Recent results on underwater acoustic communication networks

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Outline

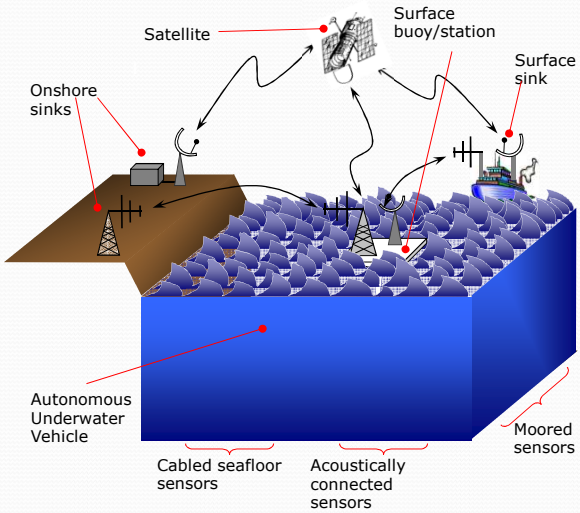
- Introduction on underwater acoustic communications
- Design challenges and opportunities
- Examples of important issues to be addressed (and of recent research results):
  - Conceptual studies via analysis
  - Simulation tools
  - Experimental capabilities
  - Practical protocol design
  - Data analysis and data-driven design criteria
- Conclusions

Why underwater networks

- Lots of applications could benefit
  - Equipment monitoring (pipelines, etc.)
  - Unmanned vehicle coordination
  - Patrolling of port/harbor/ship nearabouts
  - Environmental monitoring
- Different requirements
  - Periodic/bursty data
  - "Real-time" traffic
  - Reliability/disposability
  - Energy efficiency




Typical underwater network scenario



Autonomous Underwater Vehicles

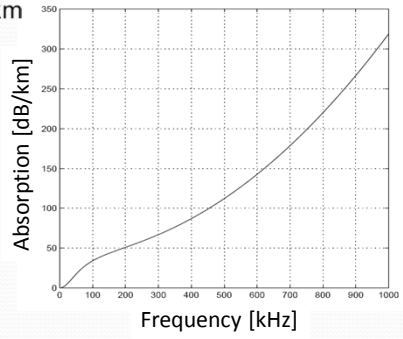

Underwater signaling technologies

- *Radio* communications
  - Tend to fade very rapidly in water
  - Some radio transceiver actually being developed
- *Optical* communications
  - Very high bit rate within (short) reach
  - Dispersion, high attenuation, need for alignment
- **Acoustic communications**
  - Technology of choice to date
  - Very long reach supports typically required transmission ranges
  - Very slow (~ 1500 m/s) propagation speed with respect to radio in air
  - Noise and attenuation are frequency-dependent
  - Limited (frequency and distance-dependent) bandwidth and data rate
  - Strong fading phenomena, especially in horizontal channels

Empirical underwater propagation model
(e.g., see Urick, "Principles of underwater sound")

- Single-path transmission loss equation → $A(r,f) = r^b a(f)^r$
- Absorption (pressure turns into heat) → Thorp's formula:

$$\left(40f^2/(4100+f^2) + 0.1f^2/(1+f^2)\right) \text{ dB/km}$$



- "Anisotropic" propagation
  - Different path loss
  - Different channel behavior (fading, convergence zones, shadow zones, …)

Noise model

- Sum of four components

$$W(f) = N_t(f) + N_s(f) + N_r(f) + N_{th}(f)$$

- Where

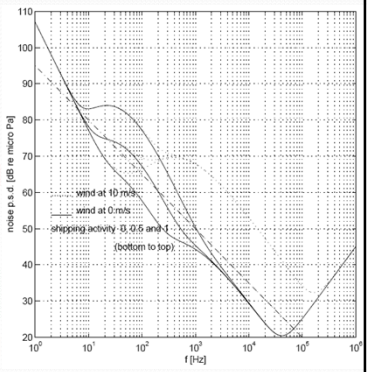
$$10\log N_t(f) = 17 - 30\log f$$

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log f - 60\log(f + 0.03)$$

$$10\log N_w(f) = 50 + 7.5w^{1/2} + 20\log f - 40\log(f + 0.4)$$

$$10\log N_{th}(f) = -15 + 20\log f,$$

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

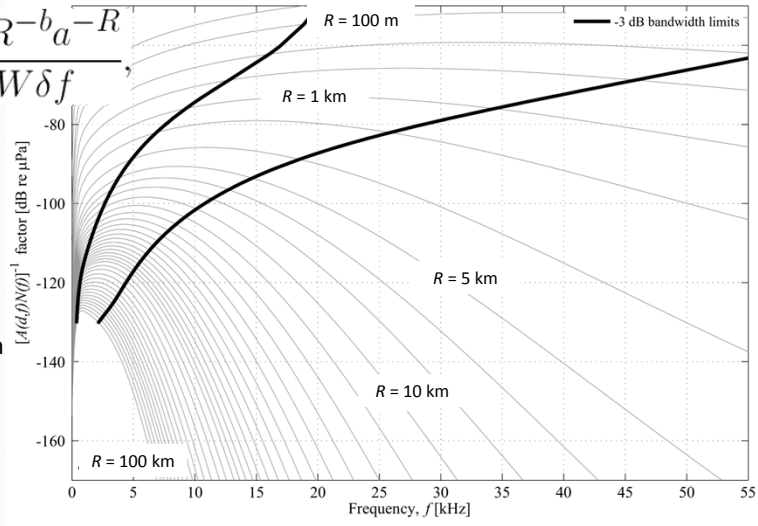


- Various sources: turbulence, shipping, wind, thermal

A consequence: distance-dependent bw

$$\mathrm{SNR} = \frac{P\,R^{-b}a^{-R}}{W\delta f},$$

Both the frequency center AND the bandwidth vary with the distance



Propagation speed of acoustic waves

- Gives rise to significant propagation delays (with respect to the packet transmission time)
- Usually averaged to 1500 m/s
- Depends on the physical characteristics of the water
  - Salinity, temperature, pressure
- Changes with depth: propagation is critically affected by the Sound Speed Profile

Underwater acoustics vs. radio

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

On underwater channel modeling

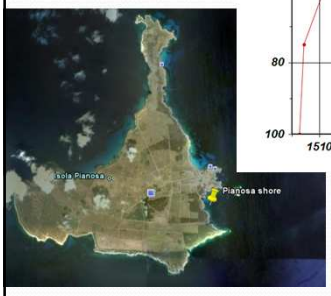
- Unlike in radio, there are no well-established models for acoustic propagation and channel behavior
  - Very erratic and hard to model, lack of interest in the past?
  - Some disconnect between acousticians and comms engineers?
- Experimental data
  - A lot of data out there (though not always easily accessible)
  - Little attention to networking metrics – not very useful as it is
- Available approaches
  - Simple empirical formulas
  - Complicated ray models based on the geometry of the environment
  - *Anything in between?*

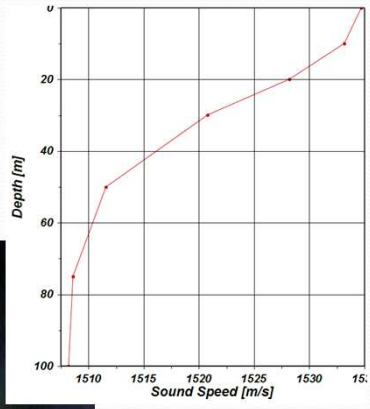
Bellhop ray tracing software

- Solves the propagation equations for sound in bounded sea water using the following environmental parameters
  - Sound speed profile
    - Function relating the speed of sound to the depth
  - Profile of surface waves
  - Profile of the sea bottom
  - Type of sediments on the bottom
    - E.g., mud absorbs part of the sound intensity, rock does not

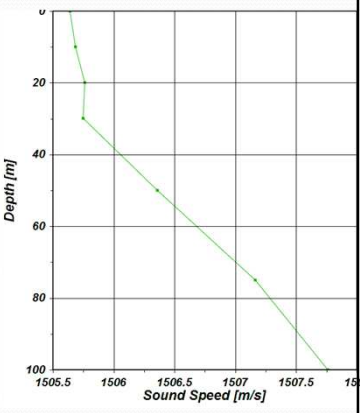
Effect of SSP on sound propagation

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



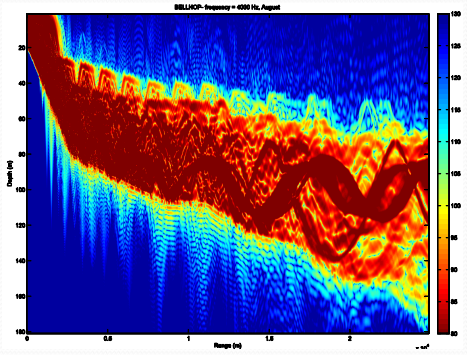


AUGUST SSP

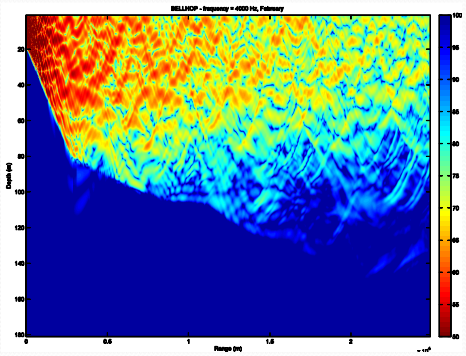


FEBRUARY SSP

Effect of SSP on sound propagation



AUGUST
Attenuation



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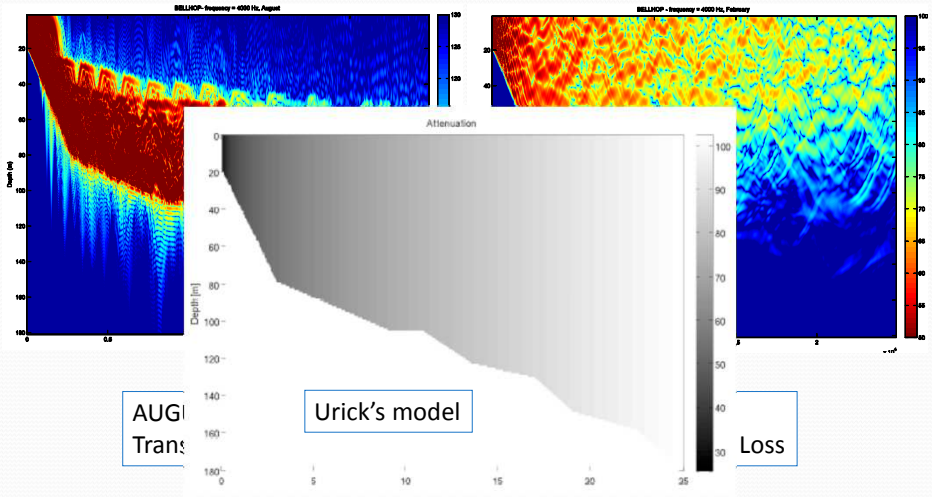

Roadmap

- Several approaches to study/design underwater systems and networks are possible/have been used
- Here we focus on the following:
  - Conceptual approaches (general results based on simple models and analytical tools)
  - Simulation approaches
  - Experimental approaches and capabilities
  - Practical protocol design (e.g., with hardware limitations)
  - Data-driven protocol design and adaptation/optimization

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- **DISCLAIMER: here we do not give a survey of existing work, but rather describe a vision using examples drawn from our own work**

The throughput of underwater networks: analysis and validation

- Question 1: can we deploy a suitable model for analyzing the throughput of underwater networks?
  - Usually this requires to approximate the propagation model using, e.g., the empirical formulas (Urick model)

The throughput of underwater networks: analysis and validation

- Question 1: can we deploy a suitable model for analyzing the throughput of underwater networks?
  - Usually this requires to approximate the propagation model using, e.g., the empirical formulas (Urick model)
- Question 2: is the model representative of more realistic channel behaviors (e.g., obtained via ray tracing)?

Approach

- Model the throughput of underwater networks using a stochastic geometry approach
- Simulate random underwater network deployments using ray tracing for computing the channel power gain
- Show that there is in fact an agreement between the simulation and the analysis…
  - …provided that the channel model parameters are properly fitted to the average channel gain yielded by the ray tracer

Assumptions

- The channel power gain at a frequency *f* consists of
  - path-loss $r^{-b}a(f)^{-r}$ → b is the path-loss exponent
  - exponentially-distributed fading $h(f)$ ($\sqrt{h(f)}$ is Rayleigh)
- Fading is independent and randomly distributed
- Noise is additive with the psd $W(f)$ shown before
- Narrowband transmission within a band δf around f_o
- Node positions distributed according to a Poisson point process (PPP)
- «Typical» RX located at the origin of the coordinate system
- All nodes transmit and interfere at the typical RX

Definitions

- Signal-to Interference and Noise Ratio (affecting the link between the RX at the origin of the coordinate system and a TX located at x_o)

$$\mathrm{SINR} = \frac{h_{x_0} R^{-b} a^{-R}}{W\delta f/P + I}$$

- where $P\,I$ is the interfering power and

$$I = \sum_{x \in \Phi \setminus \{x_0\}} h_x \|x\|^{-b} a^{-\|x\|}$$

- Probability of success of a transmission $P_s = \mathbb{P}(\mathrm{SINR} \geq \theta)$

Probability of success

- Since fading is exponentially distributed, we have
  [Haenggi et al., «Stochastic geometry and random graphs for the analysis and design of wireless networks», IEEE JSAC 2009]

$$P_s = \underbrace{\exp\left(-\frac{\theta R^b a^R W \delta f}{P}\right)}_{P_{s,\mathrm{n}}} \underbrace{\mathcal{L}_I\left(\theta R^b a^R\right)}_{P_{s,\mathrm{i}}} \triangleq P_{s,\mathrm{n}} P_{s,\mathrm{i}}$$

$$P_{s,\mathrm{i}} = \exp\left(-\lambda c_d \sum_{n=0}^{\infty} (-1)^n A_n\right)$$

$$A_0 = \bar{R}^d + \frac{d\theta R^b a^R}{(\log a)^{d-b}}\,\Gamma(d-b, \bar{R}\log a),$$

$$A_n = \frac{d\bar{R}^d a^{-Rn}}{d+bn}\,{}_1F_1(d+bn, d+bn+1; \bar{R}n\log a) + \frac{d\left(\theta R^b a^R\right)^{n+1}}{((n+1)\log a)^{d-b(n+1)}}\,\Gamma(d-b(n+1), \bar{R}(n+1)\log a), \quad n \geq 1$$

Network metrics

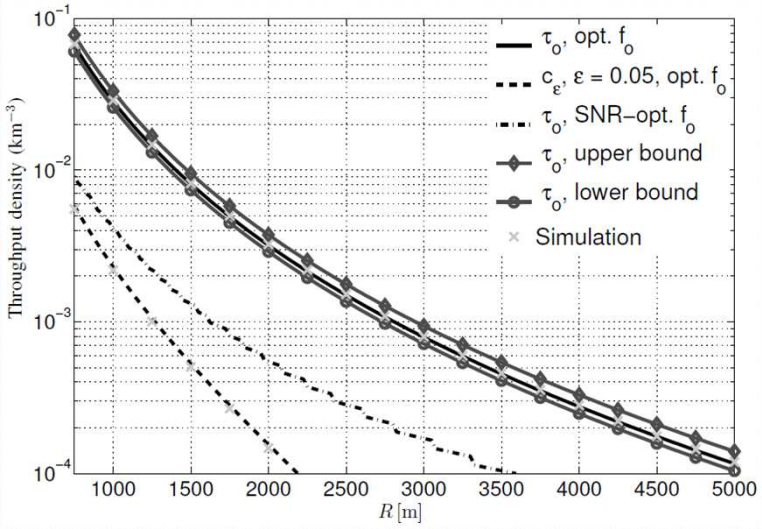
- Throughput density → $\tau(\lambda) = \lambda \exp\left(-\lambda V_d - \frac{\theta R^b a^R W \delta f}{P}\right)$
- Opt. throughput density → $\tau_o = \frac{1}{V_d} \exp\left(-\frac{\theta R^b a^R W \delta f}{P} - 1\right)$
- Transmission capacity

$$c_\varepsilon = \max\left\{\frac{1-\varepsilon}{V_d}\left(-\log(1-\varepsilon) - \frac{\theta R^b a^R W \delta f}{P}\right), 0\right\}$$

- Maximum radius for supporting a transmission capacity c_ε

$$R_{\max,\varepsilon} = \frac{b}{\log a} \mathcal{W}\left(\frac{\log a}{b}\left(-\frac{P\log(1-\varepsilon)}{\theta W \delta f}\right)^{1/b}\right)$$

Results – optimum throughput



A consequence: frequency-dependence

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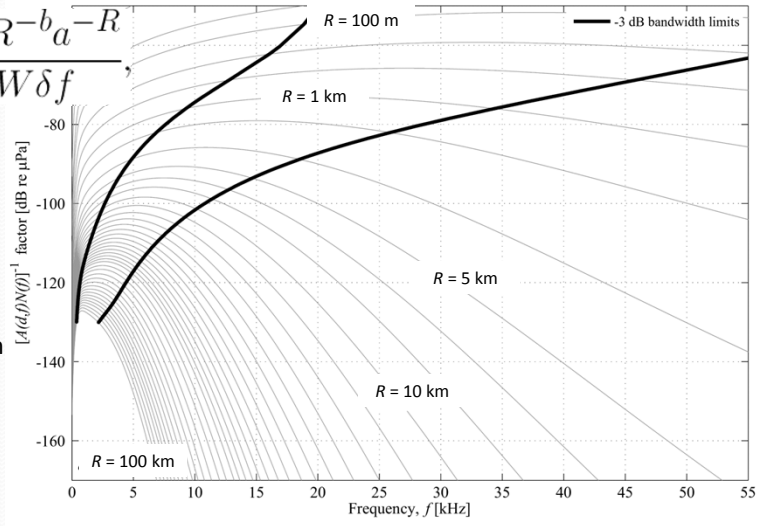

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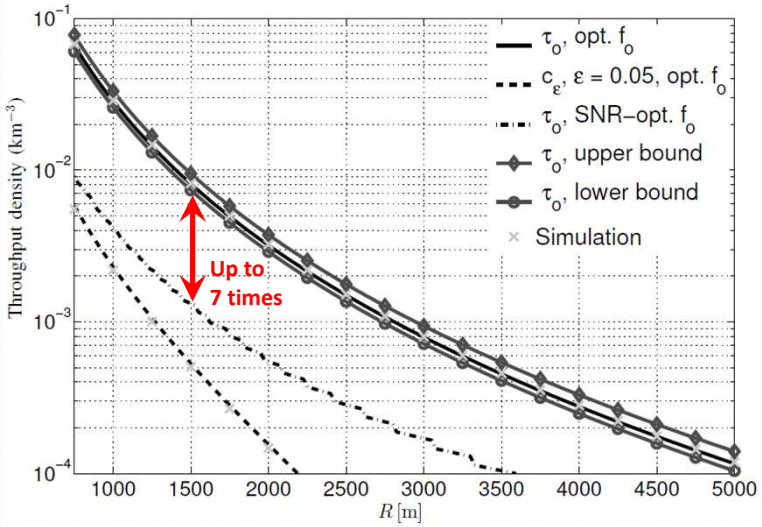
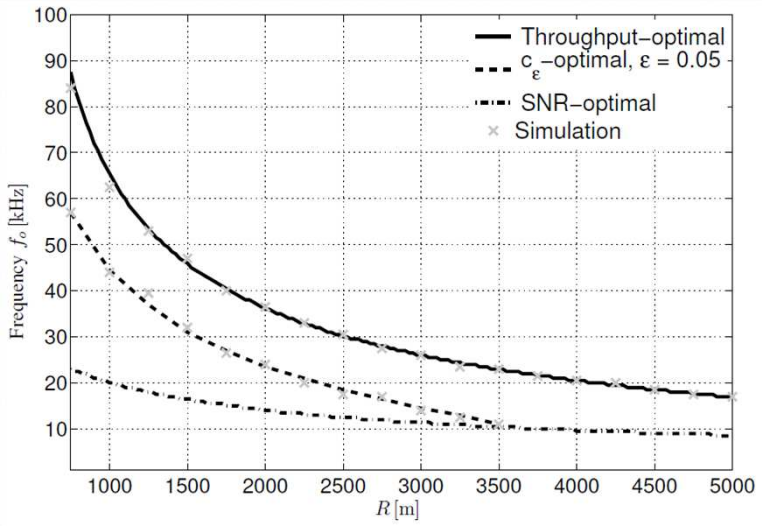


Frequency f_o for optimal throughput



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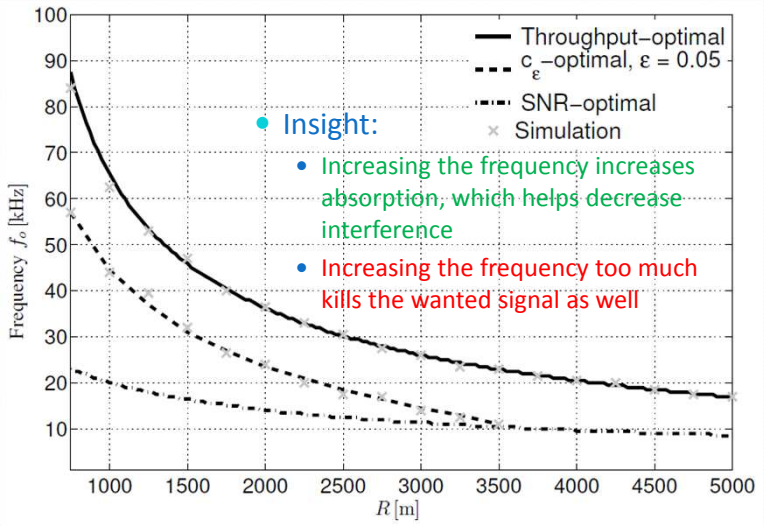

- Insight:
  - Increasing the frequency increases absorption, which helps decrease interference
  - Increasing the frequency too much kills the wanted signal as well

Validation using ray tracing

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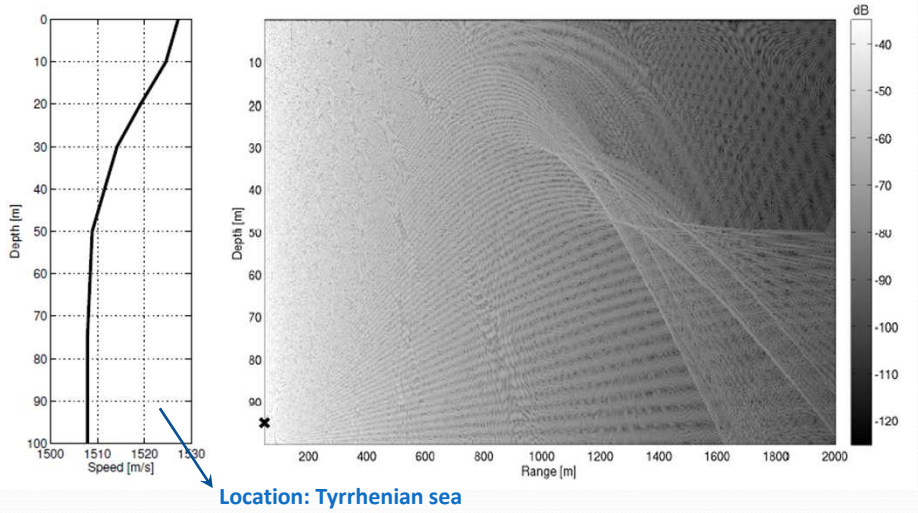
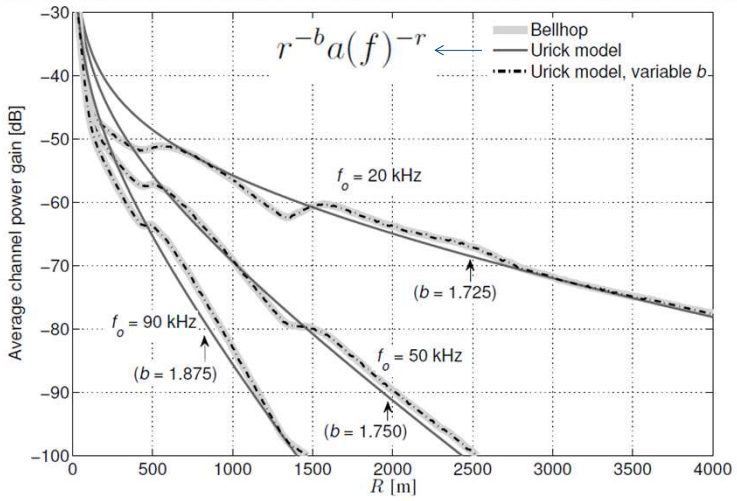
- Assumptions
  - 2D network (all nodes fixed at the same depth)
  - Flat surface profile
  - Flat bottom profile
- How to obtain a channel «fading» process with ray tracing?
  - Randomize the SSP, perform ray tracing for each random SSP
  - Use the resulting channel gains as a «database» of channel realizations to be used in simulations

Example of Bellhop output

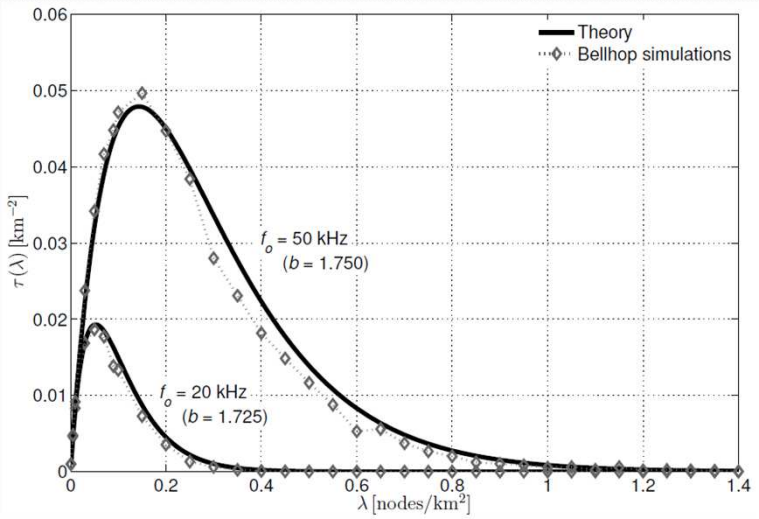


Location: Tyrrhenian sea

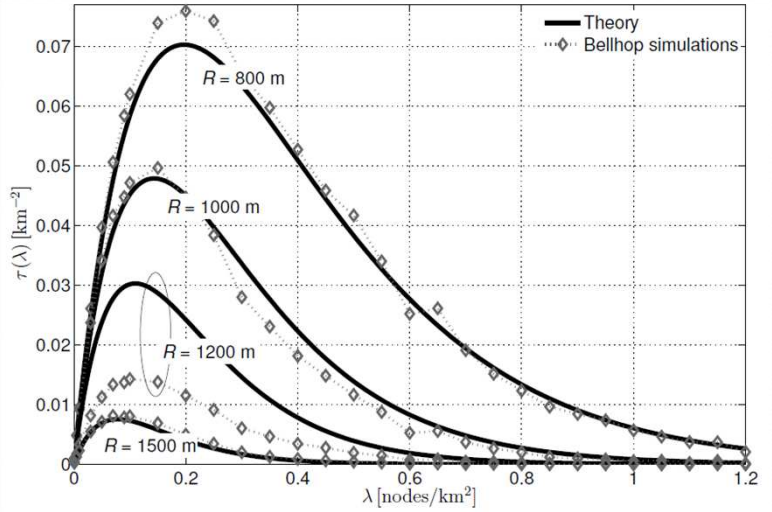
Matching the parameters of the Urick model to the output of Bellhop



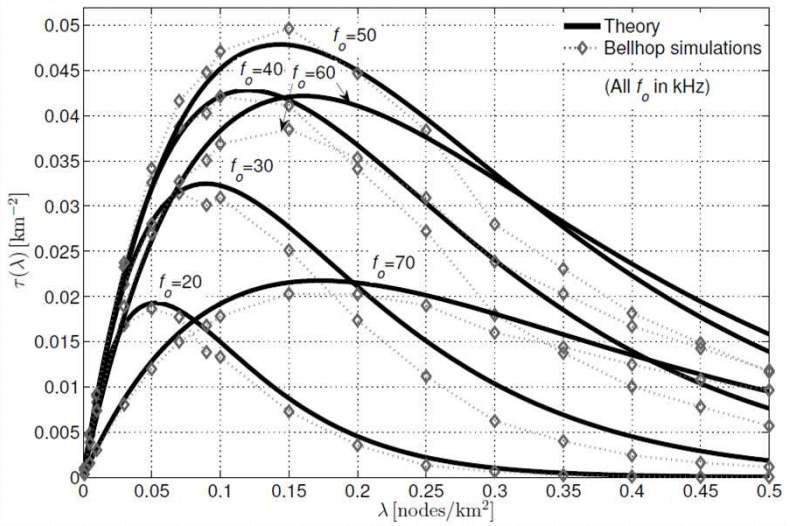
Throughput for f=20 and f=50 kHz



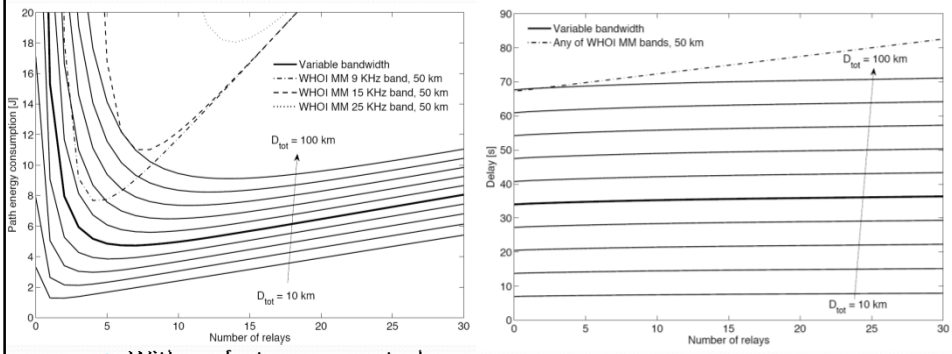
Throughput for different values of R



Frequency optimization

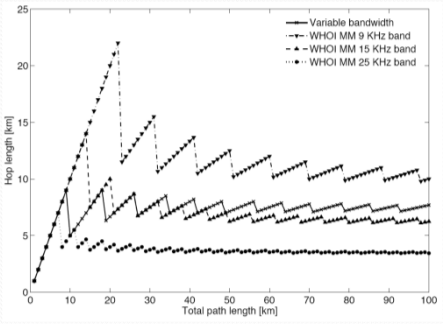


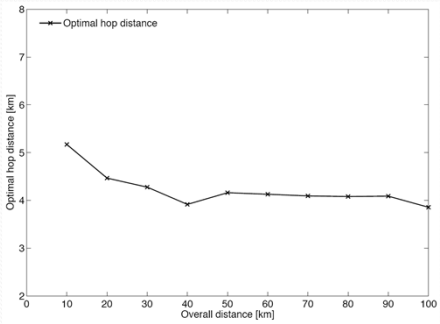
Energy-aware routing: line network



- 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 & 3D



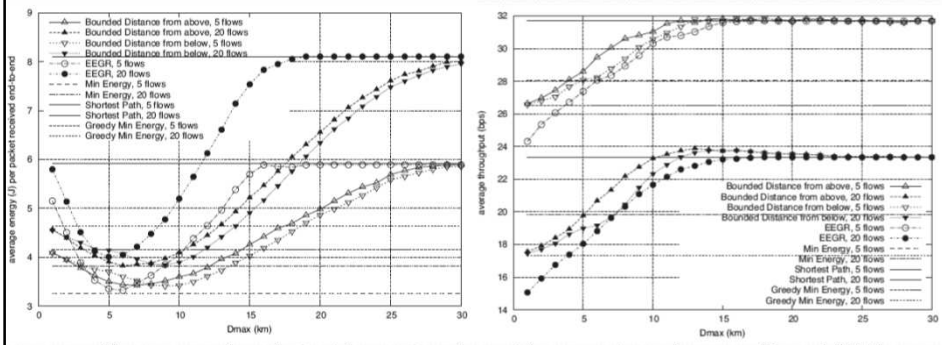


- The average density of relays that minimizes energy is relatively insensitive to the path length
- The minimum energy itself is not very critical

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
  - If no such node exists, pick the closest that is at least **X** meters away
  - Choose **X** optimally based on previous analytical results
- Compared with: Greedy minimum energy (shortest transmit distances), Shortest hop count (longest transmit distances), Optimum path centrally computed

Simulation 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

Insights…

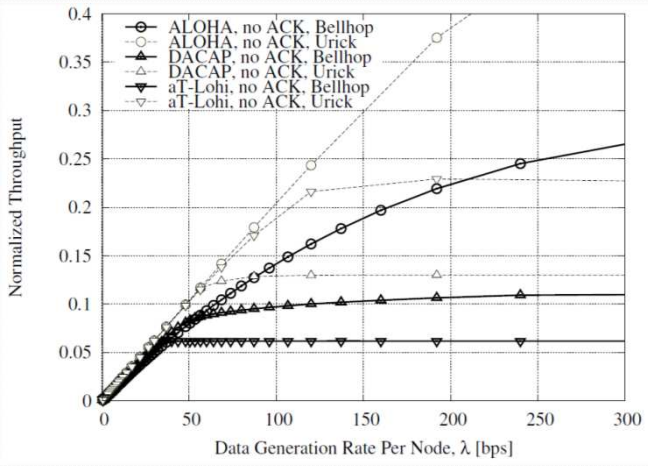
- Analytical approaches are possible and useful for general results
- However, they need to be validated for consistency with channel behaviors
- A purely experimental approach is likely infeasible, but a proper mixed of analysis, real data, and accurate models may provide useful information
- Note: some of the assumptions made (e.g., frequency tuneable transceivers) may not hold in practice

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 an 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
- 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



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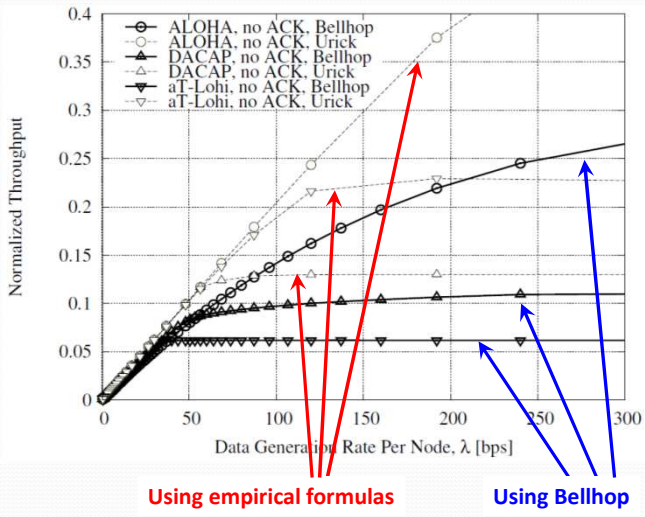

Using empirical formulas

Using Bellhop

WOSS – Example results

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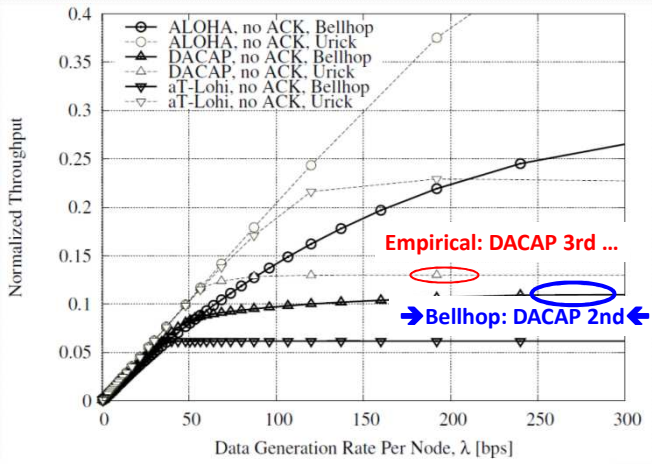


Empirical: DACAP 3rd …

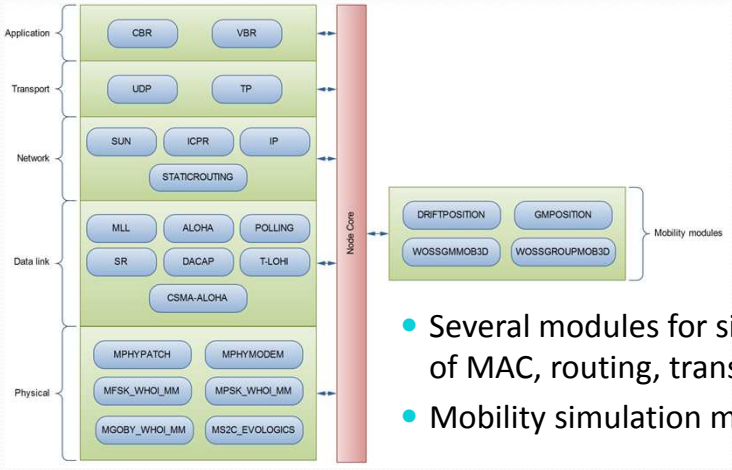
➔Bellhop: DACAP 2nd←

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

From simulation to experiments

- Simulation tools are very useful to study complex scenarios at low cost
- However, we would like to also be able to test and validate the simulation results in a real scenario
- Idea: connect simulation software to actual hardware, which saves a lot of development effort and makes simulation and experiments directly comparable
- Some platforms have been proposed for this purpose, DESERT UW is one of them that we developed

The DESERT Underwater libraries



- Several modules for simulation of MAC, routing, transport, etc.
- Mobility simulation modules

Code at http://nautilus.dei.unipd.it/desert-underwater

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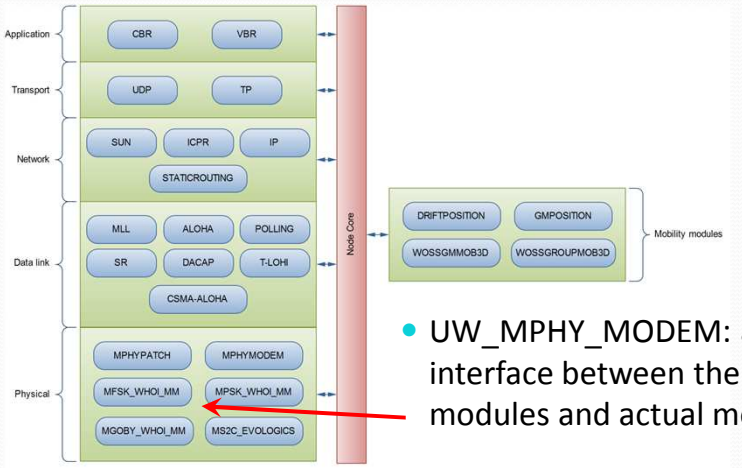

- UW_MPHY_MODEM: an interface between the simulator modules and actual modems

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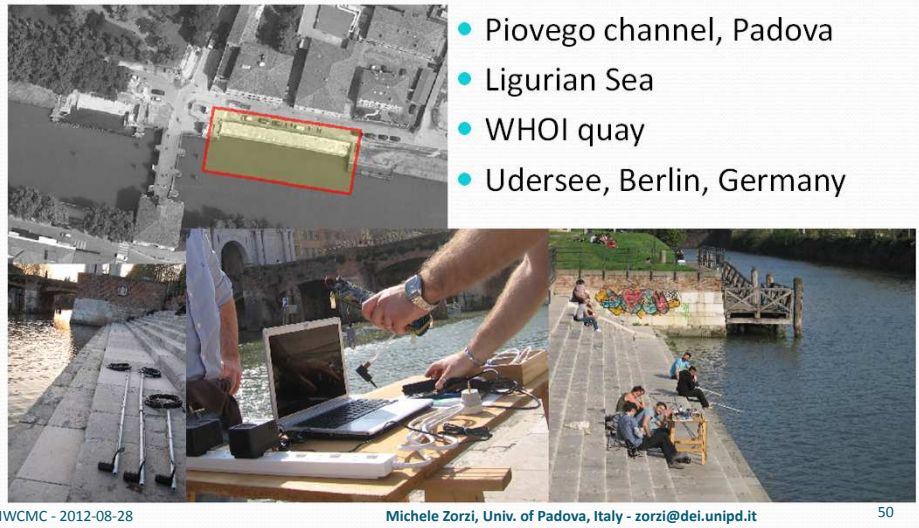
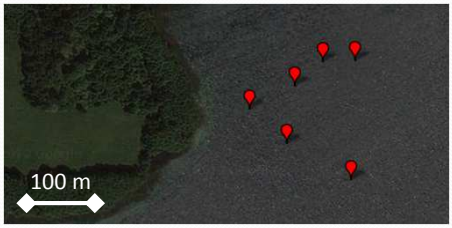
Feasibility tests in collaboration with several partners



- Piovego channel, Padova
- Ligurian Sea
- WHOI quay
- Udersee, Berlin, Germany

Recent tests of SUN using DESERT



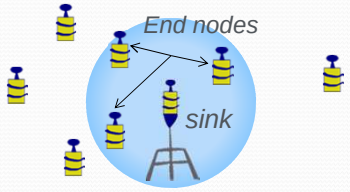
- Werbellin lake, Germany, August 2012
- 6 modems: *EvoLogics S2C mid-frequency (18-36 kHz)*

- Several experiments
  - Node failure
  - Route recovery
  - Appearance of new nodes
  - Sink mobility
- Outcomes
  - Delivery delay
  - Overhead
  - Traces of traffic in the network

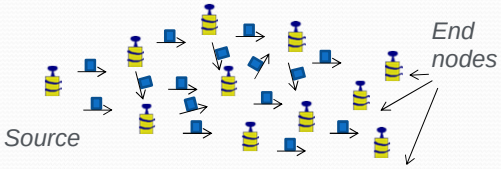
Source routing for UW Nets (SUN)

- Reactive source routing protocol
- Designed to support
  - Both stationary and mobile nodes
  - Multiple sinks
- Does not require channel state information and location information at the nodes (easy to implement)
- Some improvements compared to usual source routing
  - End nodes are periodically probed by the sink for more efficient mgm of the route replies (plus optimizations)
  - Timed transmission buffer management improves some MAC effects, decreasing congestion

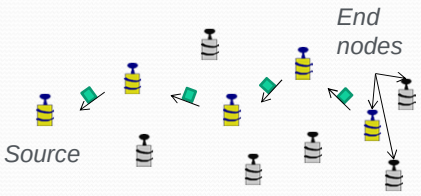
SUN phases



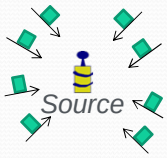
1) Periodic probing for notifying end nodes



2) Route request

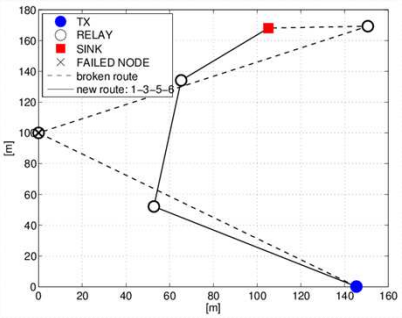


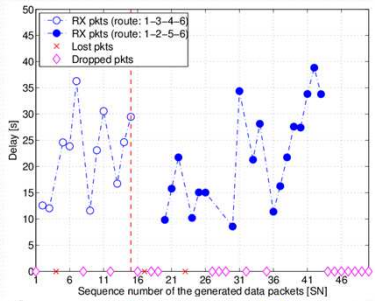
3) Route reply

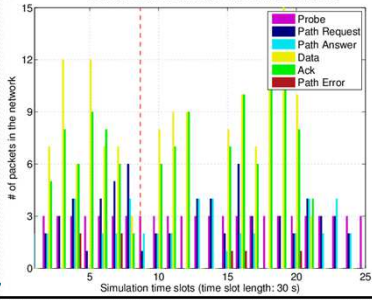


4) Selection of the best route in the presence of multiple answers

Recent tests of SUN using DESERT







- «Failed» node requires the protocol to adapt and find a new route
  - Path error packets are issued followed by new route request and replies
  - New packets follow the new route

Insights…

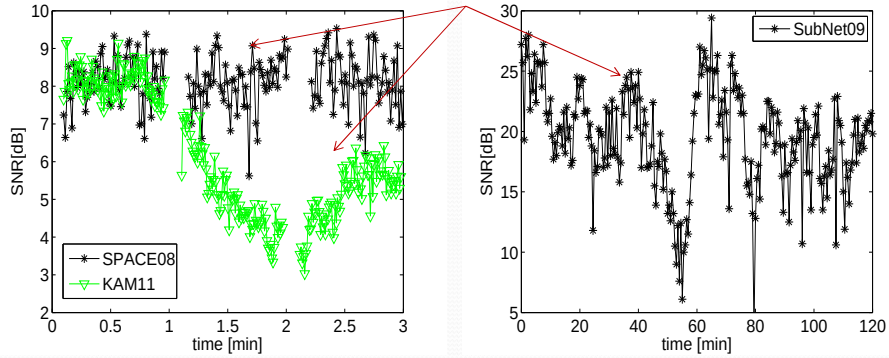
- Tools to capture complex behaviors are very useful in order to lend credibility to the results
- Experimentation is very important in order to verify the proposed approaches, but is very costly and difficult
- A proper tool to interface simulation software and real hardware has proved very useful
- Open source tools will encourage other researchers
- To develop an effective and reliable methodology to test protocols in realistic environments remains a challenge

Time-varying channel conditions in static links

- Post-processing of experimental data highlighted fluctuations of the channel quality over intervals of time relevant for both communication systems and networking protocols
- It would be useful to identify the relationship between environmental conditions and the dynamics of channel quality
- Evaluate communications techniques compensating for time-variability
- How to perform prediction of and adaptation to time-varying conditions
- Impact of time-varying conditions, link lengths and resulting performance of networking protocols

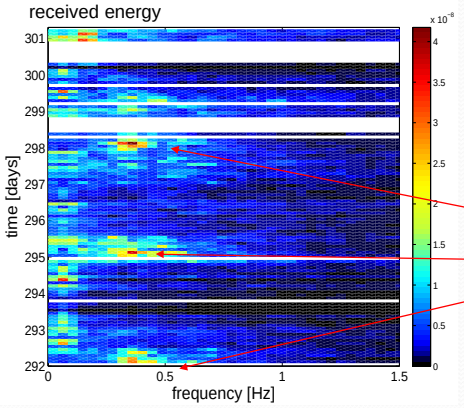
Examples of time-varying channel conditions

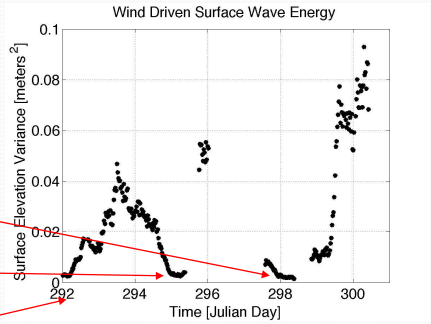
Different SNR dynamics depending on scenario and environmental conditions dominating propagation (KAM11 and SubNet09 water depth ~100 m -> ssp, SPACE08 water depth~15 m -> surface)



Impact of surface conditions on very shallow UWA comms

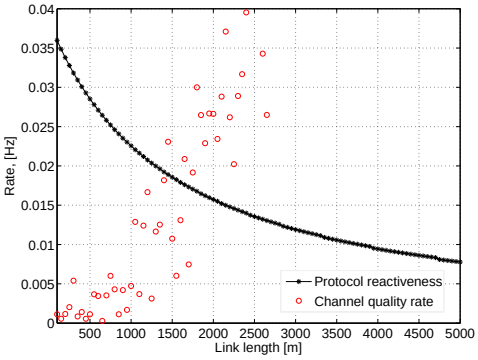
Time series of Power Spectral Density (PSD) of received energy





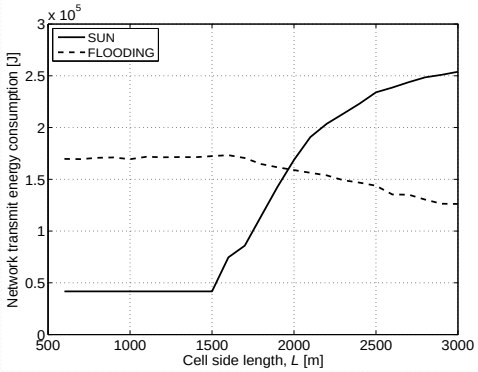
Periodic behaviors were observed in correspondence of low wind driven surface energy

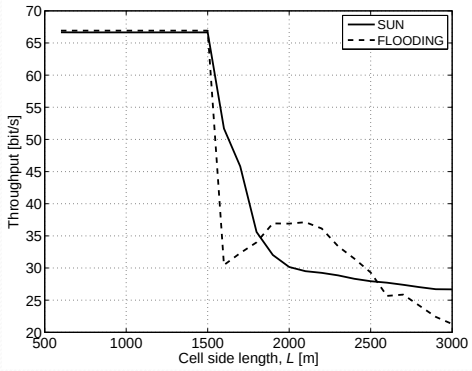
Impact of time-varying channel conditions on network performance



- Reactive (/adaptive) networking protocols may be affected by propagation delays and time-varying link quality
- Reactiveness of a protocol is a decreasing function of the link length
- However, time-varying conditions trigger adaptation
- With such a study, we find the maximum link length above which reactive protocols do not perform well

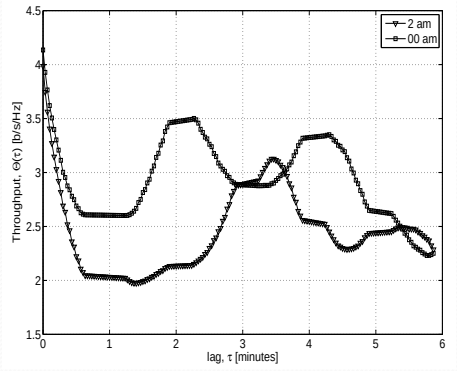
Source routing vs flooding in time-varying channel conditions





Flooding is preferable in low density networks (large cell lengh), whereas source routing outperforms flooding (at least in energy consumption) for denser deployments

Taking advantage of time-correlated behaviors: adaptation vs prediction



Throughput as a function of feedback delay in a variable-rate communication scheme.

- Time-correlated dynamics enable predictability of the channel quality
- Long propagation delays make the Channel State Information (CSI) outdated
- Therefore adaptive techniques should include a learning phase and prediction

Insights…

- Time-varying behaviors are observed in UW channels
- Dealing with them is important and challenging
- The UW channel is very difficult to characterize, but recent results show some patterns (at least from a networking perspective)
- Understanding these effects and their relationship with environmental parameters is an emerging topic
- How to use this information will involve a mixture of adaptation, prediction, and learning

Conclusions

- Underwater networking is a very exciting and promising area
- Many challenges are still present, related to modeling, propagation, proper tools for study, and design criteria
- Work has been done on protocols, but a lot remains to be done
- Conceptual studies still important, but need to be grounded
- Simulation and experimentation need to be carefully deployed
- Availability of open-source tools a key enabler for many groups
- Understanding channel behaviors and their environmental causes is a very difficult problem, at the forefront of this area of research

Thanks to our sponsors

- The Italian Institute of Technology
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- The NATO Undersea Research Centre
- The US National Science Foundation

Further reading on our web site

- http://telecom.dei.unipd.it/underwater