wiener filter
PACE by Robust Wiener Filtering

- In practice, Doppler and time delay PSDs are not perfectly known
  ⇒ robust design assuming rectangular Doppler and time delay PSDs

- SNR for the Wiener filter design can be fixed
  ⇒ no further information about the actual SNR needed during channel estimation
  ⇒ only maximum Doppler frequency, maximum time delay, and average expected SNR need to be known to design robust Wiener filter with model mismatch
  ⇒ performance loss of robust Wiener filter due to model mismatch

PACE by Adaptive Wiener Filtering

- Estimate frequency correlation function
MIMO Channel Estimation

- MIMO channel model assumes independent subchannels between M TX and N RX antennas
  ⇒ M*N independent SISO channel estimators
- M orthogonal pilot patterns are needed
  - M subchannels at 1 RX antenna can be resolved
  - Orthogonal pilots due to spreading codes
    - Additional complexity to restore orthogonal pilots
  - Disjoint pilots frequency
  - Disjoint pilots time

MIMO Techniques (1)

- Space-Time Block Codes
  \[
  B = \begin{bmatrix}
  b_{0,0} & \cdots & b_{0,M-1} \\
  \vdots & \ddots & \vdots \\
  b_{N-1,0} & \cdots & b_{N-1,M-1}
  \end{bmatrix}
  \]
  \[\text{time/frequency}\]

- Space-Time Block Codes from Orthogonal Designs
  Alamouti-Scheme (2x2x2)
  \[
  B_i = \begin{bmatrix}
  x_0 & x_1 \\
  -x_1' & x_0'
  \end{bmatrix}
  \]
  \[R = \frac{K}{N} = 1\]
Cyclic delay diversity

\[
s((k + \delta) \mod N_{FFT}) = \sum_{\ell=0}^{N_{FFT}-1} S(\ell) \cdot \exp\left(j \frac{2\pi}{N_{FFT}} \ell \delta \right) \cdot \exp\left(j \frac{2\pi}{N_{FFT}} \ell k \right)
\]

modified frequency domain signal

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System Parameters & Channel Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>101.5 MHz</td>
</tr>
<tr>
<td>Subcarriers</td>
<td>768</td>
</tr>
<tr>
<td>FFT length</td>
<td>1024</td>
</tr>
<tr>
<td>Sampling duration $T_{sd}$</td>
<td>7.4 ns</td>
</tr>
<tr>
<td>Guard interval $T_{gi}$</td>
<td>226 $T_{sp}$</td>
</tr>
<tr>
<td>Subcarrier spacing $\Delta f$</td>
<td>131.836 kHz</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>7.585 µs</td>
</tr>
<tr>
<td>OFDM symbols / Frame</td>
<td>64</td>
</tr>
<tr>
<td>OFDM Frame duration</td>
<td>0.6 ms</td>
</tr>
<tr>
<td>Modulation</td>
<td>4-QAM</td>
</tr>
<tr>
<td>Coding</td>
<td>Conv. code, R=1/2</td>
</tr>
<tr>
<td>Pilot spacing frequency</td>
<td>3</td>
</tr>
<tr>
<td>Pilot spacing time</td>
<td>9</td>
</tr>
<tr>
<td>Max delay channel estimator</td>
<td>$T_{sp}=226 T_{sp}$</td>
</tr>
<tr>
<td>Max Doppler channel estimator</td>
<td>$0.01/\Delta f$</td>
</tr>
<tr>
<td>$t_{T_{sp}}^{max}$</td>
<td>0.01/\Delta f</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>22 $T_{sp}$</td>
</tr>
<tr>
<td>$N_p$</td>
<td>12</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>1 dB</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>$2 T_{sp}^{16} T_{sp}$</td>
</tr>
</tbody>
</table>

QAM Modulation (1): BER

Parameters:
- Modulation: 4-, 16-, 64-QAM
- Coding: Conv.
- Rate: 1/2
- Spreading size: 8
- Users: 1, 8
- Data symbols/user: 64
- User groups: 1
- Detection: MRC, MMSE
- Freq. interleaving: 1D Random
- Pilot symbol: 1.0
- Pilot distance freq.: 3
- Pilot distance time: 9
- Number pilots freq.: 256
- Number pilots time: 8
- Robust Wiener filter: 15 x 4
- Optimum Wiener filter: 256 x 8
- $\Delta t = 2 T_{sp}$

Error floor for higher QAM alphabets, MMSE detector, and robust Wiener filter
Parameters:

Modulation: 4-, 16-, 64-QAM
Coding: Convol.
Rate: 1/2
Spreading size: 8
Users: 8
Data symbols/user: 64
User groups: 1
Detection: MMSE
Freq. interleaving: 1D Random
Pilot symbol: 1.0
Pilot distance freq.: 3
Pilot distance time: 9
Number pilots freq.: 256
Number pilots time: 8
Robust Wiener filter: 15 x 4
Optimum Wiener filter: 256 x 8
$\Delta t = \frac{T_{spl}}{2}$

Imperfect channel estimation for the MMSE detector causes MAI resulting in an error floor.
Parameters:

- Subcarriers: 768
- OFDM Symbols: 72
- Modulation: 4-QAM
- Coding: Conv.
- Rate: 1/2
- Spreading size: 8
- Users: 1, 8
- Data symbols/user: 96
- User groups: 1
- Detection: MRC, MMSE
- Freq. interleaving: 1D Random
- TX Antennas: 2
- RX Antennas: 1
- Pilot symbol: 1.0
- Pilot distance freq.: 3
- Pilot distance time: 9
- Number pilots freq.: 256
- Number pilots time: 8
- Robust Wiener filter: 15 x 4
- Optimum Wiener filter: 256 x 8
- $\Delta T$: 16 $T_{spl}$

MISO (2): Alamouti

MISO (3): CDD
Parameters:
- Subcarriers: 768
- OFDM Symbols: 72
- Modulation: 4-QAM
- Coding: Conv.
- Rate: 1/2
- Spreading size: 8
- Users: 1, 8
- Data symbols/user: 96
- User groups: 1
- Detection: MRC, MMSE
- Freq. interleaving: 1D Random
- Delay increment: 200
- Pilot symbol: 1.0
- Pilot distance freq.: 3
- Pilot distance time: 9
- Number pilots freq.: 256
- Number pilots time: 8
- Robust Wiener filter: 15 x 4
- Optimum Wiener filter: 256 x 8
- $\Delta t = 16 T_{eq}$

MISO (4): CDD & SISO CE

MISO (5): Alamouti, CDD, CDD & SISO CE
Conclusions

- Pilot aided channel estimation by Wiener filtering
  - Robust Wiener filter
    - 2 dB performance loss compared to perfect channel knowledge
    - Imperfect channel estimation introduces MAI leading to error floors for higher modulation alphabets and MMSE detector
  - Adaptive Wiener filter
    - 0.5 dB performance gain compared to Robust Wiener filter
    - No error floor for higher modulation alphabets

- MIMO System with pilot aided channel estimation
  - CDD
    - SISO Channel estimation: low complexity, limited maximum delay increment
    - MIMO Channel estimation: high complexity, additional MRC error, arbitrary delay increment
    - Slightly improves performance of frequency selective channel
  - Alamouti
    - MIMO Channel estimation
    - Improves performance of frequency selective channel (1.5 dB)

Thank you! Questions?