Underwater Acoustic Networks

Wireless underwater acoustic communication systems have become one of the most promising technologies for the development and deployment of future ocean observation and sensor networks. Applications range from oil prospecting and transportation to aquaculture, and include pollution control, climate recording, prediction of natural disturbances, search and survey missions, etc. The high attenuation of electromagnetic waves in underwater medium precludes them from being used as the information vehicle. Therefore, acoustic waves are the most viable alternative for the transmission. Nevertheless, the underwater acoustic channel is not free of drawbacks. On the contrary, it exhibits important obstacles that must be overcome if communication networks are to be implemented in the future. In addition, underwater systems have inherently serious problems of power supply and batteries duration. At the same time, network protocols must take into account the specific characteristics of the transmission medium, not dismissing the slow propagation speed. This talk will present an overall view of the acoustic channel characteristics and their impact on network protocols.

UNDERWATER ACOUSTIC NETWORKS

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3. Networks
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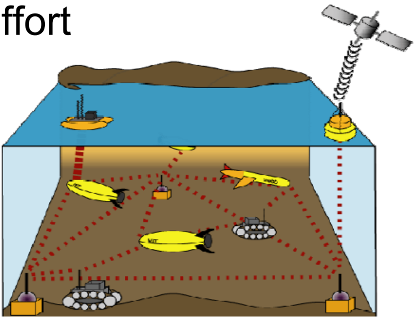
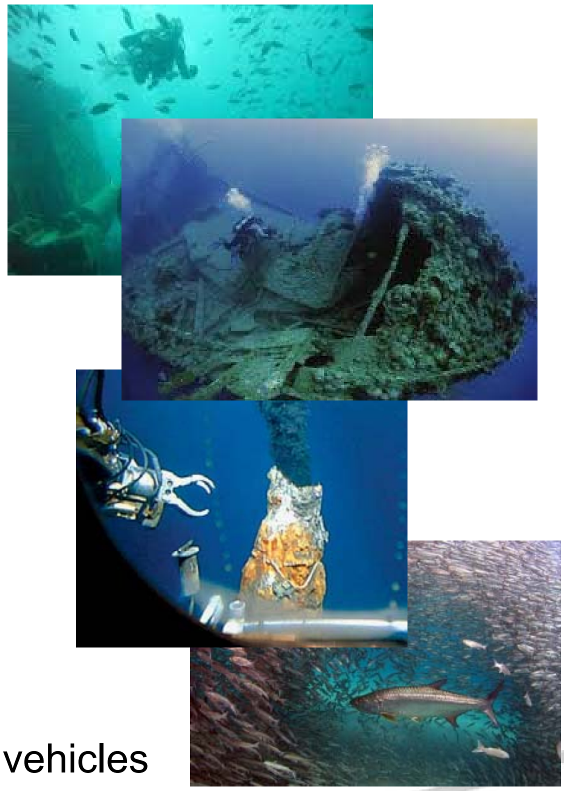
Introduction

- Oceans cover about 70 percent of the Earth’s surface, and much of this vast resource remains to be explored
  - It is possible to chat from the International Space Station and make phone calls from the summit of Mount Everest, so why can't we check our email from the ocean floor?
- The volume below the sea surface has been traditionally ignored
  - It’s a harsh environment that requires advanced technology
  - Resources are much easier to collect on the surface
  - Expansion has been possible without much effort
  - Even now, space resources look more tempting



UAC Applications

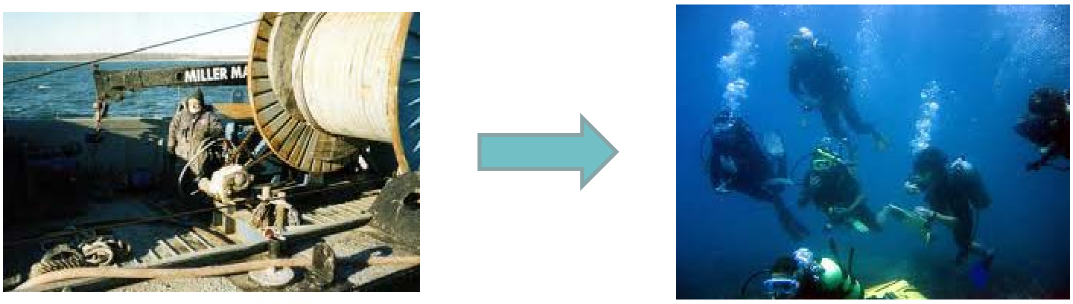


- Scientific
  - Submarine life monitoring
  - Natural phenomena forecasting
- Industrial
  - Aquaculture
  - Exploitation of mineral resources
- Environmental
  - Pollution control
  - Climate parameters recording
- Safety
  - Search and rescue missions,
  - Communication between divers and vehicles

Wireless Underwater Waves

- Traditionally, underwater communication is achieved via cables
  - Cables are expensive and heavy-weighted: several tens or hundreds of meters
  - Movement constraints for vehicles and divers
  - Safety issues as cables may pose dangers

➔ Wireless underwater communications is a must



Wireless Underwater Waves

- Radio-Electromagnetic waves
  - EM waves do not travel well through thick electrical conductors like salt water
  - Strong absorption + Huge attenuation with distance

⇒ **Only for very short range communications**

- Optical communication

  Blue-green region (450-550 nm)

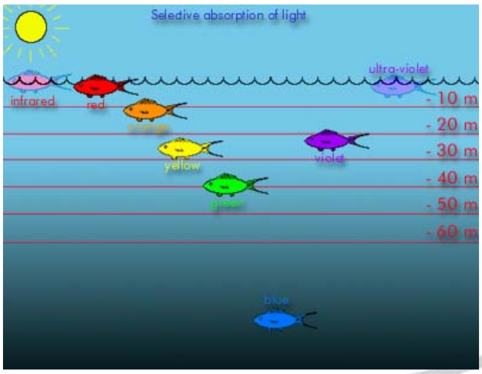
  + High bandwidth (~Mbps)

  + Negligible delay

  – Short distance (<100 m)

  – Alignment of transmitter/receiver

Light Depth Attenuation



Underwater Acoustics

- Used by submarine fauna
- Frequency range: 1 Hz - 500 kHz
  - A 30 kHz frequency (ultrasound) = 6 GHz in air (microwave) (wavelength = 5 cm)
- Negative propagation characteristics
  - Limited bandwidth: 8kHz to 48-78 kHz
  - Time-varying multipath propagation: Reflections from surface, sea floor
  - Low speed of sound underwater: ~1500 m/s

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Underwater Acoustic Channel

- The underwater acoustic channel is affected by many factors
  - Salinity
  - Temperature
  - Seabed topology
  - Speed of sound
  - Surface wind-speed
  - …
- This causes multi-paths, reverberation, Doppler, time-varying paths, …
- The result: the communication channel has poor quality and high latency
  - Challenges are very different from terrestrial wireless

Sound Speed in Sea Water

- Propagation is realized through pressure waves
- Typical value: 1500 m/s
  - Range: 1450m/s – 1540 m/s
  - Time to travel 10 km: between 6.5s - 6.9s

- A simple model

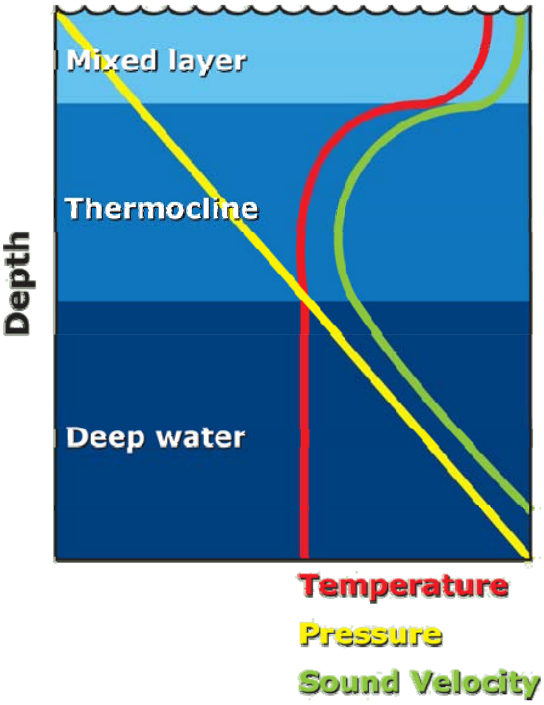
$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z$$

T = temperature (ºC), S = salinity (ppmil), z = depth (m)

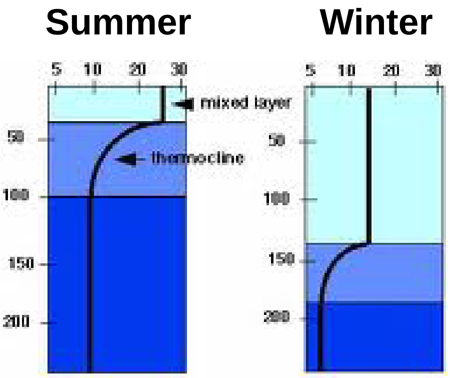
Valid for T € [0º, 35º], S < 45‰, z < 1000m

➔ Speed increases with temperature, salinity and depth

Propagation Speed



- Near the surface, speed is constant
- As depth increases, speed decreases
- After 500-600 meters the increasing pressure causes an increase in speed



Attenuation

- Attenuation is strongly dependent on frequency
  - It causes a limitation in bandwidth as distance increases
  - Smaller bandwidth → Higher distances

$$A(l,f)=\left(l/l_{ref}\right)^k\left[a(f)\right]^l$$

k = 1 (cylindrical wave)

k = 2 (spherical wave)

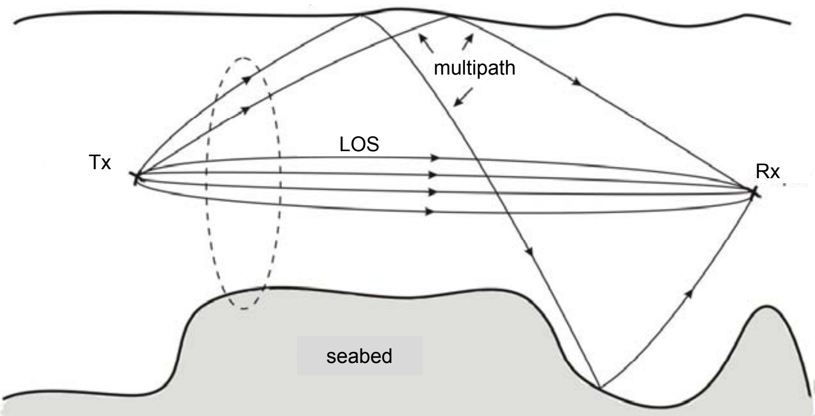
Geometrical Propagation

Absorption

- Geometrical propagation Depth<< range ⟹ cylindrical wave
  - The wavefront can be modeled as spherical (energy α $1/R^2$) (k=2)
  - However, this spherical propagation has two limits: surface and seabed
  - ➔ Propagation is indeed cylindrical for long distances (energy α $1/R$) (k=1)

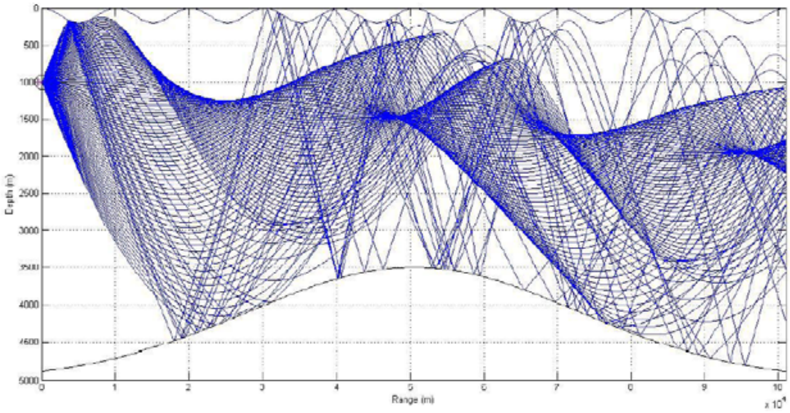
Scattering

- When the surface of the water is in movement, it causes a dispersal of the delays of the multiple reflections
- Time of coherence decreases
  - Temporal shift needed to decrease autocorrelation by 3 dB
- Experimental measurements show that scattering increases with frequency, distance and wind speed



Multipath and Fading

- When using ultrasounds, the height of the waveguide is several orders of magnitude bigger than the wavelenght, and its physical modelling is quite simple using the ray theory
  - Reflections (seabed/surface) + Refractions cause multiple paths
  - Different paths cause scattering of the propagation delays



Doppler Effect

- Caused by movement of transductors and medium (turbulences, fauna, ships, …)

- Coherence time is smaller
  - Low frequencies (≤5 kHz) → seconds
  - High frequencies → tenths of seconds (0.2s at 17 kHz)

- Causes Inter-Carrier Interference (ICI)
  - Compensation complex for Doppler dispersion higher than 3% the symbol period

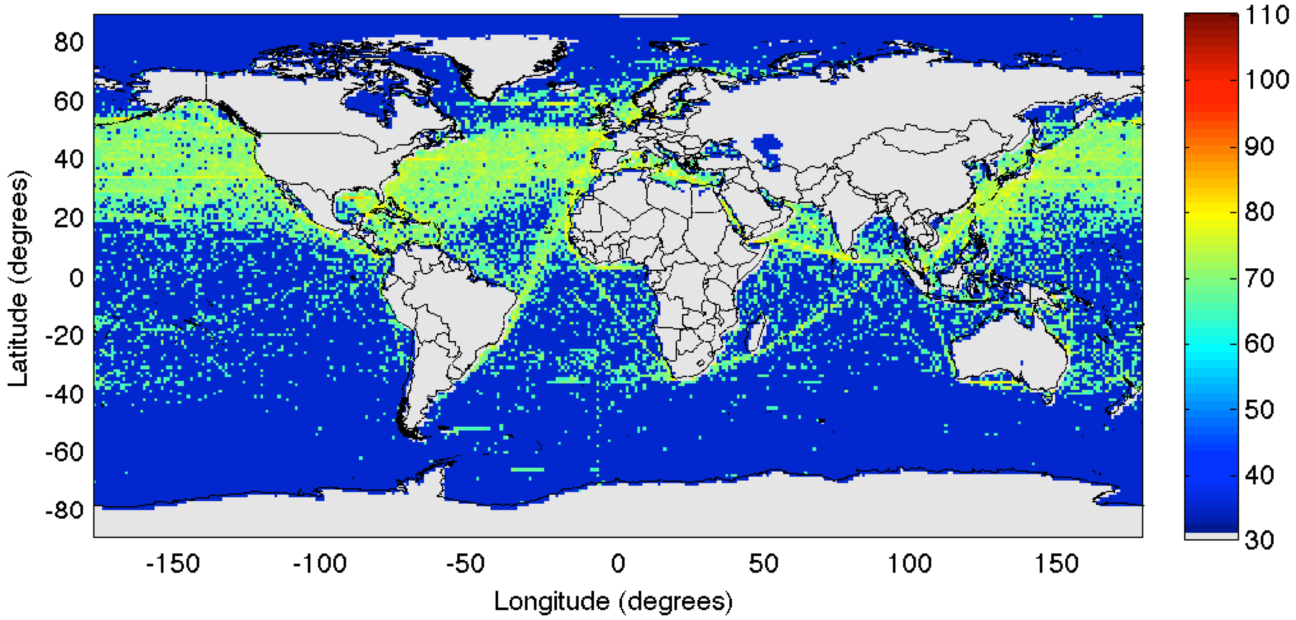
Bubbles are not So Funny

- Bubbles that appear on the surface may have a big influence on high frequency acoustic signals
- Effect: Increased attenuation of reflected signals

- Bubble density increases with wind speed
  - At 10 m/s, attenuation due to bubbles is up to 20 dB

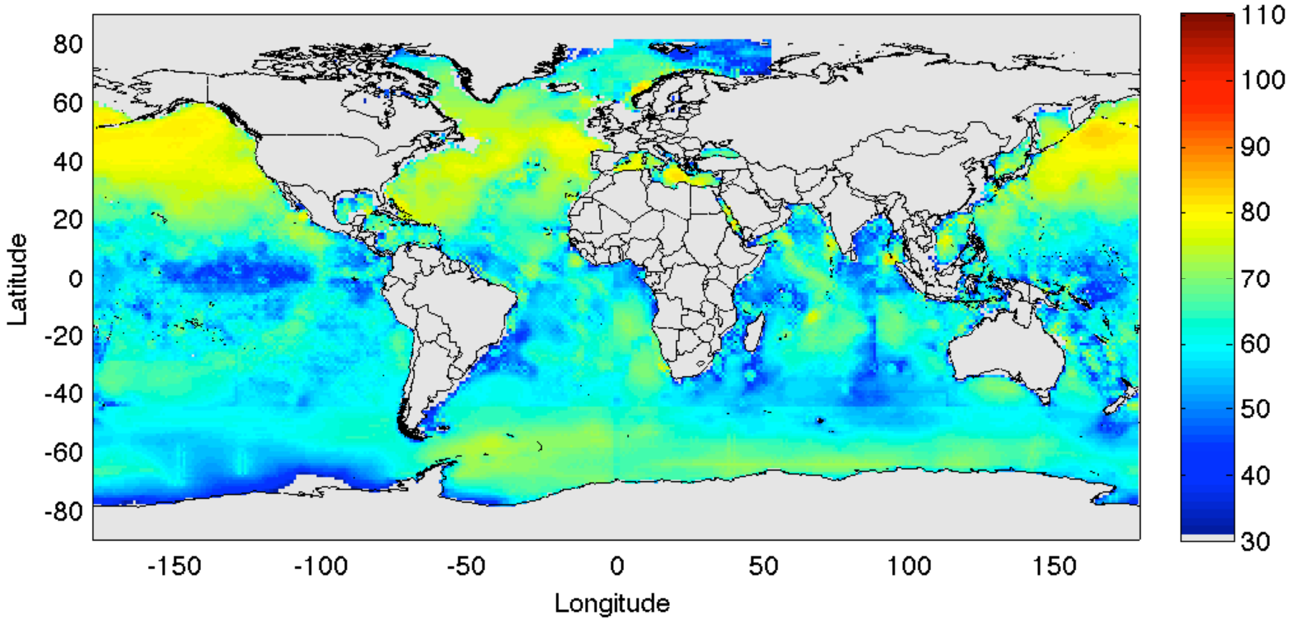
- Bubbles underwater also create additional scattering

Submarine Environment



Global Shipping Noise at 200 Hz – Points of Origin
[*Ocean Acoustics Library*]

Submarine Environment



Global Shipping Noise at 200 Hz - Aggregate

[*Ocean Acoustics Library*]

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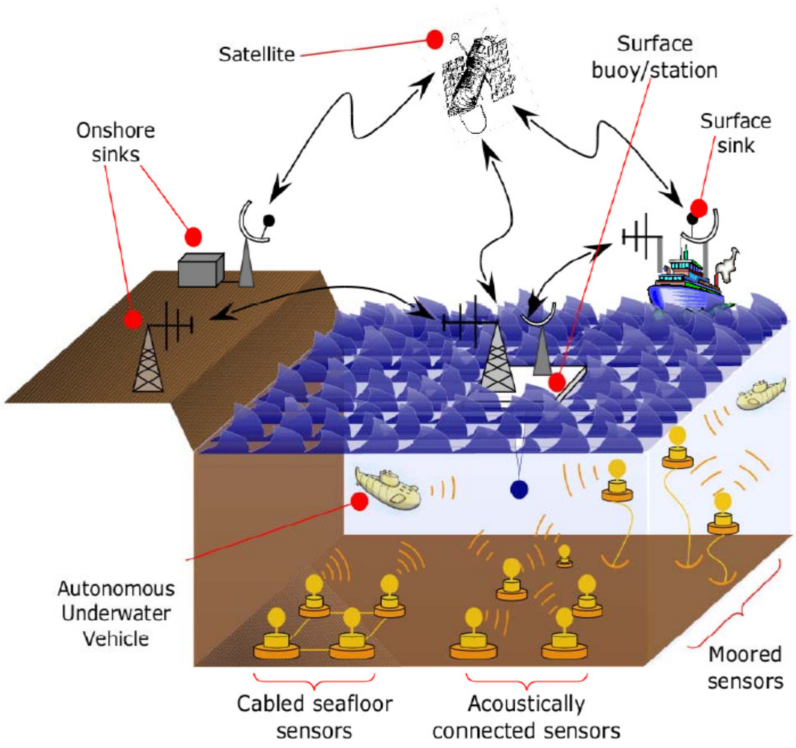
Network architecture: 3D



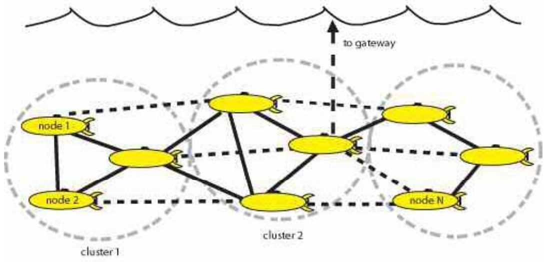
3D Networks [*Stojanovic*]

Networks

- Today: point-to-point acoustic links
  - High delay
  - Channel complexity

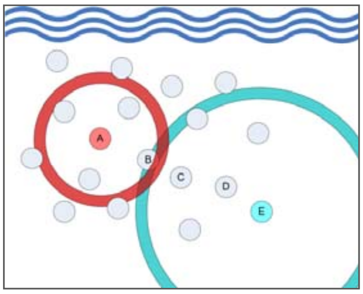
➔ Future: cooperative networks
  - Fixed, slowly moving, mobile, sensors, relays, gateways

- Issues
  - Shared access
  - Efficient routing
  - Low data rate
  - Mobility

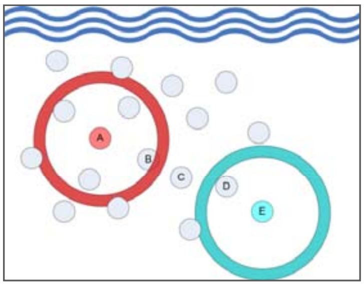


Shared Access

- Managing shared access
  - Collision detection
  - Turn sequence
  - Predefined channel allocation

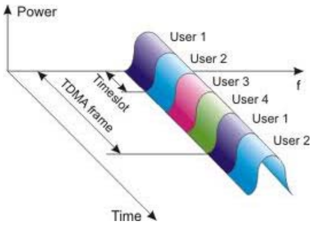


- Unsynchronized protocols are simpler but explicit coordination can improve the performance
  - Requires a time reference
  - Space-time volume: overlap packets in time while they remain distinct in space



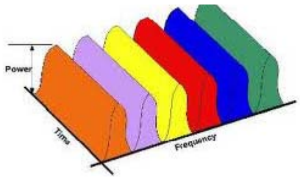
Shared Access – Static

- Static shared access
  - Nodes are allocated predetermined data channels
  - Contention-free (scheduled or deterministic protocols).
  - Problem: Inherently non-scalable.
- TDMA
  - Better performance in some aspects
    - Easy synchronization in nodes
    - More flexibility: number of allocated slots
  - Can be more flexible: number of allocated slots
  - Needs some coordination and some guard times to compensate for inconsistencies in dealing with propagation delays
  - Stable, high throughput at high loads by eliminating collision

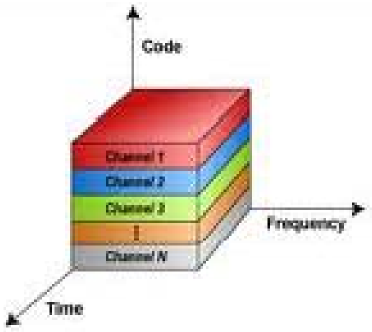


Shared Access – Static

- FDMA
  - Inefficient for underwater applications



- CDMA
  - Causes a bandwidth expansion, especially acute in narrow channels
  - Advantages
    - No slot synchronization
    - Robustness to multipath fading
    - Power control
  - Disadvantages: complex receivers/transmitters



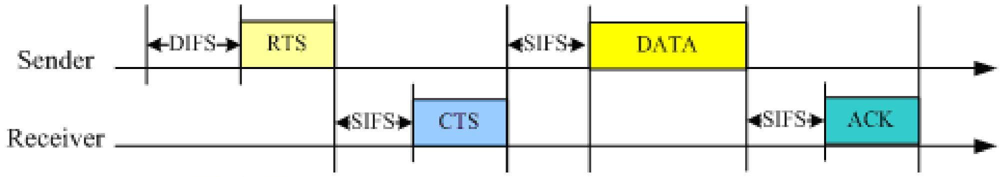
Shared Access – Dynamic

- Dynamic shared access (ad-hoc contention)
  - Nodes typically use a shared control channel over which data channels are requested

- Topologies
  - Distributed topology
    - No controlling master nodes
    - Nodes asynchronously handles data transfers
    - Dynamic MAC protocols are contention-based.
  - Centralized topology
    - A master node controls media access for nodes in neighborhood
    - May employ polling methods with no contention

Shared Access – Dynamic – Distributed Topology

- Good for scalability and no time synchronization needed
- RTS/CTS exchanges allow to measure the channel and to use optimal transmission parameters
  - Channel estimation, adaptive modulation, and power control
  - Poor performance due to latency
- Mobile AUV: DATA packet trains may pose problems
- Adaptive modulation and power control are key to maximizing channel efficiency/capacity



Shared Access – Dynamic – Distributed Topology

ALOHA

- Aloha
  - ALOHA based protocols are a good candidate for sparse low data rate networks
  - Candidate when combined with simple CSMA features
- However, Slotted Aloha degrades to pure aloha in environments with varying delay
- Proposed solution: PDT-Aloha (Propagation Delay Tolerant)
  - Add guard times to slotted ALOHA
  - Increases throughput by 17–100% compared to slotted ALOHA

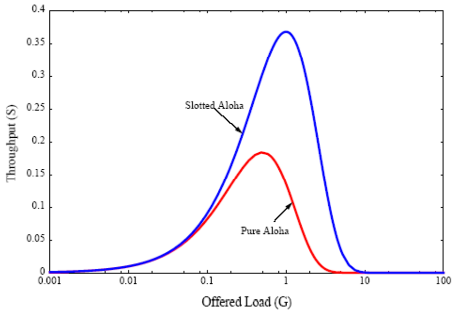


FIGURE 3.2: Throughput-Load of Pure and Slotted Aloha

Shared Access – Dynamic – Distributed Topology

CSMA

- CSMA
  - Listen-before-transmit approach
  - Requires propagation delay << packet duration
  - Latencies encountered make it very inefficient underwater
- Slotted MACA
  - Slot > delay + RTS/CTS
- DACAP: based on MACA
  - Initial signaling exchange in order to reserve the channel
  - Adds a warning message if a RTS is overheard while waiting for a reply to its own RTS

Shared Access – Dynamic – Distributed Topology

CSMA

- T-Lohi
  - Nodes that want to transmit signal their intention by sending narrowband signals (tones)
  - The number of contenders is counted
    - Contention occurs ➔ back-off in proportion to the contender count
    - Otherwise ➔ Proceed with transmission
  - Achieves efficient channel utilization, stable throughput, and low energy consumption
  - Deafness and aggressive contention can cause the reservation mechanism to fail and lose packets

Shared Access – Dynamic – Centralized Topology

- Contention for requests
  - One Master allocates rights to send
  - One channel to request (shared channel), one channel to acknowledge, several data channels
  - Decrease in bandwidth
  - Delay for acknowledgment for sending because req/ack channels will be slow channels
- Contention-Free
  - Polling
  - Delay for transmission

Clustering

- Clusters
  - Cope with scalability issues
  - Good solution to enhance the network throughput performance
- Hierarchical organization using FDMA/CDMA for separating clusters and TDMA for intra-cluster
  - Spatial re-use
- Inter-cluster comms using one of the previous options

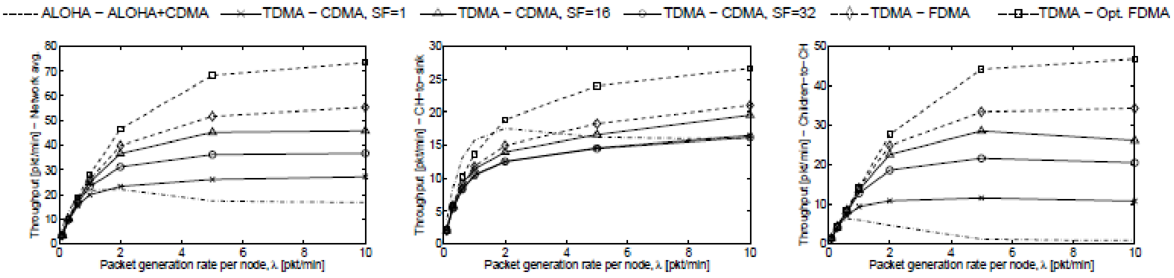


Fig. 1. Throughput (network average).

Fig. 2. Throughput (CH-to-sink).

Fig. 3. Throughput (children-to-CH).

Data Link Layer Improvements

- Select the optimal packet size
  - Depends on range, rate-distance product, error probability, …
  - Longer packets achieve better channel utilization
- Transmit packets in groups with selective acknowledgement
  - At datarates of 100 bps over 5 km links, $P_e = 10^{-3}$, packets of 256 bits, if we use groups of 16 packets, efficiency reaches 65%
- Adaptive adjustment of timeout based on measurements

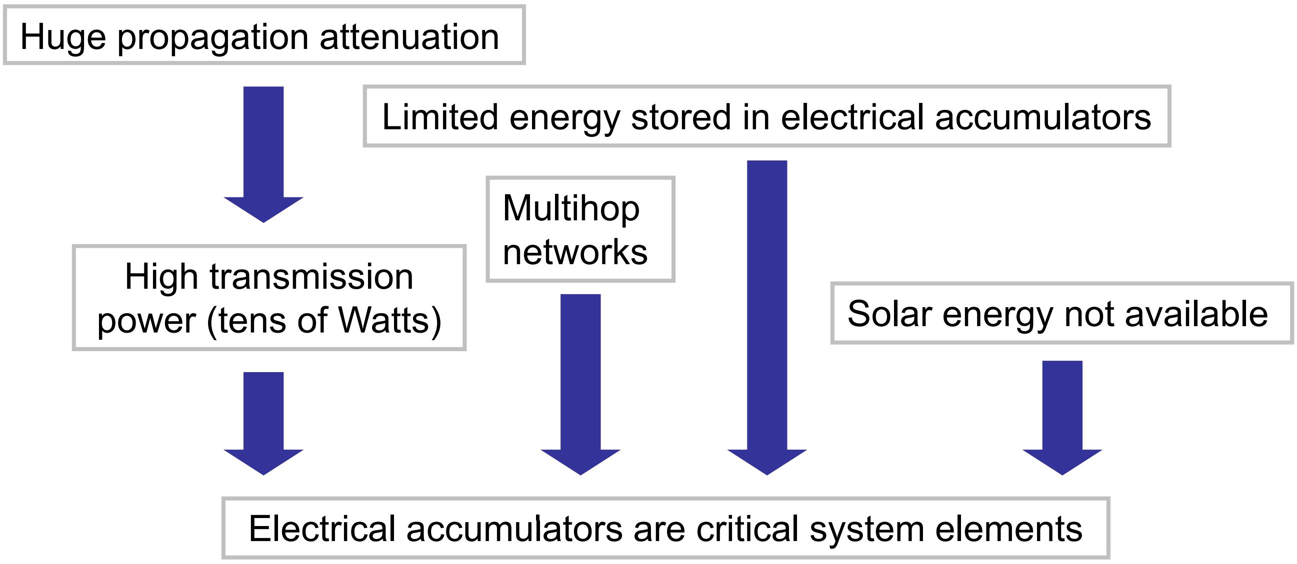
Routing

- Routing overheads should be kept as minimal as possible
- In a typical clustered topology, gateways are used
  - The gateway node manages route discovery
- In distributed routing topology, all nodes perform routing
- Proposals for 3D scenarios
  - AODV-based routing
  - Location aware source routing for dynamic AUV networks
  - Energy-Efficient routing
    - Minimize the total path energy consumption by leveraging observations made on propagation characteristics of acoustic signals
    - Shortest path performs poorly ← chooses hops that are too long
    - Greedy minimum energy path also performs poorly ← ignores the advancement towards the destination

Localization

- Ranges are used to estimate local topology
- Localization has to be repeated periodically as the network topology changes due to the inherent motion of the vehicles.
- $T_{error} = 1\ \mu s$ ➔ $L_{error} = 15$ mm
- … but low number of messages is more important
- TDMA frame timings to compute ranges
  - Sufficient Distance Map Estimation (SDME) → ~1m at d=139m
  - A single moving reference beacon (high-precision clocks) → standard deviation of 10–14m.
- Some proposals are beacon based

Efficient energy management: paramount importance



Huge propagation attenuation

Limited energy stored in electrical accumulators

Multihop networks

High transmission power (tens of Watts)

Solar energy not available

Electrical accumulators are critical system elements

Recharge or replacement of accumulators is an expensive and cumbersome process

Energy Efficiency

- Collisions should be avoided or/and detected soon
  - TDMA provides stable, high throughput
- Transmit energy costs are higher that reception ones
  - Impact on routing metrics
  - May be worth leaving nodes in an idle state and aware rather than sending them to sleep for some time
- Nodes can be waked-up by simple rx of an acoustic wave
  - Topology control: sleep but maintain network connectivity
  - However, sleep/wakeup schemes come at the cost of reduced bandwidth and additional time delays

    → long term underwater deployments
- Benefit of short-range communications

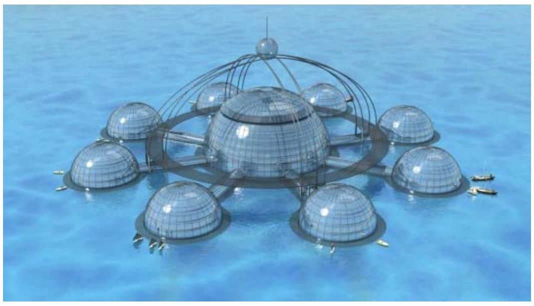
Cross-Layer

- Better data rates through cross layer optimization
  - Based on instantaneous measured link metrics
  - Based on application/service needs
- PHY + DLL + NWK
  - Adapt packet size, batch size and timers
  - Adaptive FEC code rate at the physical layer
  - Adaptive ARQ for time-varying channels
- APP + Lower Layers
  - Traffic patterns, performance requirements ↔ delay, throughput, reliability, energy efficiency

Contents

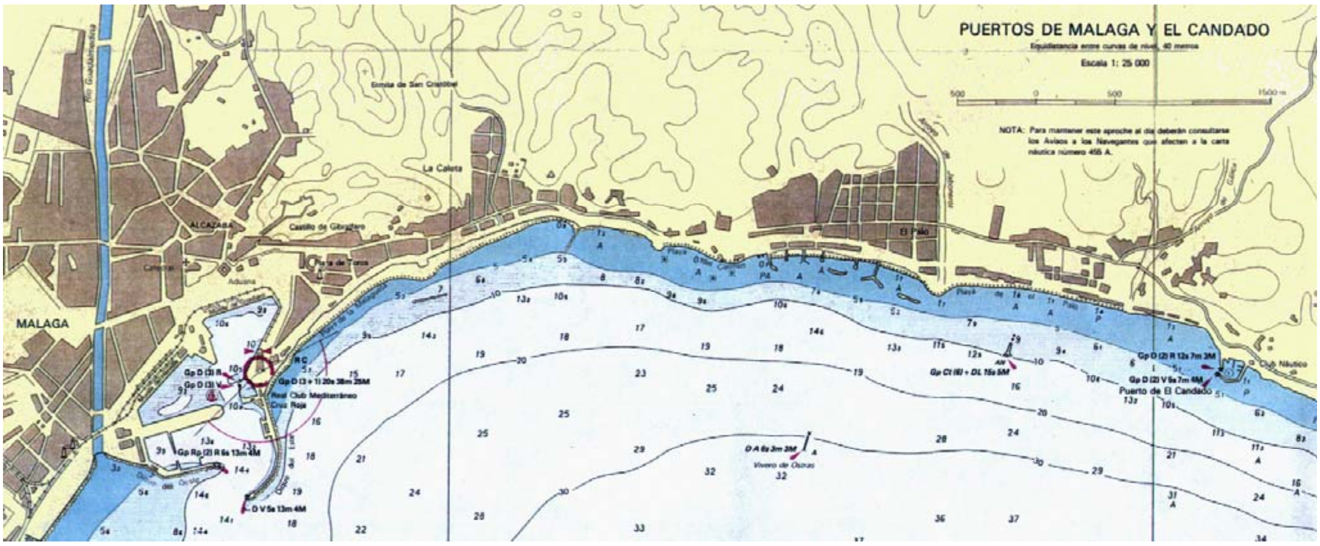
Conclusion

- There are no operational autonomous underwater networks, only isolated experimental demonstrations
- Underwater channel is very unfriendly
  - Long delays + Narrow bandwidth
- Terrestrial wireless techniques must be adapted



- Challenges
  - Channel modeling
  - Capacity of acoustic networks
  - Efficient and scalable channel sharing protocols

Bay of Malaga



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