

Underwater Communications

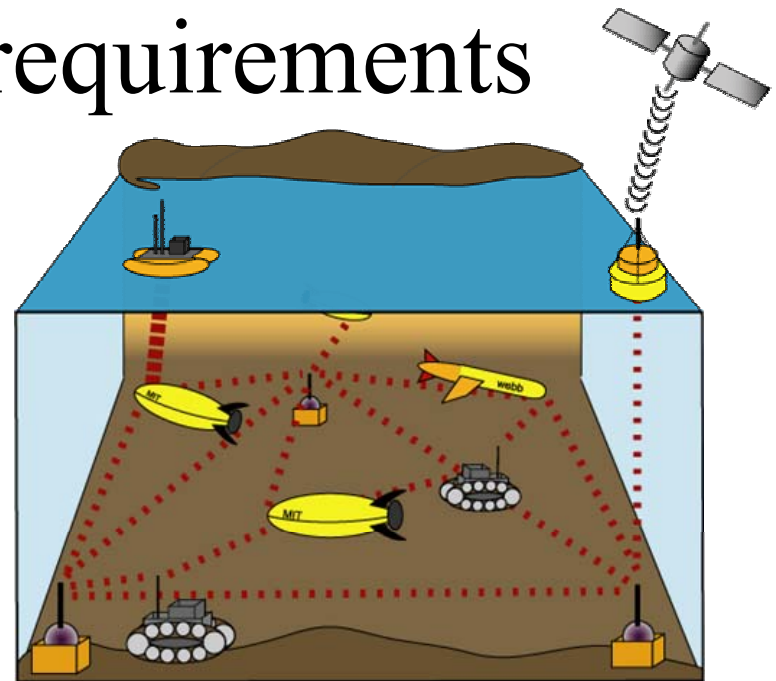
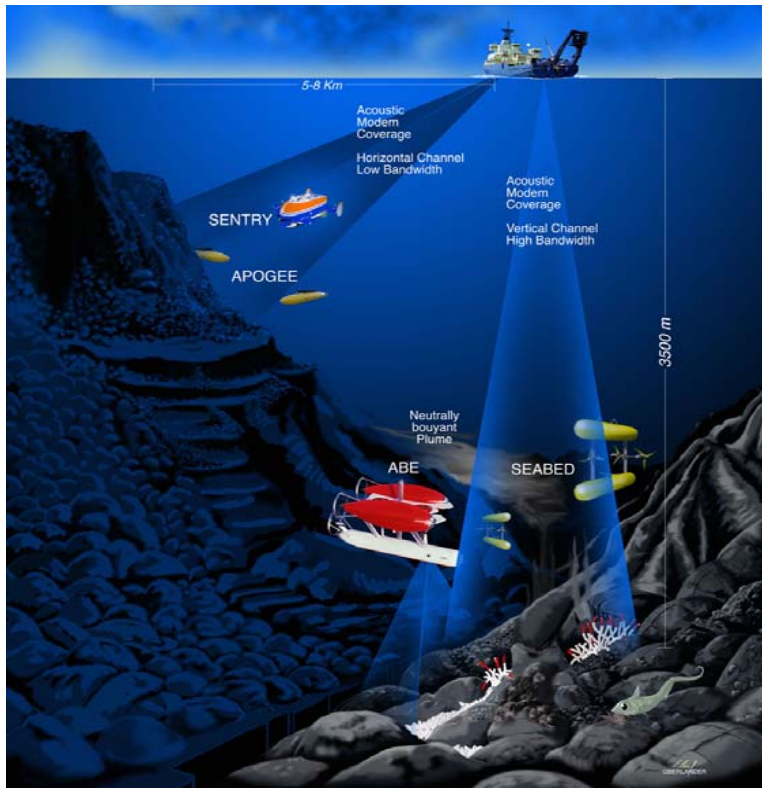
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Future systems / requirements

- Today: point-to-point acoustic links
- Future: autonomous networks for ocean observation
- Examples of future networks:
 - ad hoc deployable sensor networks
 - autonomous fleets of *cooperating* AUVs



- Types of nodes:
 - fixed, slowly moving, mobile
 - sensors, relays, gateways
- Types of signals, system requirements:
 - low/high rate (~100 bps-100kbps)
 - real-time/non real-time
 - high/moderate reliability
- Configurations:
 - stand alone
 - integrated (e.g., cabled observatories)

NSF ITR: “Acoustic networks, navigation and sensing for multiple autonomous underwater robotic vehicles.”

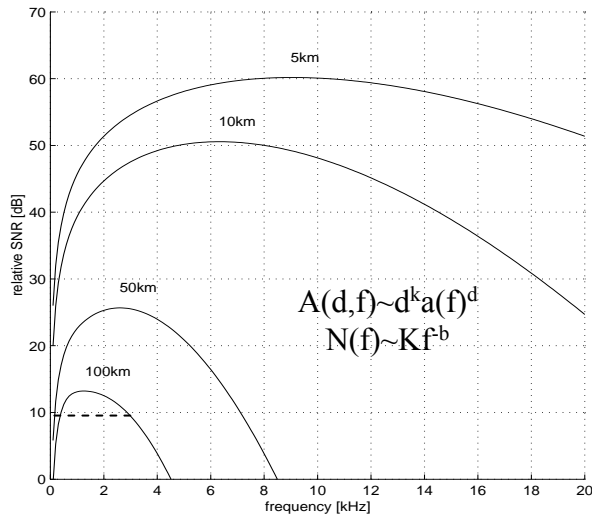
Overview

- Channel characteristics
- Signal processing: bandwidth-efficient underwater acoustic communications
- Example: application to oil field monitoring
- Future research

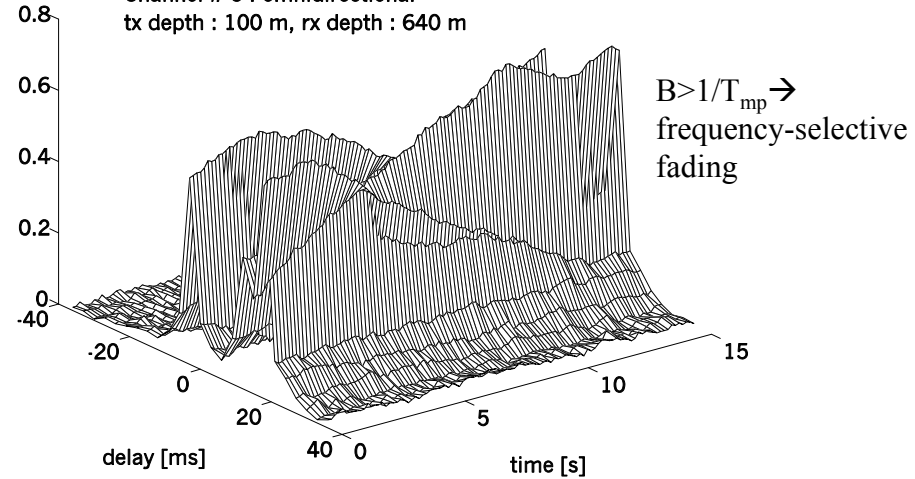
Communication channel / summary

Physical constraints of acoustic propagation:

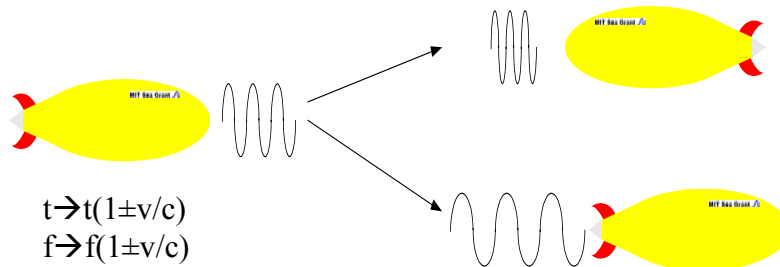
- limited, range-dependent bandwidth
- time-varying multipath
- low speed of sound (1500 m/s)



Range : 110 nautical miles
Rate : 333 sps
Channel # 6 : omnidirectional
tx depth : 100 m, rx depth : 640 m



Worst of both radio worlds
(land mobile / satellite)

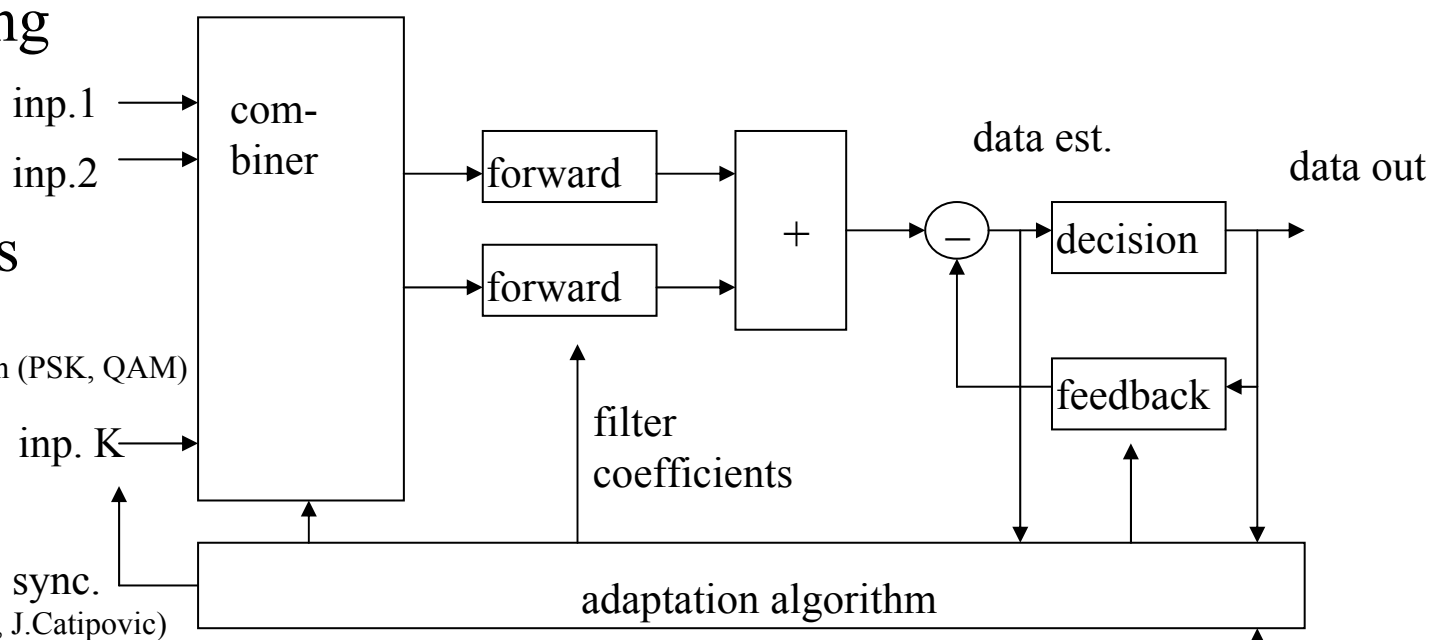


System constraints:

- transducer bandwidth
- battery power
- half-duplex

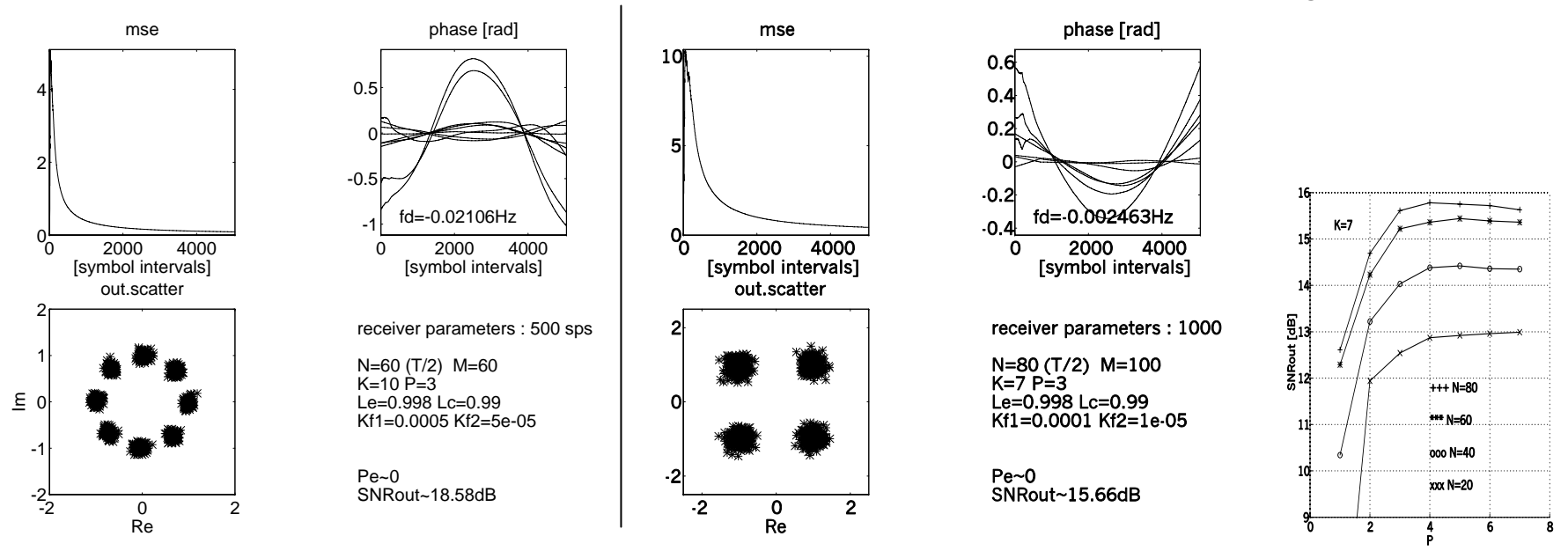
Signal processing for high rate acoustic communications

- Bandwidth-efficient modulation (PSK, QAM)
- phase-coherent detection:
- synchronization
- equalization
- multichannel combining



(JASA '95, with J.Proakis, J.Catipovic)

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



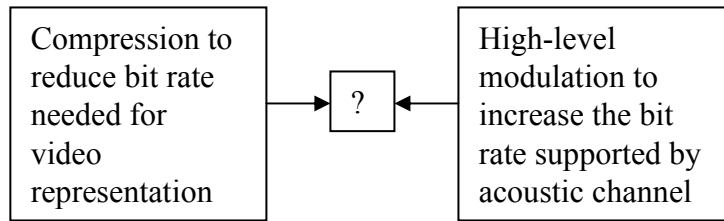
Real-time underwater video?

Underwater image transmission: sequence of images (JPEG) at < 1 frame/sec

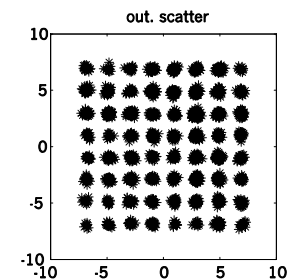
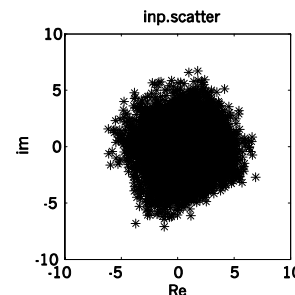
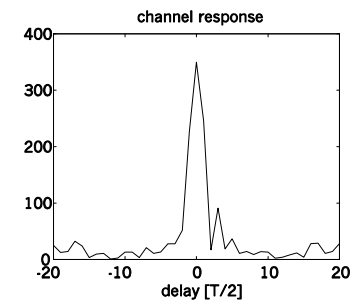
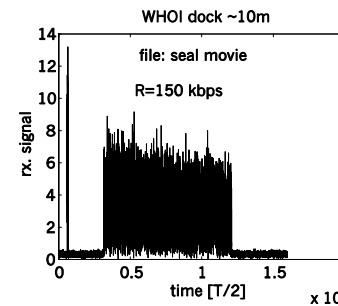
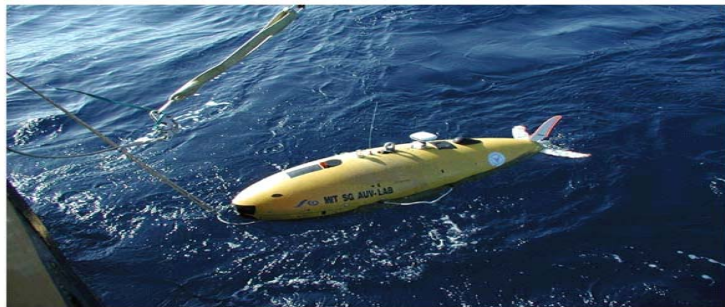
MPEG-4 : 64 kbps (video conferencing)

Can we achieve 100 kbps over an acoustic channel?

Playful
Harbour
Seal



Experiment:
Woods Hole, 2002
6 bits/symbol (64 QAM)
150 kbps in 25 kHz bandwidth



(IEEE Oceans '03, with C.Pepekanakis)

Current achievements

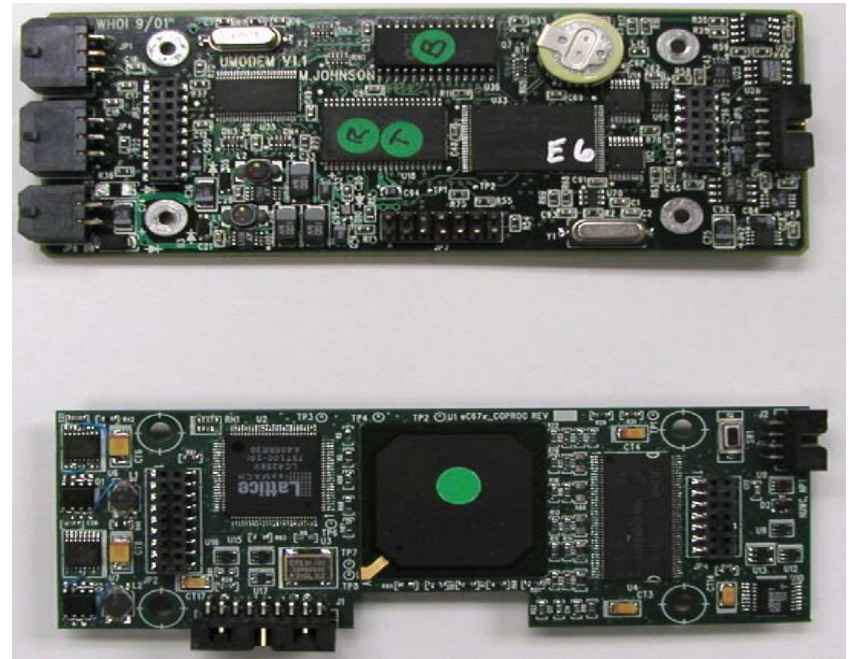
- Point-to-point (2/4/8PSK;8/16/64QAM)
medium range (1 km-10 km ~ 10 kbps)
long range (10 km – 100 km ~1 kbps)
basin scale (3000 km ~ 10 bps)
vertical (3 km~15kbps, 10 m~150 kbps)

- Mobile communications

AUV to AUV at 5 kbps

- Multi-user communications

five users, each at 1.4 kbps in 5 kHz band



Research in signal processing

Goals:

- low complexity processing
- improved performance
- better bandwidth utilization

Specific topics:

- spread spectrum communications (CDMA, LPD)
- multiple tx/rx elements (MIMO)
- multi-carrier modulation (OFDM)

WHOI micro-modem:

- Fixed point DSP
low rate FSK (~100 bps) w/noncoherent detection
- Floating point co-processor
high rate PSK (~5000 bps) w/coherent detection
(adaptive DFE, Doppler tracking, coding)
- 4-channel input
- 10-50 W tx / 3W rx (active)
- 1.75 in x 5 in.

Commercial modems: Benthos, LinkQuest.

Example: Application to oil-field monitoring

Q: Is real-time supervisory control of the AUV possible?

A: Not over long distances, where the propagation delay is many seconds, but possibly over short distances.

Bonus: The available acoustic bandwidth is much greater over short distances.

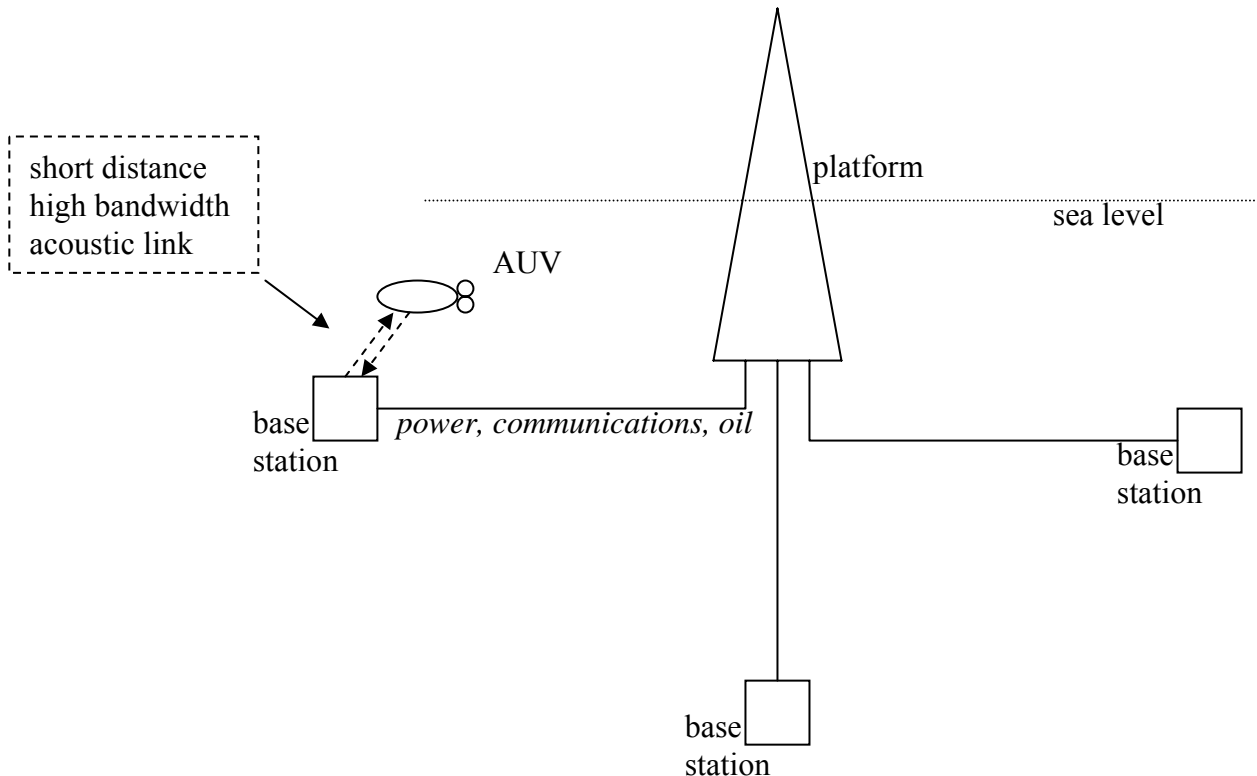
Example:

AUV to base range ~ 60 m.

acoustic link delay = 40 ms
cabled link delay = negligible

acoustic band ~ several 100 kHz
bit rate > 100 kbs : well within
current video compression technology

alternative: optical communication
high rate (Mbps)
low distance ~ 10 m



Open problems and future research

Fundamental questions:

Statistical channel modeling
Network capacity

Research areas:

Data compression

Signal processing for communications:

adaptive modulation / coding
channel estimation / prediction
multiple in/out channels (tx/rx arrays)
multi-user communications
communications in hostile environment

Communication networks:

network layout / resource allocation and reuse
network architecture / cross layer optimization
network protocols: all layers

Underwater optical communications:

blue-green region (450-550 nm)
+much higher bandwidth (~Mbps)
+negligible delay
-short distance (<100 m)

} complementary
to acoustics

Experimental networks:

System specification:

typical vs. application-specific (traffic patterns, performance requirements)
optimization criteria (delay, throughput, reliability, energy efficiency)

Concept demonstration:

simulation
in-water
prototypes

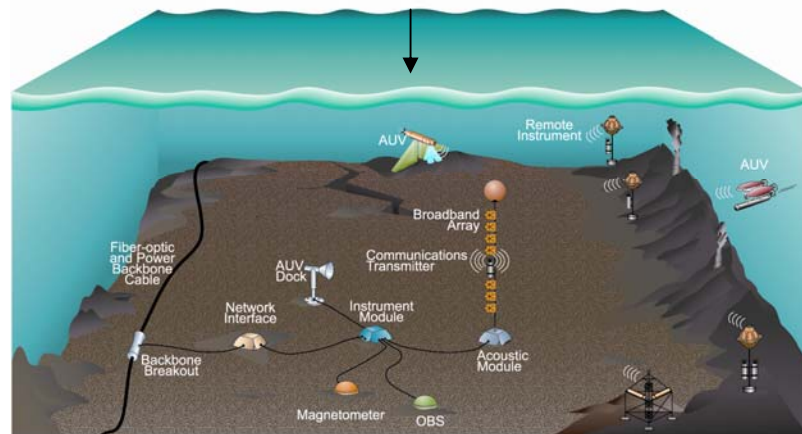
System integration:

Cabled observatories

Integration of wireless communications:

cabled backbone + mobile nodes = extended reach

Wireless extension: acoustical and optical



Deep-Sea Observatory with Acoustic Communications for AUVs and Instruments

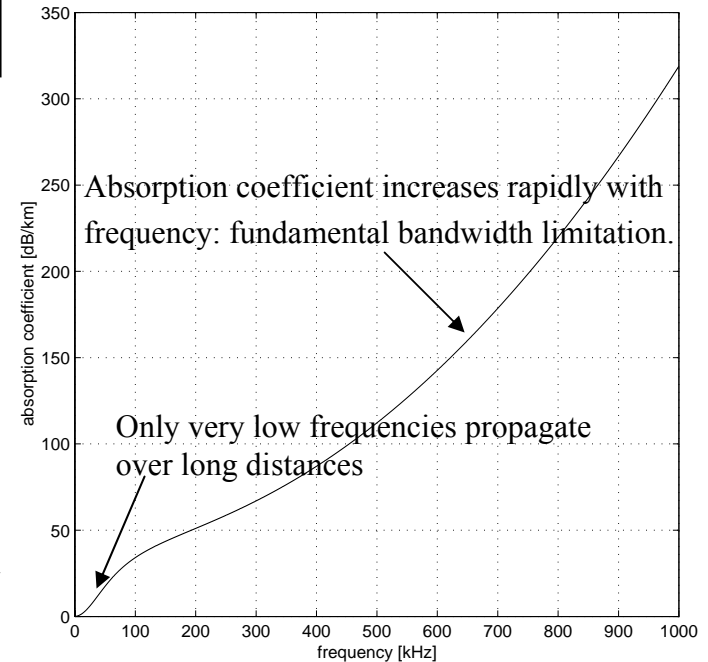


Channel characteristics: Attenuation and noise

Attenuation (path loss): $A(d,f) = d^k a(f)^d$

$$10 \log A(d,f) = \underbrace{10k \log d}_{\text{spreading loss}} + \underbrace{d \cdot 10 \log a(f)}_{\text{absorption loss}}$$

$$k = \begin{cases} 2 & \text{spherical spreading} \\ 1.5 & \text{practical spreading} \\ 1 & \text{cylindrical spreading} \end{cases}$$



Thorp's formula for absorption coefficient (empirical):

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 0.000275 f^2 + 0.003 \text{ dB/km, for } f \text{ [kHz]}$$

absorption \rightarrow fundamental limitation of maximal frequency

Noise

Site-specific:

- man-made
- biological (e.g., shrimp)
- ice cracking, rain
- seismic events

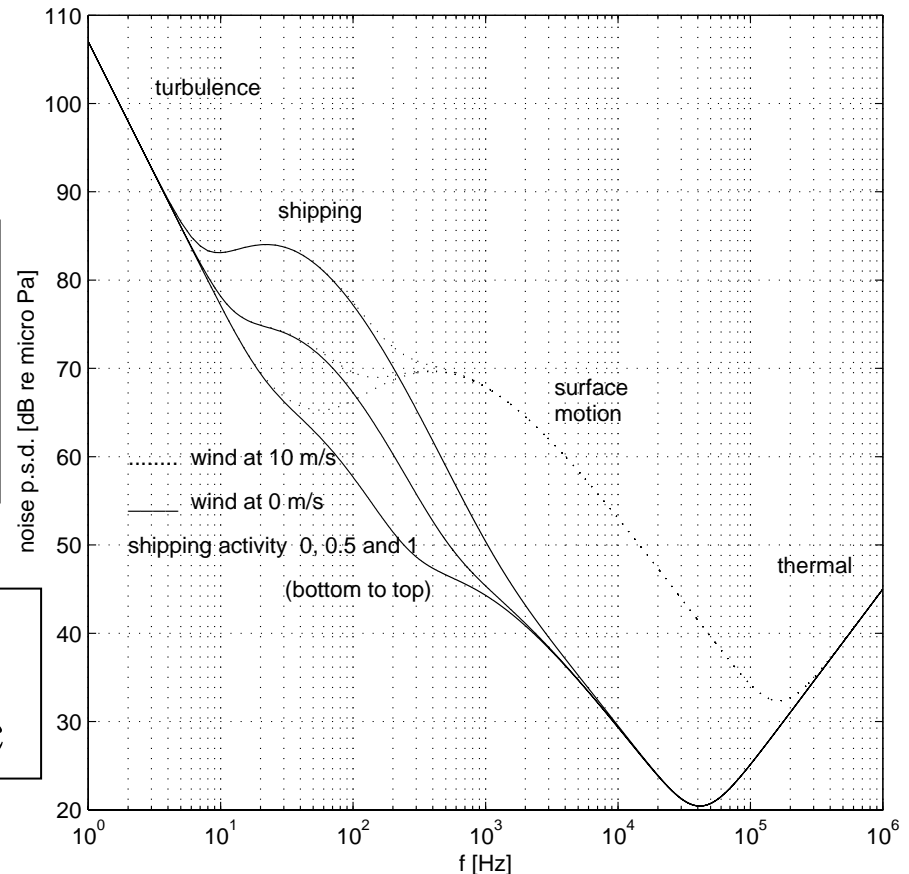
Majority of ambient noise sources:

- continuous p.s.d.
- Gaussian statistics

Approximation: $N(f) = Kf^b \rightarrow$
noise p.s.d. decays at $b = 18$ dB/dec

Ambient (open sea): p.s.d. [dB re μPa], f [kHz]

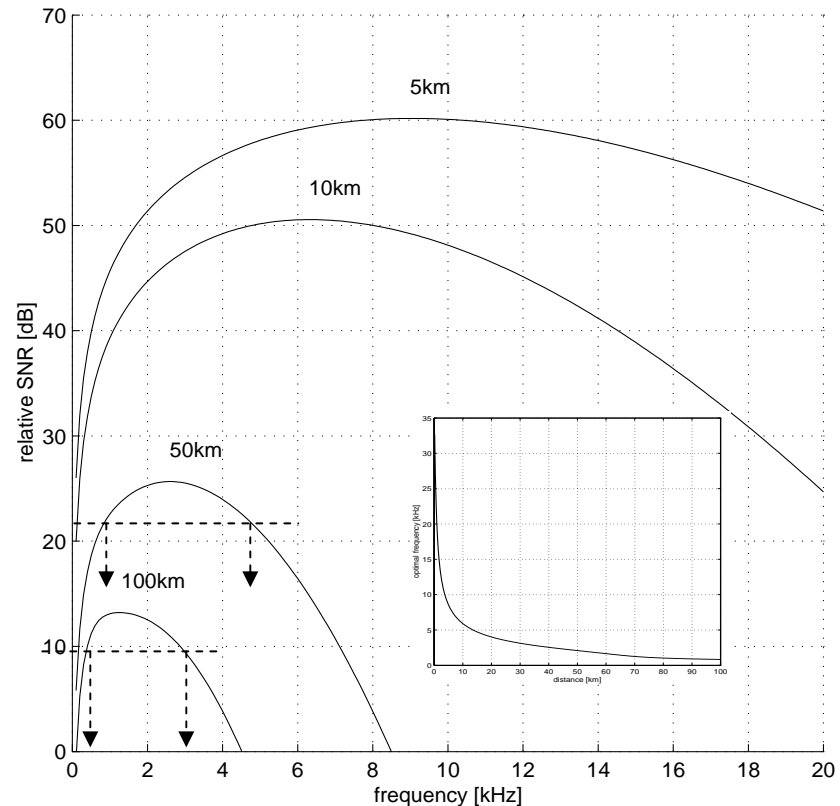
- turbulence: $17 - 30 \log f$
- shipping: $40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03)$
- surface: $50 + 7.5w^{0.5} + 20 \log f - 40 \log(f + 0.4)$
- thermal: $-15 + 20 \log f$



Signal to noise ratio (SNR)

$$\left. \begin{array}{l} P_R(d,f) \sim P_T/A(d,f) \\ P_N(f) \sim N(f)\Delta f \end{array} \right\} \text{SNR}(d,f) \sim -10 \cdot k \log d - d \cdot 10 \log a(f) - b \cdot 10 \log f$$

- There exists an optimal center frequency for a given distance.
- Bandwidth is limited: lower end by noise, upper end by absorption.
- Additional limitation: transducer bandwidth.

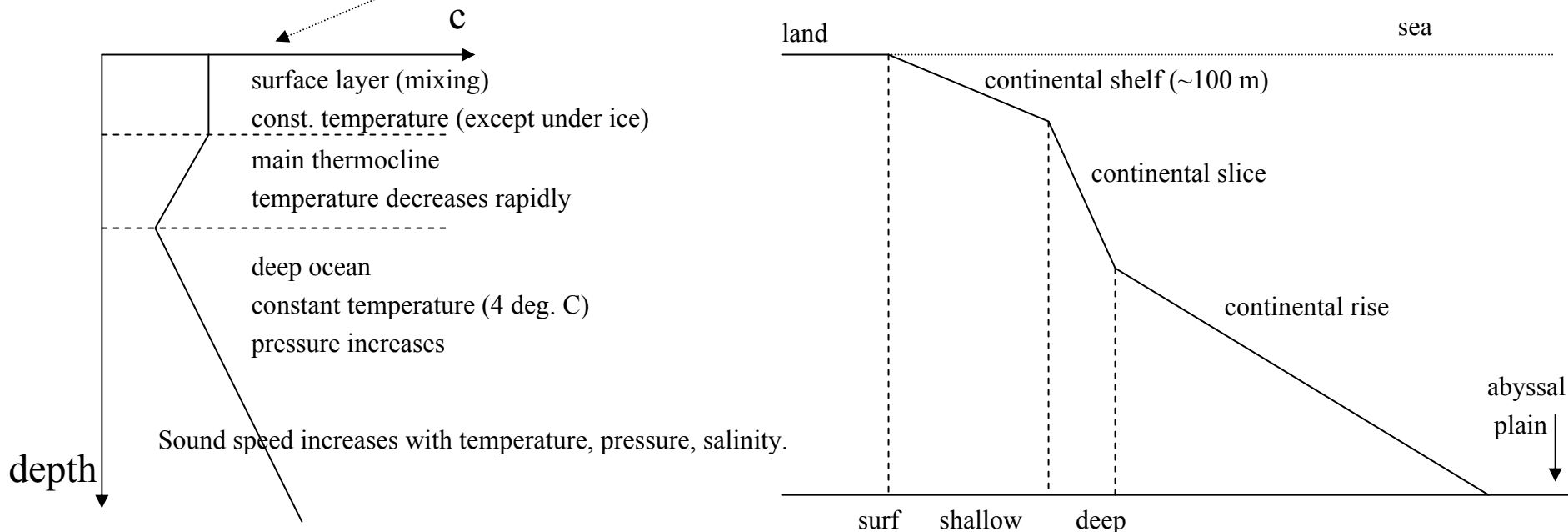


Bandwidth-efficient modulation needed for high-rate communications.

Many short hops offer larger bandwidth than one long hop (as well as lower energy consumption).

Multipath propagation

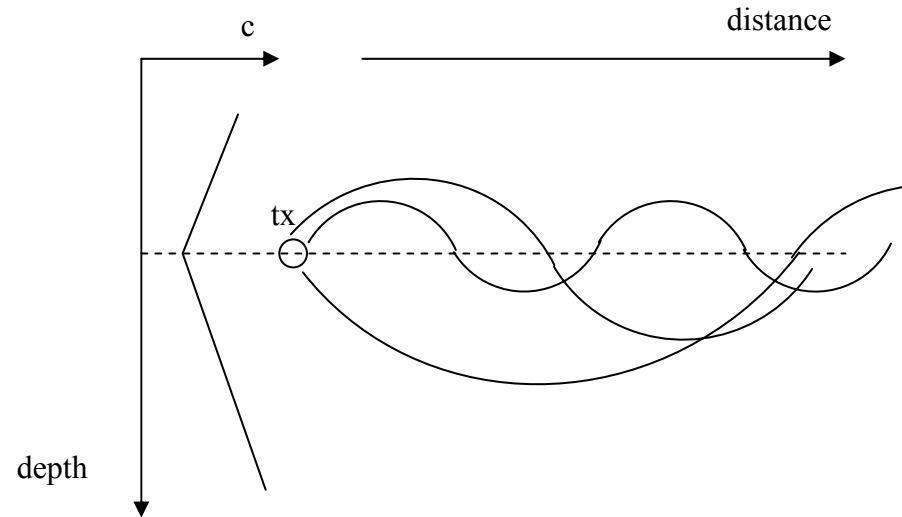
- Multipath structure depends on the channel geometry, signal frequency, sound speed profile.
- Sound pressure field at any location, time, is given by the solution to the wave equation.
- Approximations to this solution represent models of sound propagation (deterministic).
- Models are used to obtain a more accurate prediction of the signal strength.
- Ray model provides insight into the mechanisms of multipath formation:
 - deep water—ray bending
 - shallow water—reflections from surface, bottom, objects.



Mechanisms of multipath formation

Deep water: a ray, launched at some angle, bends towards the region of lower sound speed (Snell's law).

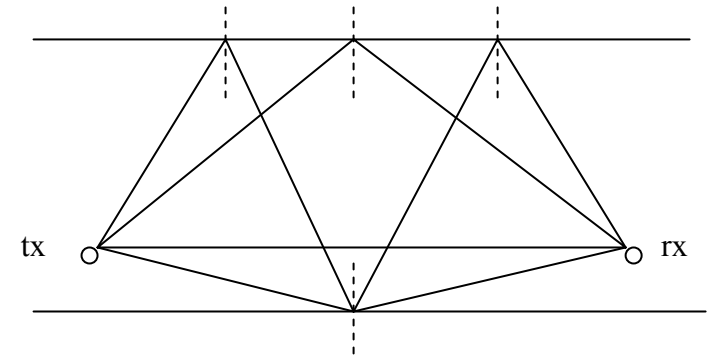
Continuous application of Snell's law \rightarrow ray diagram (trace).



Deep sound channeling:

- rays bend repeatedly towards the depth at which the sound speed is minimal
- sound can travel over long distances in this manner (no reflection loss).

Shallow water: reflections at surface have little loss; reflection loss at bottom depends on the type (sand, rock, etc.), angle of incidence, frequency.



Multipath gets attenuated because of repeated reflection loss, increased path length.

Length of each path can be calculated from geometry:

l_p : p^{th} path length

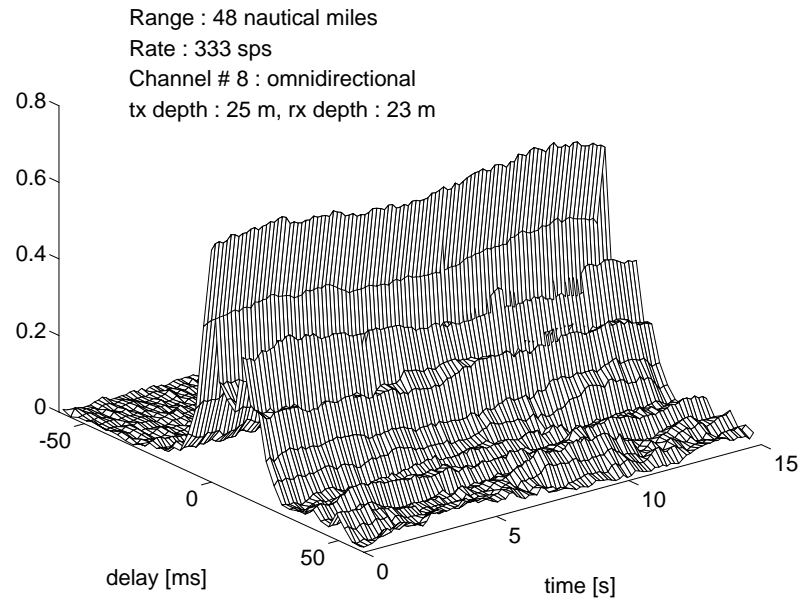
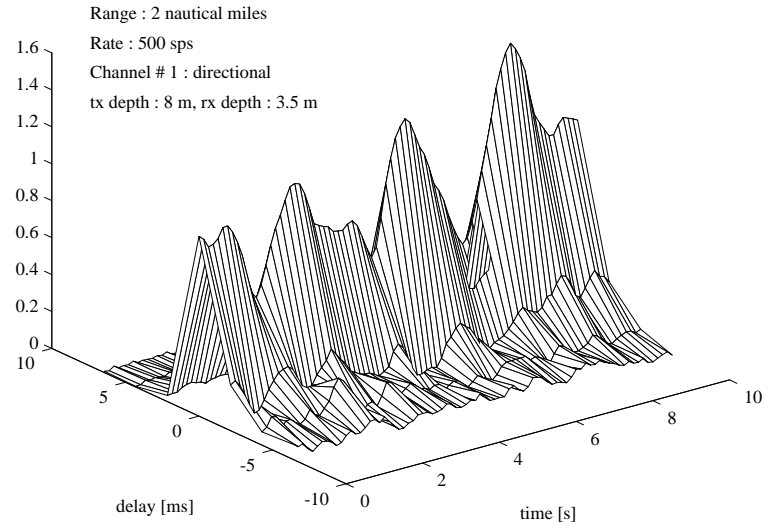
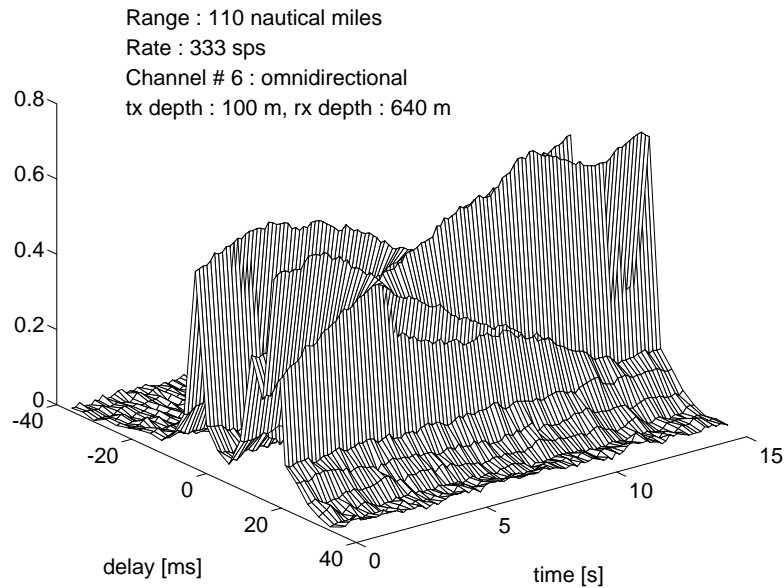
$\tau_p = l_p / c$: p^{th} path delay

$A_p = A(l_p, f)$: p^{th} path attenuation

Γ_p : p^{th} path reflection coefficient

$G_p = \Gamma_p / A_p^{1/2}$: path gain

Examples: ensembles of measured channel responses



Time variability:

- Inherent: internal waves, changes in fine vertical structure of water, small-scale turbulence, surface motion
- Motion-induced: $v/c \sim 10^{-3}$ at $v \sim$ few knots, $c = 1500$ m/s!

Propagation speed

Nominal: $c=1500$ m/s (compare to $3 \cdot 10^8$ m/s!)

Two types of problems:

- motion-induced Doppler distortion ($v \sim$ few m/s for an AUV)
- long propagation delay / high latency

