Multi-Carrier Acoustic Underwater Communications

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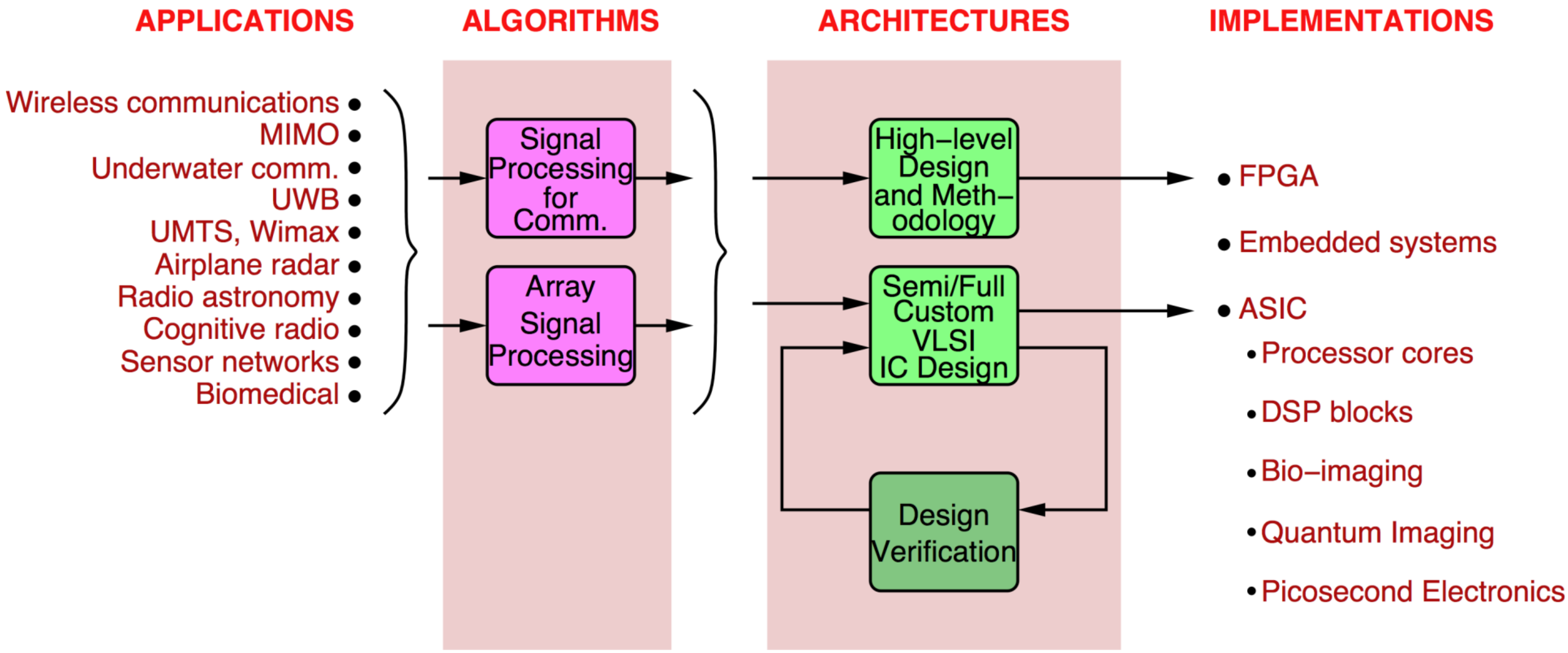
Circuits and Systems Group



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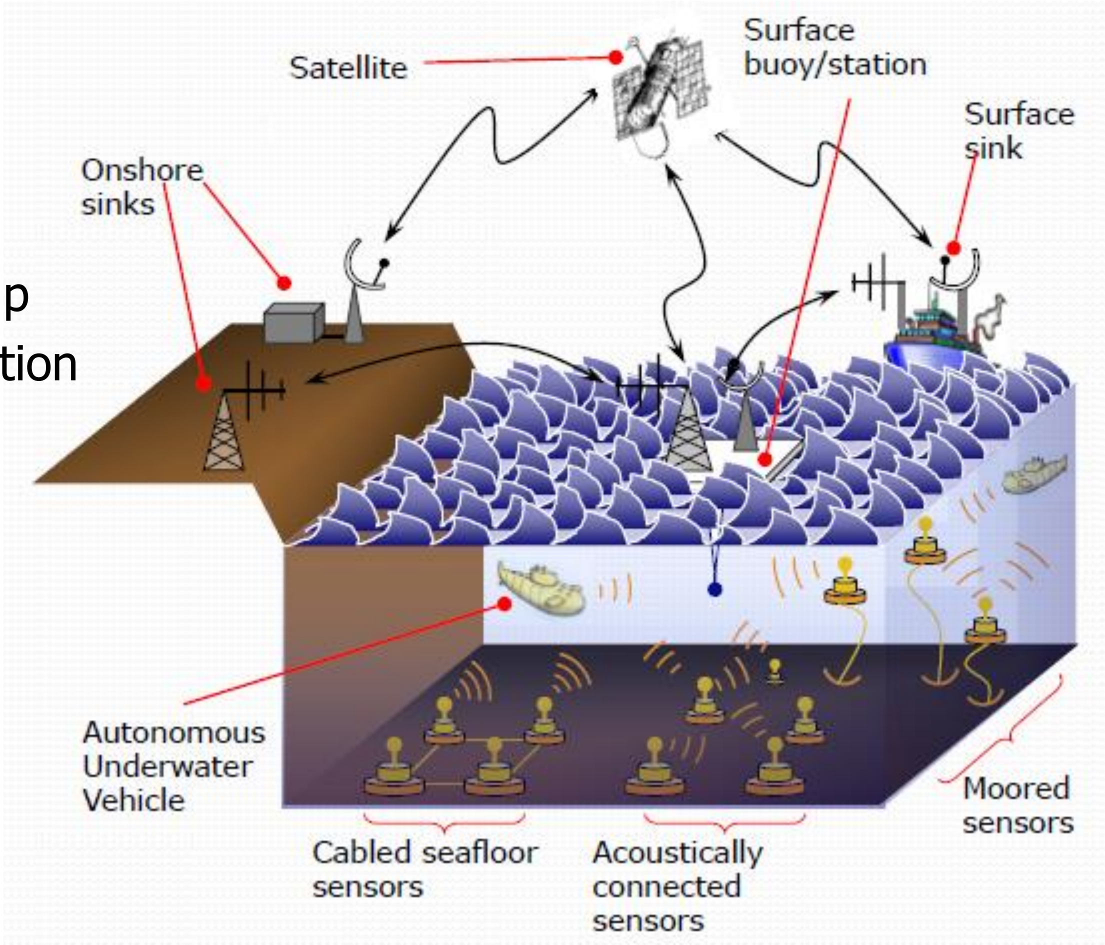
Outline

- Underwater communications
- The UCAC project
- OFDM for underwater communications
  - Channel equalization
  - Channel estimation
  - Extensions
- Application of OFDM to UCAC

Underwater Communications

- Lots of applications
  - Equipment monitoring
  - Patrolling of port/harbor/ship
  - Unmanned vehical coordination
- Different requirements
  - Periodic/bursty data
  - “Real-time” traffic
  - Reliability/disposability
  - Energy efficiency



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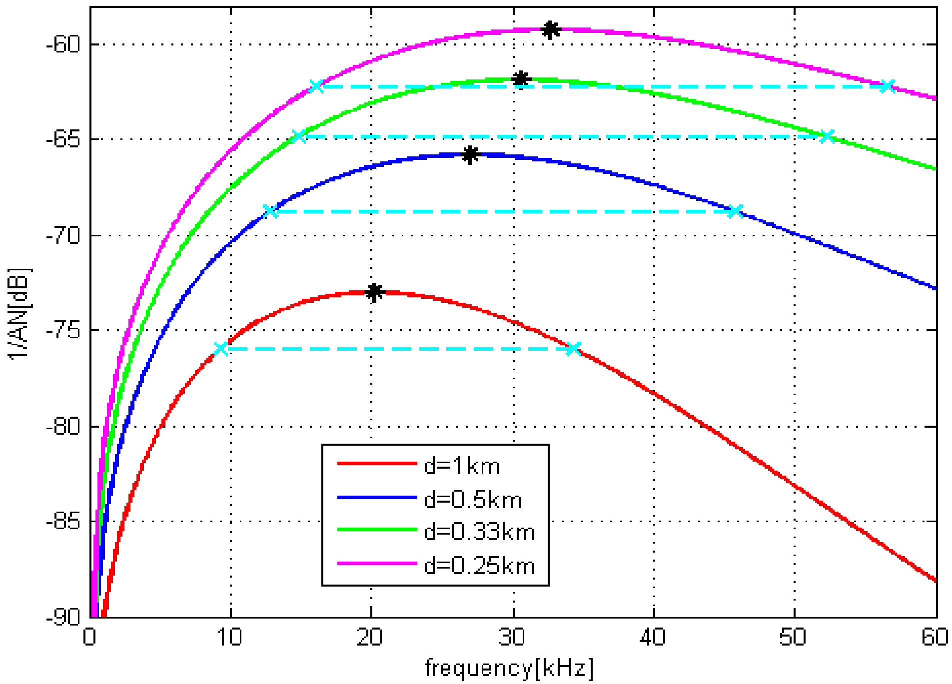
Underwater Communications

- Radio communications
  - Tend to fade rapidly in underwater environments
  - To cover large distances, huge antennas are required
- Optical communications
  - Very high bit rate over short distances
  - High dispersion and attenuation
  - Need for alignment
- **Acoustic communications**
  - Technology of choice today
  - Supports all required transmission ranges

Acoustic Communications

- Low propagation speed (1500 m/s) w.r.t. radio waves
- Severe delay and Doppler spread (especially horizontal)
- Anisotropic propagation in contrast to radio waves
- Frequency-dependent attenuation and noise
- Limited (frequency- and distance-dependent) bandwidth



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Acoustic versus Radio

Radio

- High bandwidth (MHz)
- Short prop. delays (µs)
- Well-understood propagation
- Isotropic propagation
- Distance-independent BW
- Typically white noise
- Small and cheap nodes
- Lots of research done
- Accepted channel models
- Several simulation tools used
- Easy to experiment

Acoustic

- Low bandwidth (kHz)
- Long prop. delays (s)
- Complicated propagation
- Anisotropic propagation
- Distance-dependent BW
- Frequency-dependent noise
- Bulky and expensive nodes
- Less research done
- No comprehensive models
- Lack of simulation tools
- Hard to experiment

The UCAC Project

FWG

„CEPA 10“ Project Nr. 110.060 under the Europe MoU

UUV - Covert Acoustic Communications

Bundeswehr

Participating Nations

Sweden (Lead Nation)

Norway

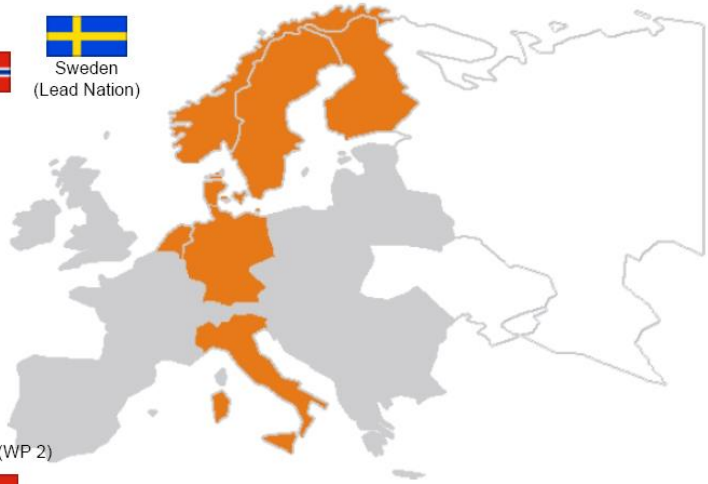
Finland (WP 3)

Denmark

Germany (WP 4)

The Netherlands (WP 2)

Italy (WP1)



project period

planed

01.01.2005 - 31.12.2007

now

16.11.2005 - 15.11.2008

project goal

Identification and demonstration of adequate methods for covert acoustic communications to and from an UUV/AUV operating at large distances from the mother ship (say several tens of kilometers)

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Wolfgang Jans

09.01.2006

Slide 3

Date: 01/2006

UCAC Goals

- Identification and demonstration of adequate methods for covert underwater communications to and from a UUV/AUV at large distances from the mother ship
- 3.6 kHz BW, center frequency 3.3 kHz and 5 kHz
- Tested modulation formats:
  - Spread spectrum – CDMA (Sweden)
  - Multi-carrier modulation – OFDM (The Netherlands)
  - Covert chirp modulation (Italy)
- Channel modeling
- Low-frequency transducer design

UCAC Sea Trials

- Sea trial 1: channel probing
- Sea trial 2: testing different modulation formats
- Sea trial 3: final demonstration of best modulation

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Multi-Carrier Modulation

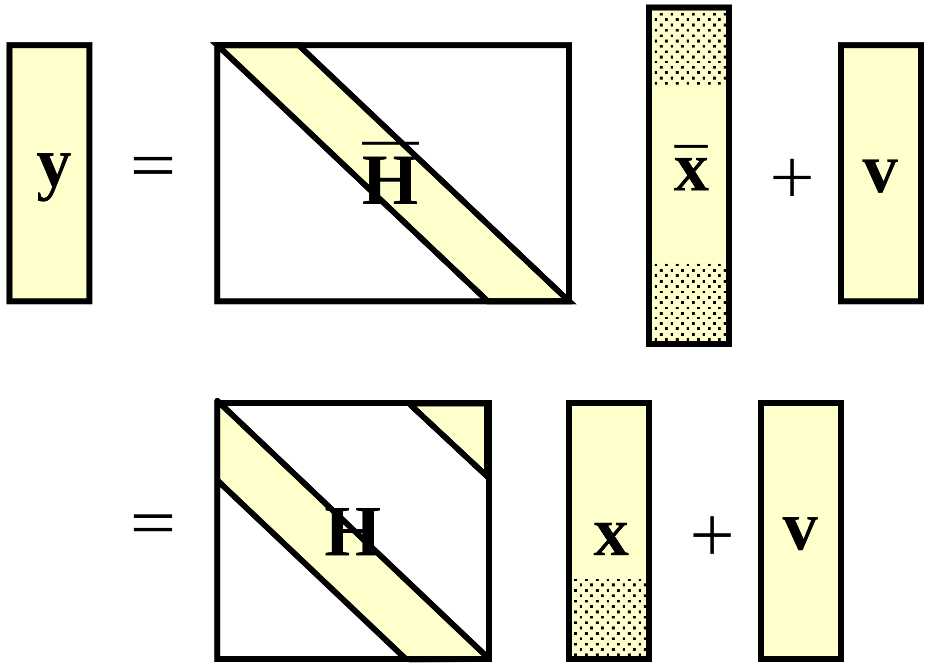
- Different data streams are sent on orthogonal carriers
- Due to time variations, the orthogonality between the carriers is lost and inter-carrier interference (ICI)
- To solve this problem, one can decrease the data rate
- We look for improved low-complexity receivers that
  - do not require a decrease of the data rate
  - can even exploit the extra Doppler diversity
- Focus is on one-shot receivers, that could be used to initialize an iterative receiver architecture

OFDM as Multi-Carrier Modulation

- Input-output relation

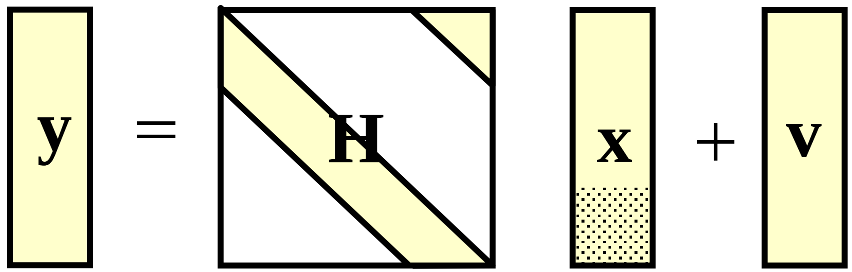
$$y_n = \sum_{l=0}^{L} h_{n,l} x_{n-l} + v_n$$

- Using a cyclic prefix, we get a *circular* convolution

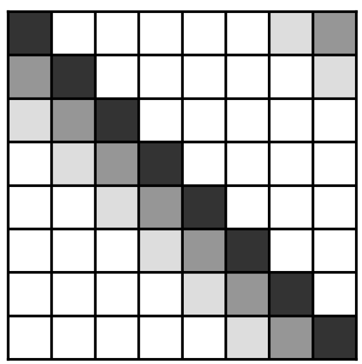


OFDM as Multi-Carrier Modulation

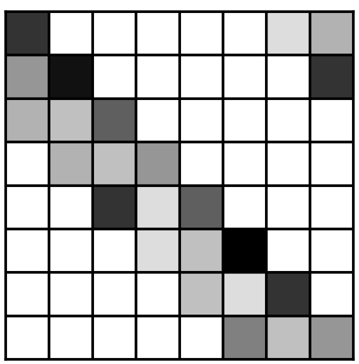
- How does this *circular* convolution look like?



time-invariant channels

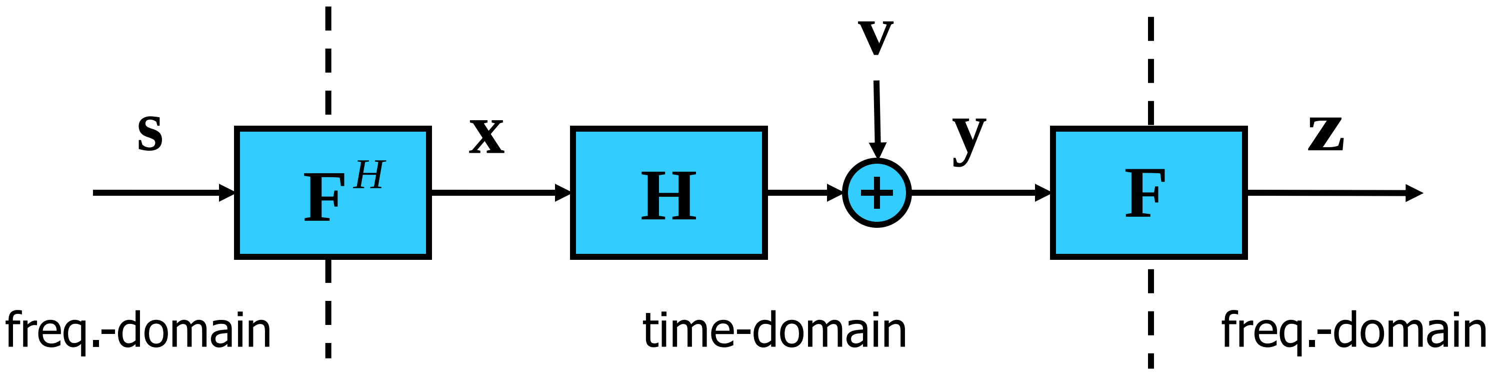
$\mathbf{H} =$ 

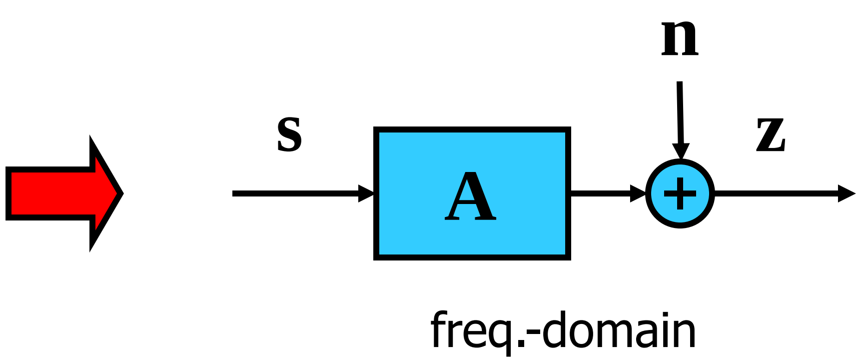
time-varying channels

$\mathbf{H} =$ 

OFDM as Multi-Carrier Modulation

- We take IDFT and DFT at transmitter and receiver:





$$\mathbf{A} = \mathbf{F}\,\mathbf{H}\,\mathbf{F}^H$$

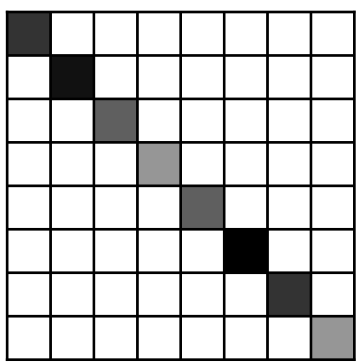
$$\mathbf{n} = \mathbf{F}\,\mathbf{v}$$

OFDM as Multi-Carrier Modulation

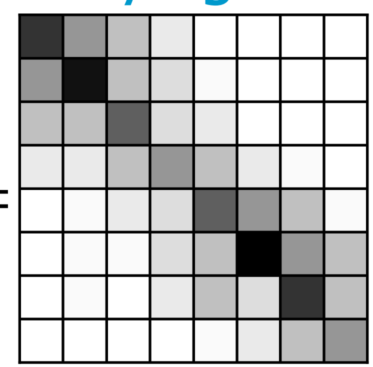
- We assume edge effects are not present:

$$\mathbf{z} = \mathbf{A}\mathbf{s} + \mathbf{n}$$

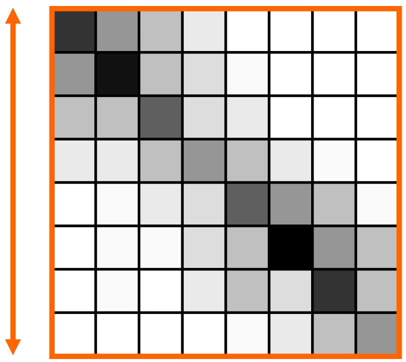
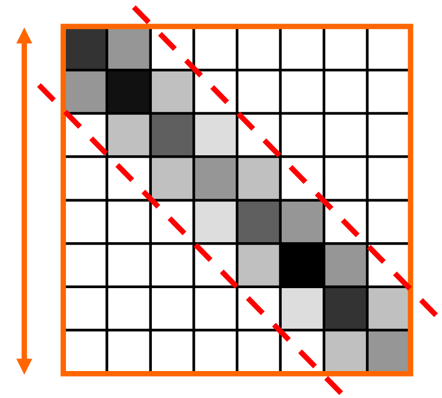
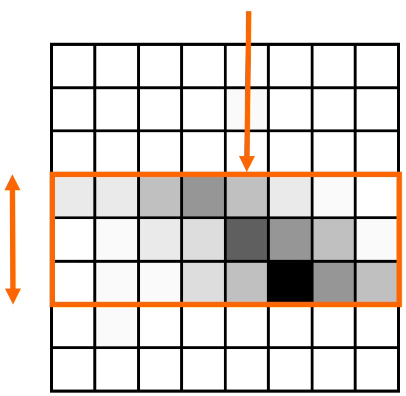
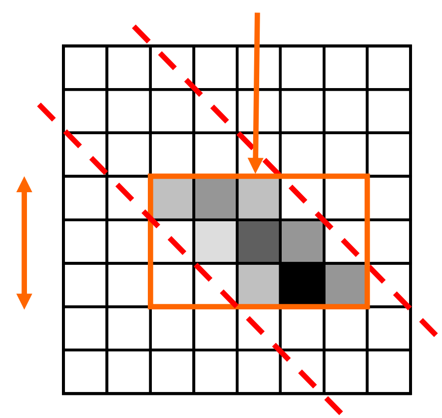
time-invariant channels

$\mathbf{A} =$ 

time-varying channels

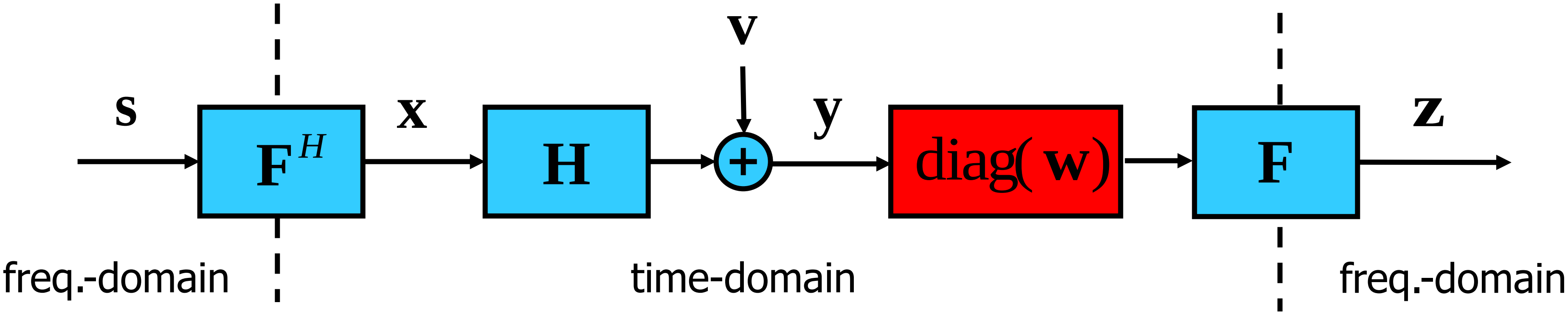
$\mathbf{A} =$ 

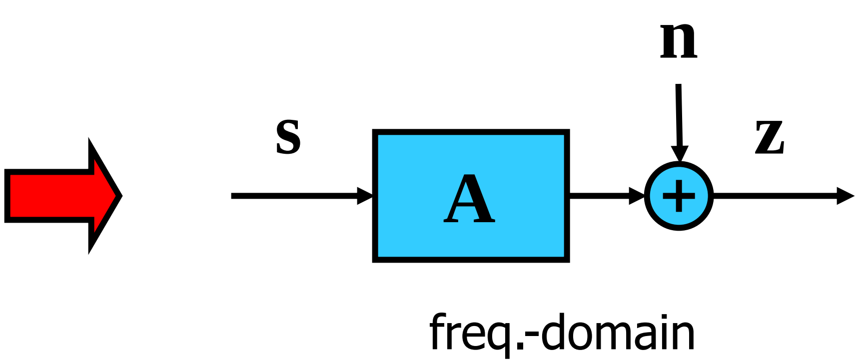
OFDM Equalization

	Non-banded equalizers	Banded equalizers
Block equalizers	 block MMSE non-banded $O(N_A^3)$ [Choi et al, TCOM '01]	 block MMSE banded $O(N_A)$ [Rugini et al, COML '05]
Serial equalizers	 serial MMSE non-banded $O(N_A^2)$ [Cai-Giannakis, TCOM '03]	 serial MMSE banded $O(N_A)$ [Schniter, TSP '04]

Receiver Windowing

- We use windowing to improve the banded assumption





$$\mathbf{A} = \mathbf{F}\,\mathrm{diag}(\mathbf{w})\,\mathbf{H}\,\mathbf{F}^H$$

$$\mathbf{n} = \mathbf{F}\,\mathrm{diag}(\mathbf{w})\,\mathbf{v}$$

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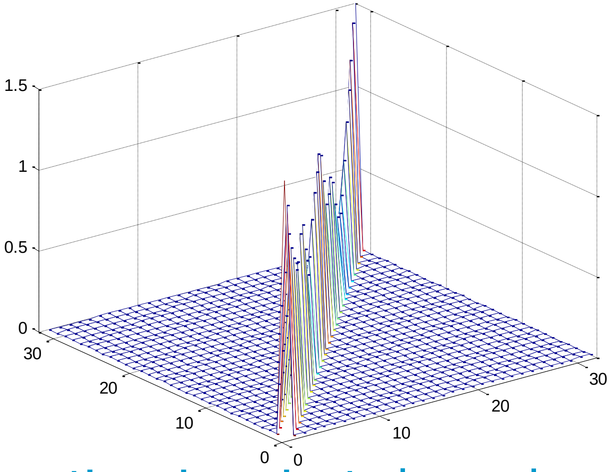
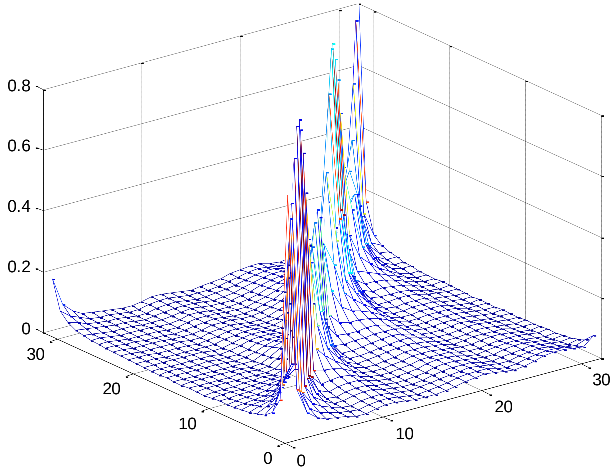
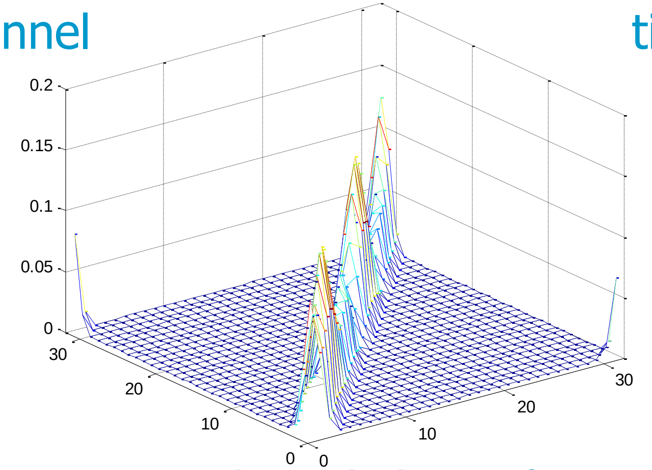
Receiver Windowing



time-invariant channel



time-varying channel



windowed channel

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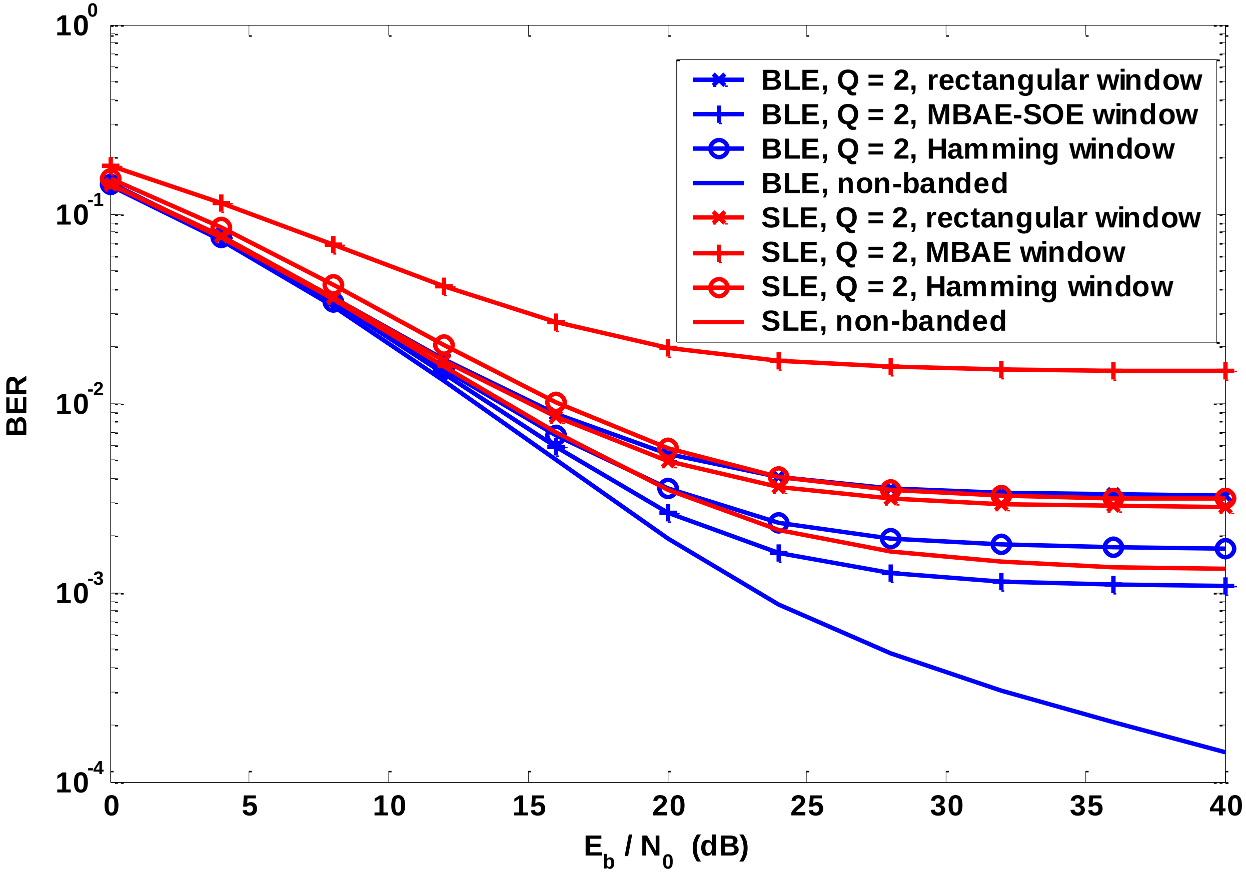
Simulation Results



$N = 128$ subcarriers

$N_A = 96$ active subcarriers

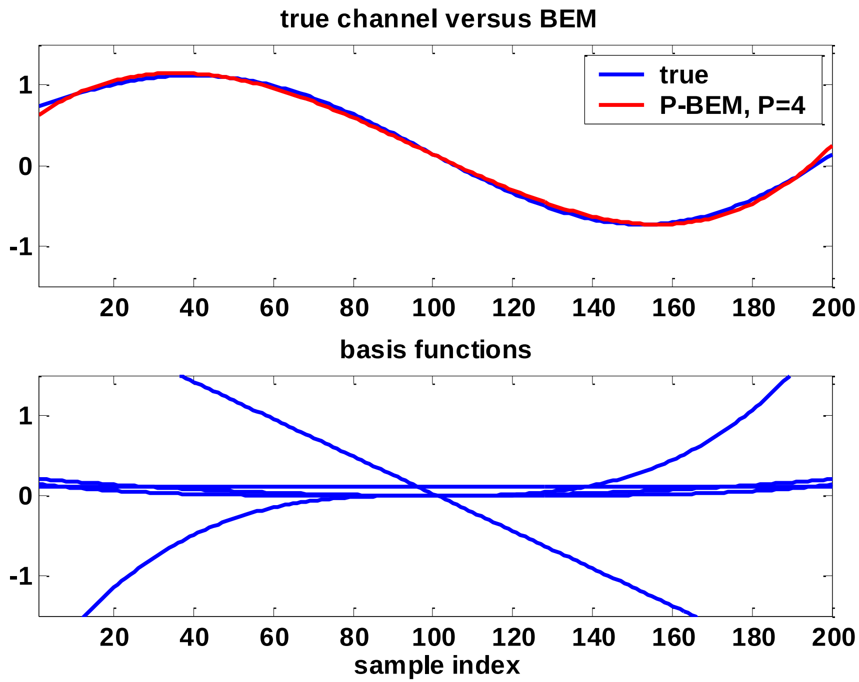
$L = 8$ channel taps

$f_D / \Delta_f = 0.15$ Doppler spread

Channel Estimation

- There are too many unknowns to estimate
- We need a reduced model that exploits the correlation

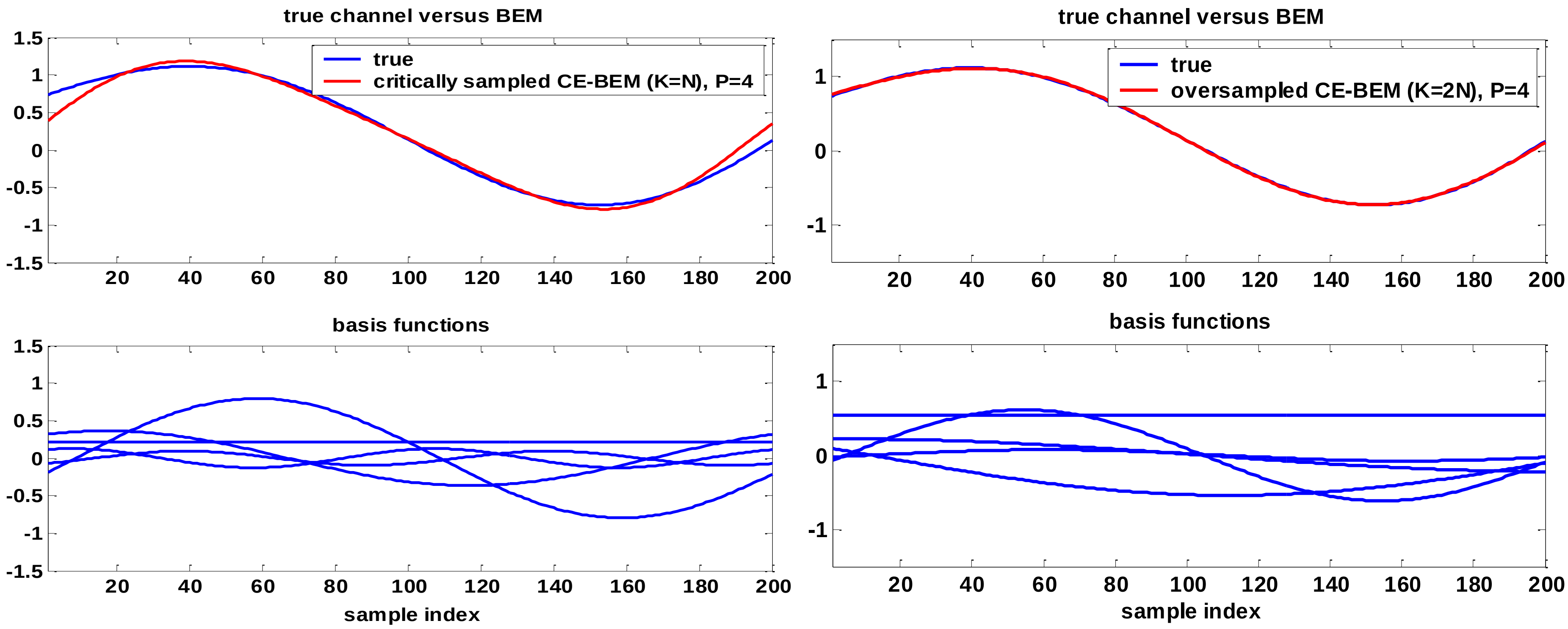
Basis expansion model (BEM)



$$\mathbf{h}_l = \mathbf{B}\,\mathbf{c}_l:\quad \begin{bmatrix} h_{0,l} \\ \vdots \\ h_{N-1,l} \end{bmatrix} = \begin{bmatrix} b_{0,0} & \cdots & b_{0,P} \\ \vdots & \cdots & \vdots \\ b_{N-1,0} & \cdots & b_{N-1,P} \end{bmatrix} \begin{bmatrix} c_{0,l} \\ \vdots \\ c_{P,l} \end{bmatrix}$$

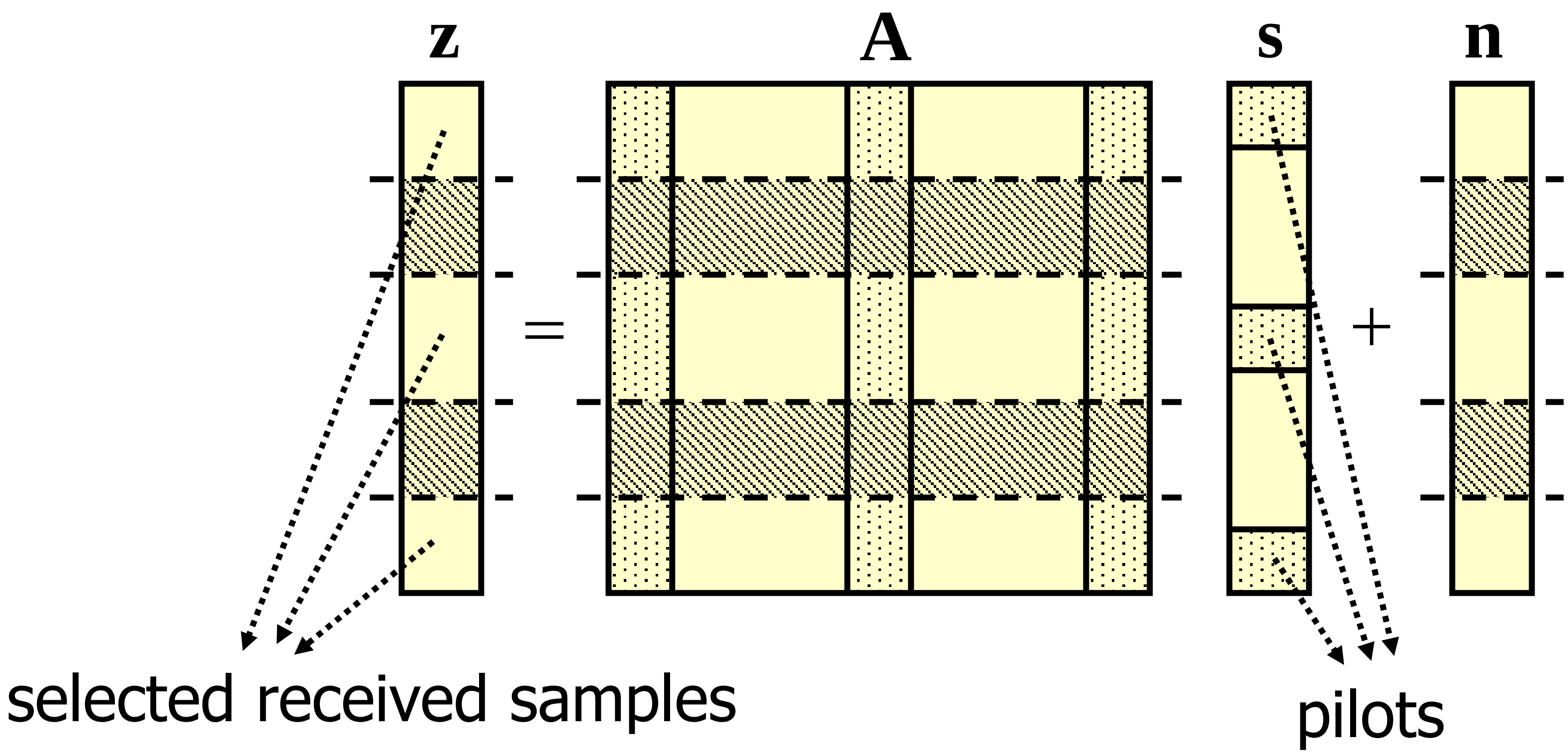
Channel Estimation

- Polynomial BEM: $b_{n,p} = (n - N/2)^p$
- Complex Exponential BEM: $b_{n,p} = \exp(j2\pi(p - P/2)n/K)$



Channel Estimation

- Pilot-aided channel estimation
- Pilots are inserted in the frequency domain



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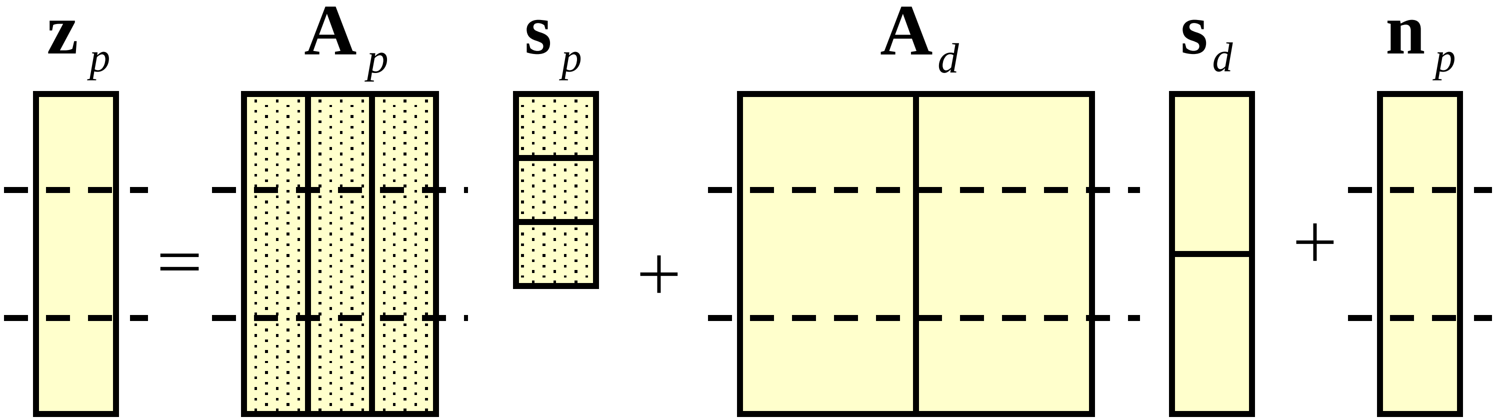
Channel Estimation

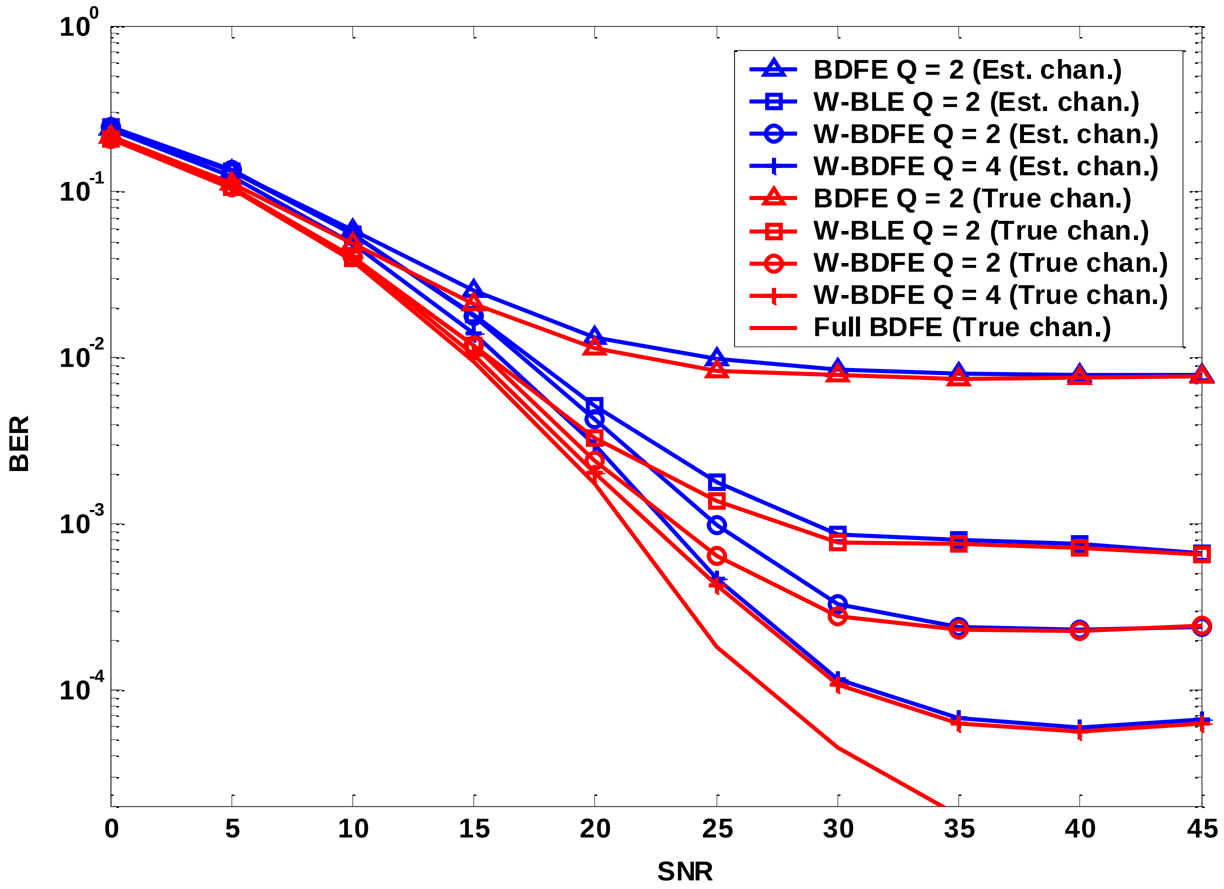
- Grouping the parts related to pilots and data



- The channel matrices $\mathbf{A}_p$ and $\mathbf{A}_d$ linearly depend on the $(L+1)(P+1)$ BEM coefficients $\mathbf{c} = [\mathbf{c}_0^T, \cdots, \mathbf{c}_L^T]^T$

$$\mathbf{z}_p = \mathbf{A}_p \mathbf{s}_p + \mathbf{A}_d \mathbf{s}_d + \mathbf{n}_p \quad \Rightarrow \quad \mathbf{z}_p = \mathbf{S}_p \mathbf{c} + \underbrace{\mathbf{S}_d \mathbf{c} + \mathbf{n}_p}_{\mathbf{i}(\mathbf{c})}$$

Simulation Results



$N = 256$ subcarriers

$N_A = N\text{-}2Q$ active subcarriers

$L = 4$ channel taps

$f_D / \Delta_f = 0.256$ Doppler spread

Channel estimation parameters:

$(L+1)(2Q+1)$ pilots

$(L+1)(2Q+1)$ received samples

$K=2N=512$ resolution CE-BEM

$P=2Q$ basis functions

LMMSE estimator

Extensions

- Banded block decision feedback equalizers
  - Also linear complexity in the block size
  - Can be carried out with and without windowing
- Soft equalizers in combination with channel code
  - Soft versions based on quality of estimates
  - Can run iteratively: turbo equalization
- Channel estimation can be included in the turbo loop
  - Channel estimate improved by soft estimates
  - Pilots can smoothly be incorporated

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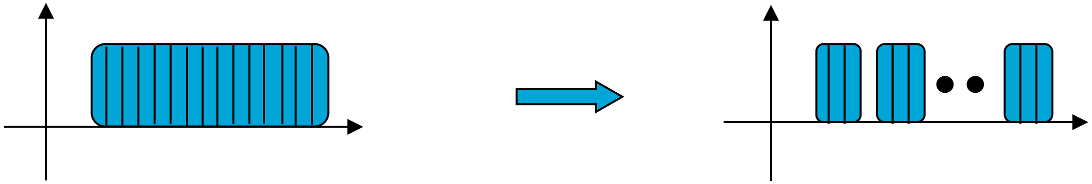
Application of OFDM to UCAC

- Delay spread < 150 ms ⟶ CP length $N_{cp}T$=150 ms
- OFDM period NT=1.2 s ⟶ carrier spacing 0.83 Hz
- 4320 carriers in 3.6 kHz ⟶ N=4320 and N_{cp} =540
- This lead us to the multiband OFDM approach



  - Split large band into J=16 smaller subbands
  - Use OFDM with N=256 and N_{cp} =32 in every subband
  - Use guard of 14 carriers in between subbands
  - This reduces receiver complexity by a factor $J^2=16^2$

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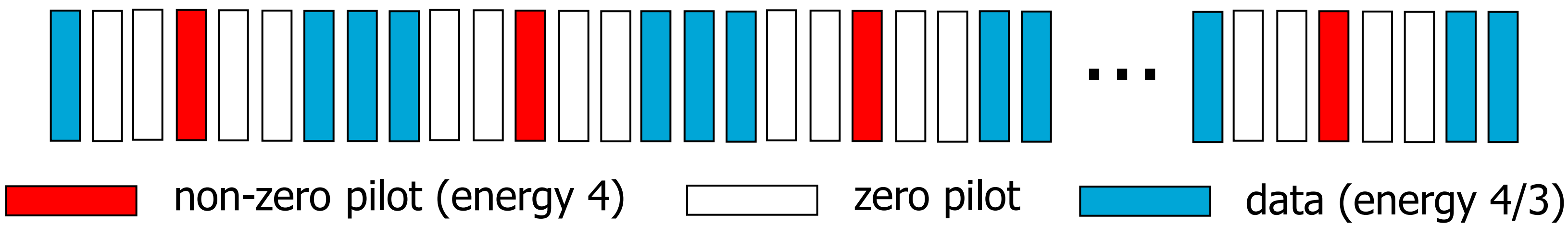
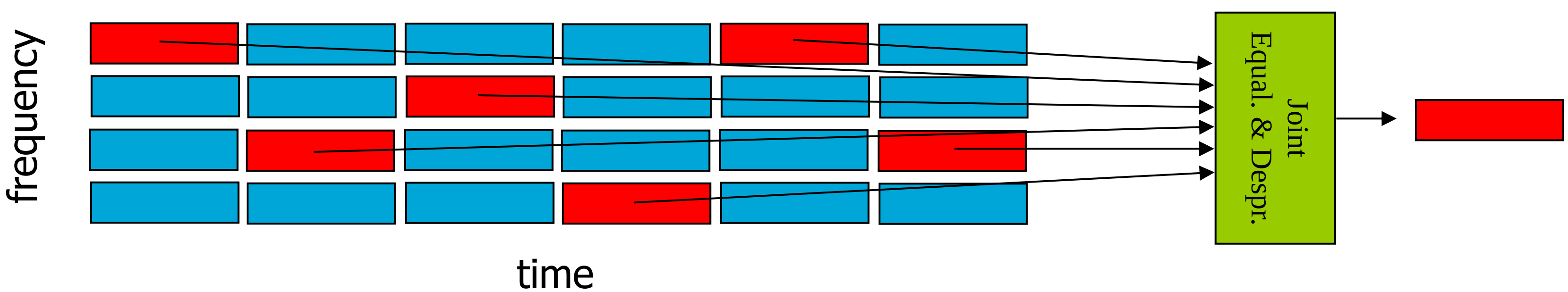
Channel Estimation and Equalization

- Training-based channel estimation
  - 160 pilots out of 256 carriers
  - 32 clusters of length 5



- We use joint equalization and despreading



Low and High Data Rate

- Low data rate (LDR) – 4.2 bit/s
  - Rate-1/3 turbo code: 125 bits -> 384 coded bits
  - 384 coded bits -> 192 QPSK symbols
  - 192 QPSK symbols -> 2 OFDM vectors
  - 1 block repeated in I=21 slots and J=16 subbands
- High data rate (HDR) – 78 bit/s:
  - Rate-1/3 turbo code: 637 bits -> 1920 coded bits
  - 1920 coded bits -> 960 QPSK symbols
  - 960 QPSK symbols -> 10 OFDM symbols
  - 3 blocks repeated in I=17 slots and J=16 subbands

Sea Trial 2

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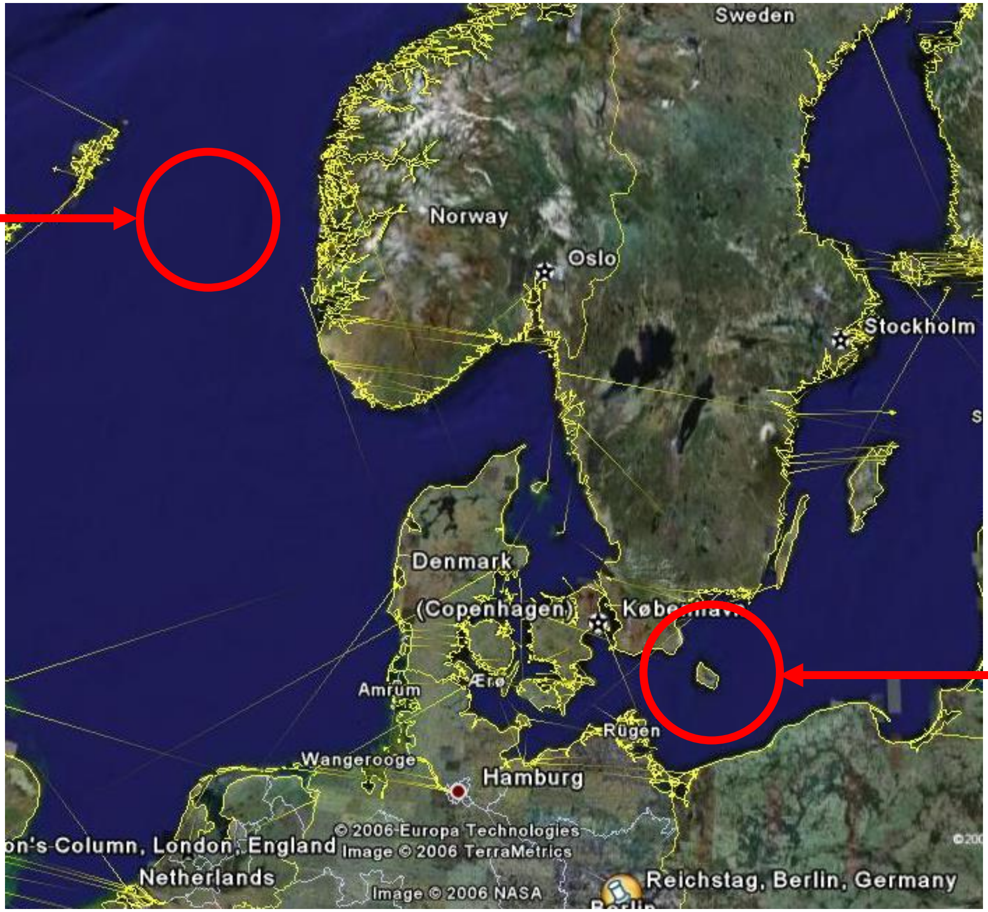
Sea Trial 2

<u>Case B:</u>
North Sea
f_c= 5kHz
TX @ 60m
RX @ 90m
TX towed
at 2.5 m/s
with fixed
source level
from 8 to 38km



<u>Case A:</u>
Baltic Sea
f_c=3.3kHz
TX @ 40m
RX @ 50m
TX fixed with
source level
changing in
steps of 2dB
at 8 and 52km

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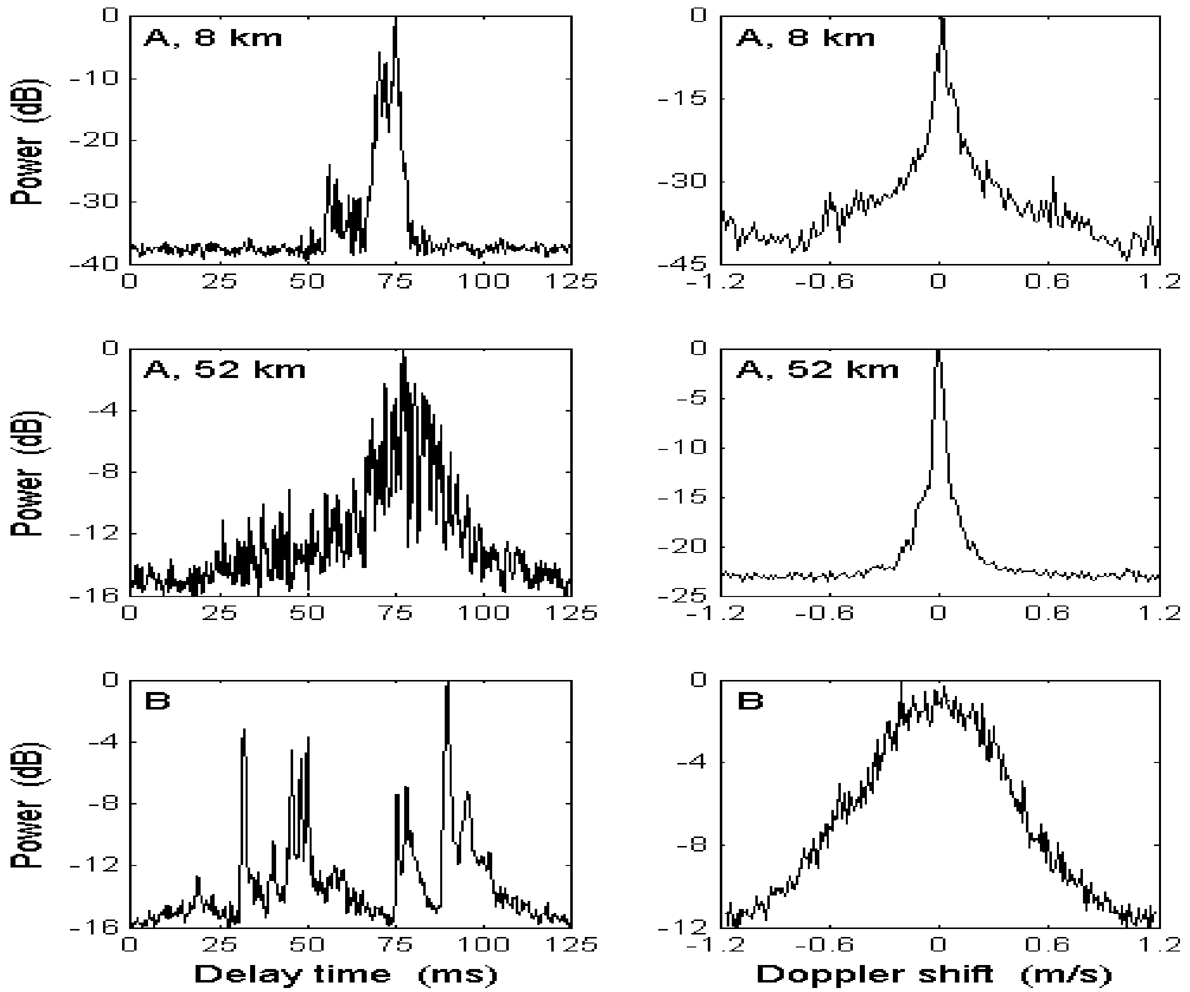
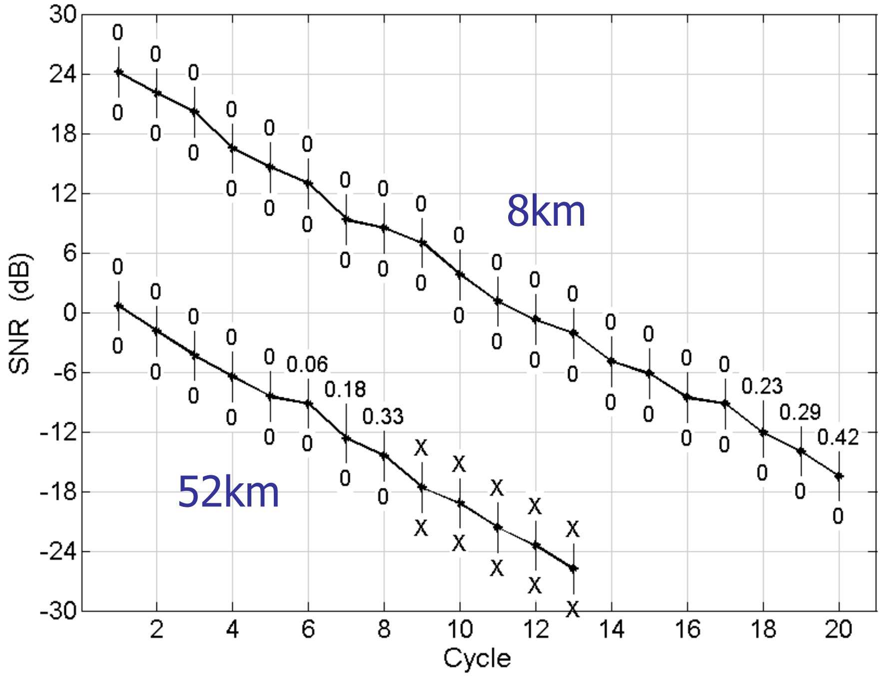
Sea Trial 2 Channels



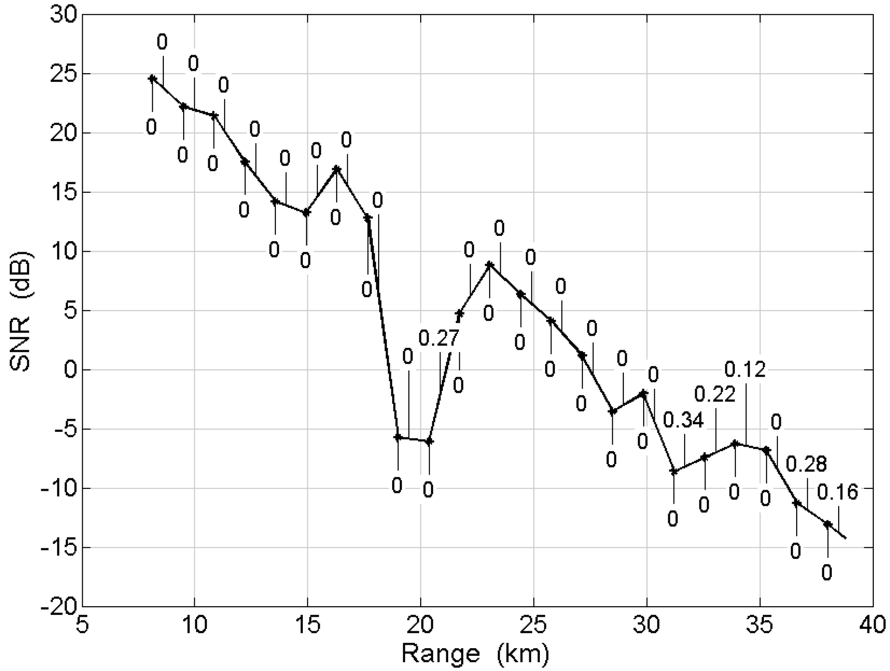
Sea Trial 2 Results

- BER for LDR (below curve) and HDR (above curve)

Case A



Case B



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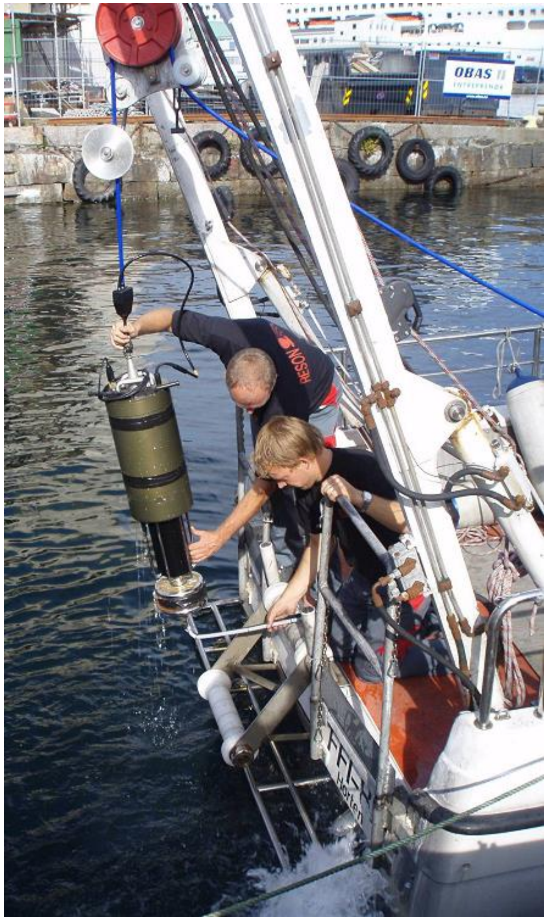
Sea Trial 3

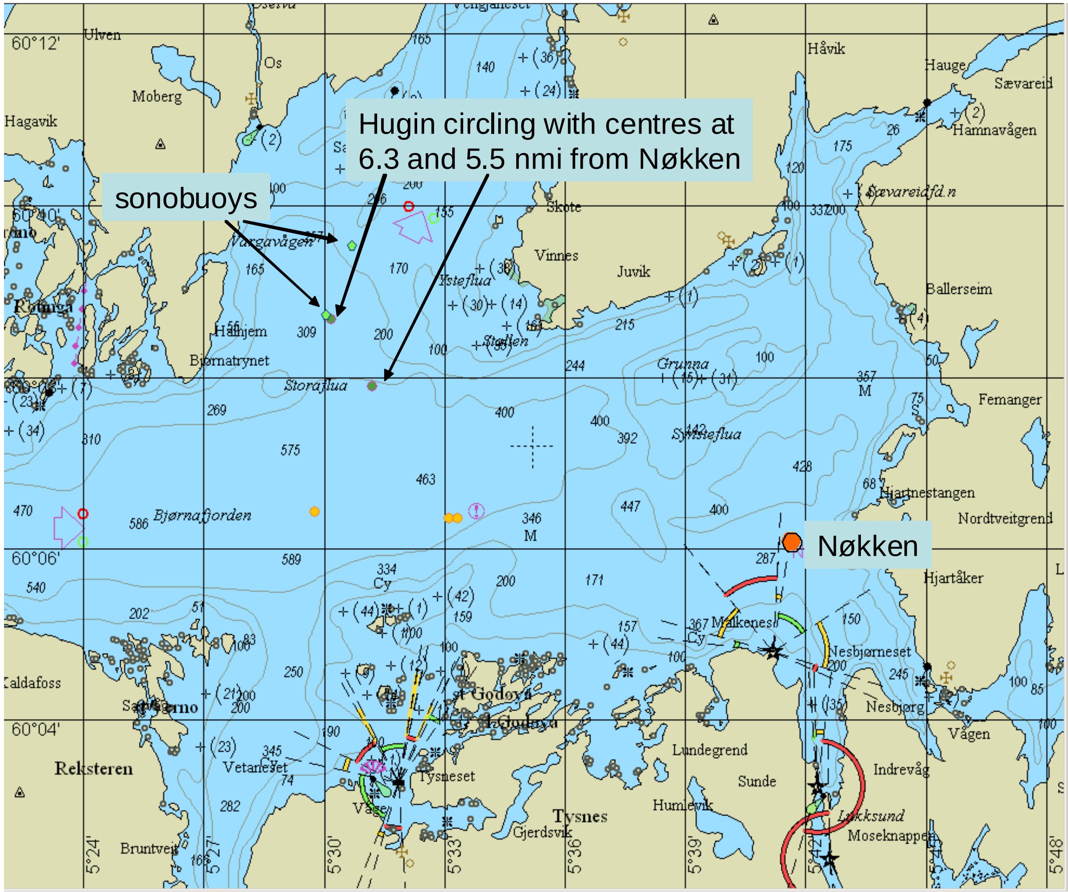
Nøkken



Hugin

Sea Trial 3

Bjørnafjorden



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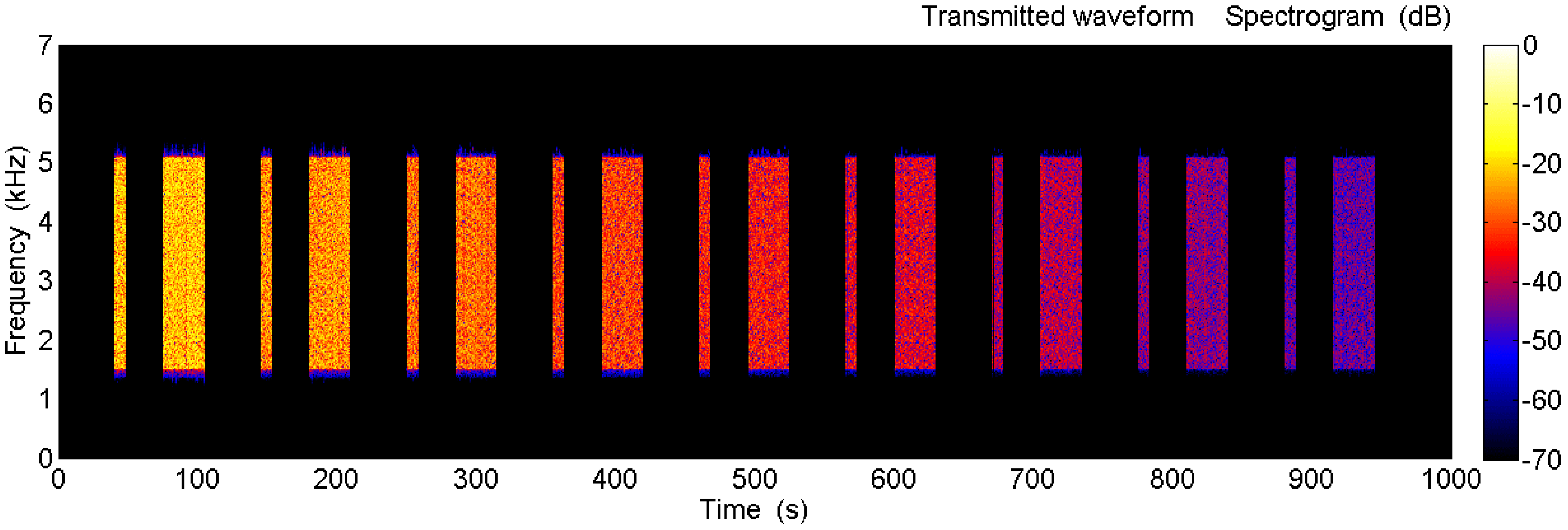
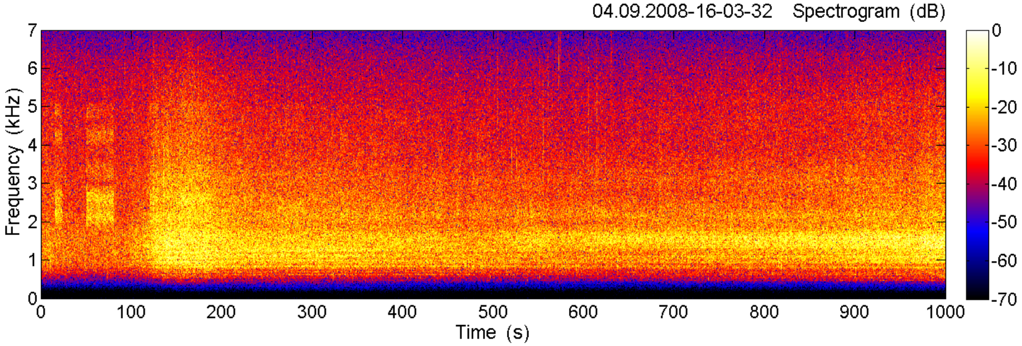
Sea Trial 3

- From Nøkken to Hugin at 5.3 nmi
- From Hugin to Nøkken at 5.3 nmi
- Transmitted waveforms:



Sea Trial 3 Results



- Bjørnafjorden
- Range = 5.3 nmi
- Nøkken modem (RX): 70 m depth
- Hugin modem (TX): 90 m depth

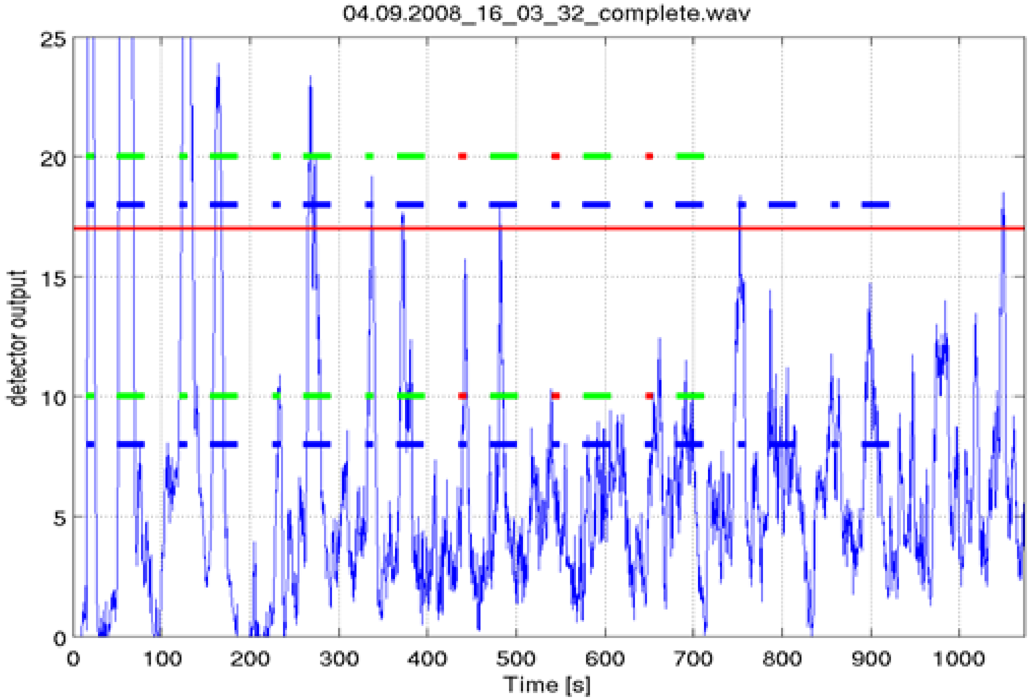
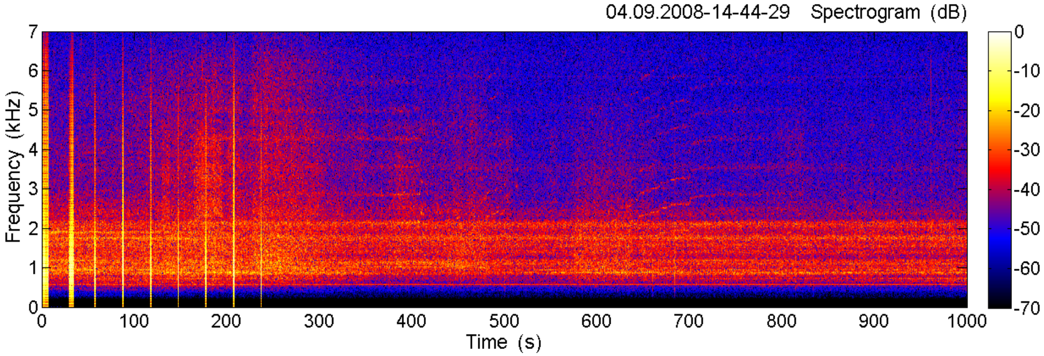


Figure 4.11. Interceptor result (blue curve) with detection threshold (red curve). Blue marks indicate expected OFDM sequences, green (BER = 0) and red (BER > 0) marks indicate detected OFDM sequences with OFDM receiver.

Sea Trial 3 Results



- ➢Bjørnafjorden
- ➢Range = 5.3 nmi
- ➢Nøkken modem (TX): 70 m depth
- ➢Hugin modem (RX): 90 m depth

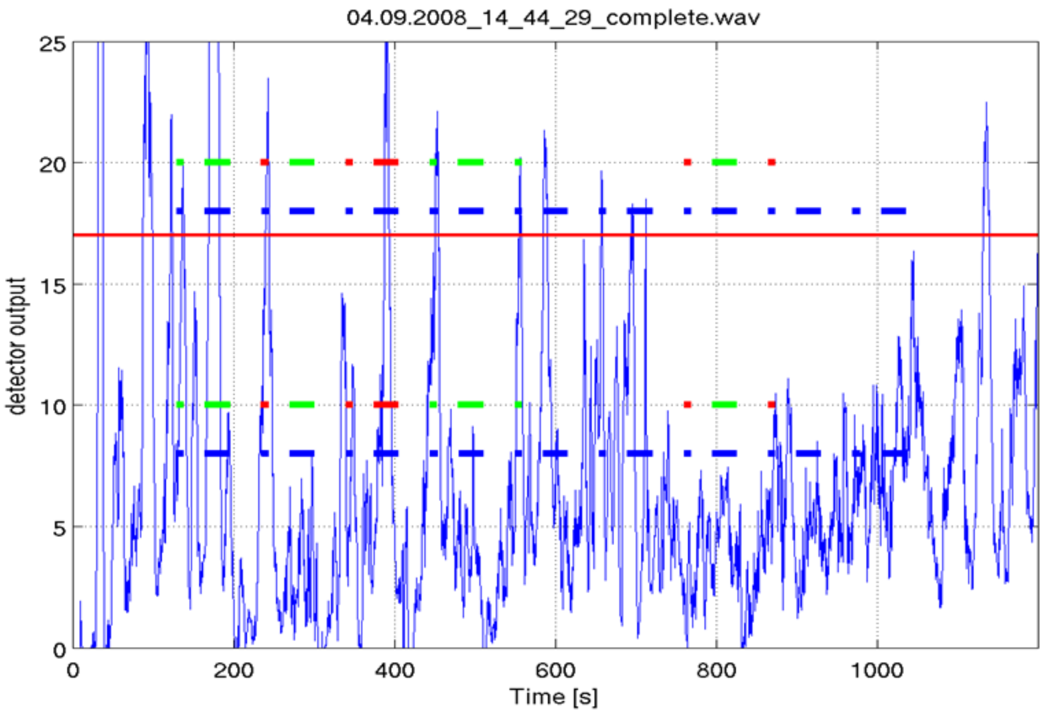


Figure 4.7. Interceptor result (blue curve) with detection threshold (red curve). Blue marks indicate expected OFDM sequences, green (BER = 0) and red (BER > 0) marks indicate detected OFDM sequences with OFDM receiver.

Conclusions

- Multi-carrier modulation has been proven successful for acoustic underwater communications:
  - The band assumption leads to low-complexity equalization for OFDM in underwater channels
  - Performances can be improved by windowing, thereby getting close to the optimal performance
  - Pilot-based channel estimation exploiting the BEM has been proposed for accurate channel estimation
  - Extensions to iterative approaches for channel equalization and estimation improve performance

Thank You! Questions?

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