MULTIMODAL UNDERWATER NETWORKS

Filippo Campagnaro

Outline

- Motivation
- Underwater communication technologies
- Underwater multimodal networks
- Conclusions and look ahead

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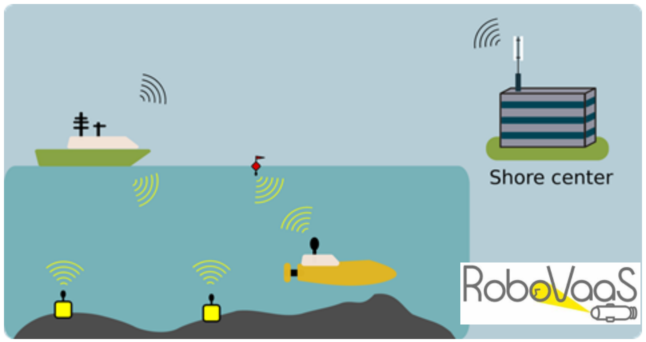
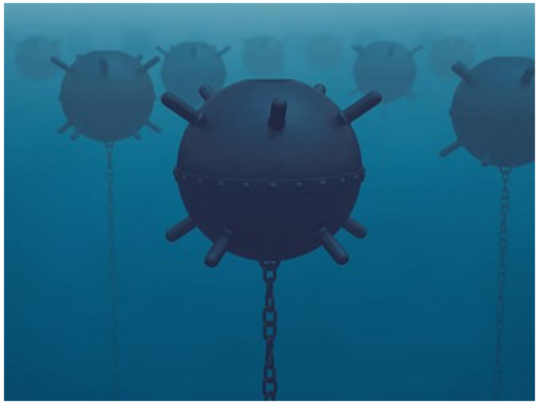
Motivation



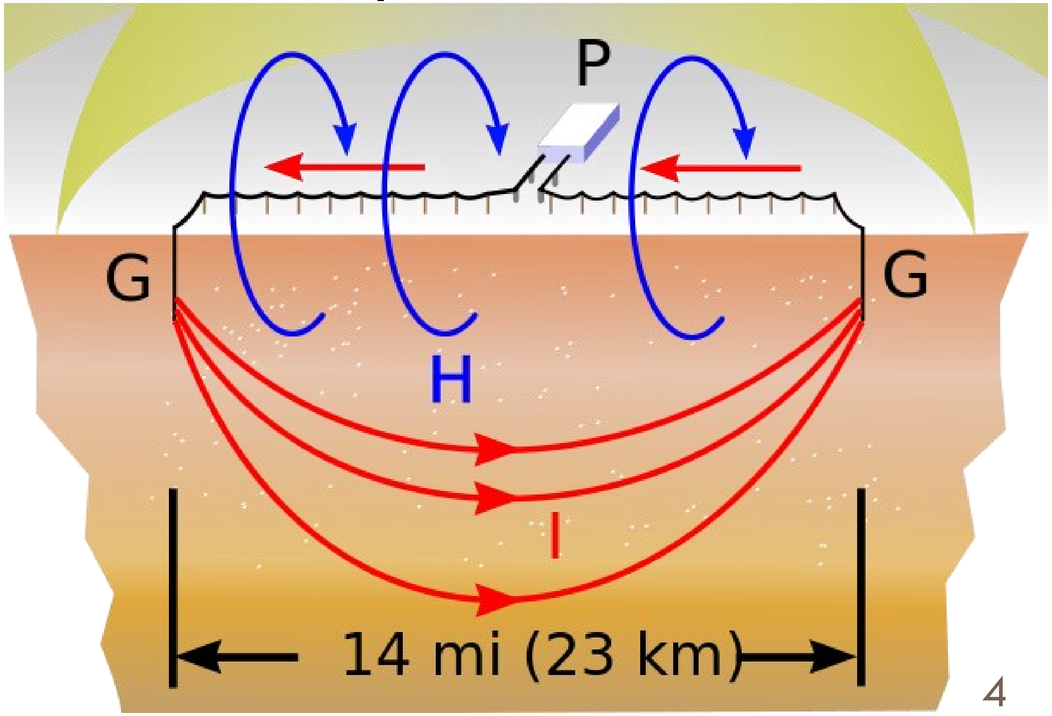


- About 71% of the Earth's surface is water-covered, but nowadays ocean exploration is still a big challenge
- Application of underwater networks
  - Tsunami prediction, coastal and seabed erosion monitoring,
  - Coastal surveillance, mine countermeasure, REA and various military application..
  - O&G pipeline monitoring
  - Smartports
  - Fish farming, water quality assessment, study of climate change and biodiversity

RF communications undersea

- WiFi works only for few centimeters
- VLF (3 – 30 kHz) **range** up to **20 meters, 300 b/s**
- ELF (3 Hz – 300 Hz) **range** up to **several miles, 1 b/s.**
- Drawback: size and power consumption

VLF
2 km



So… how to communicate?

- Blue and green light propagates a few meters

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So… how to communicate?

- Marine mammals can talk with **sound** up to miles under the sea

Existing Technologies

- Acoustic communications → Long range low rate
  - Affected by multipath, wind and ship noise: not stable

- Electromagnetic (EM):
  - Radio Frequency (RF): → Very short-range high rate
  - Magneto Inductive (MI): → Short range low rate

- Optical communications → Short range high rate
  - Affected by sunlight and turbidity, not stable

F. Campagnaro, R. Francescon, P. Casari, R. Diamant and M. Zorzi, "Multimodal Underwater Networks: Recent Advances and a Look Ahead", ACM WUWNet17

Acoustic – Pro and Cons

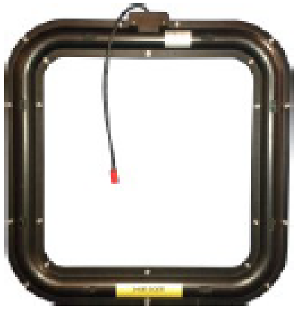
Advantages	Disadvantages
Proven technology	Affected by acoustic noise and multi-path
No need for LOS	High power consumption
Range up to 30 km	Order-of kb/s bit rates
Robust in deep water vertical link	Poor in shallow waters
Good channel models for simulation	Affected by sound speed gradient
	High latency
	May impact marine life

- Applications in all long-range communication scenarios:
  - Underwater sensors networks (biology, marine science).
  - Coastal erosion monitoring.
  - Surveillance, platforms monitoring, etc..

EM – Pro and Cons

Advantages	Disadvantages
High Bandwidth	Very short range (<10 m)
No need for LOS	Affected by water salinity and conductivity
Low Latency	Few modems available
Good performance in fresh shallow water	Susceptible to EMI
Crosses air/water/ seabed boundaries	

- Applications in very short range communication scenarios:
  - Broadband data exchange in AUV docking stations
  - Low latency low multipath data muling in short range.
  - Often used in combination with acoustic.



MI Pro and Cons

Advantages	Disadvantages
Short to medium range (10:100 m)	Low bitrate (~kbps)
No need for LOS	Few modems available
Low Latency	Susceptible to EMI
Similar performance as in air	May impact marine life
Crosses air/water/ seabed boundaries	

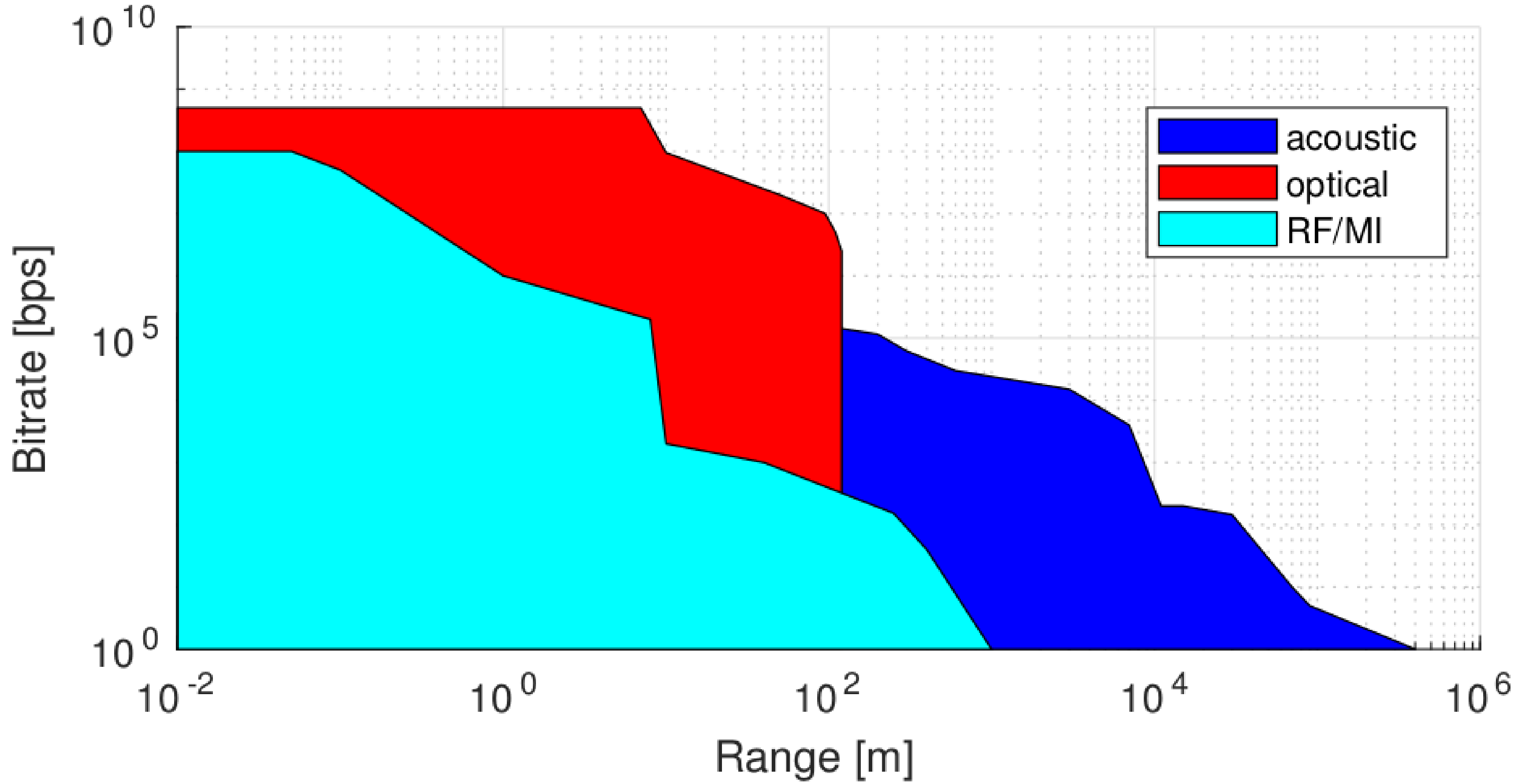
- Applications in short-medium range communication scenarios:
  - Stable low-rate data exchange up to 10s of meters
  - Often used in combination with acoustic.

Optical – Pro and Cons

Advantages	Disadvantages
Mb/s bit rates	Short range (<100 m)
High bits per Joule capacity	Affected by turbidity, marine fouling and ambient light
Low Latency	Needs LOS and good alignment
Good performance in clear dark water	

- Applications in short range communication scenarios :
  - Video streaming from an ROV in deep water scenario.
  - Broadband communication in docking stations.
  - Data muling from underwater sensors network.
  - Often used in combination with acoustic.

Existing Transmission Technologies



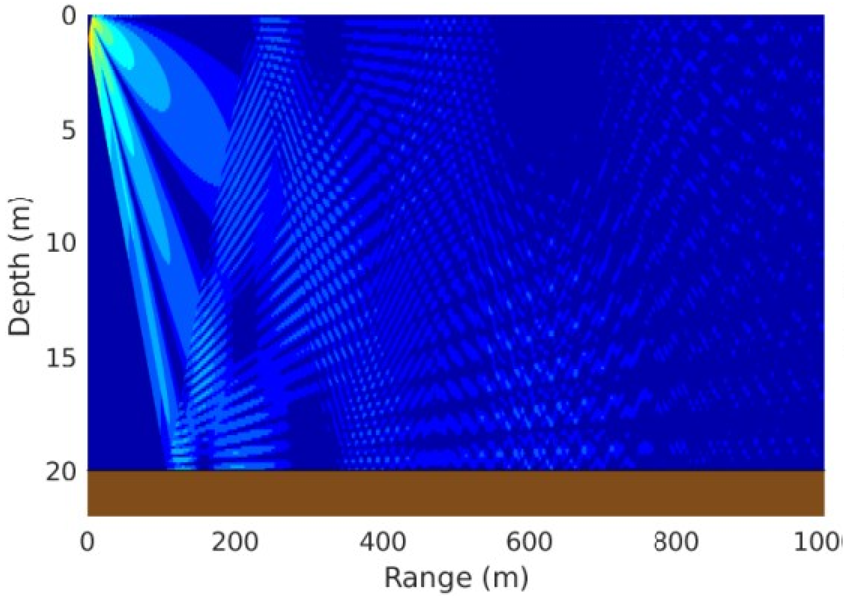
F. Campagnaro, A. Signori, M. Zorzi, "Wireless Remote Control for Underwater Vehicles," JMSE Sept. 2020

Acoustics modems

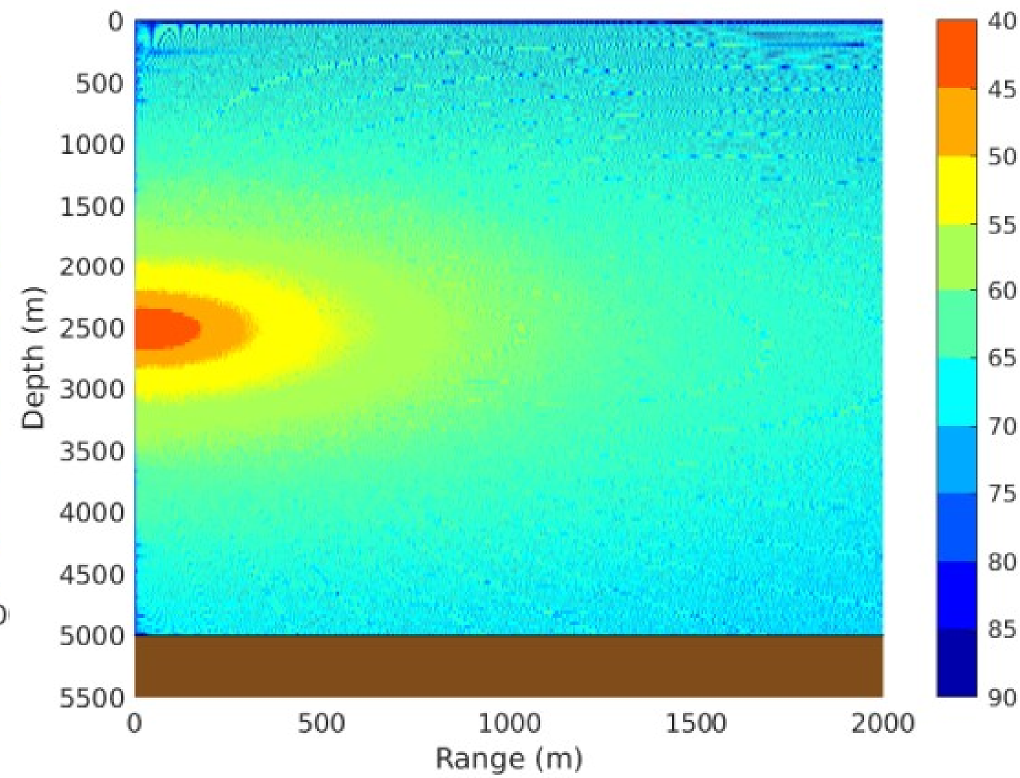
- Low frequency (LF) < 15 kHz
  - Up to **10:15 km** <2 kbps (**usually 100s bps**)
  - 100s km achievable with high power (may affect marine fauna)
  - Large, for military applications (NATO JANUS standard)
- Medium frequency (MF) < 40 kHz
  - **3 km** < 10 kbps (**usually a few kbps**)
  - The mostly installed onboard AUVs
- High frequency (HF) > 40 kHz
  - **100s m,** 100 kbps (**usually 10s kbps**)
  - Small size, easy to be installed in vehicles

Complete review of modems can be found in
F. Campagnaro, A. Signori, M. Zorzi, "Wireless Remote Control for Underwater Vehicles," JMSE Sept. 2020

Acoustics: geometry



Shallow water propagation

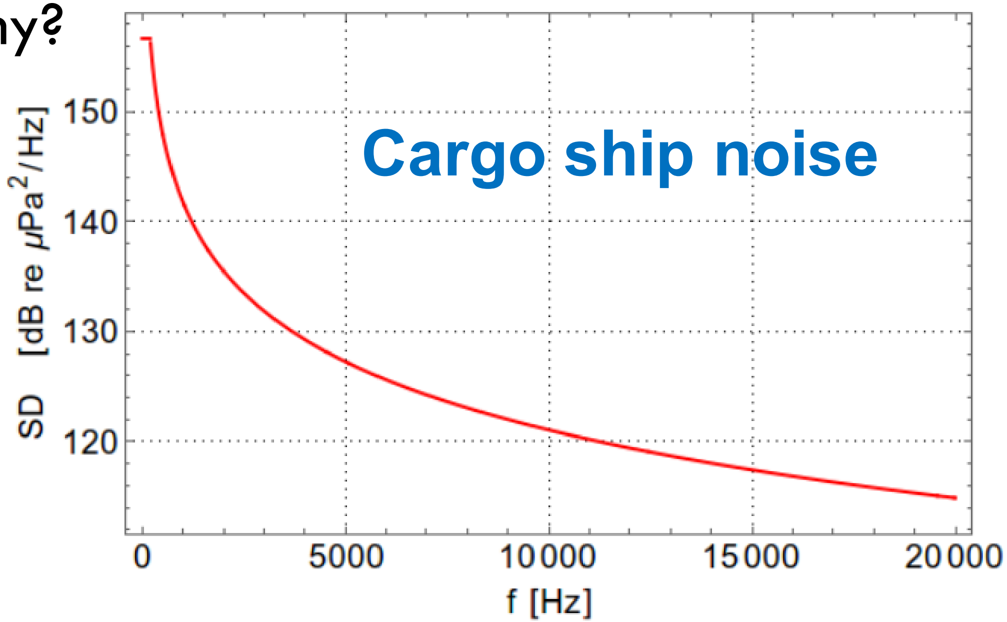


Deep water propagation

Bellhop ray tracer - http://oalib.hlsresearch.com/Rays/

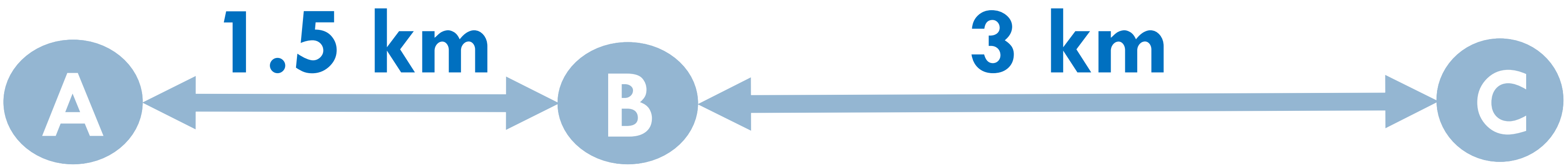
Acoustics: "strange" effects

- "Afternoon" effect
  - Changes in temperature affects sound speed
- LF modems reach a longer distance than MF and HF
  - Sometimes they don't! Why?
  - Ship noise
  - Echosounders
  - Existing LBL/USBL



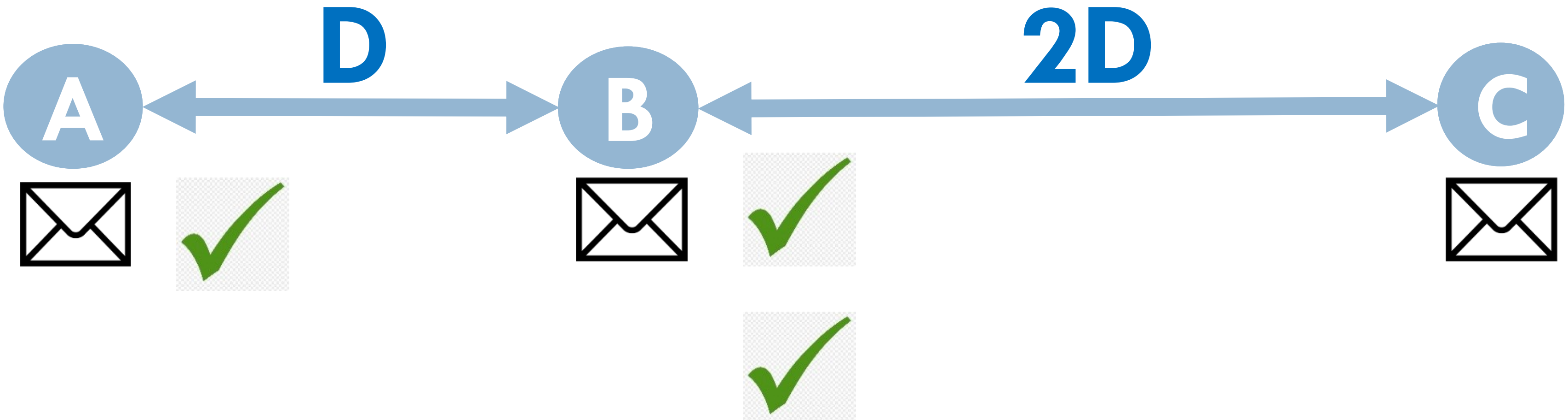
E. Coccolo, F. Campagnaro, A. Signori, F. Favaro, M. Zorzi, "Implementation of AUV and Ship Noise for Link Quality Evaluation in the DESERT Underwater," ACM WUWNet 2018, Shenzen, China

Acoustics: long delay



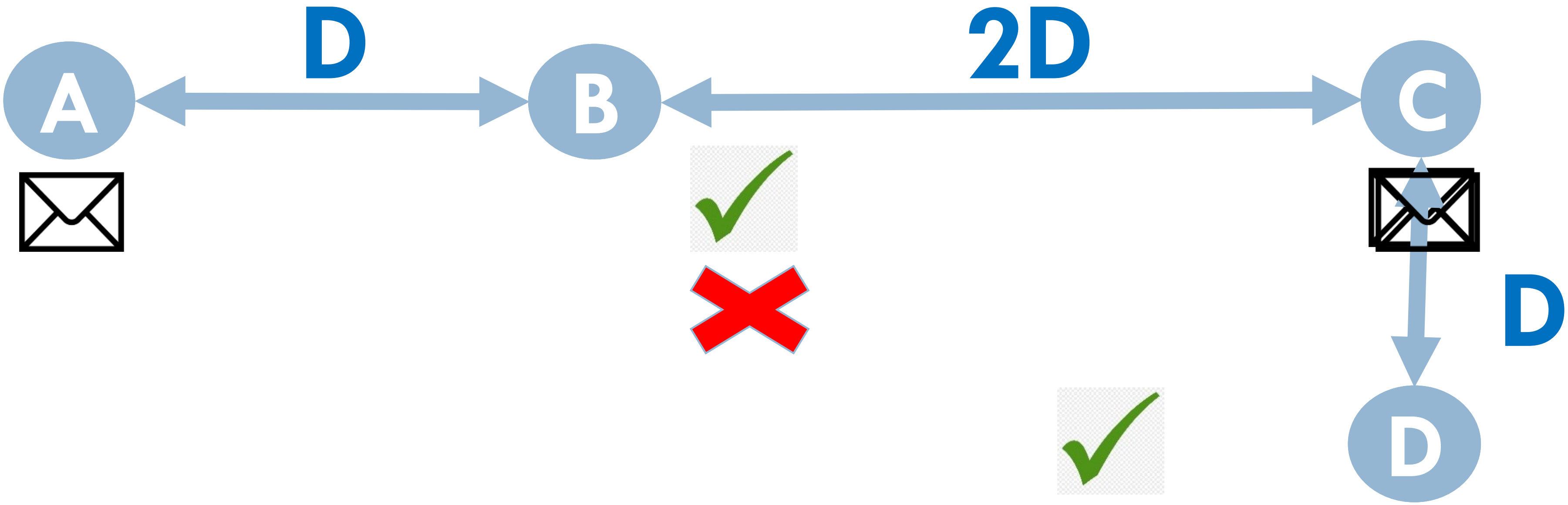
- Speed of sound = 1500 m/s
- Propagation delay **A→B = 1 s, B→C = 2 s**
- Carrier sense MAC layers ineffective
- TDMA requires 2 s time guard between slots

Acoustics: long delay



- Propagation delay A→B = 1 s, B→C = 2 s
- Packet duration = 0.5 s
- Parallel transmission without colliding!

Acoustics: near-far



- A→B, C→D, collision happens at B
- Near-far interference let B receiving from A despite the interference from C

Optical communication

- Optical transmission depends mainly on
  - Alignment
  - Ambient light noise
  - Attenuation coefficient **c**
    - Sum of absorption (**a**) and scattering (**b**) coefficients

Water type	a[m^{-1}]	b[m^{-1}]	c[m^{-1}]
Clear ocean	0.10	0.05	0.15
Coastal ocean	0.20	0.20	0.40
Turbid harbor	0.50	1.69	2.19

R. Diamant, F. Campagnaro, M. De Filippo De Grazia, P. Casari, A. Testolin, V. Sanjuan Calzado, M. Zorzi, "On the Relationship between the Underwater Acoustic and Optical Channels", IEEE Transaction on Wireless Communications 2017

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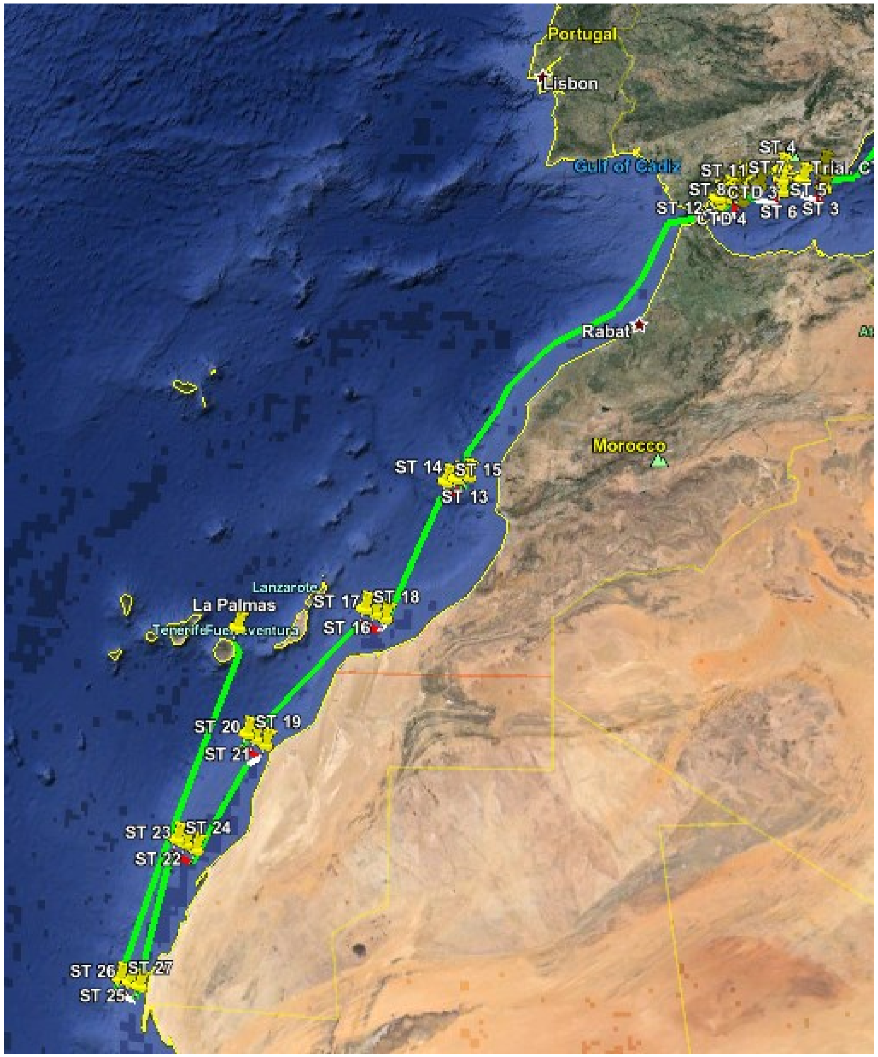
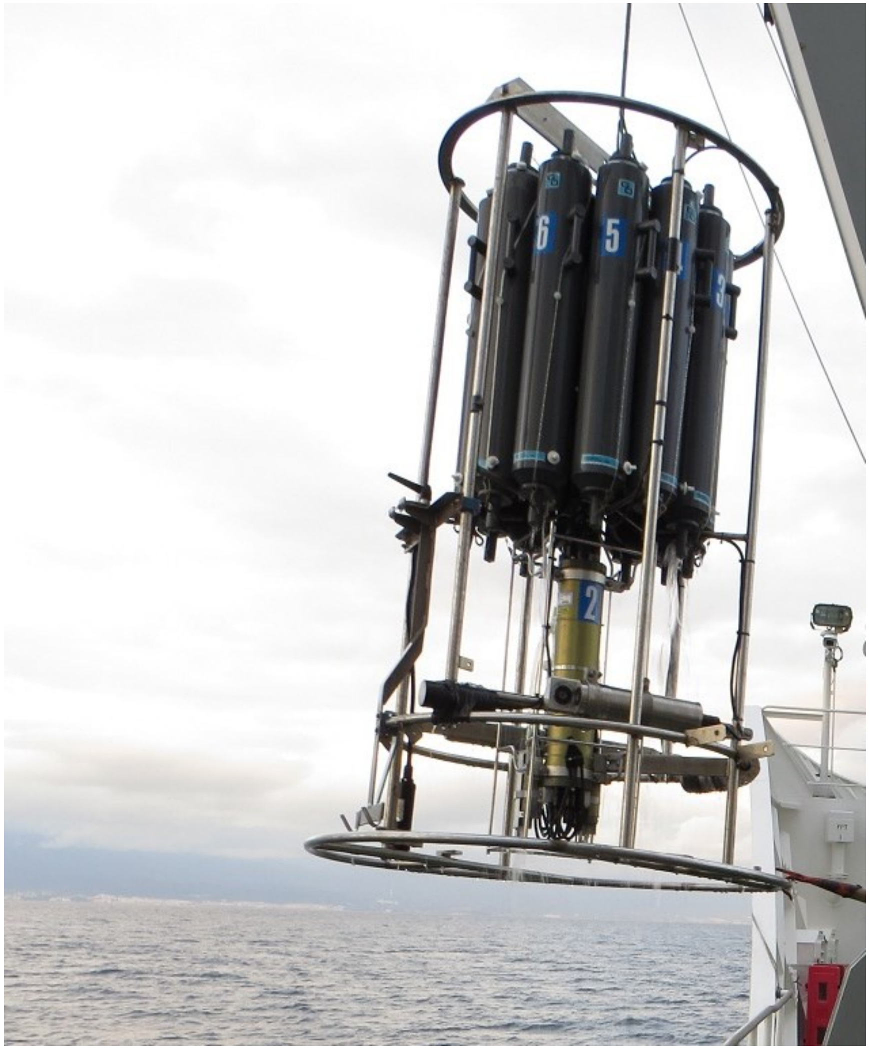
Sea campaign: ALOMEX'15



Optics Facilities



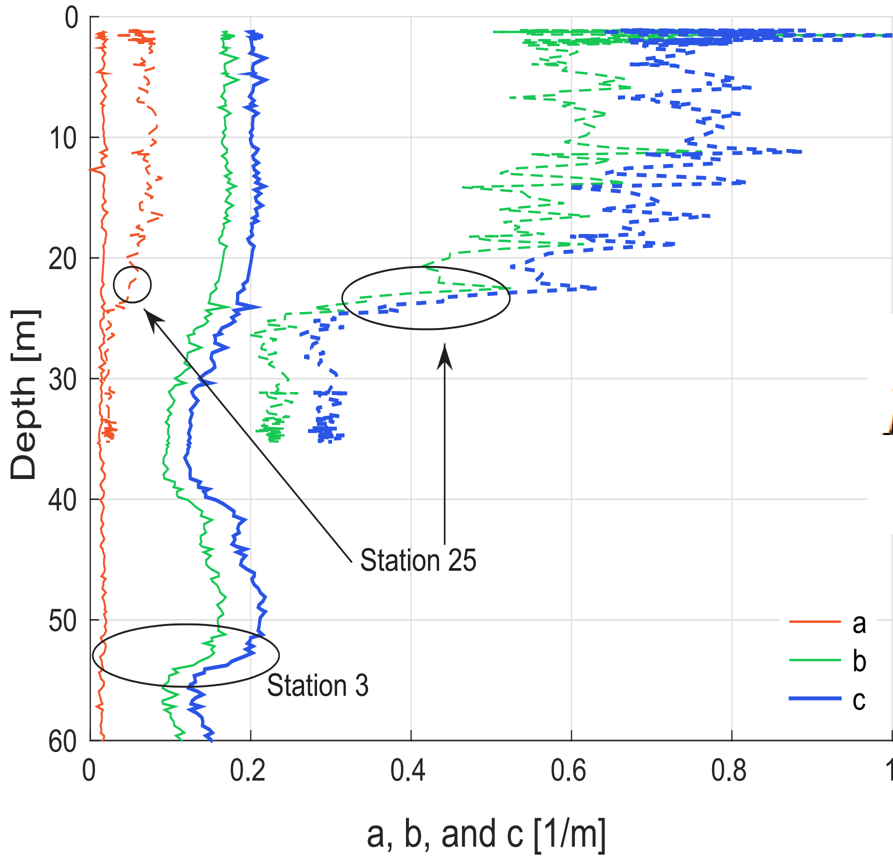
Attenuation and received power

$$c(\lambda) = a(\lambda) + b(\lambda)$$

a: absorption

b: scattering

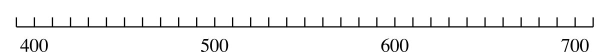
c: attenuation



$$P(r) = P_0 \cdot e^{-c(d) \cdot r}$$

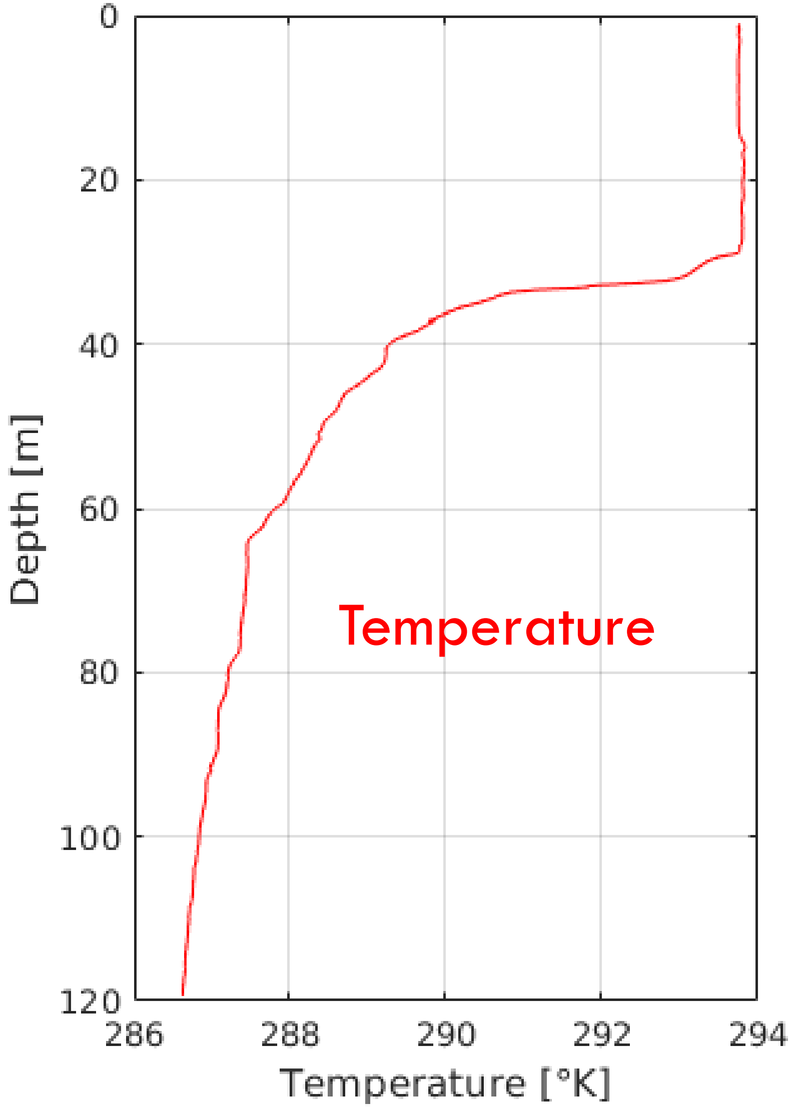
$$P(r) = P_0 \cdot \prod_{k=K_0}^{K_N} e^{-c(d_k) \cdot \Delta_r(d_k)}$$

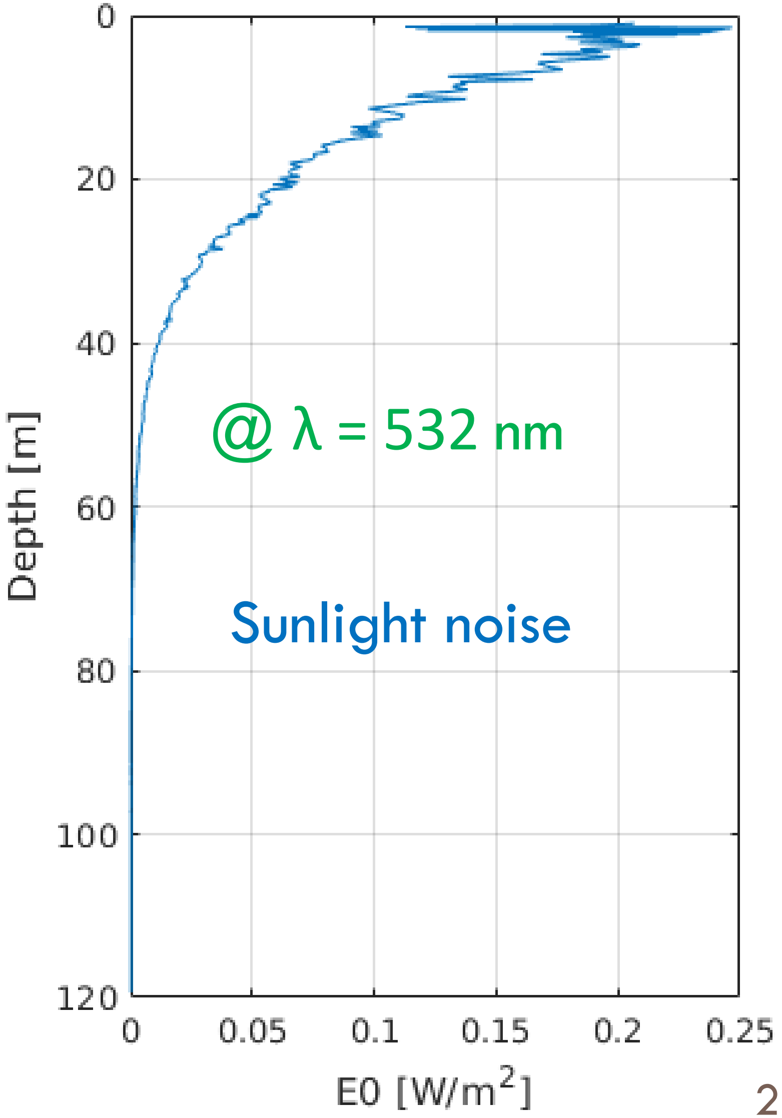
$\boxed{\lambda = 532 \text{ nm}}$



F. Campagnaro, M. Calore, P. Casari, V. Sanjuan Calzado, G. Cupertino, C. Moriconi, M. Zorzi, "Measurement-based Simulation of Underwater Optical Networks", IEEE OES Oceans 2017 Aberdeen

Optical measurements





Signal to Noise Ratio

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{i^2_{signal}}{i^2_{noise}} =$$

$$= \frac{(SP)^2}{\boxed{2q(I_D + I_{Ltot})BW} + \boxed{\frac{4KTBW}{R}} + \boxed{(N_A)^2}}$$

Shot noise (dark current + incident light)

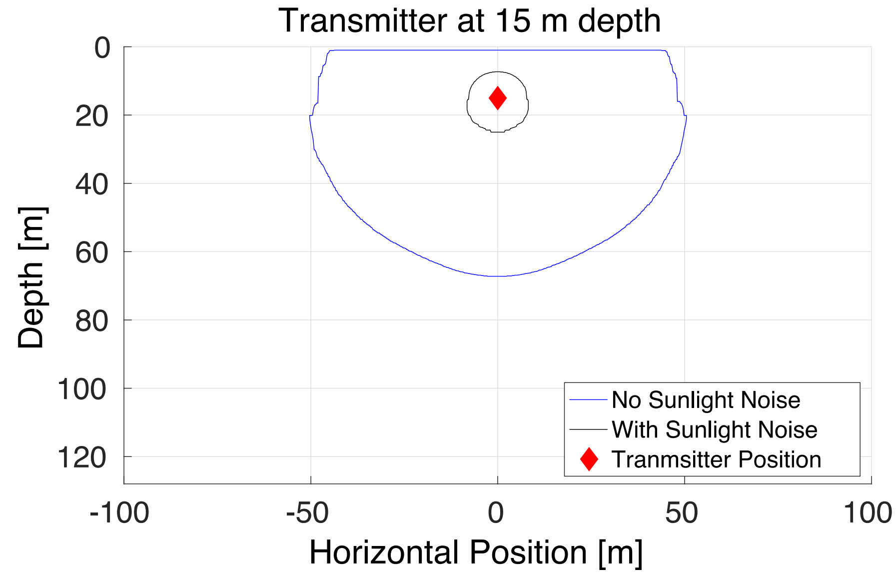
Johnson noise (thermal noise)

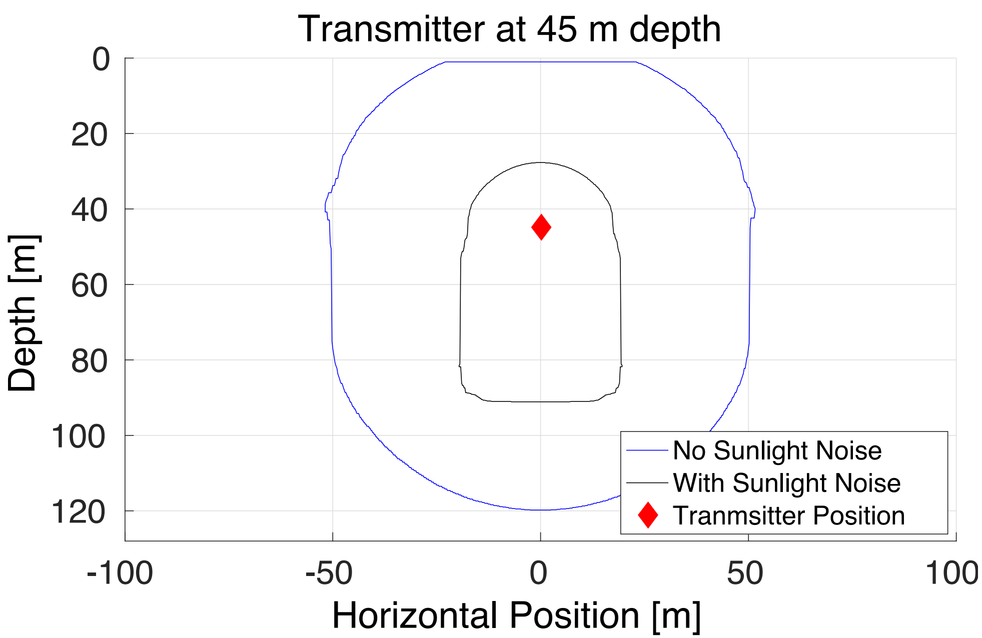
Ambient light noise

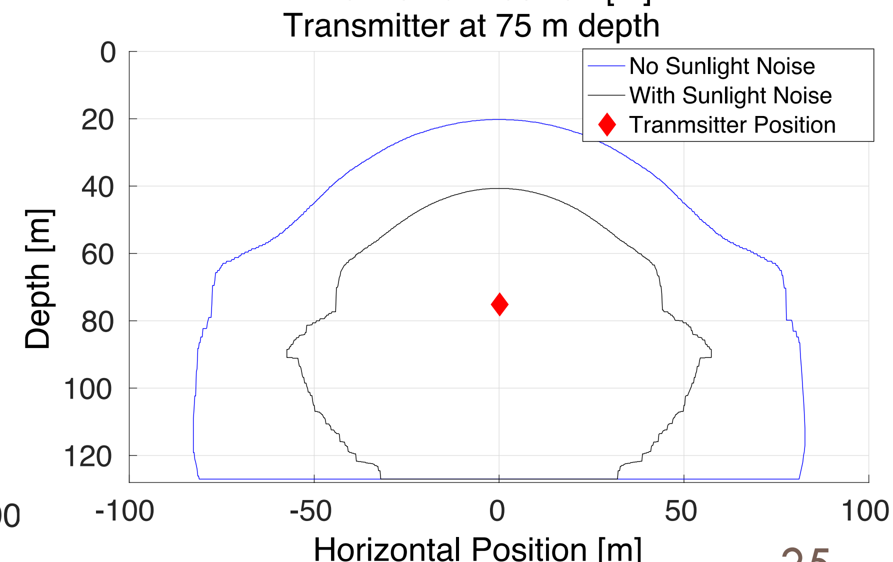
$$N_A = E_0 A_r S$$

Optical coverage area from model

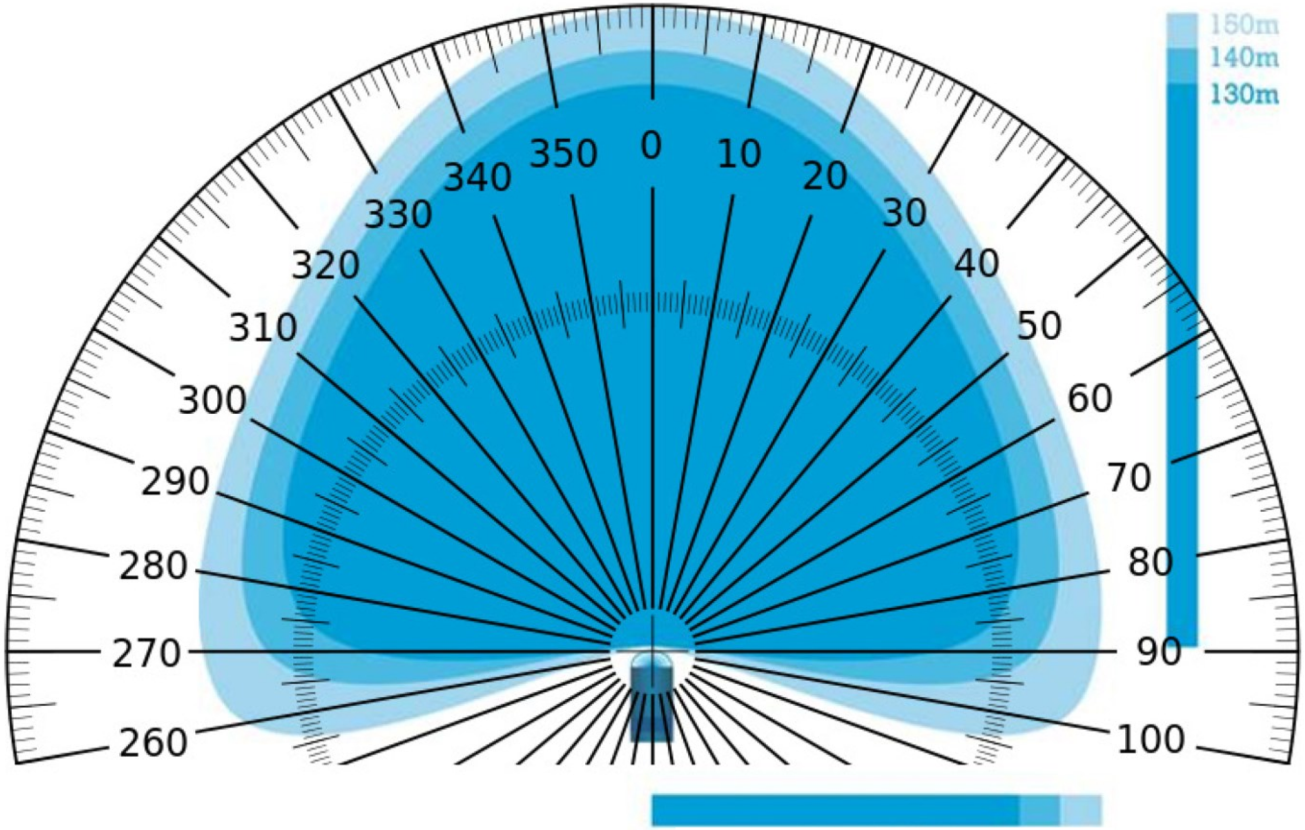
- Perfect alignment
  - LED-based transmitter
  - Si PIN Hamamatsu receiver







Real modem beam pattern

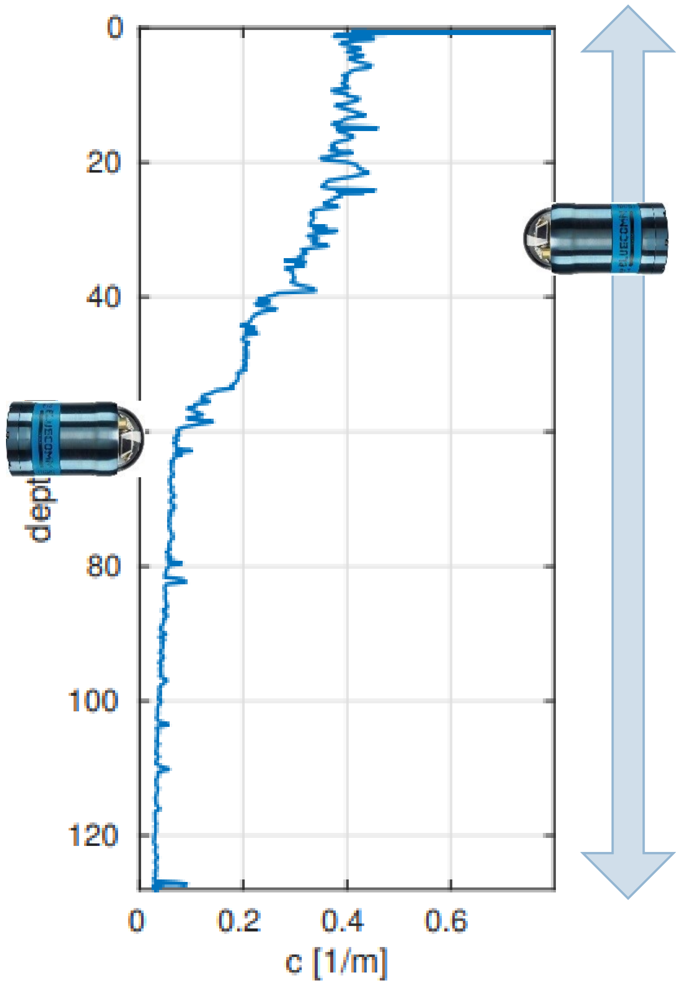


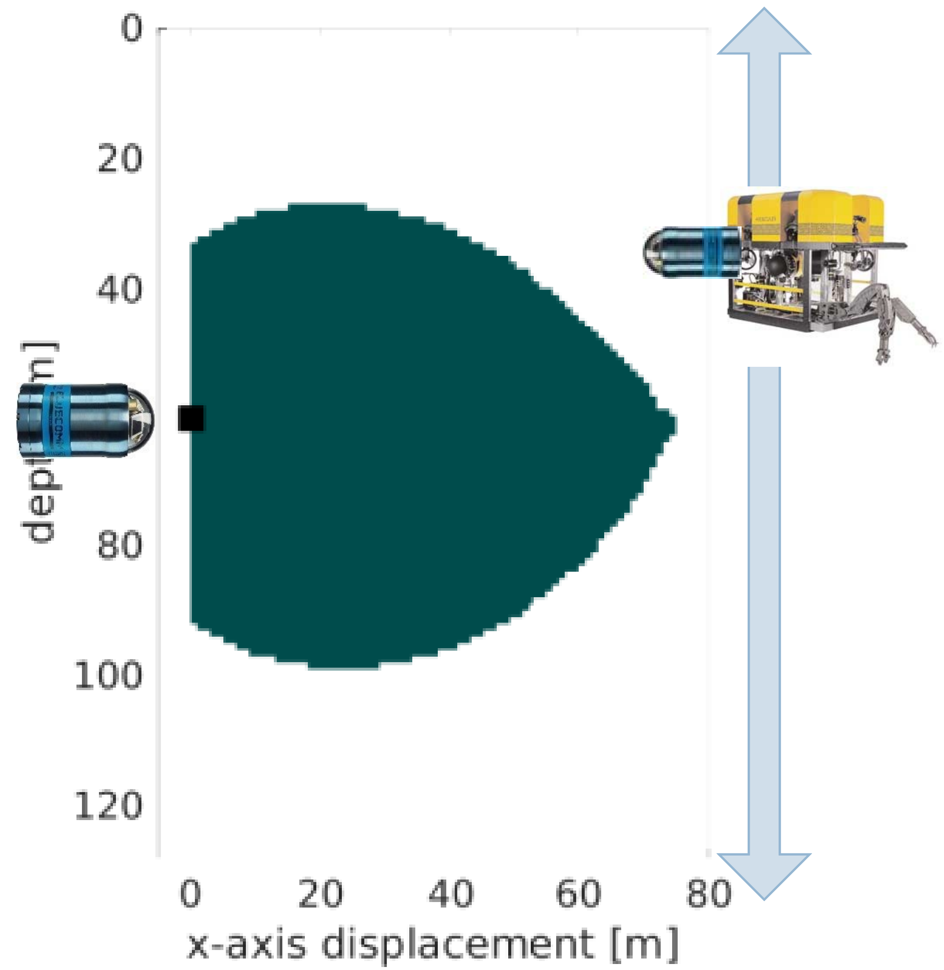
150 m 2.5 Mb/s
140 m 5 Mb/s
130 m 10 Mb/s

80 m 10 Mb/s
90 m 5 Mb/s
100 m 2.5 Mb/s

A. Signori, F. Campagnaro, M. Zorzi, "Modeling the Performance of Optical Modems in the DESERT Underwater Network Simulator", IEEE Ucomms 2018

Optical modem installation 1





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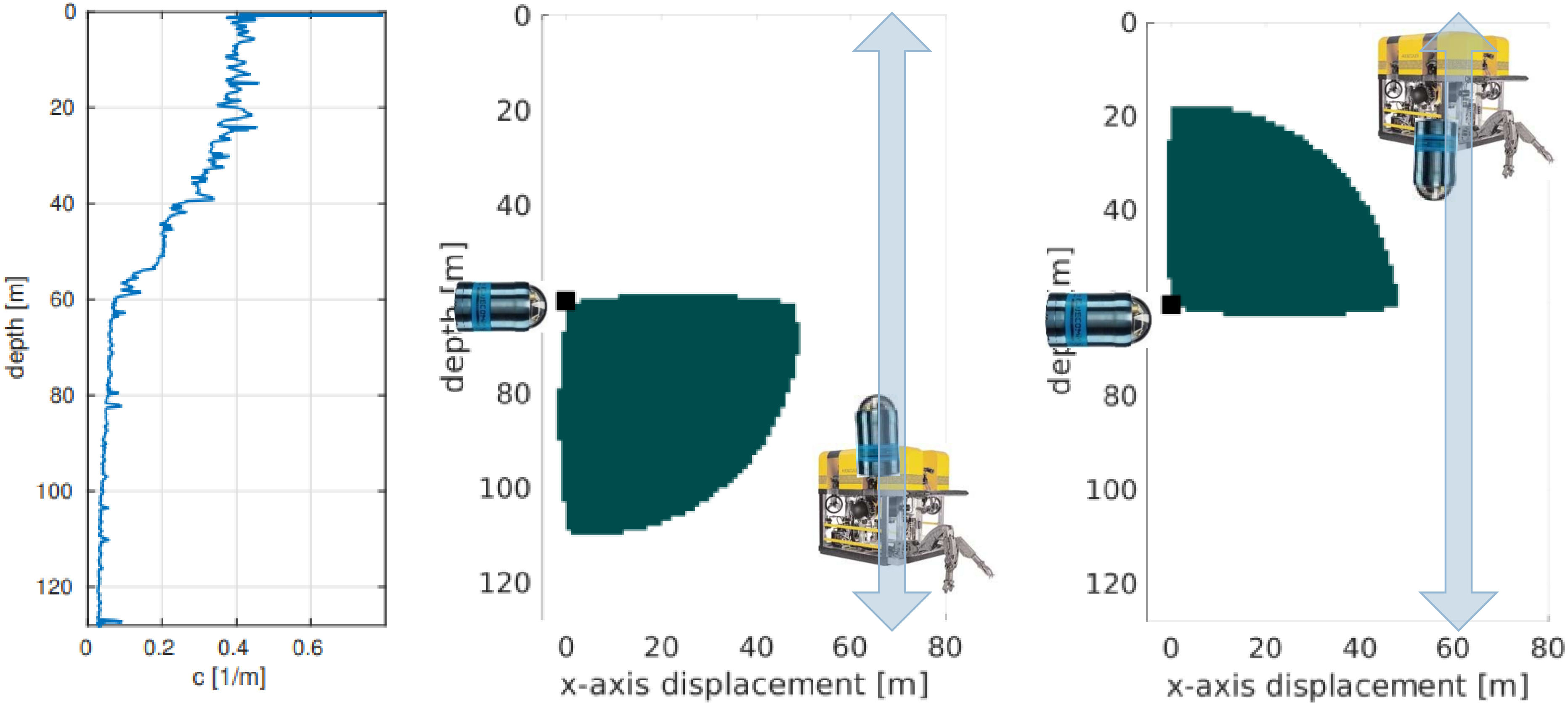
Optical modem installation 2



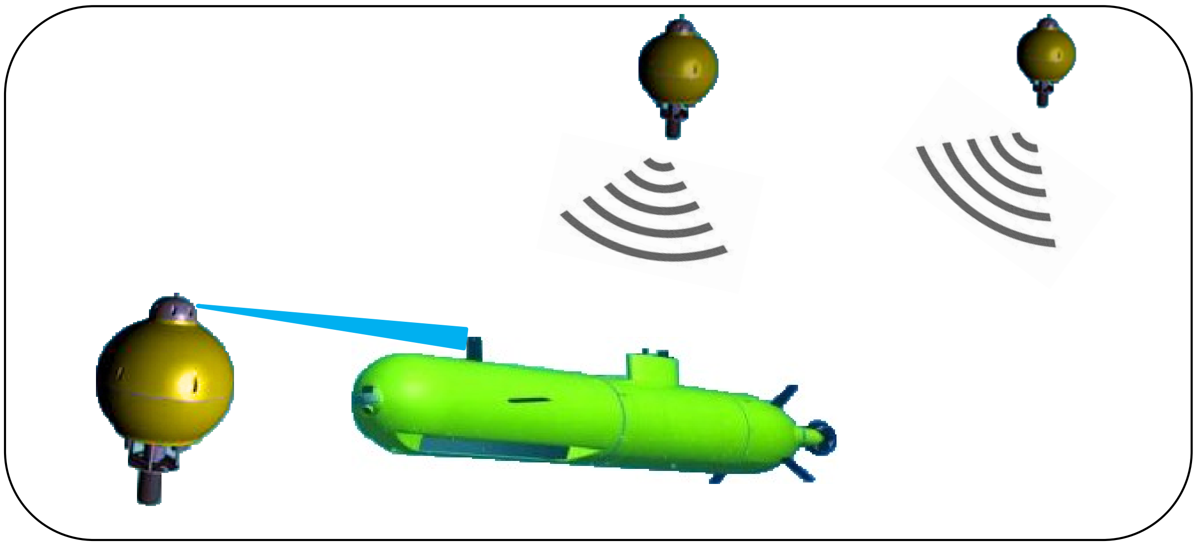
Multimodal UW Networks

Combination of multiple communication technologies in the same network provides big advantages:

- Serve different QoS depending on available technology.
  - E.g., video via optical uplink, control via acoustic downlink.
- Provide a backoff channel.
- Serve different traffic types simultaneously.
- Employing different scheduling and routing algoritms per technology in the same node.

Application of multimodal underwater networks

- Multimodal underwater networks can be employed in many applications:



Questions:

- How to combine optimally different technologies?
- How to evaluate them before the real deployment?

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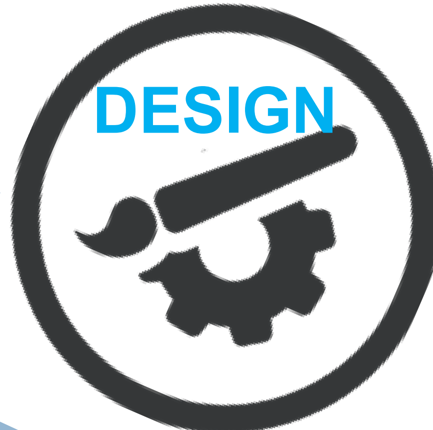
Methodology to evaluate underwater networks

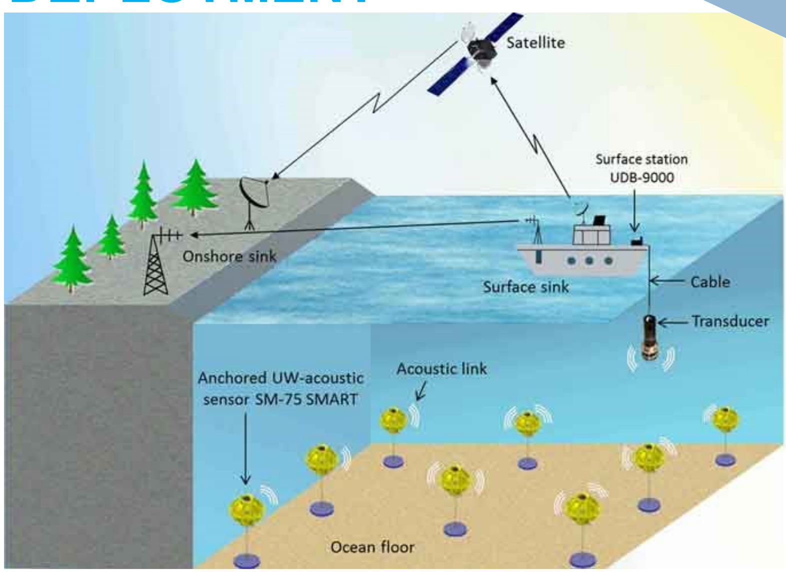
REQUIREMENTS

DESIGN

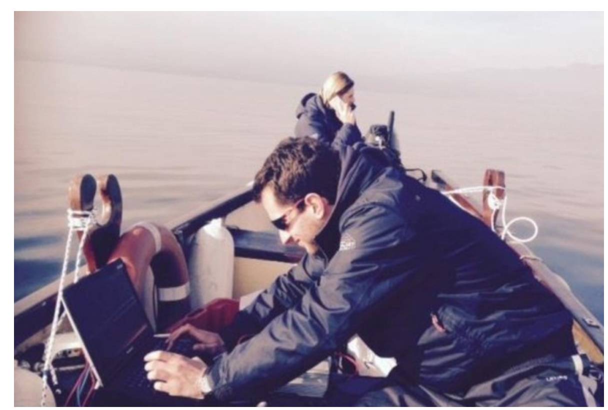


ANALYSIS & SIMULATION

DEPLOYMENT



SEA TRIAL



DESERT Underwater v3

- Simulator: DESERT Underwater*
  - includes database of optical noise and attenuation profiles
  - can use Bellhop ray tracer and statistical models to simulate acoustic channel variability, including bathymetry and sound speed profile
  - in this work we assumed deep water installation, no multipaht was considered
  - Enables code reuse for simulation and sea trial
  - Supports multimodal networks

<table>
<tr><td colspan="3">APPLICATION</td></tr>
<tr><td colspan="3">MAC</td></tr>
<tr><td colspan="3">MULTI – STACK – CONTROLLER</td></tr>
<tr><td>ACOUSTIC PHY LF</td><td>ACOUSTIC PHY HF</td><td>OPTICAL PHY</td></tr>
</table>

<table>
<tr><td colspan="3">CTR | IMAGE | HEALTH | SOS</td></tr>
<tr><td colspan="3">MULTI-TRAFFIC-CONTROLLER</td></tr>
<tr><td>TDMA</td><td>CSMA</td><td>ALOHA</td></tr>
<tr><td>ACOUSTIC PHY LF</td><td>ACOUSTIC PHY HF</td><td>OPTICAL PHY</td></tr>
</table>

*open source: https://desert-underwater.dei.unipd.it/ we are organizing a winter school

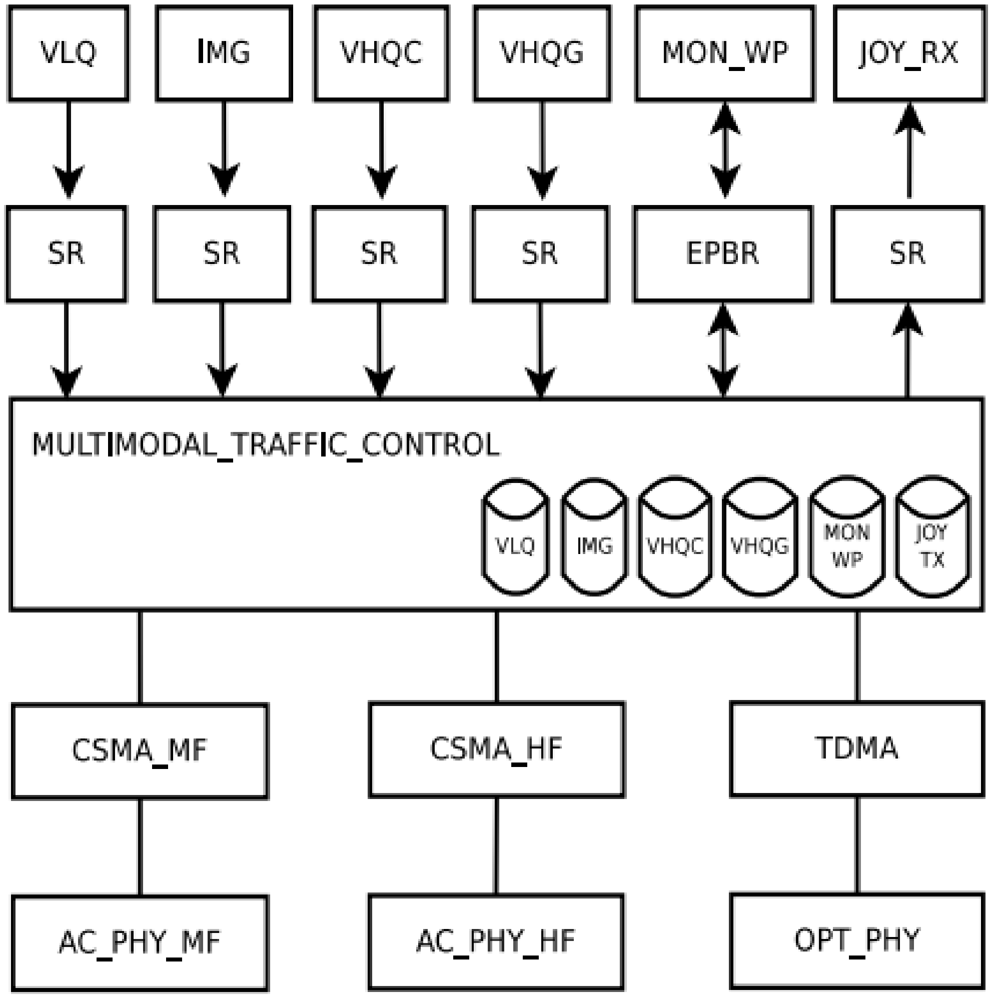
I don't have money for a sea test: what to do?

- Use data previously acquired in other tests to characterize your simulations and apply the same topologies and setup of that experiments:
  - Sol1: observe each network link evolution over time, and see how your alghoritm behaves with that link evolution

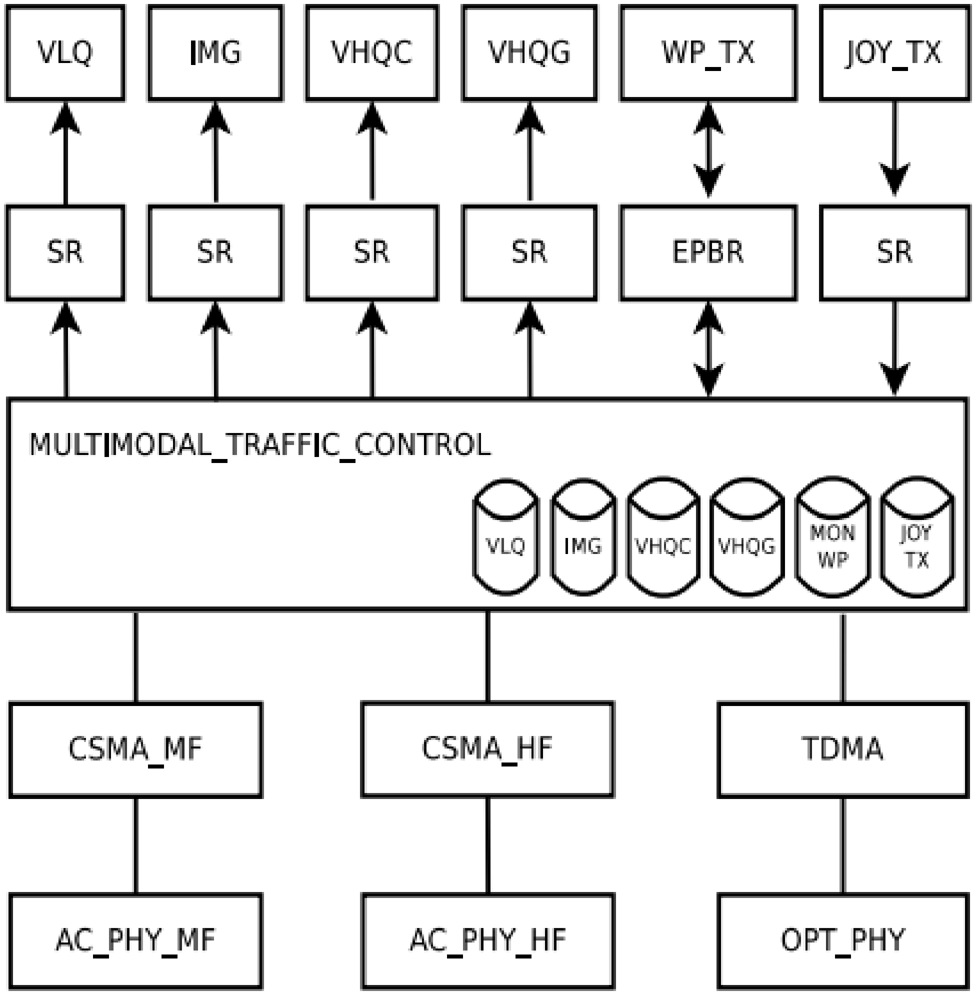
    P. Casari, et al, "ASUNA: A Topology Dataset for Underwater Network Emulation ", IEEE JOE 2021 https://sites.google.com/edu.haifa.ac.il/anl/downloads
  - Sol2: train with the measurements a Markov channel for each network link

    F. Campagnaro, N. Toffolo, M. Zorzi, "Modeling acoustic channel variability in underwater network simulators from real field experiment data," MDPI Electronics 2022

ROV protocol stack



Control station protocol stack



Switch threshold model

- Weighted average power of the received packets
  - **Prx(t)** = α**Prx(t-1)**+(1-a)Prx
- Additional probe of high-speed channels (optical and acoustic) if no packets received recently
- Acoustic LF assumed to be always in range
- Threshold computer as the "out-of-range" with hysteresis to avoid continuous switching when close to threshold
  - More details in

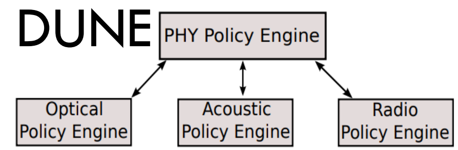
F. Campagnaro et al. "Implementation of a Multimodal Acoustic-Optic Underwater Network Protocol Stack", ACM WUWNet 206, Shanghai, China

Projects in multimodal comms in Padova

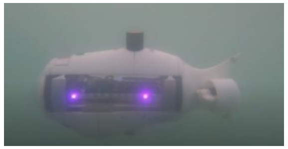
- **ONR Global:** simulate uw networks 2014-2018
- **Martera RoboVaaS:** robotic vessels as a service 2018-2021
- **Studies for O&G company** 2017-2019
- **EDA SALSA Project**
- **ITALIAN PNRR RESTART:** SEXTET project
- **Italian PRIN** BEASTIE project

Recent and current projects

- **MARLIN** multimodal routing exploits multimodal communication to achieve reliability and low-latency in an underwater network
- **SWARMs** H2020 Project used acoustic modems at different bandwidths from Evologics, TNO and Water Linked to manage up to 5 vehicles
- **CMRE** Cognitive Communication Architecture (**CCA**) support for optical, acoustic and overwater radio physical layers, AIS, DUNE and other applications



- **MARTERA UNDINA** project: UNderwater robotics with multi-moDal communlcation and Network-Aided positioning system



- TII – **Universal SDM** and **HSURF**: two internal projects at TII for high-tech and a low-cost multimodal modems for various app.
- SAIPEM **Hydrone-R** and **Flatfish**, Hydromea **ExRay**, etc.

Some pioneer studies on multimodal networks

- F. Campagnaro, "**Simulation of Multimodal Optical and Acoustic Communications in Underwater Networks,**" Oceans 2015 Genova
- F. Campagnaro, "**Measurement-based Simulation of Underwater Optical Networks,**" Oceans 2017 Aberdeen
- Filippo Campagnaro, et Al., "**Multimodal Underwater Networks: Recent Advances and a Look Ahead,**" ACM WUWNet17
- S. Basagni et Al., "**Finding MARLIN: Exploiting multi-modal communications for reliable and low-latency underwater networking,**" IEEE INFOCOM 2017
- R. Petroccia et Al., "Development of a Software-Defined and Cognitive Communications Architecture at CMRE", MTS/IEEE OCEANS 2018, Charlestone
- F. Campagnaro, et Al., "**Optimal Transmission Scheduling in Small Multimodal Underwater Networks,**" IEEE Wireless Communication Letter 2018
- R. Diamant, et Al, "**Fair and Throughput-Optimal Routing in Multimodal Underwater Networks,**" IEEE Transaction on Wireless Communications 2018
- F. Campagnaro, et Al., "**Wireless Remote Control for Underwater Vehicles,**" Journal of Marine Science and Engineering 2020
- R. Francescon, F. Campagnaro et Al., "**An Event-Based Stack For Data Transmission Through Underwater Multimodal Networks,**" IEEE Ucomms 2021

Some recent studies on multimodal networks

- I. V. Zhilin et Al., "**A Universal Multimode (Acoustic, Magnetic Induction, Optical, RF) Software Defined Radio Architecture for Underwater Communication,**" ACM WUWNet 2021
- J. Cao et al, "**Optimum Data Transmission Allocation in Multimodal Communication of Underwater Sensor Networks,**" in IEEE Communications Letters 2021
- B Tomasi et Al, "**MarTERA UNDINA project: a multi-modal communication and network-aided positioning system for marine robotics and benthic stations,**" UTC'22
- Luo H, Wang X, et al. "**A software-defined multi-modal wireless sensor network for ocean monitoring,**" *International Journal of Distributed Sensor Networks.* January 2022
- Liu, J.; et Al., "**MMNET: A Multi-Modal Network Architecture for Underwater Networking,**" Electronics 2020, 9, 2186.
- I.V. Zhilin, et Al., "**A Universal Multimode (Acoustic, Magnetic Induction, Optical, RF) Software Defined Modem Architecture for Underwater Communication,**" IEEE Transactions on Wireless Communications 2023
- B. Tomasi, et Al., "**Adaptivity in Multi Modal Underwater Mobile Networks,**" UACE 2023
- H. Dol, "**EDA-SALSA: Development of a self-reconfigurable protocol stack for robust underwater acoustic networking,**" IEEE/MTS Oceans 2023 Limerick
- M. Biagi, "**Invisible Light Communications: Ultraviolet enabling Robust High-Rate Underwater Communications,**" submitted to IEEE Communication Magazine

Conclusions an look ahead

- Multimodal optical and acoustic networks can be the enable technologies of several application, such as remote control for ROVs, and can provide significant benefits to classical applications, such as data muling
- To Design an optimal multimodal network, the whole system has to be considered: optimizing the use of each technology independently is not enough
- The evaluation should be done with both simulations and field experiments, possibly using the same code for both
  - If only simulations, at least use real field measures previously acquired

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