Underwater Wireless Sensor Networks

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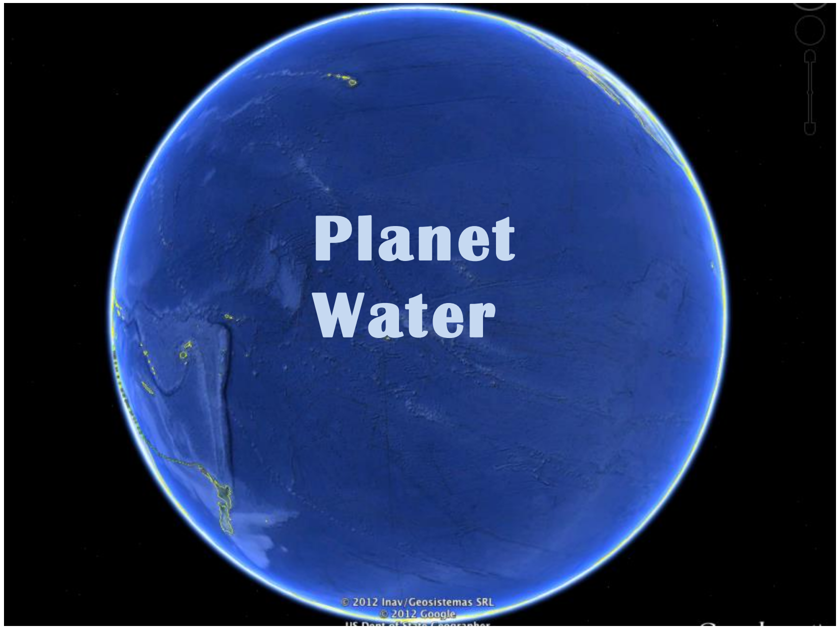
Outline

- Underwater Wireless Sensor Networks (UWSNs):
  - Motivation and applications.
- Physical Layer properties.
- Challenges at MAC and Routing Layer
  - New protocols and methods to handle channel dynamics.

Why should we care about underwater exploration?

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.

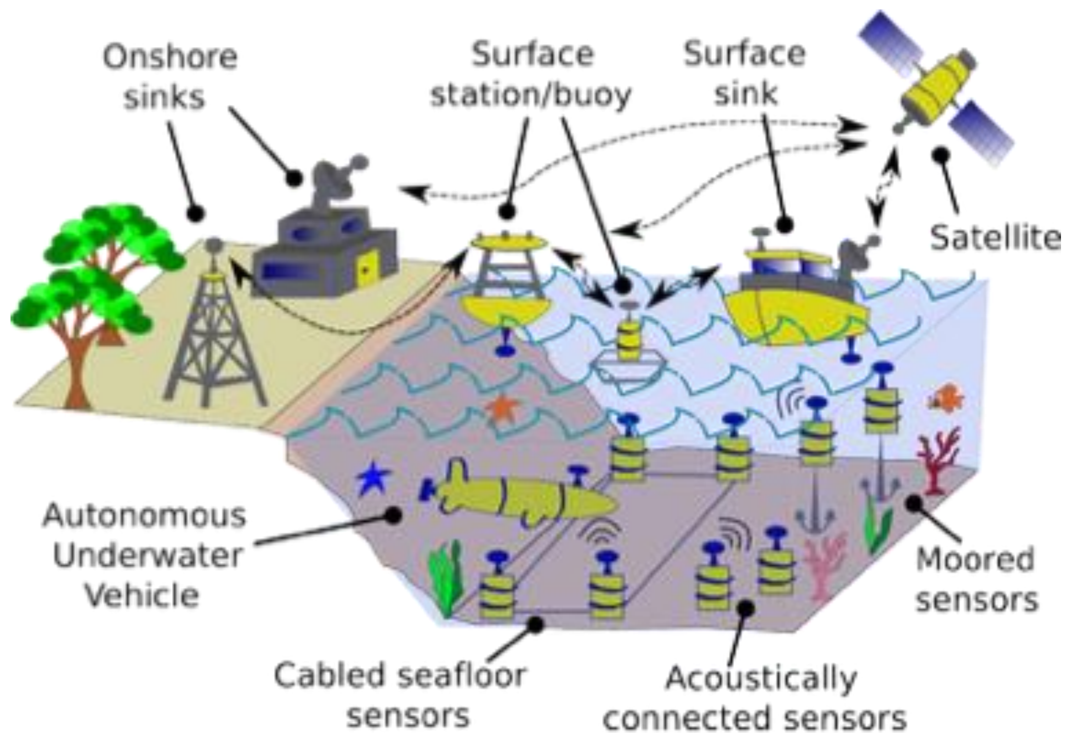


Underwater Wireless Sensor Networks

Underwater Wireless Sensor Networks (**UWSNs**) consist of a set of sensors and vehicles, deployed in an underwater environment, that communicate wirelessly to perform collaborative tasks.

Enables:

- Real-Time monitoring.
- Remote Configuration.
- Interactions with on-shore human operators!

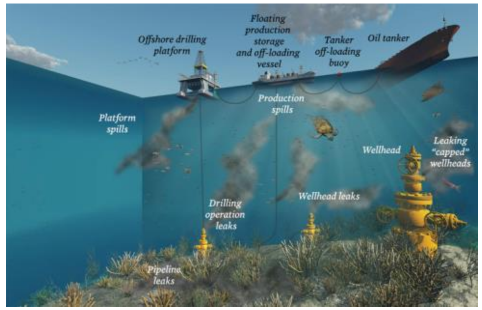


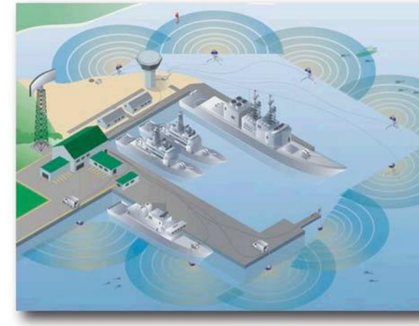
Applications

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

Oil and gas

Coastline and border protection

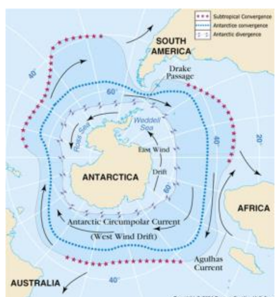




Environmental monitoring

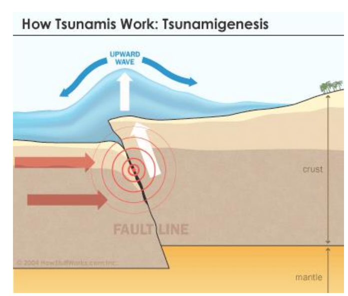
Temperature and salinity

Waves and currents



Volcanoes and earthquakes

Tsunami alert

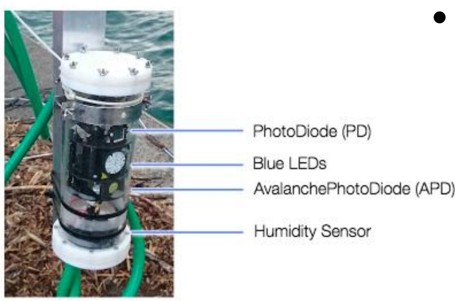


Biodiversity monitoring

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

Acoustic vs Radio vs Optic Waves

- Radio Waves
  - Propagate at long distances only at extra low frequencies (30-300Hz)
    - Large antennas and high transmission power!
  - High frequency -> short transmission range (~120 cm @443Mhz, ~1 cm @2.4Ghz WiFi).

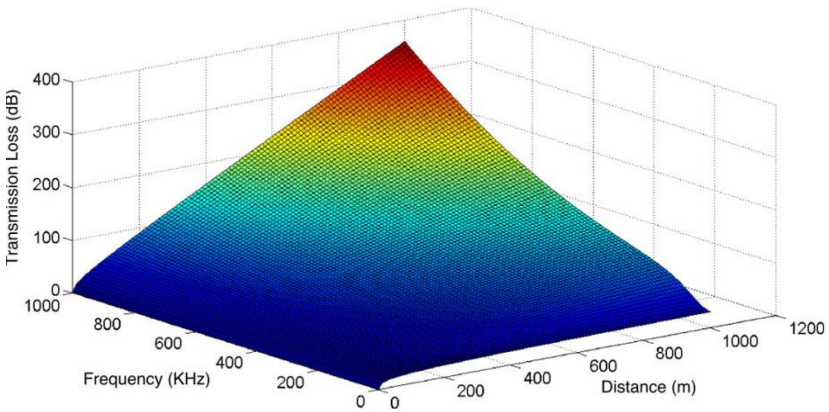


- Optical Waves
  - High data rate (up to 10Mbps).
  - Short range, e.g., 10 meters.
  - Requires high precision in pointing the narrow laser beam.

- **Acoustic Communication**
  - Long range, up to several kilometers.
  - Low data rate (80bps – 64kbps).

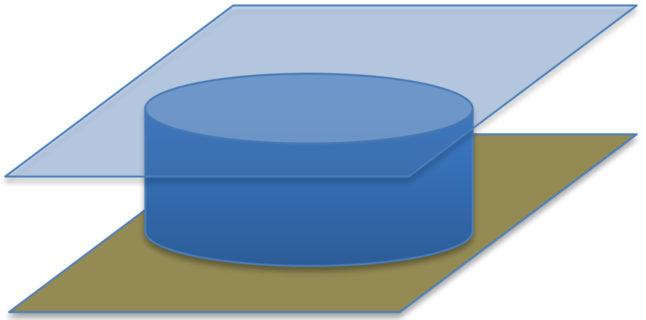
Factors Influencing Acoustic Communications

- Transmission Path Loss (TS) (loss of intensity of acoustic waves)
  - Attenuation
    - Provoked by absorption due to conversion of acoustic energy into heat, also scattering, reverberation, refraction and dispersion.
    - **Increases with varying frequency and distance.**
  - Geometric Spreading (divergence effect)
    - Spreading of sound energy as a result of the expansion of the wave-fronts.
    - **Increases with distance and independent of frequency.**
    - Beyond a given distance, waves attenuate according to a **cylindrical** propagation.



TL = 20 * Log(d) + α(f) * d + A + Noise (f)

Geometric spreading — Absorption — Multipath



M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," in *IEEE Communications Magazine*

Factors Influencing Acoustic Communications

- Noise
  - Man Made Noise
    - Machinery noise (pumps, reduction gears, power plant) and shipping activity.
  - Ambient Noise
    - Hyrodynamics(currents, storms, etc), seismic, and biological phenomena.

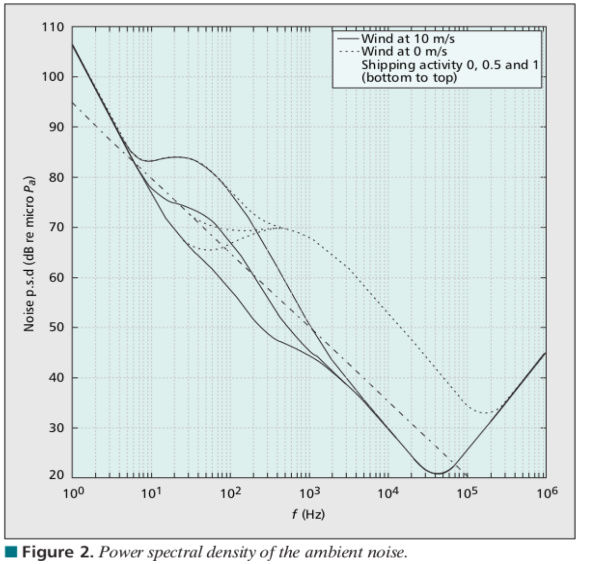
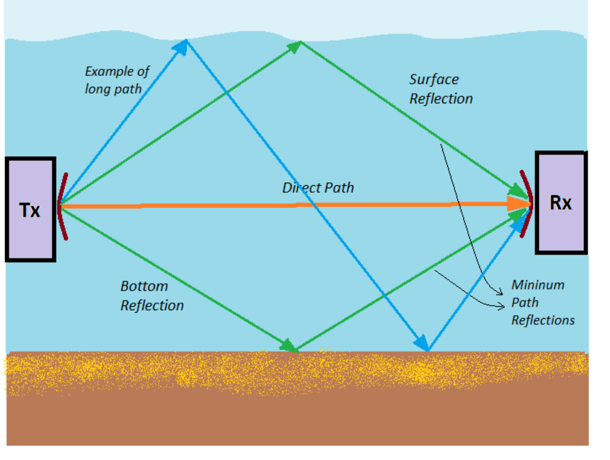


Figure 2. *Power spectral density of the ambient noise.*

- Multipath-Propagation
  - Generates Inter-Symbol-Interference, especially in shallow waters.

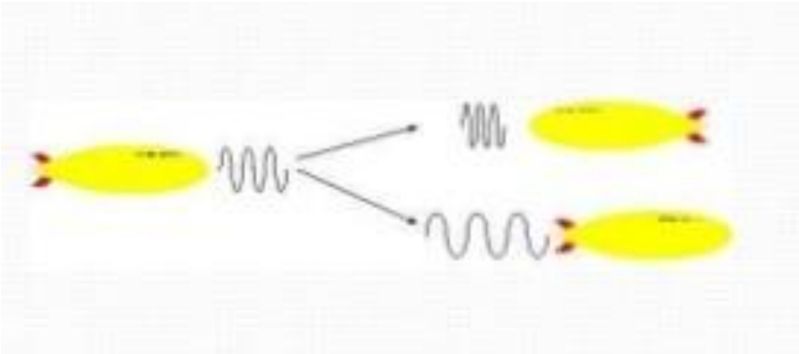


Shallow water: Multipath gets attenuated because of repeated reflection loss, increased path length.

Factors Influencing Acoustic Communications

- High Delay and Delay Variance
  - The propagation speed in Underwater Acoustic Channel **is five orders of magnitude lower** than the speed of light in radio comms (1500 m/s).
  - Long propagation delays.

- Doppler distortion
  - Can be significant in underwater channel and causes ISI.



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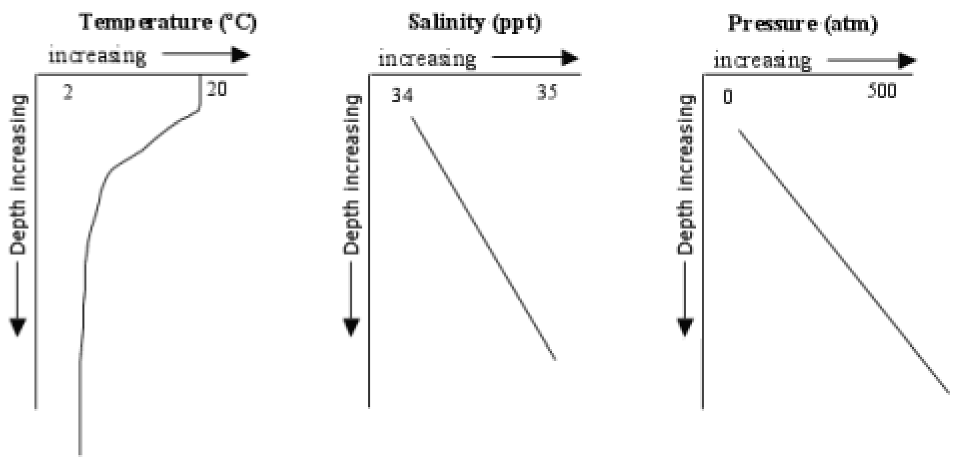
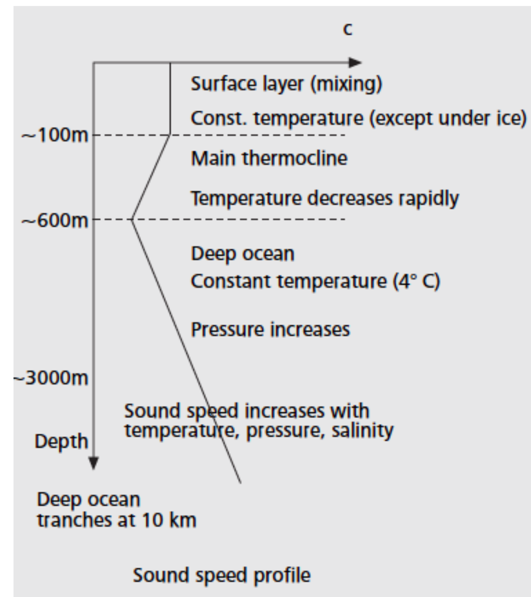
Wave propagation

SOUND SPEED PROFILE

- Acoustic waves travel at different speed at different depths.
- It is a function of pressure, temperature, and salinity.
- The sound velocity increases with the increase of temperature, pressure, salinity.





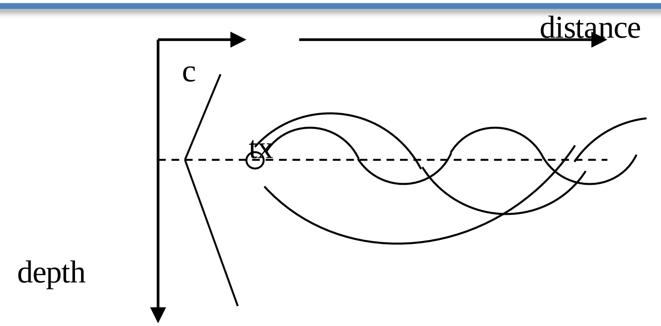
- It causes acoustic rays curvature
  - SOUND IS LAZY

Multipath Formation and Shadow Zones

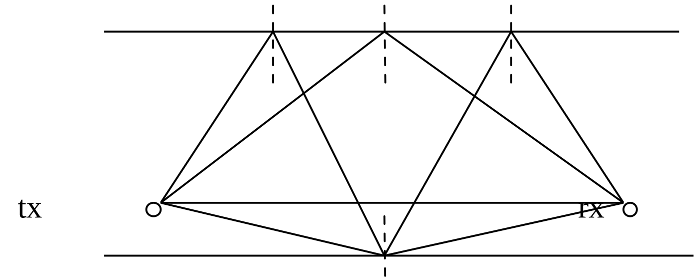
Effects of SOUND SPEED PROFILE

Rays curvature

- Cylindircal propagation: The wave energy, on large scales, spreads in two dimensions instead of three because part of the rays are curved back towards the bottom.
- Sound can travel over long distances in this manner (no reflection loss).
- Shadow-zones.



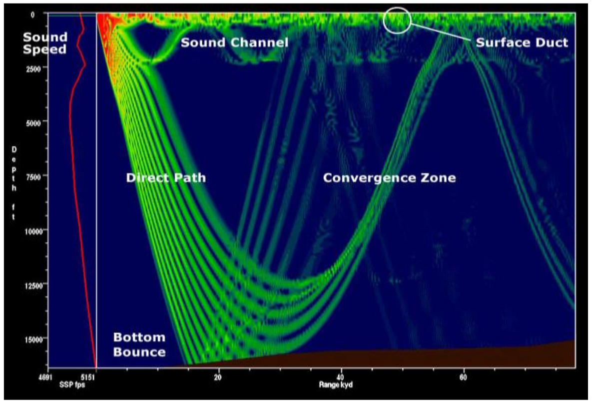
Deep water: a ray, launched at some angle, bends towards the region of lower sound speed (Snell's law).

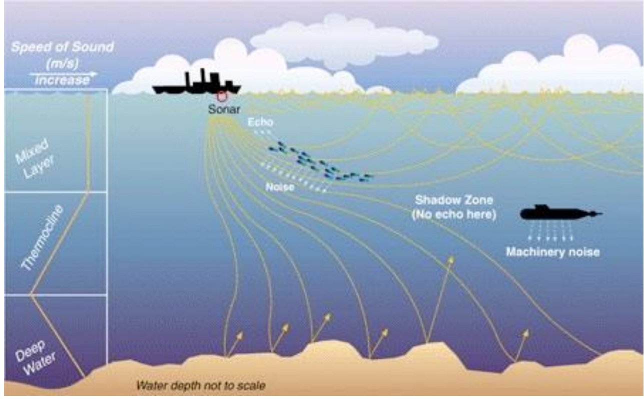


Shallow water: Multipath gets attenuated because of repeated reflection loss, increased path length.

Temporal variability due to:

- Currents.
- Surface waves.

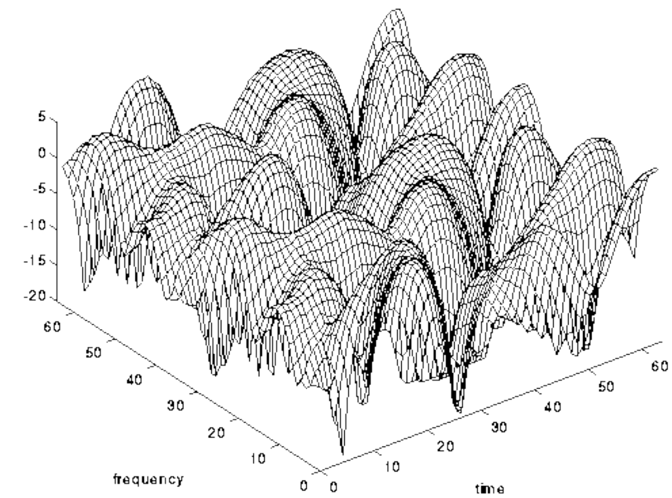


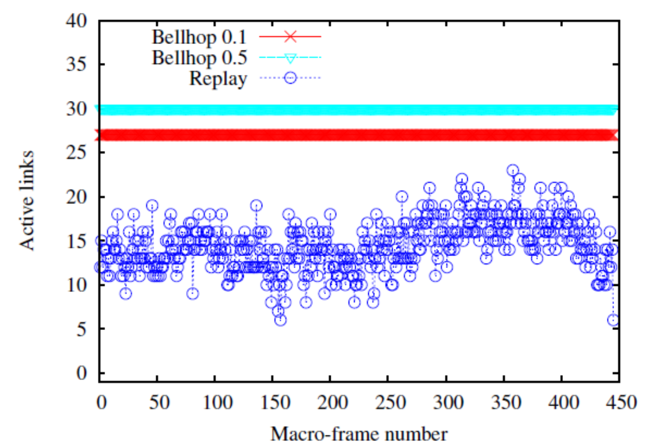


Network challenges

From networking perspective:

- UW acoustic channel presents high variability in the time and frequency domain
  - Very fast varying link quality.
  - Asymmetric links.
- Long interference range, high propagation delays.
- Very limited resources.
- High energy consumption when transmitting, still energy-efficiency is very important (up to 40W vs 0.3 W)
- Statistical characterization of acoustic communication channels still an open issue → not able to accurately predict channel performance as we usually do for terrestrial radio networks.





Active links between ray traced simulations and real-traces.

S. Basagni, C. Petrioli, R. Petroccia and D. Spaccini. «Channel Replay-based Performance Evaluation of Protocols for Underwater Routing» **MTS/IEEE OCEANS 2014**

What collision probability is all about

- In typical wireless networks, propagation time is much smaller than packet transmission time, which makes it easy to manage collisions.
- In UASNs, such time intervals are comparable.

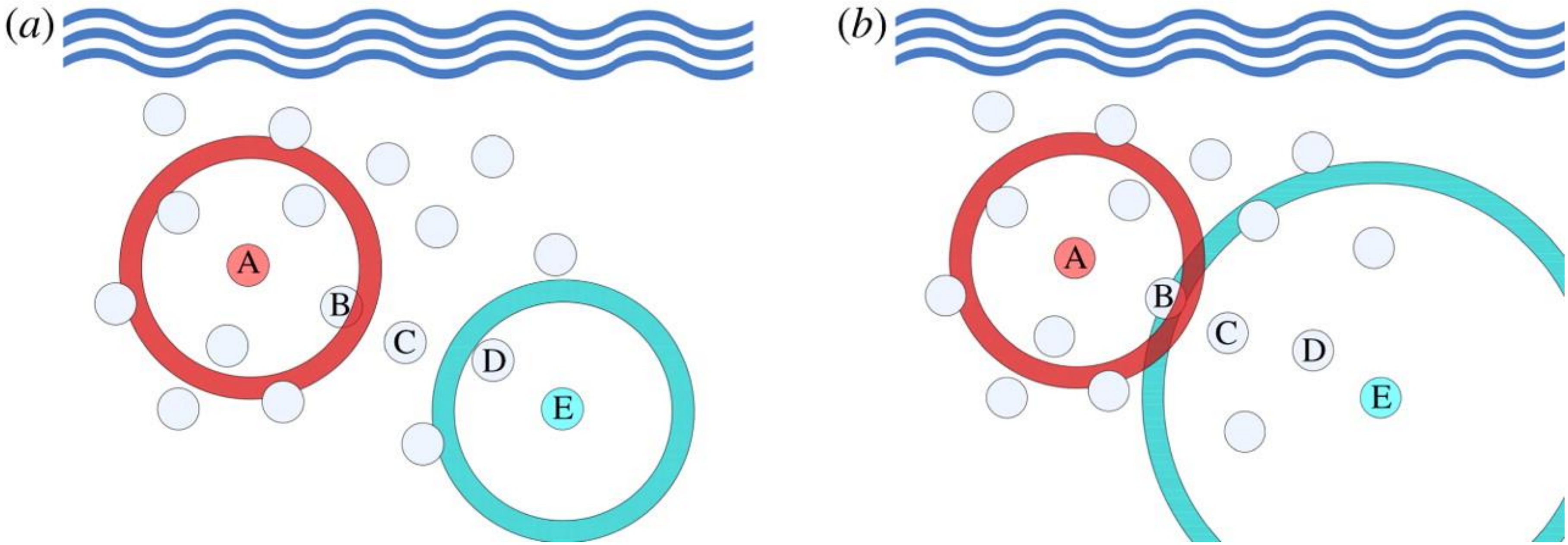


Illustration of space–time volume (Heidemann et al): long acoustic latencies mean that packets from A and E are successfully received at B and D in part (a), even though they are sent concurrently, while in part (b), packets collide at B even though they are sent at different times.

John Heidemann et al. Phil. Trans. R. Soc. A 2012;370:158-175

MAC Protocols

- Frequency Division Multiple Access (FDMA) MACs
  - Not suitable for UWSNs
    - Narrow bandwidth in UW channels.
    - Fading and multipath in spectrum bands.

- Time Division Multiple Acess (TDMA) MACs
  - Not easy to achieve precise synchronization due to variable delays.
  - High propagation delay -> larger guard times -> limited efficiency.

- Carrier Sense Multiple Access (CSMA)
  - Prevents collisions with the ongoing transmission at the transmitter side.

Distance Aware Collision Avoidance Protocol (DACAP)

Random access. Based on RTS-CTS

- 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.

B. Peleato and M. Stojanovic, “Distance aware collision avoidance protocol for ad hoc underwater acoustic sensor networks,” IEEE Commun. Lett., vol. 11, no. 12, pp. 1025–1027, Dec. 2007

DACAP: Basic Operations

- 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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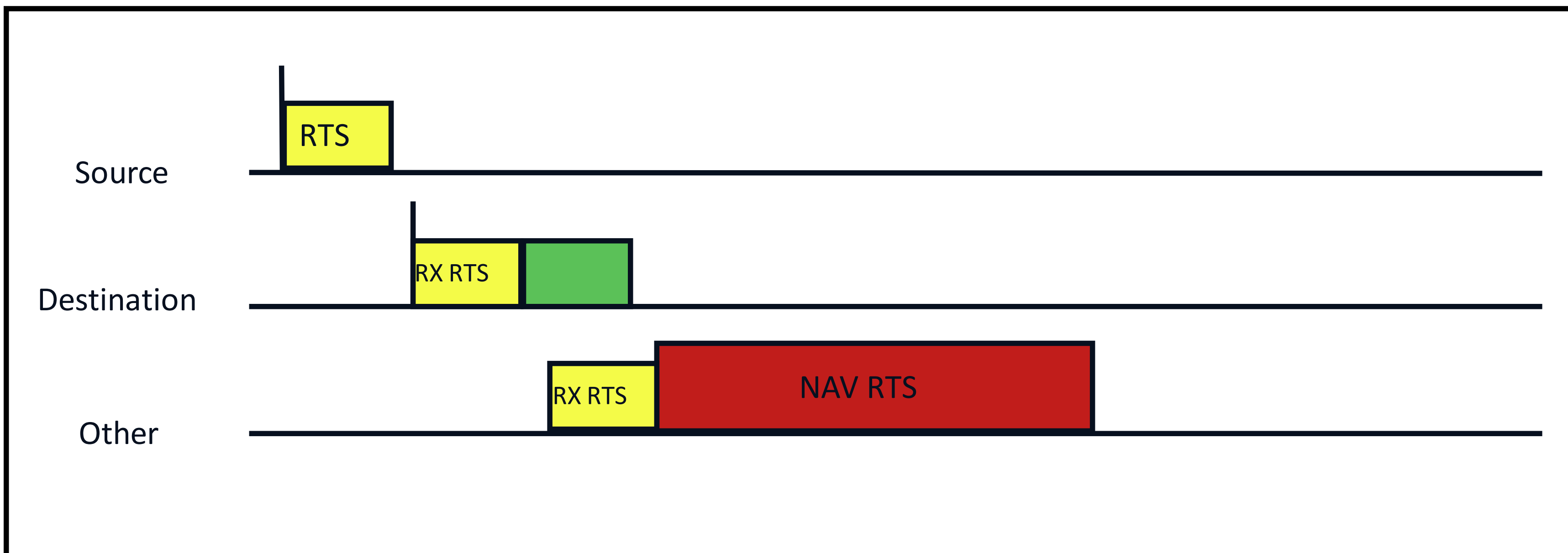

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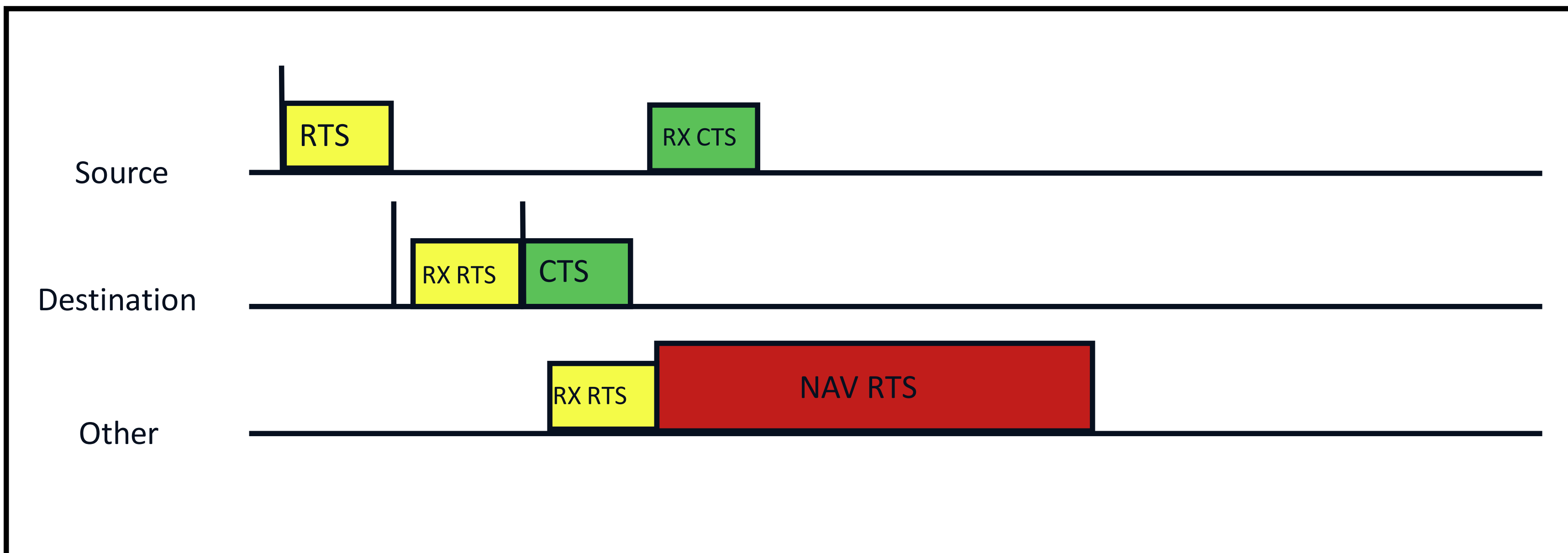

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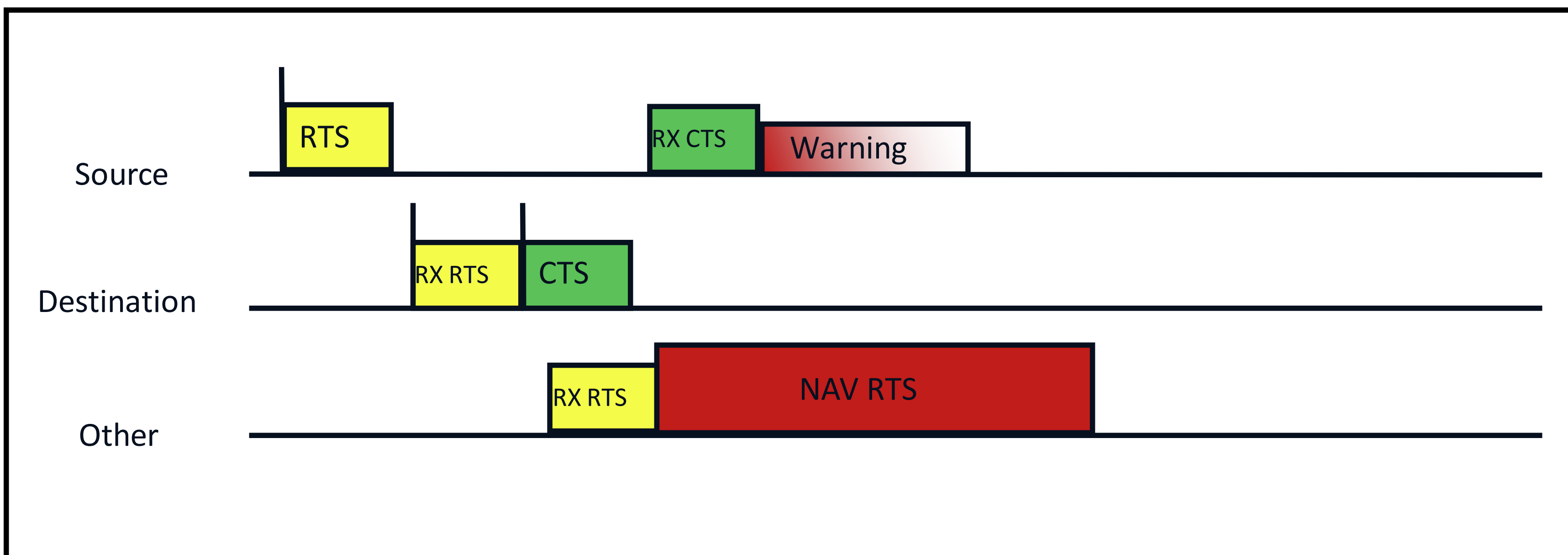

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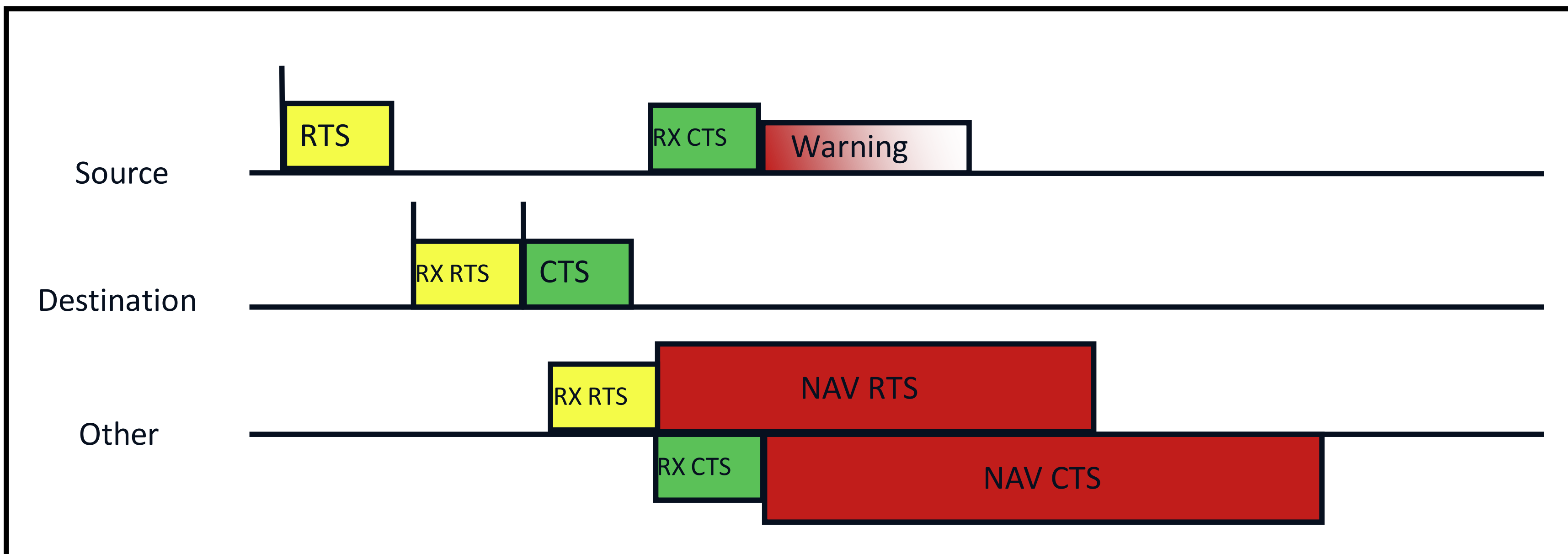

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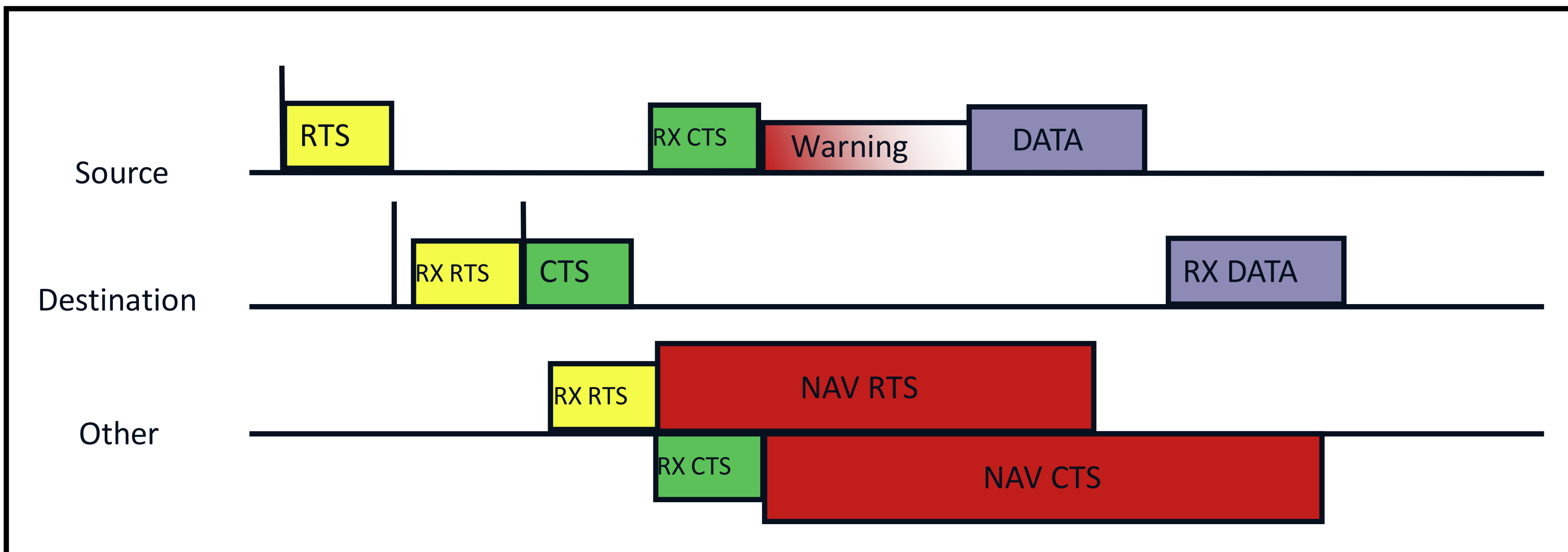

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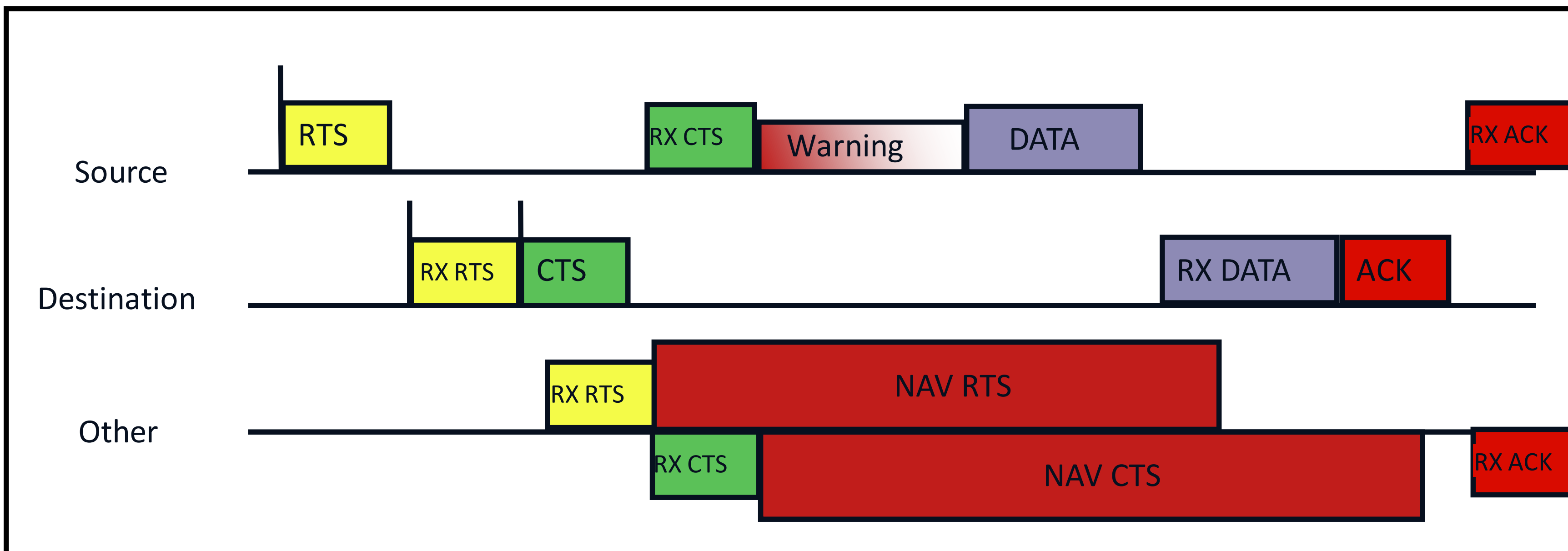
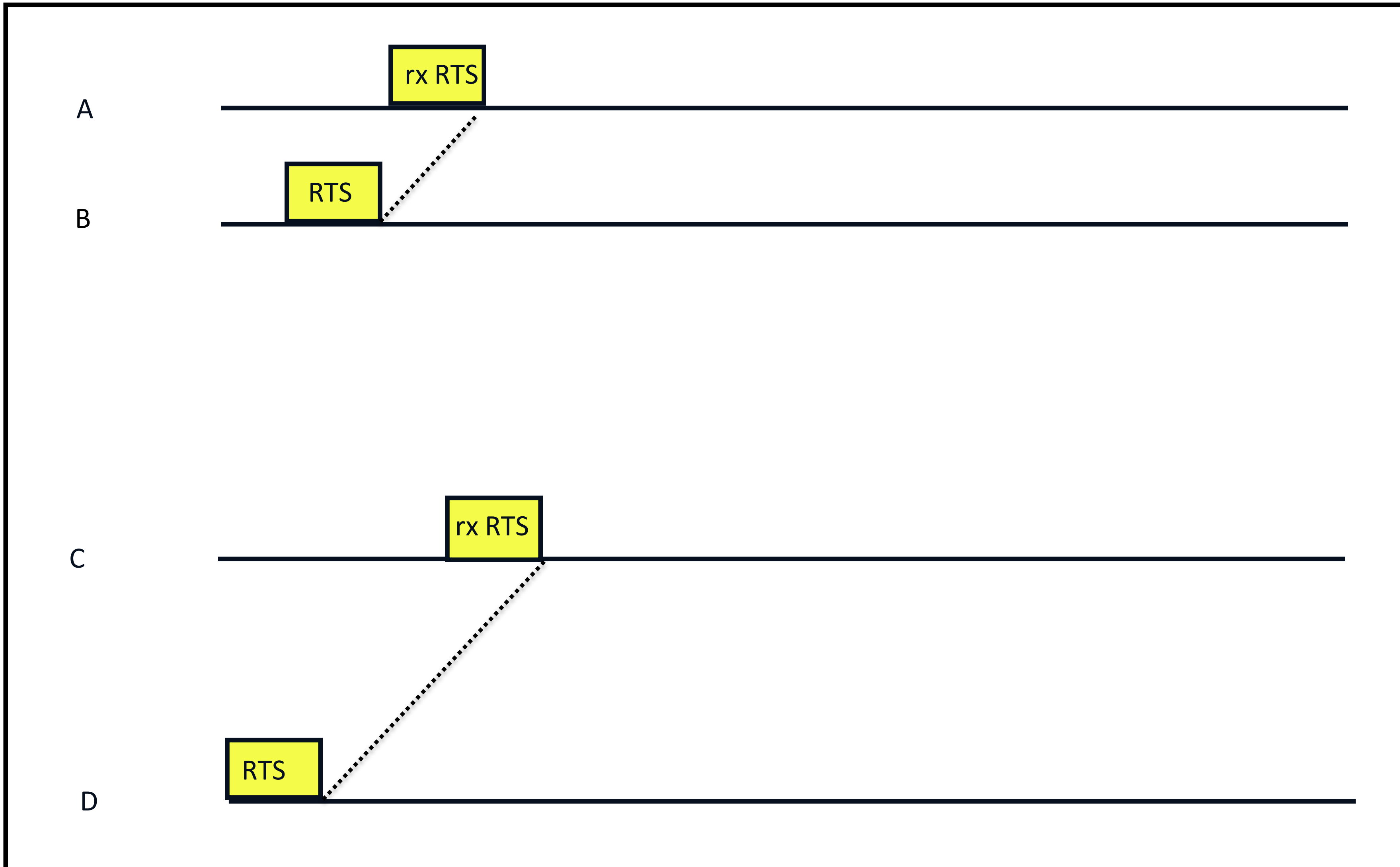


DACAP: Example of Collision Avoidance



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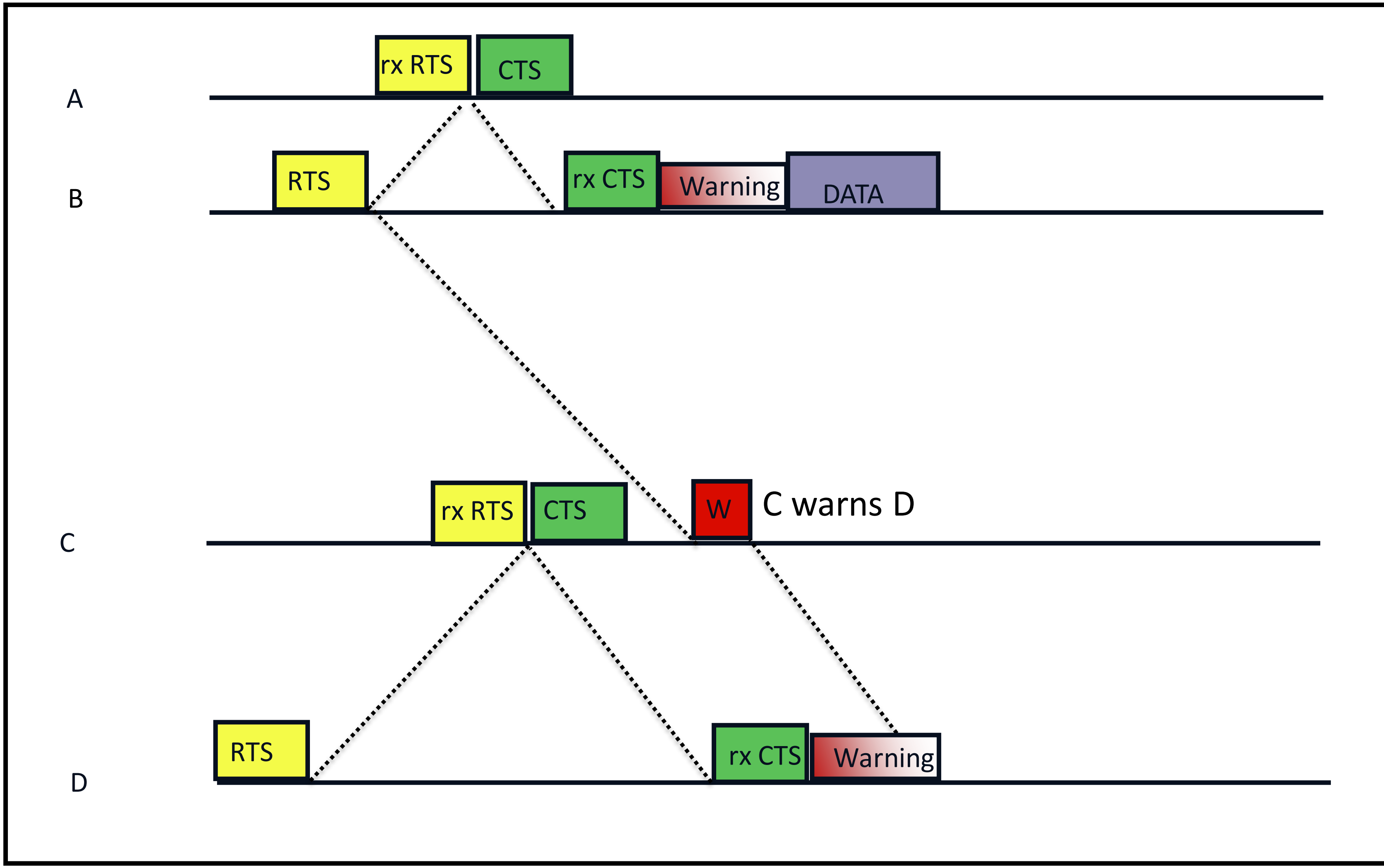

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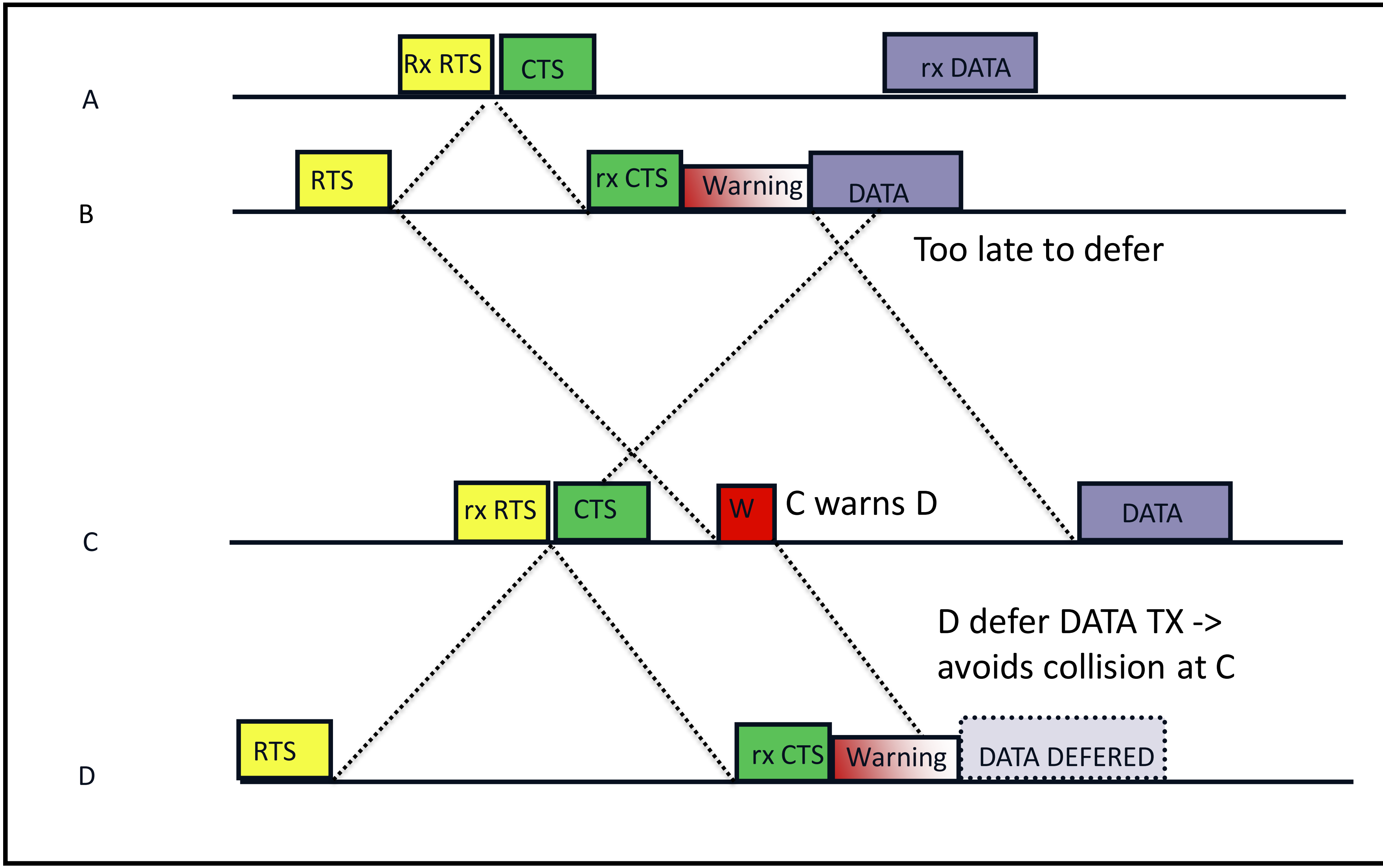
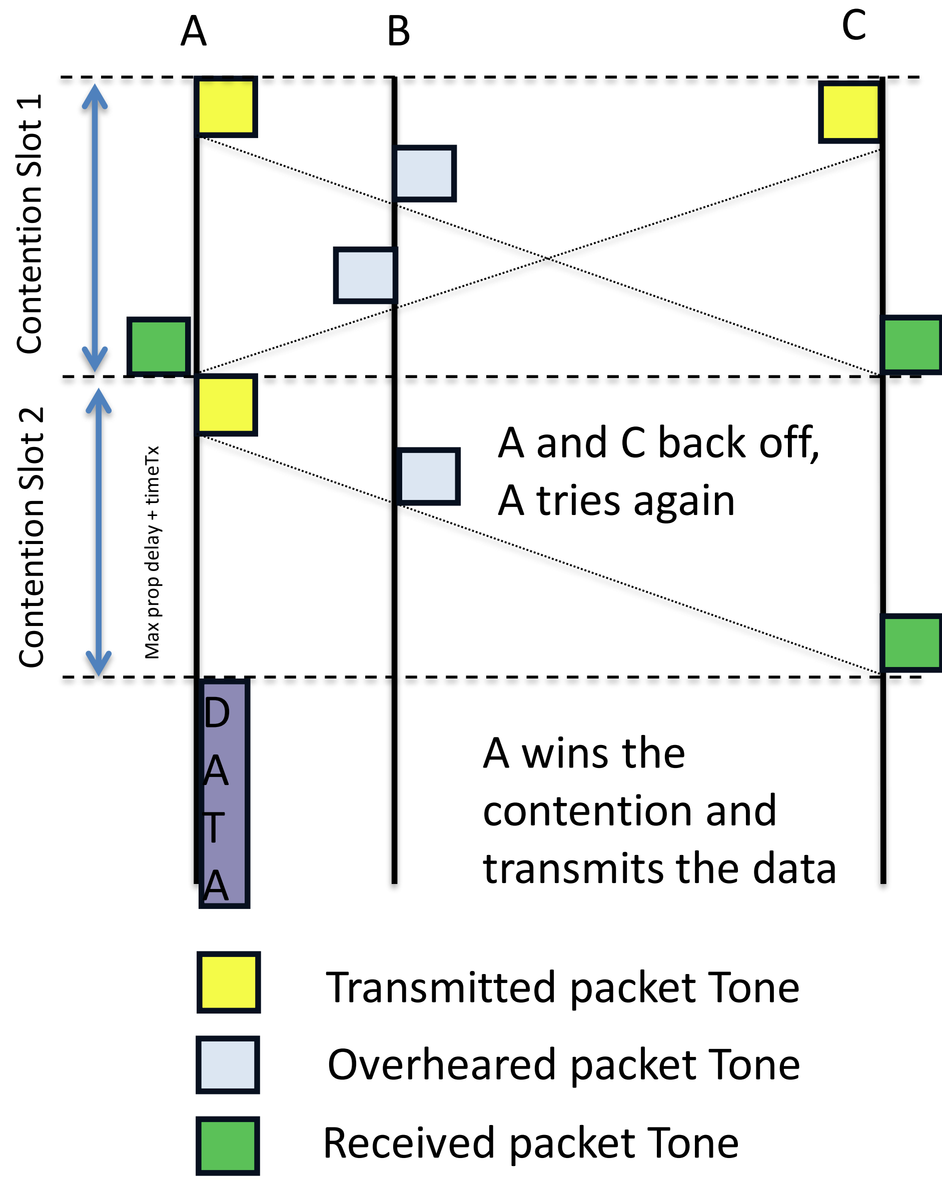


Another MAC for UWSNs: TLohi

- Uses a weak negotiation to reserve the channel.
- Nodes contend for the channel by sending a wakeup tone during a preliminary reservation phase (contains different slots).
- If other transmitters are detected in a CS, a node backs off for a random amount of time(based on the received tones) before sending another tone.
- If no other tones are receved during a CR, the contender node wins the contention.
- Different versions; synchronized, conservative and agressive (based on CS length).



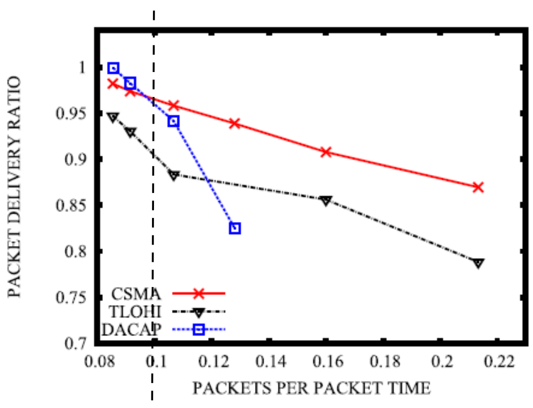
A. A. Syed, W. Ye and J. Heidemann, "T-Lohi: A New Class of MAC Protocols for Underwater Acoustic Sensor Networks," *IEEE INFOCOM 2008*

Does exist a «best» MAC?

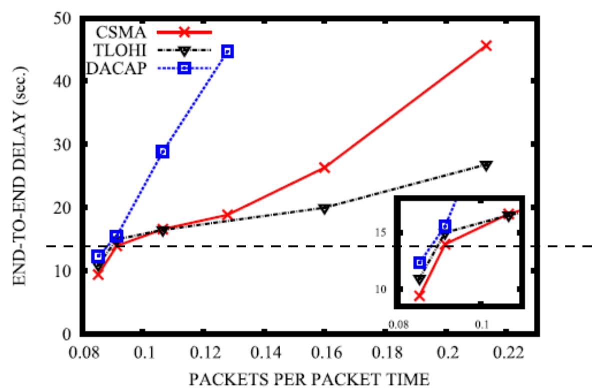
NATO ACommsNet10 Experiment:

- Protocols: CSMA + ACK, DACAP, TLOHI.
- MicroModem: Payload 32B, large transmission time due to modem overhead (about 3sec).
- Stable acoustic links : PER about 17%

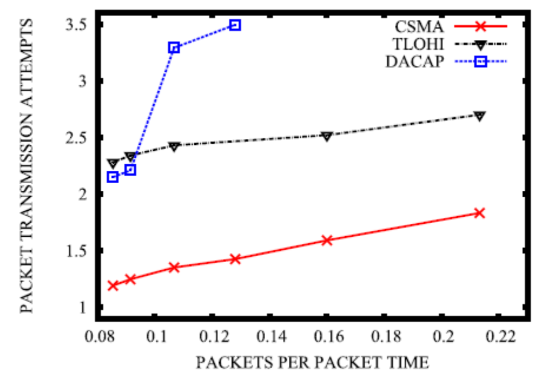
Fig. 1. Static node positions (red icons M1, M2, and M3) and gateway mooring (yellow icons GB).



Packet Delivery Ratio



Latency [sec]



Transmission Attemps

Petroccia R., Petrioli C., Potter J., «Performance Evaluation of Underwater Medium Access Control Protocols: At-Sea Experiments», IEEE JOURNAL OF OCEANIC ENGINEERING, 2017

Does exist a «best» MAC?

NATO CommsNet13 Experiment:

- Protocols: CSMA + ACK, DACAP, TLOHI
- Evologics: Payload 50B, low overhead (about 0.2sec)
- Asymmetric and variable acoustic links

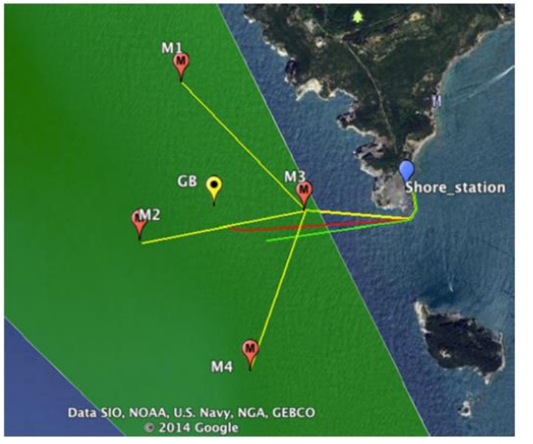
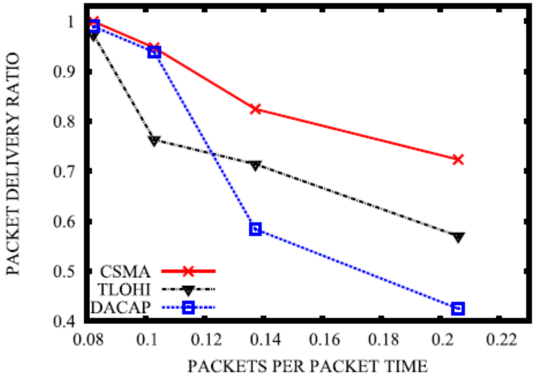


Fig. 4. Modem primary node (red icon M3) and satellite modem node sites (red icons M1, M2, and M4), gateway moorings (yellow icon GB). Shore station was on Palmaria island. The yellow lines represent the cables from the shore station to the modems, while the red line was used to connect environmental sensors.



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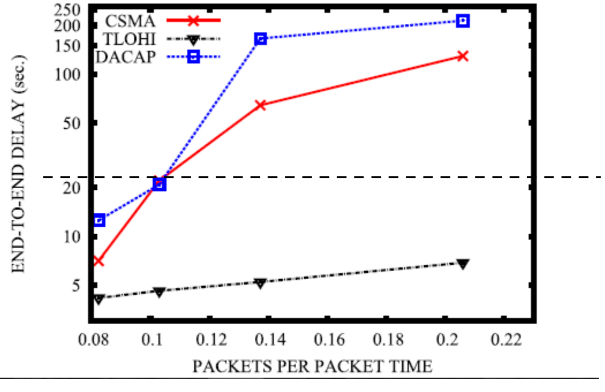

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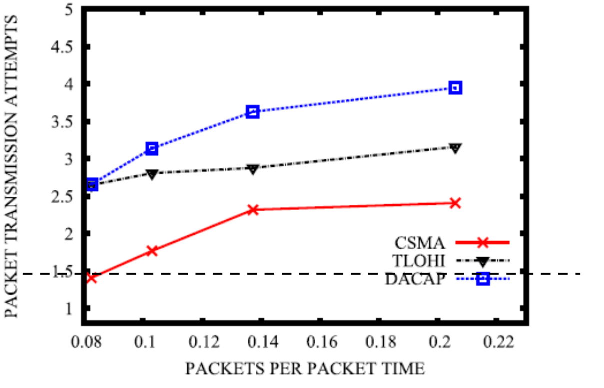

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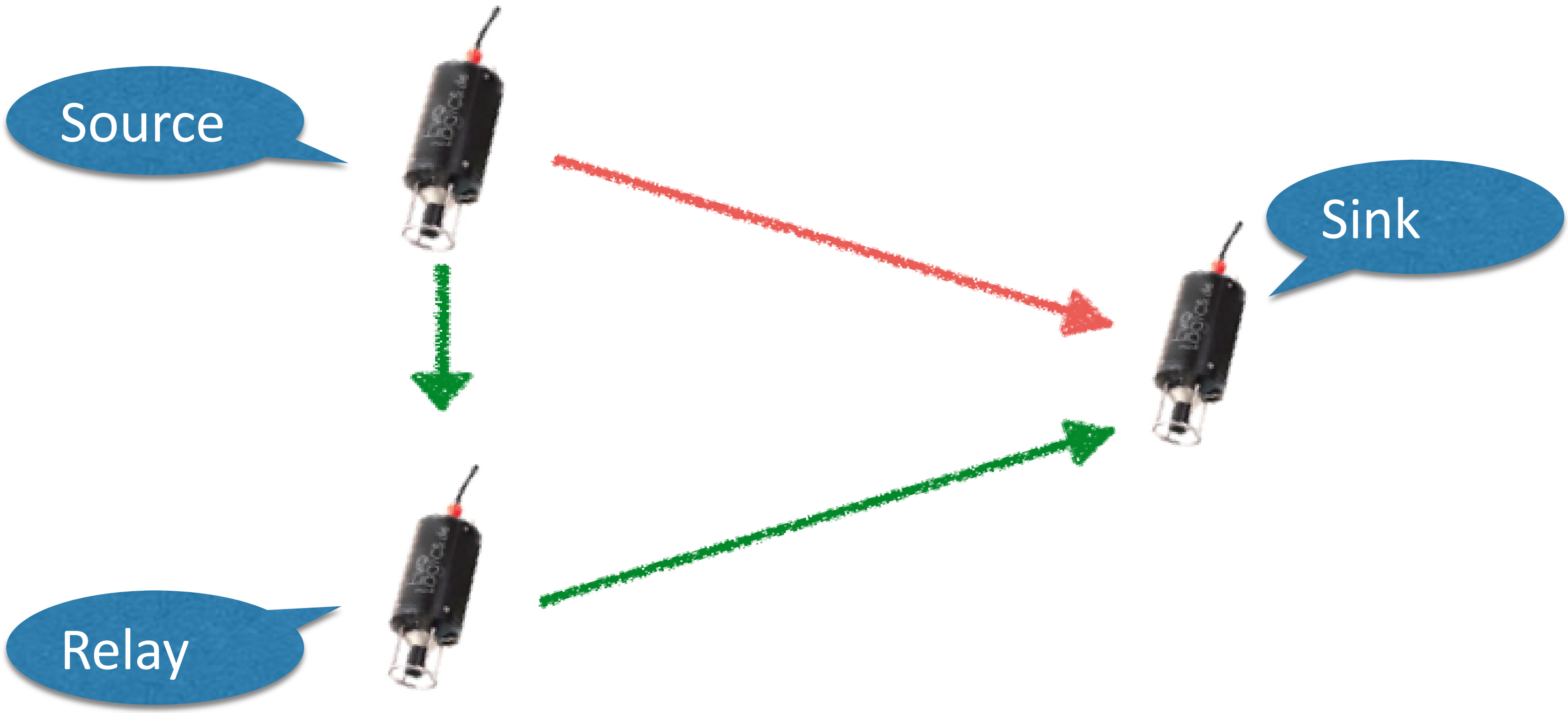
The importance of routing in UWSNs

- Cover large deployment area.
- Multi-hop comms useful also in single-hop networks to improve channel reliability.



Network Layer: State of The Art

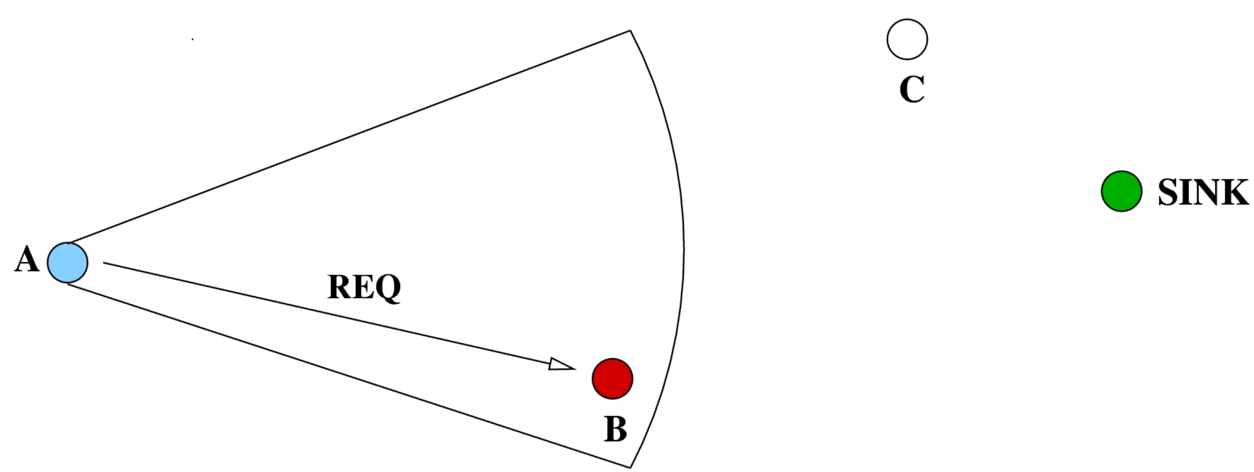
- Proactive routing protocols
  - Dynamic Destination Sequenced Distance Vector (DSDV), Optimizing Link State Routing (OLSR)
  - Not suitable for UW-ASNs
    - Large signaling overhead every time network topology has to be updated
    - All nodes are able to establish a path with others and it is not necessary

- Reactive routing protocols
  - Ad hoc On Demand Distance Vector (AODV) and Dynamic Source Routing (DSR)
  - Not suitable for UW-ASNs
    - It requires flooding of control packets at the beginning to establish paths (excessive signaling overhead)
    - High latency on establishment of paths
    - Must of the reactive protocols rely in symmetrical links

- Routing protocols designed for UWSN
  - Don't offer consistent behavior in different operational scenario
  - Fail to adapt to the ever changing environment

CARP - A new cross-layer solution for UWSNs

- The standard layered approach in protocol stack design is not suitable in underwater environment: A cross layer approach is needed.
- The state-of-art solutions do not consider the quality and the asymmetry of the links.
- Often they 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.



S. Basagni, C. Petrioli, R. Petroccia and D. Spaccini. "CARP: A Channel-aware Routing Protocol for Underwater Acoustic Wireless Networks", **Ad Hoc Networks**, Vol. 34. 2015

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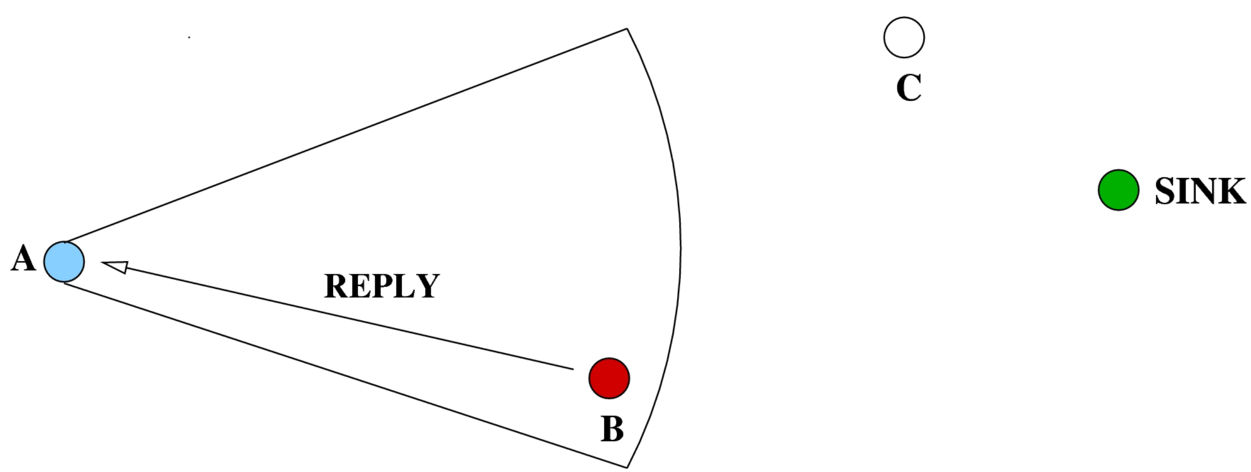

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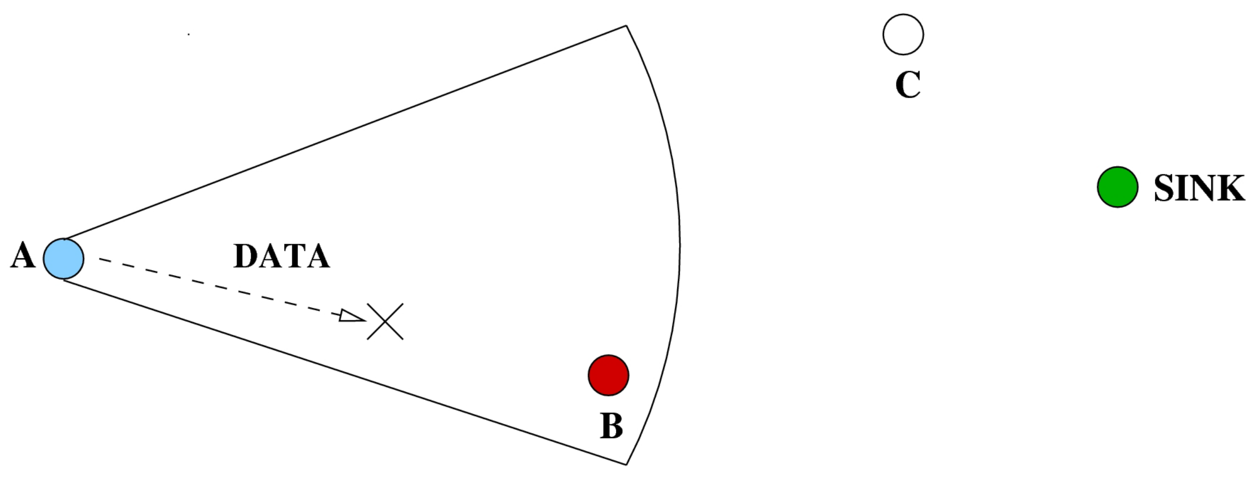

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CARP - A new cross-layer solution for UWSNs

- CARP (Channel Aware Routing Protocol) is based on short control packet exchange to determine next hop
- Power control is used to obtain similar desirable PERs for both control and data packets
- The relay selection is based on cross-layer information:
  - Link quality
  - Node residual energy
  - Node storage capacity
- Data packet trains are used to reduce the handshaking overhead.

S. Basagni, C. Petrioli, R. Petroccia and D. Spaccini. "CARP: A Channel-aware Routing Protocol for Underwater Acoustic Wireless Networks", **Ad Hoc Networks**, Vol. 34. 2015

CARP – In a Nutshell

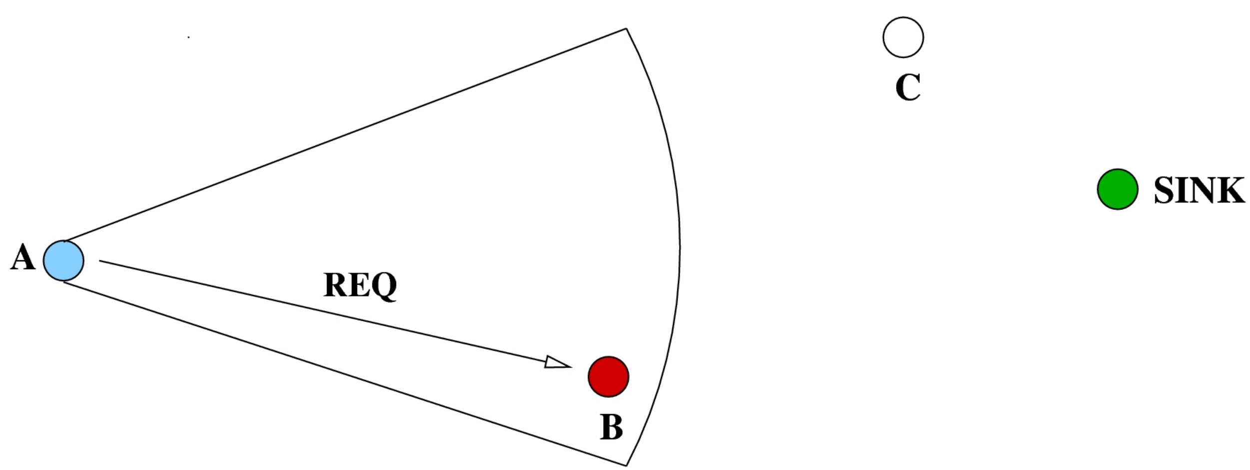
- Set-up Phase: HELLO packets are flooded from the sink through the network, containing the hop count (HC) of the sender to reach the sink.
  - Each node x receiving an HELLO packet from a node y updates its HC, if needed (update to the minimum HC).
- When a node x has a train of data to transmit:
  - It broadcast a PING packet containing the number of packet that *x* wants to transmit.
  - Each node *y* receiving a PING packet, immediately replies with a PONG packet containing its HC_y , residual energy, storage capacity and capability in relaying packet towards the sink.
  - When x receives the PONG packets, it selects the best relay computing neighbor nodes goodness (takes into account link quality, exp moving average, etc).
  - The node y with the highest ratio (goodness/HC) is chosen as the relay.

- Power control is used to obtain similar PER_control PER_data.

S. Basagni, C. Petrioli, R. Petroccia and D. Spaccini. "CARP: A Channel-aware Routing Protocol for Underwater Acoustic Wireless Networks", **Ad Hoc Networks**, Vol. 34. 2015

CARP – Performance Evaluation

- FBR: Focused Beam Routing
  - FBR is a cross-layer geographical solution.
  - Different power level are used for data transmissions.
  - Node closer to the sink is chosen as the next hop relay.



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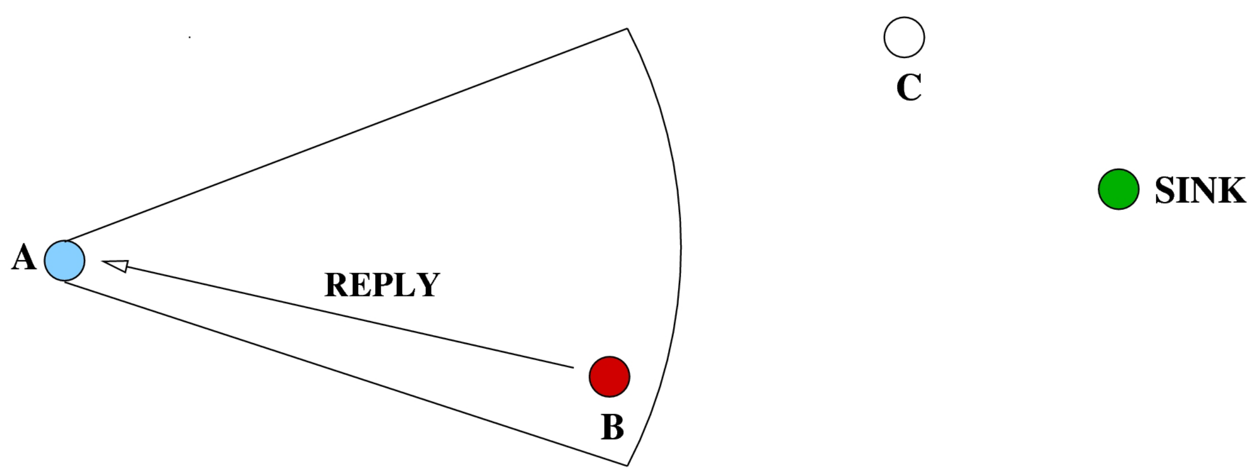

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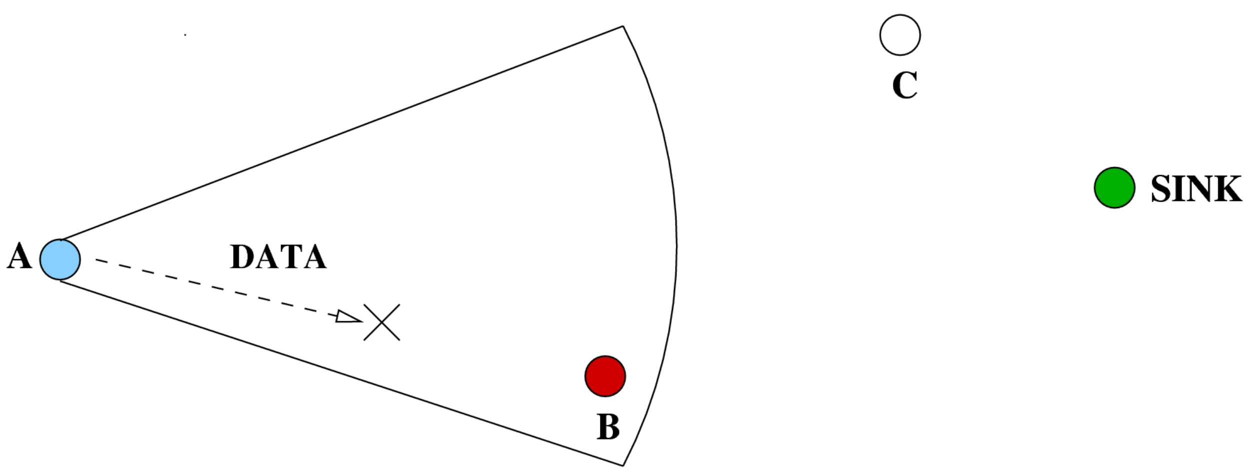

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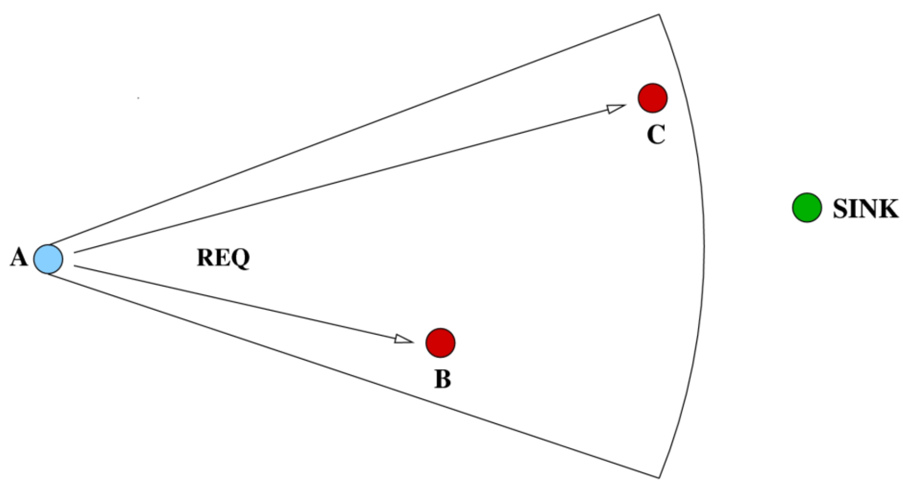

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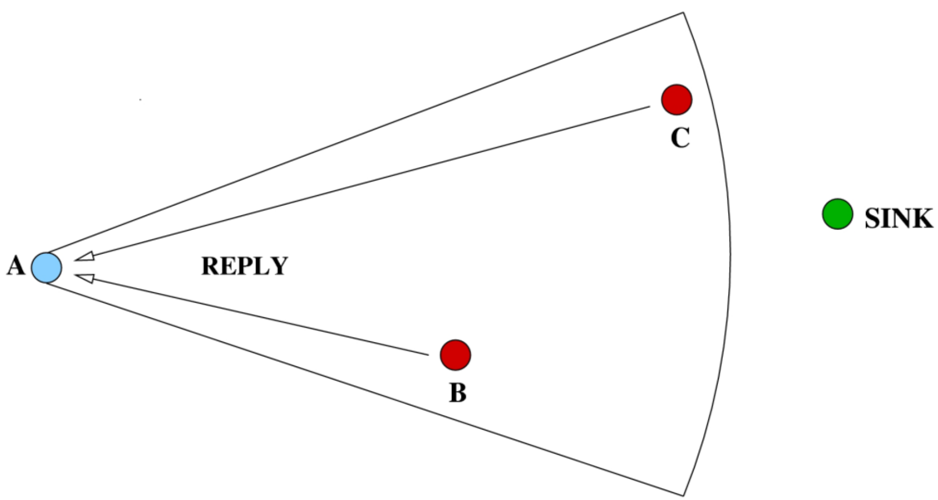

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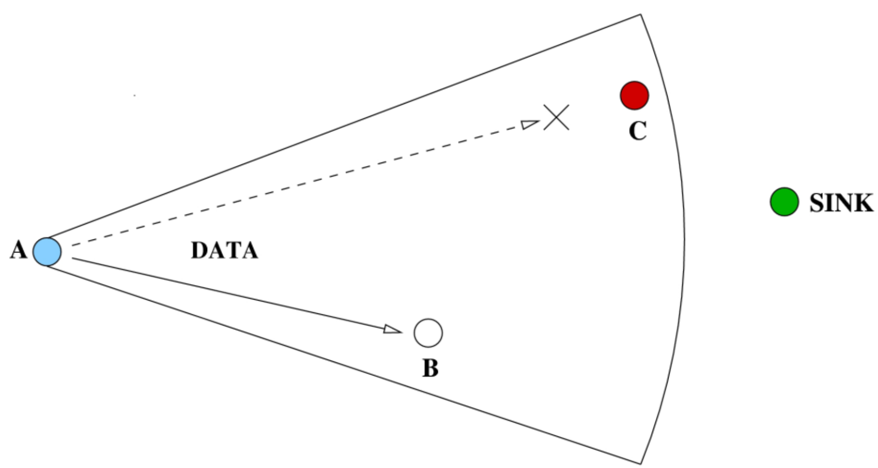

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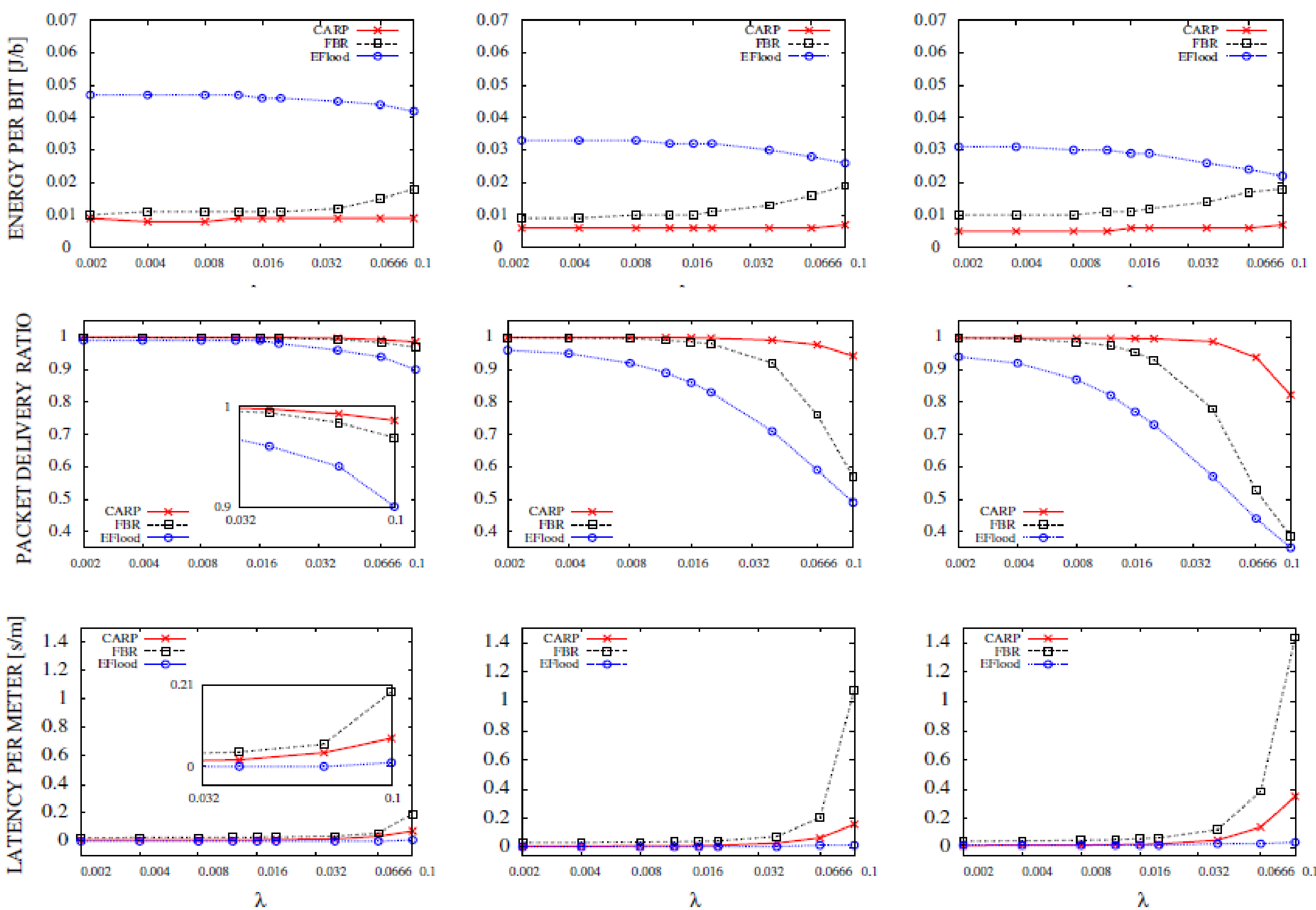
CARP : Simulation Results

20 Nodes (19 + sink)



(a) Payload of 100B. (b) Payload of 512B. (c) Payload of 1000B.

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CARP : Sea Experiments Results

CommsNet13 experiment results.

Metric	CARP	EFlood
(a) Experiment 1		
Packet delivery ratio (%)	96	96
Latency per meter (s/m)	0.038	0.009
Route length (hops)	1.35	1.6
Energy per bit (J/b)	0.03	0.049
(b) Experiment 2		
Packet delivery ratio (%)	95	87
Latency per meter (s/m)	0.054	0.01
Route length (hops)	1.36	1.4
Energy per bit (J/b)	0.027	0.040

Traffic CBR: Exp 1: 60s - Exp 2: 15s

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Can we do better?

- A recent trend is that of allowing nodes to communicate through multiple devices (*multi-modal communications*)
- Can we improve the routing performance exploiting a ***multi-modal*** communication scenario?

Can we do better?

- A recent trend is that of allowing nodes to communicate through multiple devices (*multi-modal communications*)
- Can we improve the routing performance exploiting a ***multi-modal*** communication scenario?
- Yes, using the MARLIN protocol!

MARLIN in a nutshell

- Acoustic multi-modal scenario
- Jointly selects next hop relay and acoustic modem
- Distributed routing solution
- Model-based reinforcement learning approach
- Support different QoS classes
  - Reliability class
  - Latency class

- High frequency
- 64 kbit/s up to 300 m

- Low frequency
- 4 kbit/s up to 4 km

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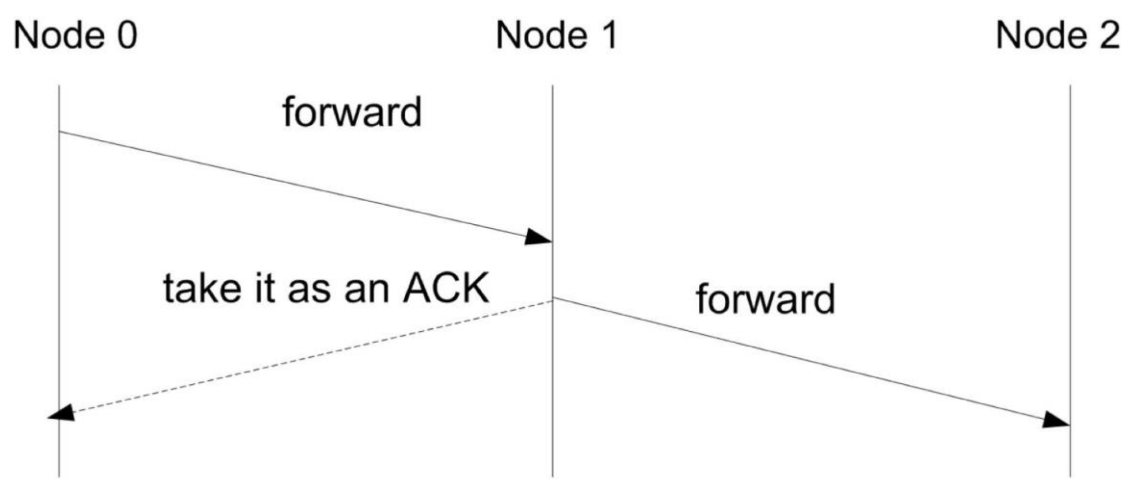
MARLIN in a nutshell

- No control packets
- Control information added in data packet header
- Low latency, less overhead



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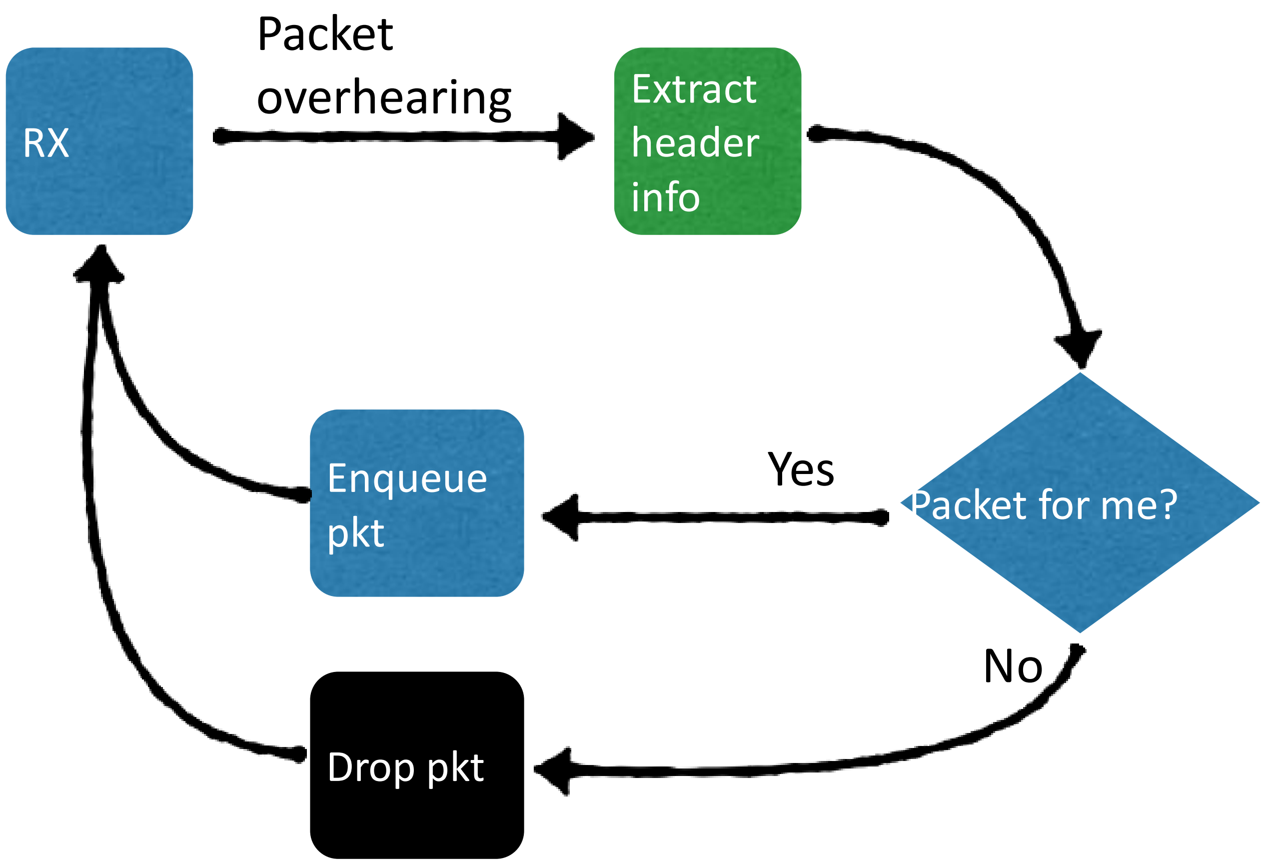
MARLIN: Packet Reception



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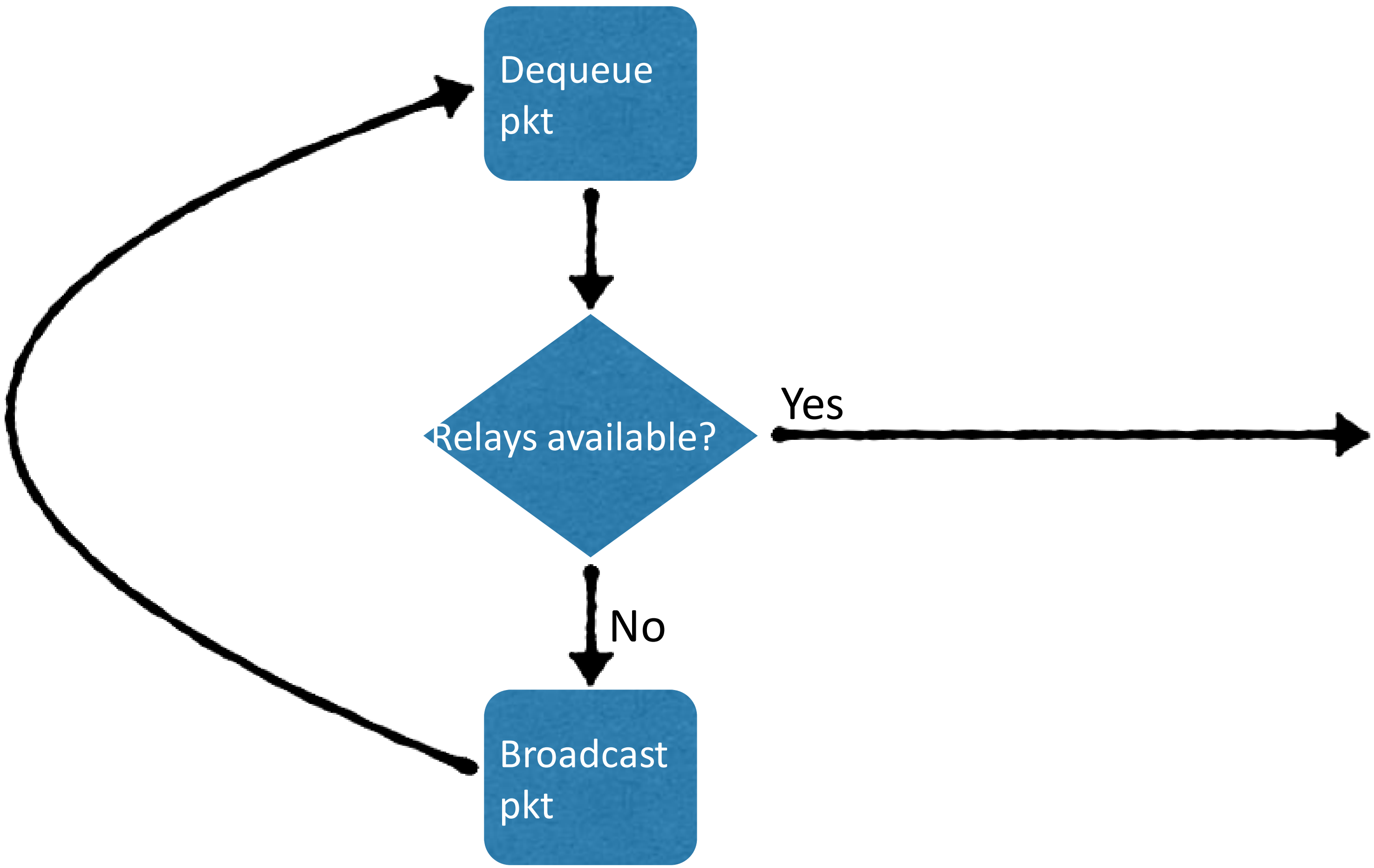
MARLIN: Packet Transmission



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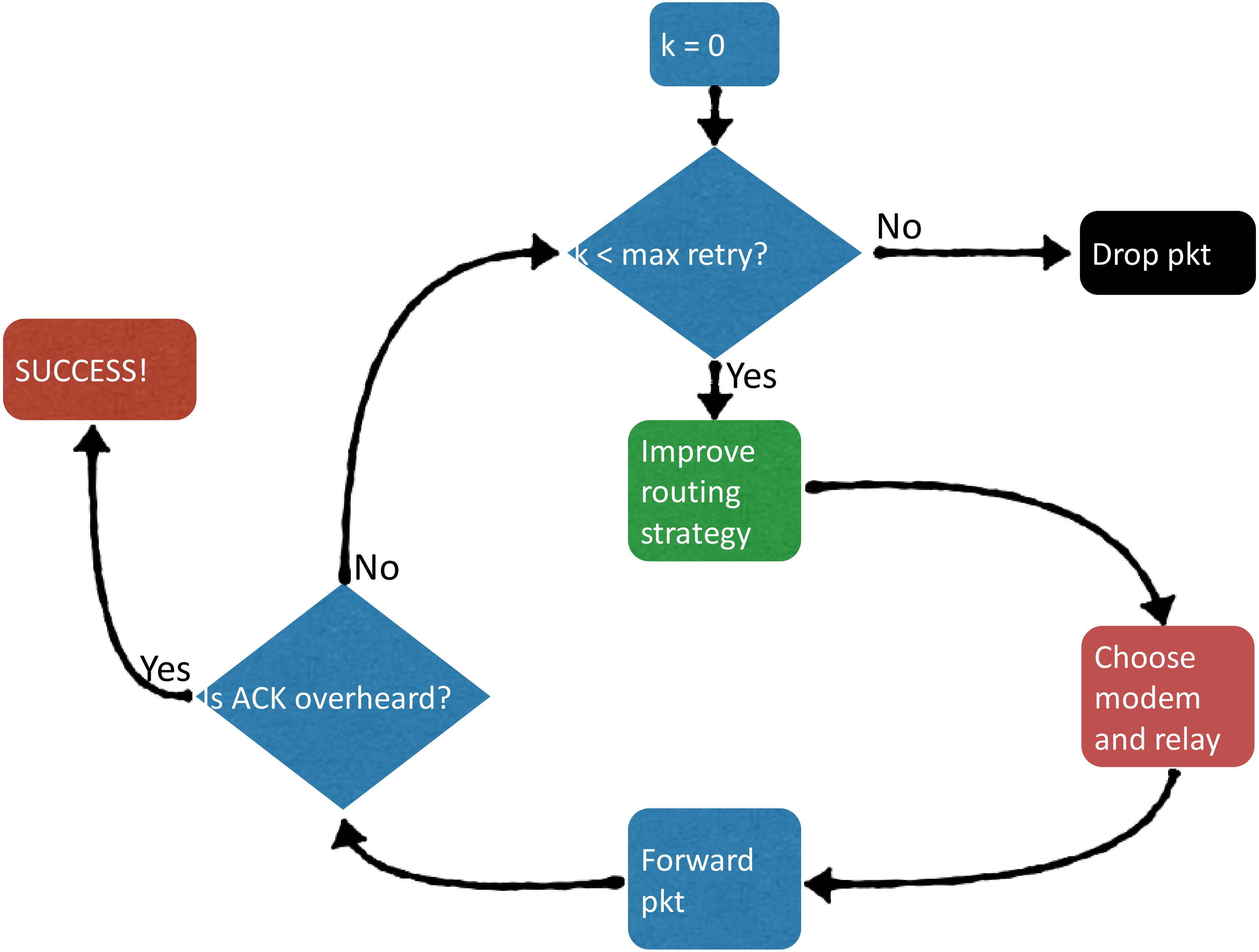

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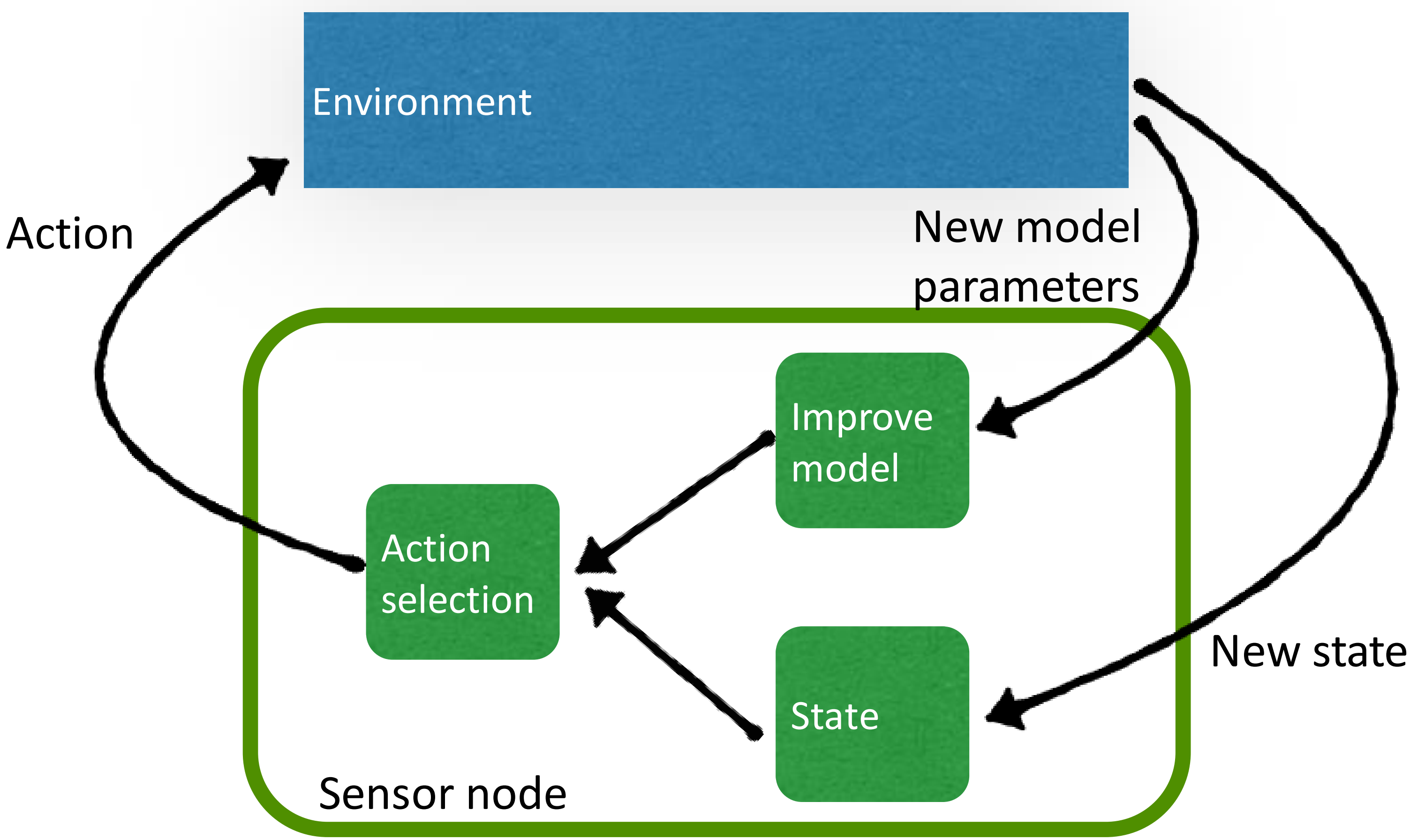
MARLIN: Modem and Relay selection

Model-based Reinforcement learning strategy



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MARLIN: Modem and Relay selection

- States: number of times the packet has been already transmitted
- Actions: all pairs <modem, neighbor node>
  - Neighbors NOT known a priori, discovered and updated at runtime
- State transitions: probability to successfully *transmit* the packet and *receive* the implicit acknowledgement
  - Estimated while transmitting data packets
  - Continuously updated at runtime

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MARLIN: Modem and Relay selection

- Cost function: time to deliver the packet to the sink plus a penalty for packet dropping

$$C = t_{local} + C_{relay} + t_{penalty}$$

Estimated by the node

Transmitted by neighboring nodes

- Learning algorithm computes the pair <modem, neighbor node> that minimizes the cost *C*

- The model is updated before each packet transmission

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MARLIN: Experimental Evaluation

- MARLIN compared to CARP, QELAR and MFLOOD, a multi-modal enhanced flooding protocol
- All protocols implemented in SUNSET simulator
- Networks made of 6, 20 and 40 nodes
- Packet rate is ≈ 6 pkt/min
- Each node has 2 acoustic modems
  - Long range, low data rate
  - Short range, higher data rate
- Acoustic channel modeled using Bellhop ray tracing tool

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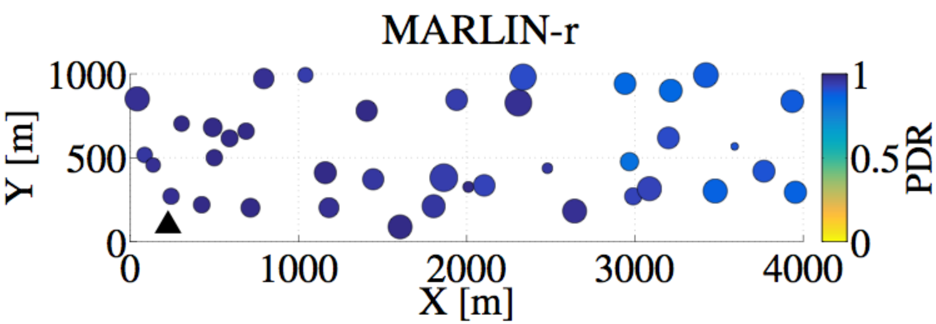
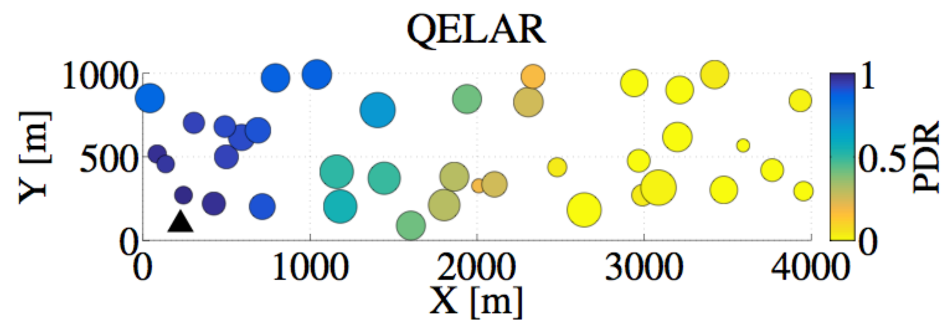
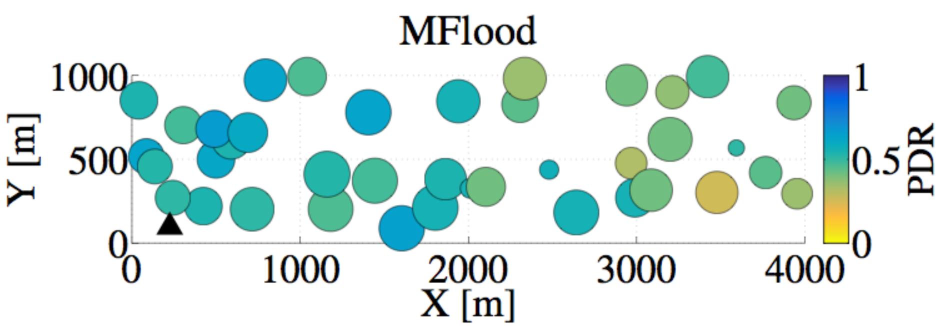
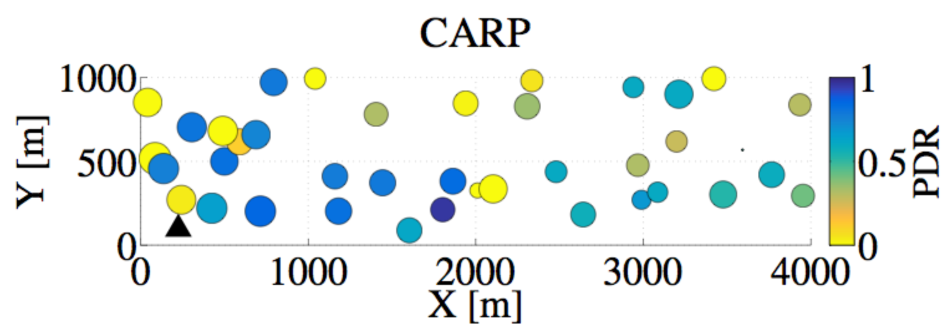
MARLIN: Experimental Evaluation

Node packet delivery (colour of the node) and packet collisions (size of node)









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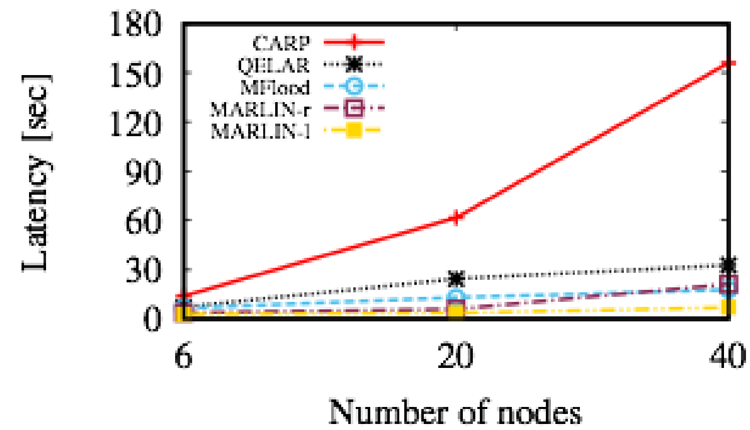
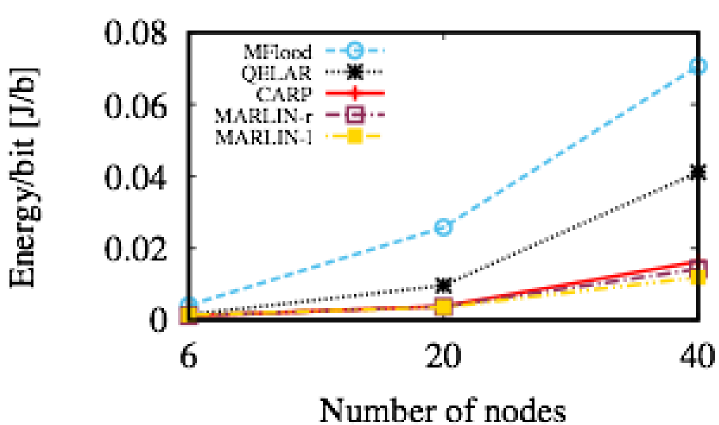
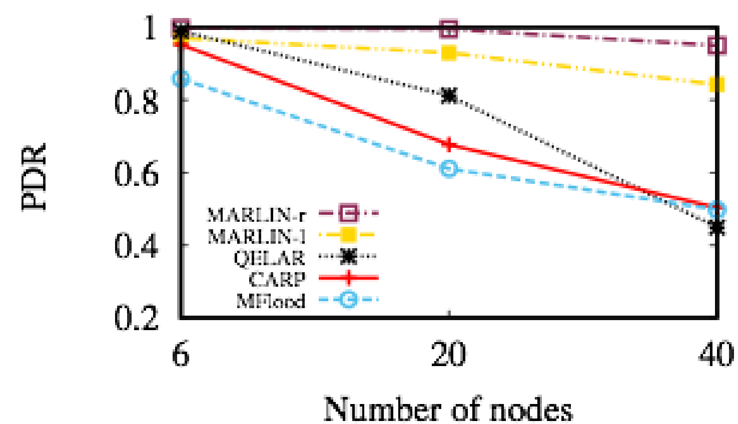
MARLIN: Experimental Evaluation

- Remarkable data delivery
- Low latencies
- Energy stable







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Whats next?

- Synchronization and localization
- Mobile networks and path planning
- Underwater security
- Communication Standards: JANUS
- Application layers: Mobile-To-Mobile comm, etc..

Conclusions

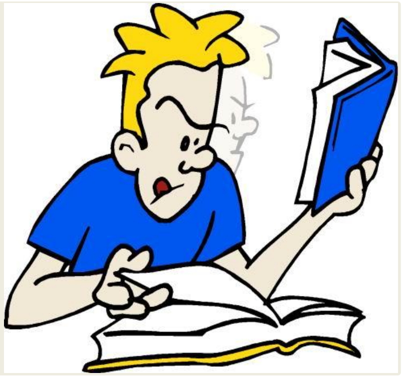
- With respect to protocols for radio networks, technical challenges in UASNs have a different priority.
- Delay can be considered (in general) a less-stringent constraint.
- Collision avoidance is definitely one of the major challenges to tackle
- Need to be adaptive to: wave propagation, network size, transmission range, node density, traffic load, wind speed, ships noise, abrupt link changes.
- Node placement and mobility planning

References

- M. Stojanovicand J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," in *IEEE Communications Magazine*

- Petroccia R., Petrioli C., Potter J., «Performance Evaluation of Underwater Medium Access Control Protocols: At-Sea Experiments», IEEE JOURNAL OF OCEANIC ENGINEERING, 2017

- S. Basagni ,C. Petrioli ,R. Petroccia and D. Spaccini. "CARP: A Channel-aware Routing Protocol for Underwater Acoustic Wireless Networks", **Ad Hoc Networks**, Vol. 34. 2015



- Mari Carmen Domingo et al «Overview of channel models for underwater wireless communication networks»

- Ian F. Akyildiz, Dario Pompili, Tommaso Melodia, Underwater acoustic sensor networks: research challenges, In Ad Hoc Networks, Volume 3, Issue 3, 2005, Pages 257-279, ISSN 1570-8705,

- S. Basagni,C. Petrioli,R. PetrocciaandD. Spaccini. «Channel Replay-based Performance Evaluation of Protocols for Underwater Routing»**MTS/IEEE OCEANS 2014**

- B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad hoc underwater acoustic sensor networks," IEEECommun. Lett., vol. 11, no. 12, pp. 1025–1027, Dec. 2007

- A. A. Syed, W. Ye and J. Heidemann, "T-Lohi: A New Class of MAC Protocols for Underwater Acoustic Sensor Networks,"*IEEE INFOCOM 2008*

- S. Basagni,V.DiValerio,P. GjanciandC. Petrioli. «Finding MARLIN: Exploiting Multi-Modal Communications for Reliable and Low-latency Underwater Networking».**IEEE Infocom 2017**

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