Protocols for Underwater Wireless Sensor Networks - Challenges and Solutions

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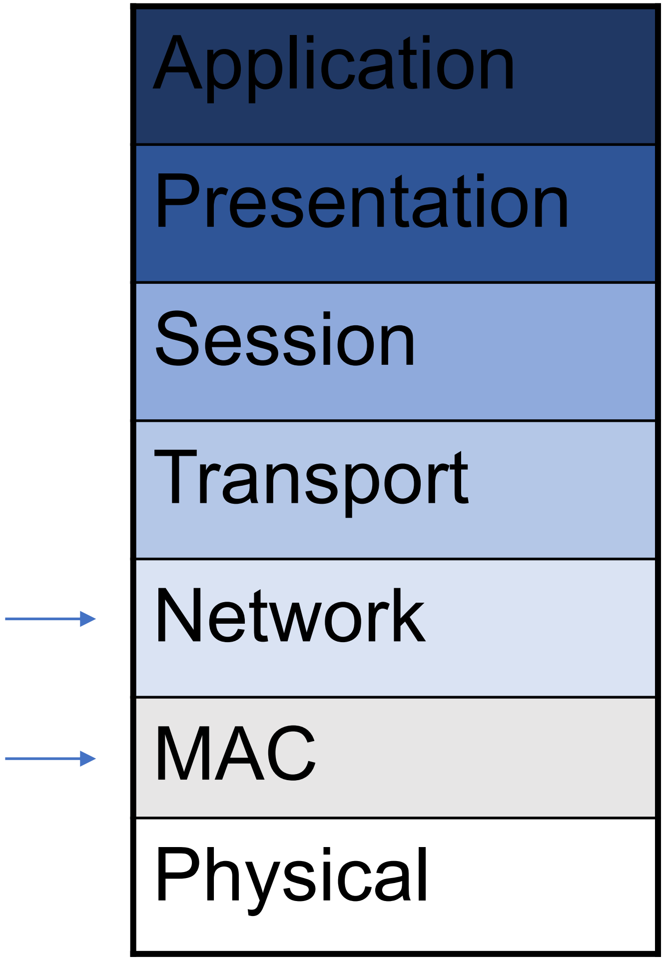
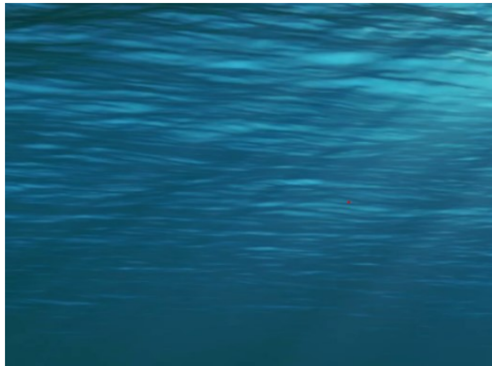
Presenter - Anne-Lena Kampen

- Associate professor at Western Norway University of Applied Sciences (HVL)
  - Main research area: Wireless Sensor Networks (WSN) - Industrial networks - Underwater communication
- June 2018 until Mars 2020 Norwegian Research Centre AS (NORCE).
  - Smart sensor networks - embedded machine learning, and underwater communication.
- Received PhD in Telematics from the Norwegian University of Science and Technology (NTNU) in 2017.
  - WSN - energy efficiency and routing-path recovery.
- Professor assistant at HVL from 2005, teaching network communication and electronics.
- Nera Network from 1996 until 2005
  - Research: reducing the energy consumption of power amplifiers. Developed microwave modules for radio links.
- Master of Science in Applied Physics from the University of Tromsø, The Arctic University of Norway, in December 1995,

Outline of the presentation

- Motivation for underwater communication
- Characteristics of underwater communication
- MAC layer
  - Discuss various approaches
- Network layer
  - Discuss various approaches
- Conclusion





Motivation

- The Sustainable Development Goals were adopted by all UN Member States in 2015.
- Goal number 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
- “
- Oceans.. generate half the oxygen we breathe, support a wealth of marine resources and act as a climate regulator…
- …overfishing and marine pollution are jeopardizing progress in protecting the world’s oceans…
- “
- As a consequence, surveillance of the underwater environment is needed.
- Solutions for underwater WSNs can borrow ideas from the vast amount of terrestrial WSN solutions.
- However, due to the special characteristics underwater environments, adjustments are required

Underwater communication - Characteristics

Underwater protocols must conform to the distinctive challenging characteristics the media [1][2]

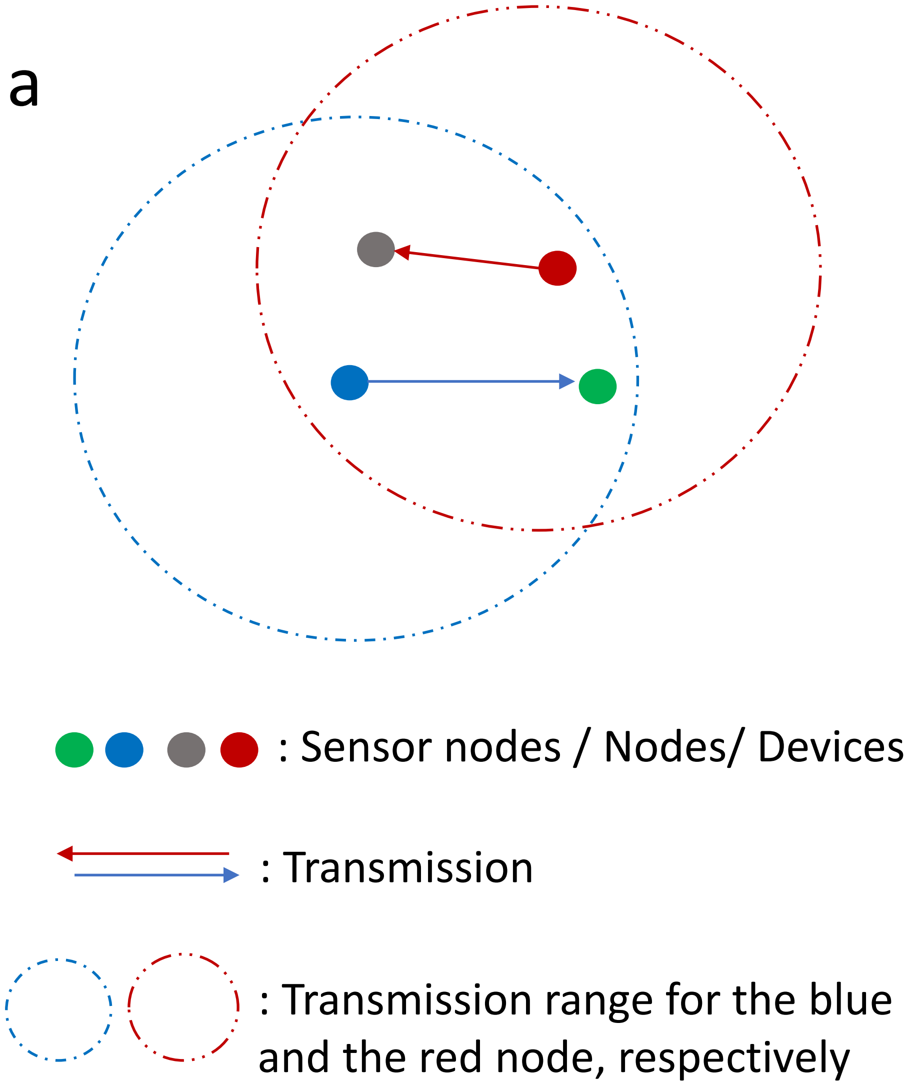
- Low and dynamic channel capacity
- Substantial signal attenuation
- Noise
  - Man made and ambient
- Asymmetric links
- Low propagation speed
  - The signal propagation for acoustic underwater communication is **five order of magnitude slower than light speed,**
  - A fundamental challenge in coordinating the access to the shared communication medium.

[1] C. M. Gussen et al., "A survey of underwater wireless communication technologies," J. Commun. Inf. Sys, vol. 31, no. 1, pp. 242-255, 2016.
[2] S. Gauni et al., "Design and Analysis of Co-operative Acoustic and Optical Hybrid Communication for Underwater Communication," Wireless Personal Communications, vol. 117, no. 2, pp. 561-575, 2021.

MAC layer
Various approaches

MAC main task

- Regulate access of a number of nodes to a shared medium
- Requirements
  - Fairly share the wireless media-resource
  - Low delay
  - Low overhead
  - Stability
  - Energy efficiency
    - Prevent collisions
    - Recue idle listening
    - Reduce overhearing
    - Reduce overhead



Schedule-based MAC

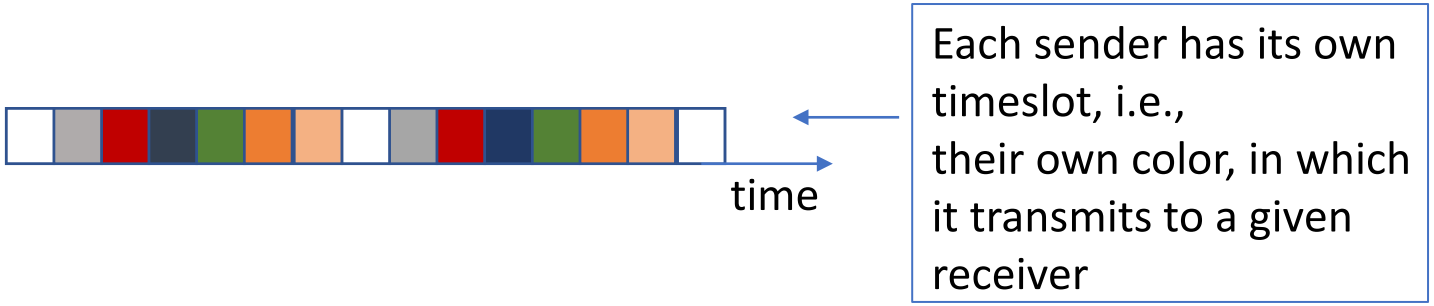
- Regulates which nodes that may use given resources at a given time
- Typical technology used for scheduling: Time Division Mutiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA)
- Schedule can be ***fixed*** or computed ***on demand***

- Advantage:
  - collisions, overhearing and idle listening are avoided/ reduced

Each sender has its own timeslot, i.e.,
their own color, in which it transmits to a given receiver

Schedule-based MAC

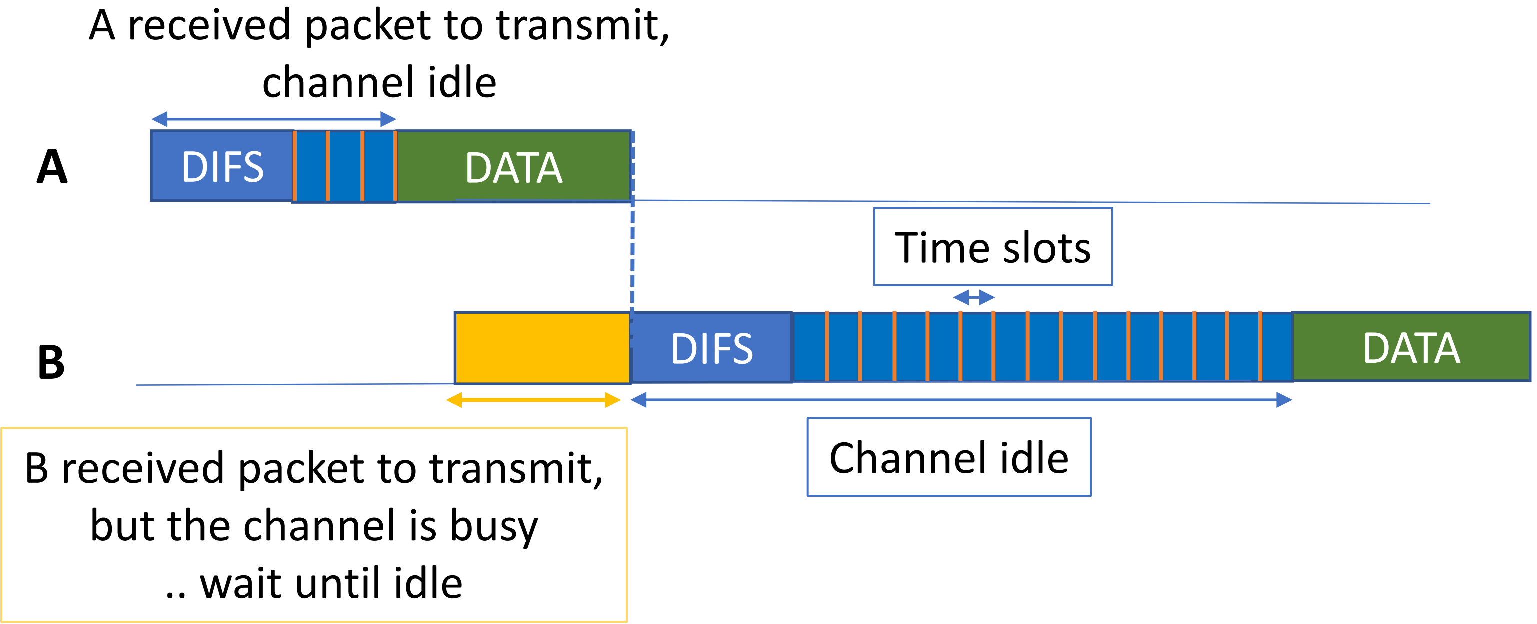
- **Challenges:**
  - Network-wide resource reservation is complex
    - Traffic from nodes in adjacent areas can interfere.
  - Underwater currents or seafloor changes may move the nodes.
  - Efficient TDMA requires precise synchronization
    - Challenging in underwater environments due to the long and variable transmission delay
    - However, short periods of static and predictable propagation delay may provide synchronization that is accurate enough [1].



[1] A. A. Syed and J. S. Heidemann, "Time Synchronization for High Latency Acoustic Networks," in Infocom, vol. 6, pp. 1-12, 2006.

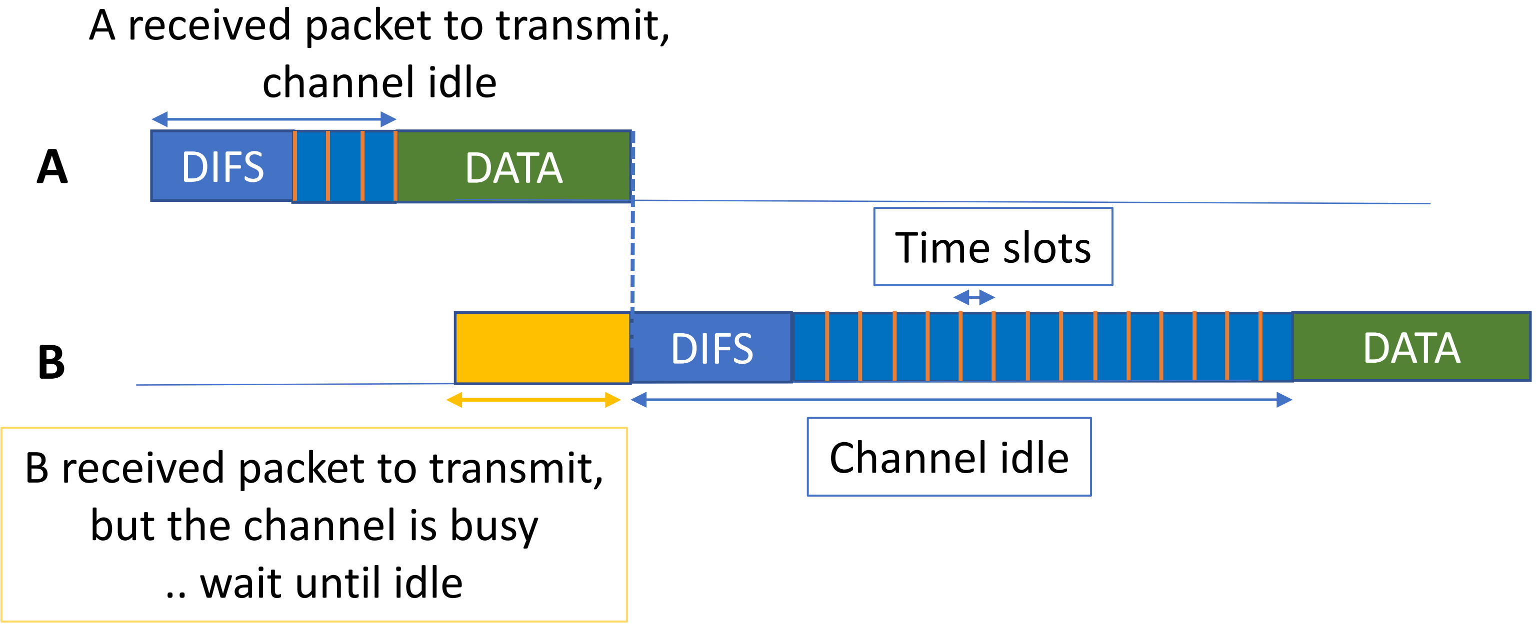
Contention-based MACs

- Random access protocols
- Requires no specific coordination among before they actually have data to transmit
  - Reduced management
- Collision may occur



Contention-based MACs

- **Challenges:**
  - The nodes must delay data transmission according to the longest possible delay
  - Long time-span increases the probability of transmission from a neighboring node.



Experimental results reported based on an NATO at-sea campaigns [1]

- CSMA
- T-Lohi
    - The node transmits a reservation-tone, after which it listens to the channel for the duration of a Contention Round (CR).
    - If no other tones are heard during CR, tx packet.
    - Otherwise, it enters back-off state for a random number of CR before repeating the procedure
- Distance Aware Collision Avoidance Protocol (DACAP),
    - RTS/ CTS to reserve the channel.
    - Receiver sends a short warning packet if it overhears control packets from other nodes after sending its CTS and before receiving the associated data packet.
    - If the sender overhears a control packet, or receives a warning form its destination while waiting for CTS, it aborts data communication.

- **The results presented :**
- Basically, solutions should be able to adapt, in a distributed way, to dynamically changing conditions.
- Using DACAP, the network performance is deteriorated when the traffic load is increased.
- CSMA reduces the transmission attempts, however, the whole packet has to be retransmitted when collisions occur.
- The end-to-end delay of CSMA and DACAP use exponential backoff making the delay increase rapidly with increased number of retransmissions.
- Not using exponential backoff, T-Lohi has lower end- to- to lay, the price played is higher packet loss.

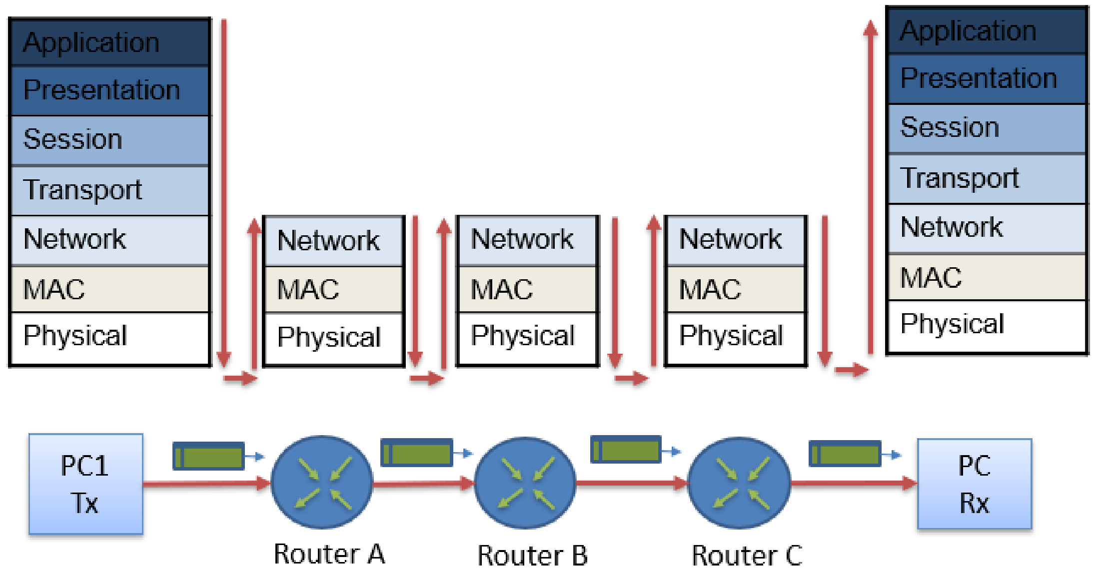
[1] R. Petroccia, C. Petrioli, and J. Potter, "Performance evaluation of underwater medium access control protocols: At-sea experiments," IEEE Journal of Oceanic Engineering, vol. 43, no. 2, pp. 547-556, 2017.

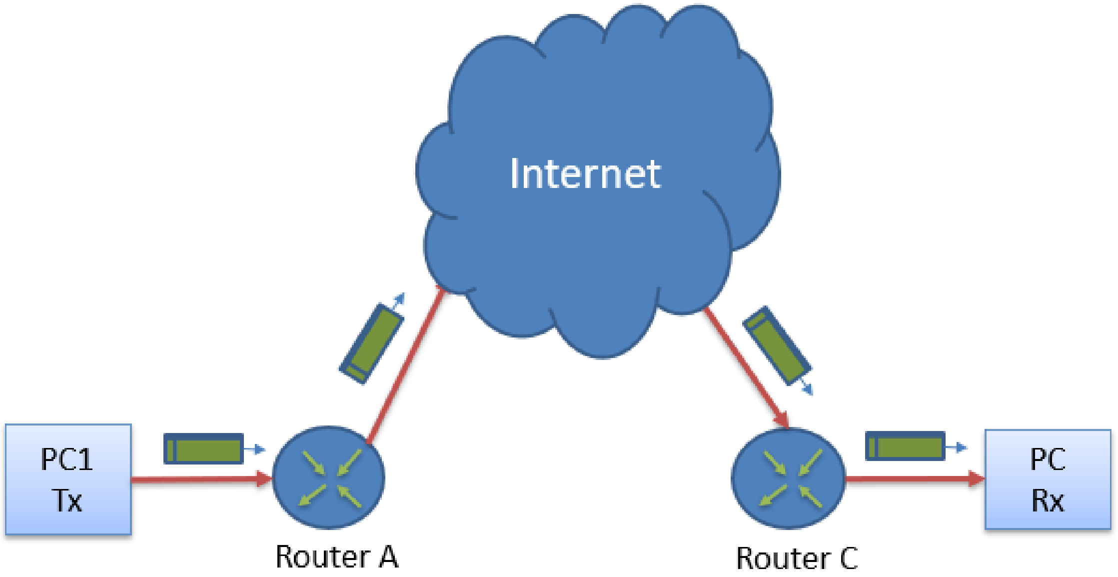
Network layer

Application
Presentation
Session
Transport
Network
MAC
Physical

Routing

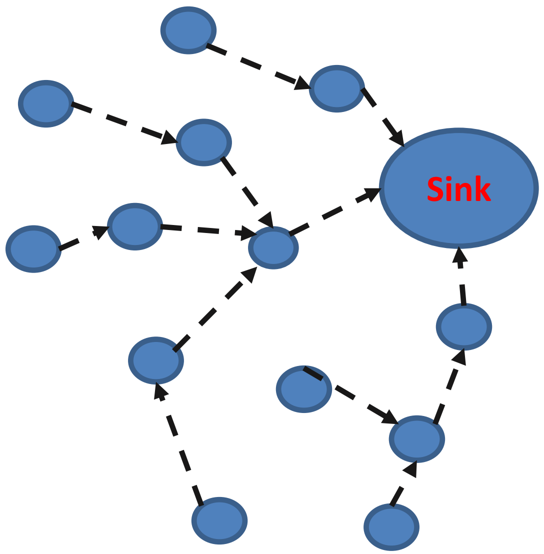
- The router is responsible for the routing of traffic between networks.
- The routing tables are used to determine the **best path** to send packets.
  - Best path is selected using a given metric (hop-count, delay, ETX …)
- Routers encapsulate the packet and forward it to the node indicated in routing table.

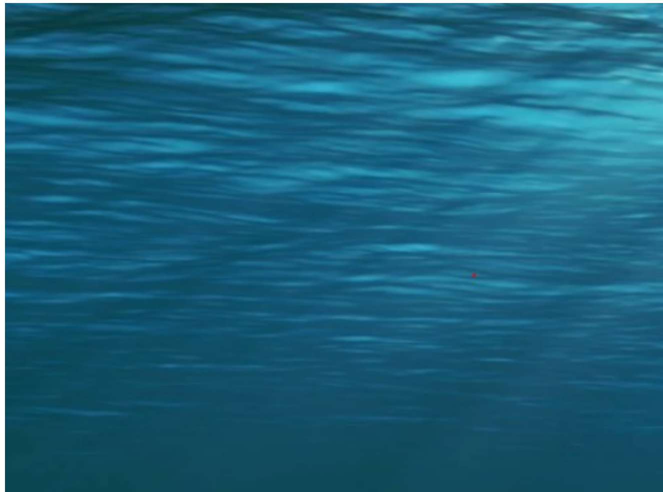




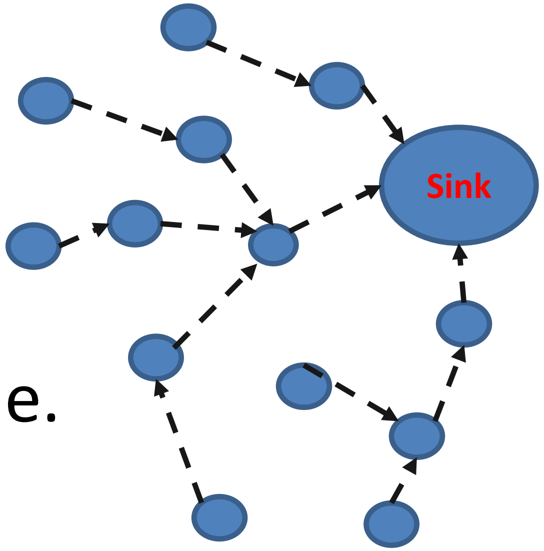
Routing

- Reactive versus proactive protocols
  - Proactive
    - Discover routing paths before data is being transmitted.
    - Maintain the paths to remain available
    - Reduces delay
    - Energy is used to maintain the paths
  - Reactive
    - Paths are discovered after an event has occurred
    - Energy consumption is reduced since path maintenance is reduced
    - Higher delay

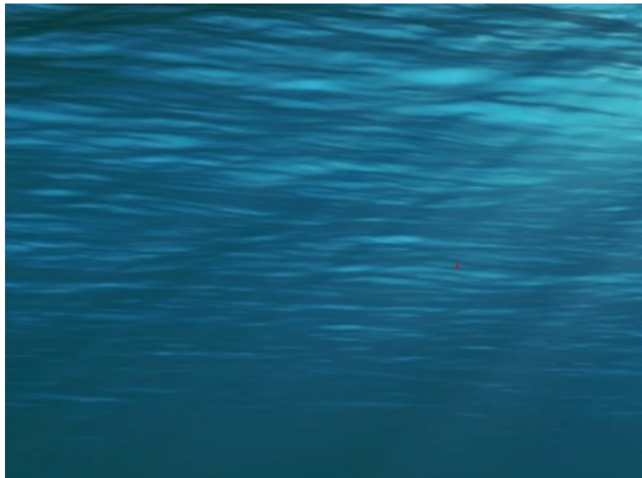




Reactive and proactive protocols

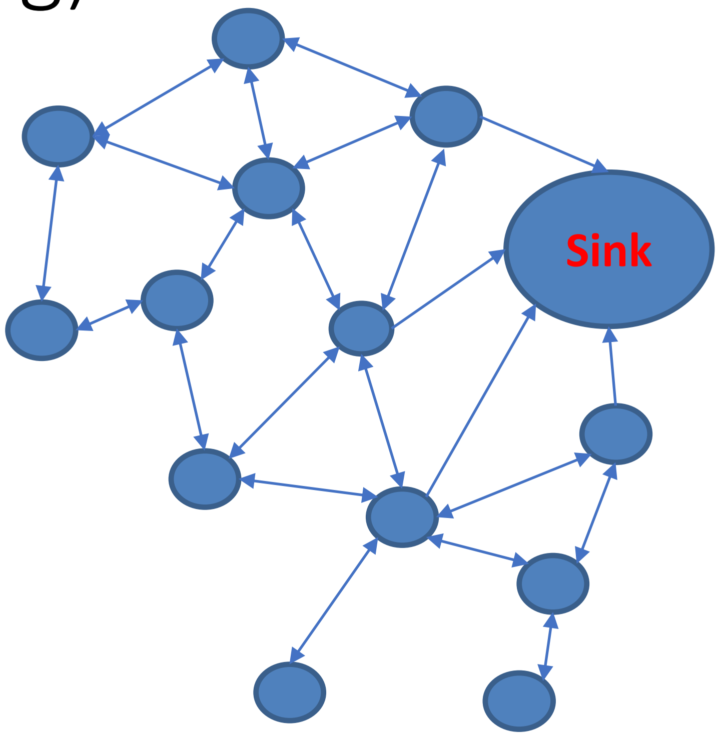


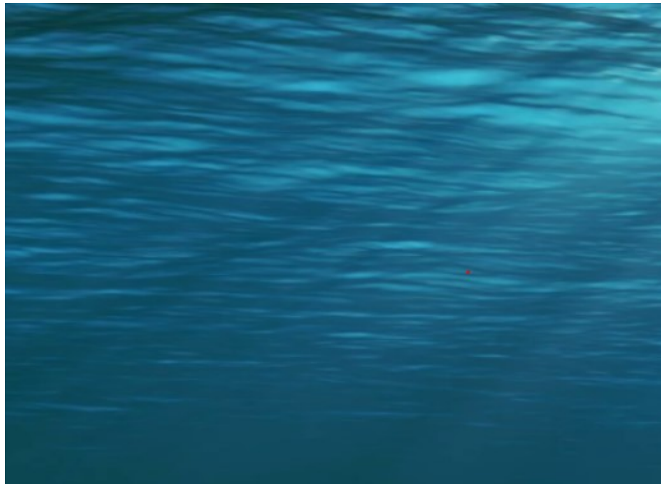
- **Underwater challenges:**
- Quality of the links are often time varying
  - Thus, proactively generated paths may not be reliable.
- Reactively created paths
  - Very long delay.
- The links may be unidirectional or asymmetric,
  - Difficult to utilize these paths.
  - Although they may be well-working and stable for communication in the correct direction.



Flooding / Broadcasting (reduced/ no routing)

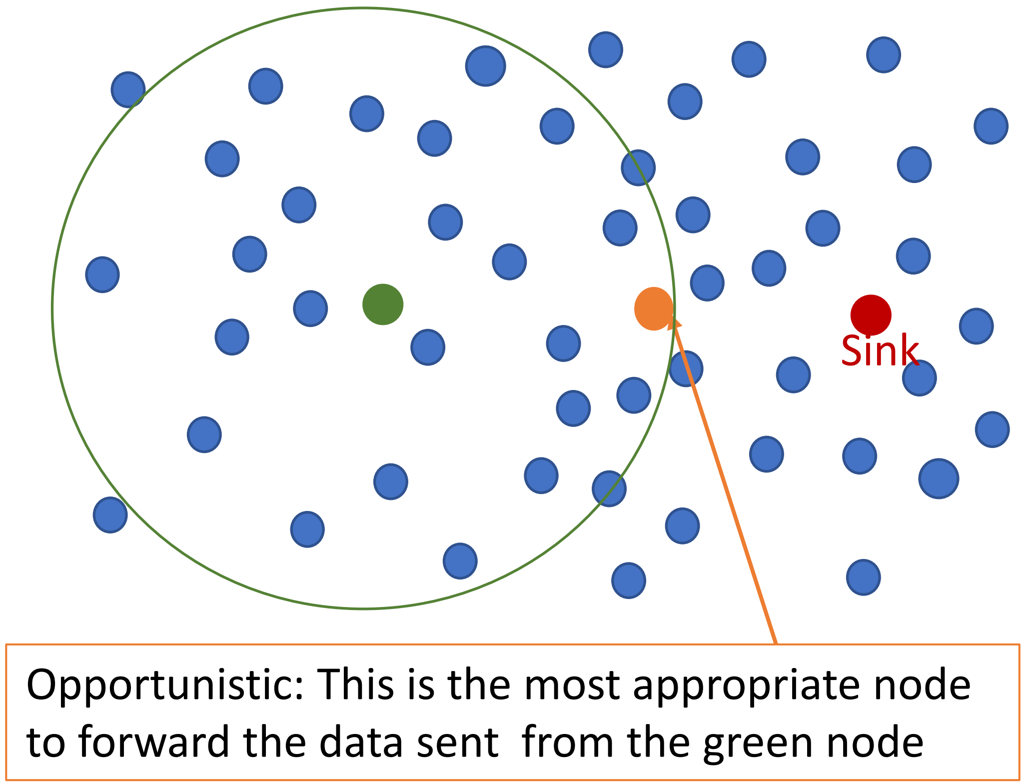
- The simplest forwarding approach
  - Broadcasting alleviates the challenges related to generating routing paths.
    - All candidate paths are tried.
    - No specific routing paths needs to be generated.
  - However, the broadcast should be constrained
    - To prevent excessive network traffic,
    - To reduce the energy consumption of the nodes.





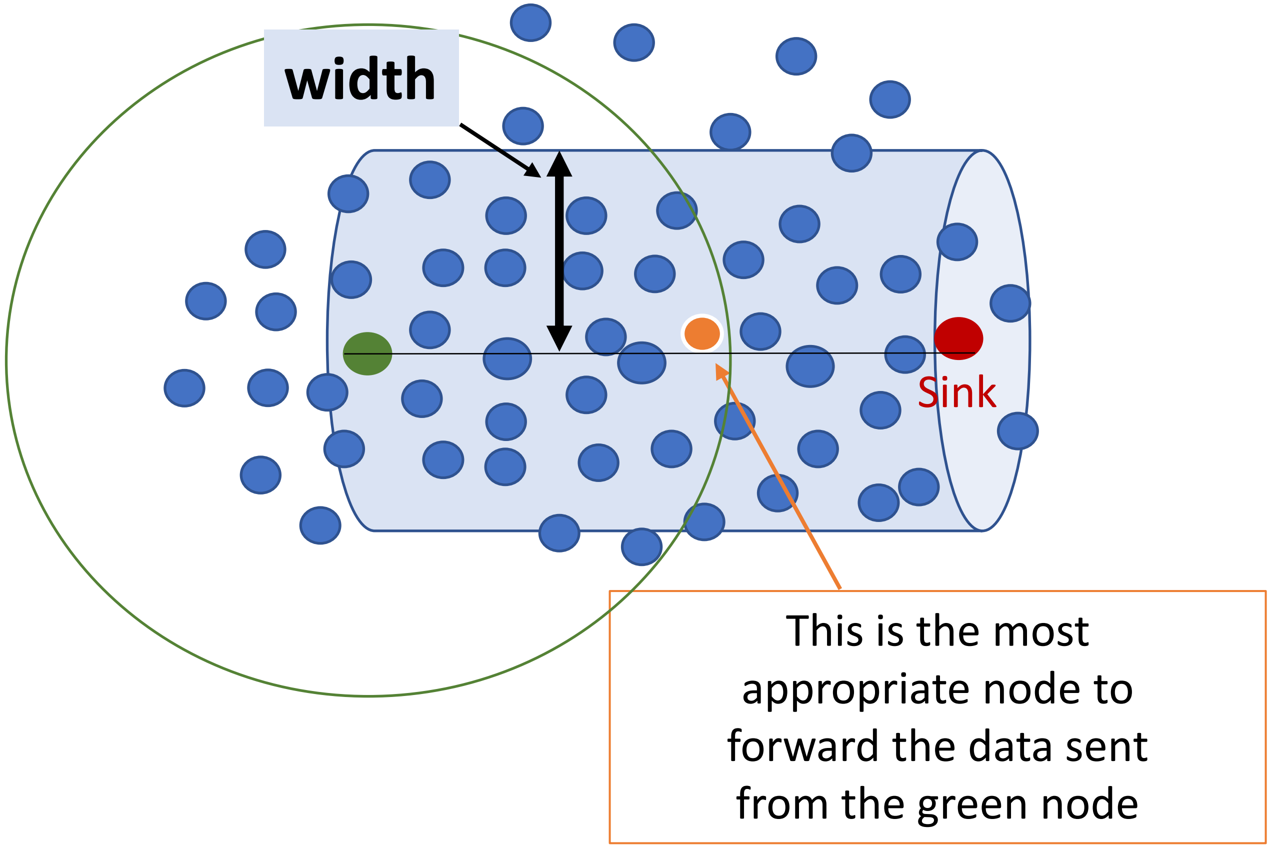
Opportunistic routing

- Utilized the broadcast nature of wireless media
  - The most appropriate node forwards the packet further toward the sink.
    - Provides the best progress.
  - Refrain from forwarding when overhearing neighbors forwarding the packet



Opportunistic routing

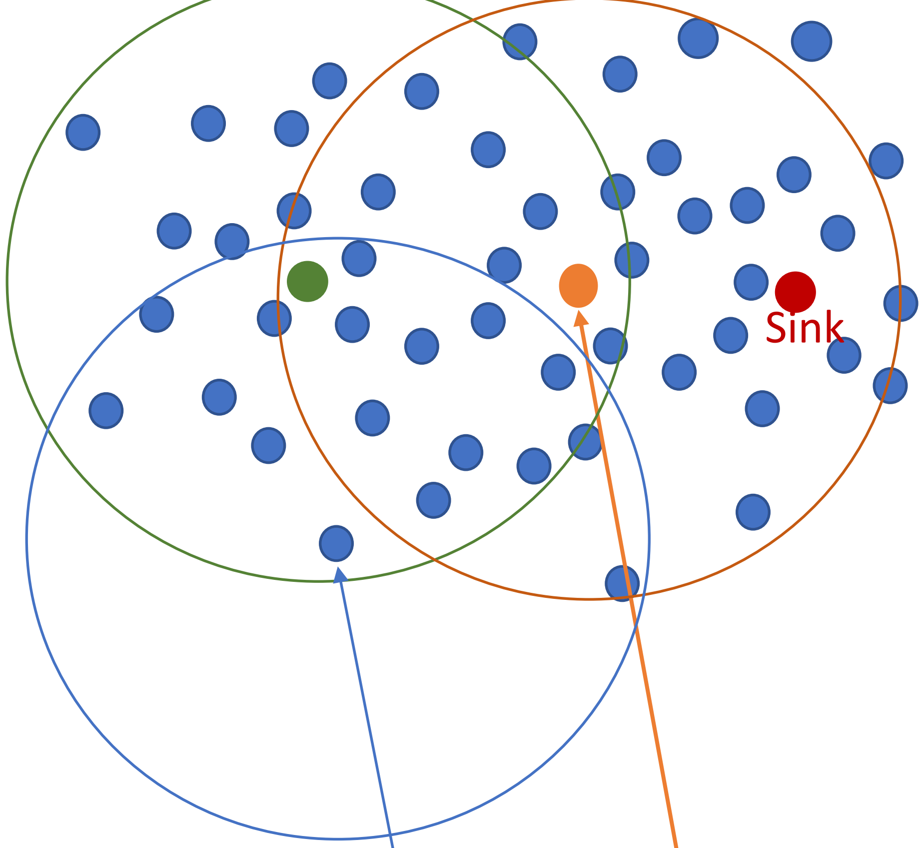
- Pipe [1]
  - Reduce the number of potential forwarding nodes
  - Only nodes inside pipe can forward



[1] S. M. Mazinani, H. Yousefi, and M. Mirzaie, "A vector-based routing protocol in underwater wireless sensor networks," Wireless Personal Communications, vol. 100, no. 4, pp. 1569-1583, 2018.

Opportunistic routing

- **Challenges:**
- Double forwarding of a packet may occur in unreliable media, and
  - if candidate forwarder nodes are outside each other's transmission range. (see figure)
- All nodes use energy to receive and read the packets.
- When the number of potential successor nodes is high, a wide range of distinct holding-time-values is required to prevent multiple nodes' timers from expiring simultaneously.
  - To provide a **broad range of distinct holding-time-values**, the average delay in the network increases



This is the most appropriate node to forward the data sent from the green node

This node doesn't hear that the orang node forwards the packet.

Conclusion

- **Long propagation delay ; Dynamic channel characteristic ; Limited bandwidth**

- **The time available for access control is reduced**
  - **The limited channel resources should not be depleted by large amount of management traffic.**
- **For efficient utilization of the limited channel capacity**
  - **Reduces the time between received packets, &**
  - **Prevents packet collisions at the receiver.**

- **Dynamic channel properties ->challenging to generate fixed routing pats.**
  - **We recommend to use constrained broadcasting techniques.**
    - **Location-based techniques seem to be promising solution.**

Thank you very much for the attention !!

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