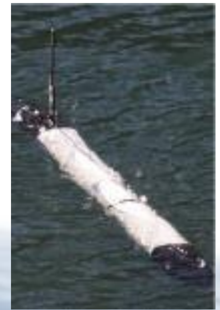
Internet of Underwater Things





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Information Society

European Commission

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For more information please check: http://ec.europa.eu/dgs/connect/

Outline

- Underwater Wireless Sensor Networks (UWSNs):
  - Motivations and possible applications
- Basics of underwater acoustic communications
- MAC protocols for underwater sensor networks & their performance comparison
- Networking solutions: Channel Aware Routing Protocol (CARP)
- SUNSET Toolchain
- In field experiments and performance evaluation results

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Why should we care about building the Internet of Underwater Things?

The Earth Planet

The Earth Planet

The Earth Planet

Why should we care about building the Internet of Underwater Things?

The future of mankind is dependent on careful monitoring, control and sustainable exploitation of the marine environments.

- ✓ Oceans and lakes cover 71% of the earth surface.
- ✓ Marine environments support the life of nearly half of all species on earth.

Why should we care about building the Internet of Underwater Things?

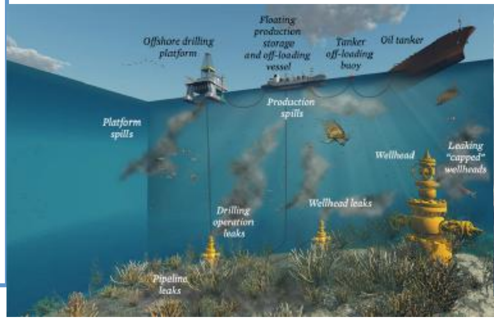
The future of mankind is dependent on careful monitoring, control and sustainable exploitation of the marine environments.

- ✓ Help sustain life by providing 20% of the animal proteins and 5% percent of the total proteins in the human diet.
- ✓ Are or are becoming a critical frontier of exploration for transport, oxygen and food production, hydrocarbon exploitation, aquaculture, biofuel production, mineral exploitation, climate and global water circulation.
- ✓ Cumulatively, the services provided by the oceans, such as the provision of food, oxygen, water and climate regulation, have been valued at over US$21 trillion, while maritime transport support 90% of global trade volume.

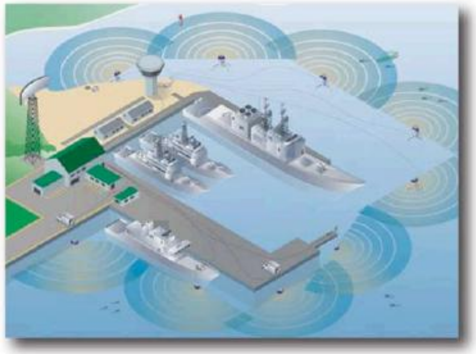
Applications

Critical infrastructure monitoring
(offshore platforms and pipelines monitoring, harbour protections)

Oil and gas



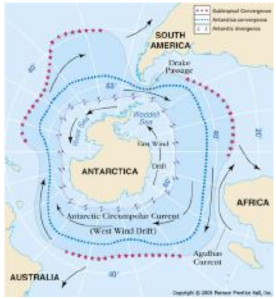
Coastline and border protection



Environmental monitoring

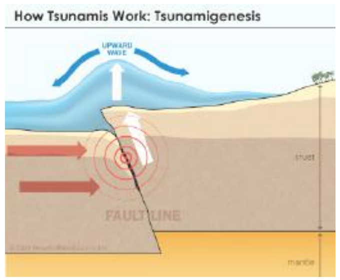
Temperature and salinity

Waves and currents



Volcanoes and earthquakes

Tsunami alert



Biodiversity monitoring

Others: assisted navigation, undersea exploration, underwater cultural heritage etc.…

Limits of traditional approaches

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

Need for real-time monitoring through an underwater wireless sensor network
Survey available at:
http://www.ece.rutgers.edu/~pompili/paper/Akyildiz_AdHoc05.pdf
(good general overview of topologies and features of underwater acoustic networks
NOT good for UWSN protocols—outdated on protocols)

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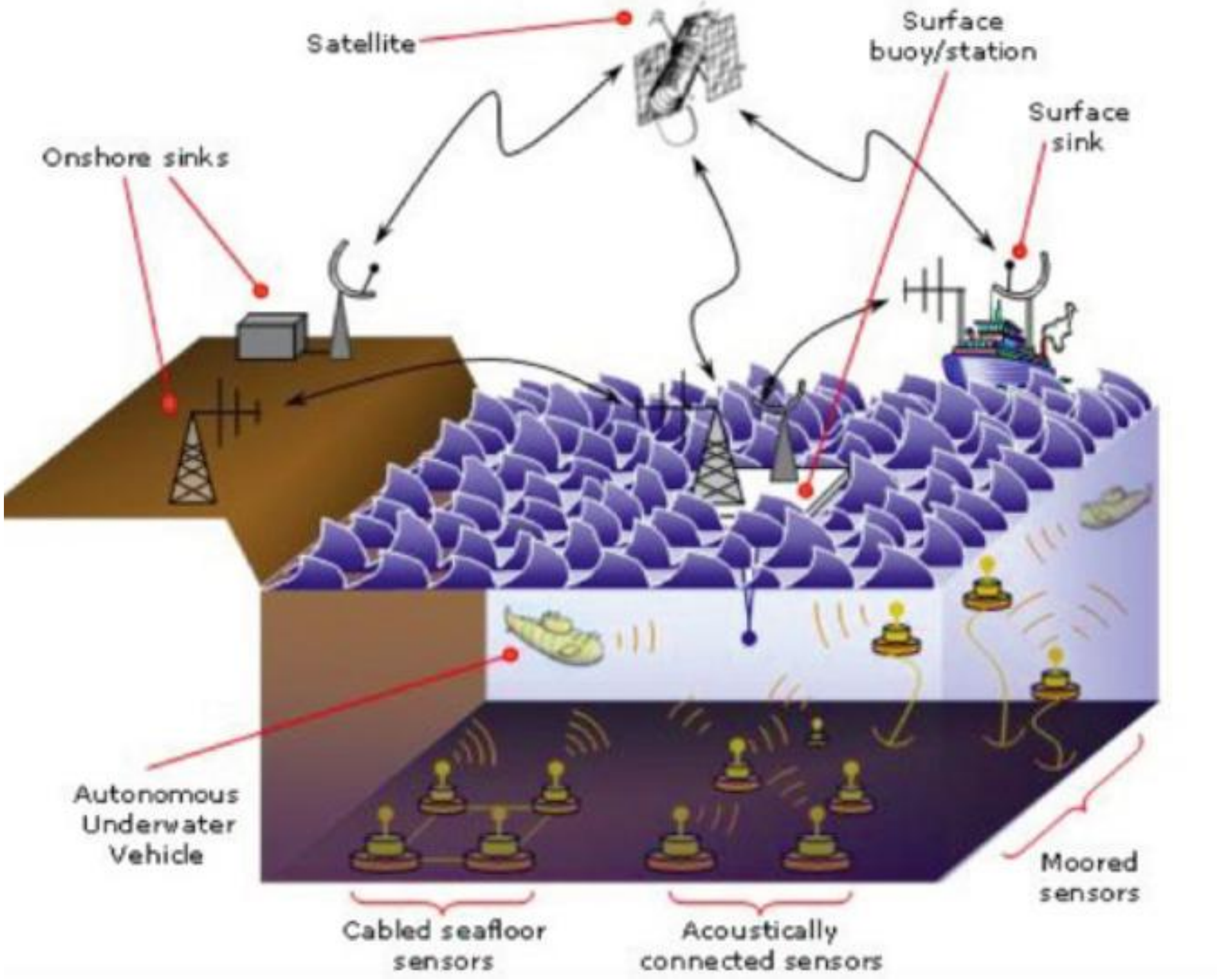
Underwater Wireless Sensor Networks



Underwater sensor nodes & networks

- Static (anchores at the sea bottom, floating at different depths)
- Mobile (AUVs, ASVs)
- Energy consumption mostly due to trasnmission (tens or hundreds W) or propulsion (for mobile assets)
- Lower cost devices (10K-100Keuros) can operate in shallow waters, but higher cost nodes (100K-millions euros) are able to operate at thousands meters depth
- Communications technologies:
  - Cabled (high maintenance costs, expensive)
  - Wireless (radio –attenuates fast- vs. optical-short range- vs. acoustic)
  - Acoustic often the technology of choice → low data rate but long range communications

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UWSNs Topologies

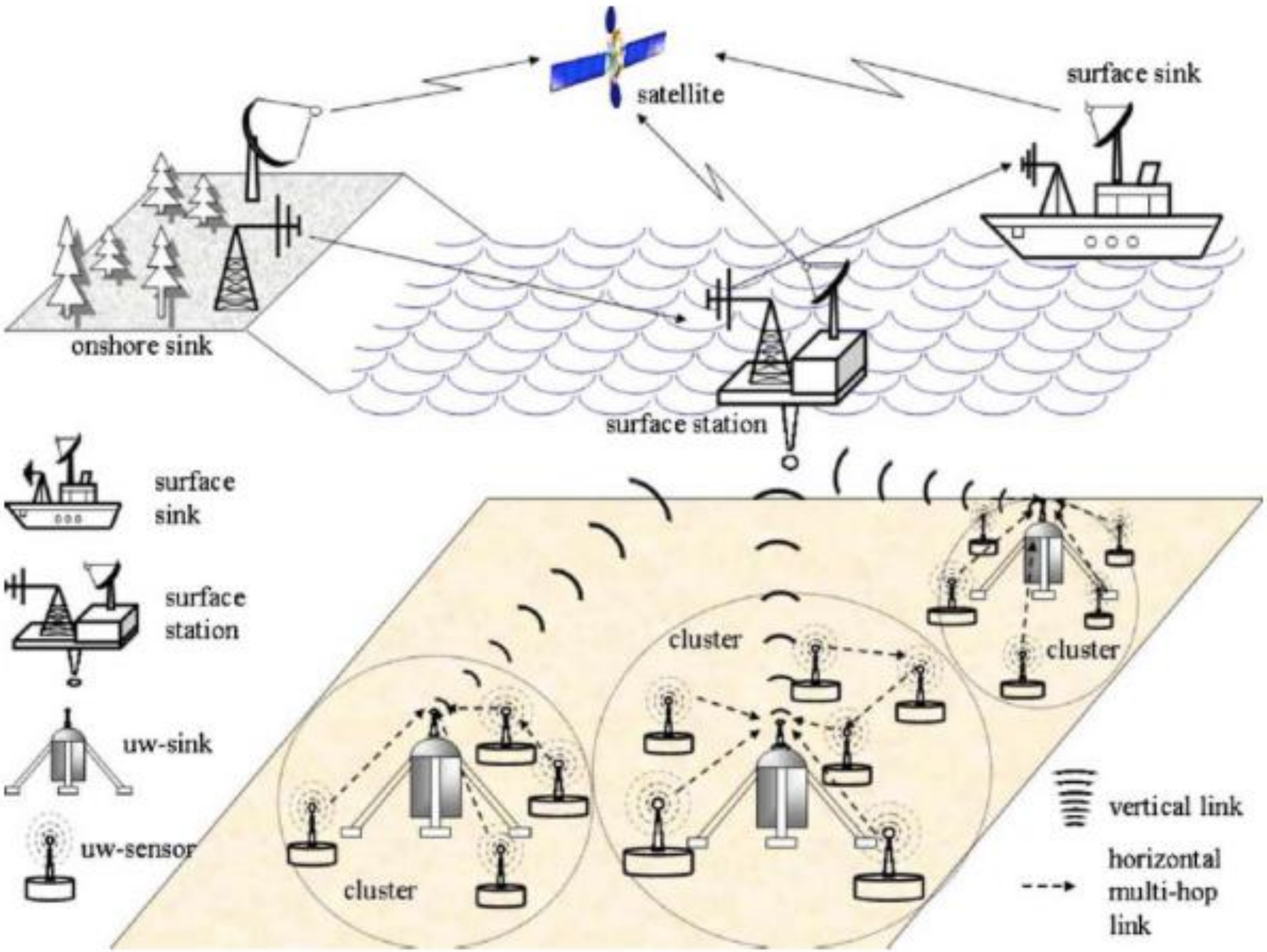


Fig. 1. Architecture for 2D underwater sensor networks.

UWSNs Topologies

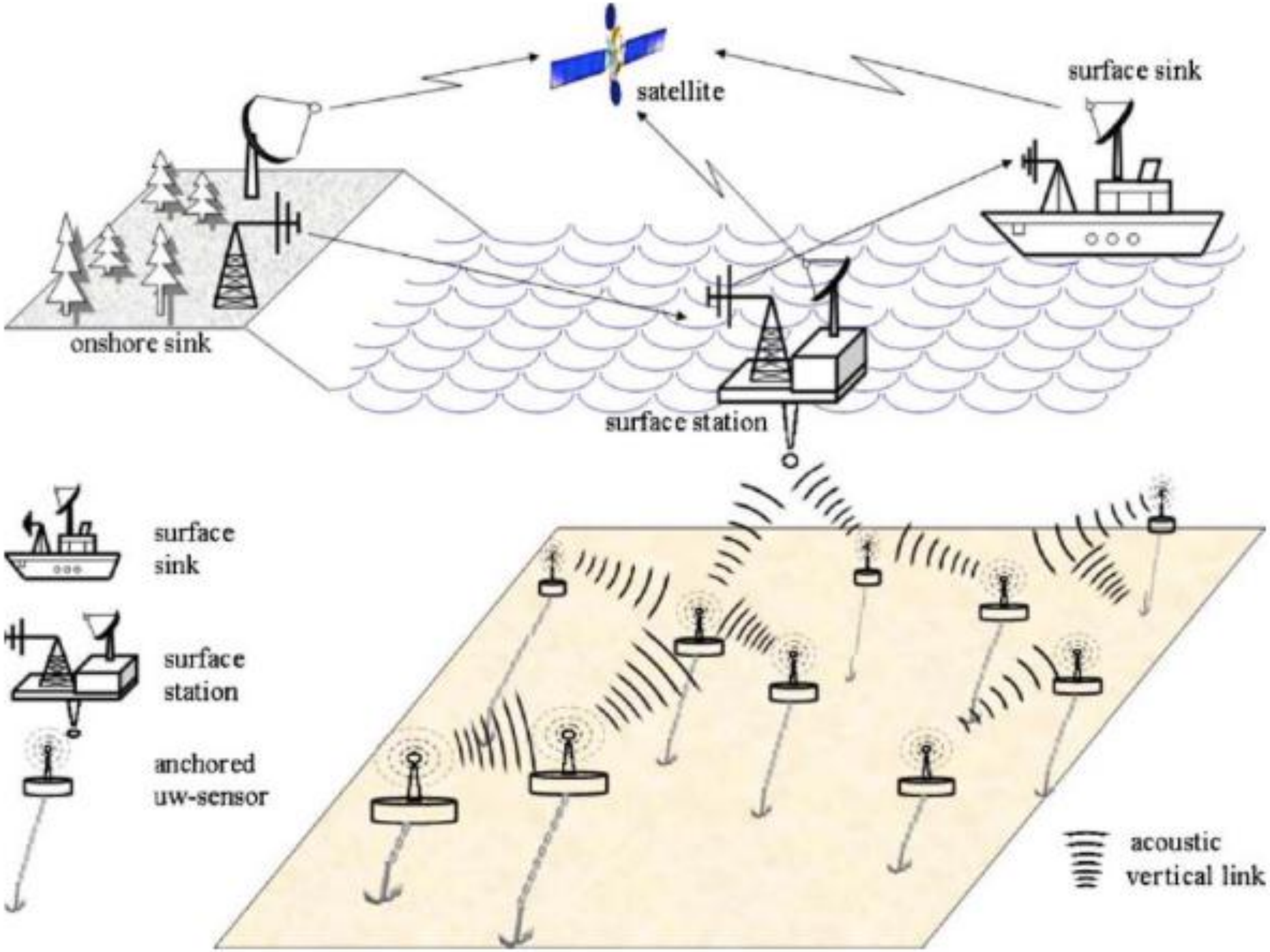
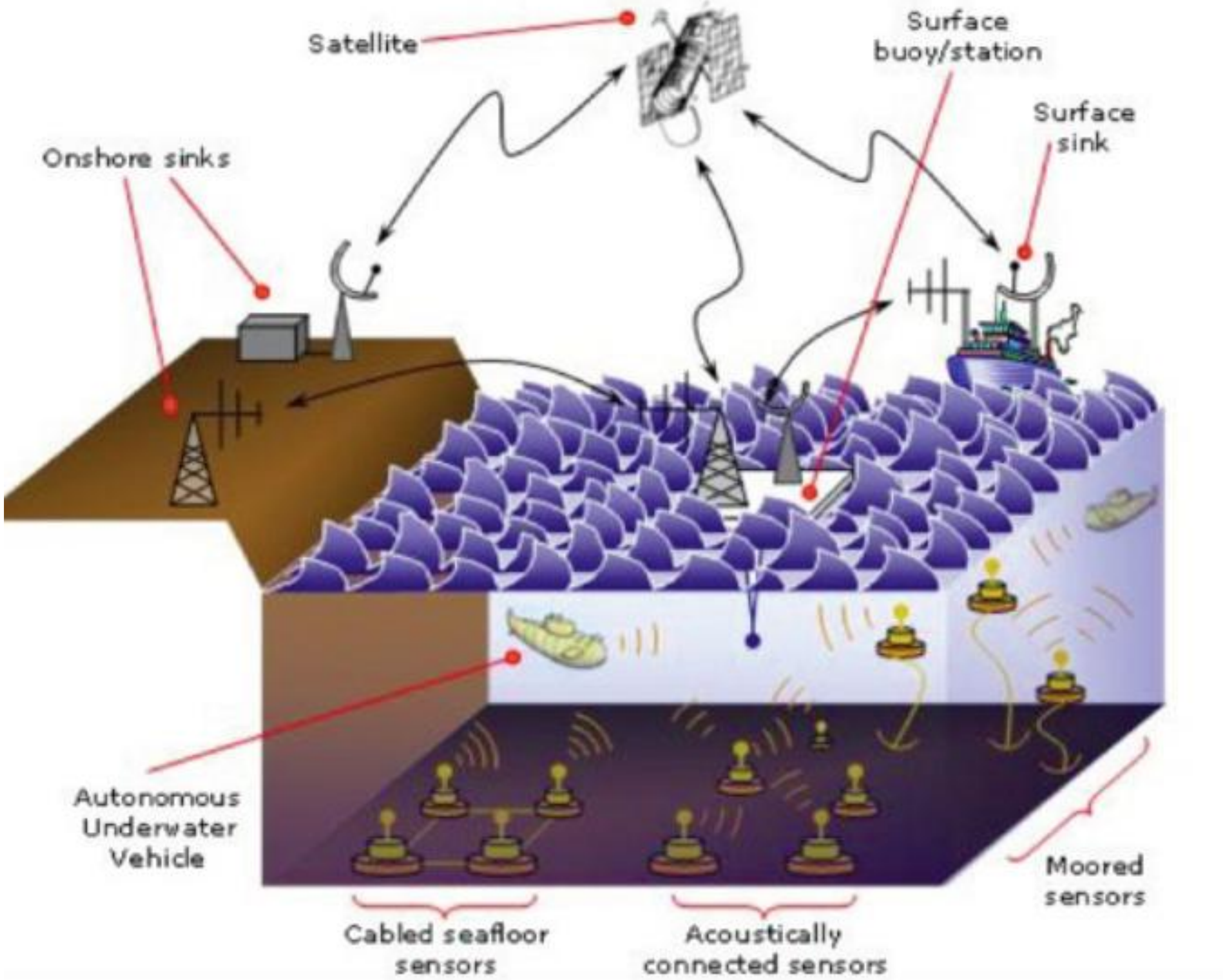
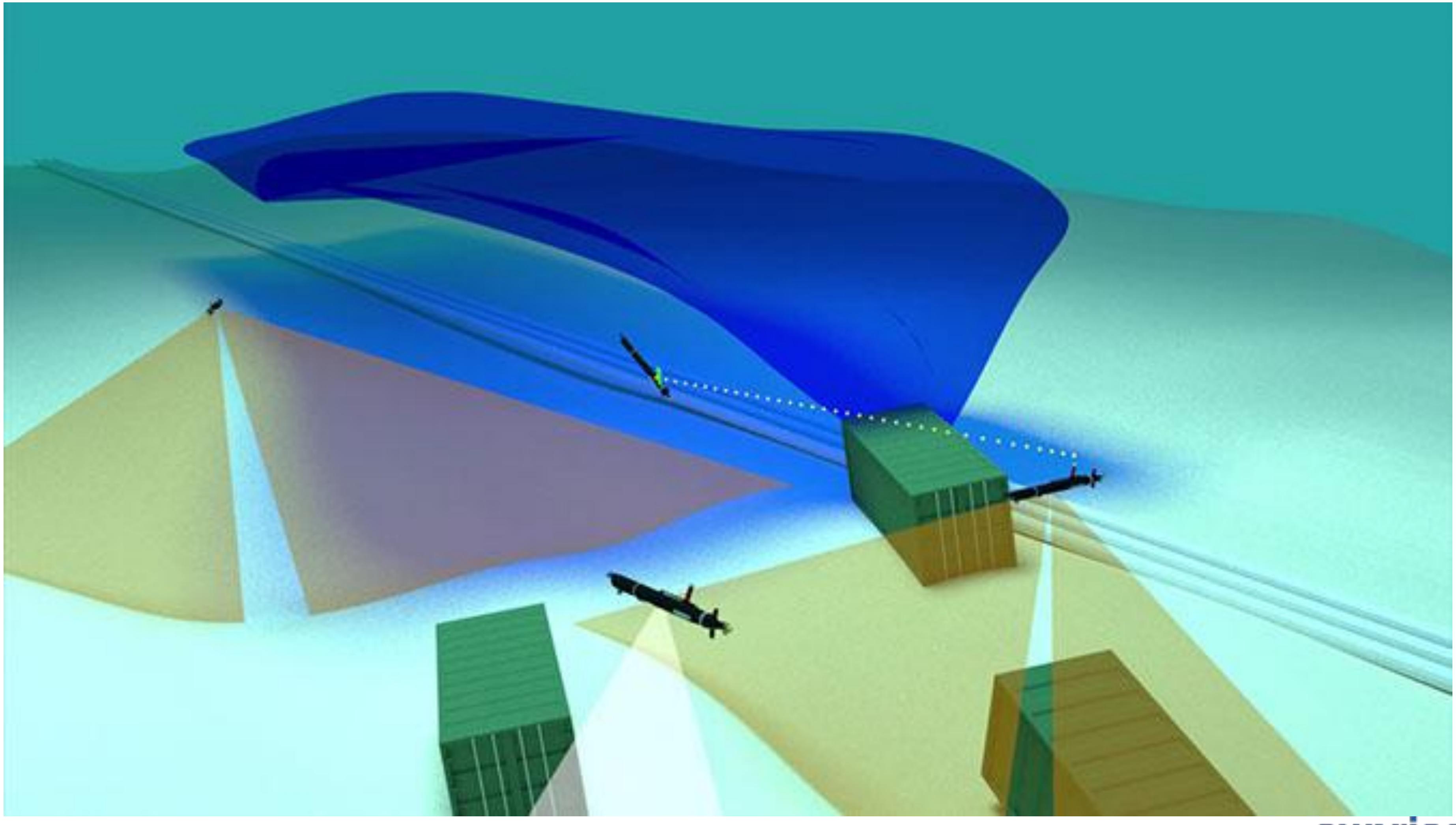


Fig. 2. Architecture for 3D underwater sensor networks.

Underwater Wireless Sensor Networks



Underwater Wireless Sensor Networks



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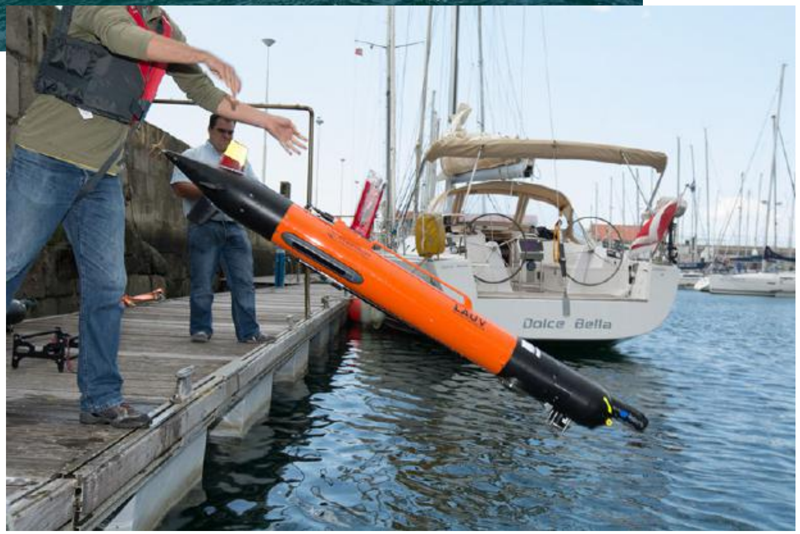
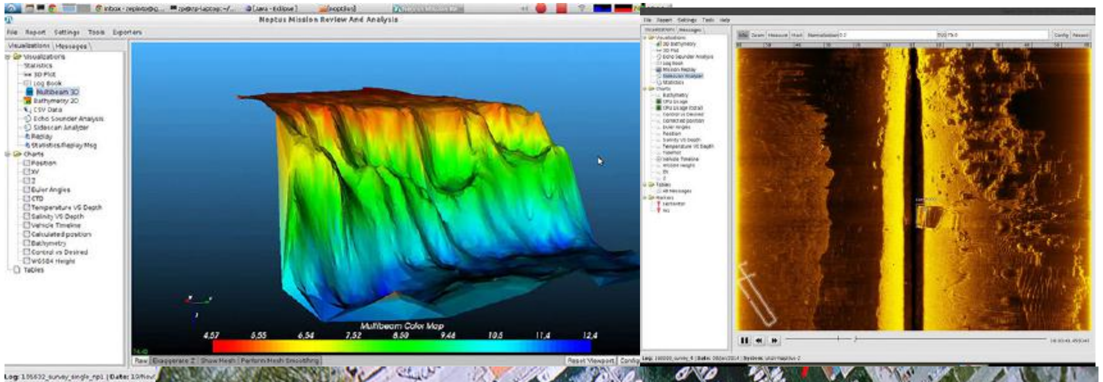
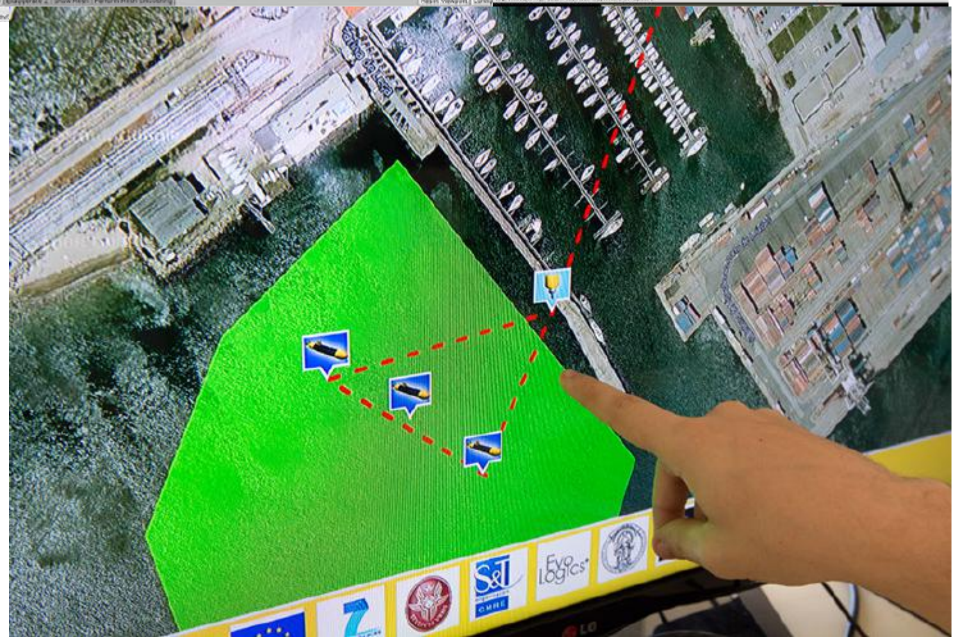






c. Marco Merola

Interoperable

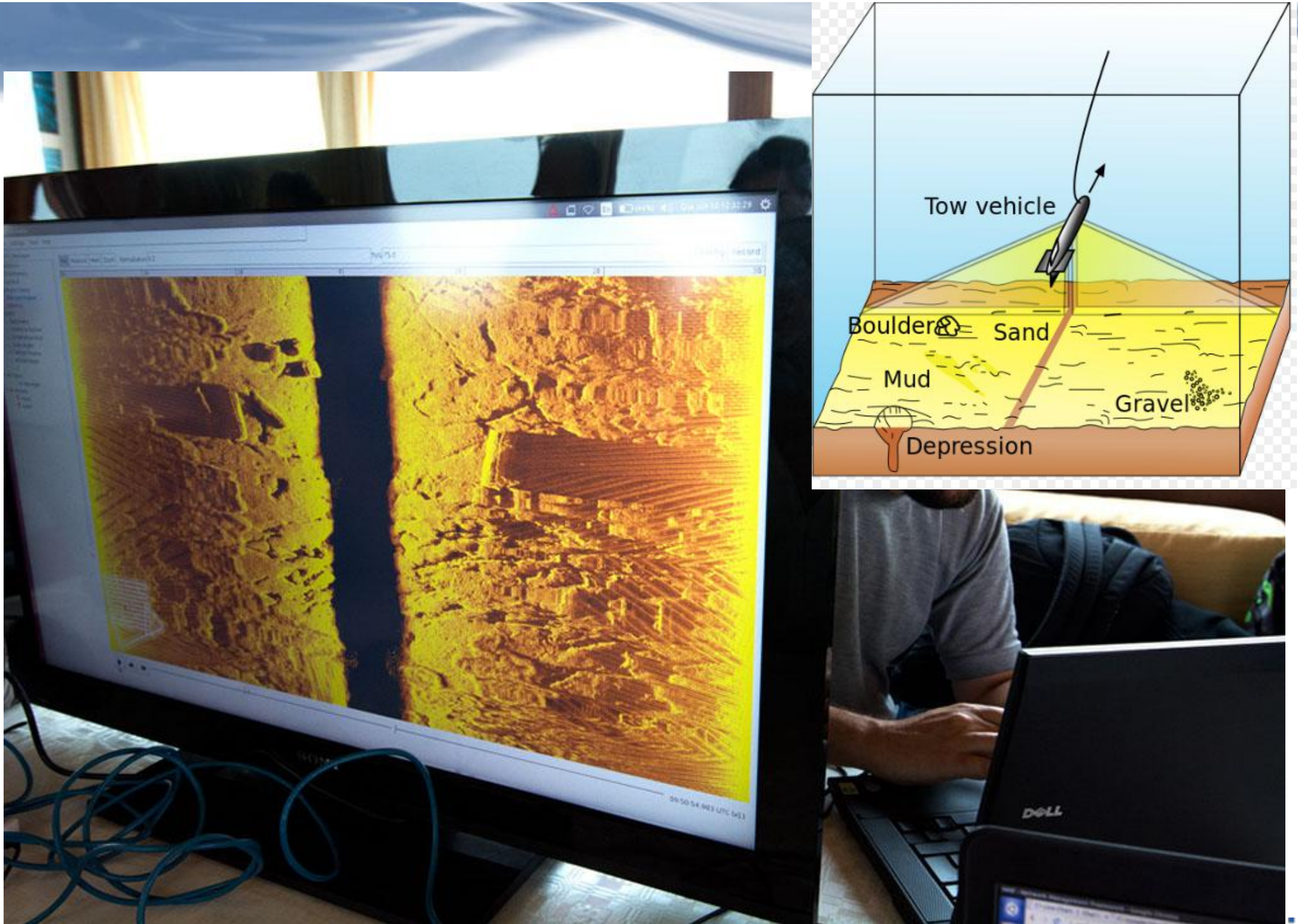
Reliable

Secure

Low cost

SUNRISE- Building the Internet of Underwater Things

VIDEOS REMOVED FROM THE SLIDES



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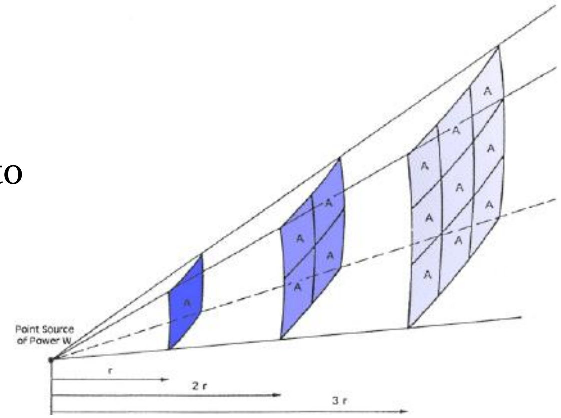
Waves propagation

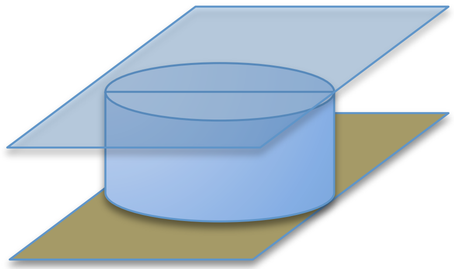
Radio waves in free space

- 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/r2).



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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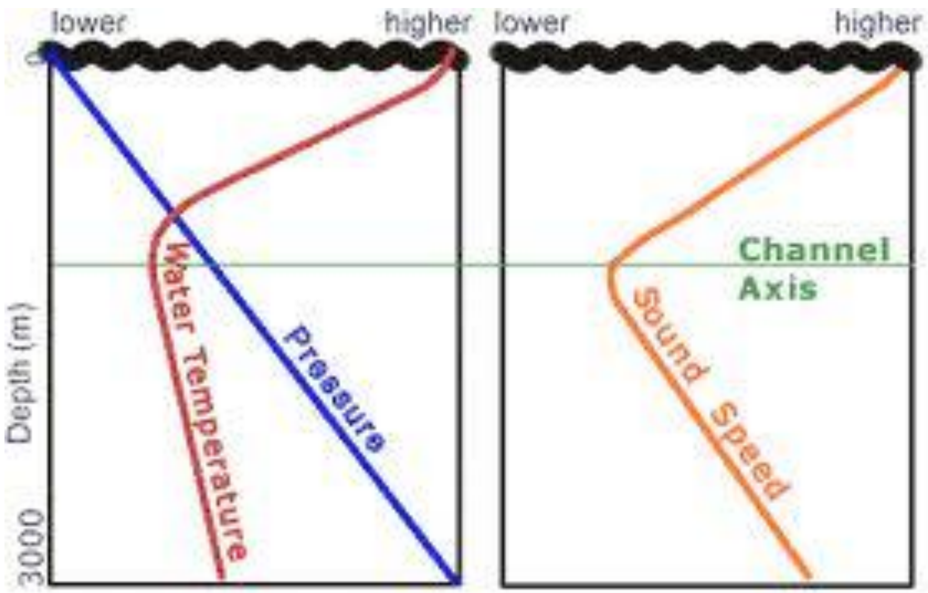
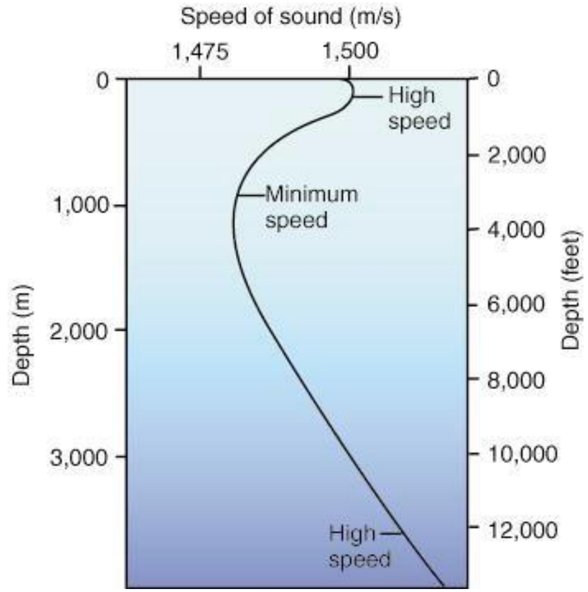
Waves propagation

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





- Sound speed profile determines how the acoustic rays bend

Waves propagation

Effects of SOUND SPEED PROFILE

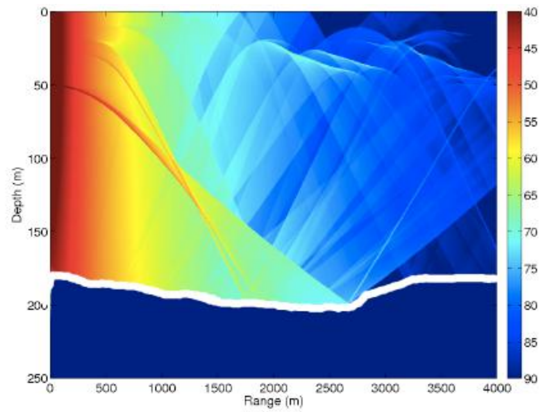
The different speeds at different depths induces rays bending, in particular:

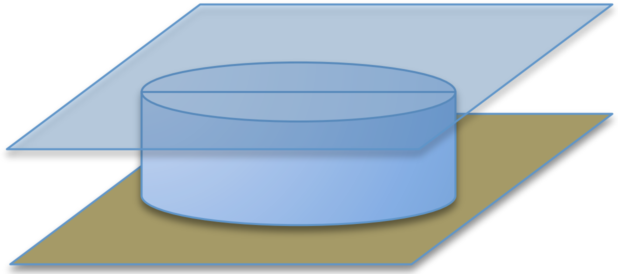
- Cylindrical Propagation: the wave energy expands in two dimensions rather than three, because part of the rays that go towards the surface are folded down and then their energy is "propagated" in the layer of water.
- The sound can propagates for hundreds of kilometers.
- Phenomenon of shadow-zones

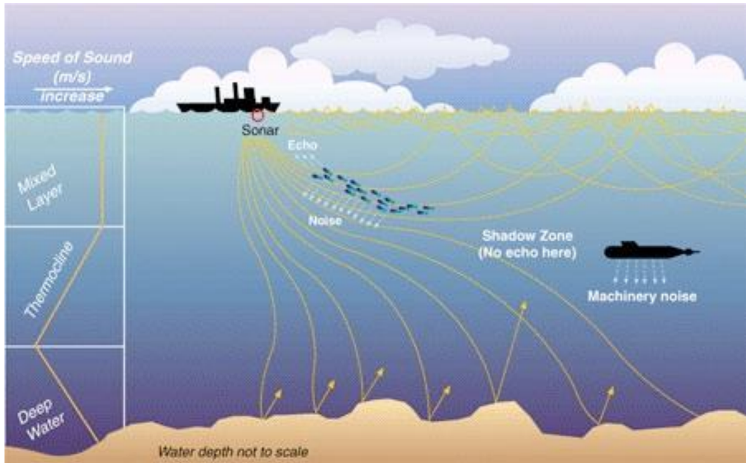
Moreover:

Temporal variability due to:

- Currents
- Wave motion on the surface



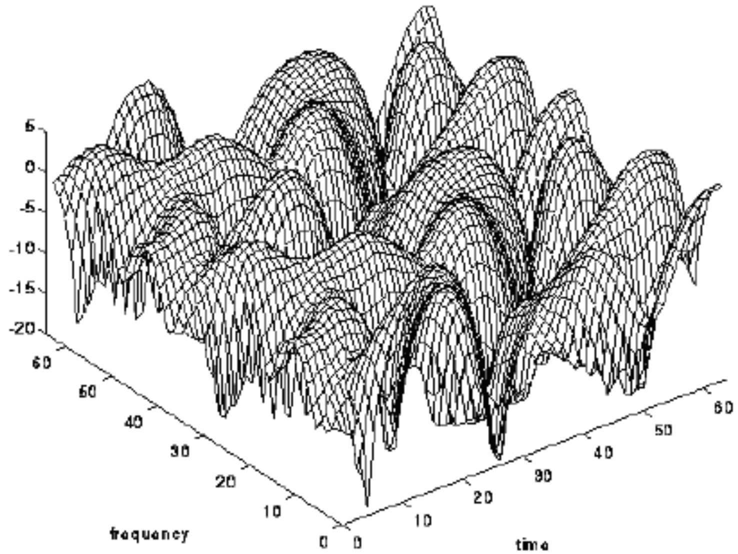




Frequency response

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).

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http://wuwnet.engr.uconn.edu/papers/p001-preisig.pdf

MAC comparison

- UASNs MAC characteristics:
  - Nodal synchronization
  - Use of control packets for channel acquisition
  - Ways for accessing the channel
  - Use of ACKs
  - Slotted or unslotted time

http://senseslab.di.uniroma1.it/administrator/components/com_jresearch/files/publications/A_Comparative_Performance_Eval.pdf

The considered protocols are:

- CSMA
- APCAP (Adaptive Propagation-Delay Collision Avoidance Protocol)
- DACAP (Distance Aware Collision Avoidance Protocol)
- PDAP

CSMA

Random Access with CSMA and backoff:

- If the channel is idle, the node transmits
- If it is busy, it waits for a backoff time

Possible use of ACKs,

- Limit of (2*delay + acktime) for retransmission
- Backoff time ~ U[0,T] with T=2^txRetry

Does not require synchronization

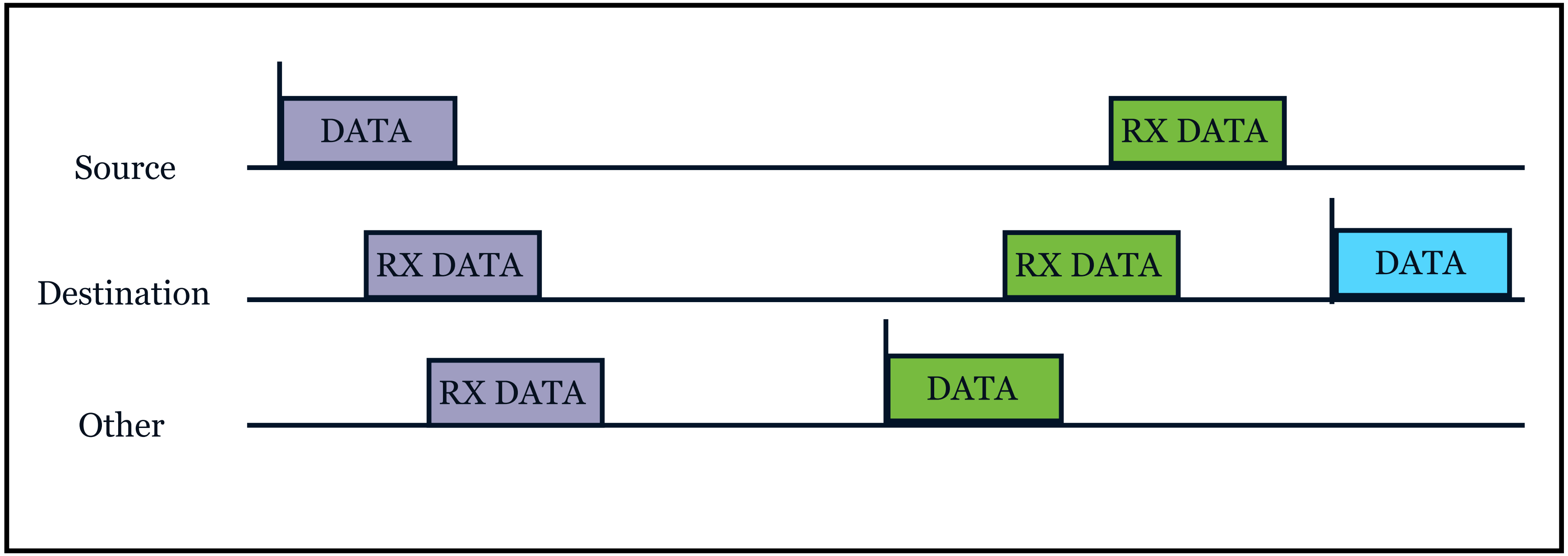
Slotted version

- slot duration is an important parameter
- time_slot = β*maxDelay + datatime

Requires synchronization

CSMA

- Nodes are not synchronized
- Uses carrier sensing.
- No control packets fo channel acquisition



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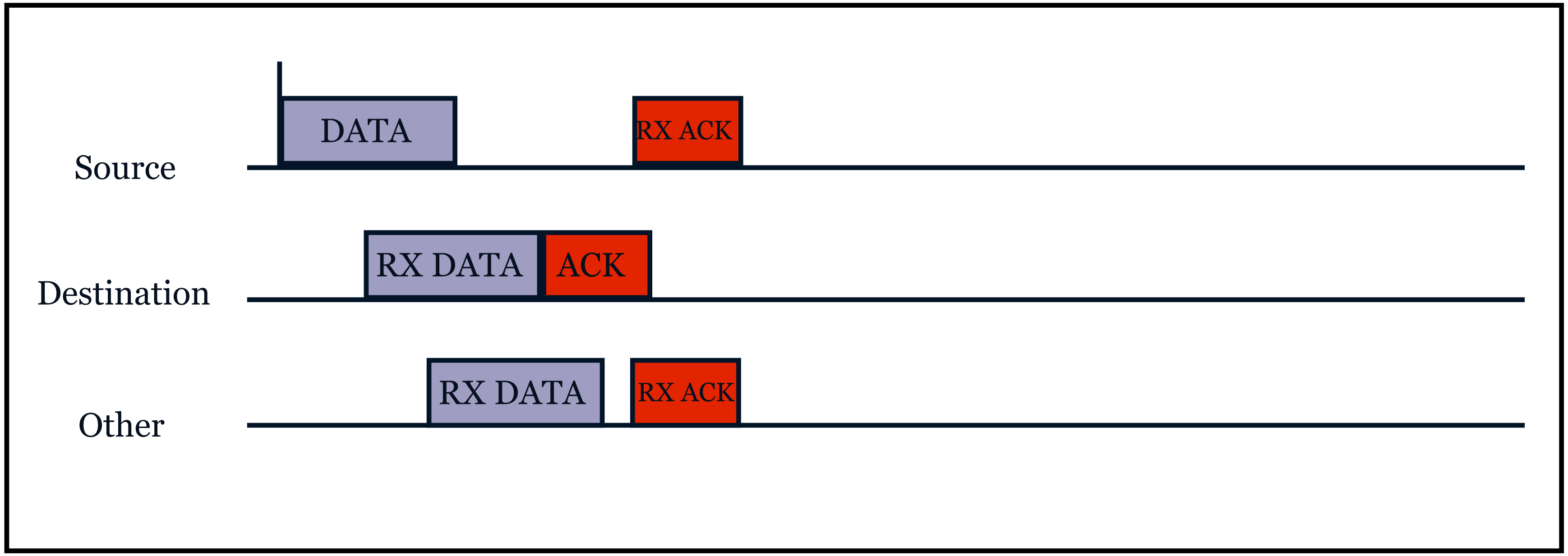
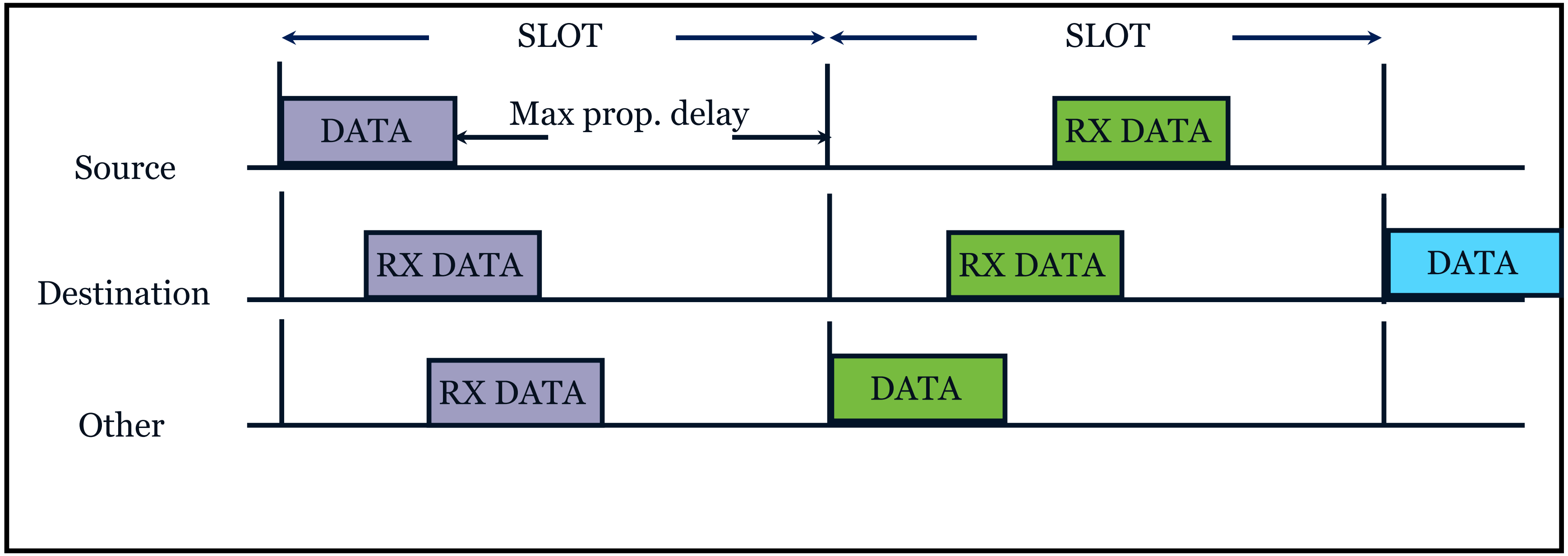


Slotted CSMA

Nodes are synchronized
Uses carrier sensing
Transmissions start at the beginning of the slot
No control packets for channel acquisition



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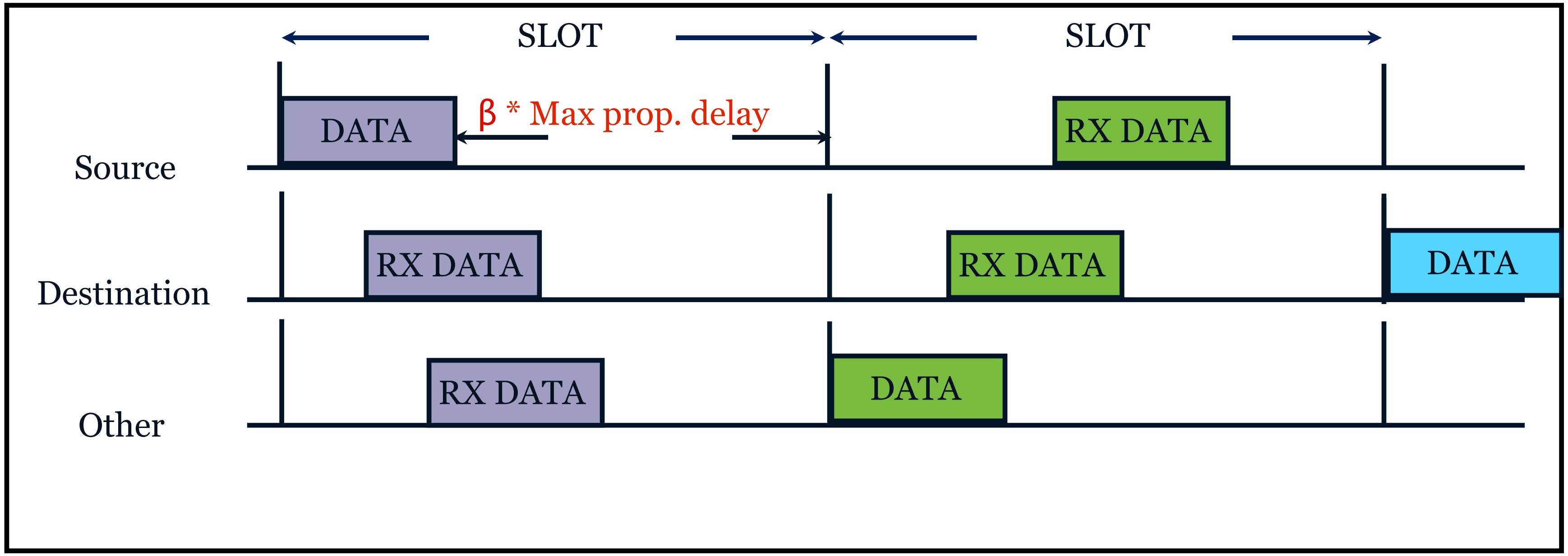

$\beta = 0.5$

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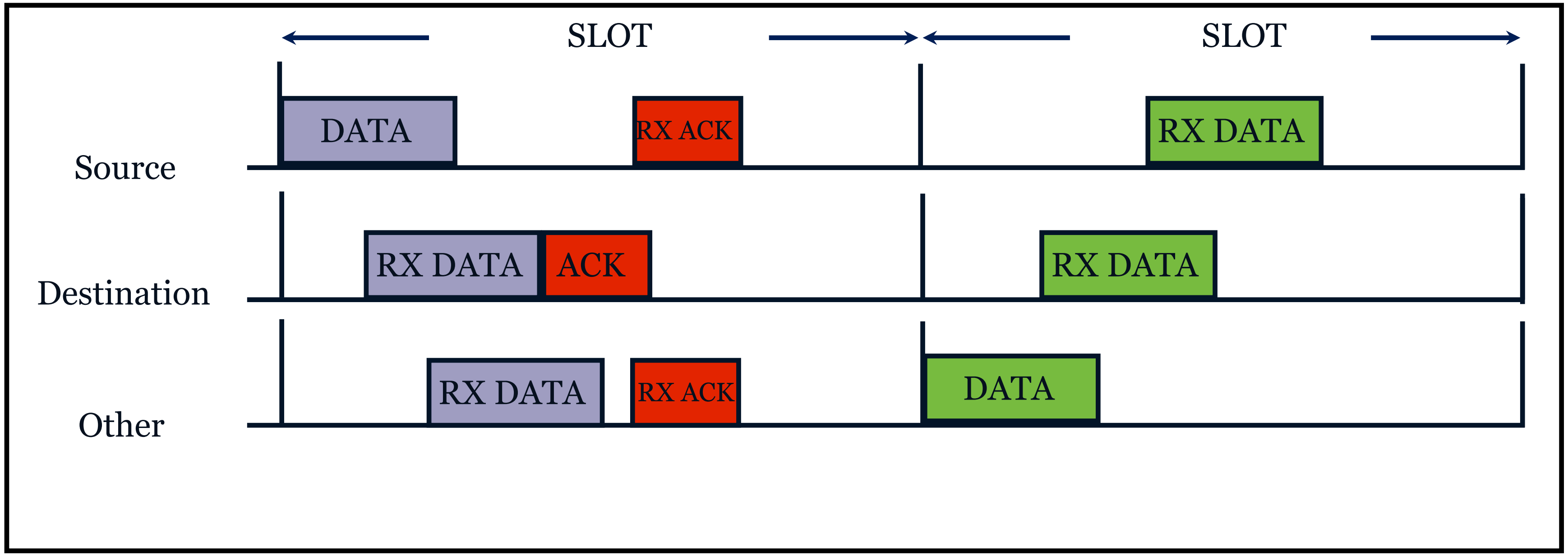

SLOT = TxTime(DATA) + TxTime(ACK) + Max propagation delay

DACAP distance aware collision avoidance protocol

Random access. Based on RTS-CTS

- Differently from APCAP, the replies are instantaneous
- Collisions are avoided through the insertion of a WARNING time between the reception of the CTS and the actual data transmission.
- During this interval, the receiver can send a WARNING packet if it hears any control packet from other nodes.
- Likewise the sender can overhear control packets.
- If the sender receives a warning or listens to other control packets during the warning time, it aborts the data transmission.
- The challenge is the best choice of the WARNING time, which is performed through an inference of the sender-receiver distance obtained by measuring the RTS CTS round trip delay

No synchronization required

DACAP distance aware collision avoidance protocol

- Nodes are not synchronized
  RTS/CTS-based channel acquisition
  Distances between nodes are measured based on control packets RTT
  Uses a warning period before transmitting for avoiding collisions

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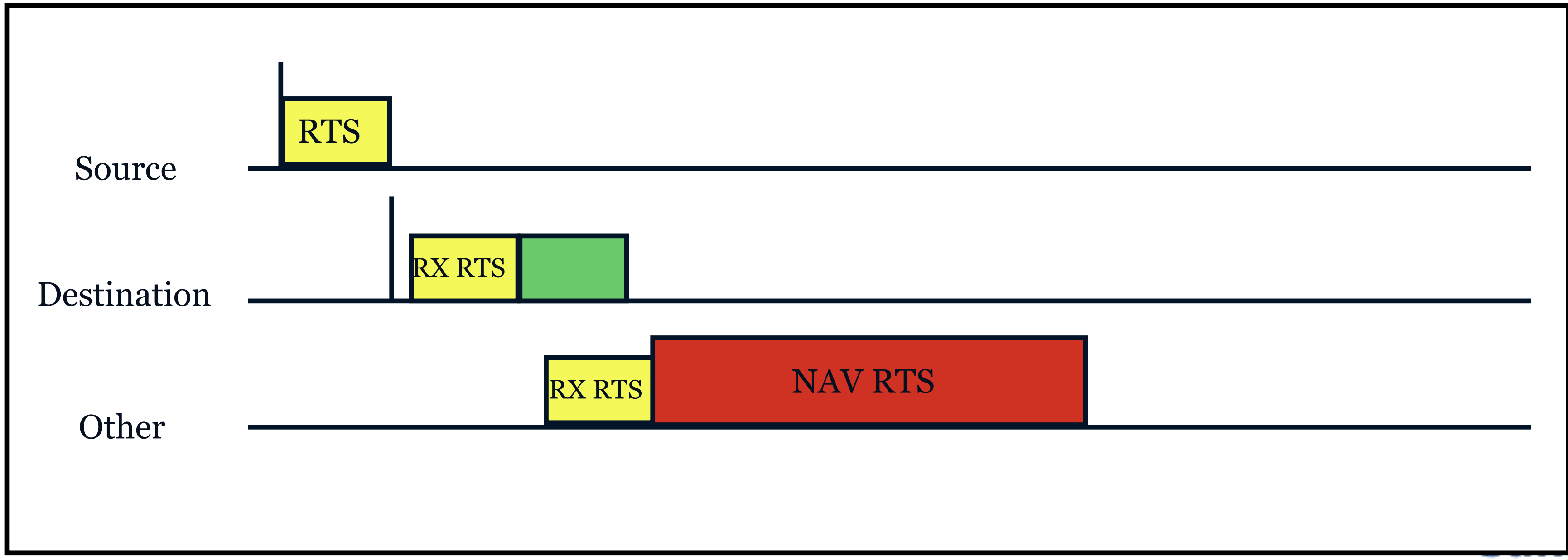

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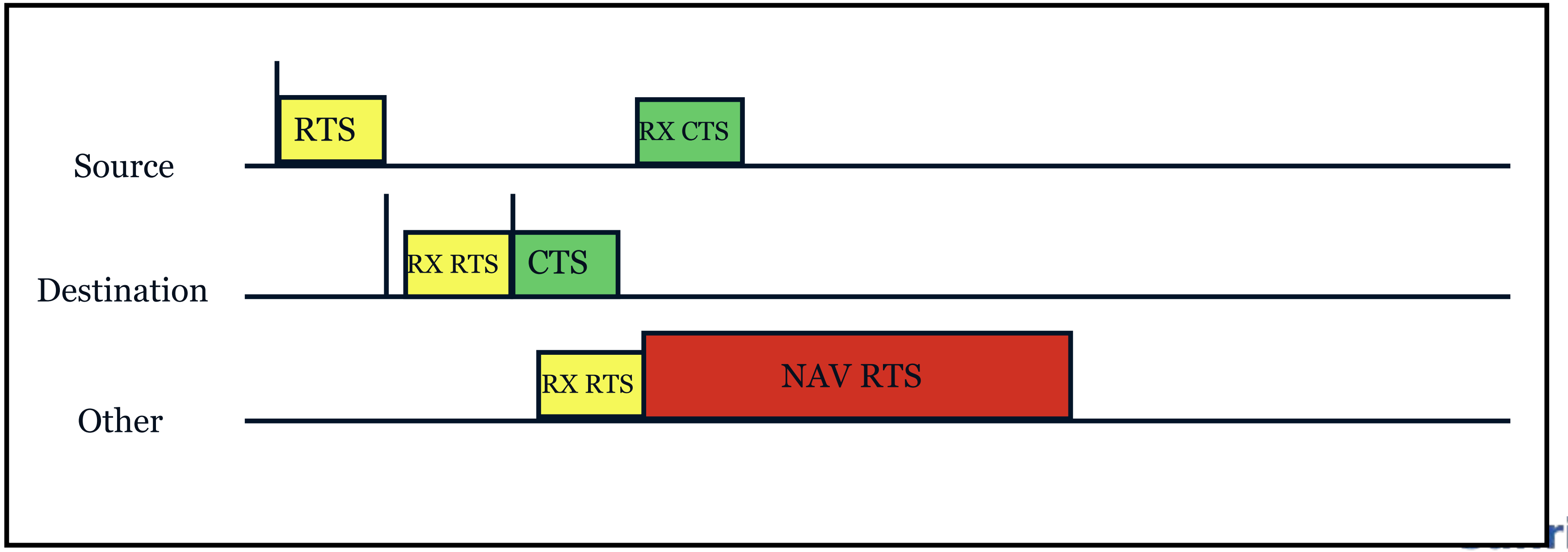

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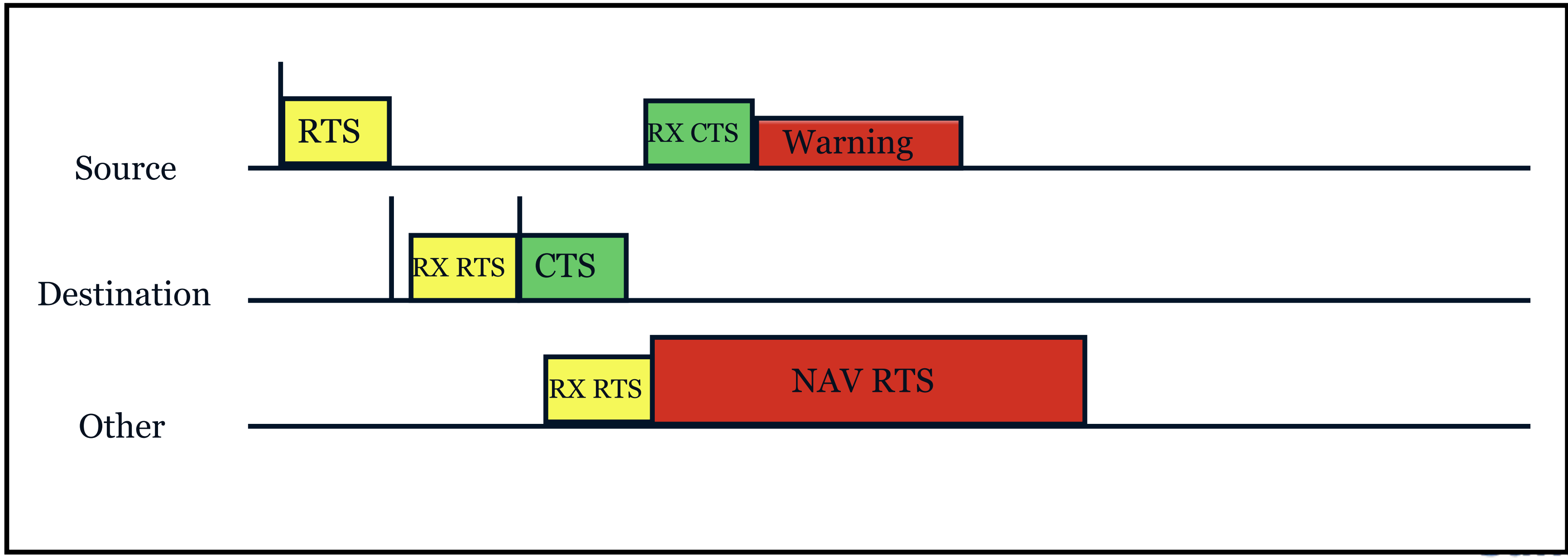

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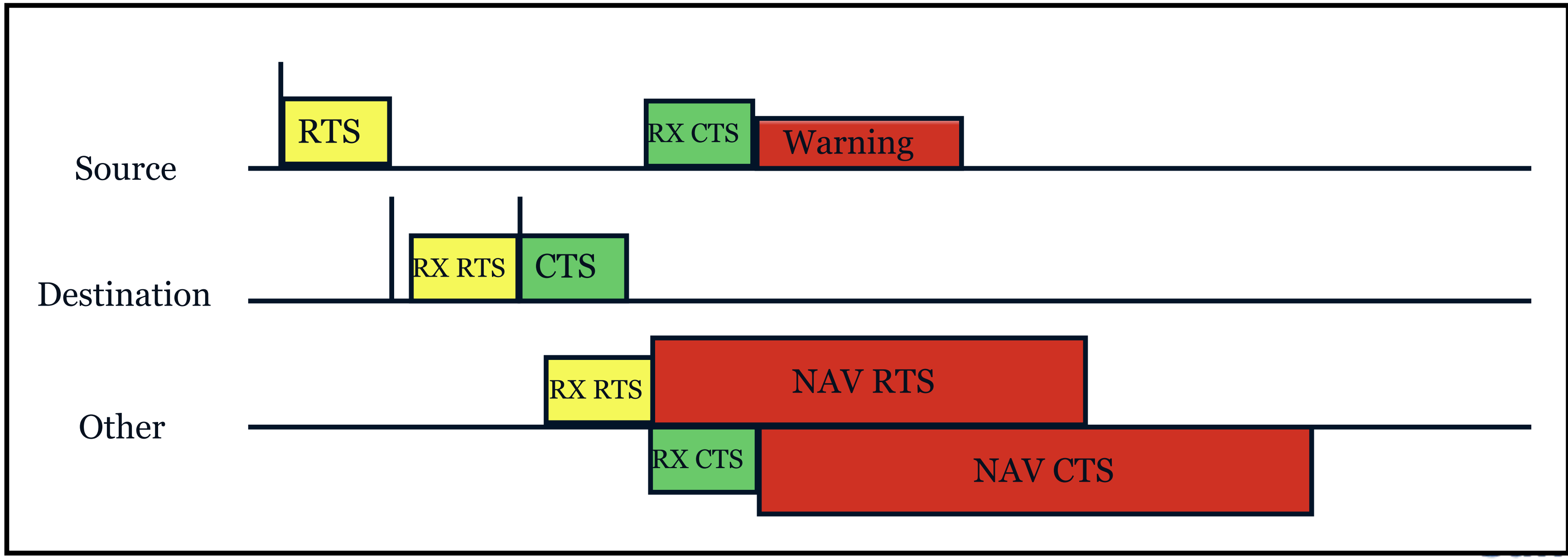

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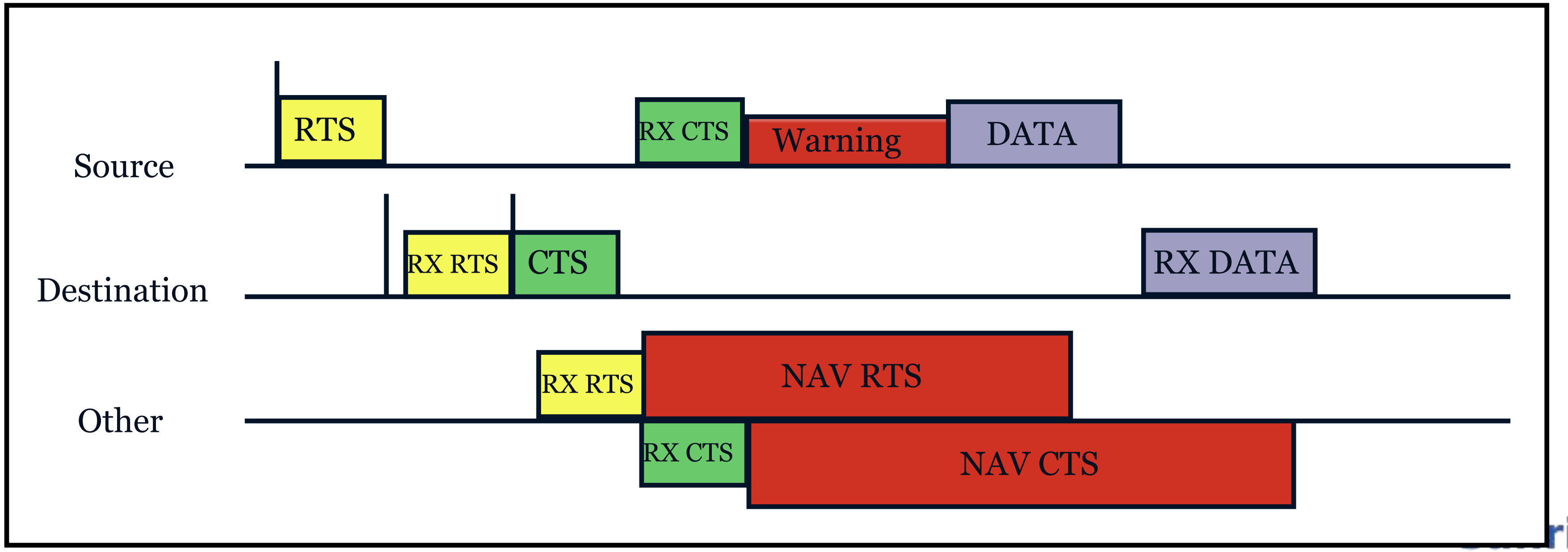

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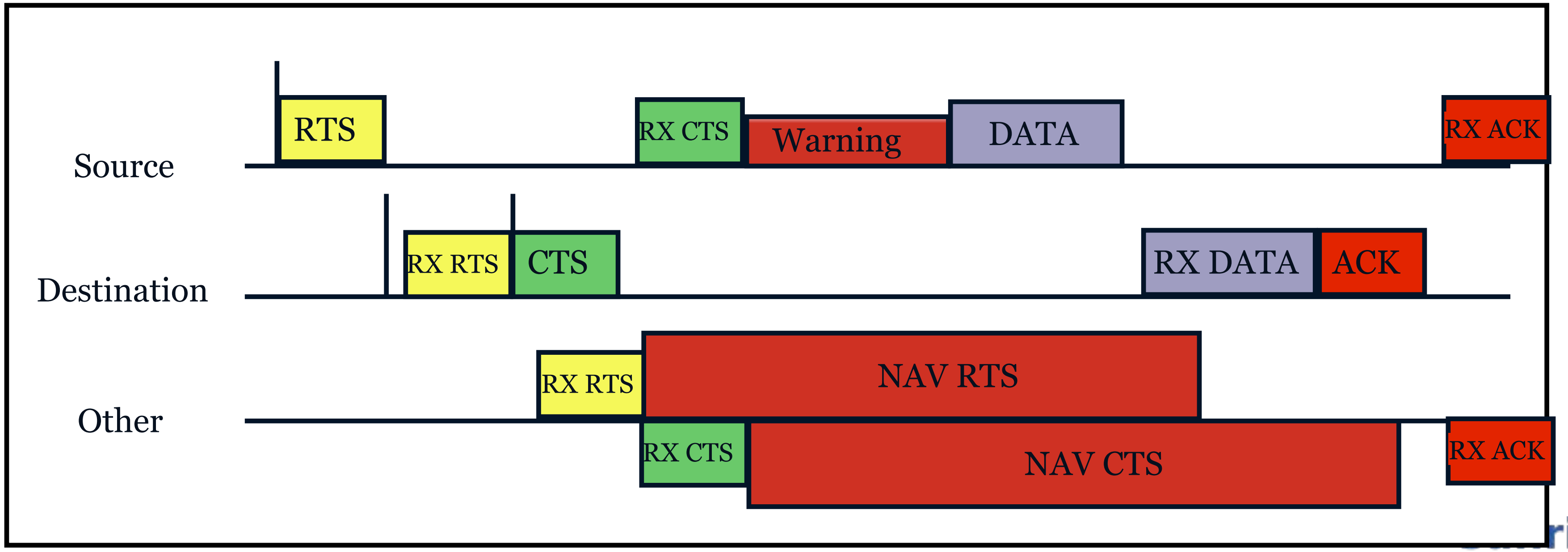

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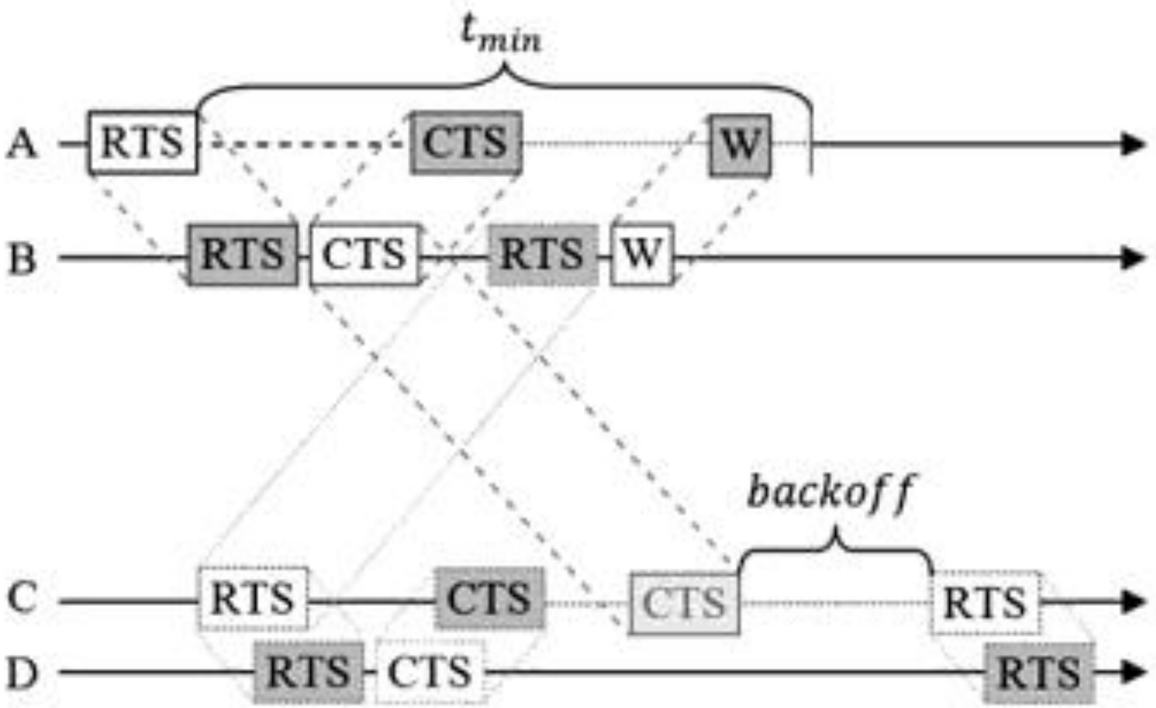


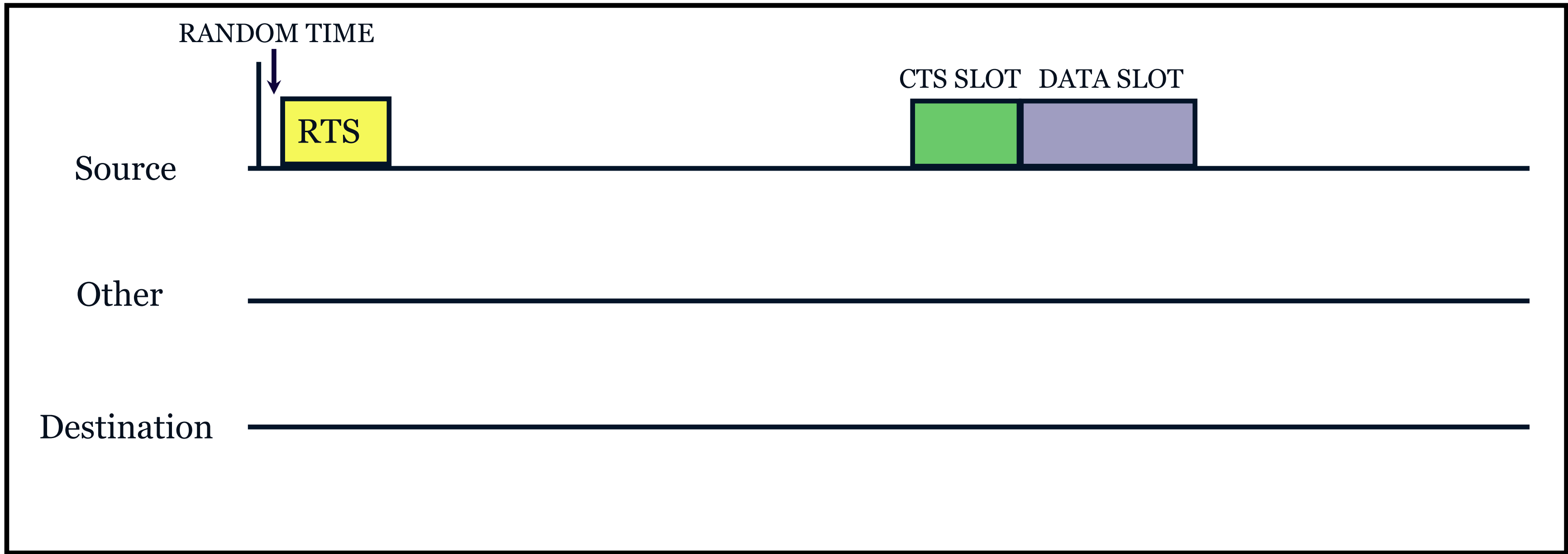
PDAP propagation delay aware protocol

Nodes are synchronized

RTS/CTS-based channel acquisition

RTS/CTS timestamp are used to compute distance between nodes
Infer distance between source and destination

Uses random time and backoff to avoid nodes synchronization and collisions
Every node has its own schedule and interleaved communications are possible



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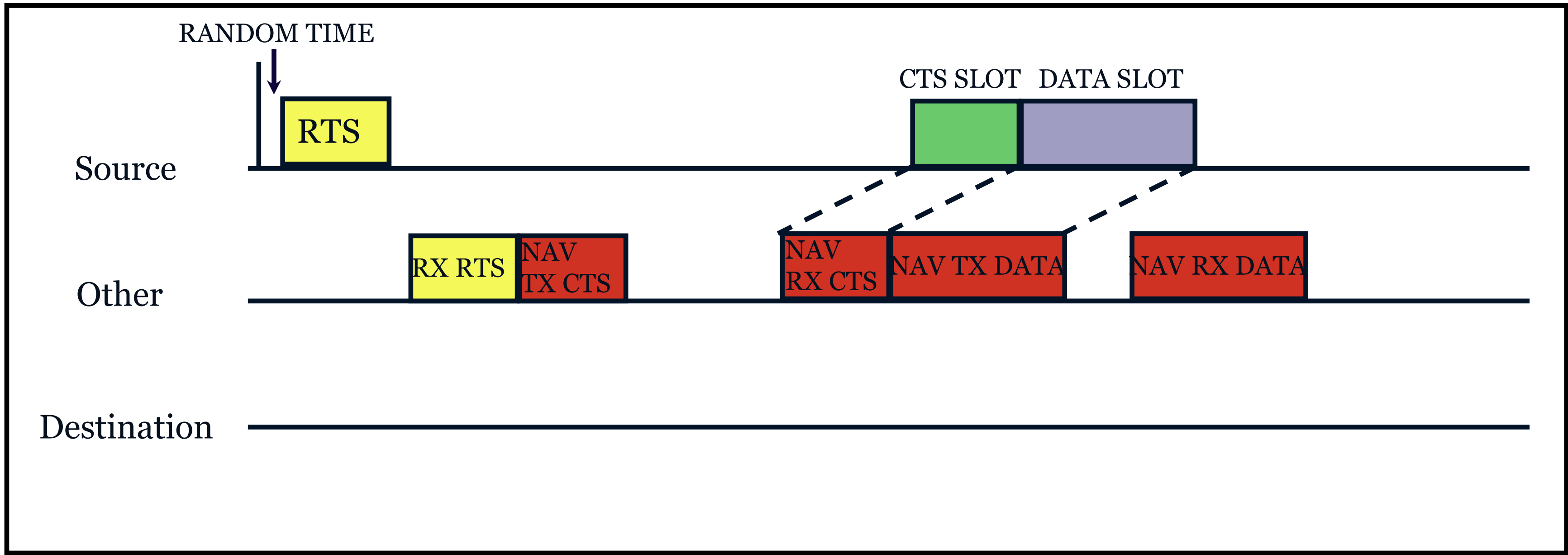

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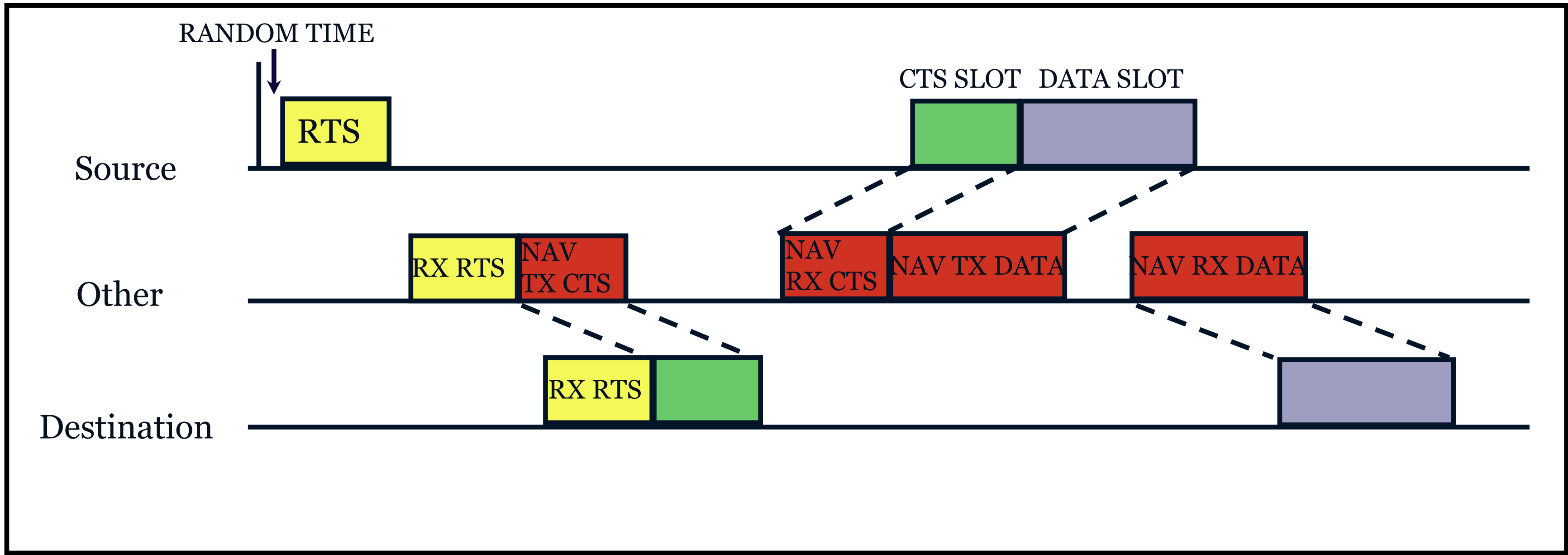

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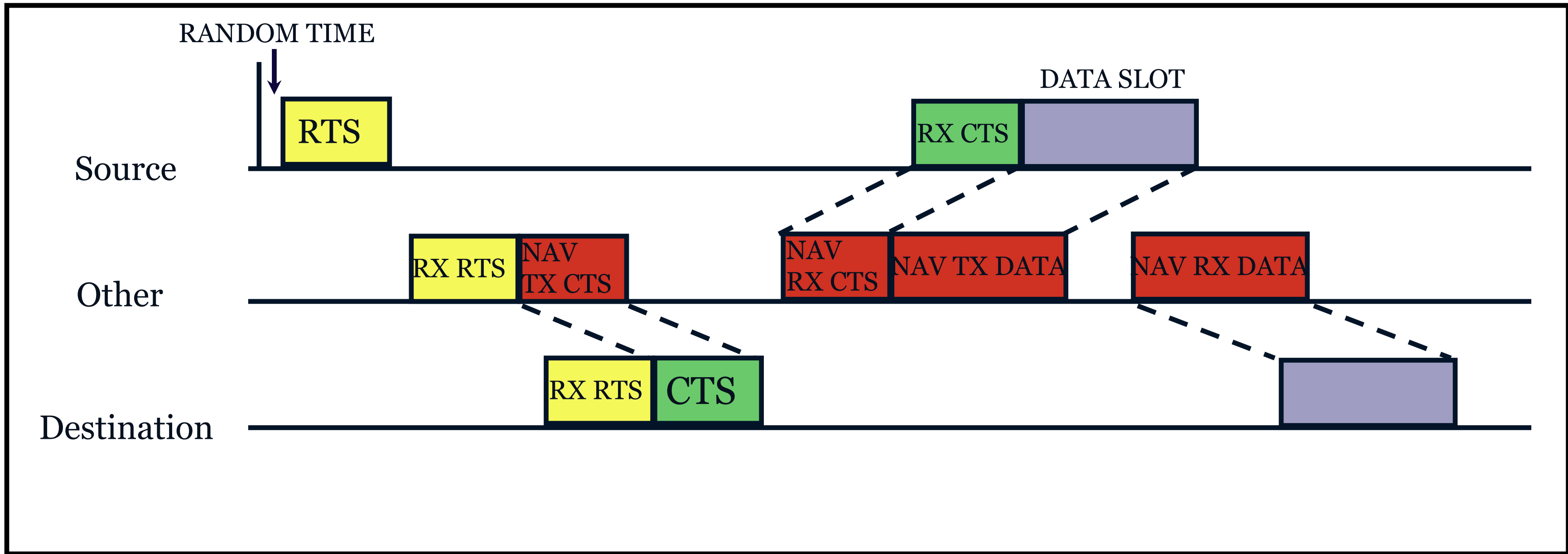

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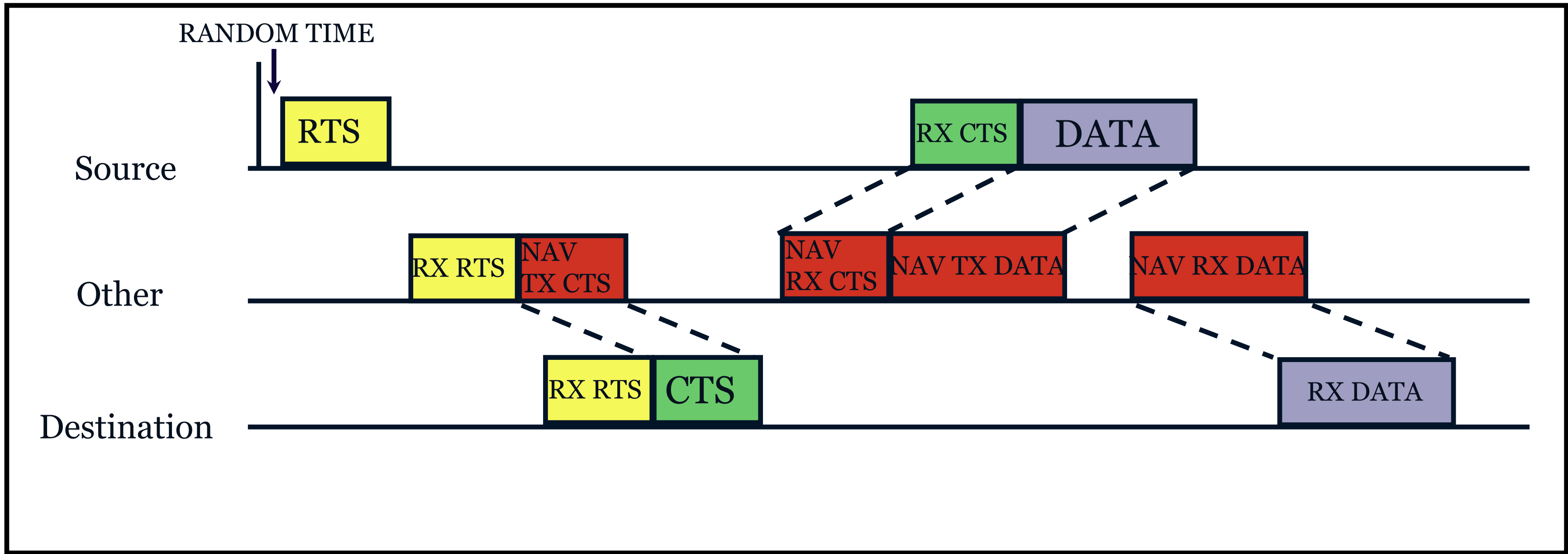

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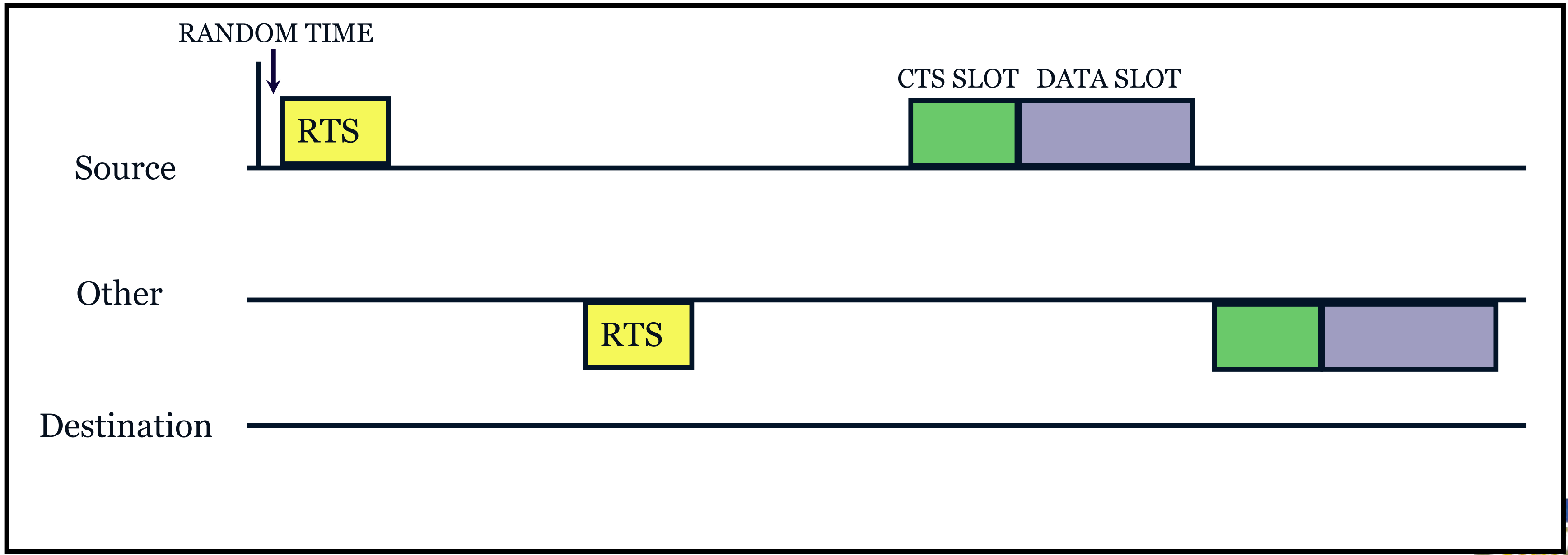

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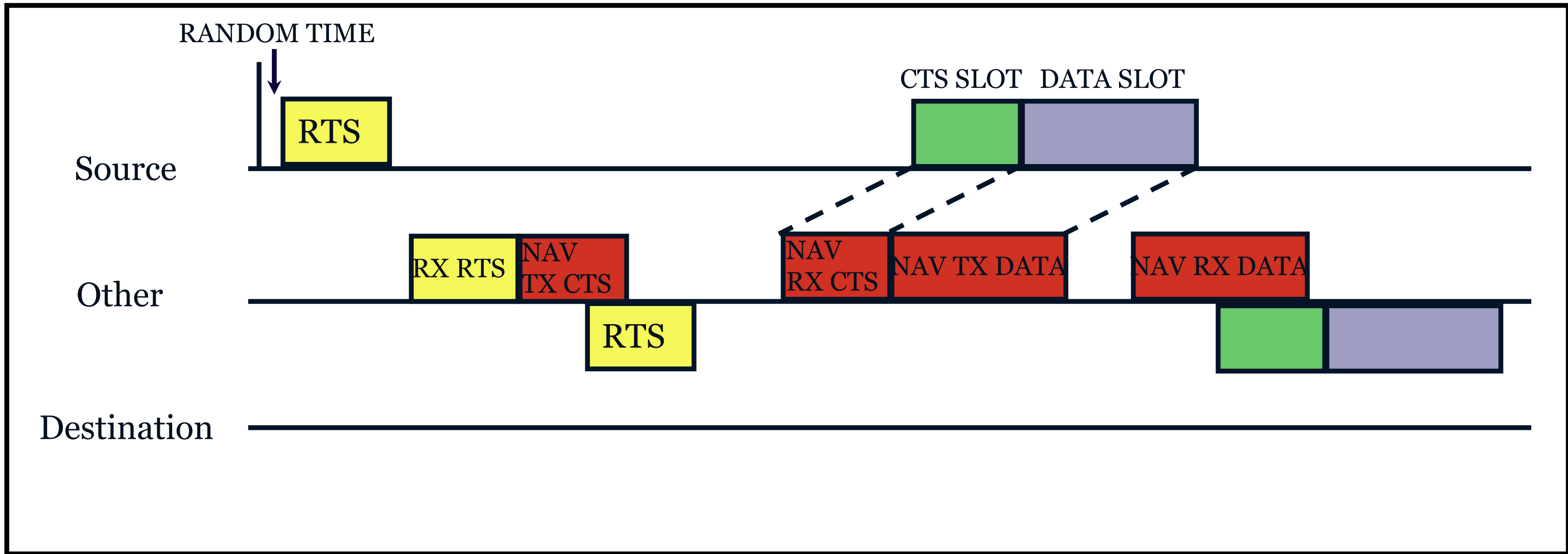

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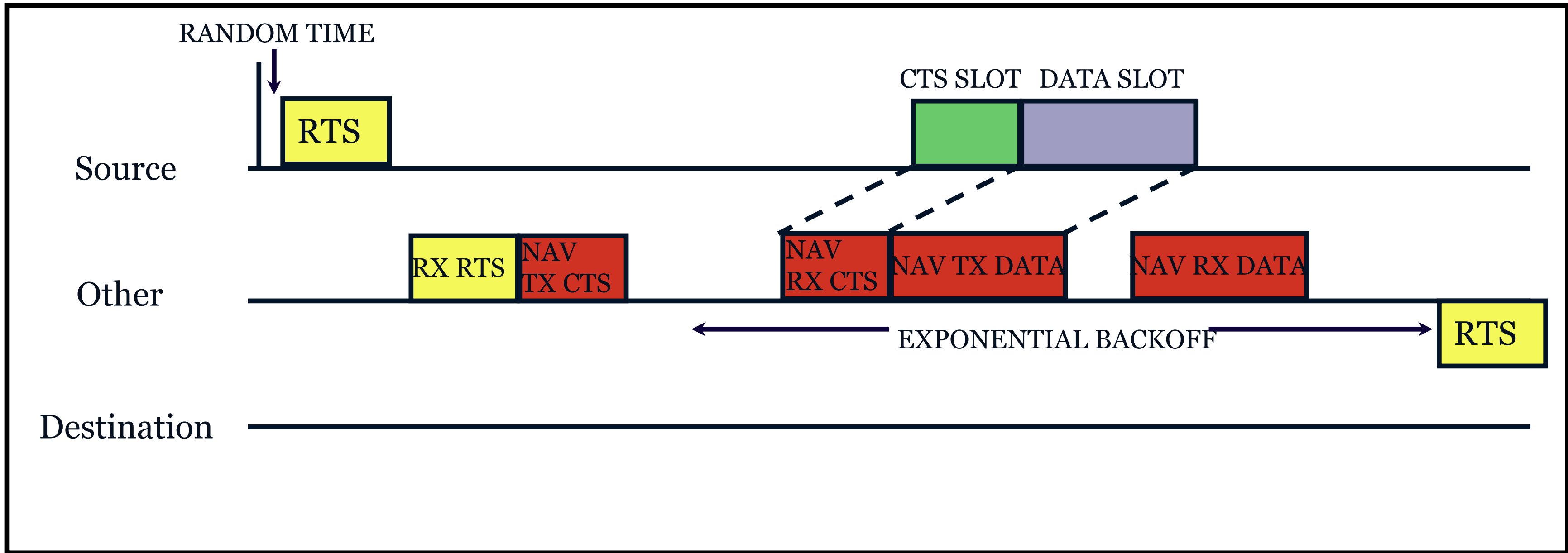

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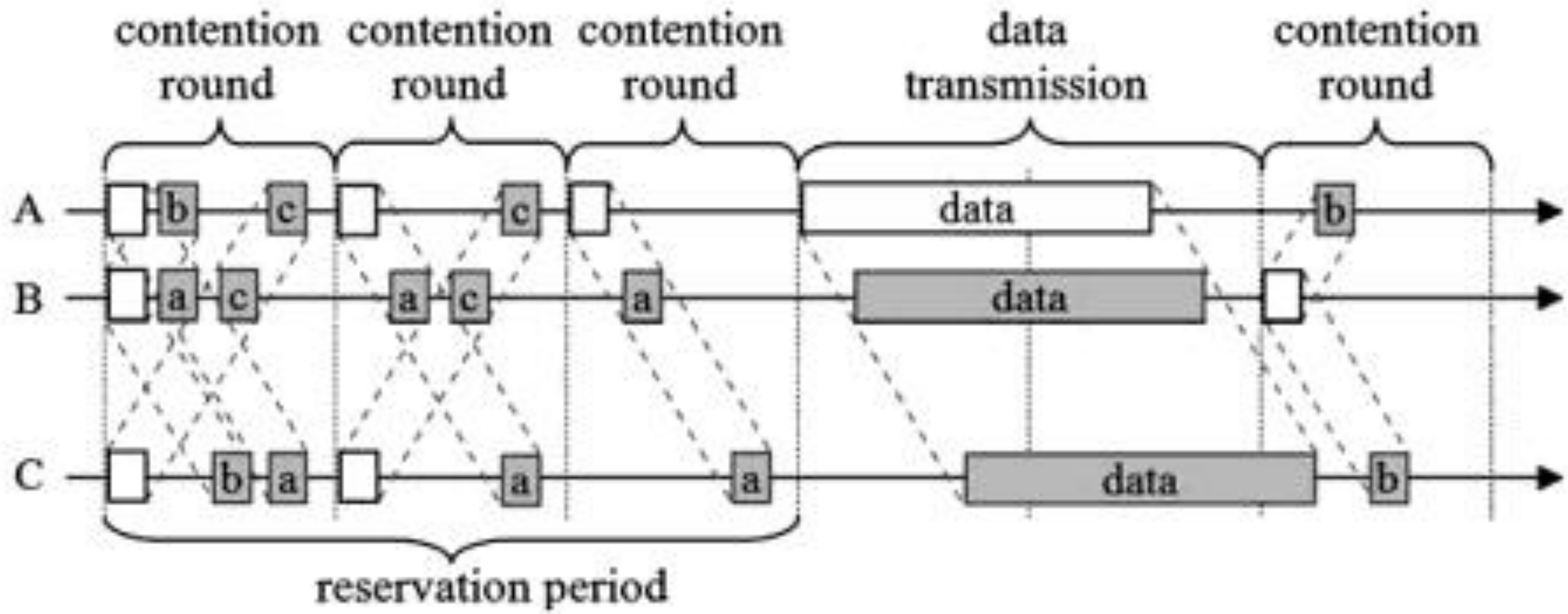
contention round
contention round
contention round
data transmission
contention round
A
B
C
b
c
a
c
a
c
a
b
a
a
a
data
data
data
b
b
reservation period

Performance evaluation (parameters)

New ns2-based simulation framework for performance comparison

- Shallow water scenario
- N static nodes randomly and uniformly scattered on the lower face of a cuboid L x L (base) x H, where H = 200m
- Single-hop and multi-hop with shortest path routing scenarios
- Different average nodal degrees (5, 10 and 15)
- Acoustic modem transmission range set to 1000m
- Poisson traffic process with different rate (low traffic up to high traffic)
- Three data rates: 2000bps, 8000bps and 28000bps
- Data packet size set to 2400 bits
- Physical header size set to 60 bytes

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Performance evaluation (metrics of interest)

- Percentage of data packets sent
- Percentage of data packets received
- Percentage of data packets lost
- End-to-end latency
- Goodput

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP	T-LOHI
100% Data delivery 2000bps						
100% Data delivery 28000bps						
more than 90% data delivery 2000bps						
more than 90% data delivery 28000bps						

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs	-	-	-	-
		λ ≤ 0,17 ACKs	λ ≤ 0,17 ACKs	λ ≤ 0,14 ACKs		
100% Data delivery 28000bps						
more than 90% data delivery 2000bps						
more than 90% data delivery 28000bps						

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps						
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps						

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps	λ ≤ 1	λ ≤ 0,5 no ACKs λ ≤ 0,27 ACKs	λ ≤ 0,03 no ACKs λ ≤ 1 ACKs	λ ≤ 0,03 no ACKs λ ≤ 0,35 ACKs	λ ≤ 0,06	λ ≤ 0,2
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps						

sunrise

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps	λ ≤ 1	λ ≤ 0,5 no ACKs λ ≤ 0,27 ACKs	λ ≤ 0,03 no ACKs λ ≤ 1 ACKs	λ ≤ 0,03 no ACKs λ ≤ 0,35 ACKs	λ ≤ 0,06	λ ≤ 0,2
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps	λ ≤ 1,2	λ ≤ 0,6 no ACKs λ ≤ 0,3 ACKs	λ ≤ 0,6 no ACKs λ ≤ 1,1 ACKs	λ ≤ 0,3 no ACKs λ ≤ 0,6 ACKs	λ ≤ 0,76	λ ≤ 0,5

Performance evaluation (Results)

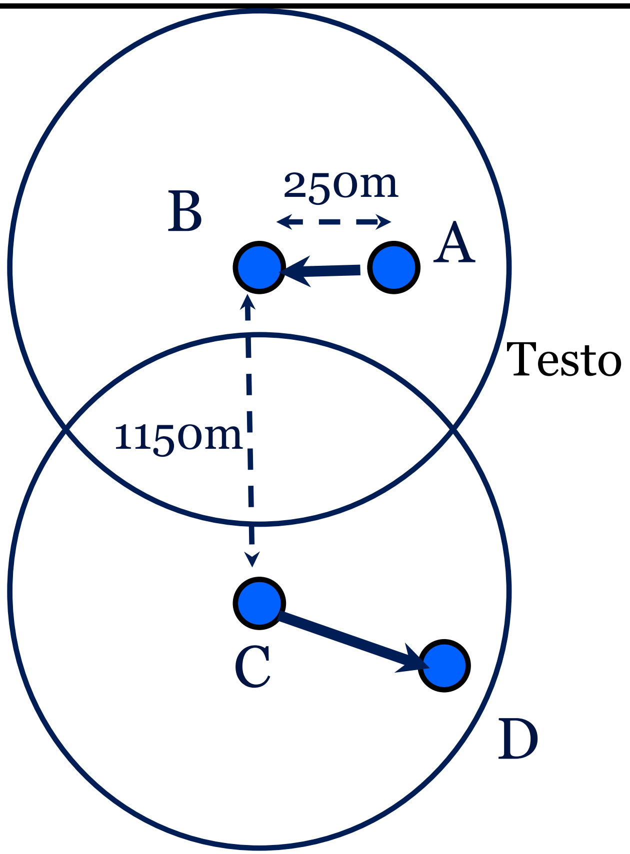
Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps	λ ≤ 1	λ ≤ 0,5 no ACKs λ ≤ 0,27 ACKs	λ ≤ 0,03 no ACKs λ ≤ 1 ACKs	λ ≤ 0,03 no ACKs λ ≤ 0,35 ACKs	λ ≤ 0,06	λ ≤ 0,2
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps	λ ≤ 1,2	λ ≤ 0,6 no ACKs λ ≤ 0,3 ACKs	λ ≤ 0,6 no ACKs λ ≤ 1,1 ACKs	λ ≤ 0,3 no ACKs λ ≤ 0,6 ACKs	λ ≤ 0,76	λ ≤ 0,5

Effects of physical level interference

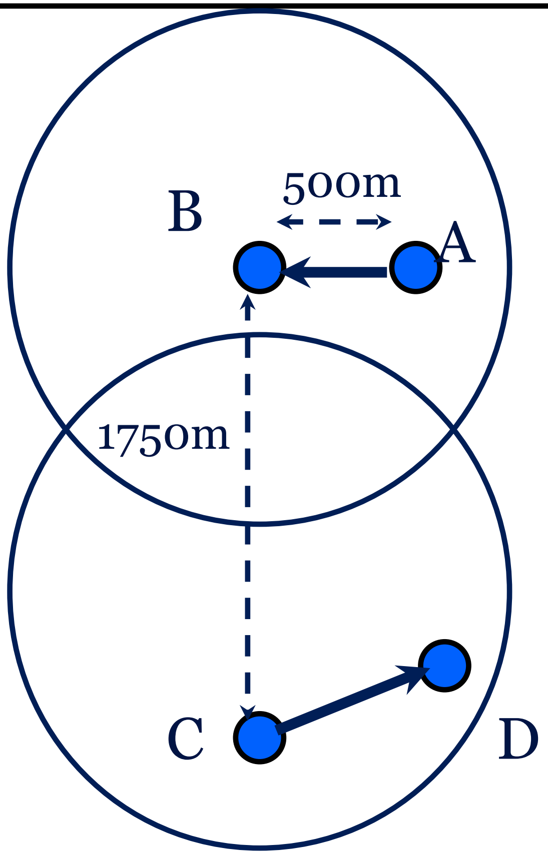


A is sending data to B
C is sending data to D
d(A,B) = 250m
d(C,B) ≤ 1150m

If while B is receiving the packet from A, it is reached by the signal transmitted by C, both packets have to be discarded

Multi-hop scenarios

Effects of physical level interference

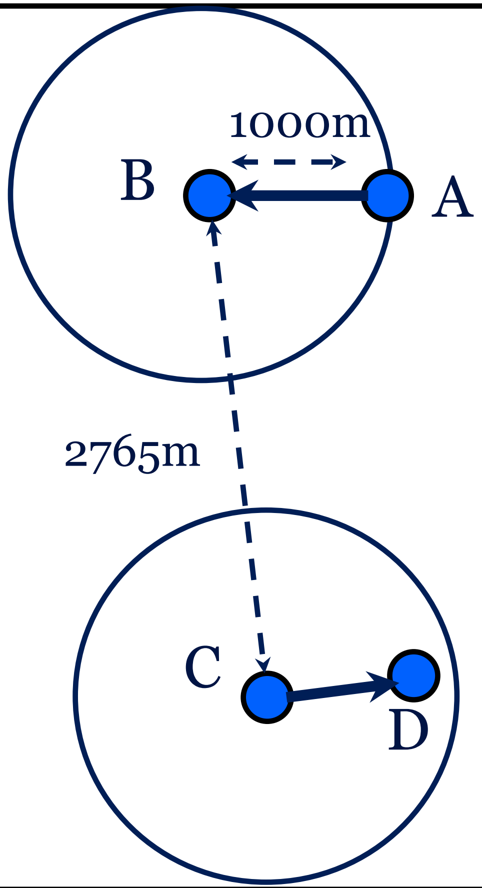


A is sending data to B
C is sending data to D
d(A,B) = 500m
d(C,B) ≤ 1750m

If while B is receiving the packet from A, it is reached by the signal transmitted by C, both packets have to be discarded

Multi-hop scenarios

Effects of physical level interference



A is sending data to B
C is sending data to D
d(A,B) = 1000m
d(C,B) ≤ 2765m

If while B is receiving the packet from A, it is reached by the signal transmitted by C, both packets have to be discarded

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP
100% Data delivery 2000bps	-	-	-	-	-
		-	$\lambda \leq 0{,}05$ ACKs	$\lambda \leq 0{,}05$ ACKs	
100% Data delivery 28000bps					
more than 90% data delivery 2000bps					
more than 90% data delivery 28000bps					

sunrise

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP
100% Data delivery 2000bps	-	- -	- $\lambda \leq 0,05$ ACKs	- $\lambda \leq 0,05$ ACKs	-
100% Data delivery 28000bps					
more than 90% data delivery 2000bps	-	- -	- $\lambda \leq 0,075$ ACKs	- $\lambda \leq 0,08$ ACKs	-
more than 90% data delivery 28000bps					

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP
100% Data delivery 2000bps	-	-	-	-	-
		-	λ ≤ 0,05 ACKs	λ ≤ 0,05 ACKs	
100% Data delivery 28000bps	-	-	-	-	-
		λ ≤ 0,07 ACKs	λ ≤ 0,33 ACKs	λ ≤ 0,33 ACKs	
more than 90% data delivery 2000bps	-	-	-	-	-
		-	λ ≤ 0,075 ACKs	λ ≤ 0,08 ACKs	
more than 90% data delivery 28000bps					

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	CSMA	SLOTTED CSMA	APCAP
100% Data delivery 2000bps	-	- -	- λ ≤ 0,05 ACKs	- λ ≤ 0,05 ACKs	-
100% Data delivery 28000bps	-	- λ ≤ 0,07 ACKs	- λ ≤ 0,33 ACKs	- λ ≤ 0,33 ACKs	-
more than 90% data delivery 2000bps	-	- -	- λ ≤ 0,075 ACKs	- λ ≤ 0,08 ACKs	-
more than 90% data delivery 28000bps	λ ≤ 0,13	λ ≤ 0,11 no ACKs λ ≤ 0,11 ACKs	λ ≤ 0,13 no ACKs λ ≤ 0,33 ACKs	λ ≤ 0,13 no ACKs λ ≤ 0,33 ACKs	λ ≤ 0,12

Towards adaptive, cross layer network protocols

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

- They must be lightweight
- To optimize trade-offs among PDR, energy consumption, latency→ They should be adaptive

Cross-layering approaches needed to account also for e.g., channel quality in making decisions on relay selection

http://senseslab.di.uniroma1.it/administrator/components/com_jresearch/files/publications/CARP_A_Channel_aware_Routing_P.pdf

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.

sunrise

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.

sunrise

CARP description

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.

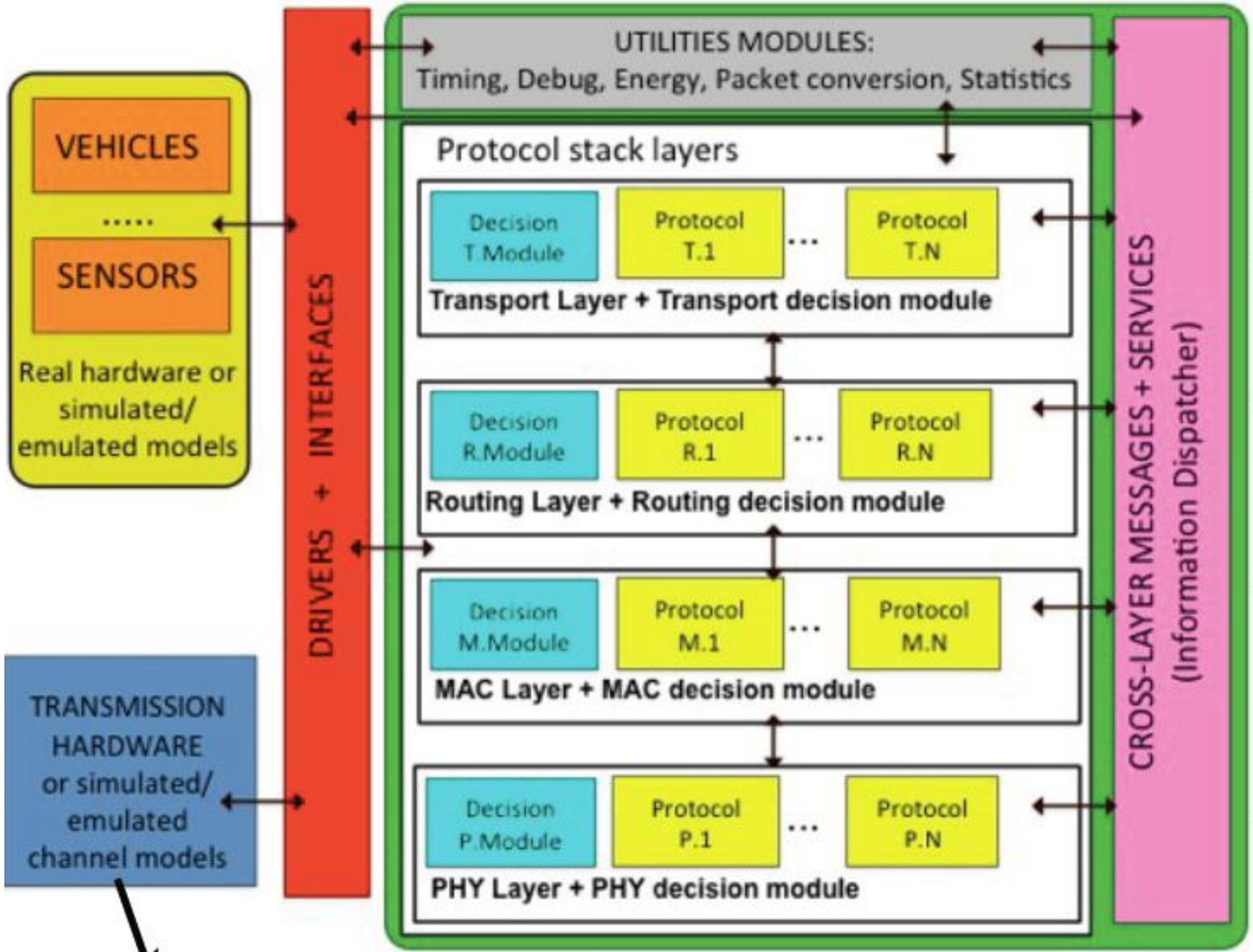
sunrise

sunrise

SUNSET simulations

- SUNSET has been the first solution extending the well know network simulator ns-2 to perform simulation, emulation and in field 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, Applicon)
  - Underwater robots (eFolaga, MARES, LAUV), surface vehicles
  - Sensing platforms (CO2, CH4, Temperature, ADCP, Pressure, PH, etc.)
- PC and small, energy efficiency embedded devices (Gumstix, BeagleBone, IGEP, and different other embedded platforms,..)

SUNSET simulation/emulation environment



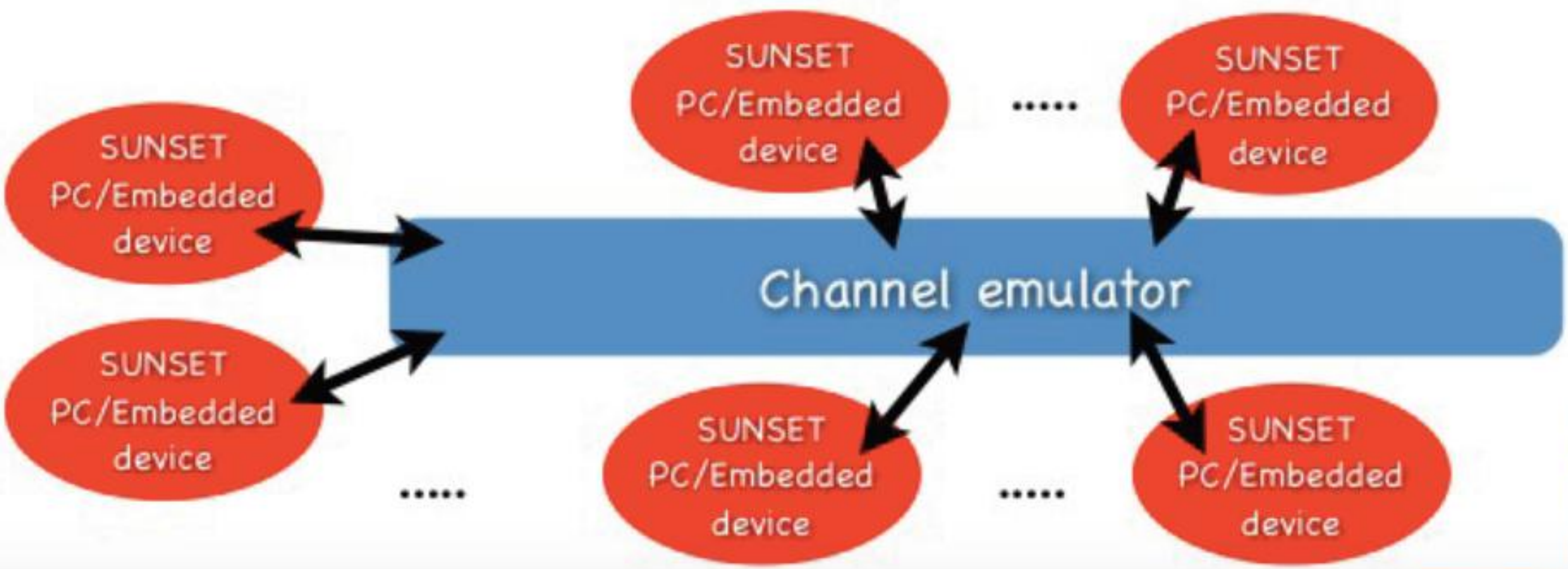
Urick, Bellhop, channel replay, modems, emulators

- 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

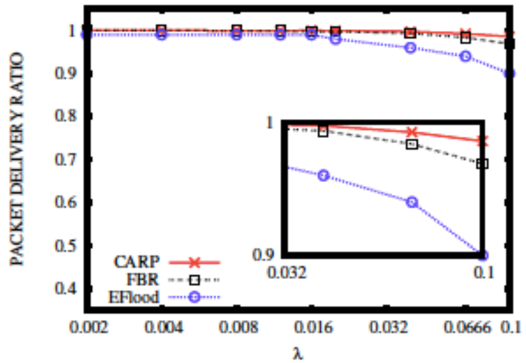
sunrise

Channel emulator

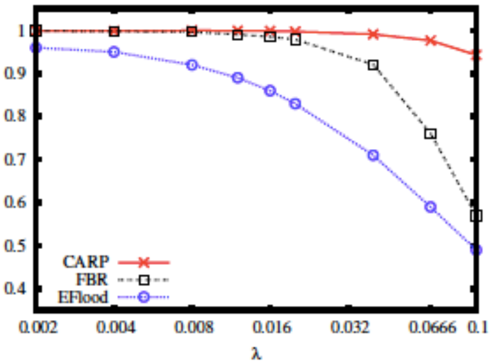
- Introduce propagation delays according to node distance
- Support node mobility
- Different topologies and acoustic channels can be configured and tested
- Protocol solution can be tested running on real hardware (PC, embedded devices and others), as it would happen during in field tests



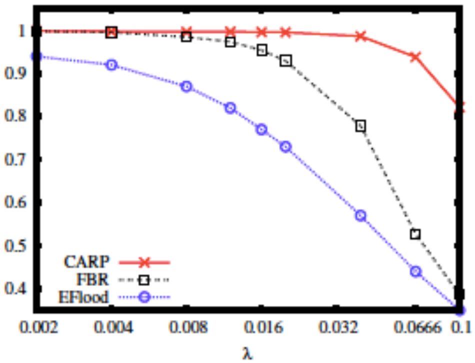
CARP Simulations



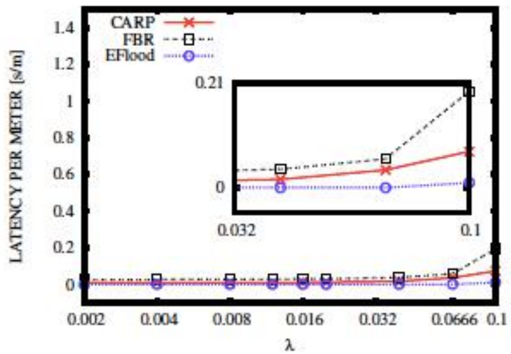
(a) Payload of 100B.



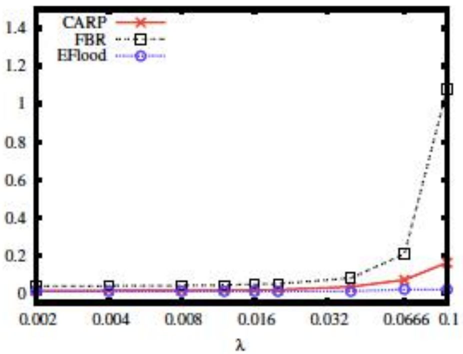
(b) Payload of 512B.



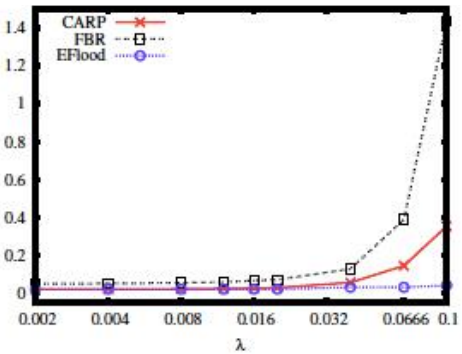
(c) Payload of 1000B.



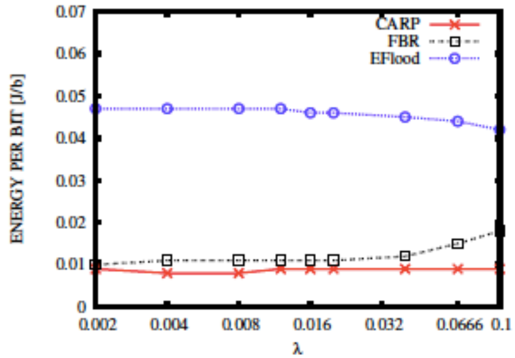
(a) Payload of 100B.

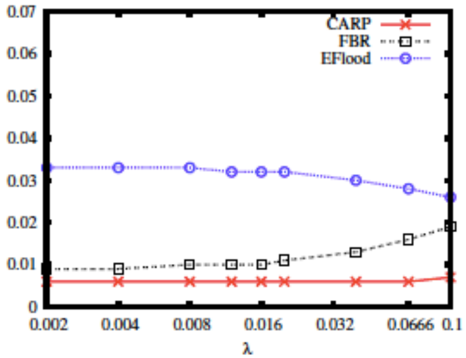


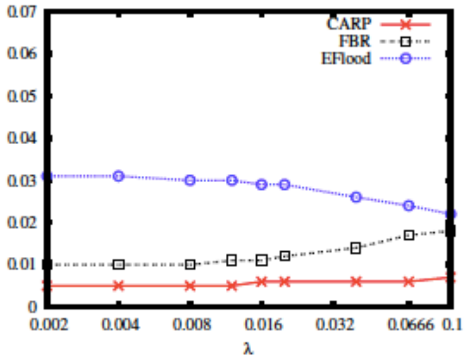
(b) Payload of 512B.



(c) Payload of 1000B.

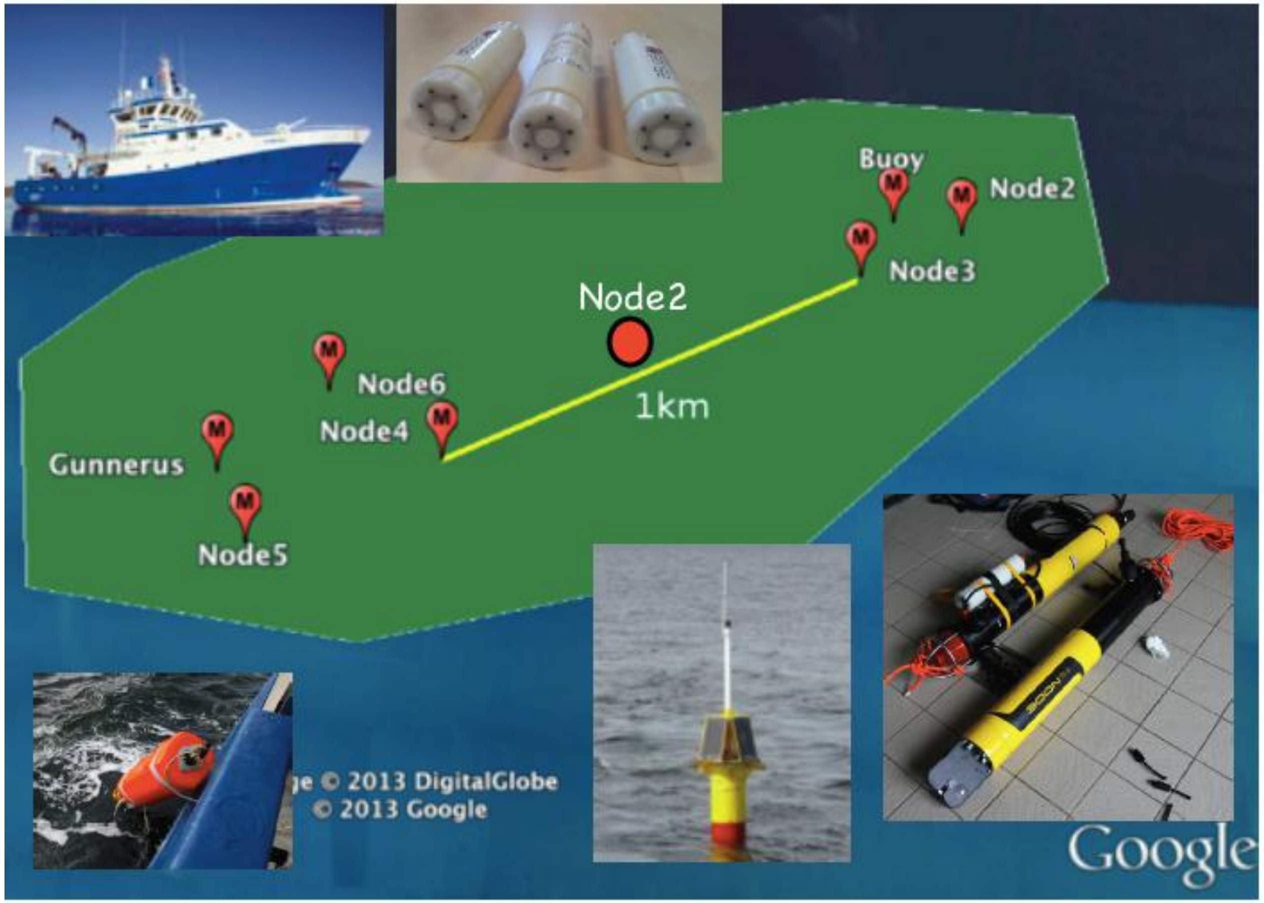






sunrise

Experiments in Trondheim



More than 50.000 packets transmitted during the trial.

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

Experiments in Trondheim

	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%	-

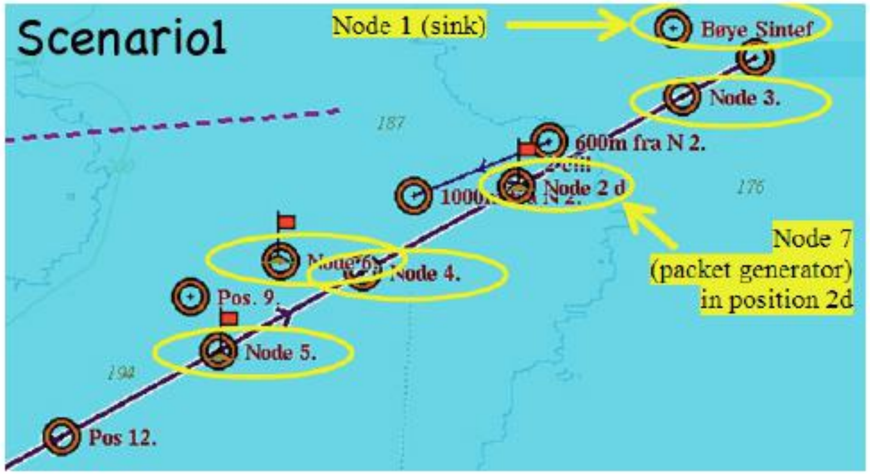
(b) Morning May 31.

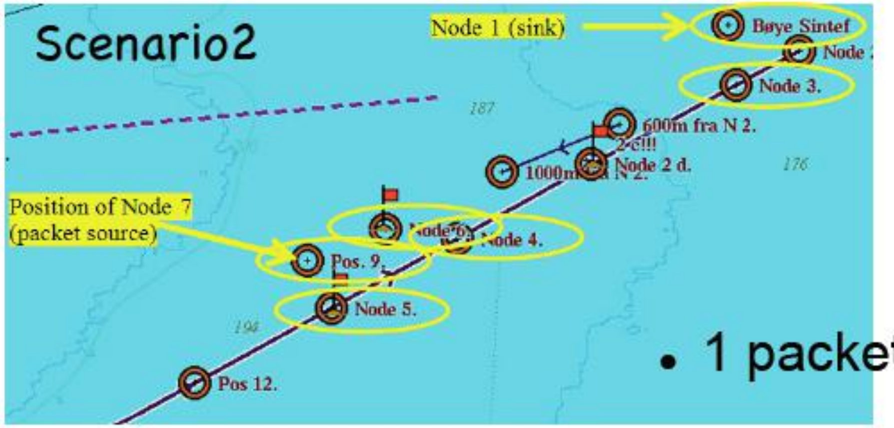
	1	3	4	5	6
1	-	40%	42%	50%	67%
3	100%	-	0%	83%	0%
4	66%	11%	-	0%	72%
5	52%	52%	0%	-	54%
6	82%	23%	76%	54%	-

(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

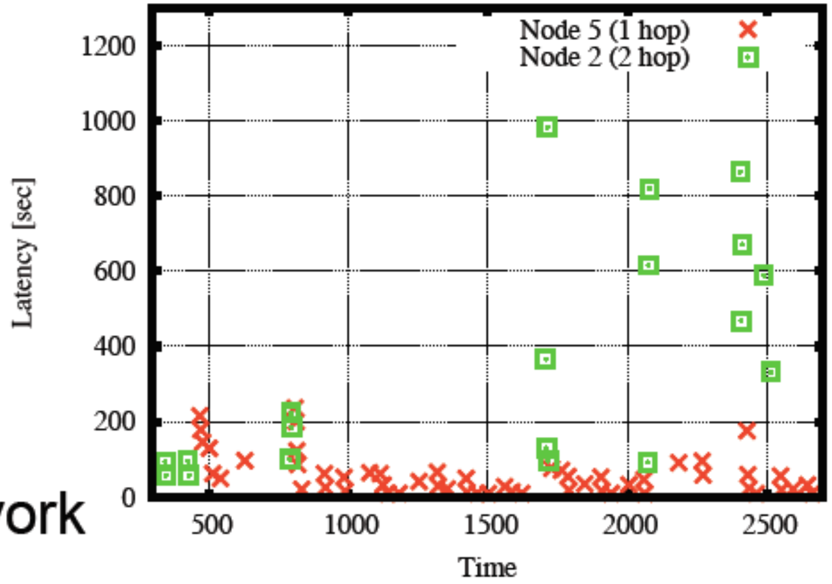
Bit rate 200 bit/s. Payload size: 48 bytes. Two nodes selected as data packets generators (one node at 1 hop and one node at 2 hops).

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

sunrise

Experiments in Palmaria

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.

sunrise

CARP evaluation in Palmaria

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

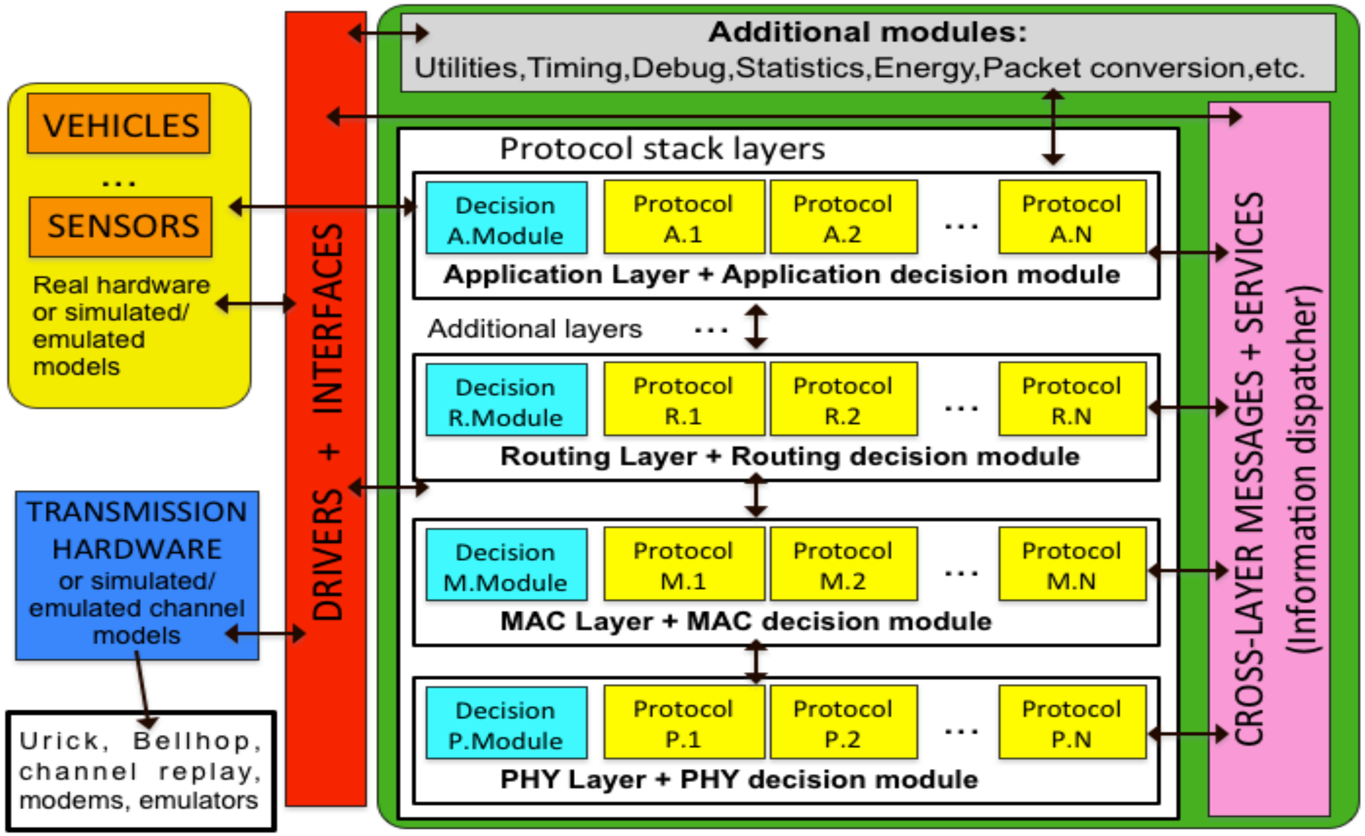
	CARP	EFLOOD
PDR [%]	96	96
Average Delay [s]	37	9
Route length [hops]	1.35	1.6
Energy Eff [J/b]	0.04	0.064

- 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

sunrise

Software defined communication stack



Adaptive schemes (changing protocol operations depending on channel
And application requirements achieve high packetd elivery ratio, low
Latency and energy consumption!)