# Wireless Underwater Communications and Networks: Current Achievements and Future Research Challenges

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# Overview

- Introduction
- Channel characteristics
- Signal processing: bandwidth-efficient underwater acoustic communications
- Underwater networks: channel sharing and multiple-access
- Future research and open problems

# Background

Motivation:

- Major scientific discoveries of the past decade (e.g., hydro-thermal vents): cabled submersibles
- Cables are heavy, deployment is expensive
- Wireless information transmission through the ocean:
  - Remote control of robots, vehicles
  - Remote data retrieval

- Wireless communication:
  - radio (30Hz-300Hz, very high attenuation)
  - optical (short distance, pointing precision)
  - acoustic
- History:
  - underwater telephone (analog modulation, 8-11 kHz).
  - DSP technology: acoustic modems (few kbps/few km).
- Research growing with new applications (and vice versa).

# Applications: ocean observation

- Environmental monitoring
  - climate recording
  - pollution control
  - prediction of natural disasters
  - oil/gas fields
  - harbor protection

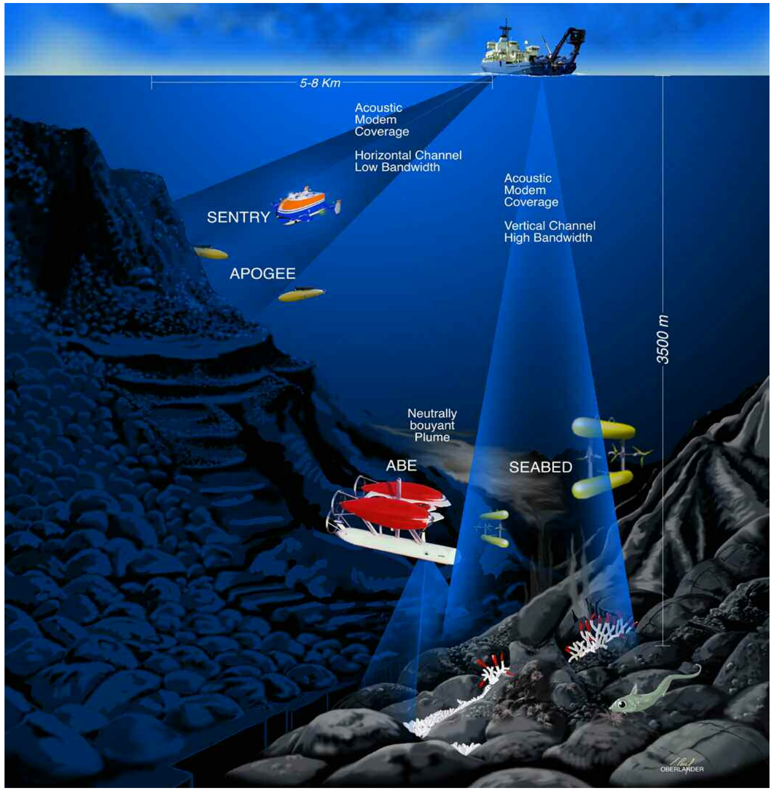
- Underwater exploration
  - discovery of natural resources
  - marine phenomena
  - deep-sea archaeology

- Scientific data collection
  - oceanography
  - geo-sciences (physics/chemistry)
  - marine biology

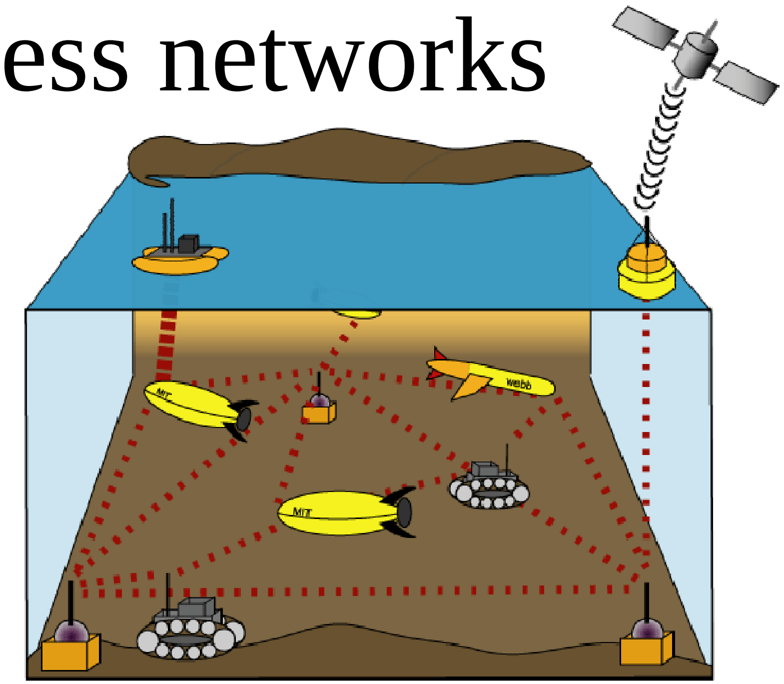
- Search and survey, military and non-military
  - detection of objects
  - ocean bottom imaging and mapping

# Underwater wireless networks

- 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




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

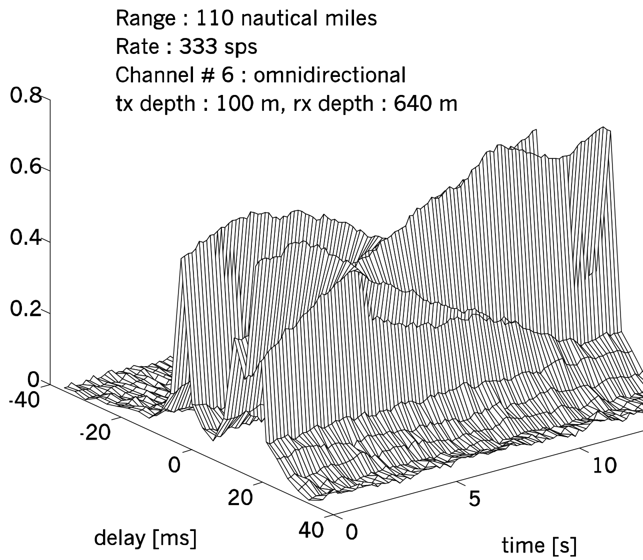



- Types of nodes:
  - fixed, slowly moving, mobile
  - sensors, relays, gateways
- Types of signals, system requirements:
  - low/high rate (~100 bps-100kbps)
  - real-time/non real-time
  - high/moderate reliability
- Configurations:
  - stand alone
  - integrated (e.g., cabled observatories)

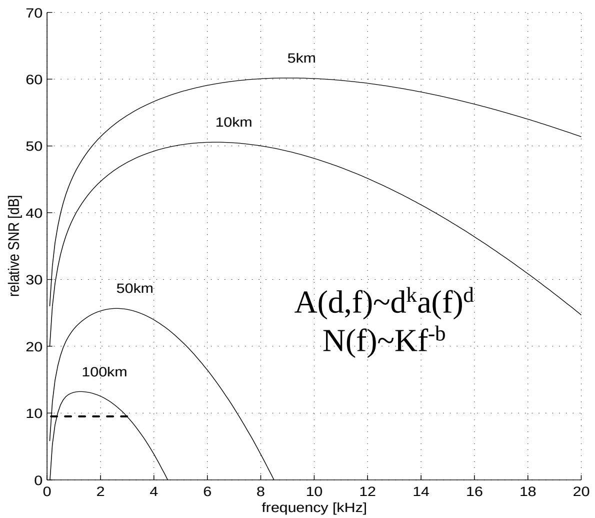
# Communication channel

Physical constraints of acoustic propagation:

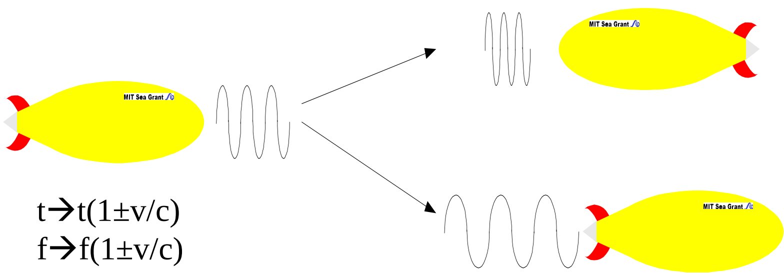
- limited, range-dependent bandwidth
- time-varying multipath
- low speed of sound (1500 m/s)




$B > 1/T_{mp} \rightarrow$ frequency-selective fading




Worst of both radio worlds (land mobile / satellite)



$t \rightarrow t(1 \pm v/c)$
$f \rightarrow f(1 \pm v/c)$

System constraints:

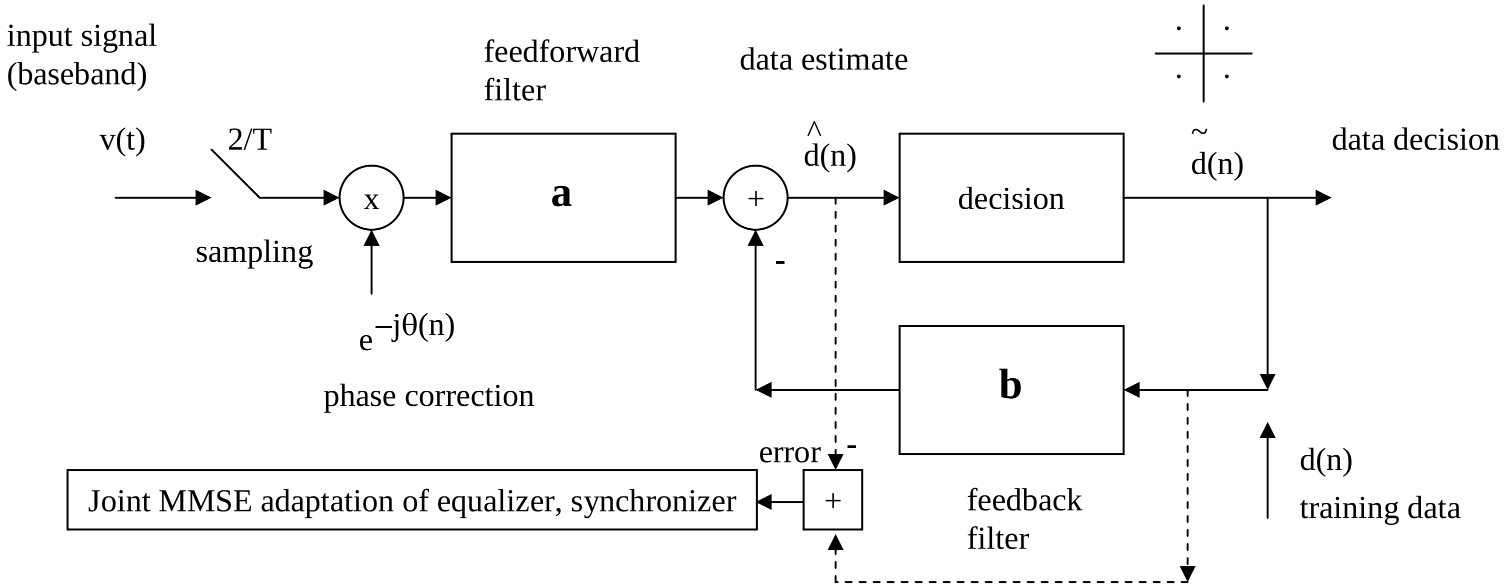
- transducer bandwidth
- battery power
- half-duplex

# Summary of channel characteristics

| Channel parameter | Acoustic/radio difference | Implications for signal processing, network design |
|---|---|---|
| Bandwidth/SNR | Bandwidth severely limited<br>Bandwidth depends on distance | Need for data compression, bandwidth-efficient modulation<br>Network topology selection, resource sharing and reuse |
| Fading/multipath | ISI spans tens of symbols<br>Fading/outage models not known | Adaptive equalization, array processing<br>Need for dynamic protocols, x-layer optimization |
| Speed of sound | Typical v/c value higher by several orders of magnitude, severe Doppler distortion<br>Very long propagation delay | Synchronization (phase, delay)<br>Channel feedback latency<br>Throughput efficiency of network protocols |

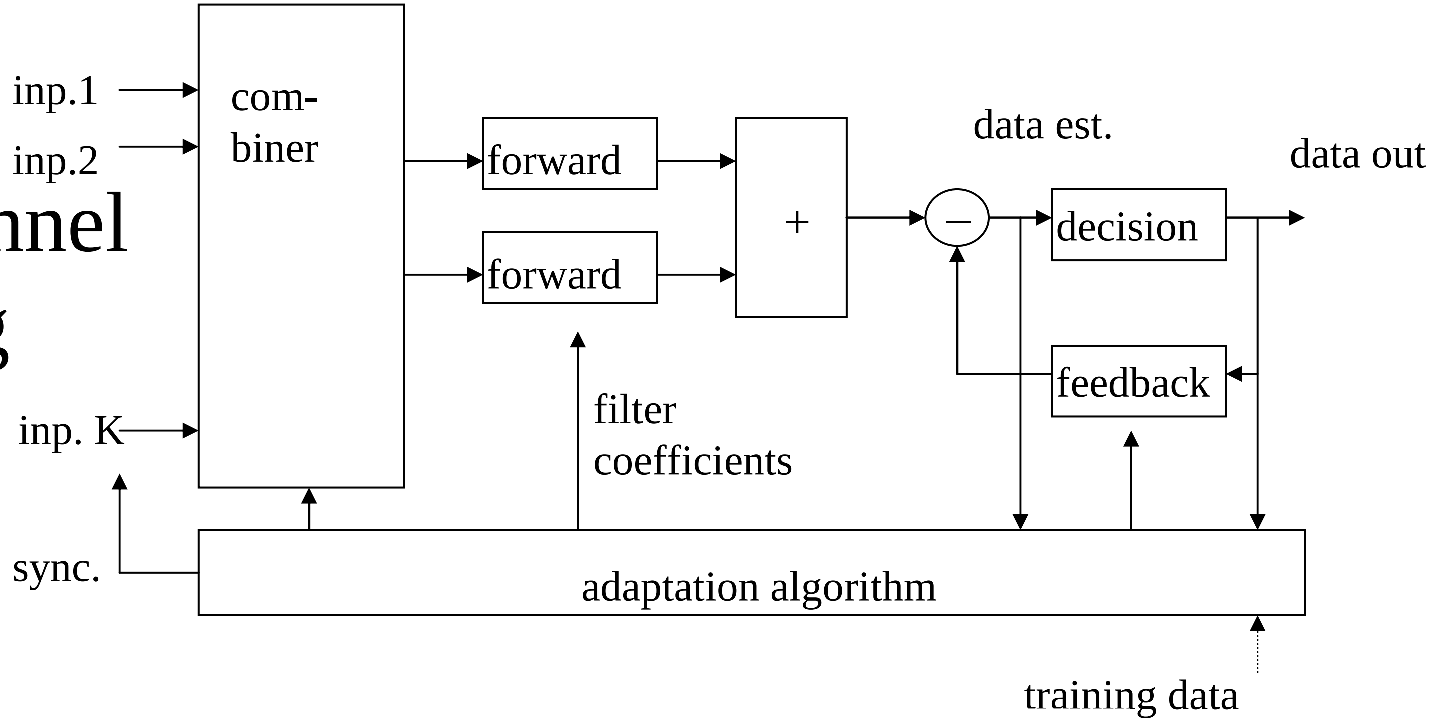
# Signal processing for high-rate underwater acoustic communications

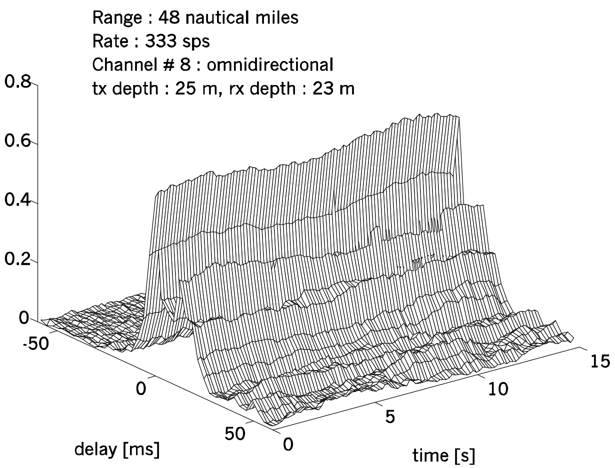
- Bandwidth-efficient modulation ($R_b/B>1$ bps/Hz ): PSK, QAM
- Coherent detection:
  - decision-feedback equalization
  - phase and delay synchronization

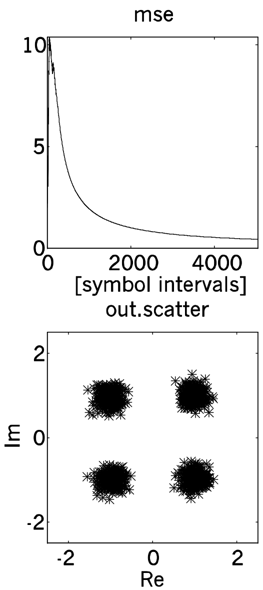


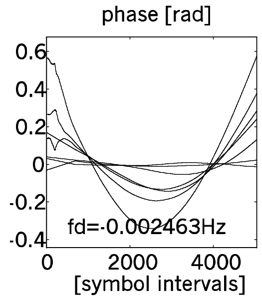

(IEEE JOE ‘94, with J.Proakis, J.Catipovic).

# Multi-channel combining



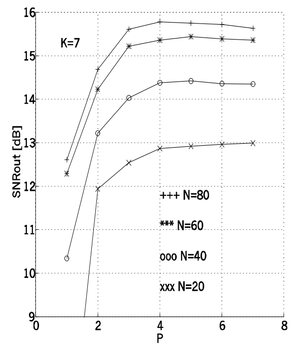




receiver parameters : 1000 sps

N=80 (T/2) M=100
K=7 P=3
Le=0.998 Lc=0.99
Kf1=0.0001 Kf2=1e-05

Pe~0
SNRout~15.66dB




Example:
New England Continental Shelf

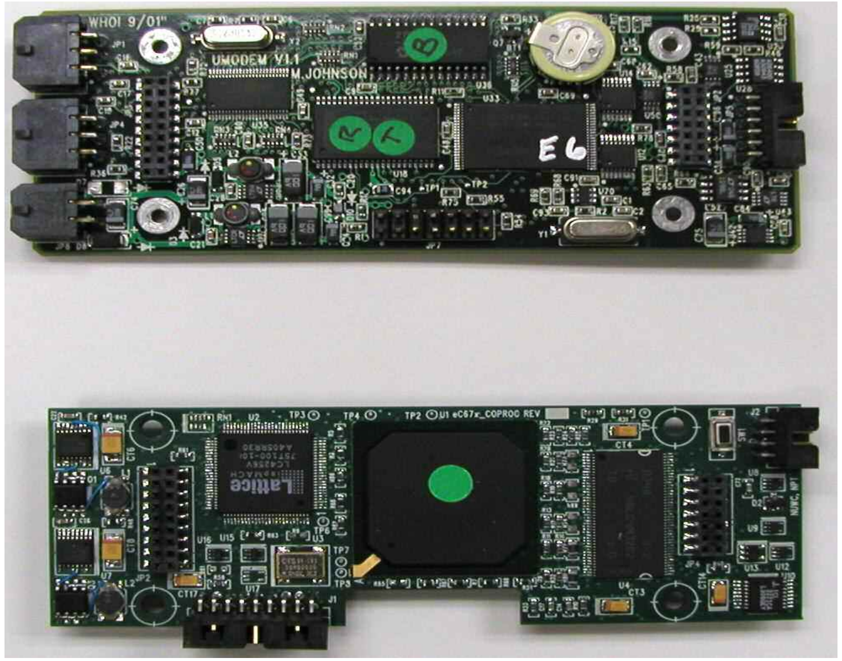
(JASA ‘95, with J.Proakis, J.Catipovic)

# 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)

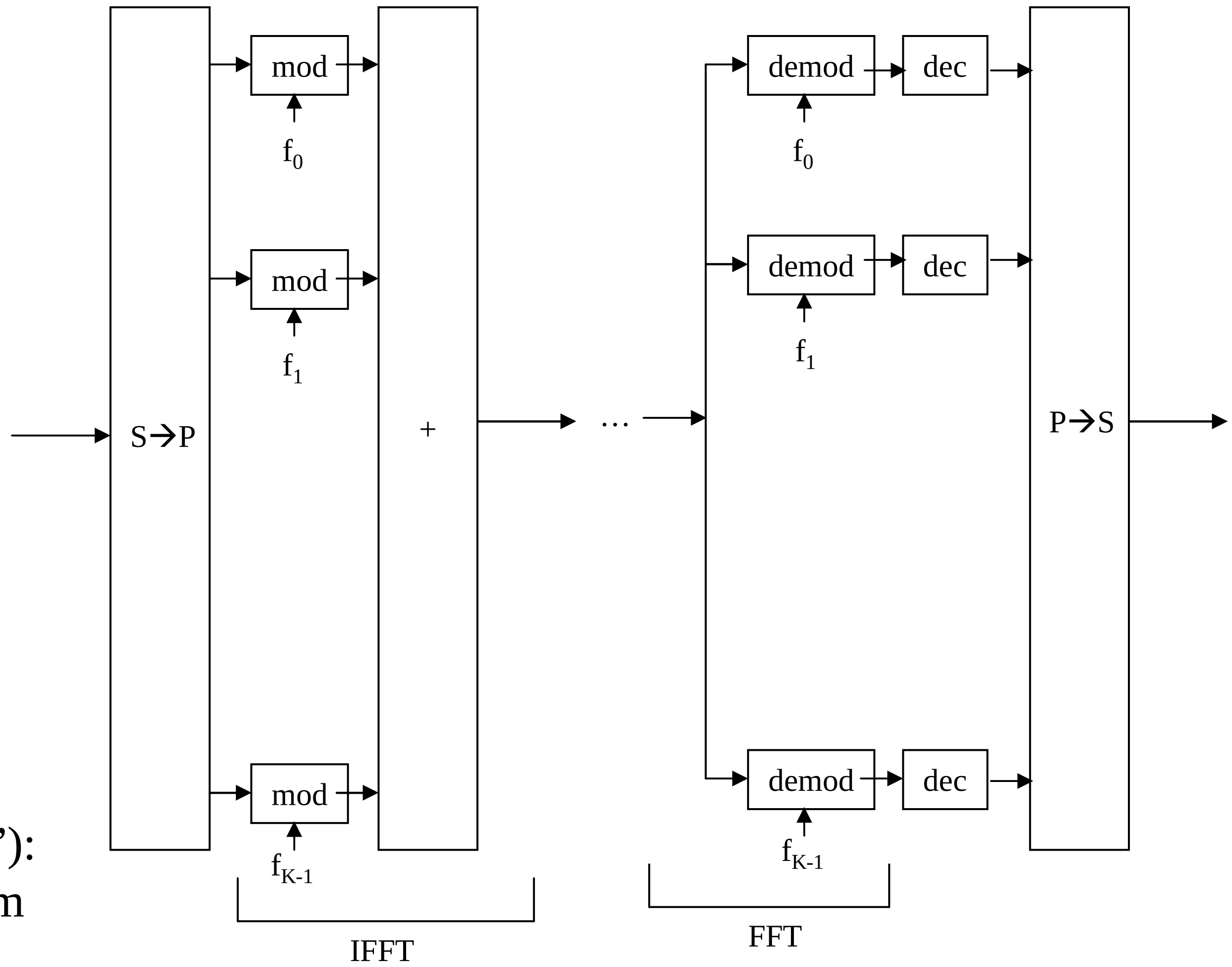
WHOI micro-modem:
- Fixed point DSP
  low rate FSK (~100 bps) w/noncoherent detection
- Floating point co-processor
  high rate PSK (~5000 bps) w/coherent detection
  (adaptive DFE, Doppler tracking, coding)
- 4-channel input
- 10-50 W tx / 3W rx (active)
- 1.75 in x 5 in.

# Multi-carrier modulation / orthogonal frequency division multiplexing

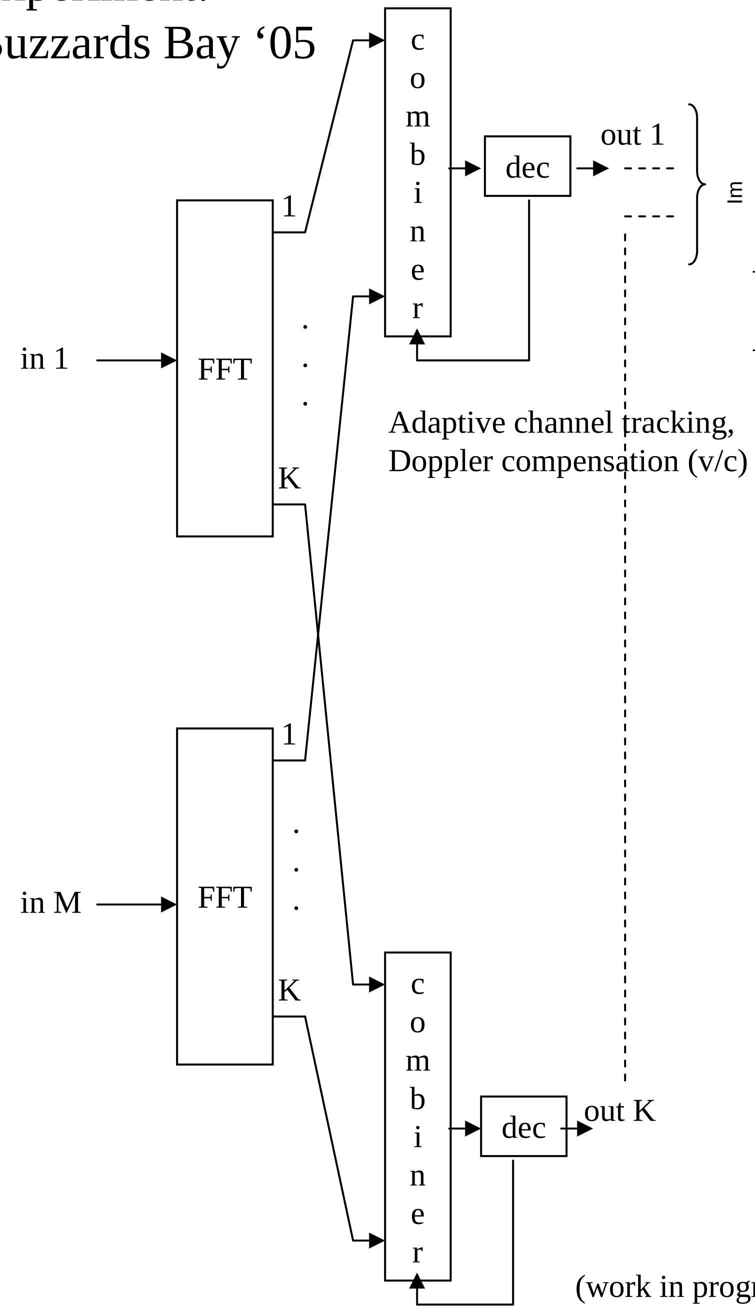
- Available bandwidth divided into narrow sub-bands: channel appears ideal (flat) in each sub-band
- OFDM: efficient implementation via FFT

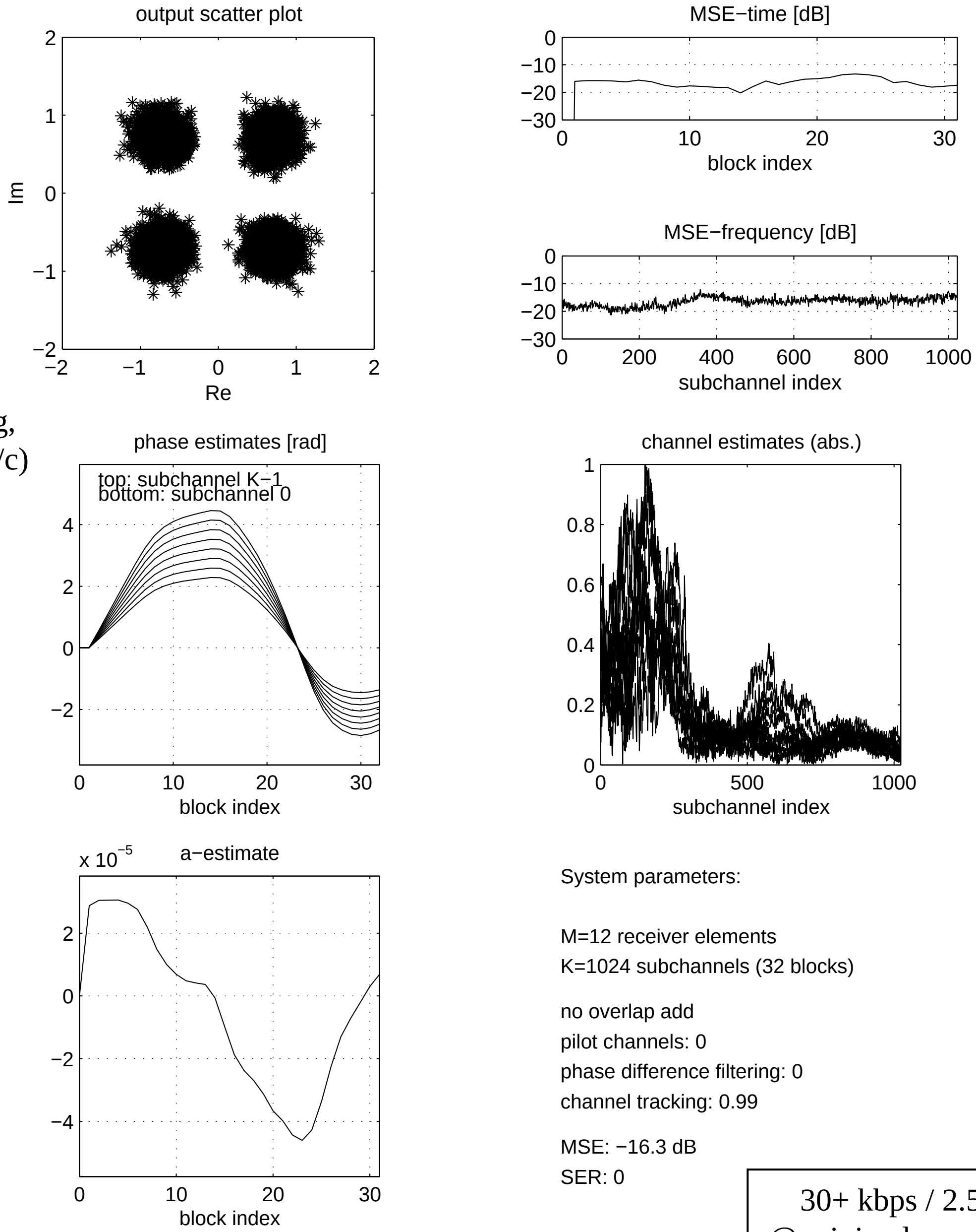
+Low-complexity equalization (frequency-domain)
-High sensitivity to frequency offset

- High-rate acoustic system is inherently wideband ("UWB"): Doppler distortion is not uniform across sub-bands



# Experiment:
# Buzzards Bay ‘05




System parameters:

M=12 receiver elements
K=1024 subchannels (32 blocks)

no overlap add
pilot channels: 0
phase difference filtering: 0
channel tracking: 0.99

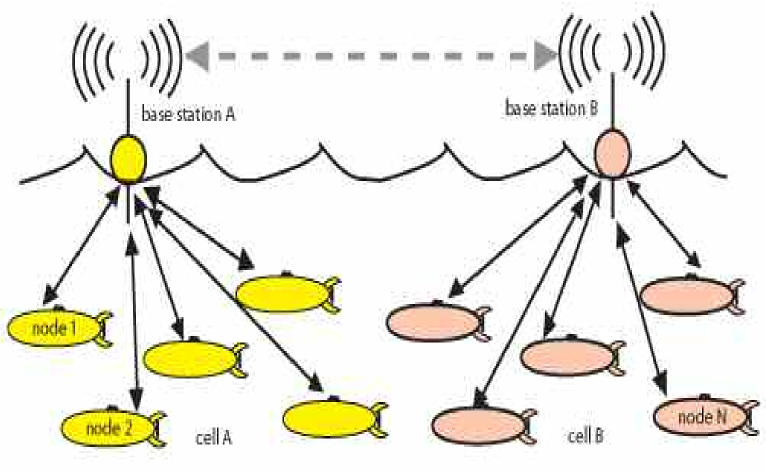
MSE: −16.3 dB
SER: 0

30+ kbps / 2.5 km
@ minimal complexity

(work in progress; IEEE Oceans ‘06)

# Future autonomous underwater systems: network topologies

- Centralized

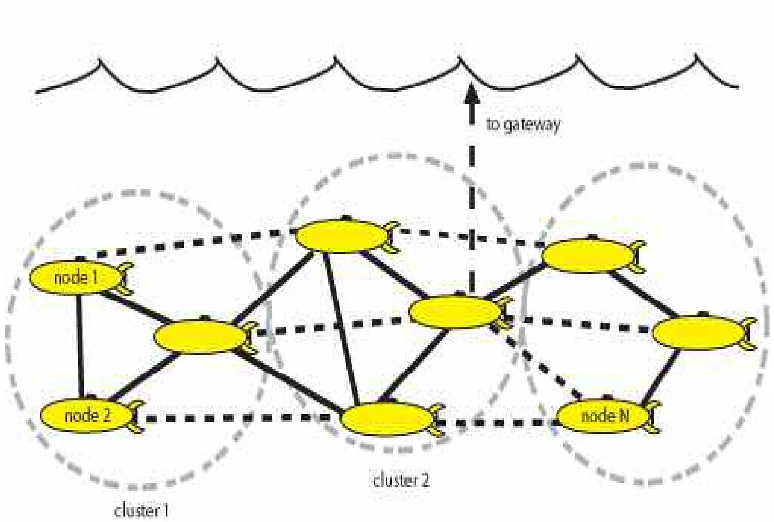



Nodes communicate via a central station (cellular network paradigm).

Channel must be shared—regulation of multiple access.

Central stations are connected through a separate infrastructure (cable on the bottom, radio on the surface).

- Decentralized




Nodes communicate through neighbors (ad hoc network paradigm).

Messages must be relayed to reach destination—regulation of channel access.

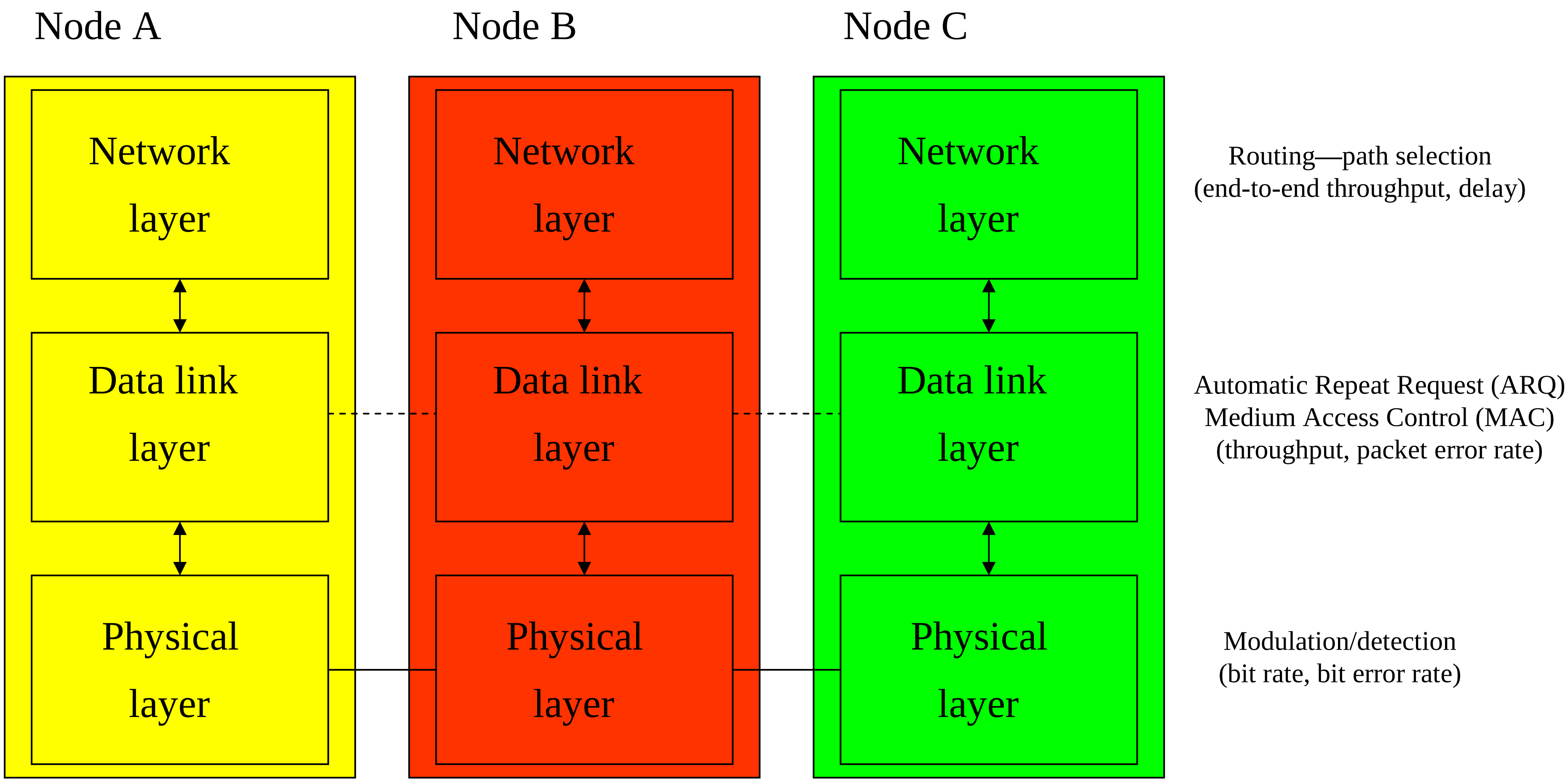
There may be an end node to gateway. Nodes may form clusters.

**Open problems** (There are no operational autonomous underwater networks, only isolated experimental demonstrations):

Capacity of an acoustic network? (Energy and bandwidth depend on inter-node distance.)

Efficient and scalable channel sharing protocols? (Speed of sound is five orders of magnitude less than speed of electro-magnetic waves.)

# Network architecture

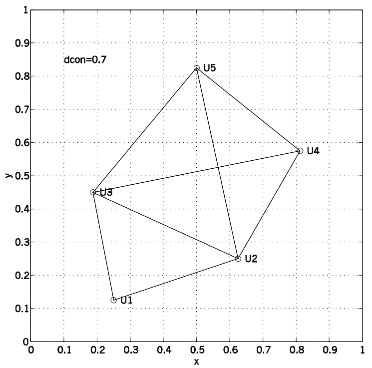


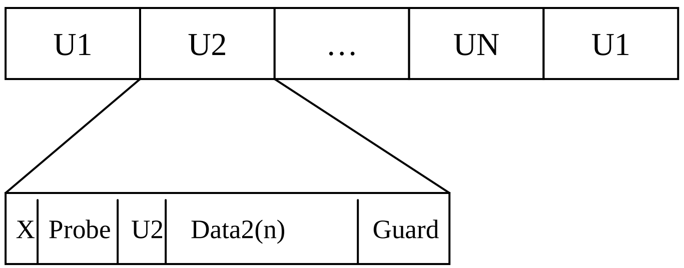

Each layer assumes perfect operation of the layer below.
There may be a total of five or more layers (transport, application).

# Channel sharing (access regulation)

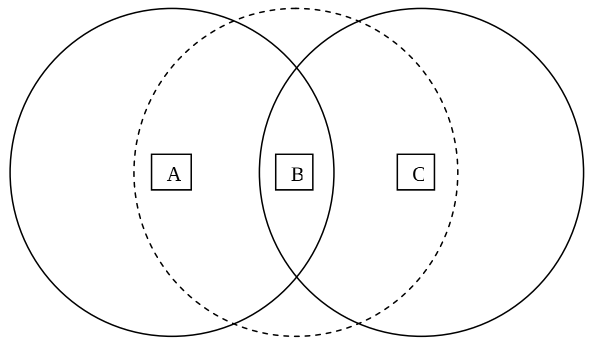
- Deterministic/scheduling
- Multiple access: frequency, time code division (FDMA, TDMA, CDMA); also space division.
- Continuous traffic, fixed number of users
- Complex, low overhead
- Scalability? Spatial reuse for efficient resource allocation (power, bandwidth).

- Random/contention
- Aloha, Carrier Sensing Multiple Access (CSMA), Multiple access with Collision Avoidance (MACA)
- Bursty traffic, variable number of users
- Simple, high overhead (RTS/CTS)
- Scalable.




Ex: N<5 for 10 sec. updating, 1km x1km, 1 sec. packet



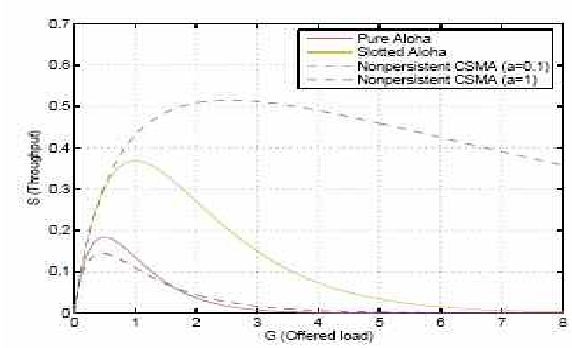

A sends RTS, including packet length.
B hears, replies with CTS including packet length;
C hears B, defers transmission to let B receive data packet.

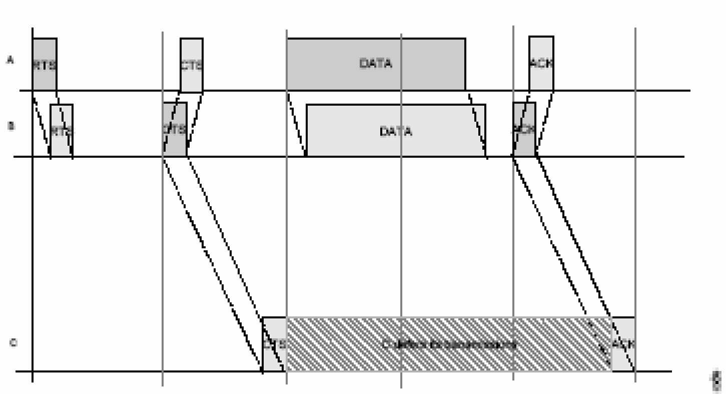
The two strategies can be combined: reservation-based protocols.

# Medium Access Control (MAC)

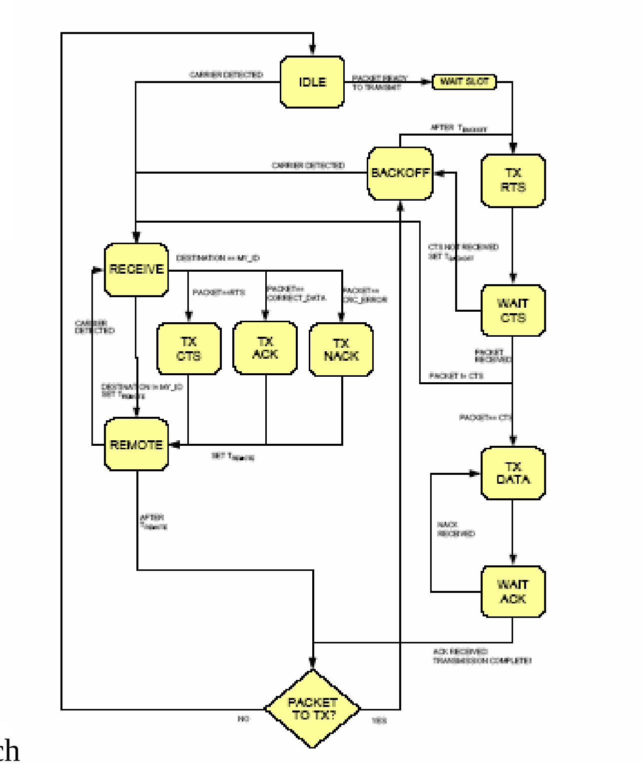
- Acoustic channel: extremely long delay→ collisions should be avoided
- Aloha: does not avoid collisions
- CSMA: good only when delay << packet duration
- MACA: to avoid collisions must have RTS/CTS > delay (control packet > data packet!)
- Collisions waste time and energy

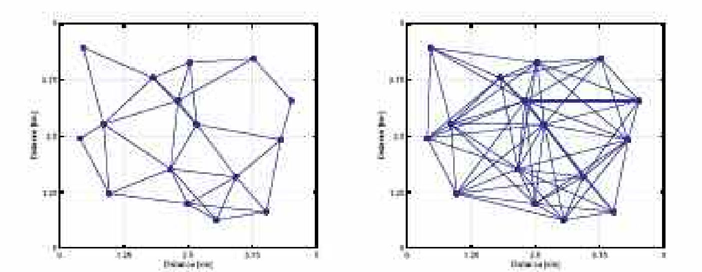
→Slotted MACA: slot > delay + RTS/CTS



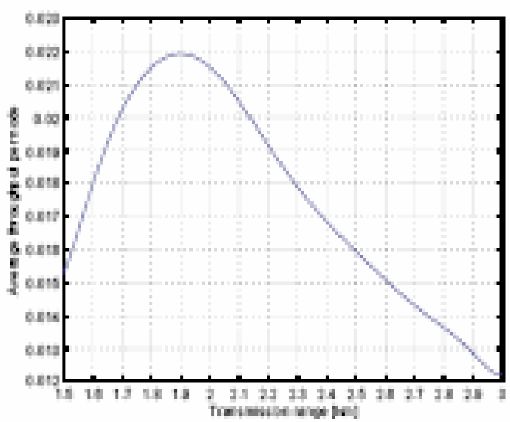

Q: What tx power to use?
Criterion: max. throughput
(packet time / average time for successful transmission)



(a) $Radius = 1.75km$ (b) $Radius = 2.5km$

Simulation: 16 AUVs, 5km x 5km, 5 kt, random direction change, 1 kbps.



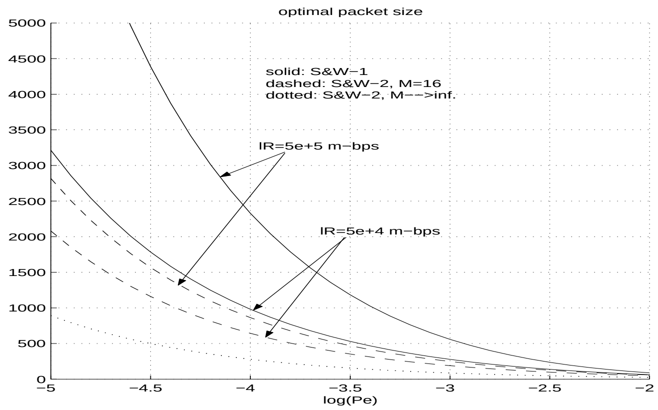
A: There exists optimal tx power, which can be calculated for a given system.

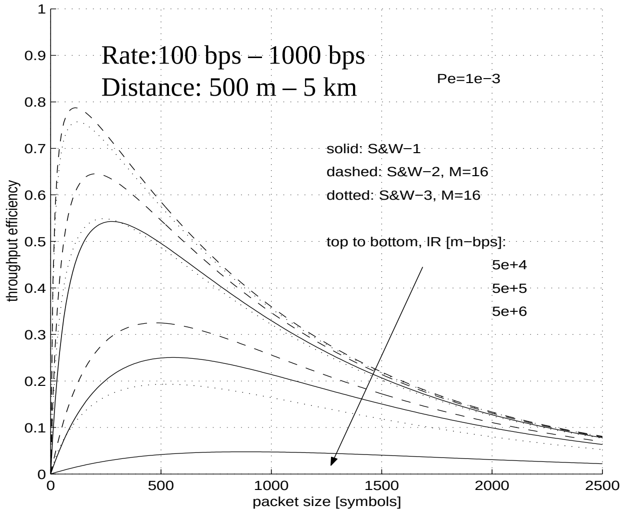
(IEEE Oceans ’06, with M. Molins)

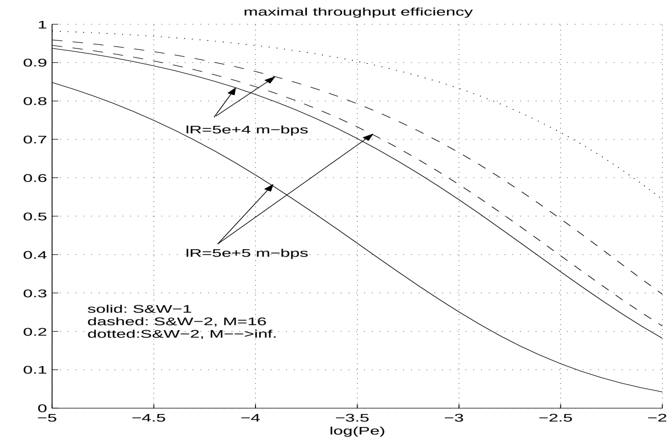
# Reliable packet transmision

(IEEE Oceans ’05)

•Data link layer ARQ
•Acoustic modems: half-duplex → ARQ based on Stop & Wait
•Acoustic channel: varying BER, long waiting time→ poor throughput efficiency = packet time / average time needed for successful packet transmission
•longer packet: better utilization of waiting time, but greater chances of packet error→ optimal packet length
•Selective S&W with M packets/group:



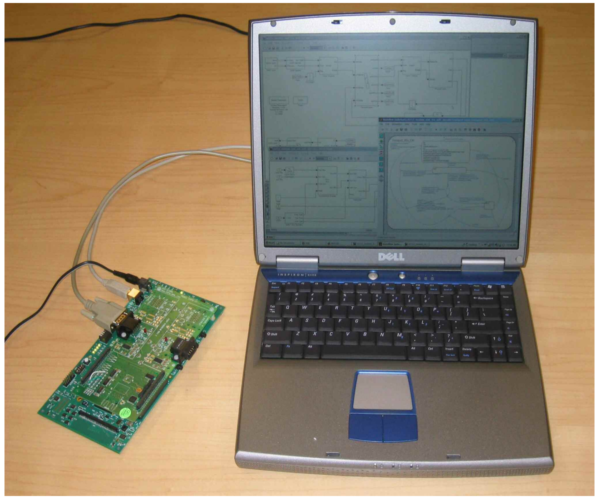



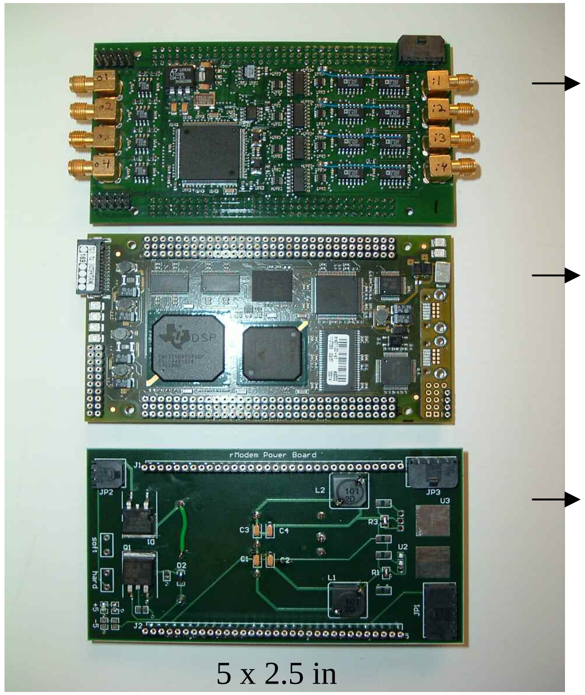

Analytical results:
•Optimal packet size depends heavily on BER, rate-distance product.
•By increasing the group size M, the problem of delay can be overcome. Maximal throughput efficiency remains limited by BER.

Future work:
•Adaptive ARQ for time-varying channels.
•Practical implementations.

# Experimental acoustic networks

- No widely accepted channel models → experimental demonstration remains de-facto standard.
- Need easily programmable and deployable networking platforms.
- Reconfigurable modem: Matlab Simulink + TI DSP=flexible, modular (software radio concept).






→ A/D and D/A board: 250 kHz sampling,
100 kHz max. frequency,
4 in/out channels.

→ Micro-line board:
TMS 320C6713 floating-point DSP,
Xilinx Virtex-II FPGA

→ Power supply carrier board (12-36 V).

Current software:
Packetizing and packet synchronization
PSK/DPSK, QAM modulation
Multi-channel decision feedback equalization
Convolutional coding, Viterbi decoding
In progress:
Doppler compensation, OFDM, FSK
MACA protocol
Hardware: power amplifier, transducer, housing.

Matlab to C code: Real Time Workshop
Compiling, downloading: Code Composer Studio

Future work (with E. Sozer):
First field test: summer 06?
Goals: open testing platform for signal processing algorithms, network protocols
in-house acoustic network.

# Open problems and future research

**Fundamental questions**:
Statistical channel modeling
Network capacity

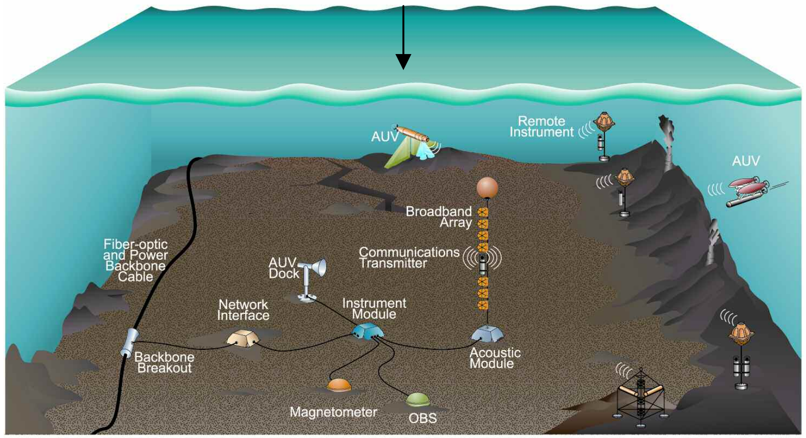
**Research areas**:
Data compression
Signal processing for communications:
adaptive modulation / coding
channel estimation / prediction
multiple in/out channels (tx/rx arrays)
multi-user communications
communications in hostile environment
Communication networks:
network layout / resource allocation and reuse
network architecture / cross layer optimization
network protocols: all layers

**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

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

} complementary to acoustics



Deep-Sea Observatory with Acoustic Communications for AUVs and Instruments