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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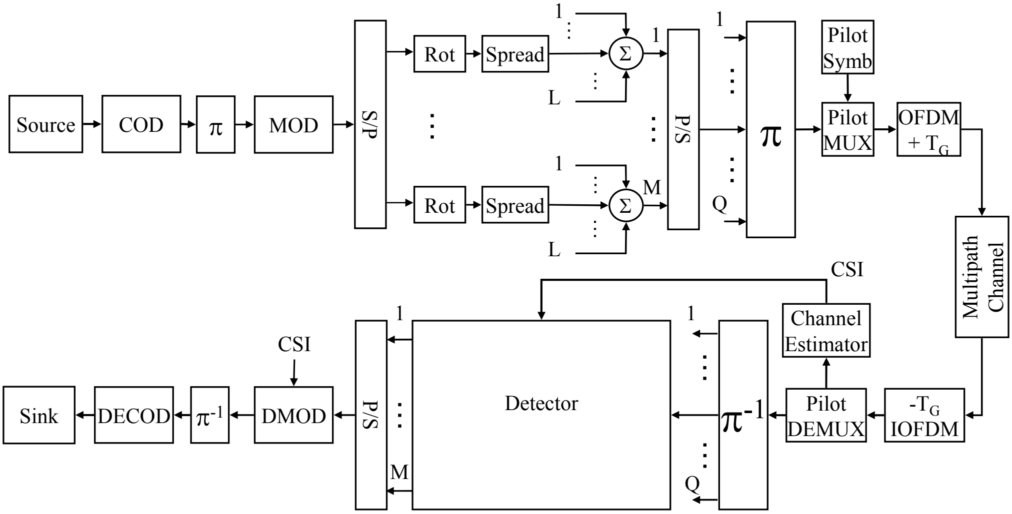
Outline

- 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 Model



System Parameters to Determine the Choice of Reference Symbols

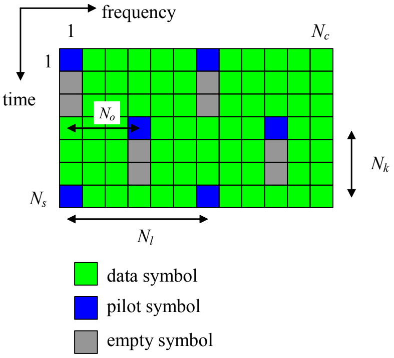
- All channel estimation algorithms need reference symbols: pilot symbols, training sequences, previously decided symbols
- Choice of reference symbols depend on
  - the time- and frequency-selective fading of the channel,
  - the subcarrier spacing,
  - the package duration,
  - the total bandwidth

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_k
  - Pilot offset: N_o
- 2 × oversampling
  - Pilot distance in frequency direction: $N_l \approx 1/(2\ \tau_{\max} \Delta F)$
  - Pilot distance between OFDM Symbols: $N_k \approx 1/(4\ f_{D\max} T_s)$
- Empty symbols
  - Frequency interleaver requires constant number of data symbols per OFDM Symbol



PACE by Wiener Filtering

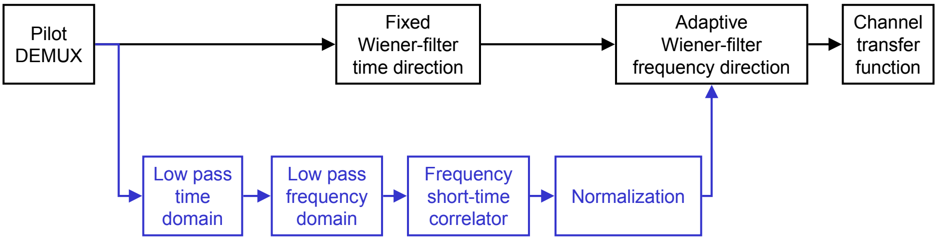
- Pilot symbols yield initial estimates for the channel transfer function at pilot symbol positions: divide received pilot symbols by the originally transmitted pilot symbols
- Filtering pilot symbols yields final estimates for the complete channel transfer function
- Filter design:
  - knowledge of 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

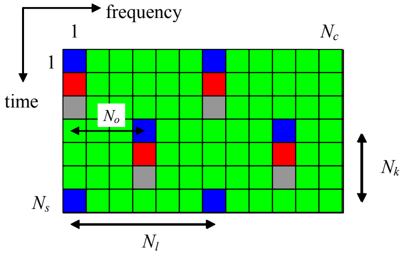
PACE by Adaptive Wiener Filtering

- 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



🟩 data symbol
🟦 pilot symbol, TX 1
🟥 pilot symbol, TX 2
⬜ empty symbol

MIMO Techniques (1)

- **Space-Time Block Codes**

$$\begin{array}{ccc} & \leftarrow \text{space} \rightarrow & \\ B = & \begin{bmatrix} b_{0,0} & \cdots & b_{0,M-1} \\ \vdots & \ddots & \vdots \\ b_{N-1,0} & \cdots & b_{N-1,M-1} \end{bmatrix} & \begin{matrix} \uparrow \\ \text{time/frequency} \\ \downarrow \end{matrix} \end{array}$$

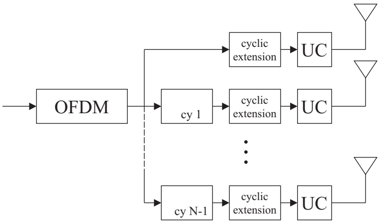
- **Space-Time Block Codes from Orthogonal Designs**

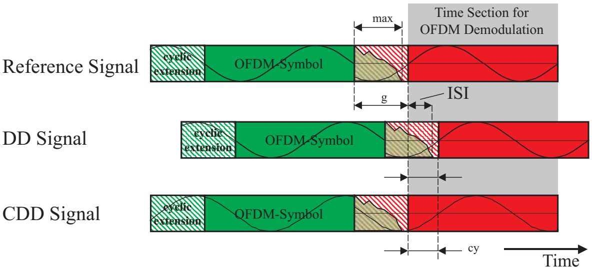
Alamouti-Scheme (2x2x2)

$$B_2 = \begin{bmatrix} x_0 & x_1 \\ -x_1^* & x_0^* \end{bmatrix} \qquad R = \frac{K}{N} = 1$$

MIMO Techniques (2)

- **Cyclic delay diversity**



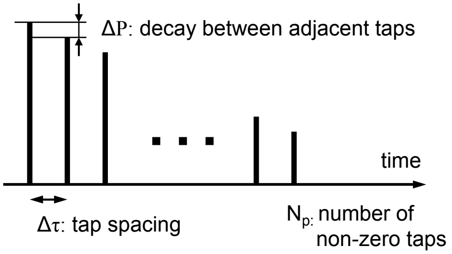


$$s\big((k+\delta)\bmod N_{FFT}\big)=\sum_{\ell=0}^{N_{FFT}-1}\underbrace{S(\ell)\cdot\exp\left(j\frac{2\pi}{N_{FFT}}\ell\delta\right)}_{\text{modified frequency domain signal}}\cdot\exp\left(j\frac{2\pi}{N_{FFT}}\ell k\right)$$

Simulation Results

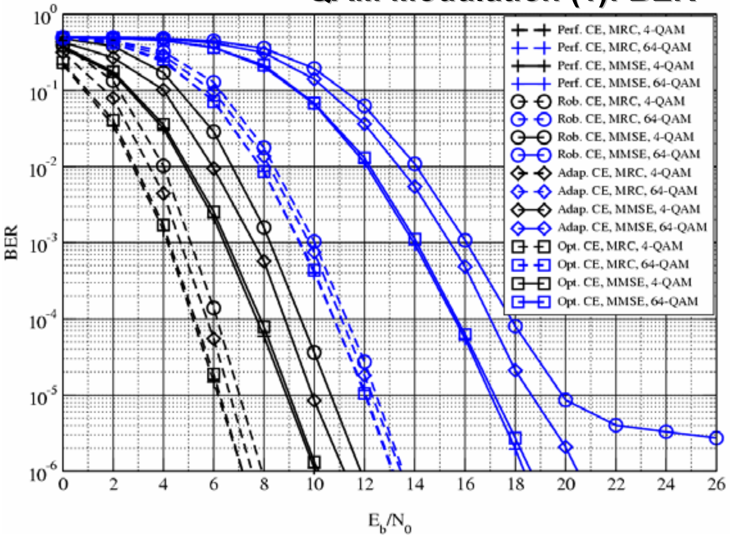
System Parameters & Channel Model

Bandwidth	101.5 MHz
Subcarriers	768
FFT length	1024
Sampling duration T_{spl}	7.4 ns
Guard interval T_{GI}	226 T_{spl}
Subcarrier spacing Δf	131.836 kHz
OFDM symbol duration	7.585 μs
OFDM symbols / Frame	64
OFDM Frame duration	0.6 ms
Modulation	4-QAM
Coding	Conv. code, R=1/2
Pilot spacing frequency	3
Pilot spacing time	9
Max delay channel estimator	T_{GI} =226 T_{sp}
Max Doppler channel estimator	0.01/Δf



$f_{D,max}$	0.01/Δf
τ_{max}	22 T_{spl},176 T_{spl}
N_p	12
ΔP	1dB
Δτ	2 T_{spl},16 T_{spl}

QAM Modulation (1): BER

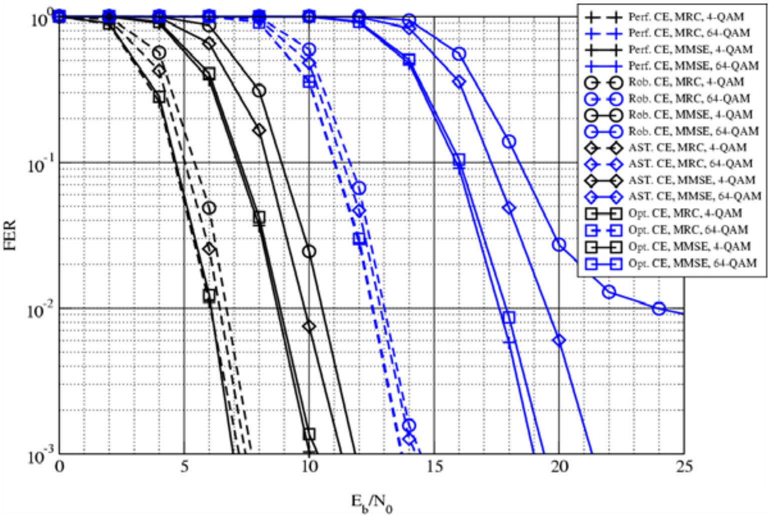


Parameters:

Modulation:	4-, 16-, 64-QAM
Coding:	Convol.
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
Δτ	2 T_{spl}

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

QAM Modulation (2): FER



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
$\Delta\tau$	2 T_{spl}

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

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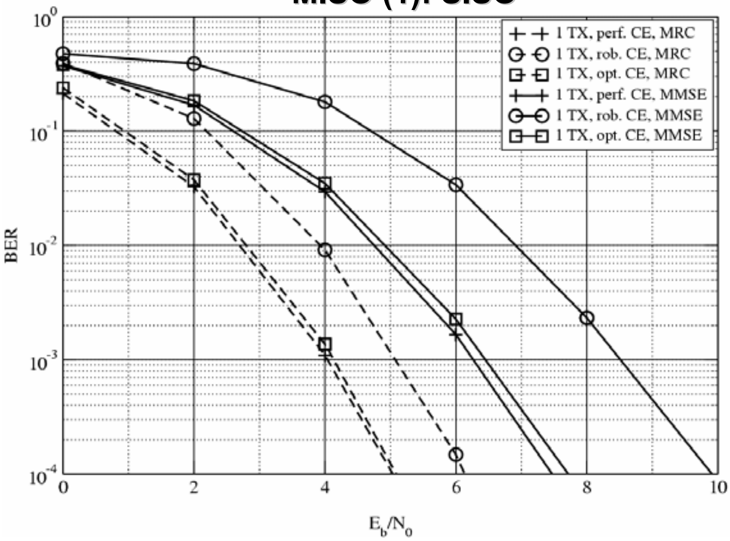
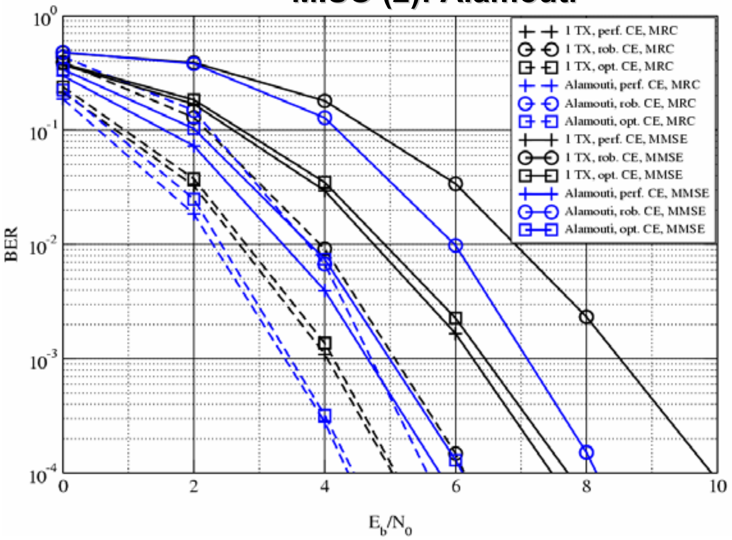
MISO (1): SISO



Parameters:

Subcarriers	768
OFDM Symbols:	72
Modulation:	4-QAM
Coding:	Convol.
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:	1
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
$\Delta\tau$	16 T_{spl}

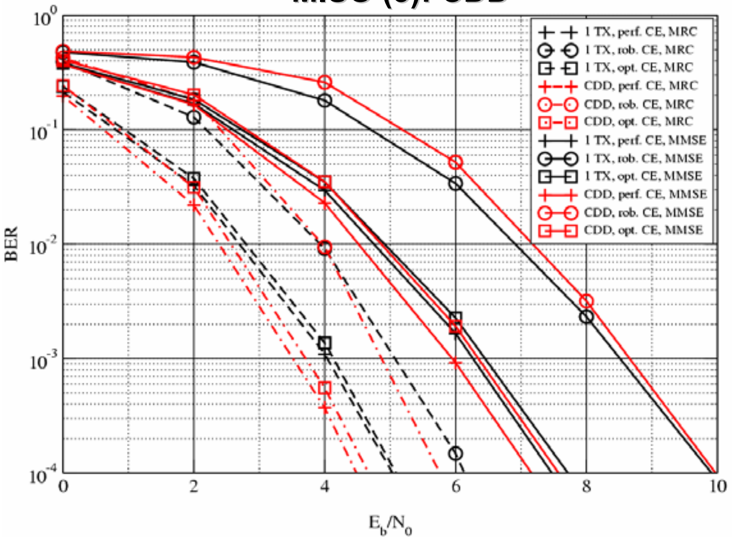
MISO (2): Alamouti



Parameters:

Subcarriers	768
OFDM Symbols:	72
Modulation:	4-QAM
Coding:	Convol.
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
$\Delta\tau$	16 T_{spl}

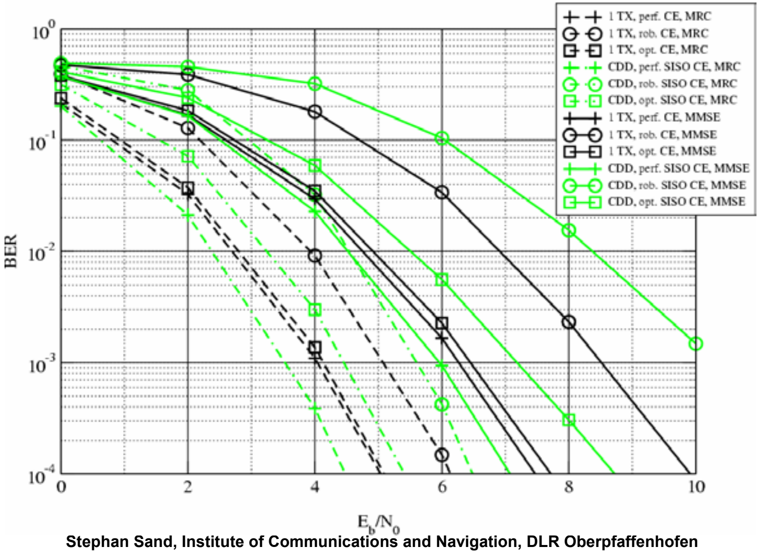
MISO (3): CDD



Parameters:

Subcarriers	768
OFDM Symbols:	72
Modulation:	4-QAM
Coding:	Convol.
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
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
$\Delta\tau$	16 T_{spl}

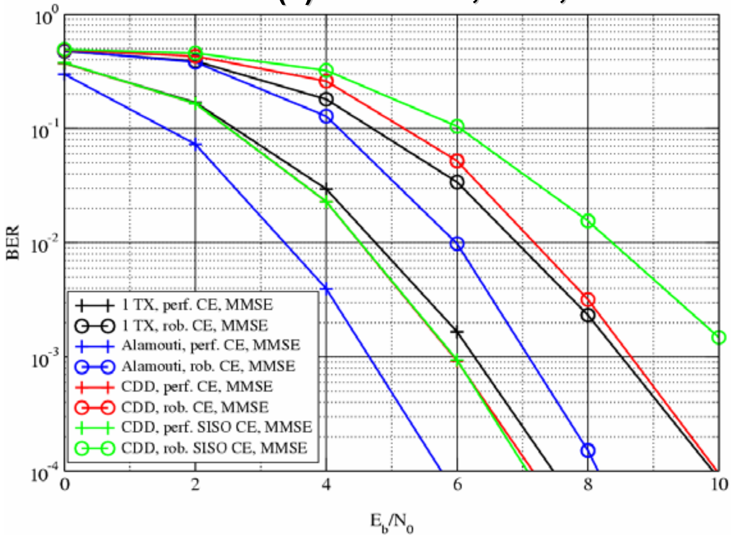
MISO (4): CDD & SISO CE



Parameters:

Subcarriers	768
OFDM Symbols:	72
Modulation:	4-QAM
Coding:	Convol.
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
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
Δτ	$16\ T_{spl}$

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



Parameters:

Subcarriers	768
OFDM Symbols:	72
Modulation:	4-QAM
Coding:	Convol.
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
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
Δτ	$16\ T_{spl}$

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?