Re-engineering Wireless Networking Protocols: the Case of Underwater Acoustic Communications

Michele Zorzi

Department of Information Engineering – University of Padova – Italy
and CalIT2 – University of California at San Diego
zorzi@dei.unipd.it

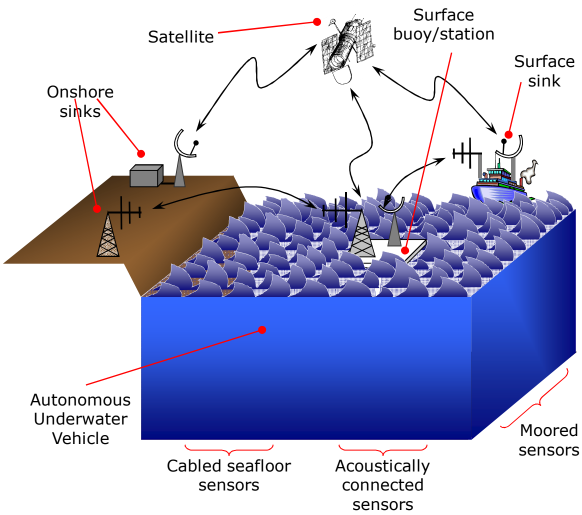
Outline

- Objectives and motivation
- Characteristics of underwater acoustic propagation
- Implications for ad hoc network protocol design
- Specific protocol examples:
  - Energy-efficient routing
  - Topology control via wake-up mode
- Discussion on propagation and simulation modeling
- Conclusions and future directions

Underwater Networks

- Many applications
  - Environmental monitoring
  - Unmanned vehicle coordination
  - Equipment monitoring
- Various requirements
  - Periodic data
  - Real-time traffic
  - Variable reliability
  - Energy efficiency

Example of Underwater Acoustic Sensor Network



Autonomous Underwater Vehicles

Underwater communications

- Radio communications
  - Radio waves tend to fade very rapidly in water
- Optical communications
  - Optical signals have a limited reach
  - Need to align the transmitting and receiving devices
- Acoustic communications
  - Very slow propagation speed with respect to radio in air (1.5 km/s typically)
  - Limited bandwidth and data rate
  - Noise and attenuation are frequency-dependent
  - Strong fading phenomena, especially in horizontal channels

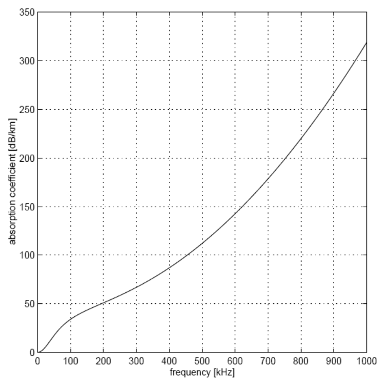
Underwater acoustic propagation

- Path loss equation:

$$10 \log A(\ell, f) = k \cdot 10 \log \ell + \ell \cdot 10 \log a(f),$$

- Absorption (Thorp's formula):

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f} + 2.75 \cdot 10^{-4} f^2 + 0.003$$



- Anisotropic propagation (e.g., more path loss in horizontal link in shallow water than vertical link in deep water)

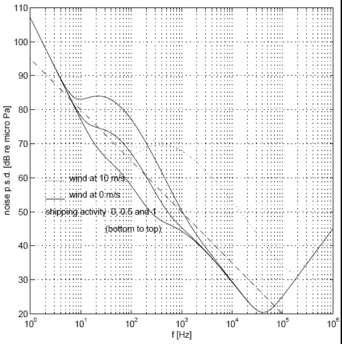
Noise

- Sum of four components:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$$

- where:

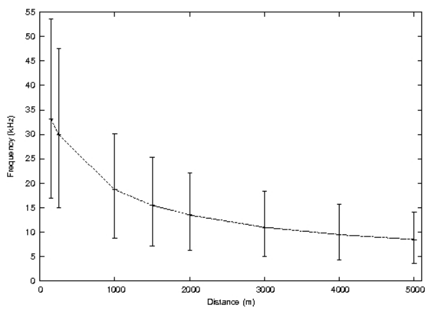
$$\begin{aligned}
10\log N_t(f) &= 17 - 30\log f \\
10\log N_s(f) &= 40 + 20(s-0.5) + 26\log f \\
&\quad -60\log(f+0.03) \\
10\log N_w(f) &= 50 + 7.5w^{1/2} + 20\log f \\
&\quad -40\log(f+0.4) \\
10\log N_{th}(f) &= -15 + 20\log f,
\end{aligned}$$

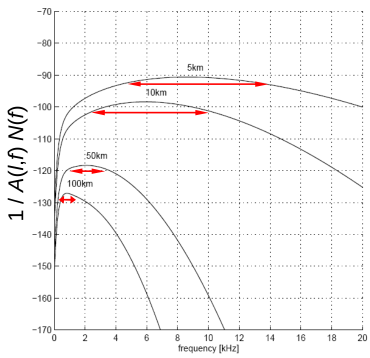


Various sources of noise: turbulence, shipping, wind, thermal

The bandwidth-distance relationship

$$SNR(l,f) = \frac{P_\Delta / A(l,f)}{N(f)\Delta f}$$





From: M. Stojanovic, "On the Relationship Between Capacity and distance in an Underwater Acoustic Communication Channel," WUWNET 2006.

- Both the center frequency AND the bandwidth vary with distance between nodes

Propagation delay

- Speed of sound in water: about 1500 m/s
- This means that propagation delays can be significant
- Example for a 1000-bit packet
  - Link of length 1 km
    - ✓ propagation delay: 0.66 s
    - ✓ transmission time @ 25 kbps: 0.04 s
  - Link of length 10 km
    - ✓ propagation delay: 6.6 s
    - ✓ transmission time @ 10 kbps: 0.1 s

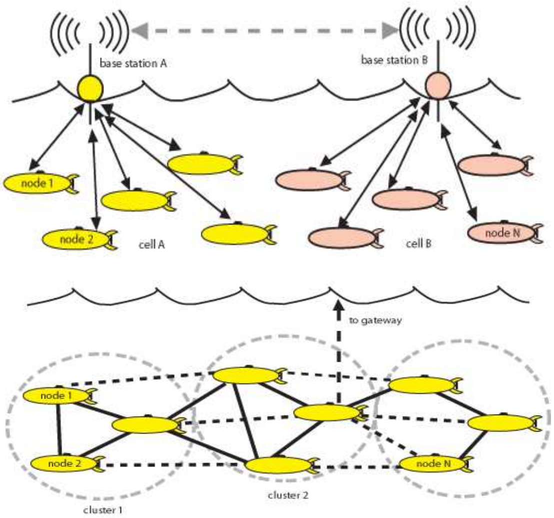
Underwater acoustics vs. radio

- Radio
  - High bandwidth (MHz)
  - Short prop delays (us)
  - Well understood propagation
  - Isotropic propagation
  - Distance-independent bandwidth
  - Typically white noise
  - Energy costs
    - ✓ TX ~ RX ~ idle >> sleep
  - Small and cheap nodes
  - Lots of research done on all communications aspects
  - Accepted channel models
  - Several simulation tools used
  - Easy to experiment
- Acoustics
  - Low bandwidth (kHz)
  - Long prop delays (seconds)
  - Complicated propagation
  - Anisotropic propagation
  - Distance-dependent bandwidth
  - Frequency-dependent noise
  - Energy costs
    - ✓ TX > RX >> idle >> sleep
  - Bulky and expensive nodes
  - Lots is known on PHY, little on networking
  - No comprehensive channel m.
  - Lack of simulation tools
  - Very hard to experiment

Networking options

cellular (clustered)

ad hoc



Ad hoc networks

- Without infrastructure
- All nodes are peer
- Self-organizing
- Multihop
- Main issues for communication/networking
  - Media access control
  - Routing for multihop operation
  - Topology control
  - Mobility
- Complexity, consumption, cost

MAC protocols

- Deterministic (FDMA, TDMA, etc.)
- Guaranteed access (polling, token)
- Random (ALOHA, CSMA)
- Hybrid (e.g., contention & reservation)

- Centralized needs coordination
- Random is quicker yet potentially error-prone

- Main performance metrics: throughput, delay, energy consumption, fairness, stability, robustness

MAC issues in UW networks

- Long propagation delays
  - Problems with CSMA protocols; long latencies with handshakes; long guard times for TDMA schemes
- Scheduling algorithms are very difficult to design
  - Propagation times often exceed the packet transmission times
  - Users may become aware of transmissions at very different times
  - As a result, the time dimension must be explicitly taken into account
- No collision detection possible
  - Similar to wireless radio networks, collision avoidance is used instead
- Very limited bandwidth
  - FDMA and CDMA may lead to very small user data rates
- Energy performance
  - Energy efficiency is paramount in UW networks

Routing protocols in ad hoc networks

- Main differences with traditional ("Internet") routing:
  - Mobile nodes
  - Unstable links cause impairments and inconsistencies
  - All nodes participate (not just "routers")
- Main issues:
  - Signaling overhead
  - Limited bandwidth
  - Interference
  - Topology
  - Mobility
- Some trade-offs:
  - Proactive vs. reactive (overhead vs. latency)
  - Hierarchical vs. flat (structure vs. flexibility)
  - Centralized vs. distributed (complexity vs. performance)
  - …

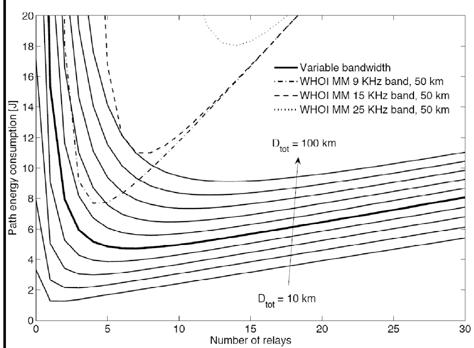
Energy consumption and routing protocols

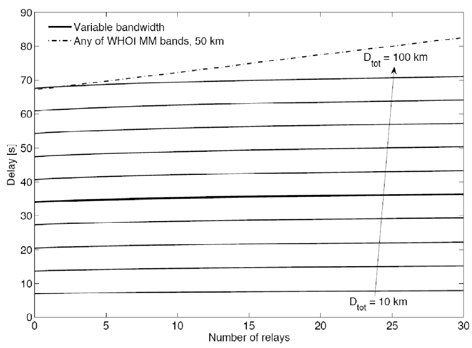
- Energy-aware routing
  - Route selection explicitly incorporates energy metrics
  - Various objectives: total energy, network lifetime, etc.
- Well studied topic in RF wireless
- New challenges in UW networks
  - Propagation characteristics are different
    - ✓ Anisotropic characteristics: link orientation matters
  - Bandwidth (and frequency) depend on link length: transmitting further requires more power, but also more time
    - ✓ Relationship between link distance and energy consumption is non-trivial (also, noise is not white)
  - Short hops: more hops (delay), more modems on (energy), less power, more bandwidth
  - Longer hops: fewer hops, more power (energy & interference), longer transmission times, more channel access delay
- New routing protocols can be designed following these guidelines

Example: Bounded distance protocol

- We developed a protocol based on these observations
- Bounded distance protocol: methodology
  - Analysis
    - ✓ Effect of increased total path length
    - ✓ Effect of increased number of relay nodes
  - Metrics
    - ✓ Delay
    - ✓ Energy consumption (transmit and receive)
  - Develop simple routing strategy
    - ✓ Based on analysis
  - Simulation
    - ✓ Matlab (simple multihop results)
    - ✓ ns2 (actual protocol operation)

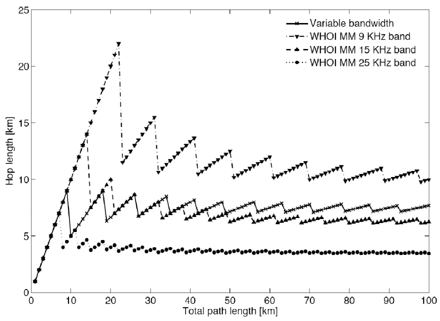
Linear Network

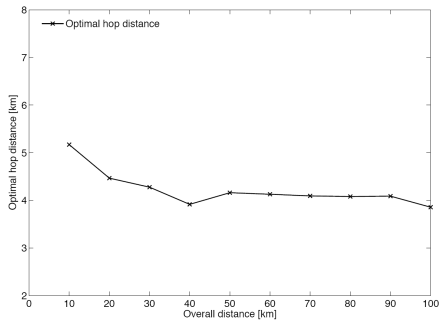




- With perfect power control
- Delay increases, but slowly and not linearly (shorter hops, more bw)
- For each total path length, there is a number of relays that minimizes the overall path energy

Sensitivity to exact distance: 1D and 3D



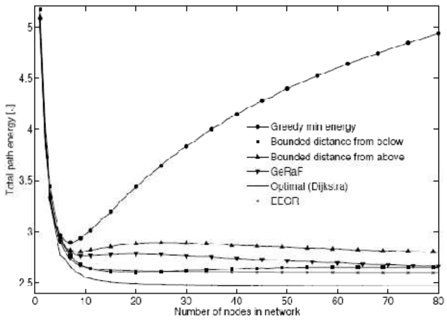


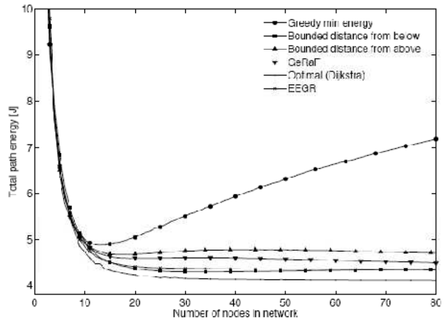
- The average density of relays that minimizes energy is relatively insensitive to the path length
- The minimum energy itself is not very critical

Bounded Distance Protocol

- The previous results suggest that there is some kind of "universally optimum hop length" for minimum energy (given the scenario)
- Idea: bounded distance routing protocol
  - Attempt to transmit to farthest node within **X** meters, but towards the destination (i.e., within some angle)
    - ✓ Note: shorter hops are "less suboptimal" than longer ones
    - ✓ More refined selection rules can be adopted
  - If no such node exists, pick the closest that is at least **X** meters away
  - Choose **X** optimally based on previous analytical results
- Comparison
  - Greedy minimum energy (shortest transmit distances)
  - Shortest hop count (longest transmit distances)
  - Our protocol
  - Optimum path centrally computed

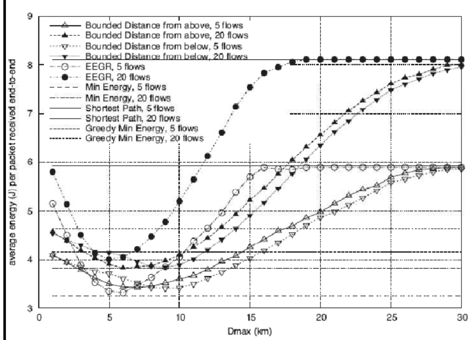
MATLAB results

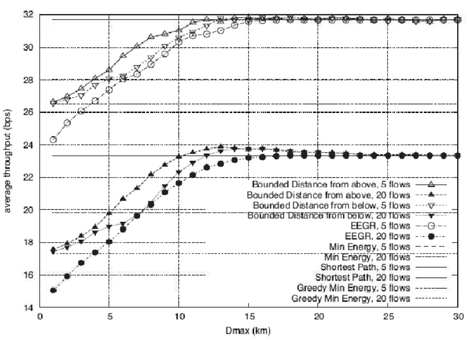




- Shortest path is always very energy-inefficient
- Greedy minimum energy is good with few nodes, but for high densities tends to choose too many hops
- Bounded distance is always very close to optimum

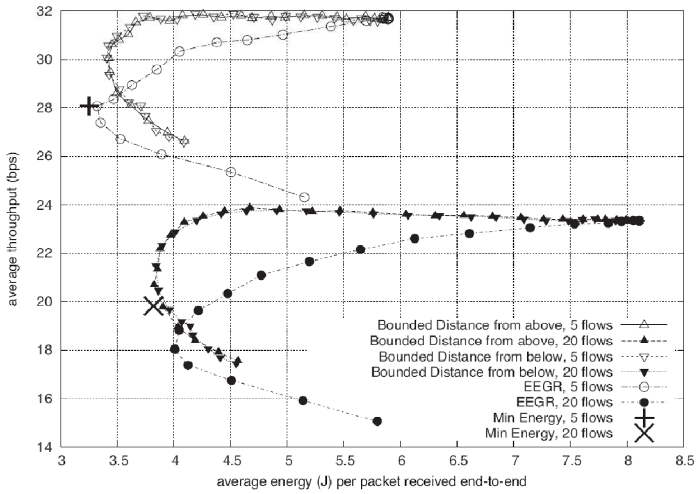
ns2 Results





- Here we simulate the actual routing protocol as well as MAC
- Energy is smaller in our scheme (optimal tradeoff)
- There is no delay penalty
- The minimum-energy point corresponds to better throughput

Energy-throughput trade-off



Topology control issues

- Use of sleep modes to save energy (many schemes for RF nets)
- Acoustic modems can listen while in low-power mode
- In UW, the energy consumption relationships are different
  - Radio: TX ~ RX ~ idle >> sleep
    - ✓ Conclusion: sleep is the only meaningful way to save energy
  - Acoustics: TX > RX >> idle >> sleep
    - ✓ Conclusion: idle listening may be better than sleep-cycles

Card	Transmit	Receive	Idle	Sleep
Cisco Aironet [1]	2240	1350	1350	75
Micro Modem [2]	10,000	3,000	80	≈ 0

Table 1: Power consumption (mW) for interface modes

Schemes compared

- Optimal
  - Genie-aided, maximal sleep, knows exactly when it should wake up
- Wake-up
  - Always in low-power idle listening mode, nodes can be woken up on demand
- STEM
  - Nodes sleep and periodically wake up, link can be established by persistent signaling until the intended receiver is available
- All results normalized to a continuously receiving node

Topology control example

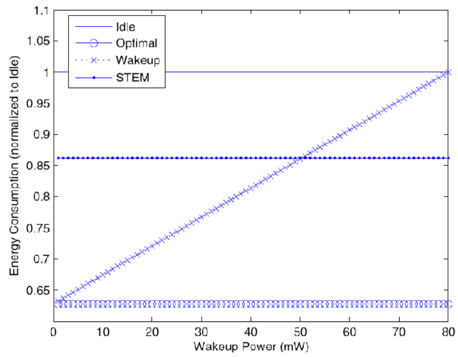


Figure 3: Total energy consumption of the network vs. wakeup mode cost.

Topology control example

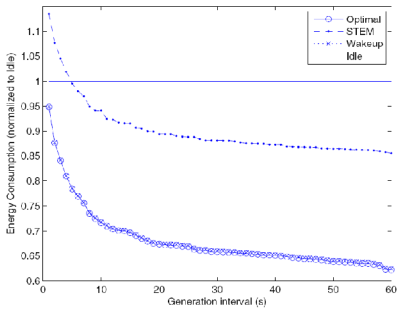


Figure 1: Total energy consumption of the network vs. traf generation interval.

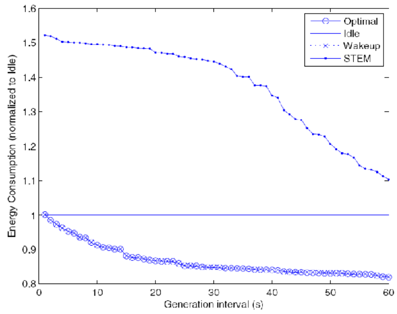


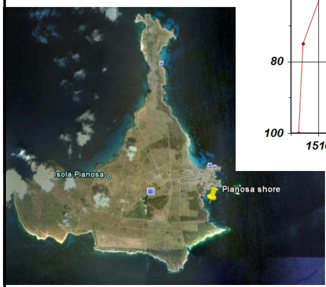
Figure 2: Highest energy consumption of a node vs. traffic generation interval.

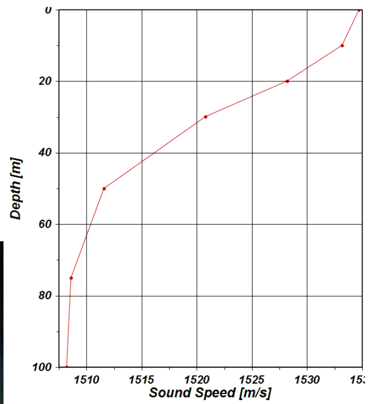
A word on models…

- Unlike in radio, there are no well-established models for acoustic propagation and channel behavior
  - Very erratic and hard to model, lack of interest?
  - Some disconnect between acousticians and comms engineers?
- We would like to have something like the path-loss/shad/fading or WSSUS statistical representation – is this even possible?
- Simulation tools for networking studies
  - Even for radio they are not that good (poor PHY support)
  - Here PHY support is even more important (e.g., disk coverage makes no sense at all)
- Experimental data
  - A lot of data out there (though not easily accessible)
  - Little attention to networking metrics – not very useful as it is

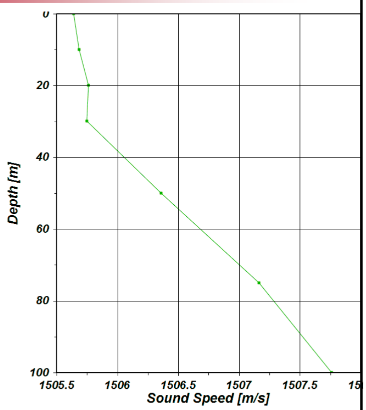
More accurate propagation models

Example:
transmission at 4 kHz, from the shore of the Italian island of Pianosa (42.585°N, 10.1°E)



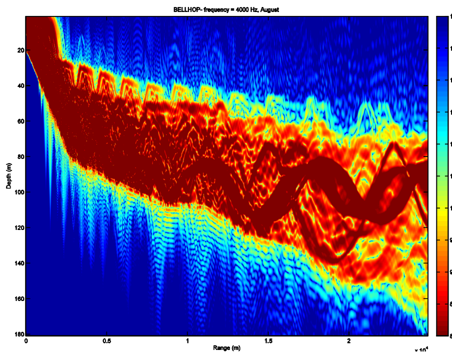


AUGUST SSP

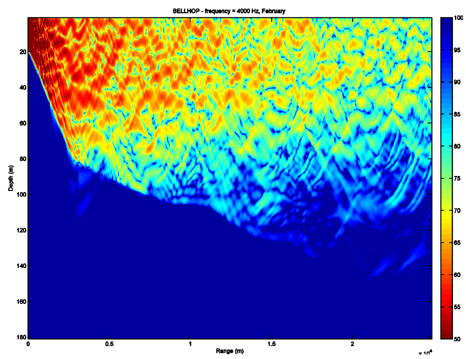


FEBRUARY SSP

More accurate propagation models

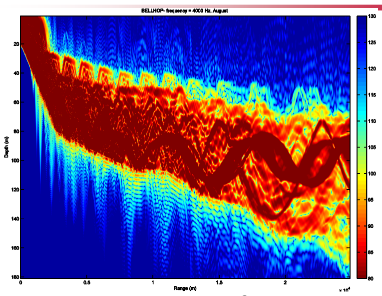


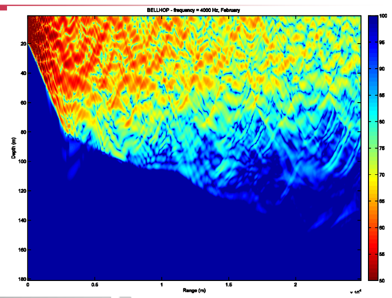
AUGUST Transmission Loss



FEBRUARY Transmission Loss

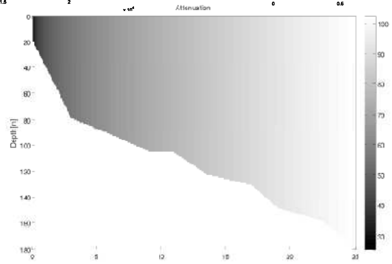
Empirical and ray-tracing compared





AUGUST
Transmission Loss

FEBRUARY
Transmission Loss

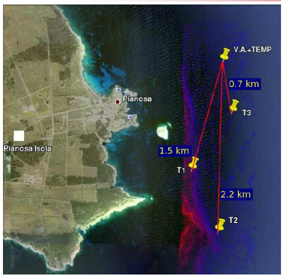


Urick's formulas

Towards networking-oriented channel modeling

- Goal: develop an accurate simulator for realistic evaluations of UW acoustic networks
- Include protocols as well as reasonable PHY representation
- Statistical analysis of data to reveal behaviors and come up with some stochastic models
  - Issues related to correlations due to the need to simulate simultaneous links
  - Time correlations as well
- Use of traces for simulations (maybe)
- Develop some "typical" channels
- The type and quantity of data needed is being evaluated
  - We are working with partners who have experimental capabilities and are planning sea trials in the near future

Current modeling efforts through experimental data



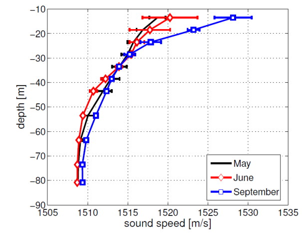


Figure 2. Average and standard deviation of SSP during experiments on May 30, June 5 and September 2.

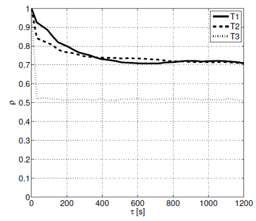
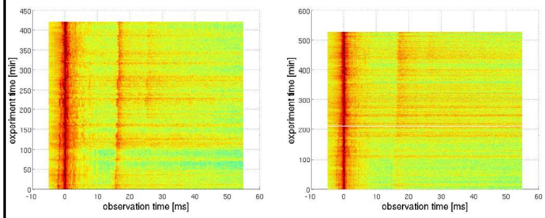


Figure 6. Channel correlation coefficient ρ as a function of time lapse τ in May. The links considered are from each transmitter T1, T2, T3 to hydrophone H4.



(a) Link T1–H4, May.

(b) Link T1–H4, June.

Figure 3. Pseudocolor plot of measured channel impulse response amplitudes for

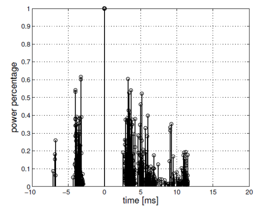


Figure 10. Normalized power delay profiles during May. The transmitter is T1, the receiver is H2.

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WOSS – World Ocean Simulation System

- The *World Ocean Simulation System* (WOSS) is a fully automated framework for integrating channel and network simulation software
- Originally thought as a full-fledged interface between ns2 and Bellhop, it can be interfaced with *any* channel simulator, to which it can provide all required environmental data
- WOSS provides a flexible, extendable, technology-independent API for
  - ✓ retrieving and manipulating bathymetry, Sound Speed Profiles (SSPs) and bottom sediment data from standard or custom databases
  - ✓ manipulating transmission loss or channel power-delay profile as output by the channel simulator and feeding it to the network simulator
  - ✓ optionally storing and retrieving channel simulation outputs in a custom database for later use

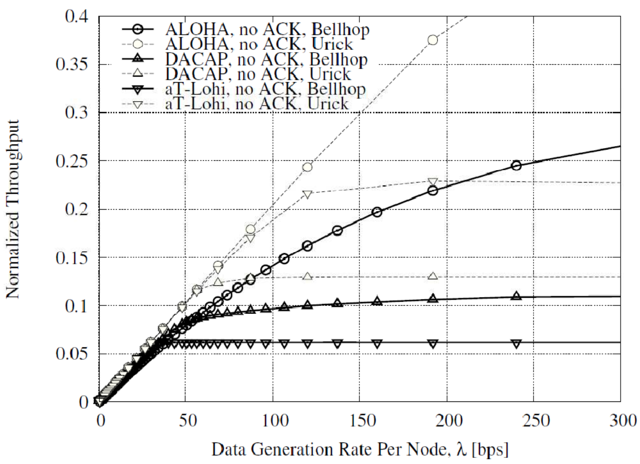
WOSS – World Ocean Simulation System

Current and future capabilities

- The current version provides:
  - Interface implementation and custom netcdf db of monthly averaged SSPs taken from the World Ocean Atlas database (2005)
  - Interface implementation for the GEBCO netcdf bathymetry database (both '03 and '09 versions).
  - Interface implementation and custom netcdf data analysis of the DECK 41 database, for bottom sediments composition and parameters
  - Fully detailed interface for the Bellhop ray tracing program
- Future versions will include interfaces to other channel simulators
- Code available at http://telecom.dei.unipd.it/ns/woss/

WOSS – Example results

- Throughput normalized to channel capacity
- Attenuation higher with Bellhop → lower SNR, increased bit error rate, decreased throughput



WOSS – Example results

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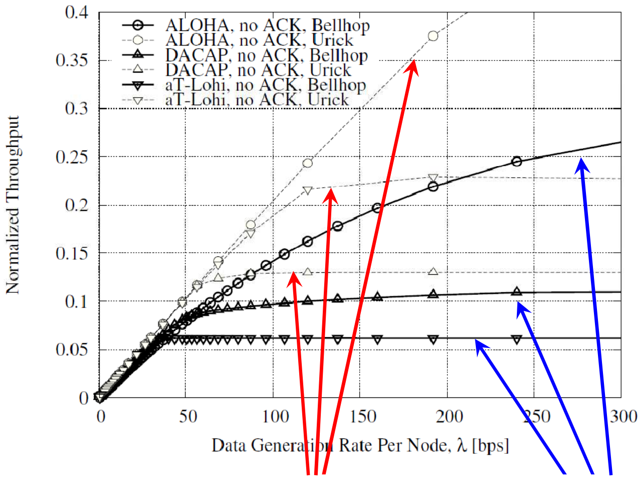
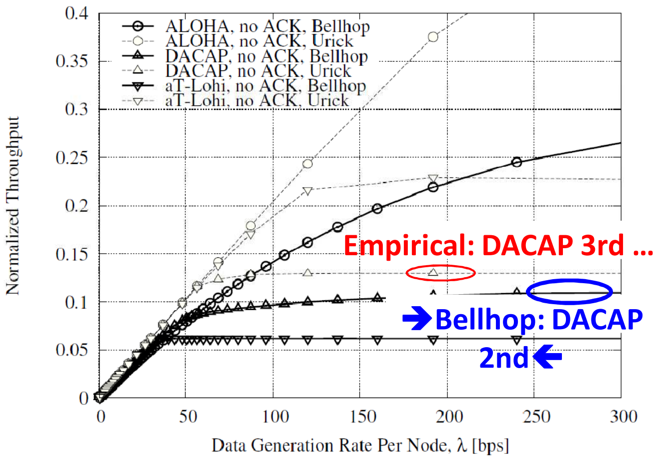


Using empirical formulas Using Bellhop

WOSS – Example results

- Throughput normalized to channel capacity
- Attenuation higher with Bellhop ➔ lower SNR, increased bit error rate, decreased throughput



- **DACAP and aT-Lohi's ranking is different for different channel modeling**

Some more discussion…

- An accurate simulation tool is very important and useful, but making the right choice in the accuracy/complexity space is a challenge
- A detailed understanding of the propagation features of the underwater acoustic environment is very important
- However, a detailed simulation of the propagation behaviors may be computationally too heavy, and not even necessary
- It is still not completely clear what are the important effects and which are those that can be ignored
  - How do network behaviors depend on propagation details?

Conclusions

- Efficient support for mobile communications and networking in UW is an important and challenging issue
- Main issues include: topology, resource allocation, multiple access, routing, error control, etc.
- Known solutions for RF networks abound, but they do not necessarily apply here (in fact, in many cases they don't)
- Features of the propagation environment and of the devices are to be explicitly taken into account for a proper design
- Importance of real implementation and testing of competitive solutions, but also of effective channel models and simulation tools

Thanks to our sponsors

- Italian Institute of Technology
- European Commission
- US Office of Naval Research
- NATO Undersea Research Centre

For more details...

- A.F. Harris III, M. Stojanovic, and M. Zorzi, "Why Underwater Acoustic Nodes Should Sleep with One Eye Open: Idle-time Power Management in Underwater Sensor Networks," ACM International Workshop on UnderWater Networks (WUWNet) 2006
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- More papers at http://telecom.dei.unipd.it/pages/read/75
- WOSS code can be downloaded from http://telecom.dei.unipd.it/ns/woss/