Signal Processing for Underwater Communications

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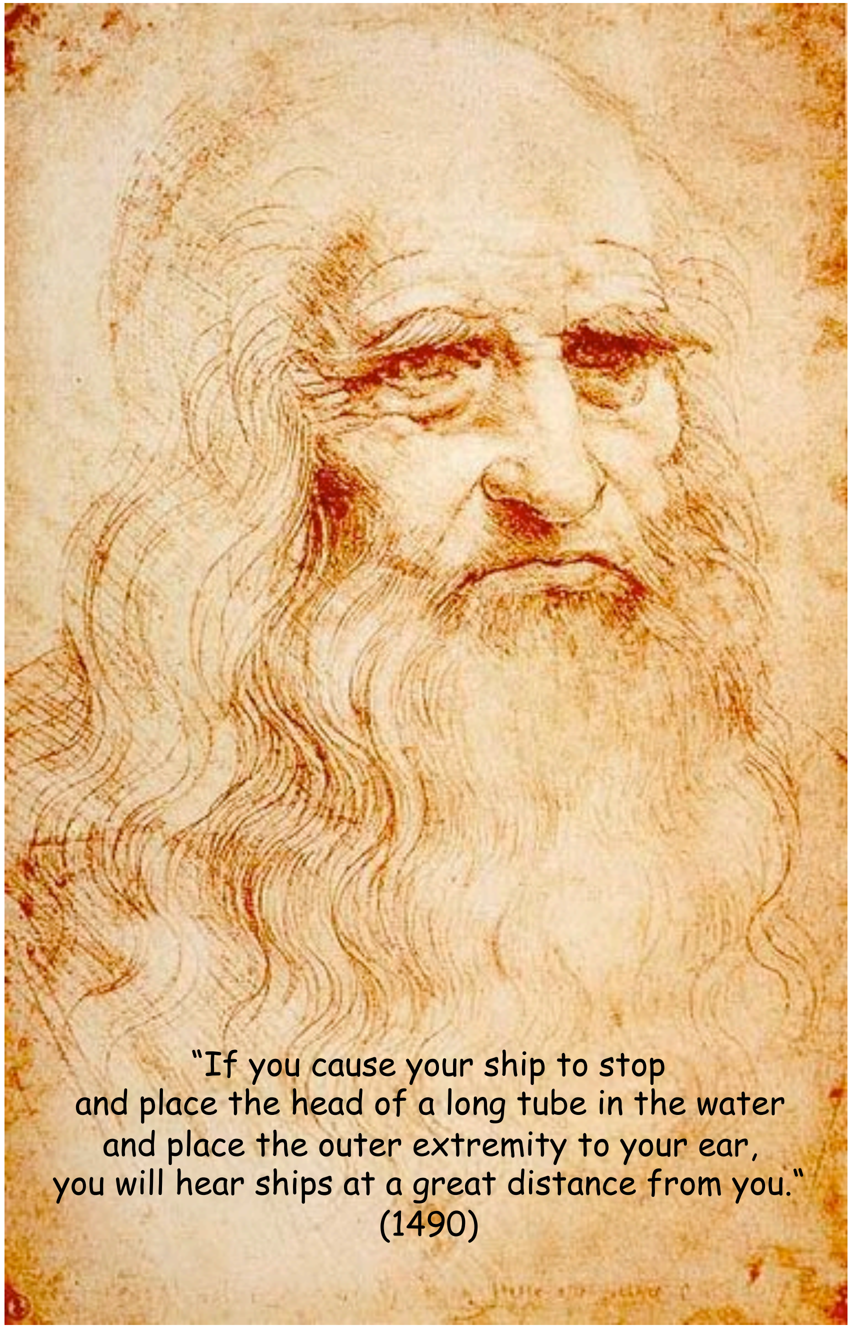
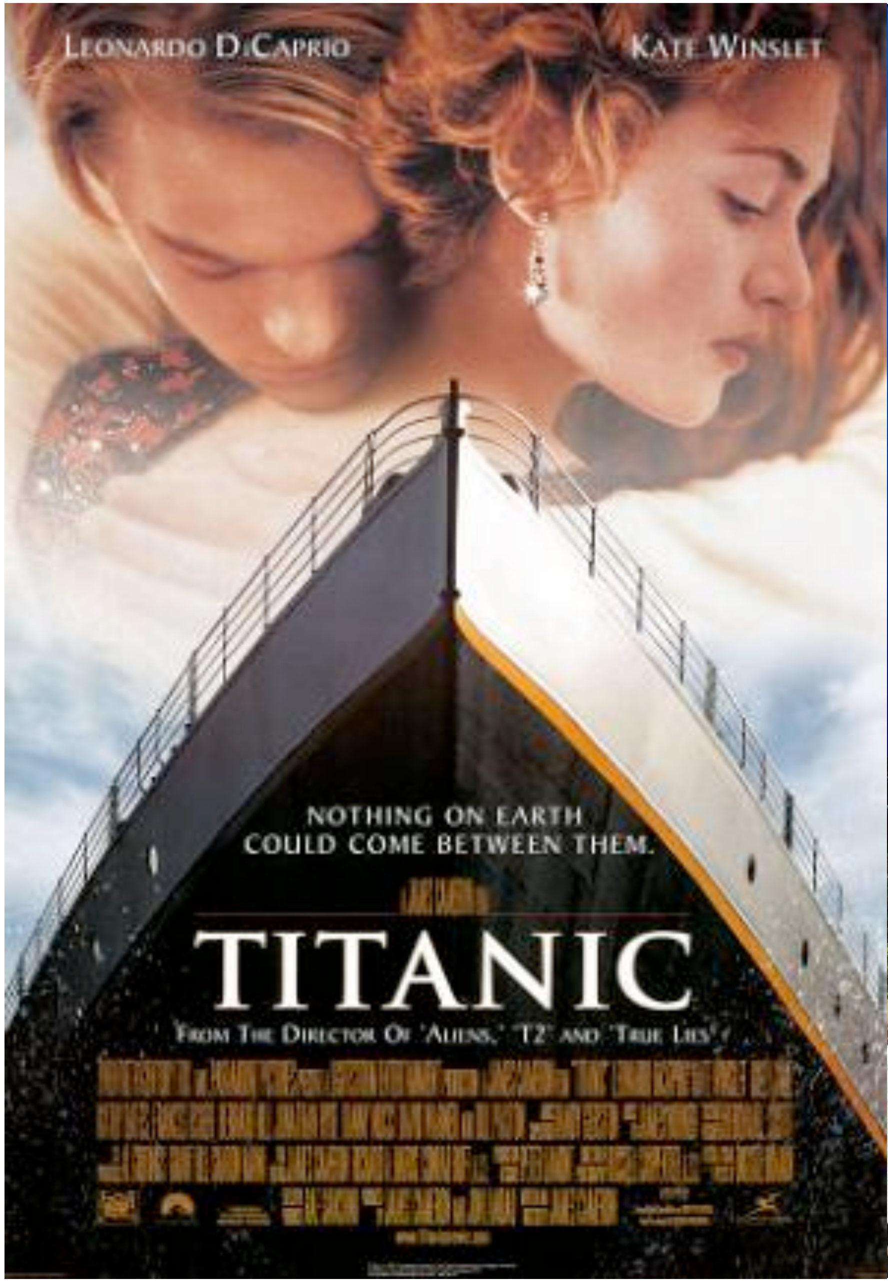
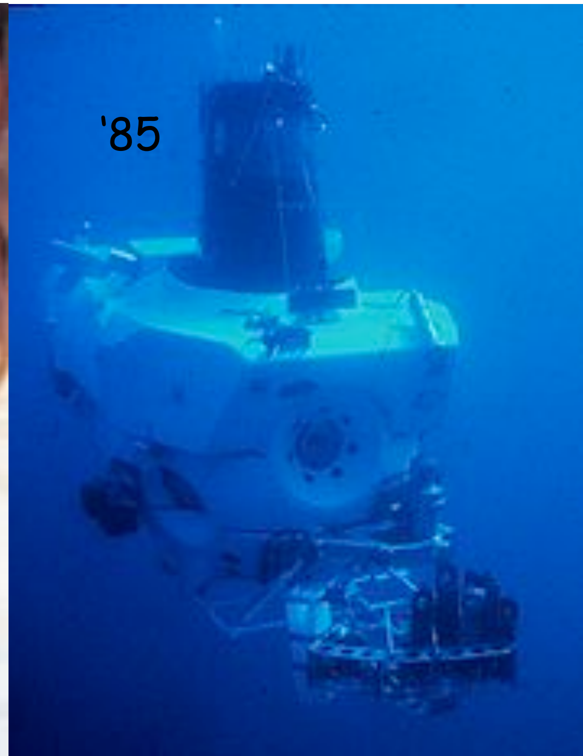

"If you cause your ship to stop
and place the head of a long tube in the water
and place the outer extremity to your ear,
you will hear ships at a great distance from you."
(1490)


LEONARDO DiCAPRIO
KATE WINSLET
NOTHING ON EARTH
COULD COME BETWEEN THEM.
TITANIC
FROM THE DIRECTOR OF 'ALIENS,' 'T2' AND 'TRUE LIES'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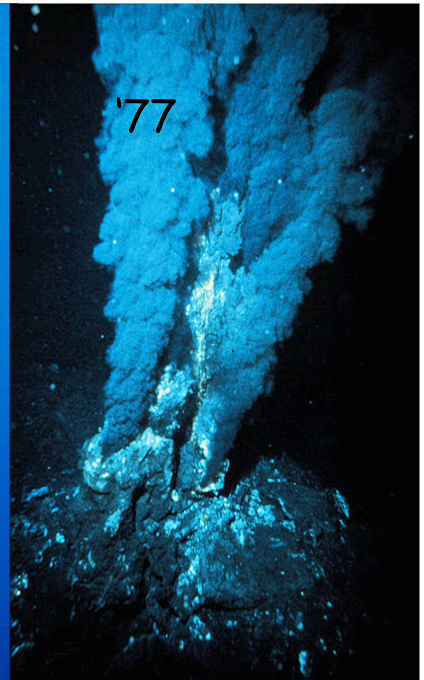
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Underwater wireless communications

Why?

Major scientific discoveries: cabled submersibles
Cables are heavy, expensive, restrict motion (but offer high bandwidth)
Applications:
-ocean monitoring (climate, pollution, oil, fisheries, earthquakes,…)
-underwater exploration (marine archaeology, natural resources, …)
-search and survey (shipwrecks, mines, area mapping,…)

How?

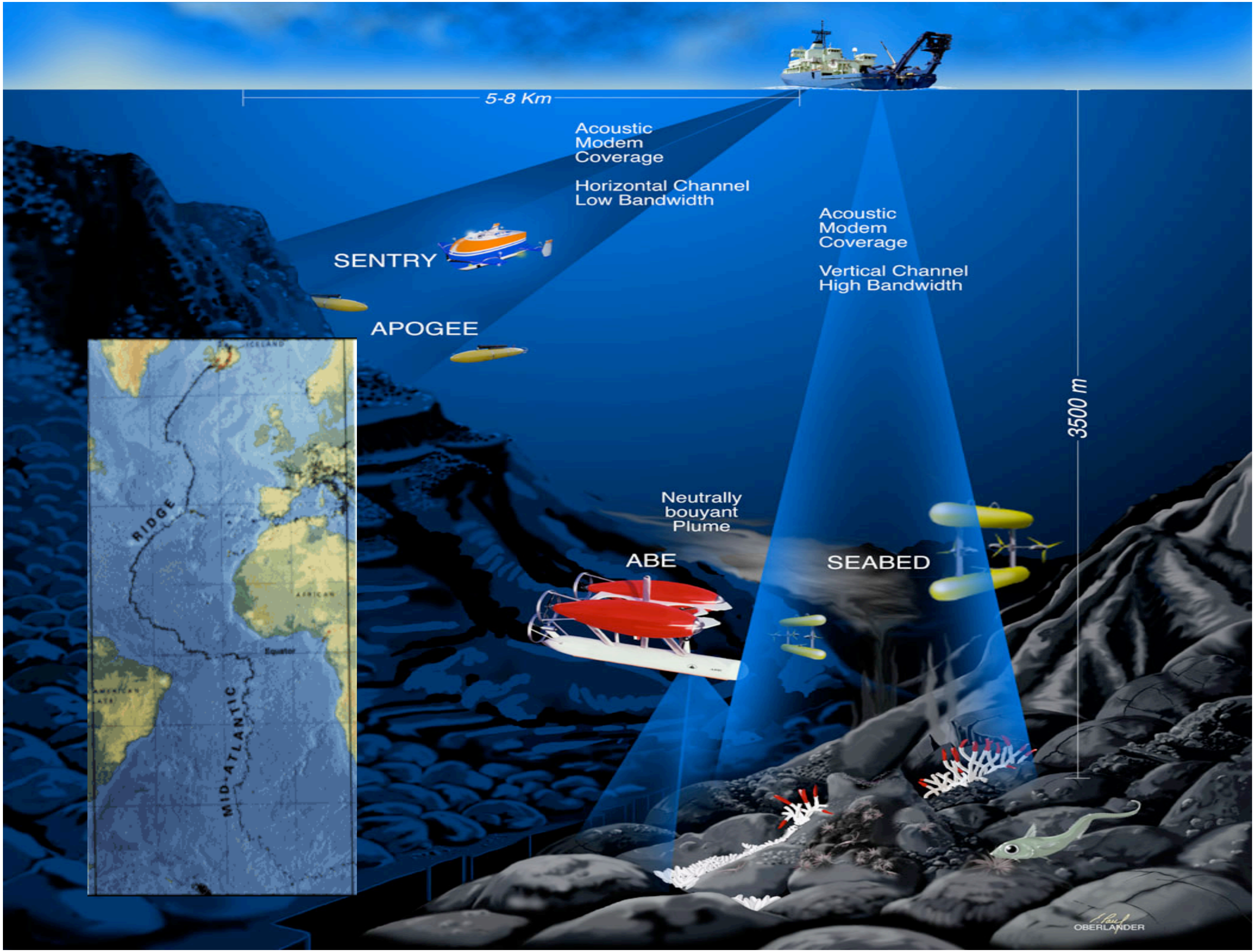
Radio: ~100 Hz, very high attenuation (~m @ 10kHz)
Optical: short distances (<100m), pointing precision
Acoustical: a solution

What has been done?

Underwater telephone (WW2, analog SSB 8-11 kHz)
DSP technology: acoustic modems (few kbps over few km)
- 70's,80's: noncoherent mod/demod → commercially available
- 90's: bandwidth-efficient mod/demod→ prototypes

What is next?

More signal processing, networks.


5-8 Km
Acoustic
Modem
Coverage
Horizontal Channel
Low Bandwidth
Acoustic
Modem
Coverage
Vertical Channel
High Bandwidth
SENTRY
APOGEE
3500 m
Neutrally
bouyant
Plume
ABE
SEABED
RIDGE
Equator
MID-ATLANTIC
OBERLANDER

Overview

communication channel

- attenuation and noise
- multipath propagation
- time-variability

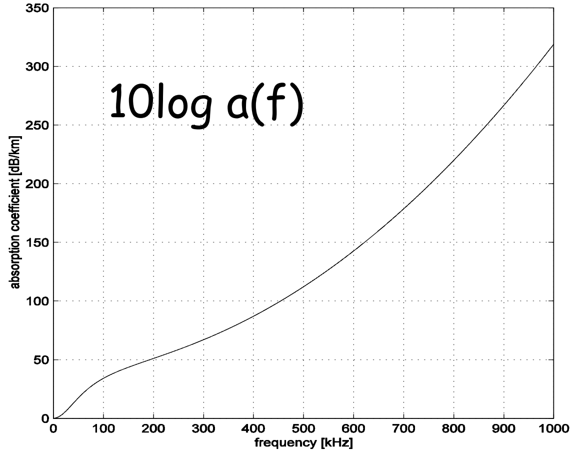
signal processing

- single-carrier, multi-carrier
- single-user, multi-user (SIMO/MIMO)

implications for networking

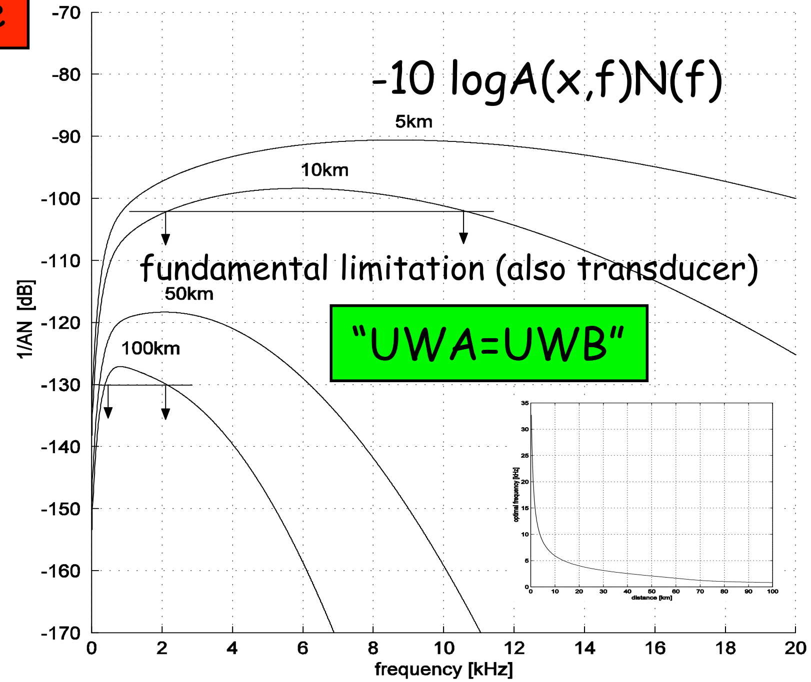
Underwater acoustic channel: attenuation and noise

$A(x,f) \sim x^k a^x(f)$ spreading + absorption (k:1-2)



$10 \log a(f) = 0.11\, f2/(1+f2) + 44\, f2/(4100+f2) + 0.000275\, f2 + 0.003$ dB/km, for f [kHz]

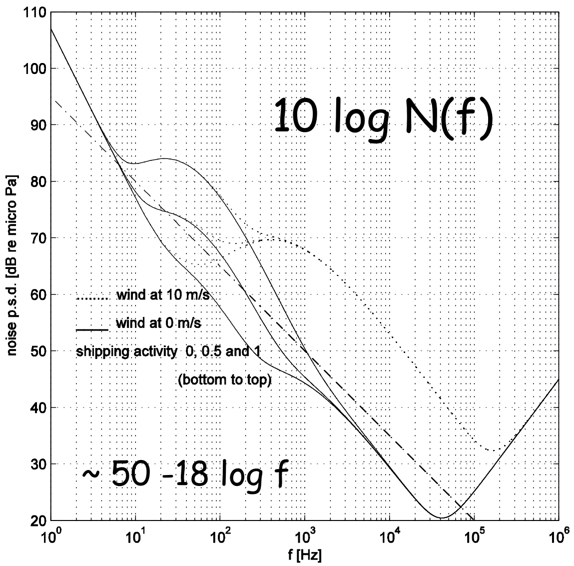
$$SNR = \frac{P_x}{P_{noise}} \sim \frac{P/A(x,f)}{N(f)\Delta f} \sim \frac{1}{A(x,f)N(f)}$$



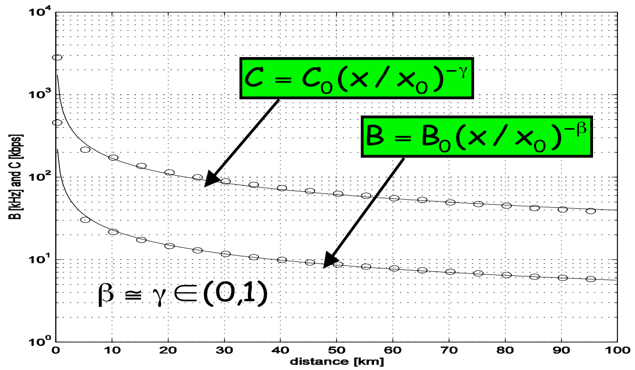
noise=
turbulence+
shipping+
surface+
thermal+
other

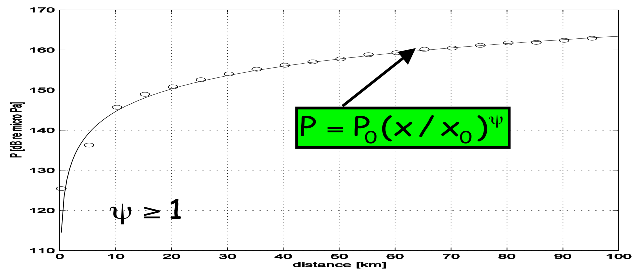
↓

site-specific:
man-made
biological
ice, rain
seismic



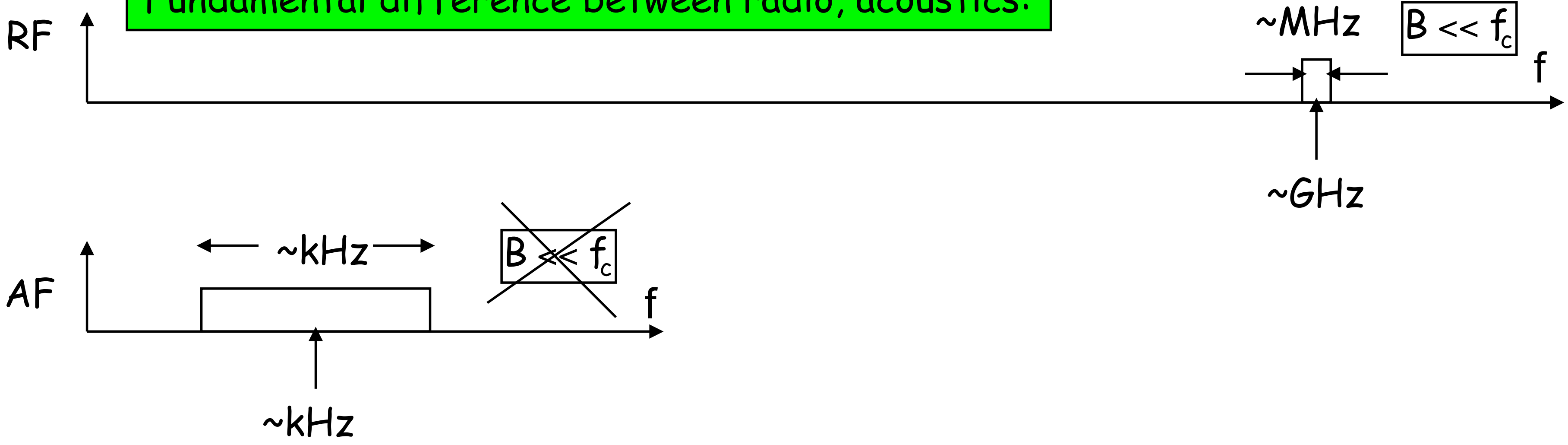
capacity, bandwidth, power:
dependence on distance





A "high-rate" acoustic system is inherently wideband ("UWA=UWB")

Fundamental difference between radio, acoustics:

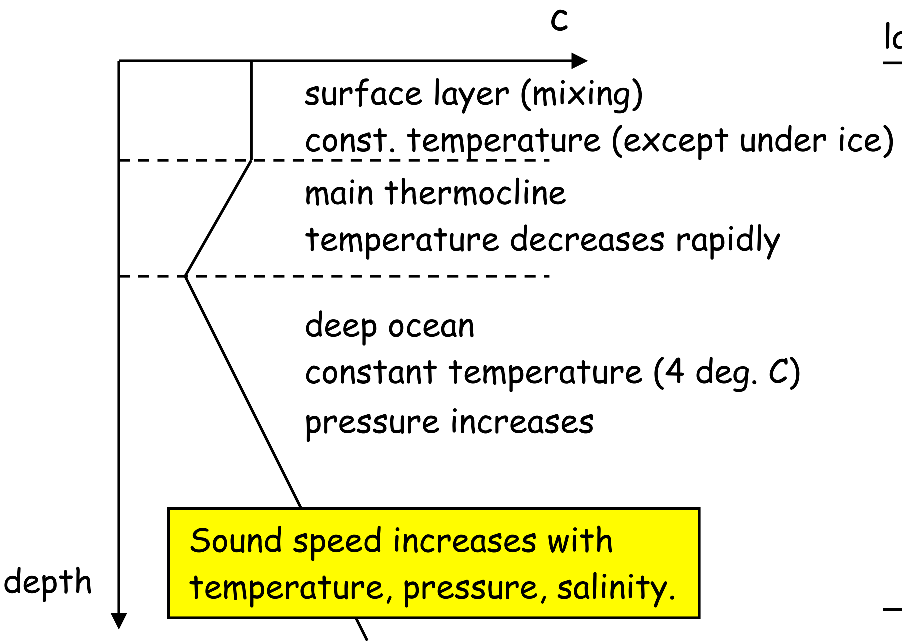


Absolute bandwidth may be "low," but it is **not** negligible w.r.t. center frequency (e.g. 1 kHz @ 1 kHz, 5 kHz @ 10 kHZ, 20 kHz @ 30 kHz).

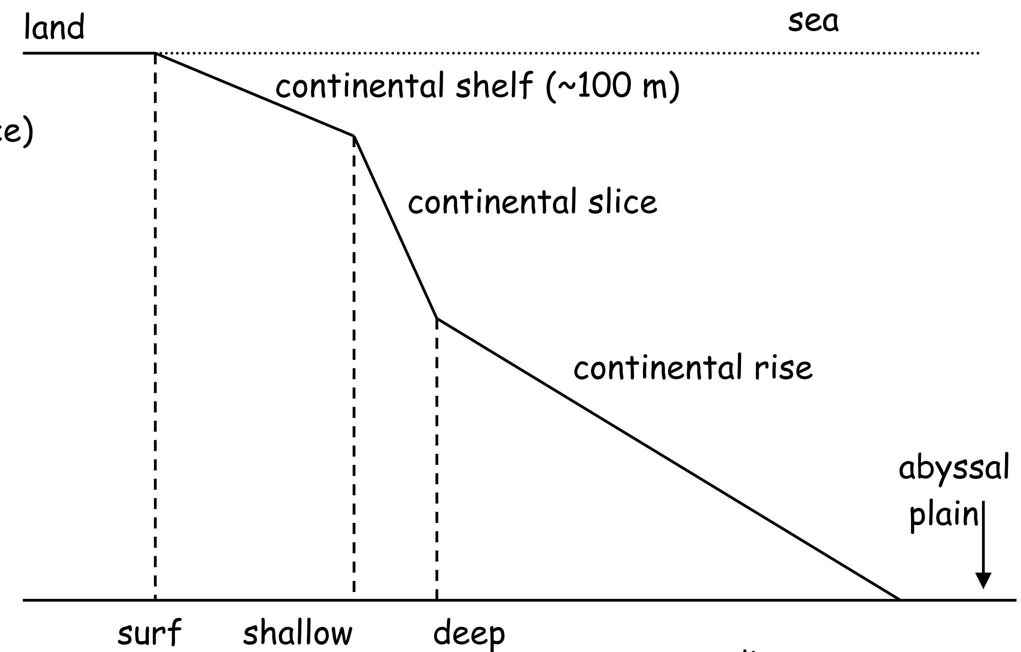
System is band-limited, narrowband assumption does **not** hold.

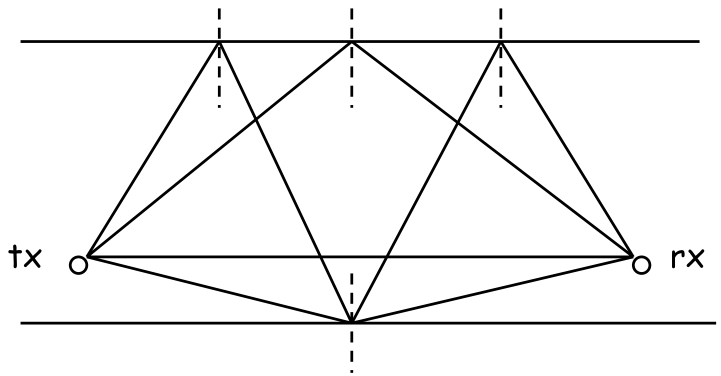
Implications :
- need bandwidth efficient modulation methods (coherent detection)
- cannot use signal processing methods that rely on narrowband assumption (array processing, synchronization)

Underwater acoustic channel: multipath and time-variability

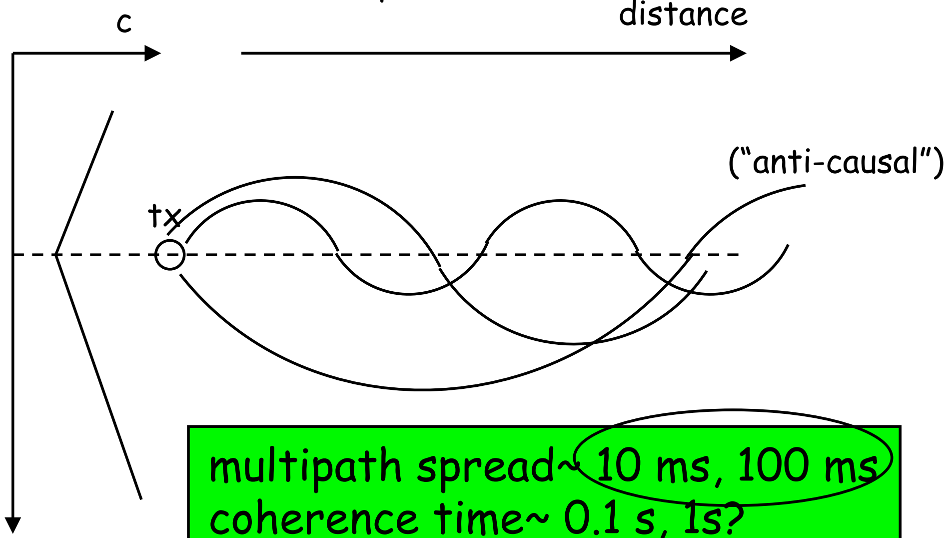


Sound speed increases with temperature, pressure, salinity.



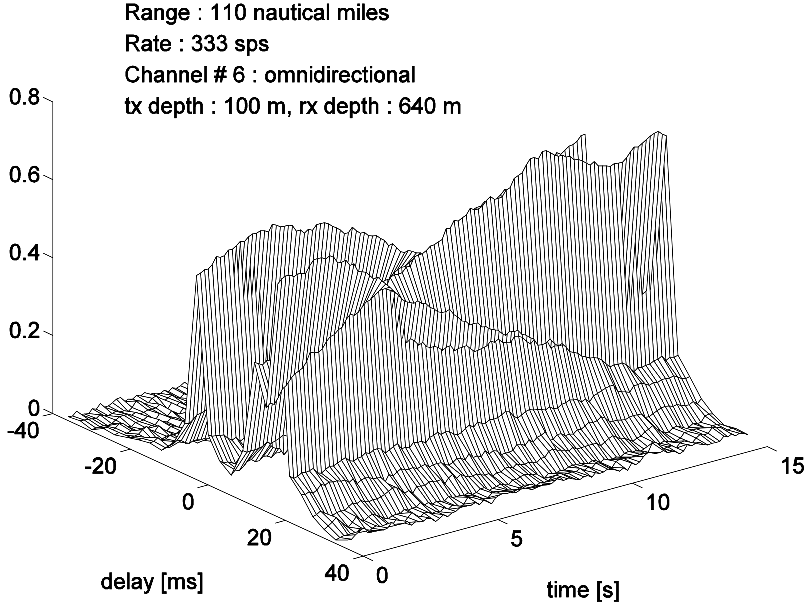


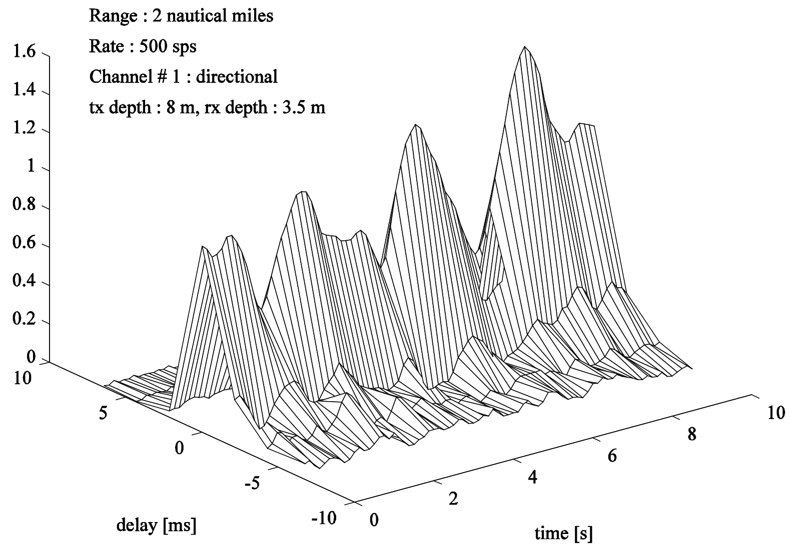
Channel variation: large/small scale→
surface motion, internal waves, turbulence,
fine changes in the sound speed profile.

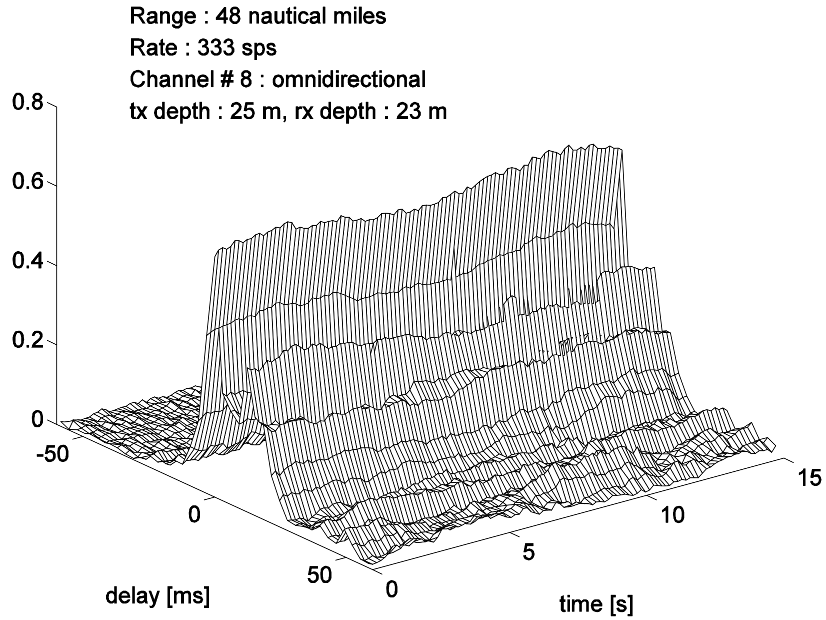


multipath spread~ 10 ms, 100 ms
coherence time~ 0.1 s, 1s?

Examples: measured channel responses



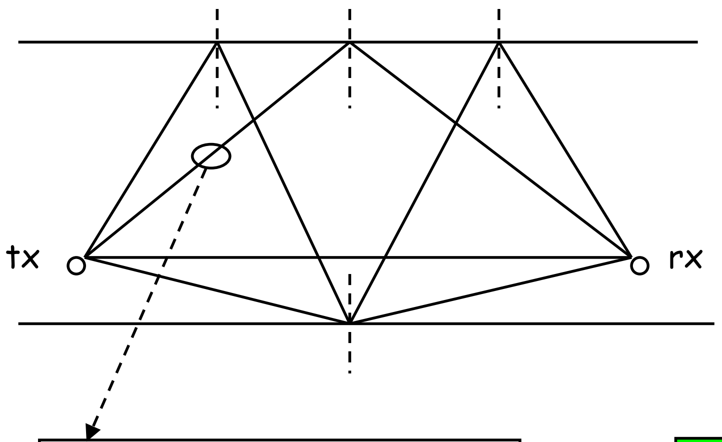




There are no widely accepted statistical channel models.

Channel modeling (for signal processing)

(1) time-invariant channel



$$\overline{H}_p(f) = \frac{\Gamma_p}{\sqrt{A(l_p, f)}} \leftrightarrow \overline{h}_p(\tau)$$

Each path:

- length, delay
- propagation loss A
- reflection coefficient Γ

Each path in an acoustic channel acts as a (low-pass) filter.

$$\overline{H}(f) = \sum_p \overline{H}_p(f) e^{-j2\pi f \tau_p} \leftrightarrow \overline{h}(\tau) = \sum_p \overline{h}_p(\tau - \tau_p) \approx \sum_p \overline{h}_p \cdot \overline{h}_o(\tau - \tau_p) \neq \sum_p \overline{h}_p \cdot \delta(\tau - \tau_p)$$

path filters: same shape, different gain

(2) time-variation

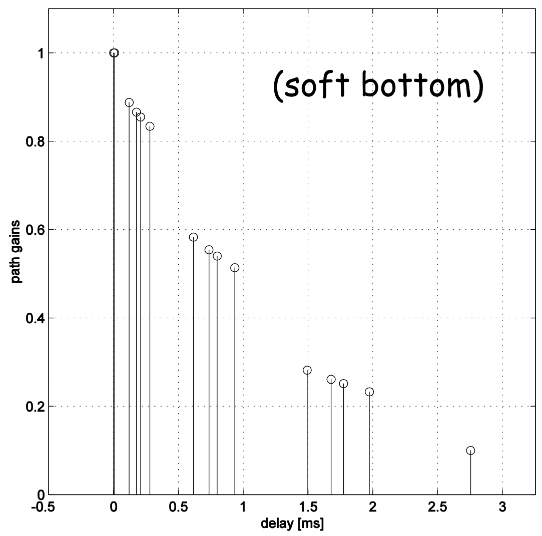
$$\overline{h}(\tau) \rightarrow h(\tau, t) \approx \sum_p h_p(t) \cdot \overline{h}_o(\tau - \tau_p(t))$$

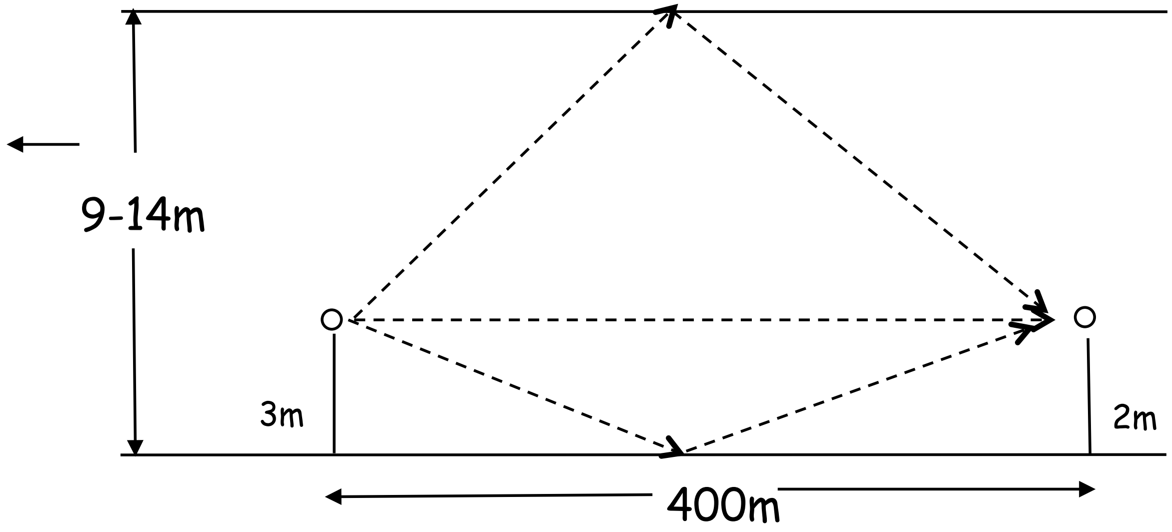
time variation: inherent, motion-induced
(random, deterministic/unknown)

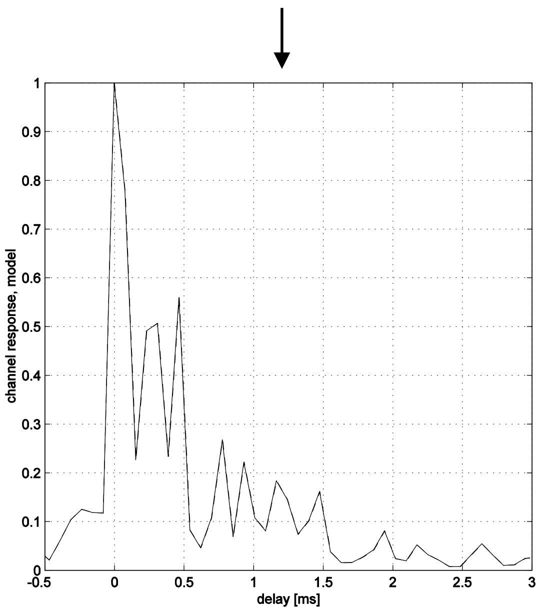
Example

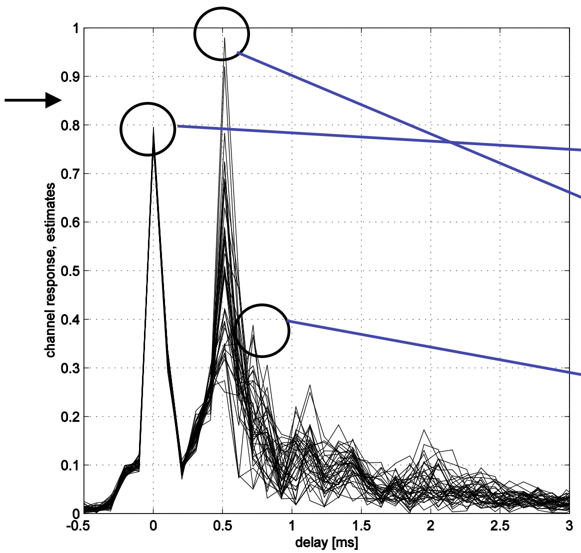
Narragansett Bay, March 2008

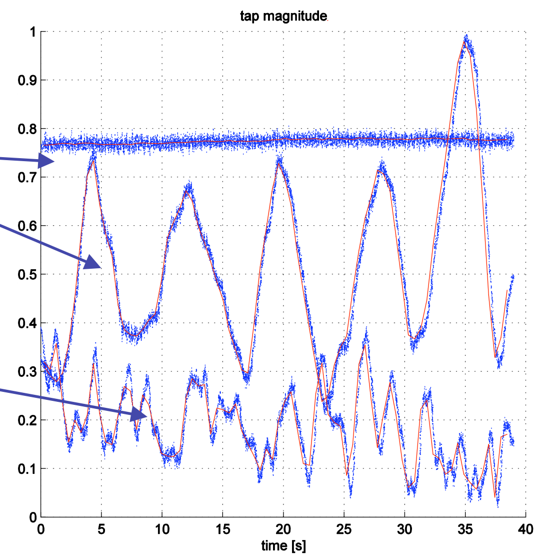
8-18 kHz





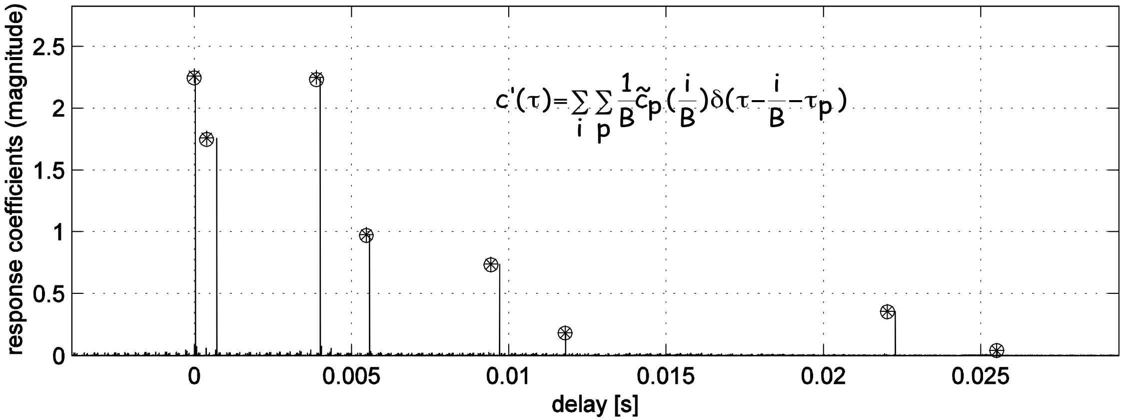






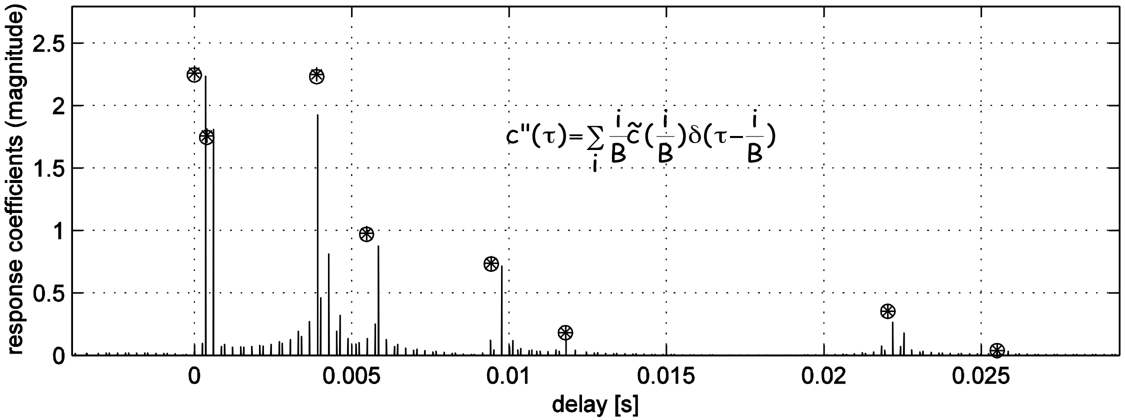
(no motion of tx/rx)

Equivalent band-limited baseband discrete-path models



non-uniform tap spacing

tx/rx: 1 km / 75 m
fc=10 kHz, B=5 kHz



uniform tap spacing

30 ms @ 5 ksps = 150 symbols.

Implications:

- reduce complexity and noise via **sparse** channel estimation.
- greater B → longer response (# symbols), but better resolution in both time **and** delay.

win-win ☺

...respect the physics of the channel, and ...

Motion-induced time-variation: the Doppler effect

$t \rightarrow t+at$ time dilation/compression

$f \rightarrow f+af$ frequency offset

$a=v/c$

v ~ m/s → with or without intentional motion

c=1500 m/s

$a \sim 10^{-4}$ → comparable only to LEO satellite systems

Implications: explicit synchronization is necessary.

Time variation:

- inherent → Doppler spreading
- motion-induced → Doppler shifting (and spreading)

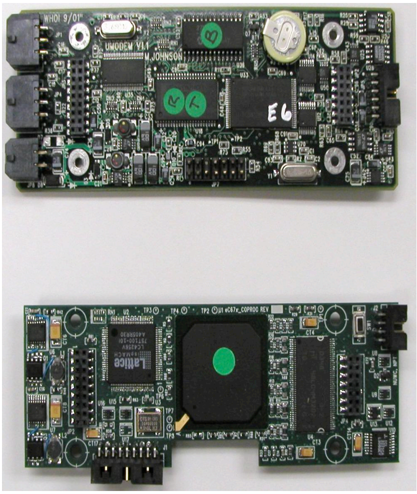
Doppler spreading → adaptive channel estimation (slow)

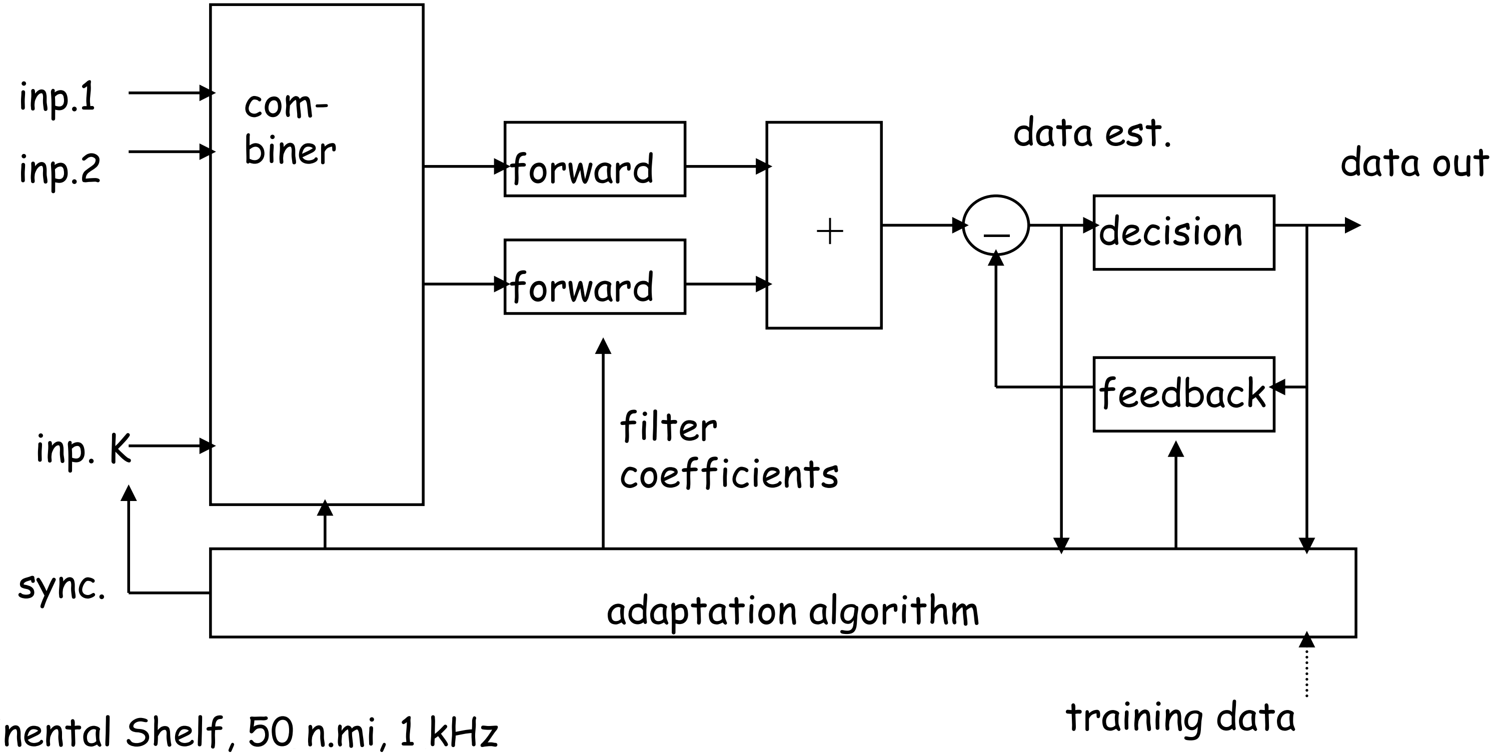
Doppler shifting → synchronization (fast)

synchronization (fast) → tacking $\theta(t)$ vs. $e^{j\theta(t)}$

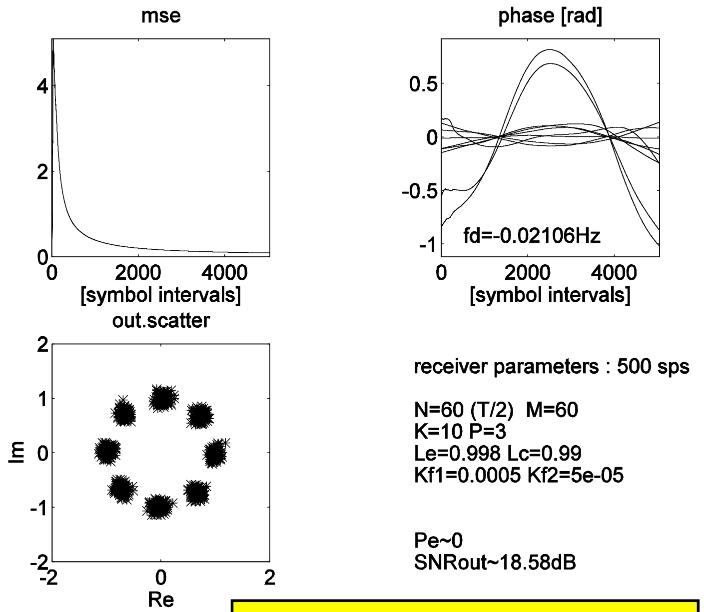
…respect the physics of thy channel …

Single-carrier systems





Ex. New England Continental Shelf, 50 n.mi, 1 kHz



receiver parameters : 500 sps

N=60 (T/2) M=60
K=10 P=3
Le=0.998 Lc=0.99
Kf1=0.0005 Kf2=5e-05

Pe~0
SNRout~18.58dB

"the faster the better"

Current achievements:

Point-to-point (2/4/8PSK;8/16/64QAM)
- medium range (1 km-10 km ~ 10kbps)
- long range (10 km – 100 km ~1kbps)
- basin scale (3000 km ~ 10bps)
- vertical (10 m~150 kbps, 3 km~15 kbps, 10 km~5 kbps)

New

Mobile communications
AUV to AUV at 5 kbps

Multi-user communications
five users, ~ kbps in 5 kHz band

CDMA underwater?

Conventional assumptions do not hold:

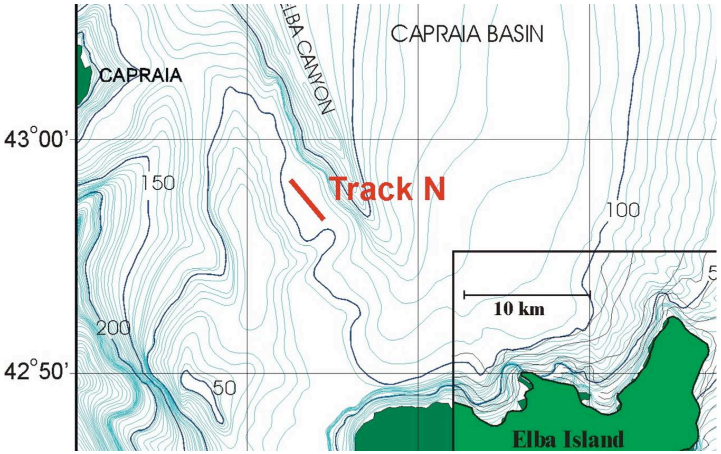
- ISI is not negligible
- channel is not constant over one symbol

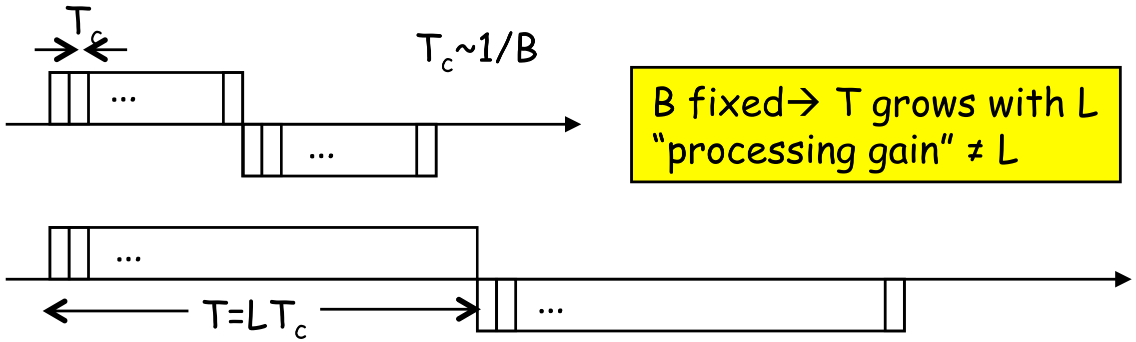
Receiver design:

- chip-rate filtering
- chip-rate adaptation

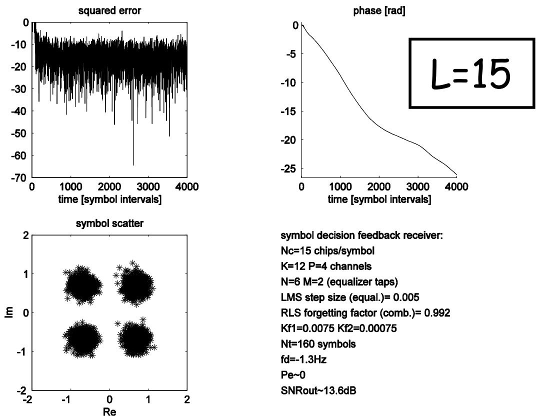
Experiment:

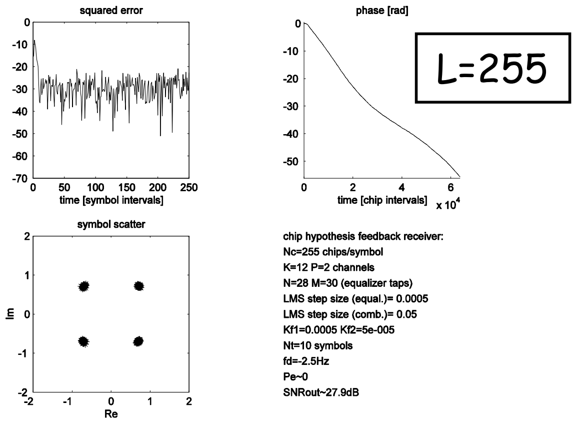
- range: 2.5 km
- center frequency: 33 kHz
- chip rate: 19,200 chips/sec
- four users, up to 2.5 kbps
- spreading factor (15-255)

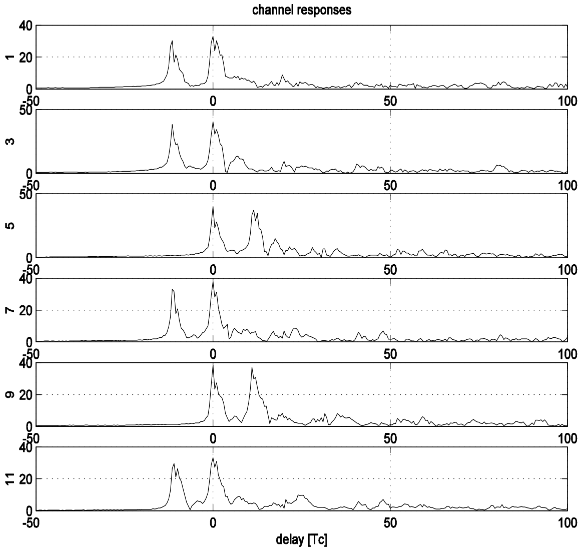


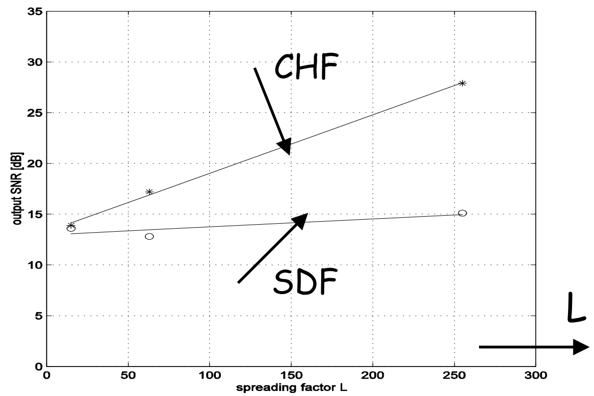


B fixed→ T grows with L
"processing gain" ≠ L









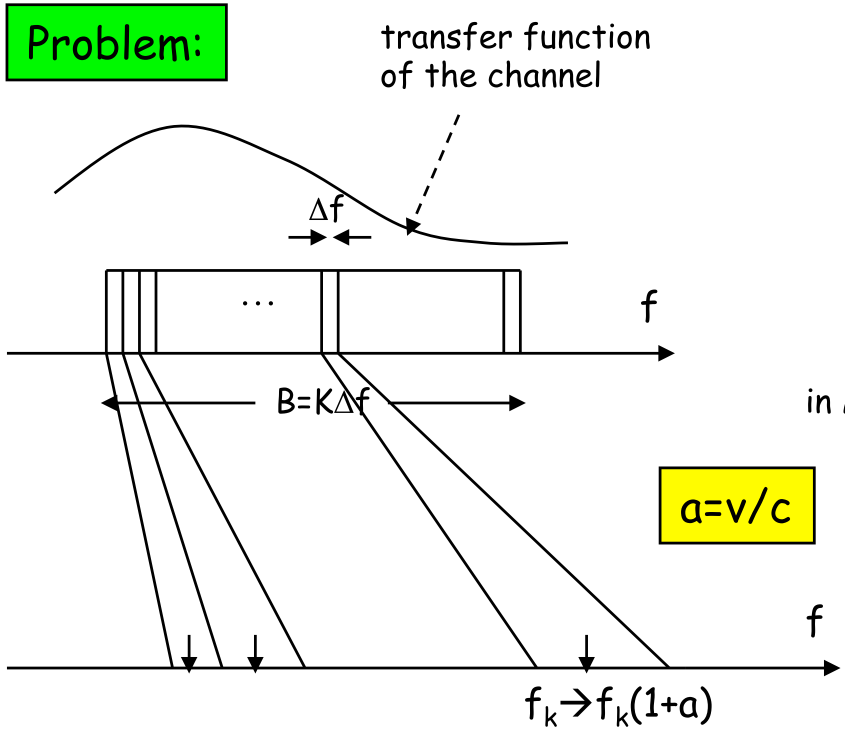
"chip hypothesis feedback" recovers processing gain.

Mobile experiments in 5 kHz band: direct sequence spread spectrum feasible at 15 knots.

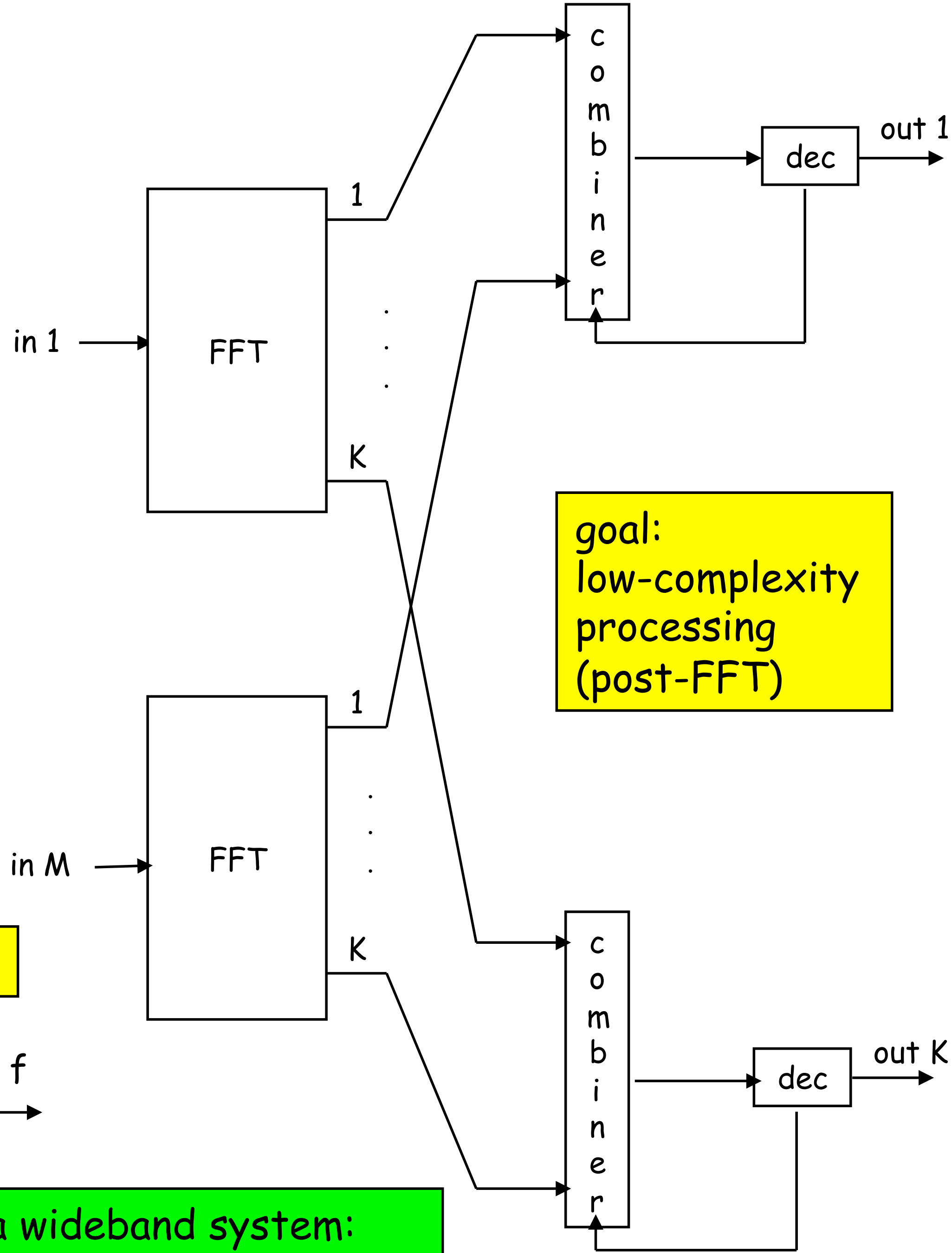
Multi-carrier systems

OFDM:
+equalization
-frequency offset

Problem:

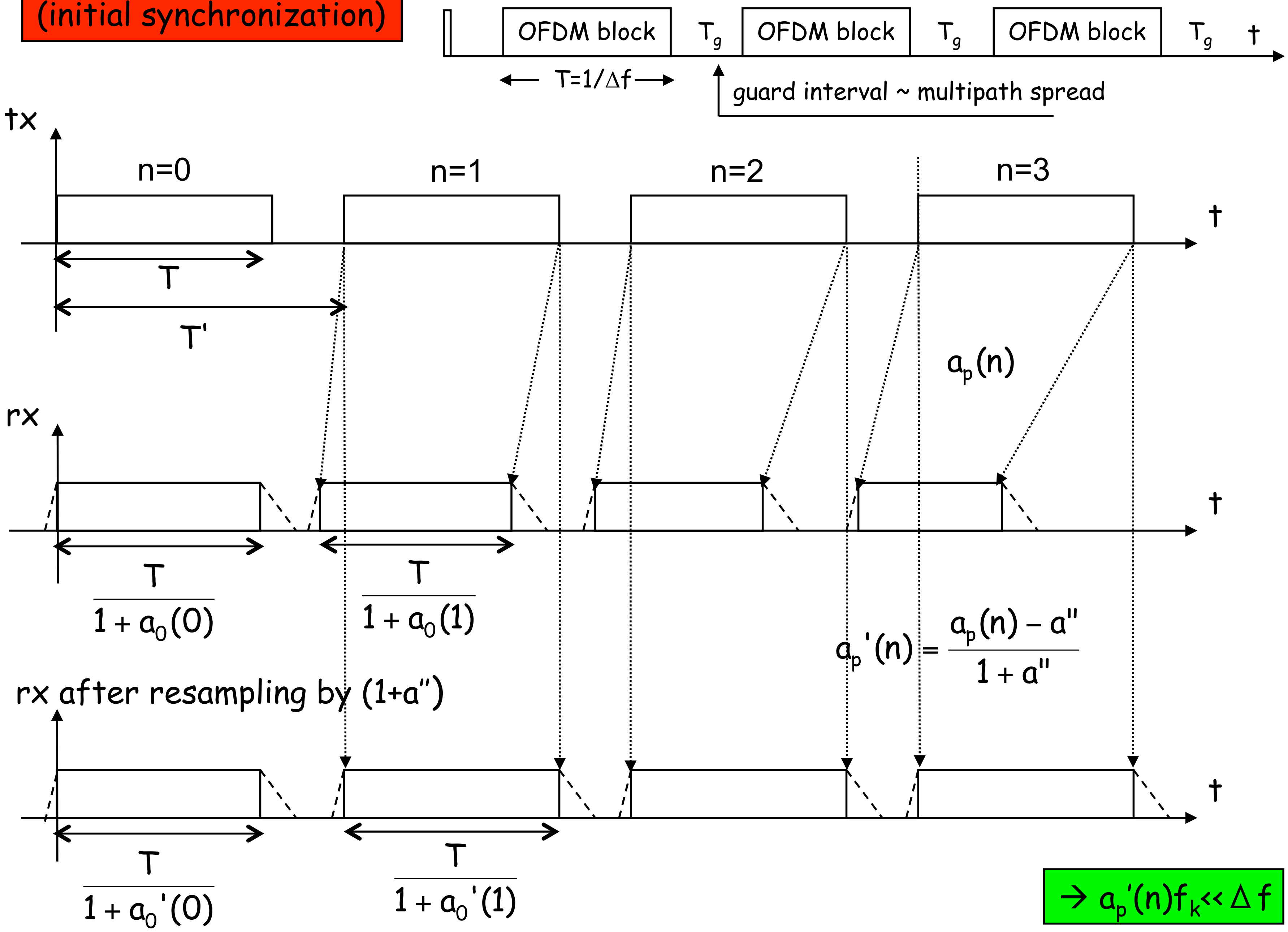


Motion-induced Doppler distortion in a wideband system:
non-uniform frequency shifting across the signal bandwidth



goal:
low-complexity
processing
(post-FFT)

Pre-processing (initial synchronization)



→ $a_p'(n) f_k \ll \Delta f$

Trade-offs

some numbers:
T_{coh}~0.1 ms; T_{mp}~10 ms

T=10 ms, B=10 kHz → K=100
T=50 ms, B=20 kHz → K=1000

$$\frac{R}{B} = \frac{1}{1 + T_g B / K}$$

→ want large K

… but this means small Δf / large T, i.e. more vulnerability to residual frequency offset / inherent time-variation

→"optimal" number of carriers: greatest for which post-FFT processing is still possible.

Implications: have to estimate/track large number of phases.

A simple approach to "Doppler" tracking

$$y_k(n) \sim \sum_l H_{k,l}(n) d_k(n) \sim H'_k(n) e^{j\theta_k(n)} d_k(n)$$

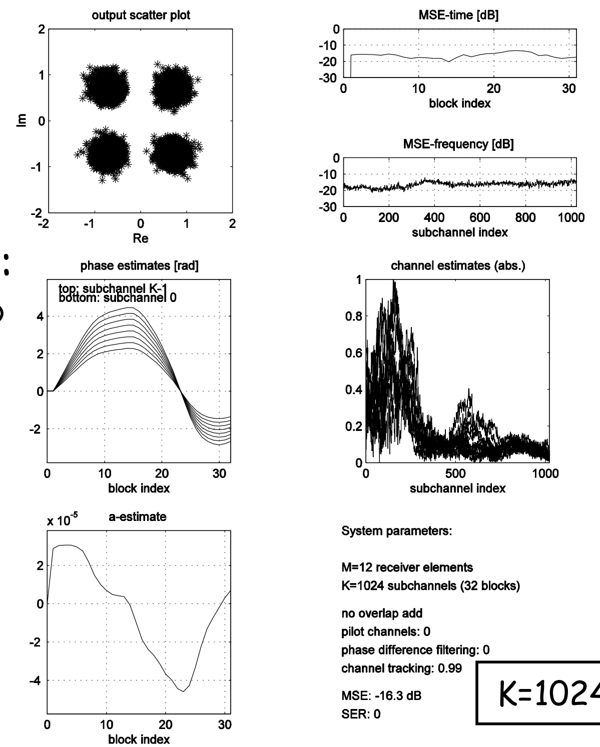
→ time-variation:
- phase offset
- ICI

$$\theta_k(n) \sim 2\pi a' f_k n T' \sim \theta_k(n-1) + 2\pi a' f_k T'$$

- estimate the Doppler factor a'(n)
- use this (single) estimate to compute all K phases

30 kbps @ minimal complexity →

Buzzards Bay, 2.5 km, 24 kHz



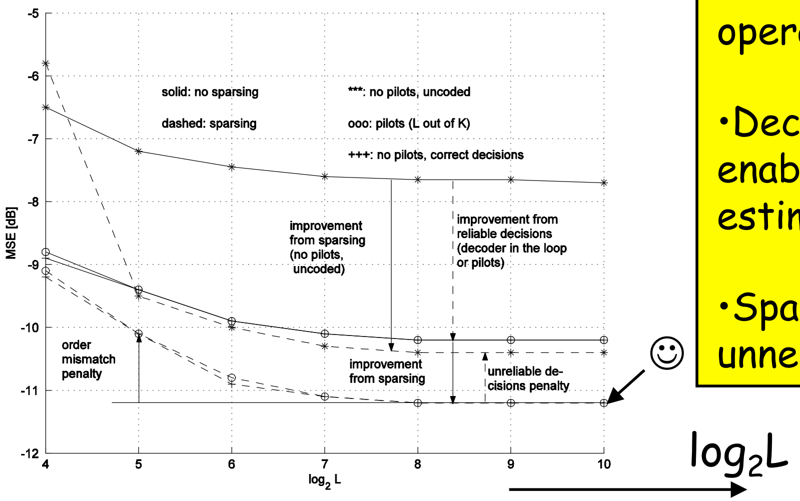
K=1024

OFDM: channel estimation

transfer function $H_k(n)$	← FFT_K →	impulse response $h_l(n)$
K coefficients (system parameter)		J (out of L) coefficients (channel parameter)

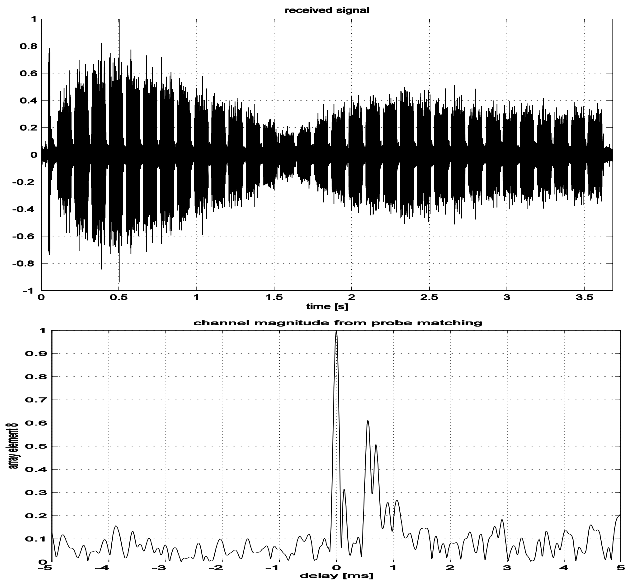
- non-adaptive: each block detected independently: need L pilots per block ($\sim T_{mp}B$)
- adaptive: each block detected using knowledge from previous block

channel sparsing: keep J strongest taps only.	J/L	J/K
data-aided: can use all K symbols per block.	L/K	



- Adaptive synchronization enables decision-directed operation (no null subcarriers)
- Decision-directed operation enables full-size channel estimation (low pilot overhead)
- Sparsing eliminates unnecessary estimation noise.

Panama City Beach, 1 km, 12 kHz



Pushing performance limits: MIMO OFDM (for spatial multiplexing gain)

$R/B = M_T / (1+T_g B/K)$ symbols/sec/Hz

Want: M_T , K as large as possible. $(M_T \leq K/L)$

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

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); ICI arises.

Work in progress: MIMO channel estimation, ICI equalization, pulse-shaped MCM, …
Experiment: 4-tx, Martha's Vineyard, 1 km, 10 kHz (nudging 10 bps/Hz)

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

Open problems

channel: statistical characterization
(for simulation, performance bounds)

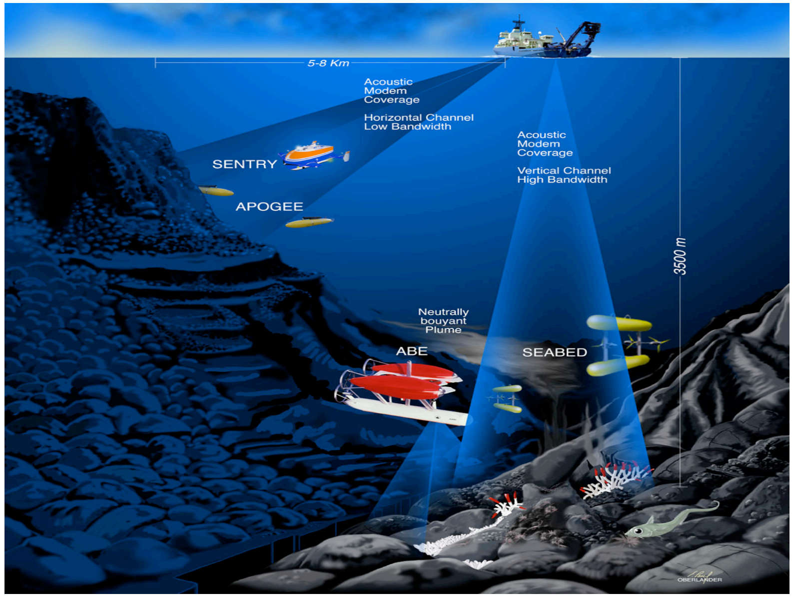
tx: adaptive modulation / power control (channel state prediction)
spectrum shaping, coding,...

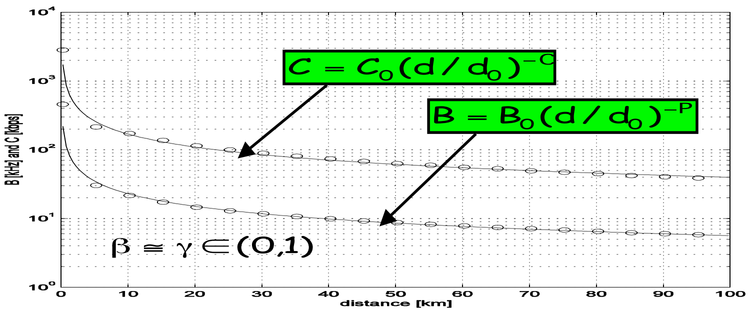
rx: adaptive receivers (single- and multi-carrier; single- and multi-input)
model-based processing (e.g., path-specific Doppler)

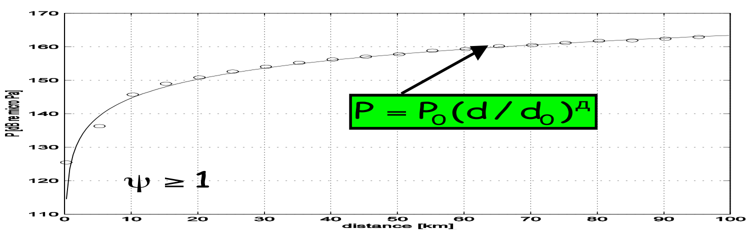
networks: efficient and scalable protocols on all layers
topologies, architectures ("typical applications?")
capacity?

system integration and optimization:
from data compression to navigation (and back)

Underwater networks

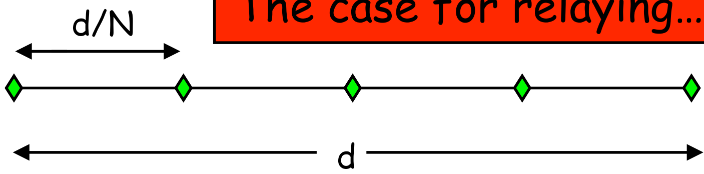






capacity depends on distance

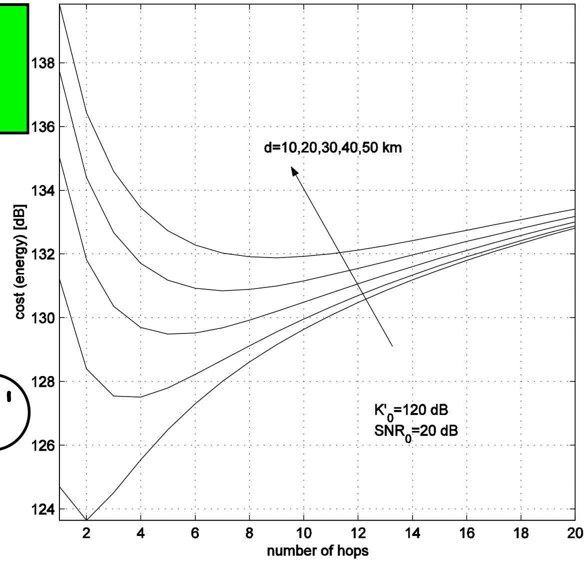
The case for relaying…

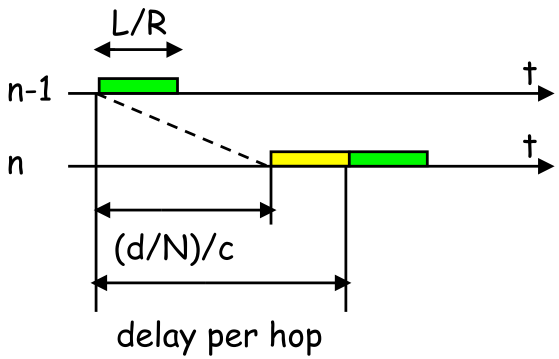


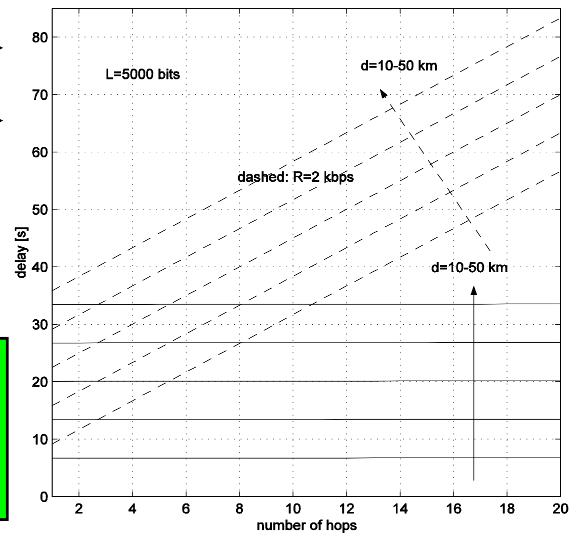
power and bandwidth improve with # hops

$$E_N(d) = P_N(d)/C_N(d)$$
$$= NP(d/N)/C(d/N)$$

$$K'(N) = E_N(d) + (N-1)K_0'$$
$$\rightarrow \text{min. w.r.t. } N$$







delay penalty negligible if bit rate adjusted to distance.

… is the case for signal processing.