Signal processing for Underwater Acoustic MIMO OFDM

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ONR
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Orthogonal frequency division multiplexing (OFDM)

total bandwidth → many narrow subbands→
→ easy equalization in the frequency domain

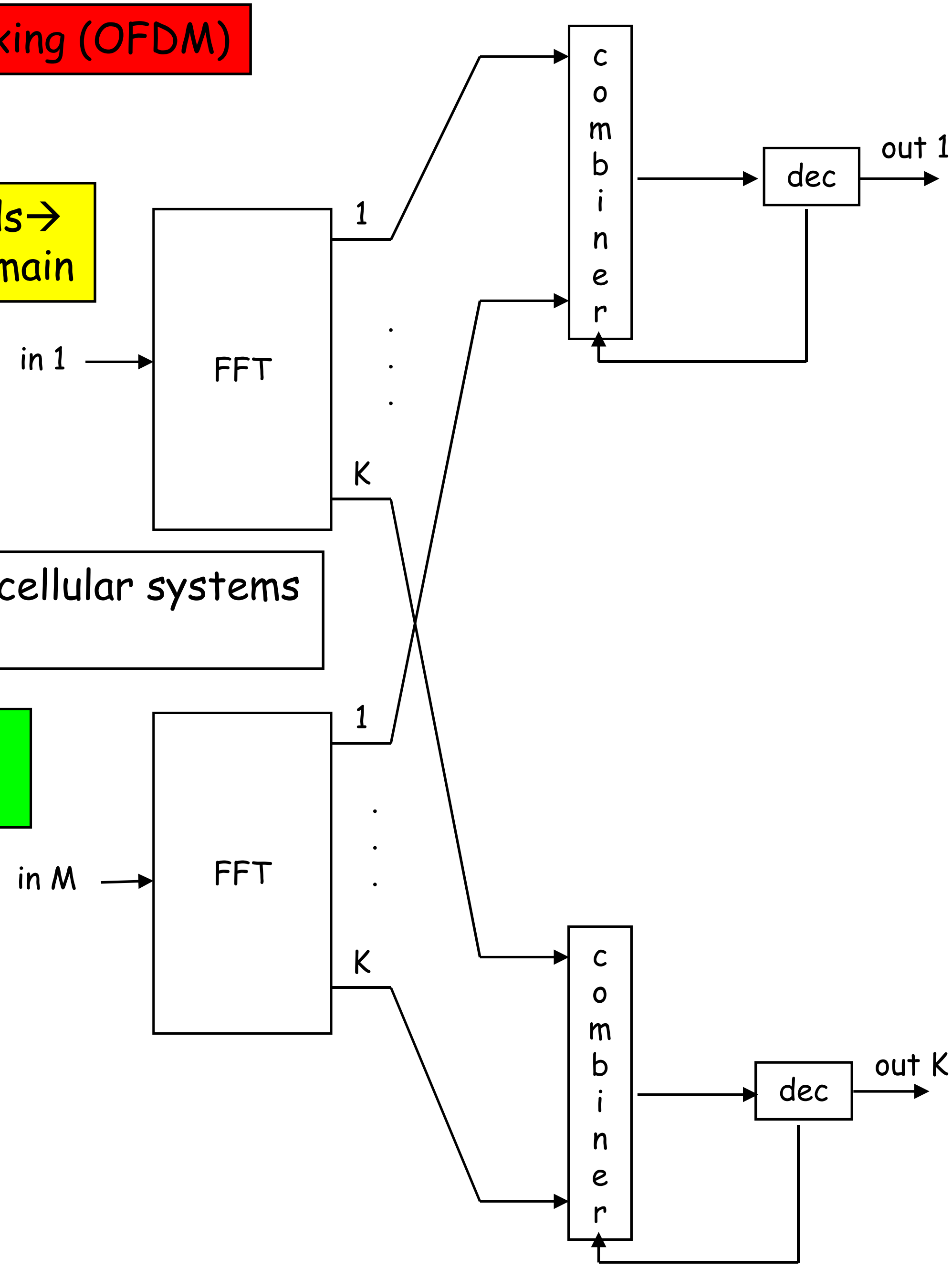
$B=K\Delta f$, $T=1/\Delta f$

$\Delta f \ll 1/T_{mp}$, $T \ll 1/B_d$

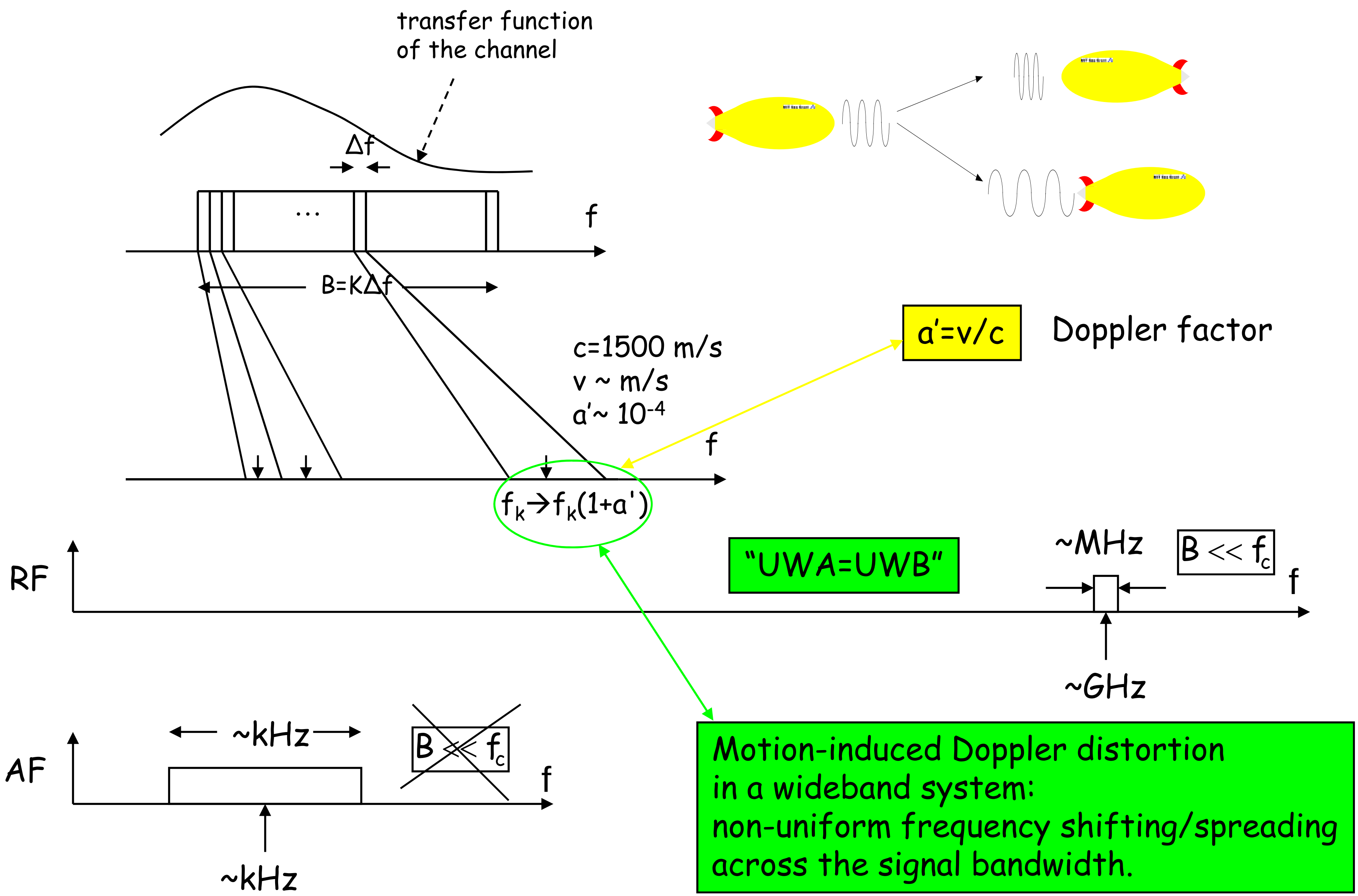
Radio: WLAN,DAB/DVB, 4th generation cellular systems
Acoustic: single-carrier

OFDM: low-complexity, low-maintenance
MIMO: spatial multiplexing

Signal processing:
-synchronization
-channel estimation
-data detection

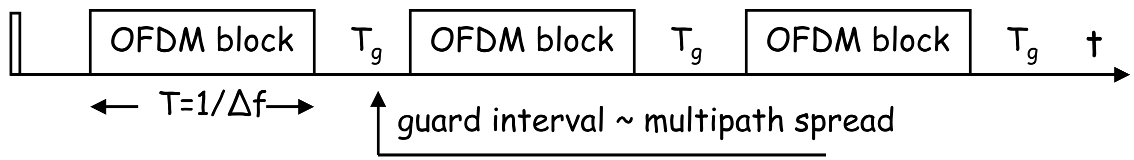


Acoustic (vs. radio) propagation



OFDM: Signal processing check-list

- pre-FFT: initial synchronization (acquisition, resampling)
- post-FFT: phase tracking, channel estimation, data detection



synchronization:
- initial
- tracking

$a' f_k \rightarrow a f_k \ll \Delta f$

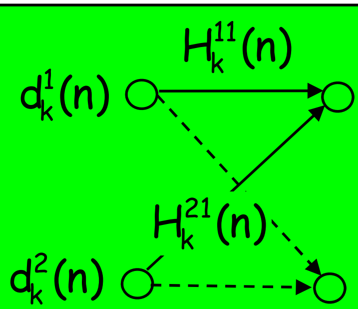
data detection:
- non-adaptive (block-by-block)
- adaptive (block-to-block)

channel estimation:
- transfer function domain
- impulse response domain → full / sparse

configurations/performance:
- multiple receivers: diversity (SIMO)
- multiple transmitters: spatial multiplexing (MIMO)

Experiments:
BB'06
AUV Fest'07
BB VHF'08
RACE'08
SPACE'08

MIMO configuration



$$y_k^1(n) = H_k^{11}(n)e^{j\theta_k^1(n)}d_k^1(n) + H_k^{21}(n)e^{j\theta_k^2(n)}d_k^2(n) + z_k^1(n)$$

$$y_k^2(n) = \ldots$$

not enough observations to estimate the channel in the frequency domain

t,r: transmitter, receiver
k,n: subband, block

goal: exploit frequency correlation in an optimal manner

Signal model

received signal:

$$y_k^r(n) = \sum_{t=1}^{M_T} H_k^{tr}(n)d_k^t(n)e^{j\theta_k^t(n)} + z_k(n)$$

phase:

$$\theta_k^t(n) = \theta_k^t(n-1) + 2\pi a^t(n)f_k T'$$

Data detection

LS

$$\hat{\mathbf{d}}_k(n) = \mathbf{y}_k(n)\hat{\mathbf{H}}_k'(n)[\hat{\mathbf{H}}_k(n)\hat{\mathbf{H}}_k'(n)]^{-1}\hat{\boldsymbol{\Theta}}_k^*(n)$$

Phase synchronization

Doppler factor prediction/estimation

Idea: estimate Doppler factor; infer phase distortions in **all** subbands.
MIMO: a different Doppler factor may be needed for each transmitter.

Assuming an existing estimate of the Doppler factor, predict phase for current block:

$$\breve{\theta}_k^\dagger(n) = \hat{\theta}_k^\dagger(n-1) + 2\pi\hat{a}^\dagger(n-1)f_k T'$$

Use this phase, existing channel, to obtain tentative data decisions;
update Doppler estimate, channel.

$$\psi_k^\dagger(n) \propto \left\langle \hat{d}_k(n)\bar{d}_k^*(n) \right\rangle \qquad \hat{a}^\dagger(n) = \frac{1}{K}\sum_k \frac{\psi_k^\dagger(n)}{2\pi f_k T'} \qquad \hat{\theta}_k^\dagger(n) = \hat{\theta}_k^\dagger(n-1) + 2\pi\hat{a}^\dagger(n)f_k T'$$

Channel estimation: SISO, SIMO

transfer function $H_k(n)$ ← FFT_K → impulse response $h_l(n)$

K coefficients (system parameter)

L(J) coefficients (channel parameters)

- non-adaptive:
  each block detected independently, L pilots per block (L~BTmp)
  performance same as frequency domain estimation with all K symbols known

- adaptive: $\mathbf{y}_k(n) = \mathbf{H}_k(n) e^{j\theta_k(n)} d_k(n) + \mathbf{z}_k(n)$

$$\hat{\mathbf{h}}_l(n+1) = \lambda \hat{\mathbf{h}}_l(n) + (1-\lambda)\mathrm{IFFT}[\mathbf{y}_k(n) e^{-j\hat{\theta}_k(n)} \tilde{d}_k^*(n)]$$

note: channel may be "anti-causal"
insert, not append, zeros before FFT

channel sparsing: keep J strongest taps only. — J/L

data-aided: can use all K symbols per block. — L/K

J/K → MSE reduction

Channel estimation: MIMO

Signal model

L: total multipath spread (contiguous taps [1/B])
J: number of significant taps

$$\mathbf{H}_k(n) = \sum_{l=-A}^{L-1-A} \mathbf{h}_l(n) e^{-j2\pi kl/K}$$

channel coefficients (M_TxM_R)

$$\mathbf{Y}(n) = \sum_{l=-A}^{L-1-A} \mathbf{\Phi}^l \mathbf{D}_\theta(n) \mathbf{h}_l(n) + \mathbf{Z}(n)$$

$\mathbf{Y}(n)$: KxM$_R$; $\mathbf{\Phi}^l$: KxK; $\mathbf{D}_\theta(n)$: KxM$_T$; $\mathbf{h}_l(n)$: M$_T$xM$_R$

this model is crucial for channel estimation

$$\mathbf{Y}(n) = \begin{bmatrix} \mathbf{y}_0(n) \\ \vdots \\ \mathbf{y}_{K-1}(n) \end{bmatrix} \qquad \mathbf{D}_\theta(n) = \begin{bmatrix} \mathbf{d}_0(n)\mathbf{\Theta}_0(n) \\ \vdots \\ \mathbf{d}_{K-1}(n)\mathbf{\Theta}_{K-1}(n) \end{bmatrix} \qquad \mathbf{\Theta}_k(n) = \mathrm{diag}[\theta_k^1(n),\ldots,\theta_k^{M_T}(n)]$$

$$\mathbf{\Phi} = \mathrm{diag}[1, e^{-j2\pi/K}, \ldots, e^{-j2\pi(K-1)/K}]$$

full size model (L)

$$\mathbf{Y}(n) = \boldsymbol{\Delta}(n)\mathbf{h}(n) + \mathbf{Z}(n) \qquad \mathbf{h}(n) \text{ contains all coefficients}$$

$$\boldsymbol{\Delta}(n) = [\boldsymbol{\Phi}^{-A}\mathbf{D}_{\theta}(n) \quad \ldots \quad \ldots \quad \boldsymbol{\Phi}^{L-1-A}\mathbf{D}_{\theta}(n)] \qquad (K\mathrm{x}M_T L)$$

sparse model (J)

$$\mathbf{Y}(n) = \underline{\boldsymbol{\Delta}}(n)\underline{\mathbf{h}}(n) + \mathbf{Z}(n) \qquad \underline{\mathbf{h}}(n) \text{ only significant coefficients}$$

$$\underline{\boldsymbol{\Delta}}(n) = [\boldsymbol{\Phi}^{l_1}\mathbf{D}_{\theta}(n) \quad \ldots \quad \boldsymbol{\Phi}^{l_J}\mathbf{D}_{\theta}(n)] \qquad (K\mathrm{x}M_T J)$$

MIMO channel estimation: some observations

$$\mathbf{Y}(n) = \mathbf{\Delta}(n)\mathbf{h}(n) + \mathbf{Z}(n)$$

If **all** the data symbols are known, **Δ(n)** can be constructed (using phase estimates).

LS estimate (one shot)

$$\hat{\mathbf{h}}(n) = [\mathbf{\Delta}'(n)\mathbf{\Delta}(n)]^{-1}\mathbf{\Delta}'(n)\mathbf{Y}(n)$$

$$K \geq M_T L$$

→for a given number of carriers K, at most K/M_T channel coefficients can be estimated
→for a given channel span L, at least $M_T L$ observations are needed (per receiver)

If only **pilot** symbols are known, corresponding rows are extracted from **Y(n)**, **Δ(n)**, to form a reduced set of observations ($P = M_T L$).

Decision-directed operation: more observations, better channel estimates. Also, less overhead.

"win-win"

...in either case, an $M_T L$ inverse is required...

Channel estimation: initial (LS)

$$\hat{\mathbf{h}}(0) = [\boldsymbol{\Delta}'(0)\boldsymbol{\Delta}(0)]^{-1}\boldsymbol{\Delta}'(0)\mathbf{Y}(0)$$

Make full size initial estimate. Identify significant coefficients, if any (magnitude).
Note: the inverse can be pre-computed (phase estimates are zero at n=0). .

Channel estimation: adaptive

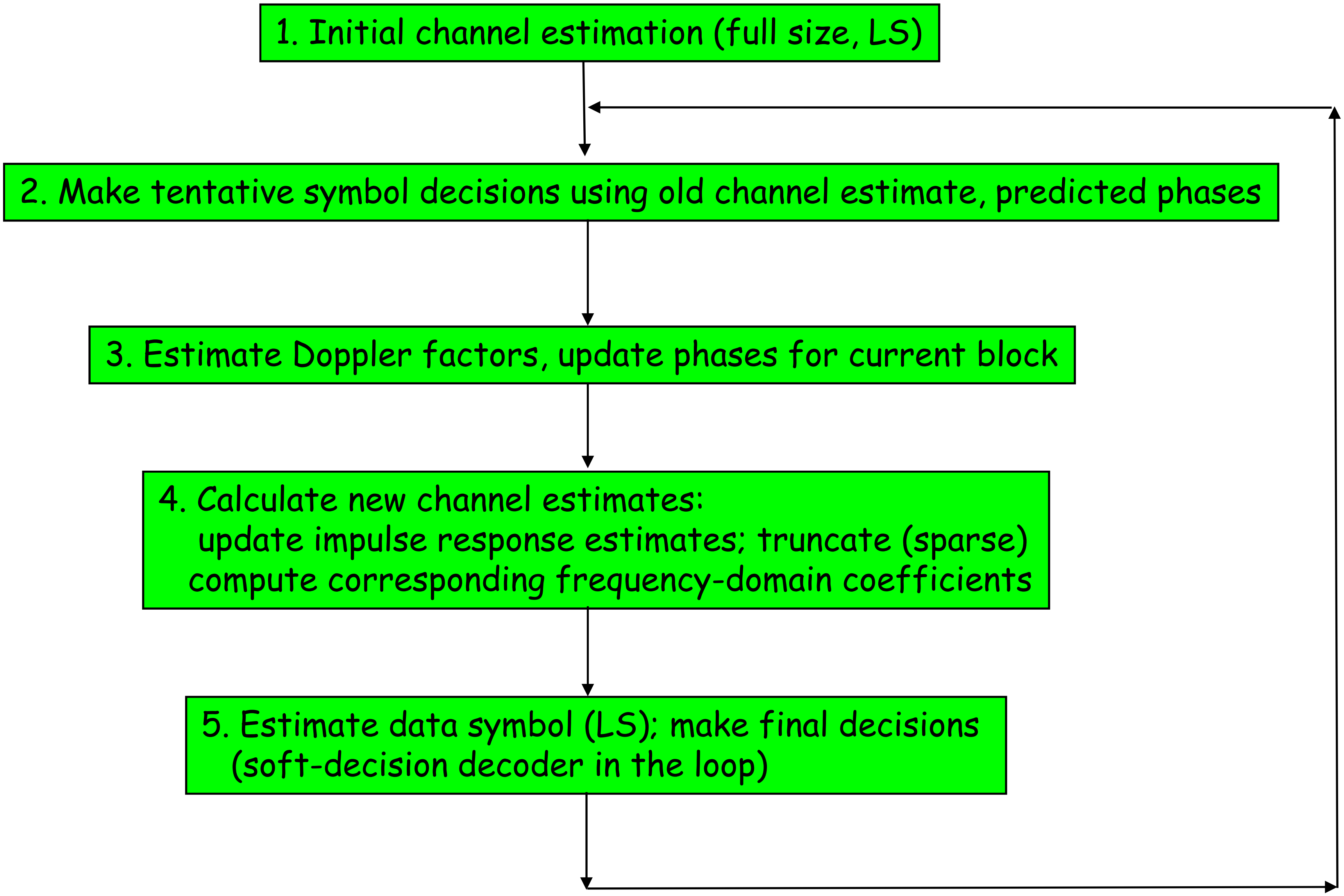
1 $$\underline{\hat{\mathbf{h}}}(n) = \lambda\underline{\hat{\mathbf{h}}}(n) + (1-\lambda)[\underline{\boldsymbol{\Delta}}'(n)\underline{\boldsymbol{\Delta}}(n)]^{-1}\underline{\boldsymbol{\Delta}}'(n)\mathbf{Y}(n)$$

2 $$\underline{\hat{\mathbf{h}}}(n) = \underline{\hat{\mathbf{h}}}(n-1) + \mu\underline{\boldsymbol{\Delta}}'(n)[\mathbf{Y}(n) - \underline{\boldsymbol{\Delta}}(n)\underline{\hat{\mathbf{h}}}(n-1)]$$

Switch to decision-directed mode, and continue to update (reduced-size) estimate.
Note: further sparsing can be performed before data detection.

Alg. 2 can be interpreted as:
-LMS for the in/out relationship $\mathbf{Y}(n)=\boldsymbol{\Delta}(n)\mathbf{h}(n)+\mathbf{Z}(n)$
-Alg. 1 under stochastic approximation $\underline{\boldsymbol{\Delta}}'(n)\underline{\boldsymbol{\Delta}}(n)\approx K\mathbf{I}$ and with $\mu=(1-\lambda)/K$.
Note: this approximation is better justified if all K carriers, not only pilots, are used.

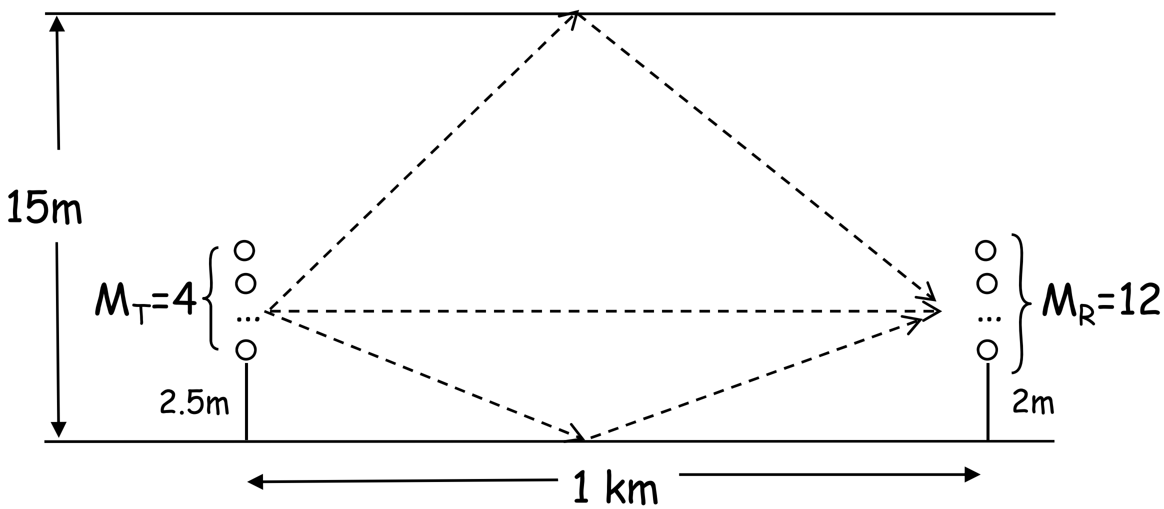
Receiver algorithm



Experiment: SPACE'08

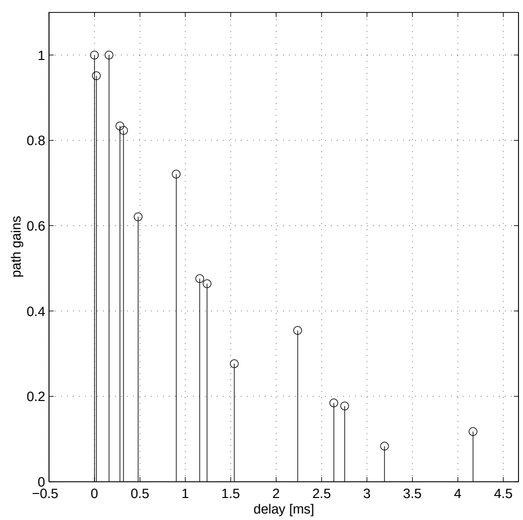
8-18 kHz

South of Martha's Vineyard, October 2008

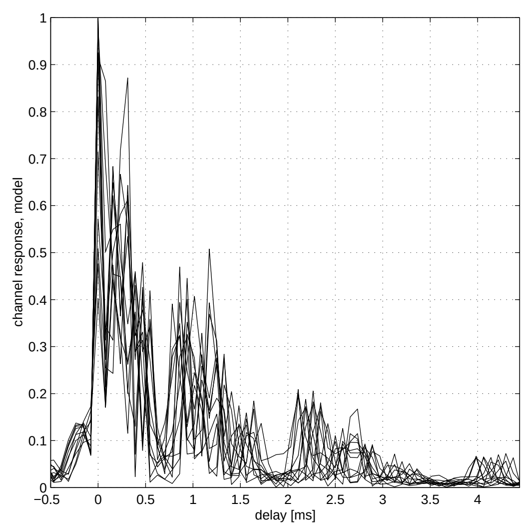


4&8 PSK, BCH(64,10)
B=10 kHz
Tg=16 ms
K=128-1024 carriers
Δf=76-9.5 Hz
T=13-105 ms
N=128-16 blocks
β = 0.86-0.45 sps/Hz/tx

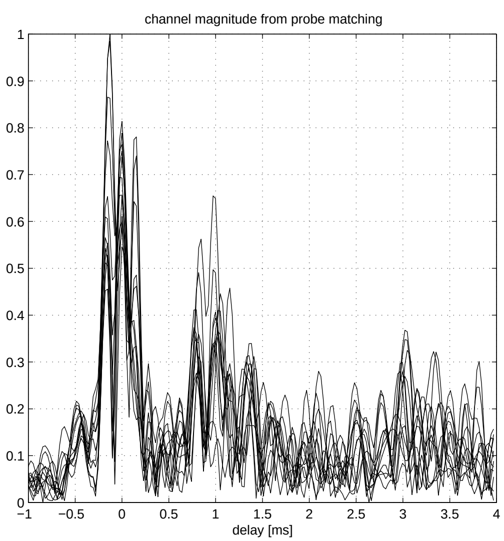
$$\frac{R_b}{B} = M_T \frac{m}{r}\frac{1}{1+\beta} \in \begin{cases} 0.8-7.8 \\ 0.1-1.2 \end{cases}$$



path gains, model



channel response, model



channel response, measured

SPACE'08: example

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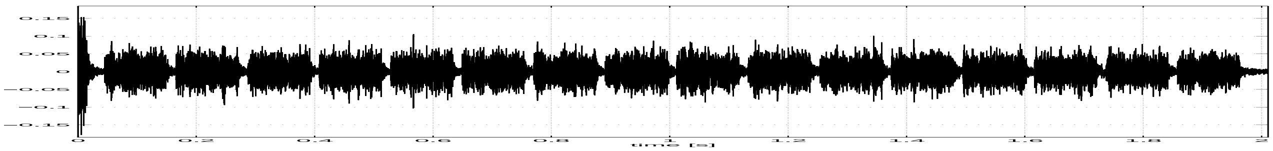
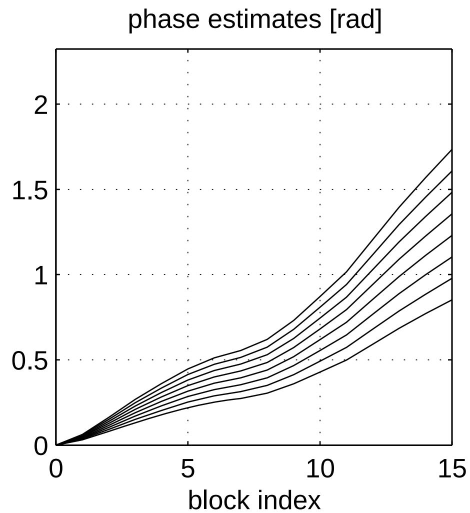
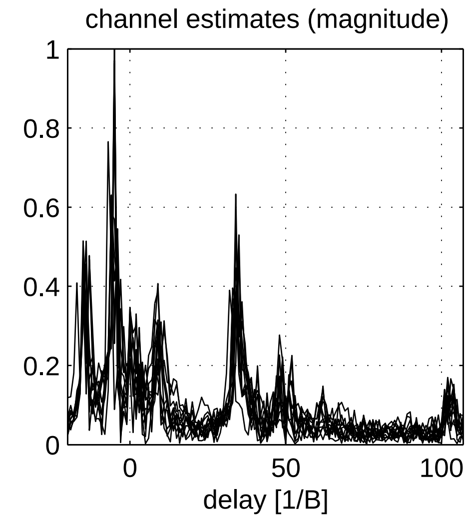
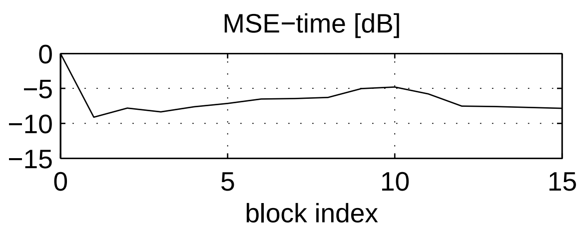
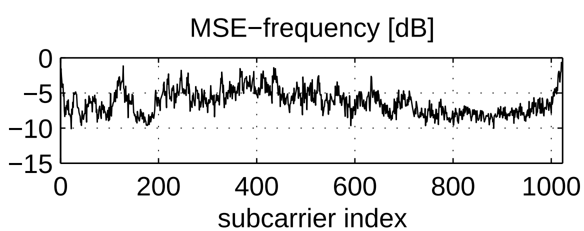
1024 carriers, tx # 1 out of 3, QPSK/8PSK











4−PSK

M_T=3 transmit elements (showing # 1)

M_R=12 receive elements

K=1024 carriers, N=16 blocks

L=128 coefficients per channel (~13 ms)

A=20 coefficients before reference

J=128 significant coefficients

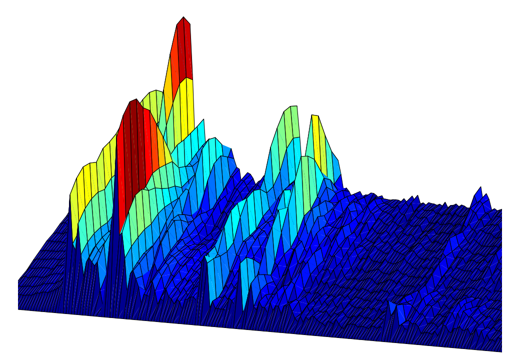
no sparsing

P= 0 pilot channels

μ= 0.0005

overlap add: −3 ms, 7 ms

MSE=−5.9 dB, BER=0 w/BCH (64,10)



SPACE'08: example summary

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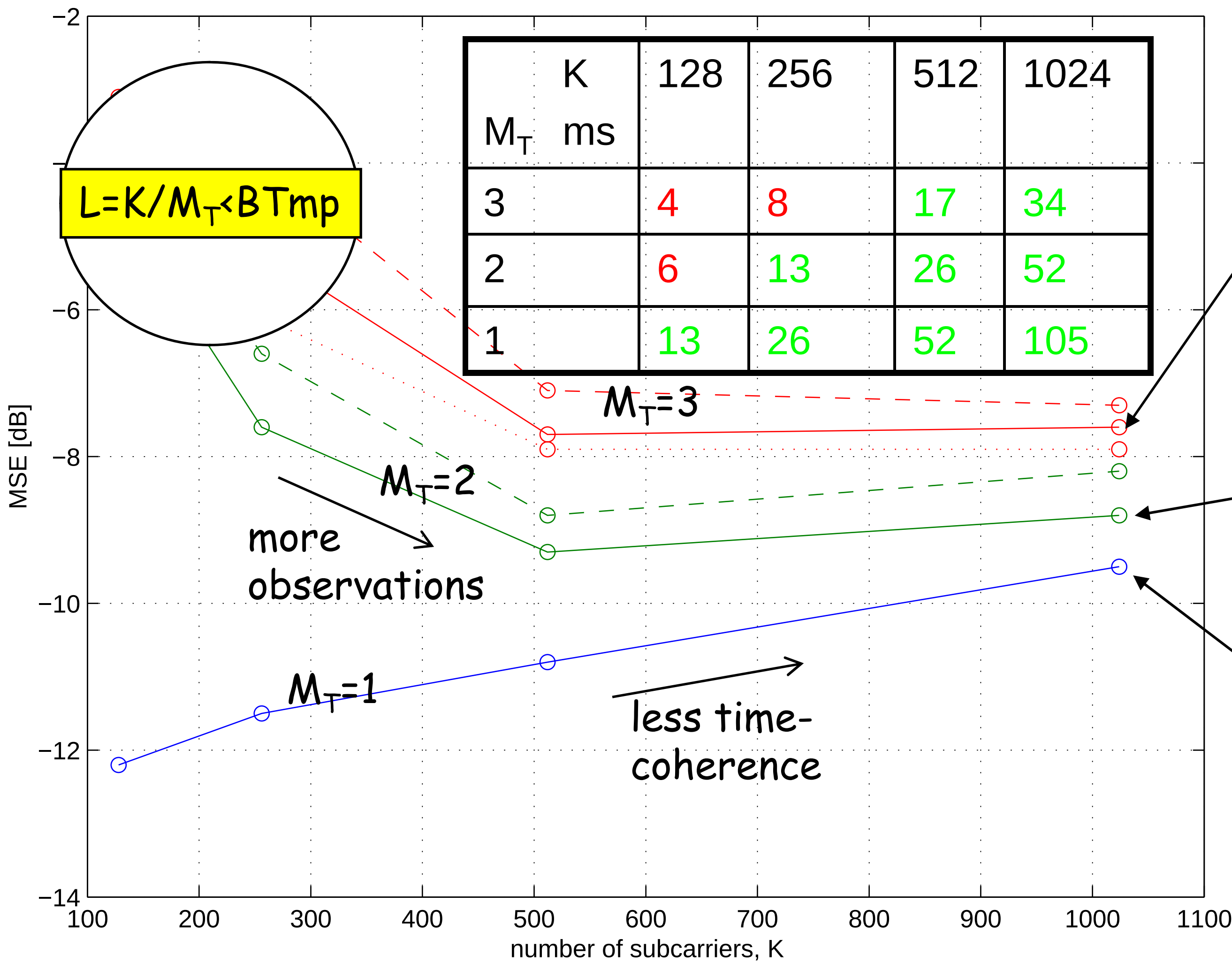
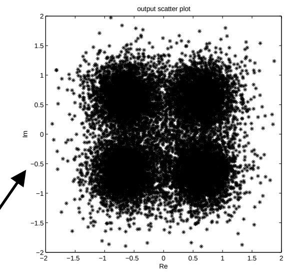
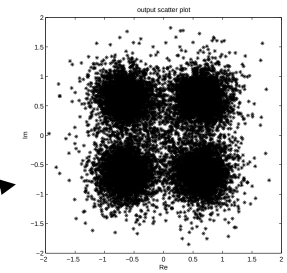
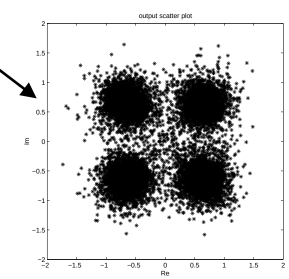


M_T \ K ms	128	256	512	1024
3	4	8	17	34
2	6	13	26	52
1	13	26	52	105







Pushing performance limits: MIMO OFDM bandwidth efficiency

$R/B = M_T / (1+T_{mp}B/K)$ symbols/sec/Hz

Want: M_T , K as large as possible.

($M_T \leq K/L$)

$$R/B \leq \frac{K^2}{LK+L^2} \sim \frac{K}{L}$$

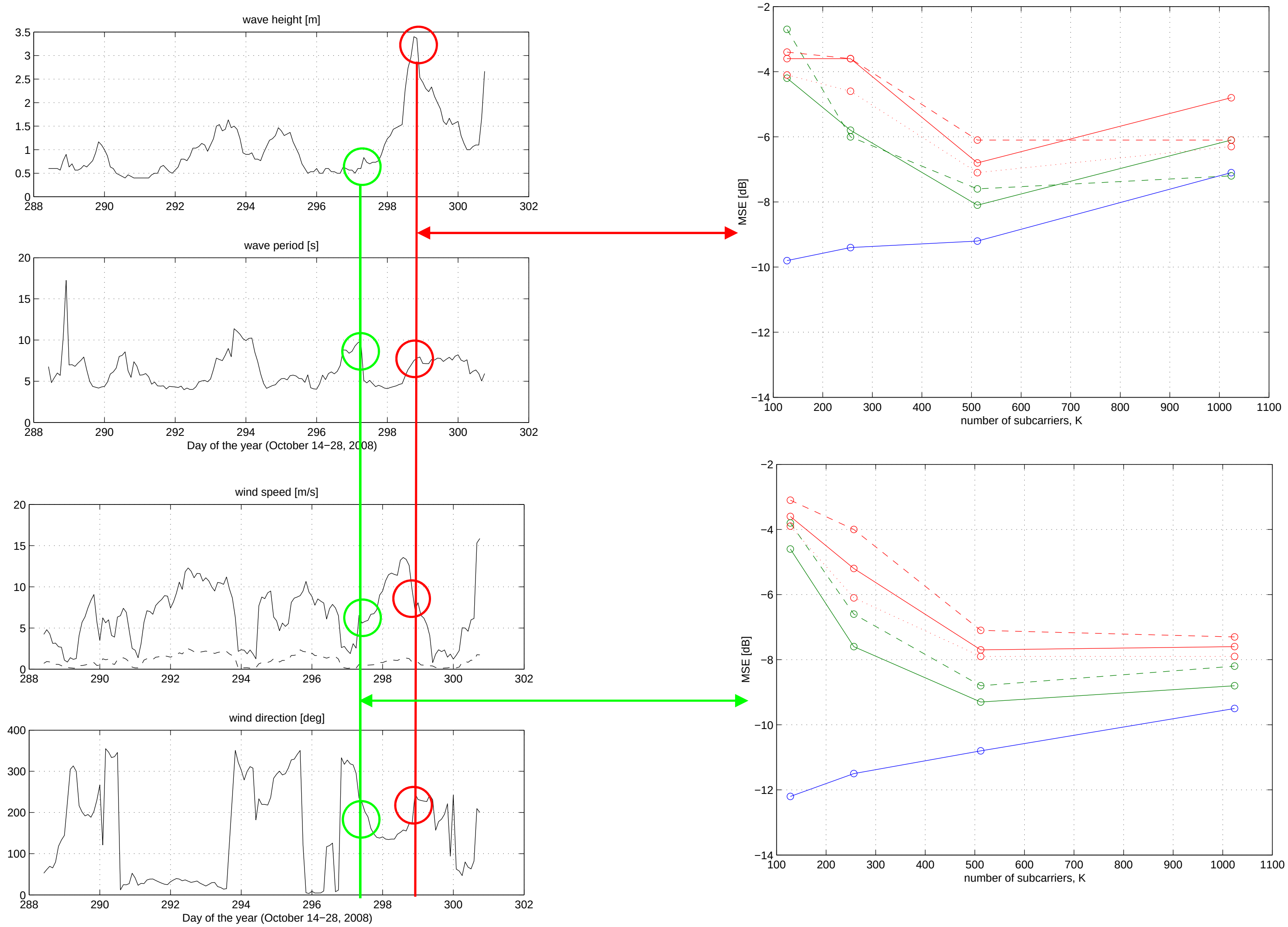
frequency coherence: $\Delta f \ll 1/T_{mp} \rightarrow L \ll K$

Increasing M_T increases cross-talk between channels, size of the estimator; MIMO channel estimation becomes more difficult.

Increasing K increases block duration (T=K/B), tracking becomes more difficult; ICI arises.

Q: What is the performance limit?
Time variability?
Does it "depend on the weather?"

SPACE'08: environmental conditions & performance



Summary

OFDM = low complexity
MIMO = spatial multiplexing

impulse response estimation = optimal exploitation of frequency correlation

phase, channel prediction = decision directed operation =>
=> low (no) overhead; all symbols available for channel estimation.

adaptive algorithms:
1 requires matrix inversion—useful only in reduced-size (J).
2 does not require matrix inversion—can be run in full size too (L).

Design principles:
- choose K as large as time-coherence will permit (win-win)
- choose M_T as large as BER will permit, max. K/L (win-loose)

Future work:
ICI compensation (coherent/differentially coherent, SIMO/MIMO)
long-term channel observation / modeling of time-variation