UCLA

DOTS: A Propagation Delay-aware Opportunistic MAC Protocol

for Underwater Sensor Networks

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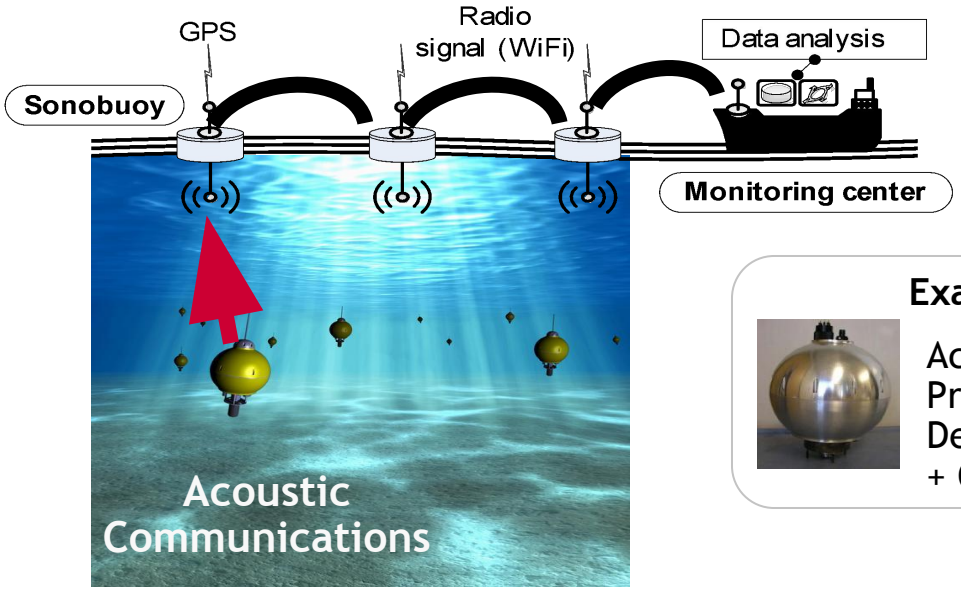
Network Research Lab
Communication Innovation

SEA-Swarm (Sensor Equipped Aquatic Swarm)

- Monitoring center deploys a large # of mobile u/w sensors (and sonobuoys)
- Mobile sensors collect/report sensor data to a monitoring center
- Monitoring center performs data analysis including off-line localization
- Short-term "ad hoc" real-time aquatic exploration: oil/chemical spill monitoring, anti-submarine missions, surveillance etc.



Example: UCSD Drogues

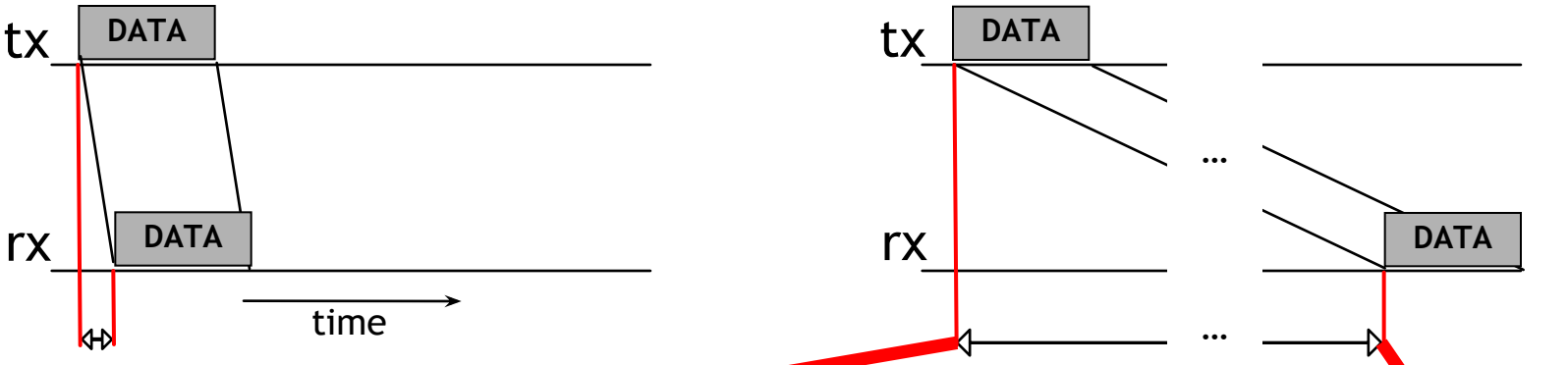
Acoustic modem
Pressure (depth) sensor
Depth control device
+ Other sensors

Pictures from:
http://jaffeweb.ucsd.edu/node/81

Outline

- Motivation
- Intro to DOTS & Our Approach
- Time Sync Experiment
- Simulation Results
- Summary and Future Work

Problem Definition: SEA-Swarm MAC protocols



Radio propagation latency

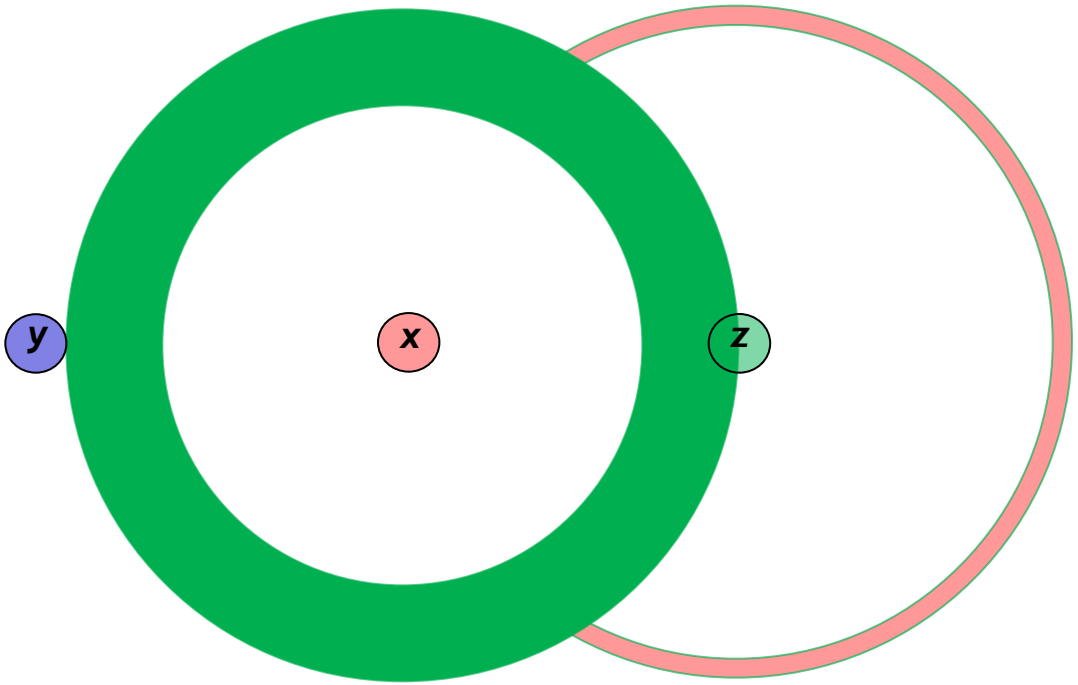
Acoustic propagation latency

(a) Radio *(b) Acoustic*

2 X 10^5 longer

- Long propagation latencies (3 × 10^8 m/s)
- Bandwidth limitations (< 100kbps)
- Transmit energy costs (transmission is expensive, 1:125)
- **Node mobility (<1m/s)**

Observation: w/o temporal reuse



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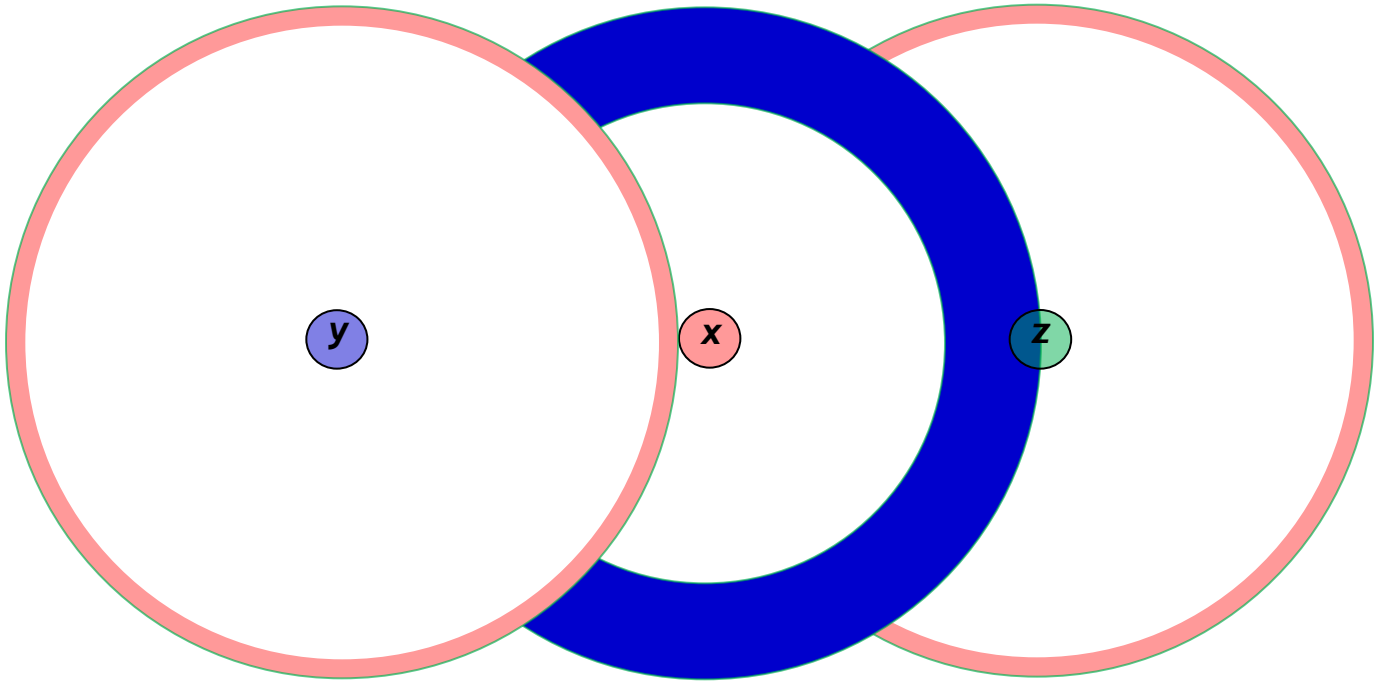
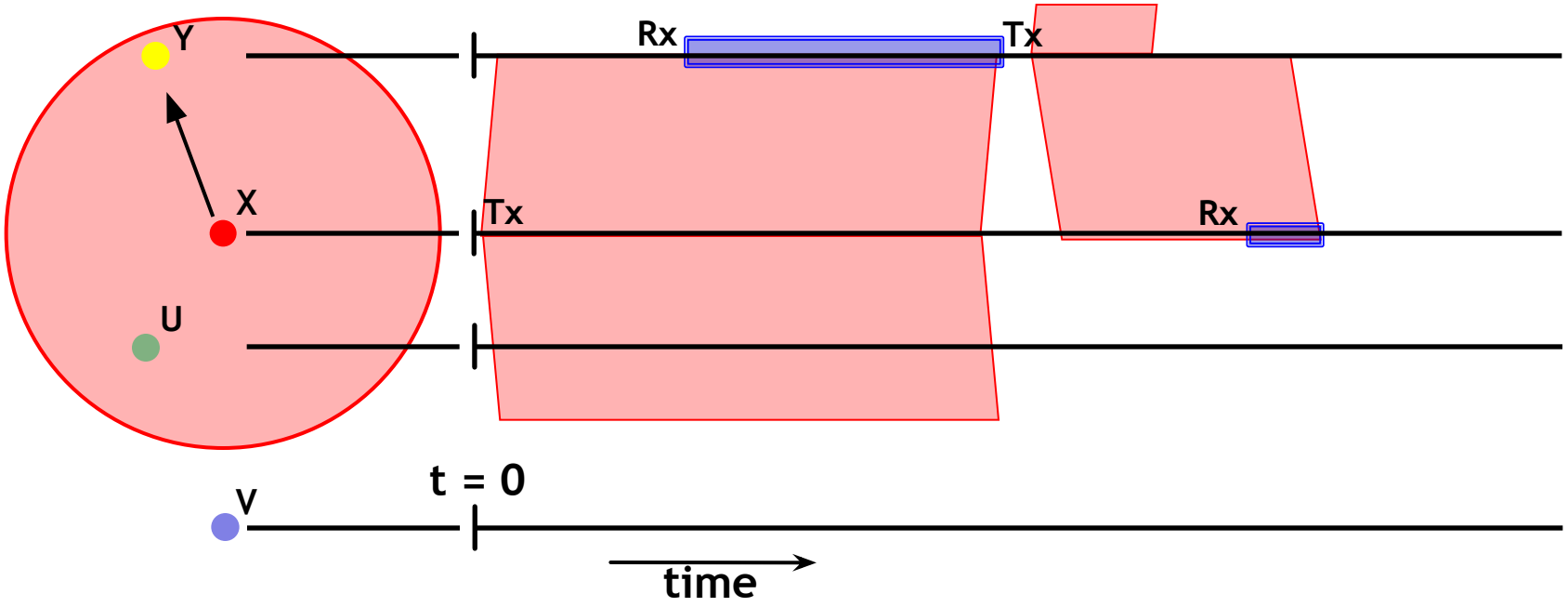
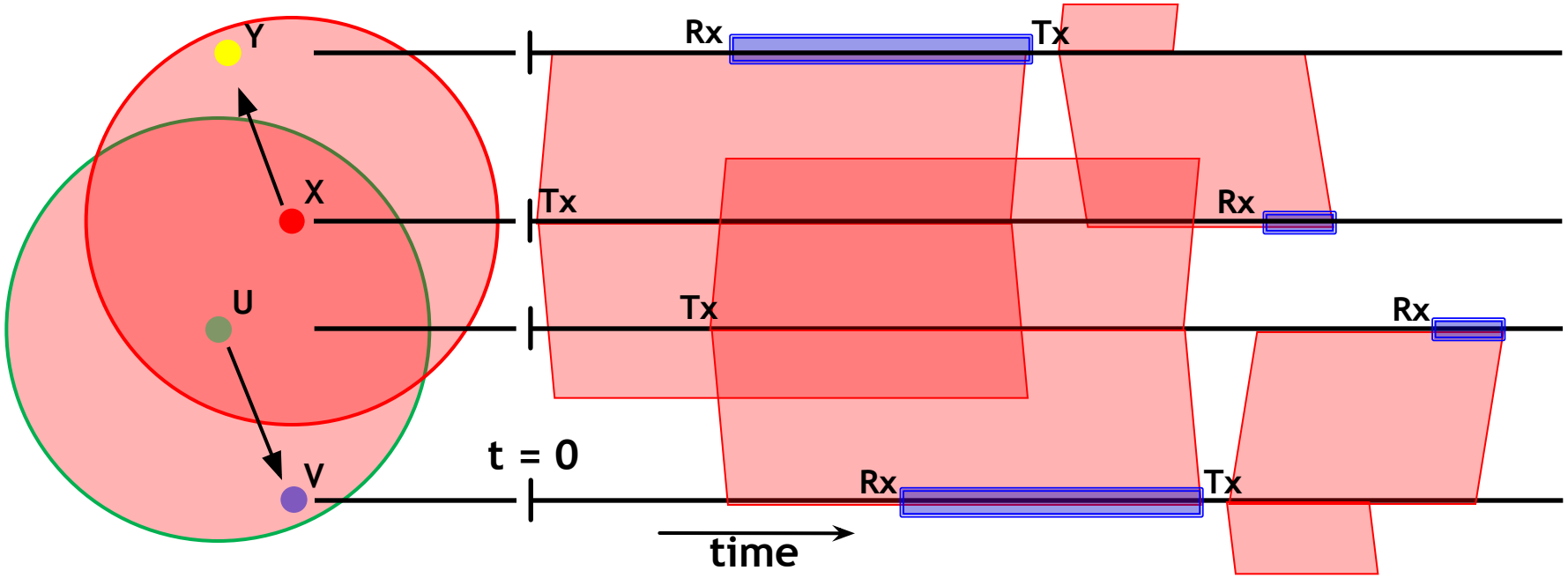


Observation: w/o spatial reuse



Observation: w/ spatial reuse

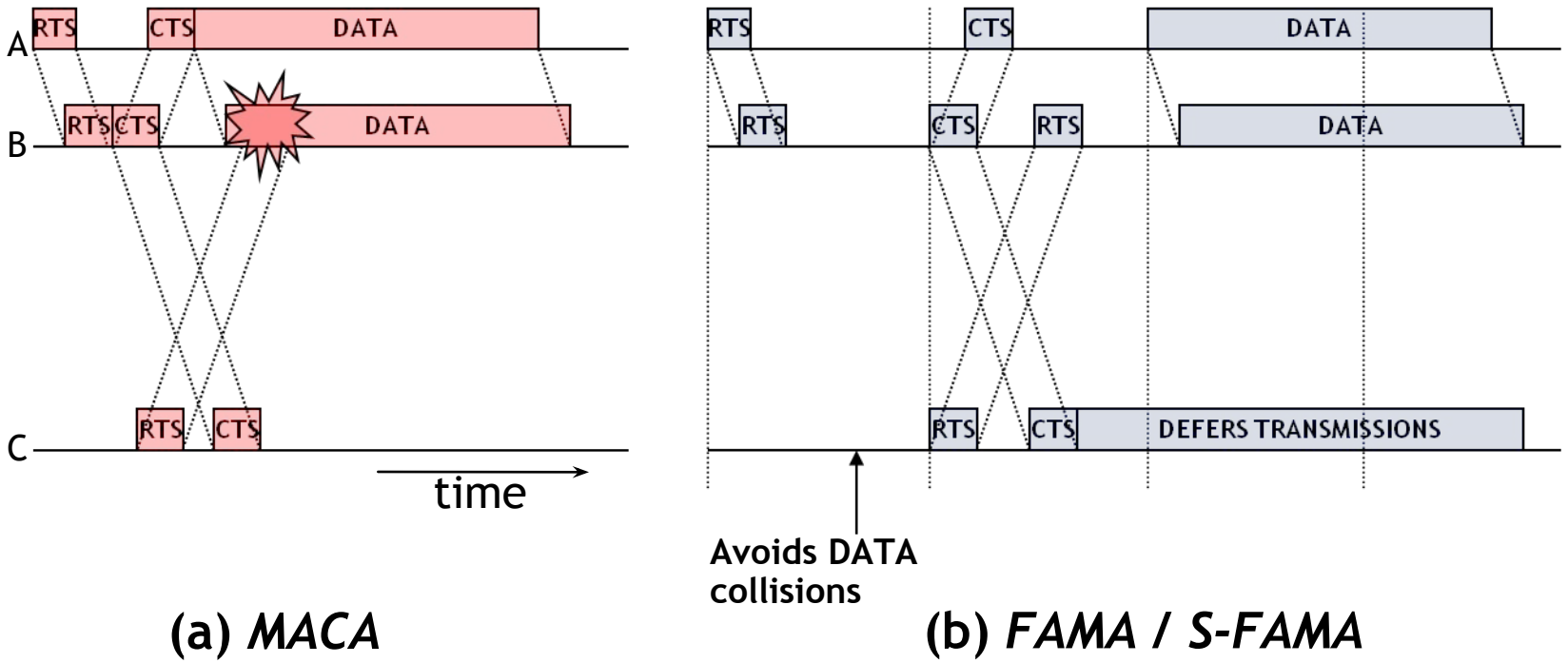


Objectives: harnessing temporal and spatial reuse

- Objectives of DOTS design:
  - Harness *temporal and spatial reuse*
  - Support *node mobility*

- Approach
  - CSMA-like random access protocol
  - *Using **passively** overheard packet information*
  - *Collect inter-node delay information based on*
    - *Timestamp with time sync*
    - Data length
    - *Expected propagation delays*

Base Design on DOTS

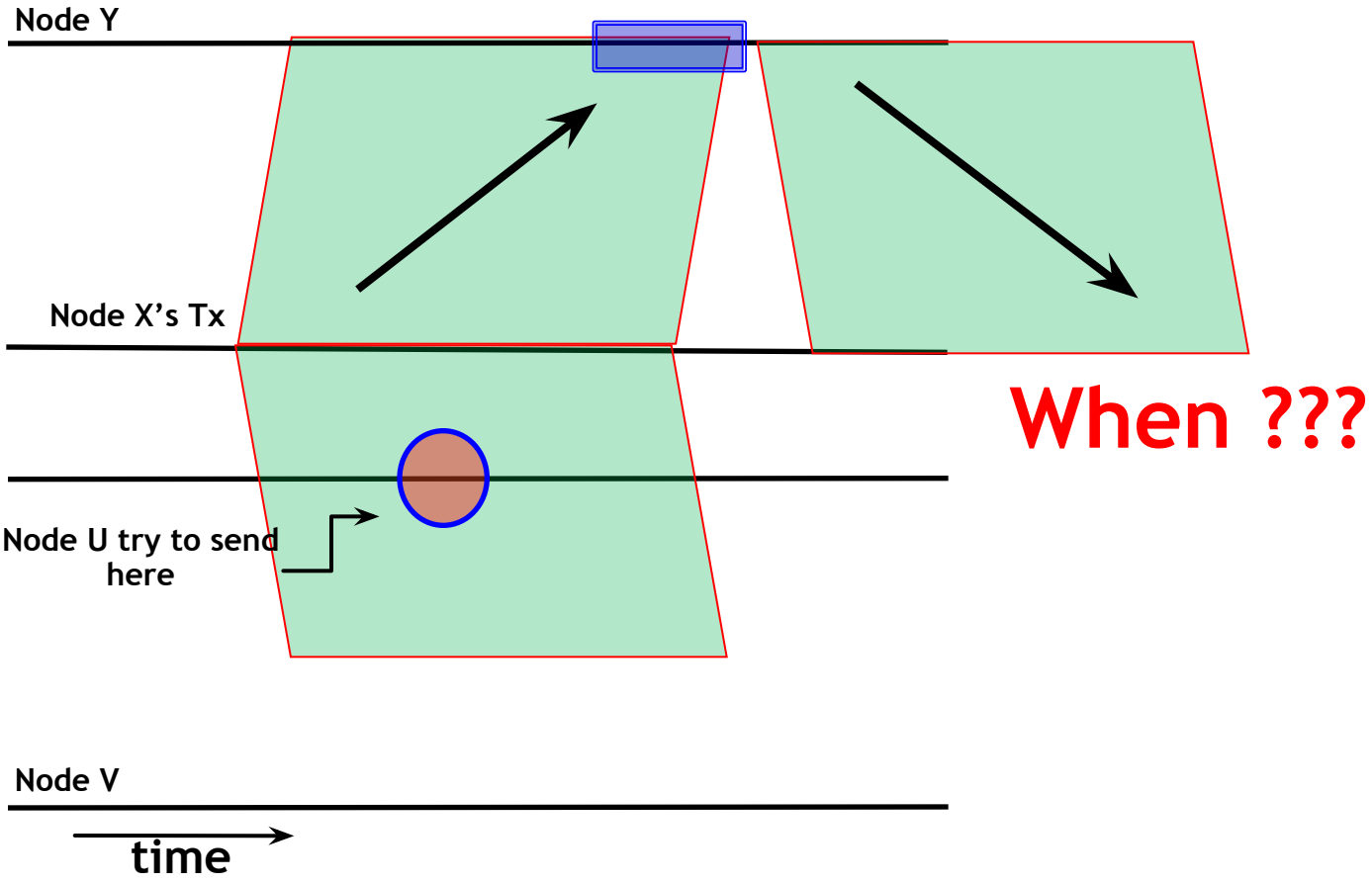


(a) *MACA* **(b) *FAMA / S-FAMA***

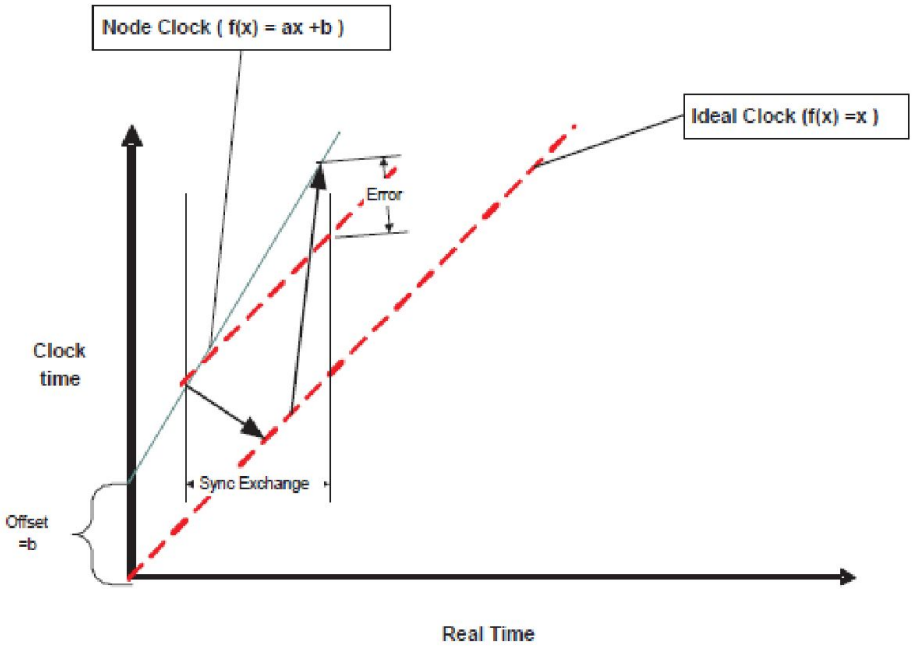
- RTS duration: CTS should wait greater than the maximum propagation delay.
- CTS duration: DATA should wait greater than RTS length + twice the maximum propagation + h/w transmit-to-receive transition time.

(MACA: Karn, CNC'90) (FAMA: Fullmer et al., SIGCOMM'95) (S-FAMA: Molins et al., OCEANS'06)

Passive overhearing does not tell everything!

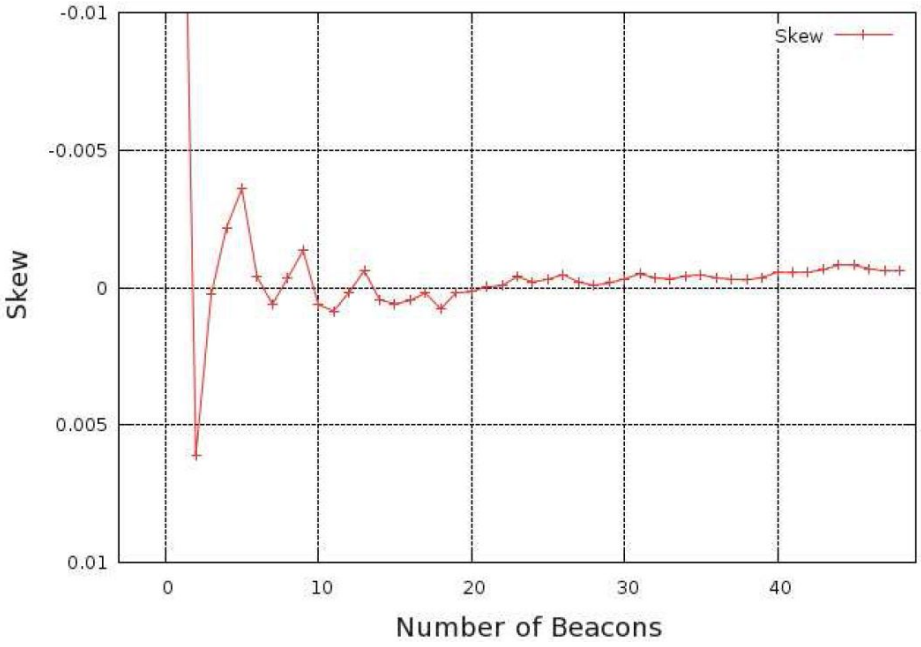


Time Synchronization



- Implement Time Sync for High Latency (TSHL) (Syed et al., INFOCOM'08) on Underwater Acoustic Networking plaTform (UANT)
- Clock offset:
  - Requires 2 msg exchanges
- Clock rate:
  - Requires about 10 msg exchanges
  - Computes a linear regression
- Dedicated h/w will decrease # of msgs
- Overhead of periodic resynchronization can be reduced by reference clock

Time Synchronization



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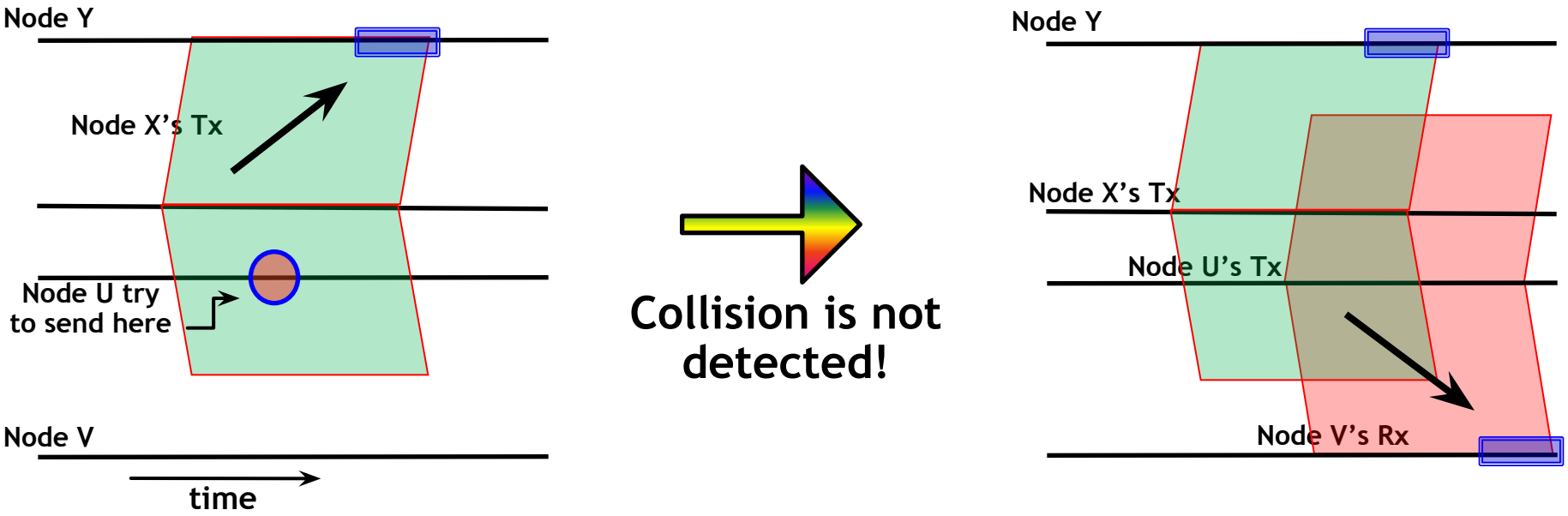
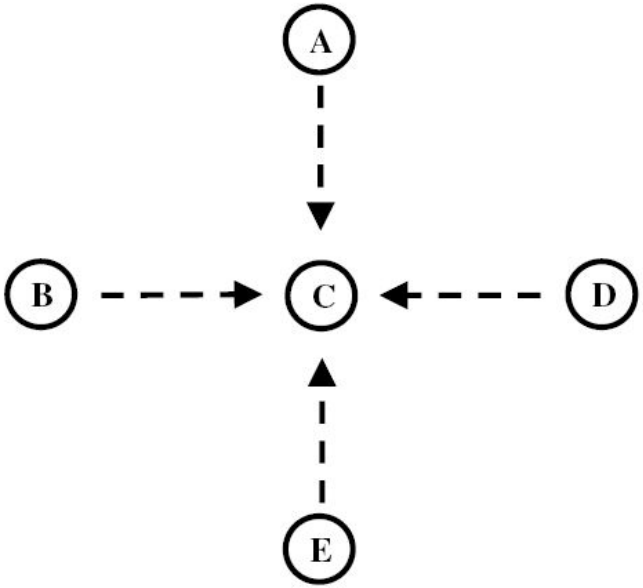
Tx Scheduling based on delay MAP



- 1. **Tx collision free Condition**
  - Based on delay MAP, check whether its transmission interferes neighbors' receptions.
- 2. **Rx collision free Condition**
  - Check whether intended receiver's reception is interfered with neighbors.
- 3. If either collision is detected, node 'U' will be backed off.
- 4. If both collisions conditions are not detected, node 'U' transmits.

Simulation Setup:



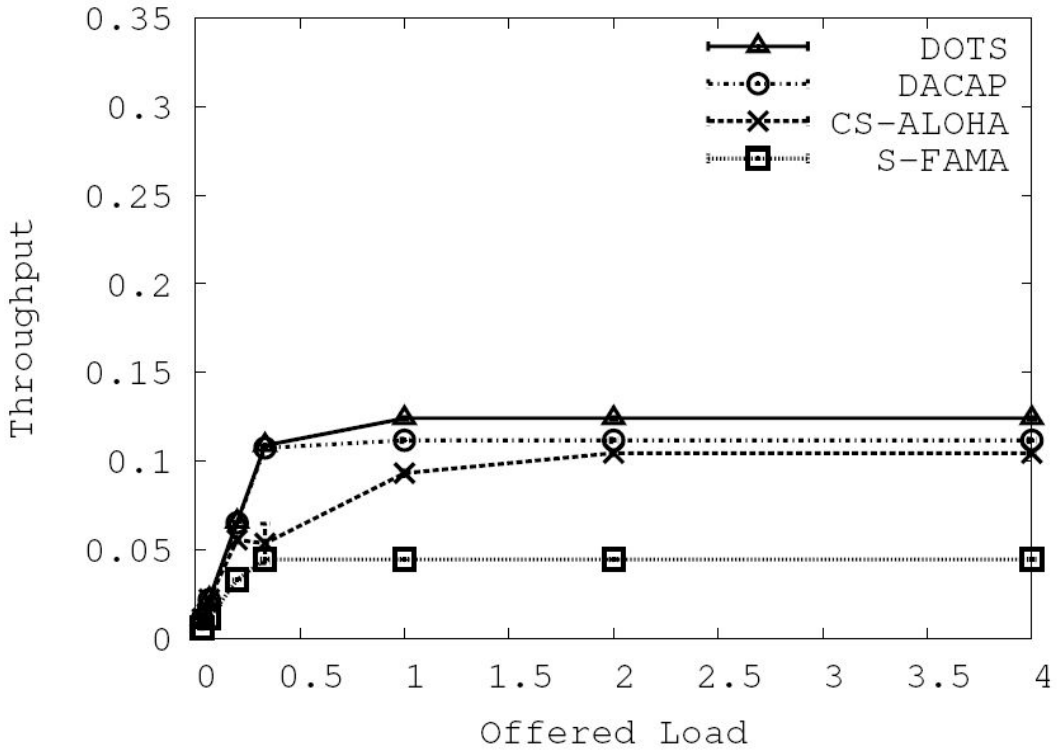
Simulation setup

- 3D region of 5km*5km*5km
- Distance between two nodes is 750m
- Data rate is set to 50kbps
- The packet size are varied from 512bytes to 1kbyte
- The load is varied between generating a single frame every 30sec down to a single frame every 0.25sec

Topology

- Line topology: exposed terminal
- Star topology: one sink and four srcs

Results: line topology



Line topology (exposed terminal case)

Throughput as a func of offered load

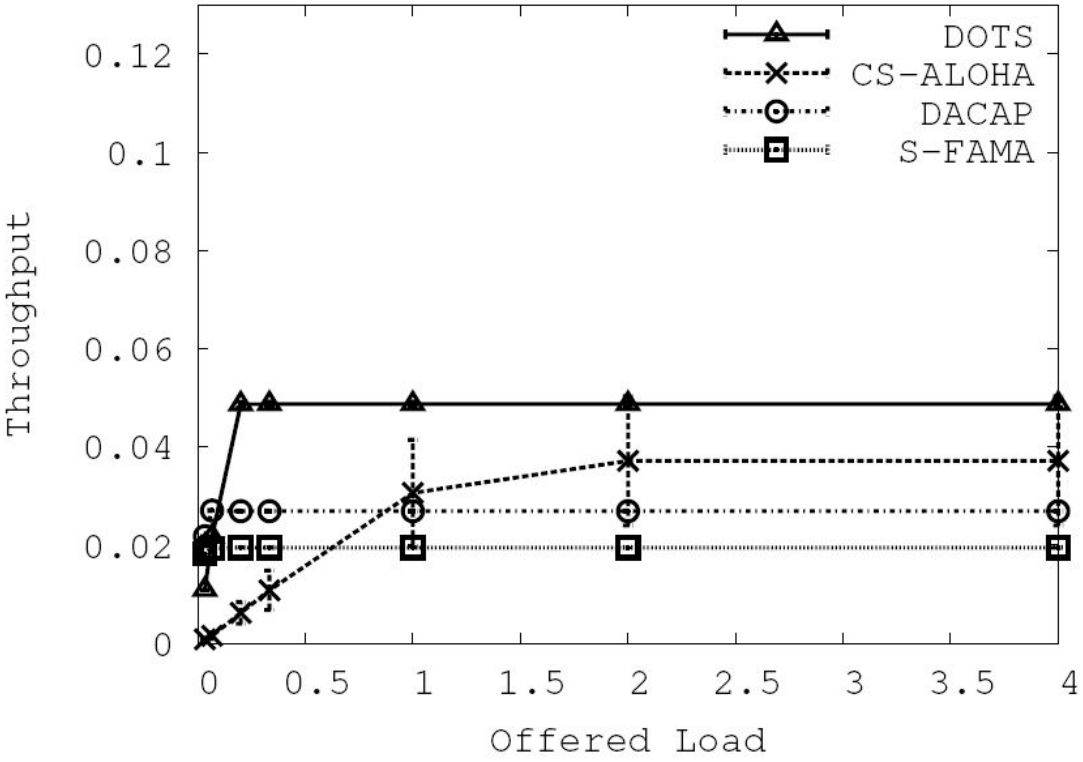
With fixed data size (512bytes) and transmission range (750m)

S-FAMA: CSMA/CA

CS-ALOHA: CSMA

DACAP: CSMA with warning signaling

Results: star topology

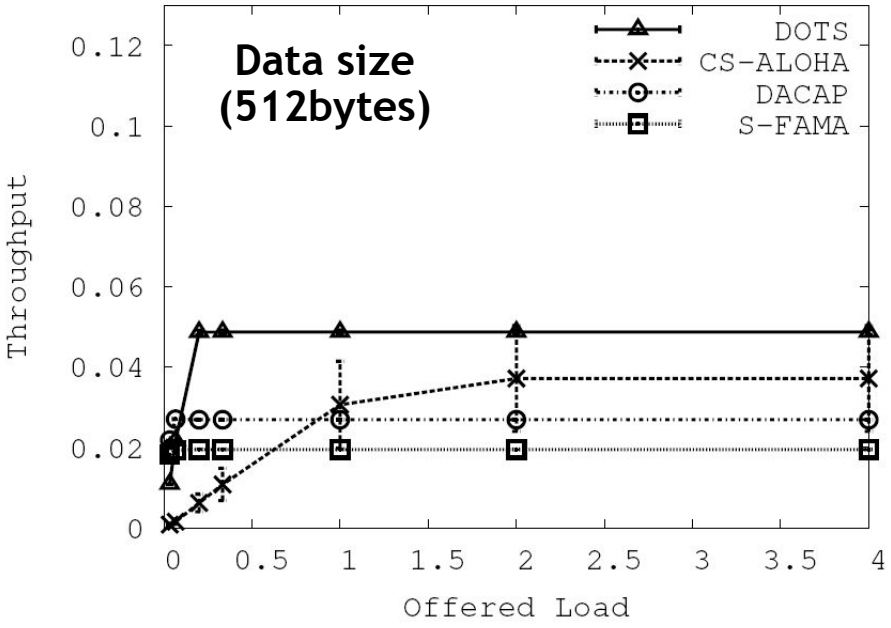


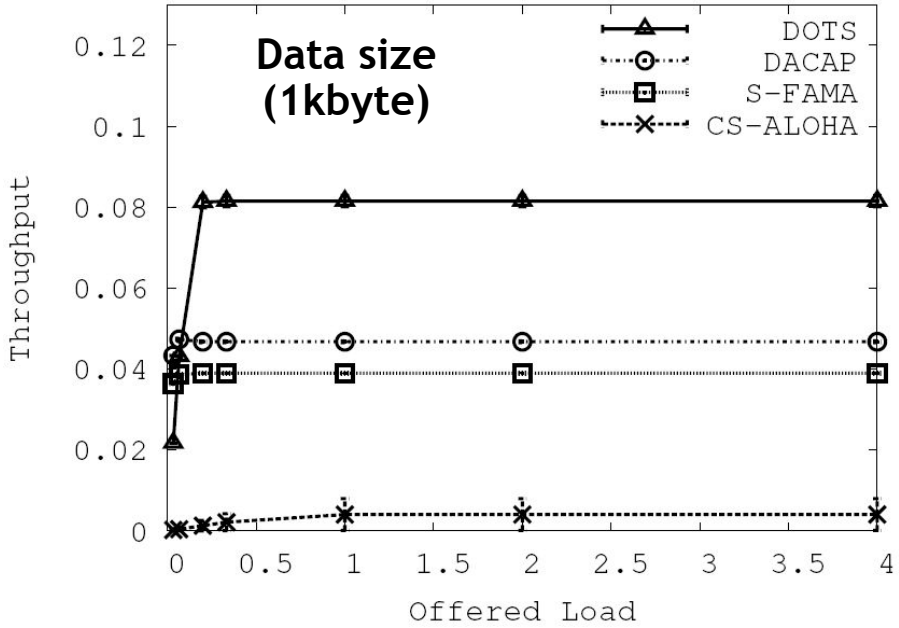
Star topology (aggressive contention)

Throughput as a func of offered load

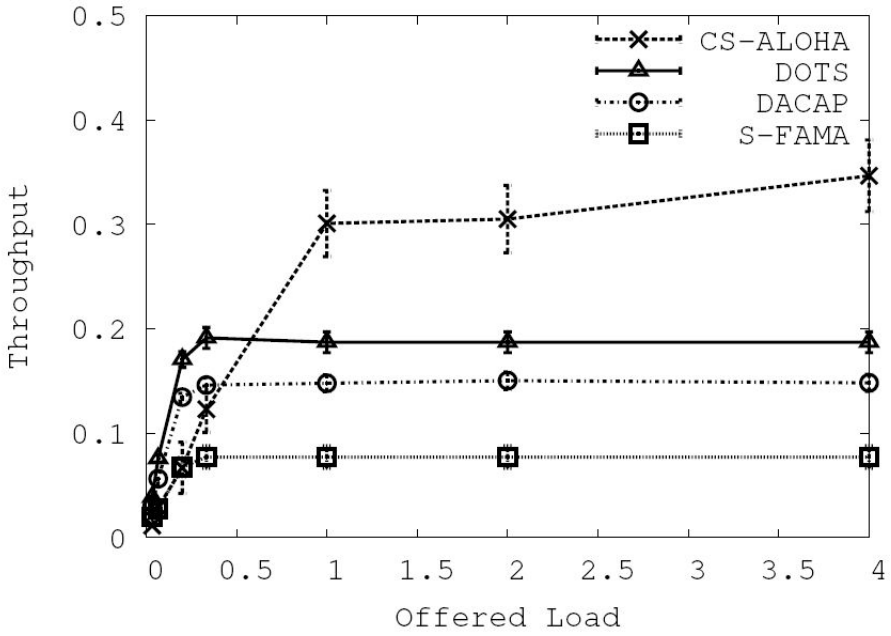
With fixed data size (512bytes) and transmission range (750m)

Results: star topology





Results: random topology w/ MCM

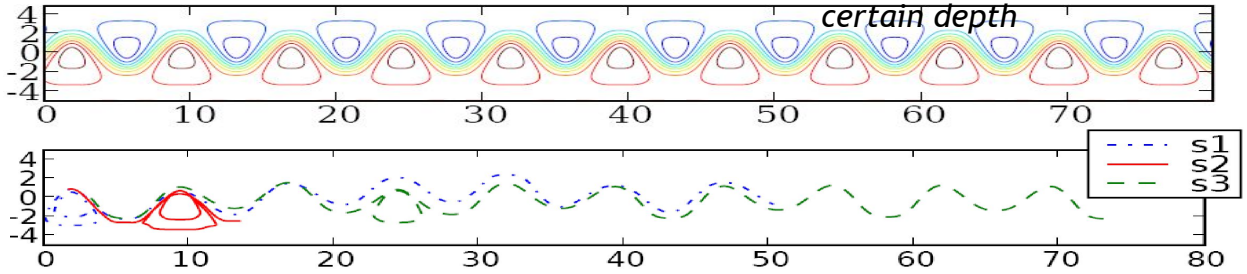


Random topology

Throughput as a func of offered load

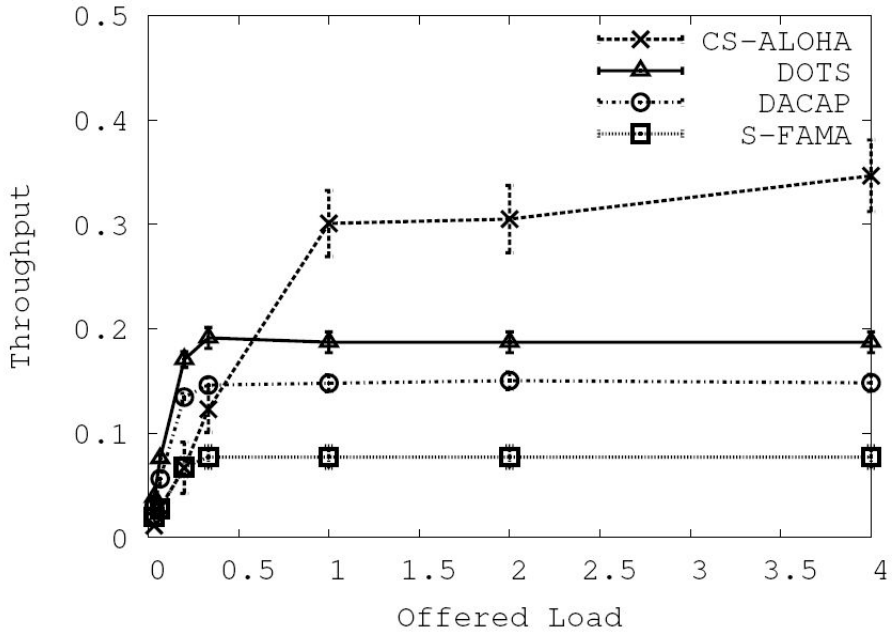
With fixed data size (512bytes) and transmission range (750m)

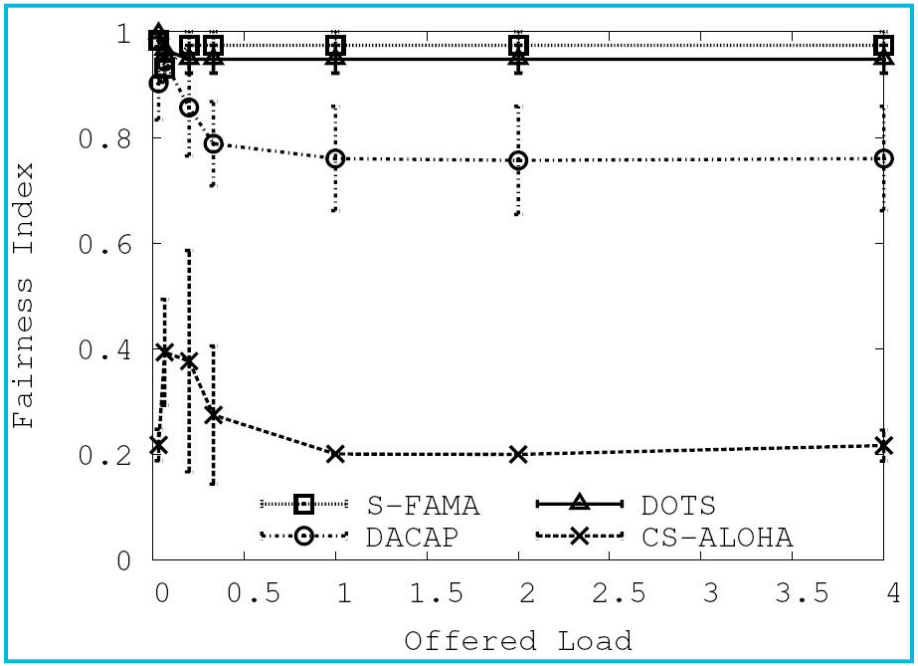
2D area at a certain depth



Example trajectories of three nodes: s1, s2, s3

Results: random topology w/ MCM





$$\text{Fairness Index} = \frac{(\sum x_i)^2}{(n \cdot \sum x_i^2)}$$

where x_i denotes the throughput of node i and n denotes the number of nodes in the network.

Summary & Future Work

Summary

- DOTS:

  - Harnessing temporal and spatial reuse

  - Improving throughput and providing fairness

  - Supporting underwater mobility

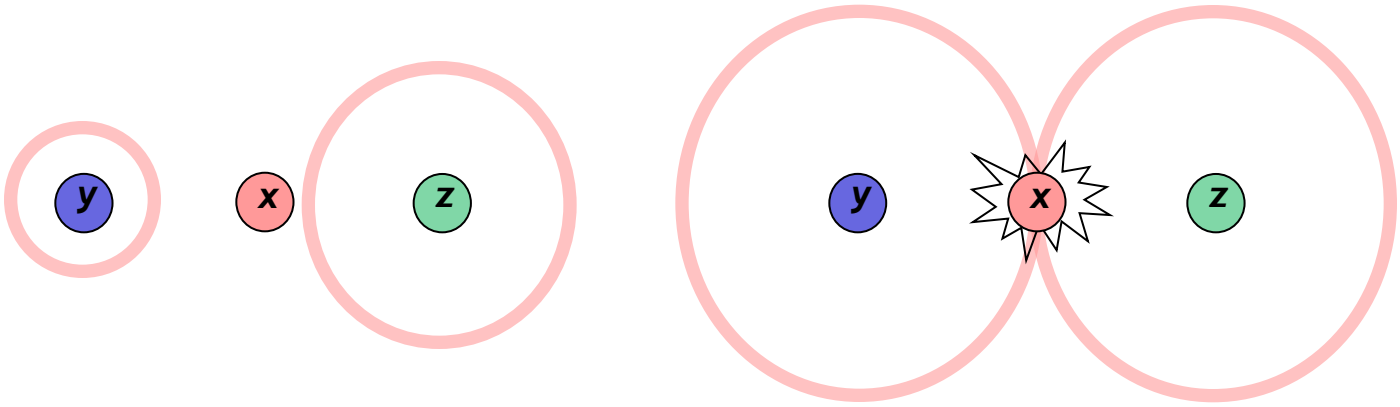
Future Work:

- Protocol performance as a function of time sync error
- Windowed ACK
- Interference aware MAC protocol with channel capturing

Q&A

Condition of Collision

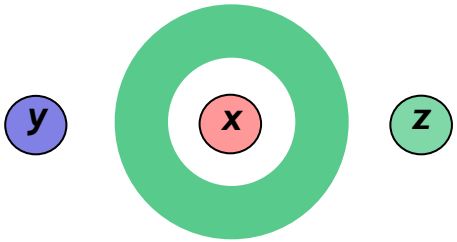
A "collision" occurs when a receiver is in the reception range of two transmitting stations, and is unable to cleanly receive signal from either station.



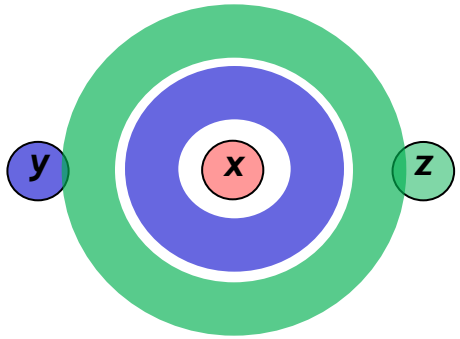
(a) x will receive frames from z and y sequentially w/o any collision.

(b) Collision happens: z cannot decode any of two frames.

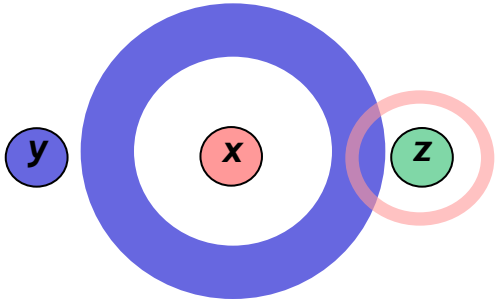
Observation: w/ temporal reuse



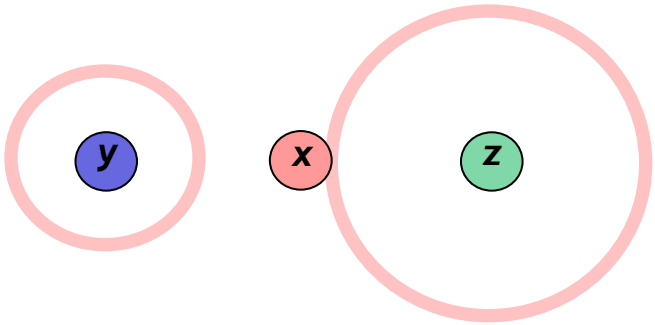
(a) x sends DATA to z



(b) x sends DATA to y and z

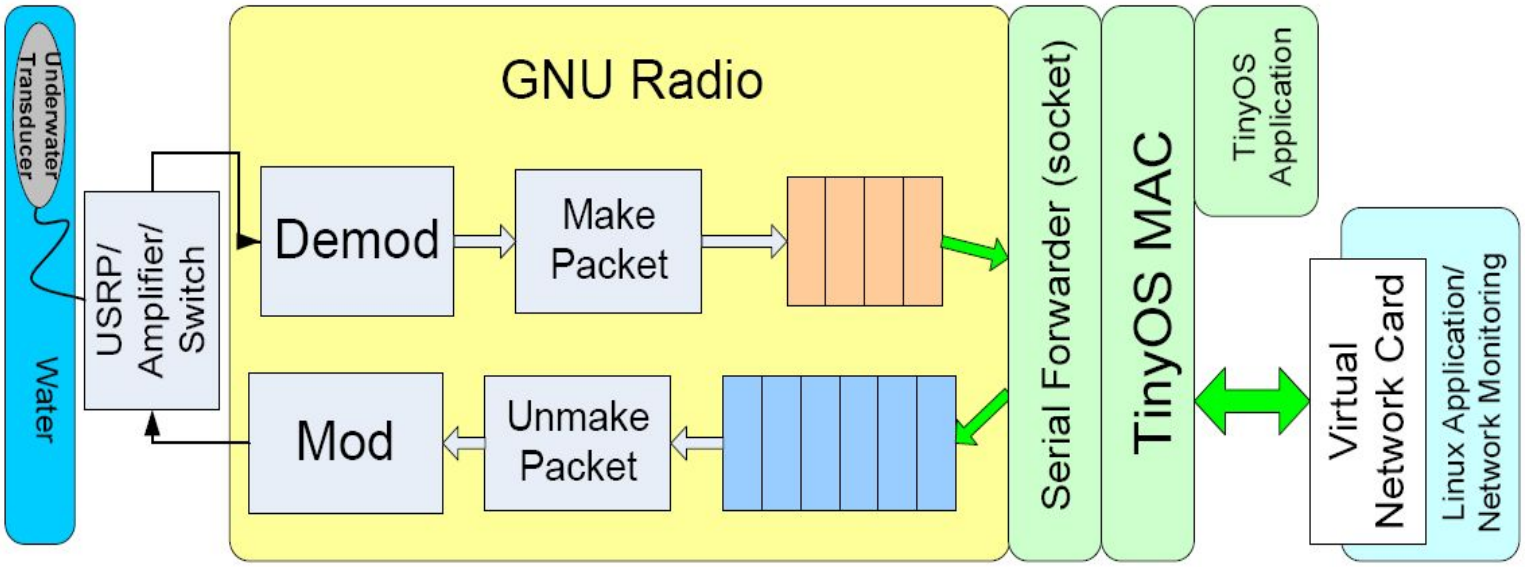


(c) x sends DATA to y and z sends ACK back to x

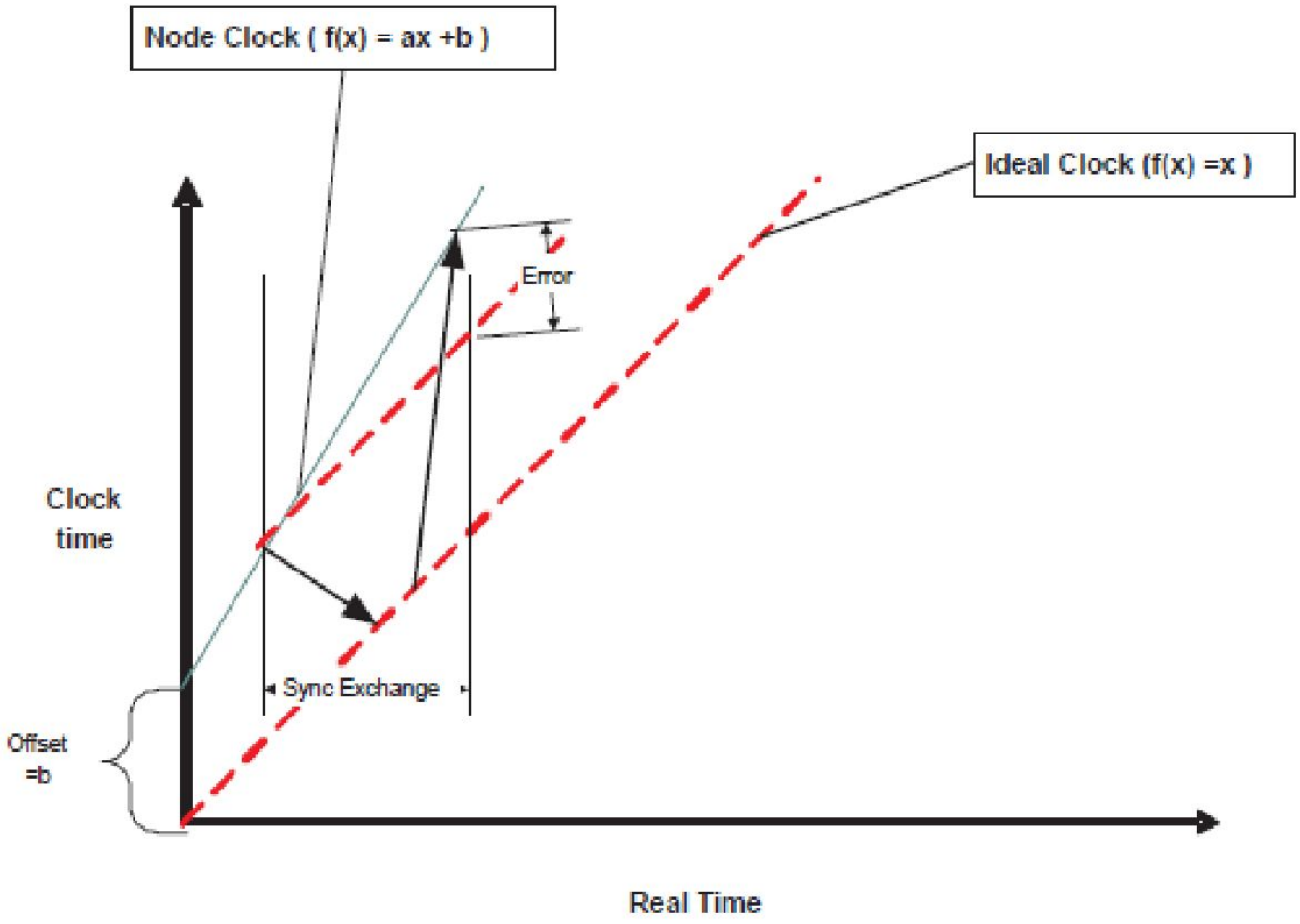


(d) z and y send ACK back to x

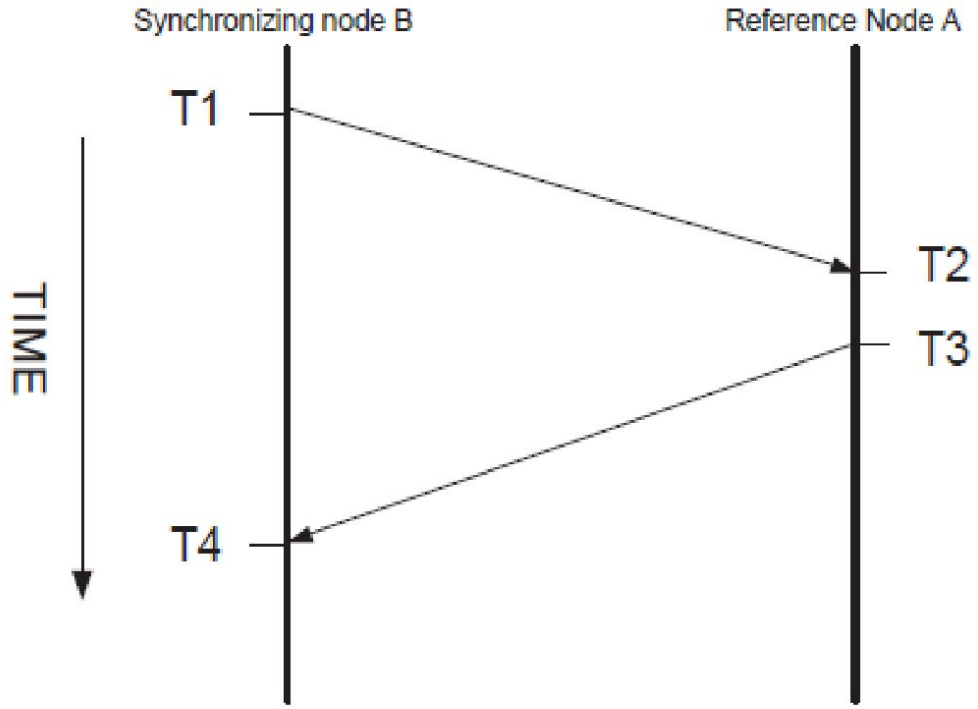
UANT System Architecture



Time Synchronization High Latency



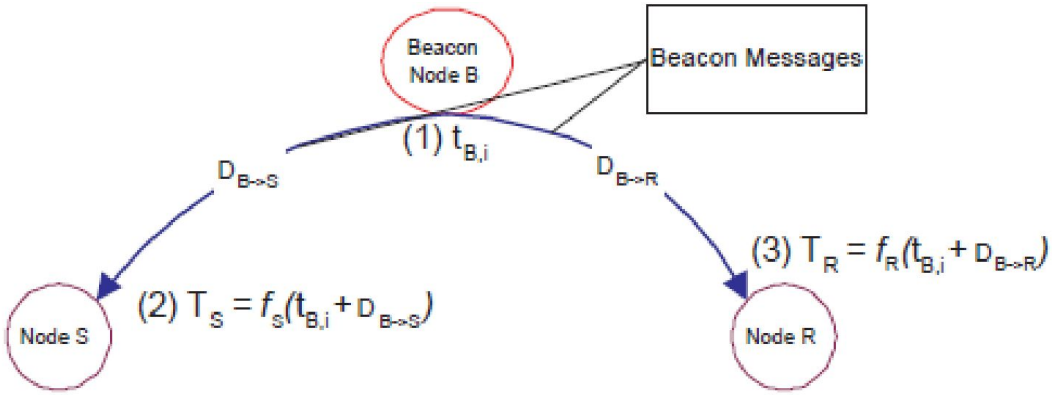
TSHL-Phase two



Phase offset = [(T2-T1) - (T4-T3)]/2
Propagation Delay = [(T2-T1) + (T4-T3)]/2.

TSHL-Phase one

Model the skew of a node's clock so that each node is skew synchronized.

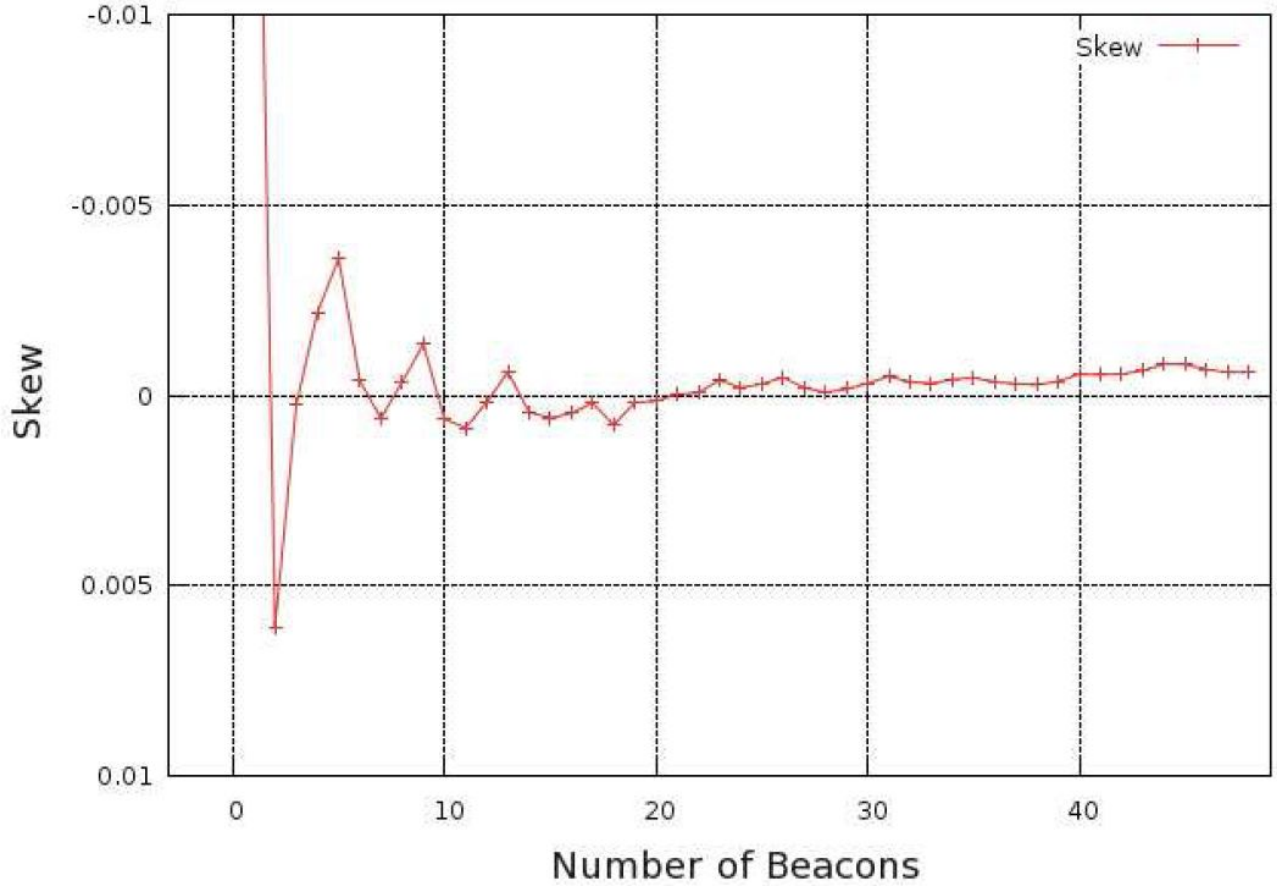


$f_R(t), f_S(t)$ represent the individual, unsynchronized clocks of nodes R & S.

Linear regression

- (Local Time, Beacon Time – Local Time)

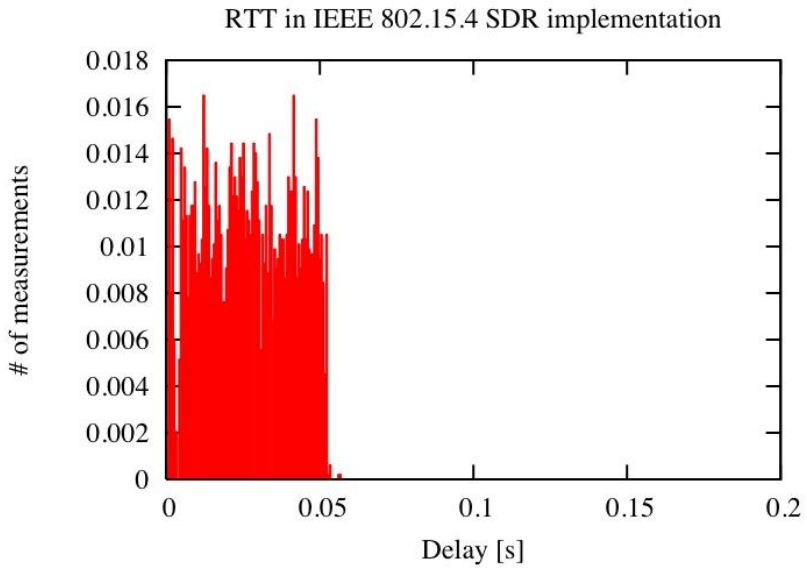
Results – # of Beacons

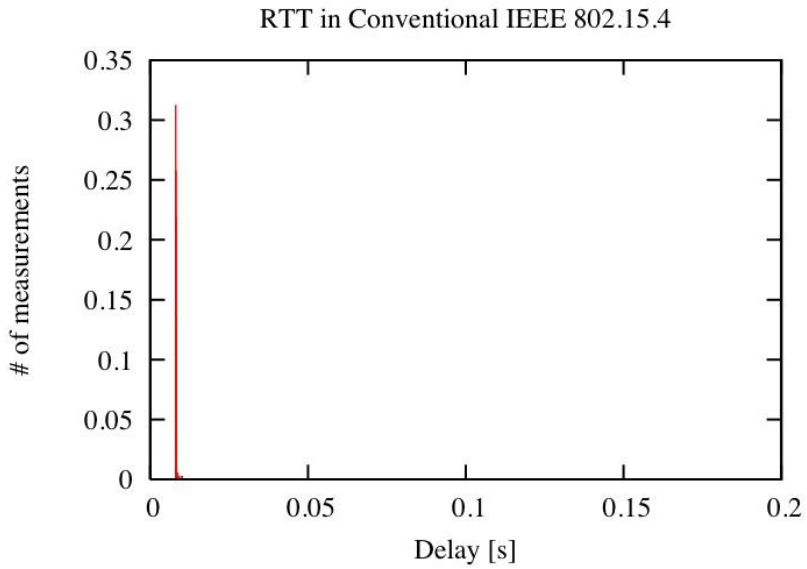


Non-deterministic Latency

Latency introduced to and from USRP and host machine

For acoustics, it is manageable due to low propagation speed and limited bandwidth





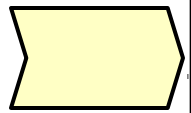
Schedule Recovery (appendix)

A node may miss its neighbors' RTS/CTS

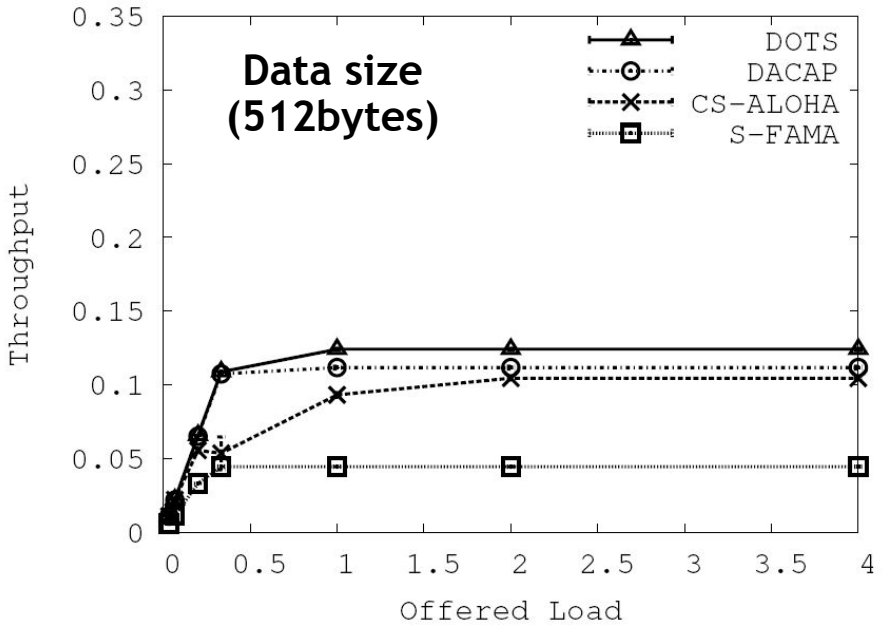
- Cause: the half-duplex and lossy nature of the acoustic modem
- Result: cause frame collision
- To minimize the damage caused by a collision and avoid deadlocks

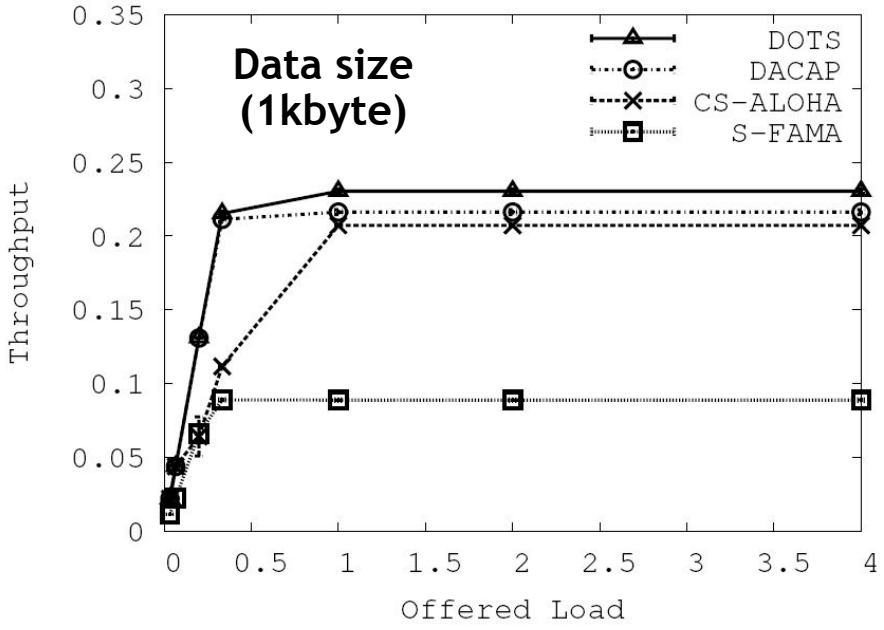
Method

- Using the timestamp knowledge in its delay map database to give preference to the earlier transmission schedules
- To reduce the damage of schedule conflict



Results: line topology (appendix)



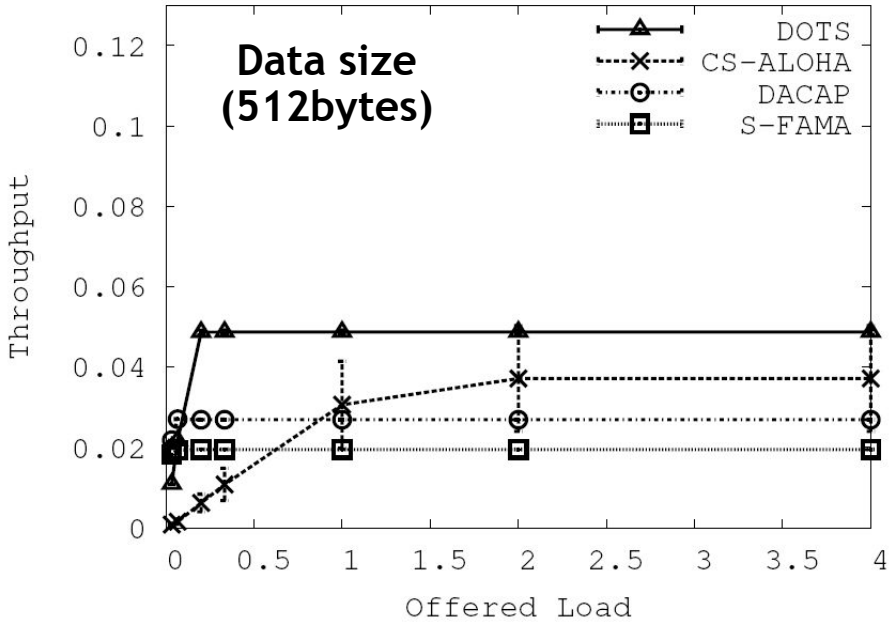


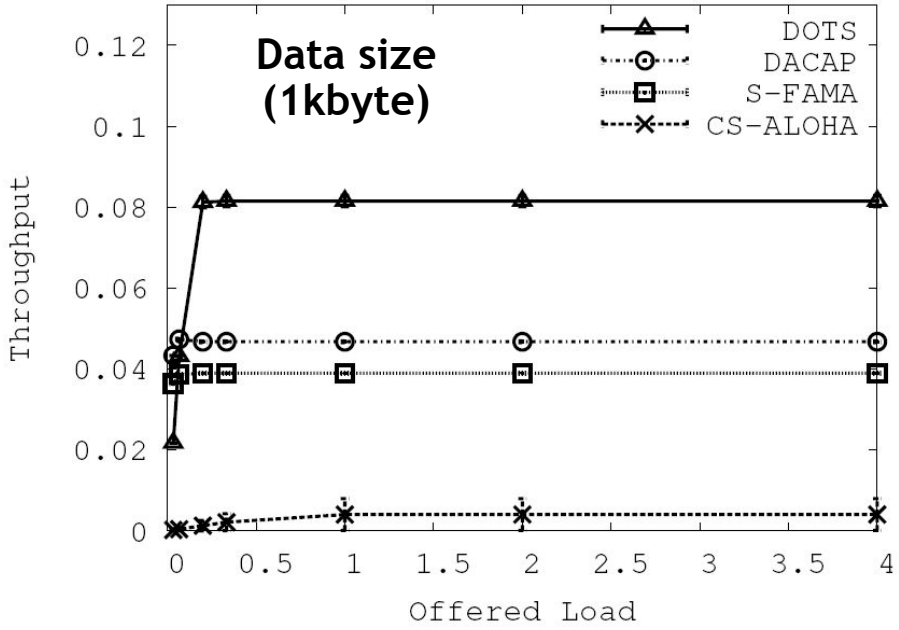
$$\text{Throughput} = \frac{\#\text{ of } data \text{ rx} \times \Delta_{data}}{\text{Simulation Duration}}$$

where Δ_{data} denotes the duration of transmitting a data frame.

$$\text{Offered Load} = \frac{\#\text{ of Generated } data \times \Delta_{data}}{\text{Simulation Duration}}$$

Results: star topology (appendix)





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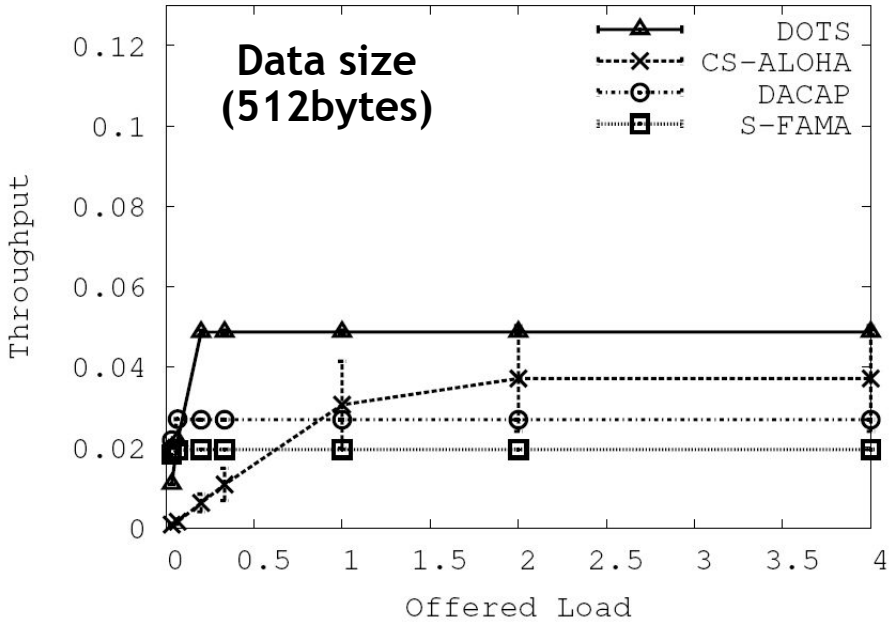

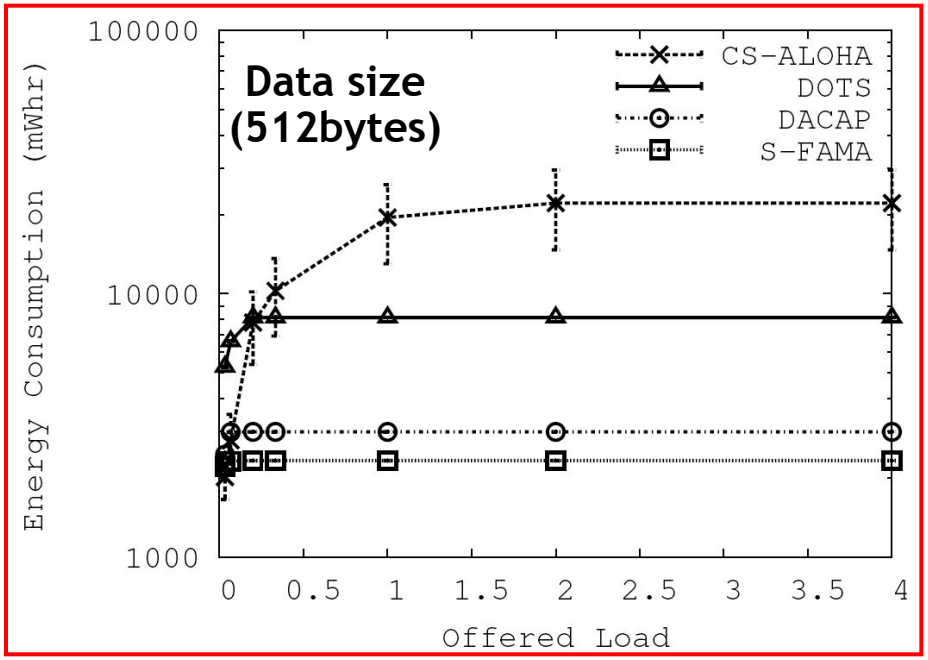

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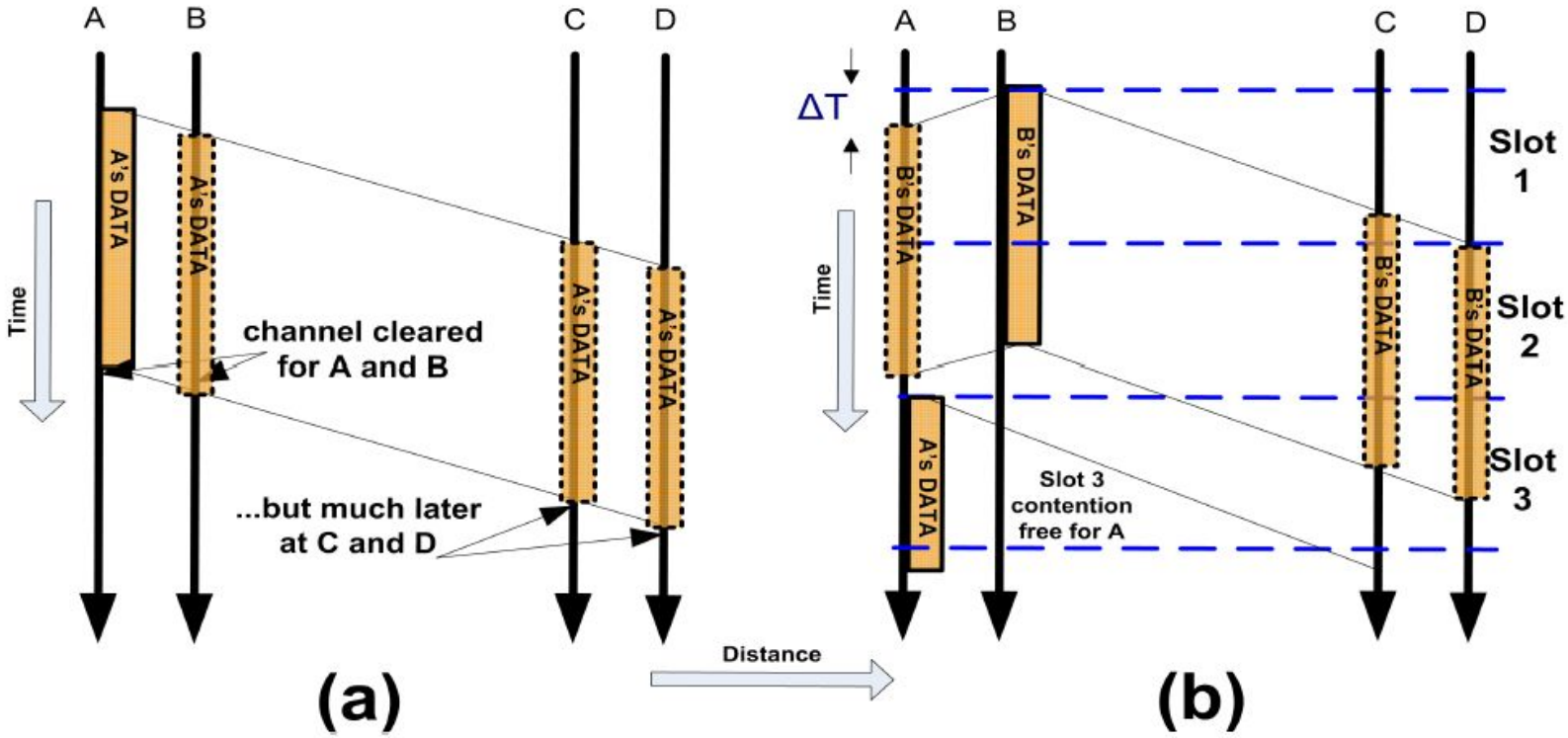
Spatial Unfairness



Simulation Setup

- QualNet 3.9.5 enhanced with an acoustic channel model
  - Urick's u/w path loss model: $A(d, f) = d^k a(f)^d$ where distance d, freq f, absorption $a(f)$
  - Rayleigh fading to model small scale fading
- 8 nodes are randomly deployed in an area of "670m*670m*670m"
  - Mobility model: 3D version of Meandering Current Mobility (MCM) [INFOCOM'08]