Underwater Wireless Sensor Networks

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Outline

- Underwater Wireless Sensor Networks: Motivations and possible applications
- Underwater acoustic communication
- Networking solutions: Channel Aware Routing Protocol (CARP)
- SUNSET: The underwater networking enabler
- In field experiments and results (SUNSET & CARP)

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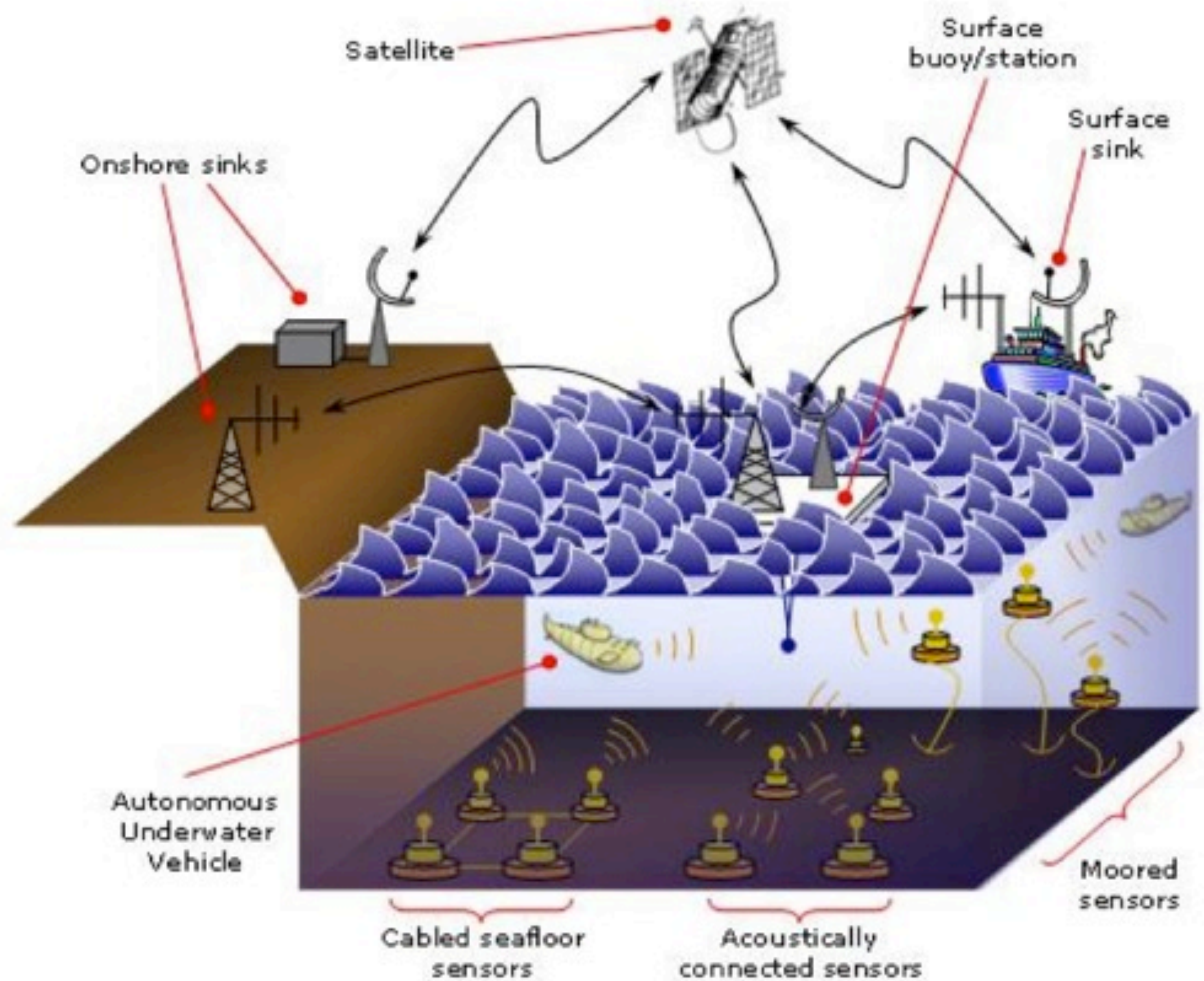
Underwater Wireless Sensor Networks



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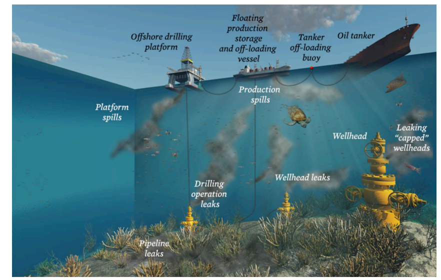
Applications

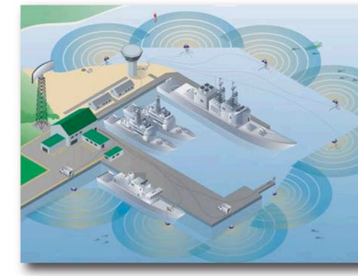
Critical infrastructure monitoring

(oil and gas pipelines and extractions sites, harbor, marine protected areas, etc.)

Oil and gas



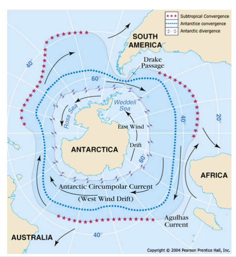
Coastline and border protection



Environmental monitoring

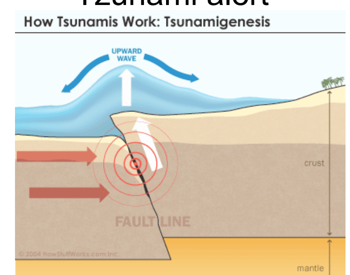
Temperature and salinity

Waves and currents



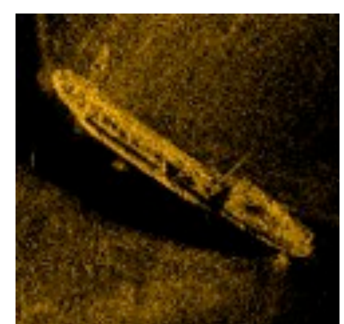
Volcanos and seisms

Tzunami alert



Submarine flora

Others: Cultural Heritage, Assisted navigation, Undersea exploration, etc.



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Motivations

Traditional approaches and the use of cabled solutions are no longer effective, suffering of several limitations: High costs, logistic complexity, etc.

No real-time monitoring

- The recorded data cannot be accessed until the instruments are recovered

No on-line system configuration

- Interaction between onshore control systems and the monitoring instruments is not possible

No failure detection

- If *failures* or *misconfigurations* occur, it may not be possible to detect them before the instruments are recovered

Limited storage capacity

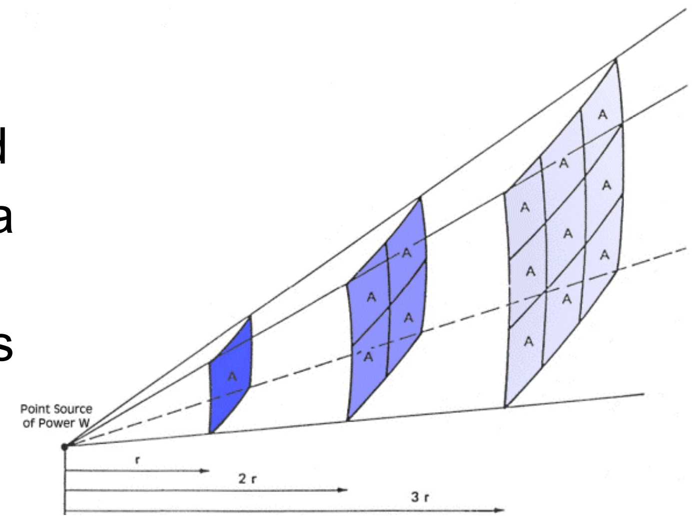
- The amount of data that can be recorded by every sensor is limited to the capacity of the onboard storage devices

- Underwater wireless networks supporting remote and real-time interaction with the system are needed

How to communicate wirelessly underwater?

- Radio: Short range and high energy consumption
- Optical: Medium range with the problem of transmitter/receiver alignment, water turbidity and bubbles, etc.
- Acoustic: Long range - nowadays it is the most reliable and robust underwater communication solution - it is however really challenging
  - Frequency dependent attenuation. Low bandwidth and low bit-rate.
  - The propagation delay is five orders of magnitude greater than in the radio channel and varies in space and time.
  - Links quality changes quickly and can assume very different mean values over time.
  - Asymmetric links.

Waves propagation

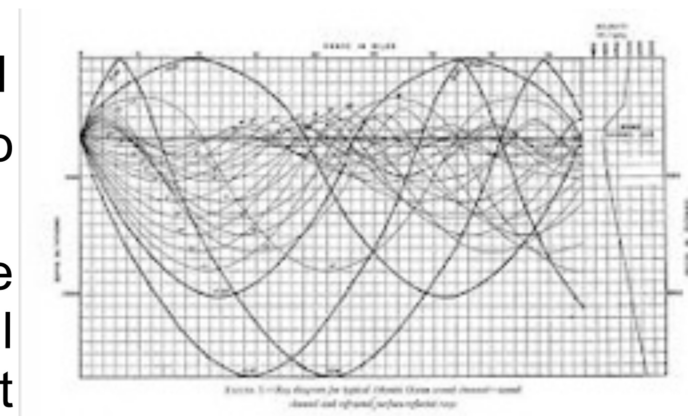


Radio waves in free space

- Speed: 3 * 10^8 m / sec
- In the presence of an obstacle the wave is partially reflected
- In the absence of obstacles, the wave propagates in a straight line (up to a certain limit).
- The power incident on the same surface element diminishes with the inverse square of the distance (~ $1/r^2$).

Acoustic waves in water:

- Speed: 1.5 * 10^3 m / sec
- In the presence of an obstacle the wave is partially reflected
- In the absence of obstacles, the wave can bend, due to variations in pressure and temperature.
- Thanks to waves bending, over a certain distance, the wave propagates according to a law of attenuation cylindrical rather than spherical. The power decays (in first approximation) as 1/r.



channel attenuation: $A(r,f) = A_0 a(f)^r \frac{1}{r^k}$

a(f) = absorption coefficient: increases with f

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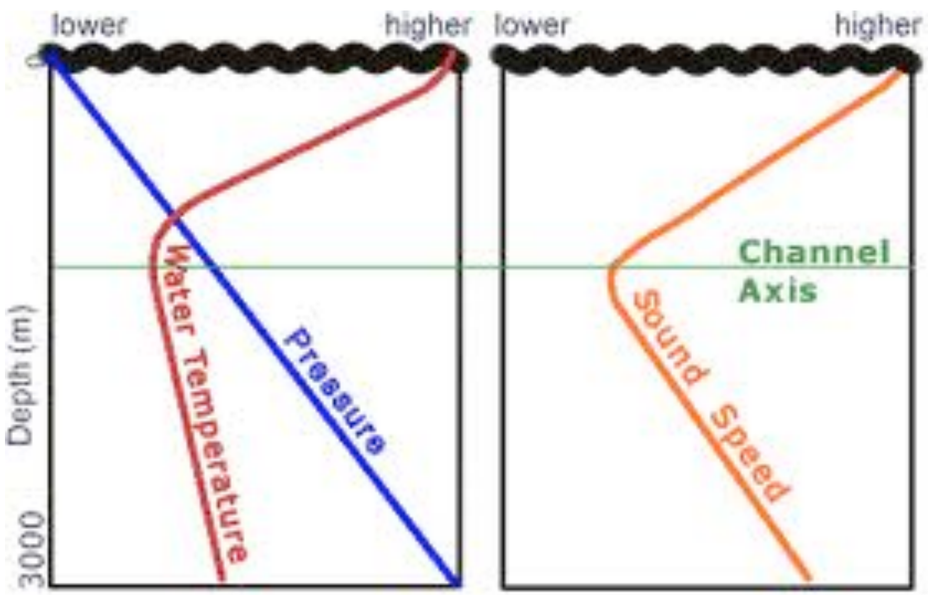
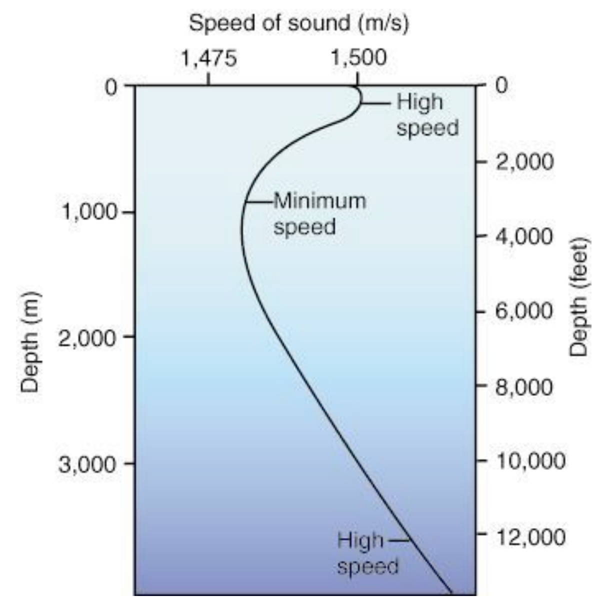
Waves propagation

SOUND SPEED PROFILE

- It expresses the speed of propagation of the acoustic wave at the different depths
- It depends on the temperature and pressure at the different depths





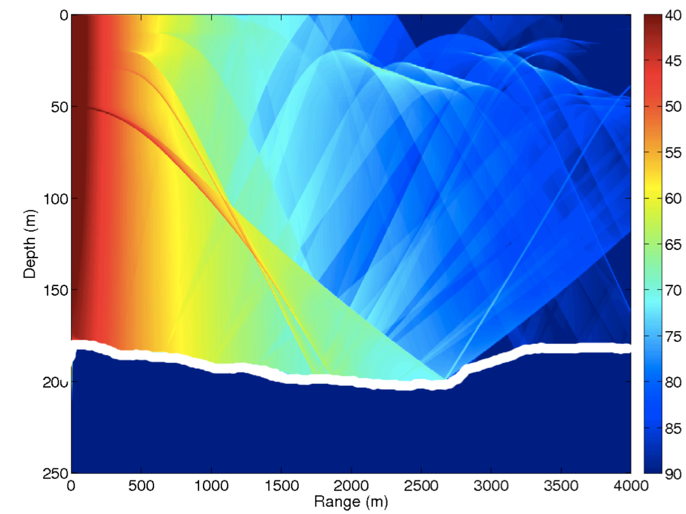
The sound speed profile determines how the acoustic rays bend

Waves propagation

Effects of the SOUND SPEED PROFILE

The different speeds at different depths induces rays bending, in particular:

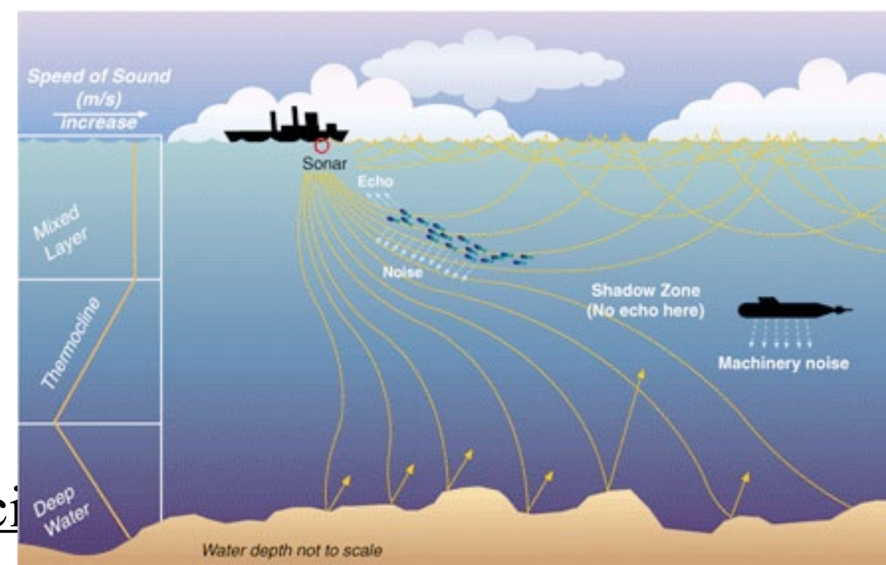
- Cylindrical Propagation: the wave energy expands in two dimensions rather than three, because part of the rays that go towards the surface are folded down and then their energy is "propagated" in the layer of water.
- The sound can propagates for hundreds of kilometers.
- Phenomenon of shadow-zones



Moreover:

Temporal variability due to:

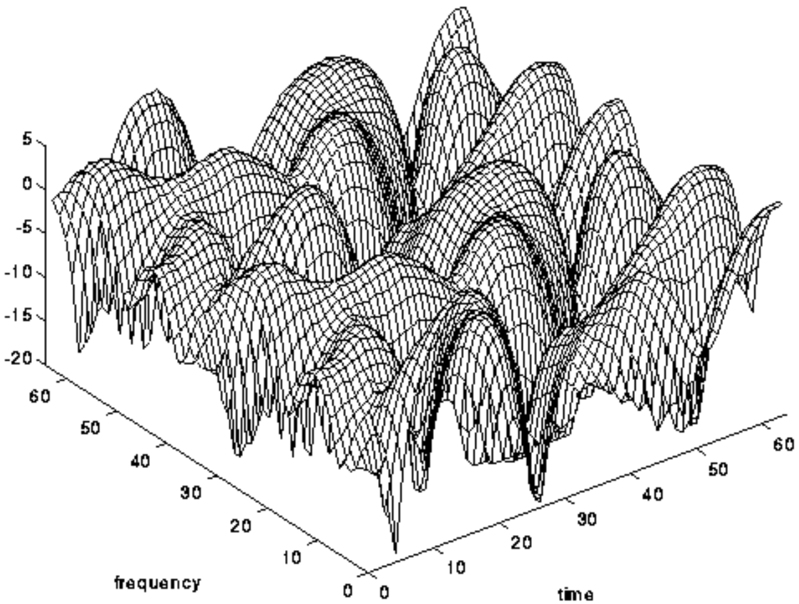
- Currents
- Wave motion on the surface



Frequency response

The effects described so far result in different behavior on different frequencies

- The underwater acoustic channel presents significant variations both in time and in frequency
- Time spread and Doppler spreads



It is difficult to obtain sub-orthogonal channels

The noise may come from noise sources (ships, harbor activities), different than acoustic modem.

The interference between nodes is one of the biggest problems for Underwater Acoustic Sensor Networks (UASNs), also due to the long propagation distances).

Networking solutions for UASNs

New protocol solutions are needed to make the use of underwater networks really effective

The protocols for UASNs must be, as far as possible, adaptive.

Several routing protocols determine a next hop relay based on the correct exchange of short control packets.

- An acceptable PER for short control packets might result in a (too) high PER for data packets, which are usually considerably longer.

If a greedy selection of the next hop relay is made, ignoring lower layer information, it can strongly affect network performance.

- Cross-layer solution combining link quality information with next hop relay selection should be preferred.

CARP

- CARP (Channel Aware Routing Protocol) is a cross-layer protocol based on short control packet (RTS/CTS) handshaking to access the channel and to determine next hop relay. First solution of SoA considering link quality on relay selection.
- Power control is used to obtain similar Packet Error Rates for both control and data packets.
- The relay selection is based on cross-layer information carried by the RTS/CTS packets:
  - Link quality (based on the success of past data/control packets transmissions to the neighbors).
  - Distance in hop from the sink node (Hop Count).
  - Node residual energy.
  - Node storage capacity.
- Data packet trains are used to reduce the handshaking overhead.

CARP (description)

When CARP starts there is a set-up phase to collect information on the network topology.

- HELLO packets are flooded from the sink through the network, containing the hop count (HC) of the sender to reach the sink, HC(sink) = 0.
- Each node x receiving an HELLO packet from a node y updates its HC, if needed:
  - If HC(x) > (HELLO(HC(y)) + 1).
  - x updates its HC(x) to (HELLO(HC(y))+1).
  - x retransmits the HELLO packet containing its HC(x).

CARP (description)

When a node x has a train of data to transmit:

- It broadcast a PING packet containing the number of packet that x wants to transmit and its hop count.
- Each eligible node y receiving a PING packet replies with a PONG packet containing its HC, residual energy, storage capacity and capability in relaying packet towards the sink.
- Relaying capability (Lq) is defined as an exponential moving average on the success ratio of data packet transmissions.
- When x receives the PONG packets, it selects the best relay computing neighbor nodes goodness:

$$goodness(y) = Lq(y) + Lq(x,y)$$

- The node i with the highest ratio goodness(i) / HC(i) is chosen as the relay. Energy and storage information are used to break ties. The number of data packets that will be sent depends on the PONG storage capacity value.

CARP (power management)

To select links which are reliable for long data packets, making use of short control messages exchange we proceed this way:

- Let's say P_data is the power used for data packet transmissions, it will result in a Bit error rate BER_data and Packet error rate PER_data.
- Using P_data for short packets we obtain the same Bit error rate but a lower Packet Error Rate having less bit to be received, PER_control < PER_data.
- We select a lower transmission power P_control < P_data such that BER_control > BER_data and PER_control ~ PER_data.
- Selected link using short control packet will be reliable also for data packet transmissions.

How to evaluate protocol performance?

- Simulations: Different underwater acoustic channel models have been proposed but they are not able to accurately capture channel dynamics and fluctuation in time, frequency and space
- In field experiments are needed
- The cost and logistic complexity of in field experiments, as well as the low accuracy and heterogeneity of existing simulators, pose a major barrier for solution validation, evaluation and benchmarking
- Despite the growing number of contributions on the design of protocols for underwater networks, research is still not moving at the speed required by emerging applications

What is needed?

A novel framework which can be shared by the community providing the following key features

- Flexible design to run in simulation, emulation and to real-life test mode
- Re-uses of the same implemented solutions for simulations, emulations and at-sea testing with no code rewriting
- Open architecture to allow the integration with different hardware and software (communication devices, computational boards, AUV and ASV control systems, sensing platforms, etc.)
- Remote and real-time control on the underwater device after their deployment

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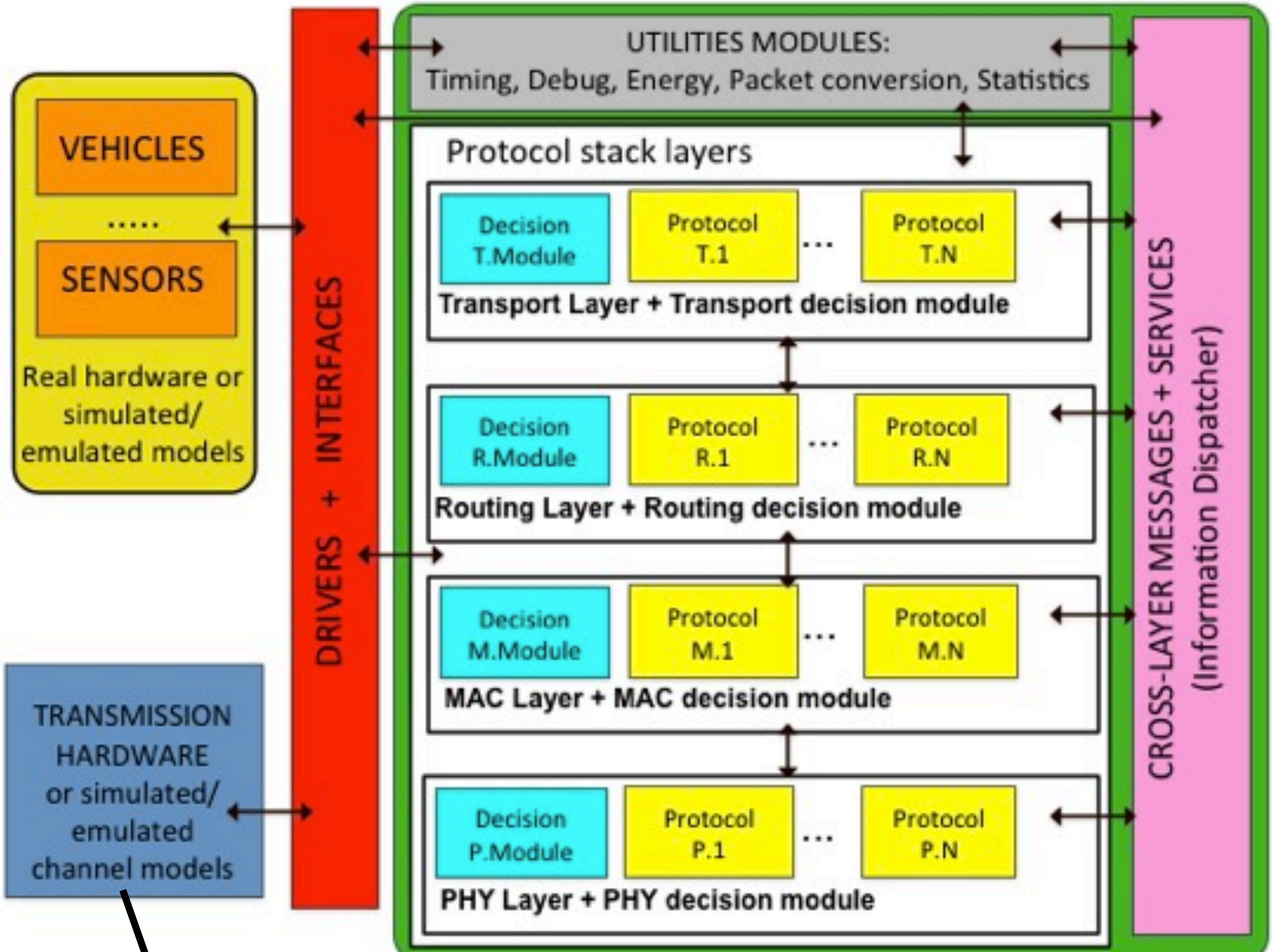
SUNSET

- SUNSET has been the first solution extending the well know network simulator ns-2 to perform simulation, emulation and in filed tests. No code rewriting
- SUNSET has been significantly extended according to the experience gained through more than two dozens in field experiments
- It is lightweight enough to run on PCs or embedded devices
- SUNSET currently includes and supports multiple:
  - MAC, Routing and cross layer solutions
  - Acoustic modems (Evologics, Kongsberg, Teledyne Benthos, WHOI)
  - Underwater robots (eFolaga, MARES, LAUV), surface vehicles
  - Sensing platforms (CO2, CH4, Temperature, ADCP, Pressure, PH, etc.)
  - PC and small, energy efficiency embedded devices (Gumstix, IGEP, etc.)

SUNSET v2 architecture



Urick, Bellhop, channel replay, modems, emulators

- Separation of protocol stack from additional components
- Layered structure
- Multiple solutions at each layer
- Possibility to share information among the different layers
- Additional modules to make transparent to the user moving from simulation to at sea tests
- Additional modules for pre-deployment tests and parameter tuning

SUNSET additional modules

- **Timing**: Handles all external hardware delays used for protocol stack timeouts computation. It includes transmission, computational, operational delays and constraints related to modem packet size.

- **Utilities**: Is responsible to schedule events, update time, and (de)allocate memory according to the used running mode (simulation or emulation).

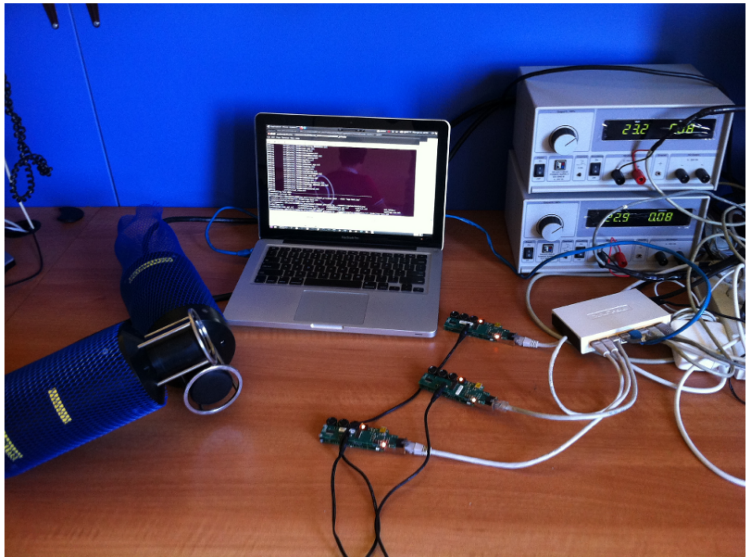
- **Debug**: Allows to assign to each information to log a debug level and display only the requested information.

- **Statistics**: Allows the user to collect statistical information to evaluate the protocol performance. Different metrics of interest decided by the user can be collected and evaluated online or with post processing.

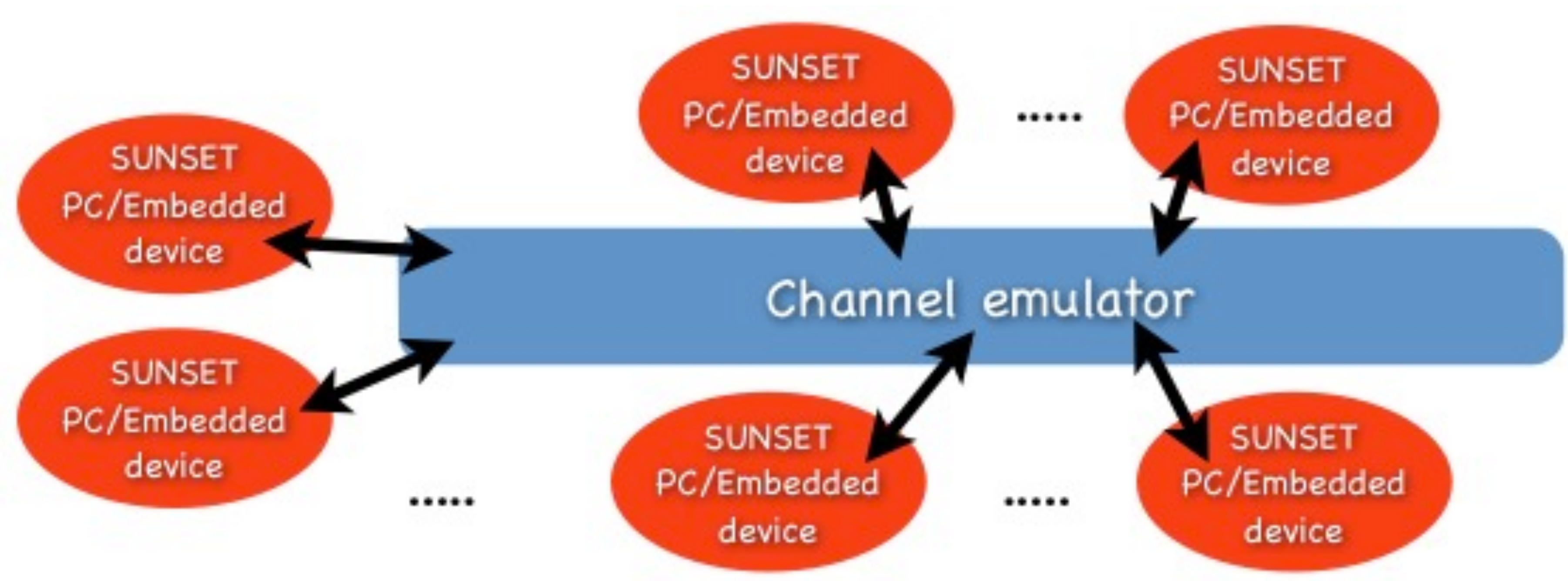
Interfacing SUNSET to real world hardware

- **Real-time elapsing**: Implementation of an improved real-time scheduler.
- **Information conversion**: New module (Packet Converter) to convert ns-2 packets into a stream of bytes and vice versa, compressing the information in the header to the minimum size, with a precision to the bit.
- **Connection with real hardware**: Drivers to handle the functionalities and data exchanging with acoustic modems, AUV and ASV navigation and control systems, sensing platforms, etc.
- **Running real test in a transparent way**: New module handling packet conversion and timing information for the upper layers with no changes on the protocol stack.

Channel emulator



- Introduce propagation delays according to node distance
- Support node mobility
- Different topologies and acoustic channels can be configured and tested
- Protocol solution can be tested running on real hardware (PC, embedded devices and others), as it would happen during in field tests



Backseat driver

- Remote control and reconfiguration of an heterogeneous underwater acoustic sensor network
- Interact with and operate an underwater network via single-hop and multi-hop acoustic transmissions without the need to retrieve nodes from water to investigate and evaluate:
  - Different underwater protocol stacks
  - Different protocol and network parameter configurations and device behavior policies
  - Different network investigations, remotely activating only selected subset of nodes, if needed
- A direct access to at least one node in the network is required.
- Activation of external software and system services

SUNSET evaluation and validation

- Several in field tests have been conducted in the past years in collaboration with different Researching groups, Institutions and Companies.
- First version of SUNSET presented in 2010 has been strongly improved and extended to be used during at sea tests.
- **At sea campaigns**: WHOI (2010), NATO CMRE AcommsNet 2010 and 2011, INESC Porto Trial; Sesimbra test (2012); NATO CMRE CommsNet 2012; Evologics Tests (2012); Horten Tests (2012); Trondheim Tests (2013); NATO CMRE CommsNet 2013.

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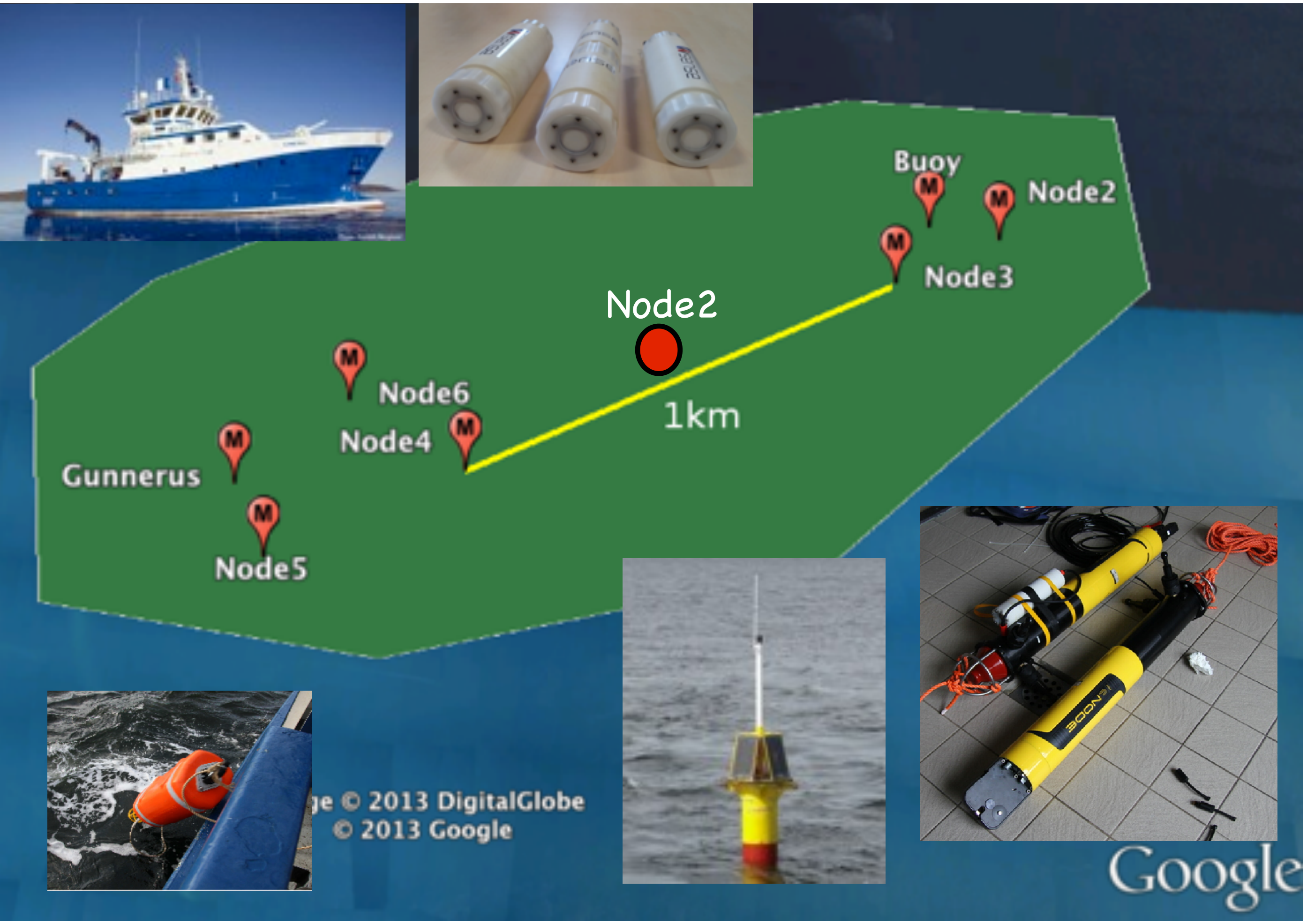
SUNSET v2 validation in Trondheim



7 CLAM nodes

Maximum distance ~2Km, up to 3 hops. Nodes deployed at 200m depth

Kongsberg modem

Investigation of 3 different routing solutions and multiple MACs

Network reconfiguration starting and stopping each test in less than 30 seconds

One week of continuos operation on the network

Backseat driver used also to start external tests and release the node from the seafloor

More than 50.000 packets transmitted during the trial.

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Samples of the experienced link quality

	1	2	3	4	5	6
1	-	76%	89%	79%	65%	75%
2	73%	-	3%	3%	28%	5%
3	60%	5%	-	4%	88%	4%
4	53%	6%	15%	-	6%	95%
5	46%	2%	25%	0%	-	25%
6	50%	3%	10%	94%	39%	-

(a) Midday May 30.

Entry (i,j) is the percentage of messages successfully received over the link from i to j

	1	3	4	5	6
1	-	75%	75%	38%	77%
3	53%	-	0%	40%	0%
4	100%	28%	-	0%	85%
5	53%	39%	0%	-	65%
6	63%	2%	68%	61%	-

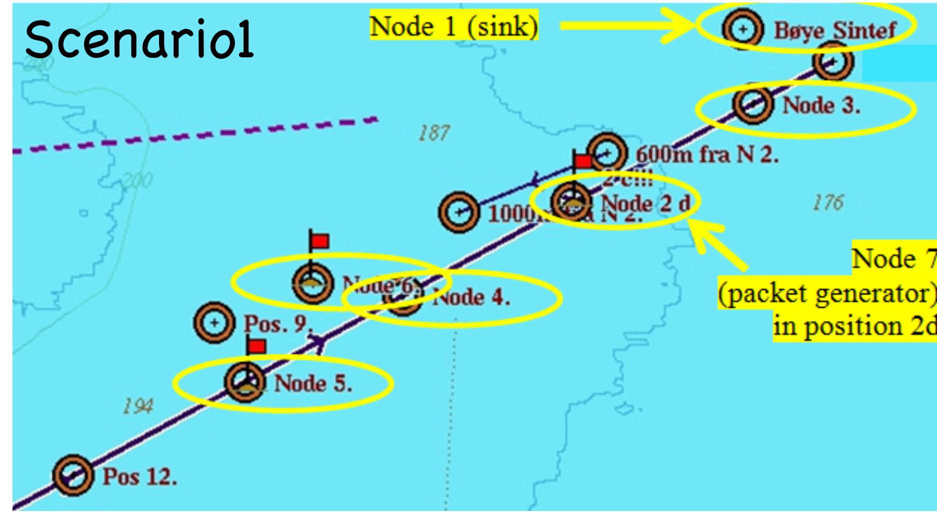
(b) Morning May 31.

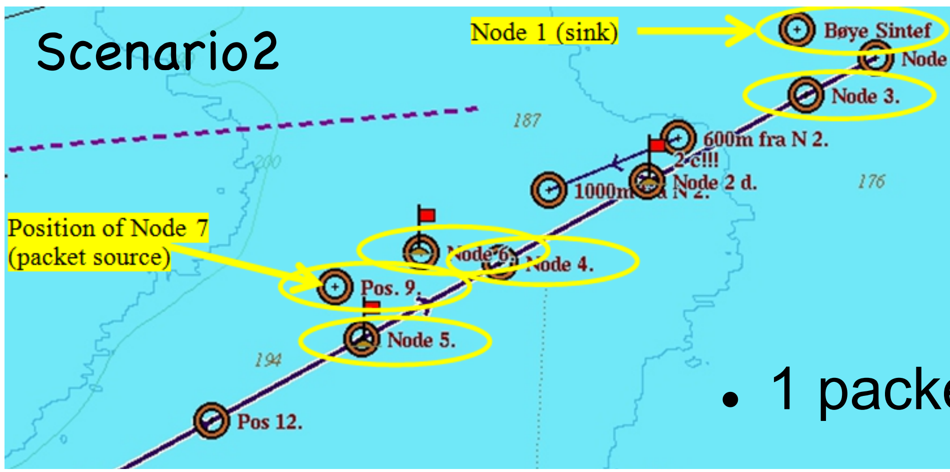
	1	3	4	5	6
1	-	40%	42%	50%	67%
3	100%	-	0%	83%	0%
4	66%	11%	-	0%	72%
5	52%	52%	0%	-	54%
6	82%	23%	76%	54%	-

(c) Afternoon May 31.

CARP evaluation in Trondheim

Bit rate 200 bit/s. Payload size: 24 bytes. Three nodes selected as data packets generators (two nodes at 1 hop and one node at 2 hops).





- 1 packet in the network every 20 seconds

	Scenario1	Scenario2
PDR [%]	82	80
Average Delay [s]	78	36
Route length [hops]	1.3	1.3
Energy Eff[J/s]	0.09	0.09

CARP evaluation in Trondheim

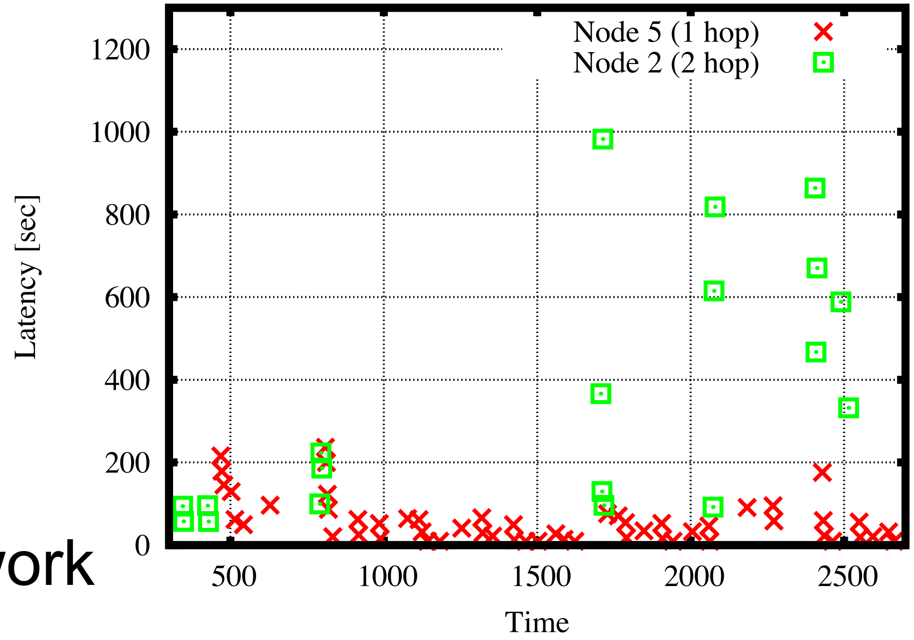
Bit rate 200 bit/s. Payload size: 48 bytes. Two nodes selected as data packets generators (one node at 1 hop and one node at 2 hops).

1 packet every 20 seconds in the network

	CARP	EFLOOD
PDR [%]	60	42
Average Delay [s]	207	13
Route length [hops]	1.31	1.05
Energy Eff [J/b]]	0.06	0.075

CARP evaluation in Trondheim

Bit rate 200 bit/s. Payload size: 48 bytes. Two nodes selected as data packets generators (one node at 1 hop and one node at 2 hops).



1 packet every 20 seconds in the network

	CARP	EFLOOD
PDR [%]	60	42
Average Delay [s]	207	13
Route length [hops]	1.31	1.05
Energy Eff [J/b]]	0.06	0.075

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SUNSET v2 validation in Palmaria (CommsNet13)

Up to 12 devices (4 cabled, 4 at surface, 4 with no direct link)

Maximum distance 3Km, up to 4-5 hops

3 different modems

5 routing solutions, 5 MACs

Network reconfiguration in less than 35 seconds

Multiple overnight tests

More than 70.000 packets transmitted during the trial.

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CARP validation in Palmaria (CommsNet13)

Acoustic Modem: Evologics Acoustic Modem.

Bitrate 480 bit/s. Payload size: 50 bytes.

Three nodes selected as data packet generators.

Different data generation rates in the network have been considered.

- 1 packet in the network every 20 seconds

	CARP	EFLOOD
PDR [%]	96	96
Average Delay [s]	37	9
Route length [hops]	1.35	1.6
Energy Eff [J/b]	0.04	0.064

- 1 packet in the network every 10 seconds

	CARP	EFLOOD
PDR [%]	95	87
Average Delay [s]	52	10
Route Length [hops]	1.36	1.4
Energy Eff [J/b]	0.05	0.095

Underwater robots control & formation maintenance

To reduce the size of this file the video about the control of the underwater vehicle has been removed.
It can be seen and downloaded at

http://reti.dsi.uniroma1.it/UWSN_Group/index.php?page=experiments&year=2012&place=porto&menu=

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Underwater robots control & formation maintenance

To reduce the size of this file the video about the two surface vehicles moving in formation has been removed.
It can be seen and downloaded at

http://reti.dsi.uniroma1.it/UWSN_Group/index.php?page=experiments&year=2012&place=porto&menu=

SUNSET for the user

To download, install and use SUNSET version 2.0 two different options are currently provided:

- A complete virtual machine that already includes SUNSET and everything is needed
- SVN repository with all the SUNSET code, libraries, scripts and examples. All the additional software have to be manually installed by the user.

Great effort has been devoted to provide detailed documentation and guidelines on how to use it, and on how to develop new solutions within SUNSET

Several scripts and examples have been provided together with a detailed description of how to download and install SUNSET

A user-group has been set up with the intention to create a community of researchers and developers supporting SUNSET and an open environment to ask questions, solve problems and share ideas.

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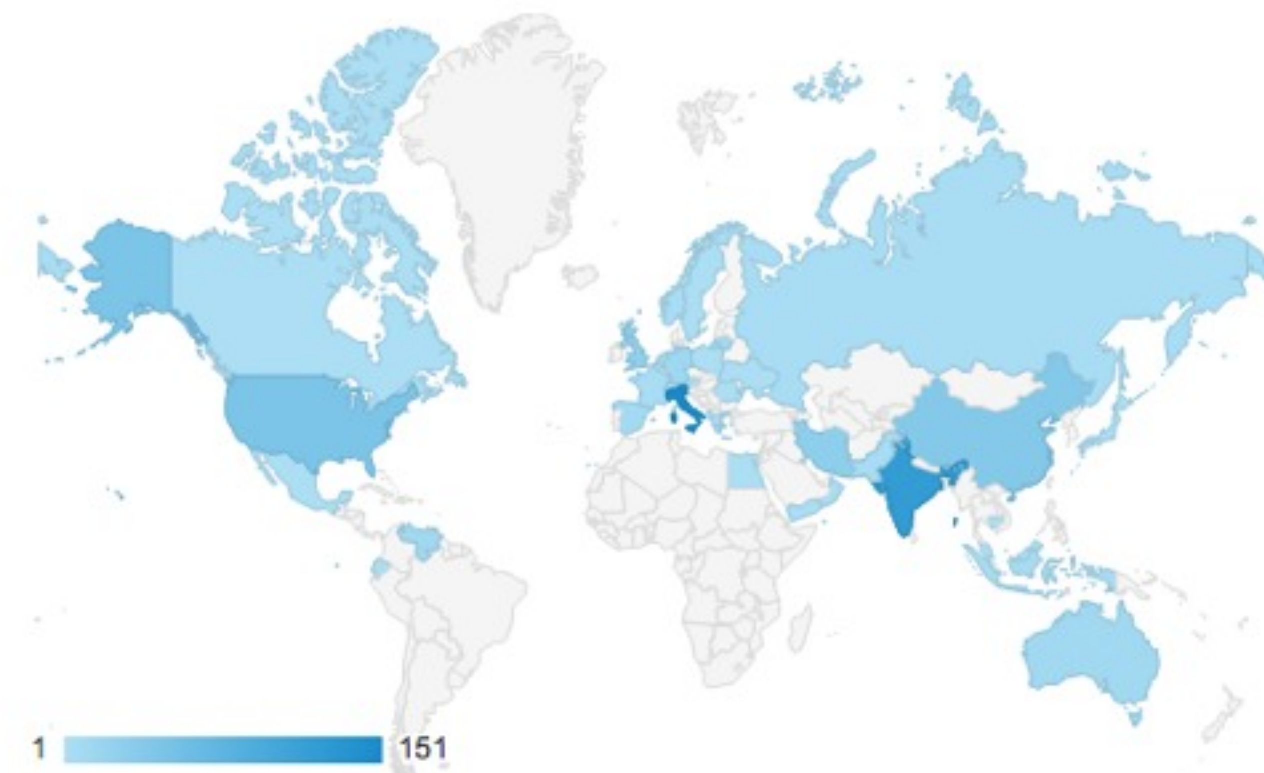
SUNSET visitors and users

- In the past two months the SUNSET web page has been visited on average 10 times per day
- Visitors from more than 40 countries
- First ten countries are:

1. Italy 28%
2. India 22%
3. United States 9%
4. China 8%
5. Iran 7%
6. United Kingdom 5.6%
7. Germany 3%
8. Australia 2.5%
9. Venezuela 1%
10. Lithuania 0.6%



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SUNSET in EU projects

- SUNSET has been selected as the framework to be used for simulations, emulations and in field tests within the CLAM project
- New modules and functionalities have been developed during the three years of the project
- SUNRISE project has now selected SUNSET as the standard tool to be used and extended within the project.
- SUNRISE will provide novel infrastructures to the users in order to collect environmental information and to investigate novel protocol solutions for sensing, networking, communication, navigation, etc.

Conclusions

- We have introduced Underwater Wireless Sensor Networks, and underwater acoustic communication challenges
- A new cross layer solution, CARP, for UASNs has been presented
- The SUNSET framework has been described which provide a powerful tool to develop and investigate the novel protocol solutions by means of simulation, emulation and in field tests.
- Using SUNSET, researchers and developers can fast identify underperforming or malfunctioning communication modules, before and during in field tests.
- A lot of time and resources can be saved during experimental campaigns, significantly increasing the results that can be obtained in field
- In field experiments have been presented evaluating and validating the SUNSET framework and the CARP solution.

THANKS

Any questions?

To download and collect additional information on SUNSET and our current experimental activities please visit:

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http://www.wsense.it

CLAM project **http://clam.ewi.utwente.nl**

SUNRISE project **http://fp7-sunrise.eu/**

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