"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)
Underwater Sensor Networks:
Random Access and Compressive Censing

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Underwater wireless communications

Why?

Major scientific discoveries: cabled submersibles
Cables are heavy (tons!), 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: very high attenuation (~m @ 10kHz)
Optical: blue/green, short distances (<100m), pointing precision
Acoustical: a solution for anything over 100 m (but low bandwidth)

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, operational hardware

What is next?

More signal processing, channel characterization, networks.
Overview

communication channel: basics

signal processing: current capabilities

underwater sensor networks: random access and compressive sensing
**Underwater acoustic channel: attenuation and noise**

\[ A(x,f) \sim x^k a(x,f) \]

spreading + absorption

(k:1-2)

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

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

\[ 10 \log N(f) \]

\[ = 10 \log f \]

\[ = 10 \log f \]

-10 \log A(x,f)N(f)

fundamental limitation (also transducer)

\[ \text{noise}=\text{turbulence}+\text{shipping}+\text{surface}+\text{thermal}+\text{other} \]

\text{site-specific: man-made biological ice, rain seismic}

\[ "UWA=UWB" \]
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 for “high” bit rates
- cannot use signal processing methods that rely on narrowband assumption
Multipath propagation

- Surface layer (mixing)
- Constant temperature (except under ice)
- Main thermocline
- Temperature decreases rapidly
- Deep ocean
- Constant temperature (4 deg. C)
- Pressure increases

Sound speed increases with temperature, pressure, salinity.

Channel variation: tx/rx displacement, surface motion, internal waves, turbulence, fine changes in the sound speed profile.

Multipath spread ~ 10 ms, 100 ms
Coherence time ~ 0.1 s, 1 s?
Examples: measured channel responses

There are no widely accepted statistical channel models.
Time variability

(1) inherent: random $\rightarrow$ adaptive channel estimation, equalization
(2) motion-induced: deterministic $\rightarrow$ synchronization

Doppler effect:

\[ t \rightarrow t+at \]
\[ f \rightarrow f+af \]

\[ a=v/c \]

\[ v \sim \text{m/s} \quad \text{with or without intentional motion} \]
\[ c=1500 \text{ m/s} \]
\[ a\sim10^{-4} \quad \text{comparable only to LEO satellite systems} \]

...respect the physics of the channel ...
Single-carrier systems

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

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)

Mobile communications
AUV to AUV at 5 kbps

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

"the faster the better"
Multi-carrier systems

OFDM: low complexity “equalization”

problem: carrier offset

Also:
- MIMO OFDM
- adaptive bit loading

radio: WLAN, DAB/DVB, LTE
acoustic: single-carrier

2.5 km, 22-46 kHz

30 kbps @ min complexity

transfer function of the channel

\[ f_k \rightarrow f_k(1+a) \]

\[ B = K \Delta f \]

\[ a = \frac{v}{c} \]

\[ \text{FFT} \]

\[ \text{dec} \]

\[ \text{combiner} \]
Underwater acoustic networks

industry
climate/pollution
search/mapping

sensor networks
cooperating vehicles

battery-powered
high latency
long packets

fixed/mobile nodes
low/high rate links
high/low reliability
real/non-real time
stand alone/integrated

(none routinely operational, only experimental)
Types of networks

- nodes communicate via a central station
- channel must be shared
- central stations are connected through a separate channel
  (cable on bottom, radio on surface)

“centralized” (cellular, infrastructure-based)

“decentralized” (ad hoc, multi-hop)

- nodes communicate through neighbors
- channel must be shared, messages must be relayed
- there may be an end node to gateway: nodes may form clusters

hybrid
1. Compressive sensing:
- N nodes, one fusion center (FC)
- nodes transmit local observations to FC, FC reconstructs the field map
- map data is sparse → FC employs compressive sensing techniques to reconstruct the map from fewer-than-N observations (Ns = CSlog N)

2. Random access communication:
- some packets collide
- some packets are also received in error due to channel noise, distortion (CRC detects them)

3. Integrated sensing & communication—key ideas:
- discard bad packets, keep only the useful ones
- it does not matter where they come from so long as
  (i) there are sufficiently many
  (ii) they appear to come from randomly selected nodes

  → collisions/errors do not change this model
  → bonus: no downlink needed

4. Design & optimization—a probabilistic approach:
- probability of sufficient sensing $P_s$
- per-node sensing (packet generation) rate $\lambda_1$

  Find $\lambda_1$ s.t. $P(\text{FC receives } N_s \text{ or more useful packets}) > P_s$

Figure of merit: energy per bit (per reconstruction)
System model

• Node at location \((i,j)\) measures the field \(u_{ij}(t)\) at some average rate \(\lambda_1\) (Poisson).

• Process \(u_{ij}(t)\) is slow, does not change much during one collection interval \(T\) → focus on one such interval (drop \(t\)).

• Node encodes the measurement into a data packet, sends packet to FC.

• FC receives packets, discards collisions and erroneous packets, decodes the information and is left with \(y = Ru + z\).

• FC uses the sparse nature of the measurements, \(u = \Psi v\), to reconstruct \(v\), infer \(u\).

• Matrix \(R\): those nodes that transmitted minus those that collided, minus those that didn’t pass CRC → useful packets.

• Note: \(z\) represents measurement noise; communication noise is implicitly present in \(R\).

• Collisions and packet errors are random → cannot guarantee \(N_s\) useful packets in \(T\); can only guarantee it with some probability → design parameter \(P_s\)

Probability of sufficient sensing = \(P\{\text{FC receives } N_s \text{ or more useful packets in } T\} > P_s\)
Modeling the arrival of useful packets: Poisson conjecture

\( K \): number of useful packets in \( T \)

\[
X' = \left( N \lambda_1 \right) \cdot e^{-2N\lambda_1 T_p} \cdot \left( 1 - P_E \right) \cdot \frac{1 - e^{-\lambda_1 T}}{\lambda_1 T}
\]

\( (N = 2500, T = 1000 \text{ s}, \lambda_1 = 10^{-4} \text{ packet/s}, T_p = 0.2 \text{ s}, P_E = 0.1. ) \)
probability of sufficient sensing

\[ P\{K \geq N_s\} \geq P_s \Rightarrow \lambda'T = \alpha \geq \alpha_s \]

necessary packet rate

\[ \alpha = Ne^{-N\lambda'T_p}(1 - P_E)(1 - e^{-\lambda'T}) \geq \alpha_s \]

- In order for a solution to exist, the bit rate (bandwidth) has to be greater than some minimum.
- When sufficient bandwidth is available, choose smallest allowable packet rate → minimum energy consumption.

(N = 2500, S = 10 or S = 16, C = 2)

(T = 1000 s, L = 1000 bits/packet, Tp = L/B, PE = 0.1)

(S = 16)
RACS: Bandwidth and energy requirements

\[ E = N\lambda_1 T \cdot P_T \cdot T_p = N\lambda_1(B) T \cdot \gamma_0(P_c) A N_0 \cdot L \]

minimum bandwidth needed to ensure sufficient sensing (closed form analytical approximation exists)

At \( B=10 \) kbps, lower bound is closely approached.

minimum packet rate \( \rightarrow \) lower bound on energy (analytical solution)

\[ \lambda_1(\infty) = \ln(1 - \frac{\alpha_s}{N(1-P_c)})^{-1} \]

\[ E_{\text{low}} = N\lambda_1(\infty)T\gamma_0 A \]
Analytical results demonstrate savings in bandwidth, energy (substantial). Illustration shows good quality of map built using RACS applied to real data.
I'd like to transmit this image, but it's too big for the acoustic link. I should extract only the important features and transmit those.

I can't hear anything! I must be in a shadow zone...let me move a little and see if things get better...

Everyone, the time here is 12:02:17. Your reports are due in 5 minutes.

Come over here, I think I found a target!

I really need to get the information from all those guys, but there is too much. I think I'll ask only some, and figure out later how to reconstruct the full picture.

I can't understand what he's saying, he must be moving too fast

...confusion?

no, just a list of open problems 😊