RISM: An Efficient Spectrum Management System for Underwater Cognitive Acoustic Networks (UCANs)

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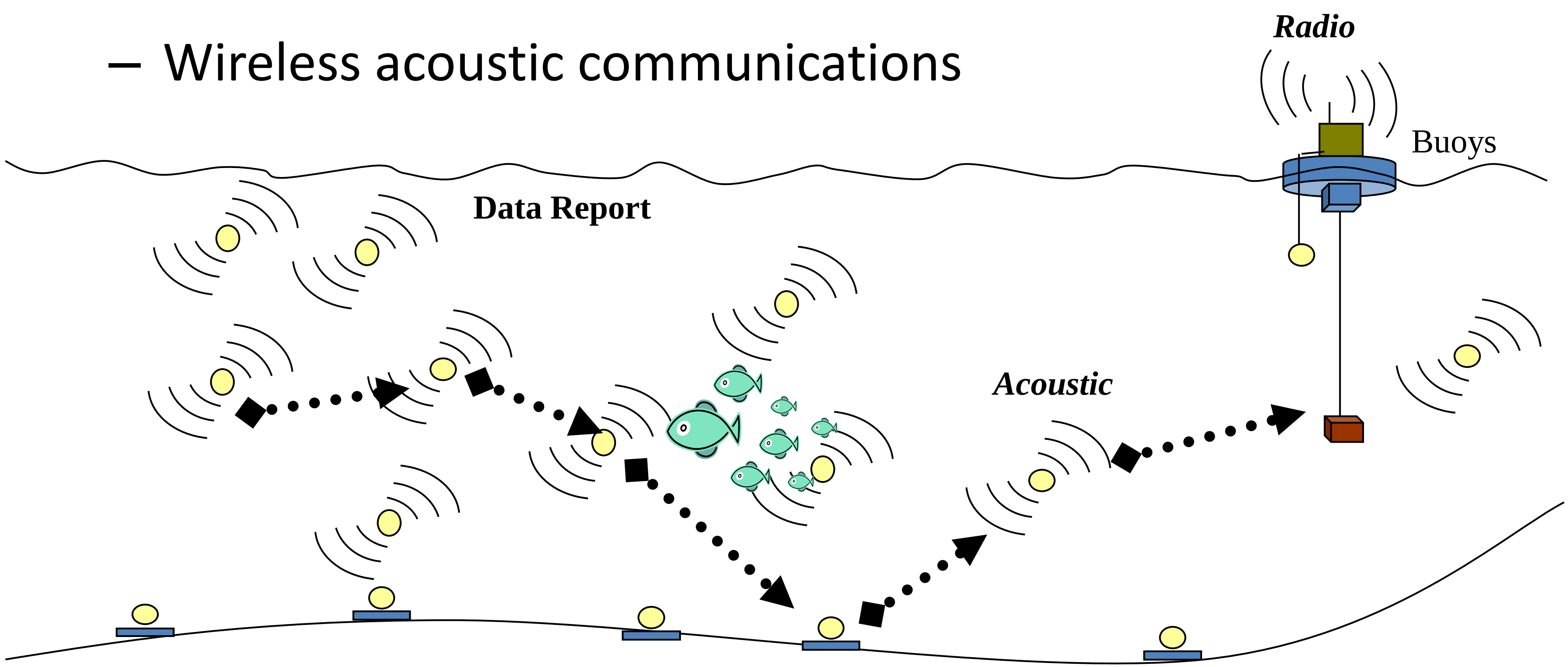
Underwater Acoustic Networks (UANs)

- What is an UAN?
  - An interconnected system
  - Distributed autonomous nodes
  - Wireless acoustic communications



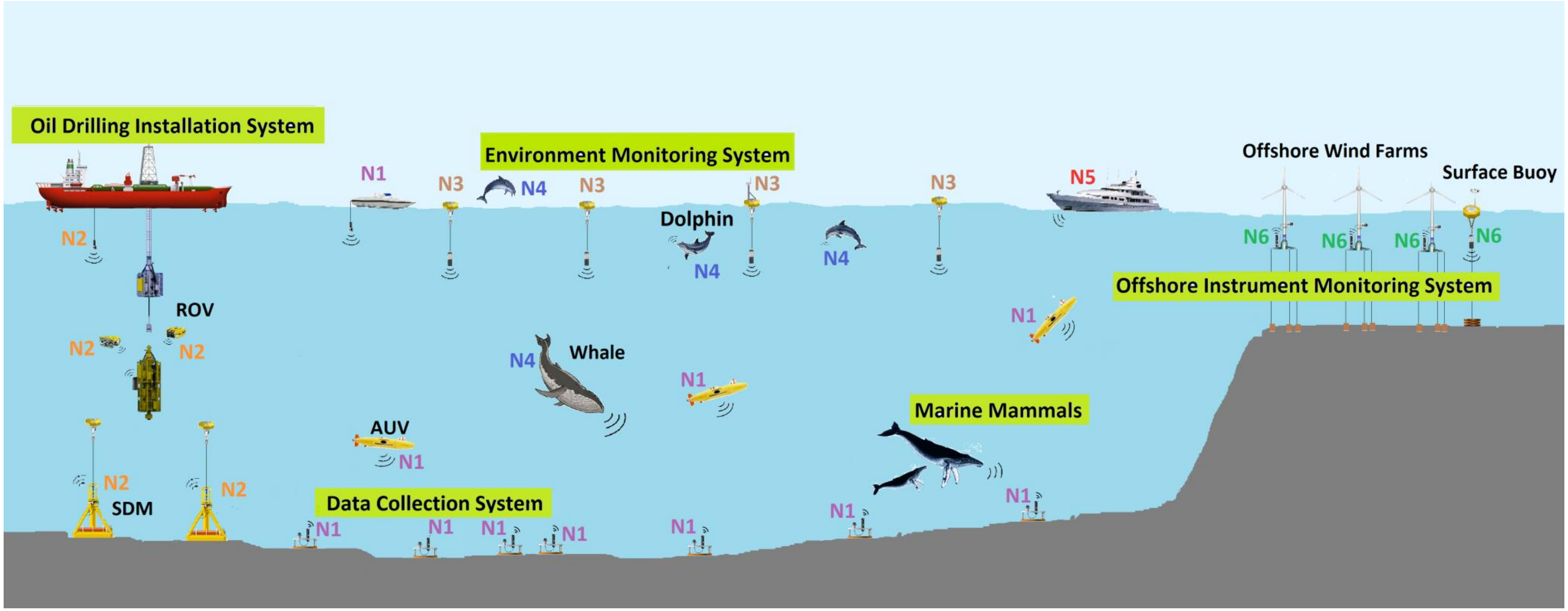
Underwater Acoustic Networks (UANs)

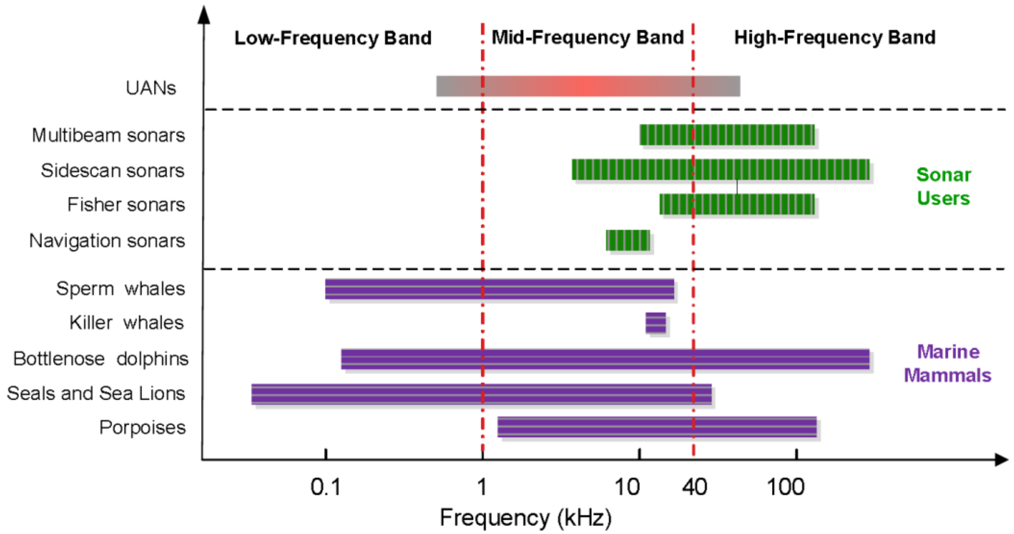
- UAN challenges
  - Low bandwidth
  - High error probability
  - Long and variable propagation delay
  - Multi-path and Doppler effects
  - Passive or active node mobility
  - Spatial and temporal uncertainty
  - Limited available energy
  - Prone to failures (e.g. fouling, corrosion)
  - Expensive costs
  - Heterogeneity and link asymmetry
  - …

- **New research at every layer of the network is demanded**

- Question: can UANs be more environmentally friendly?

UANs share channel resources with multiple acoustic systems in the ocean





- **Sonar systems**
  - Fish finder
  - Navigation
- **Marine mammals**
  - Whale
  - Dolphin
- **Other UANs**
  - Environment monitoring
  - Instrument monitoring

Limitation of conventional UANs:

- Focus on **single network scenario**
- Aggressive channel sharing, so **environment-unfriendly**

The Underwater cognitive acoustic network (**UCAN**) :

- **Environment-friendly transmissions:** Users in UCANs suspend transmitting or switch to other vacant frequencies when the presence of primary users (PU) are sensed.
- **Channel-efficient communications:** high throughput, efficient channel utilization and short end-to-end delay

Outline

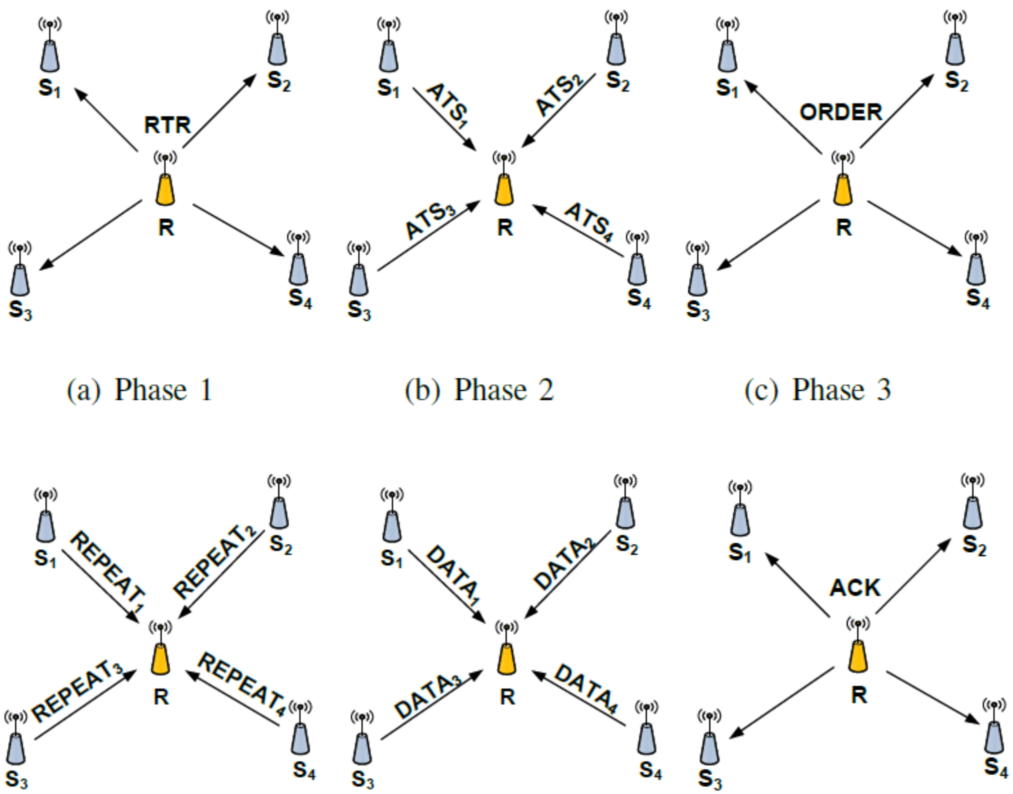
- **Overview** of receiver-initiated spectrum management (RISM) system
  - **Receiver-initiated** **spectrum sharing** (RISS) scheme
  - **Collaborative** **spectrum sensing**
  - **Collision avoidance** and **spectrum decision**
- **Performance evaluation**
- **Conclusions**

Overview of RISM

- RISM is a "**Semi-centralized**" system
  - Receiver initialize the negotiation process
  - Receiver collect local sensing information for collaborative sensing
  - Receiver assign channel to intended senders
- Handshaking process is utilized in
  - Collaborative spectrum sensing
  - Channel allocation
- Following features of underwater systems are considered
  - Non-synchronized communications
  - Long propagation delay
  - Spectrum characteristics of marine mammals

Receiver-initiated spectrum sharing (RISS)

Objective: Schedule control packets for **spectrum sensing**, **channel allocation** and **collision avoidance**



(a) Phase 1 (b) Phase 2 (c) Phase 3

(d) Phase 4 (e) Phase 5 (f) Phase 6

RTR: Request-to-receive

ATS: Available-to-send

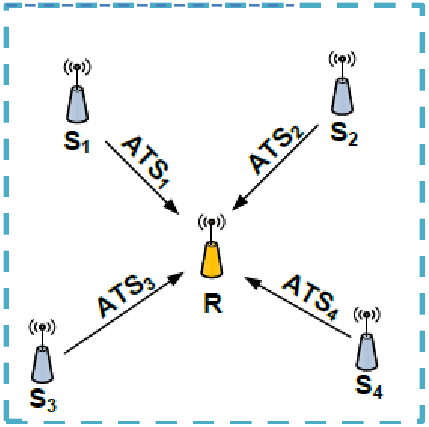
ORDER: Order packet

REPEAT: Repeat packet

DATA: Data packet

ACK: Acknowledgement

Collaborative spectrum sensing (1)



Objective: Improve sensing accuracy and efficiency

Assumption: Each CA user can only sense a limited number of channels in one period

Challenge: The network can be non-synchronized

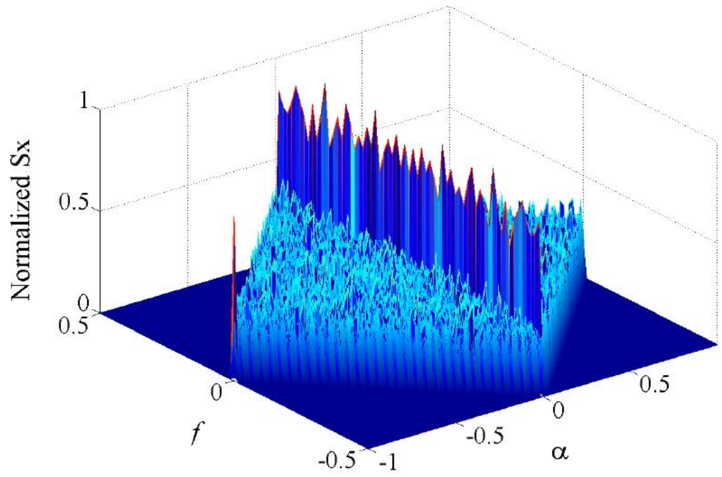
Common **quiet period** for spectrum sensing is not available

When some CA users are sensing, others may be transmitting

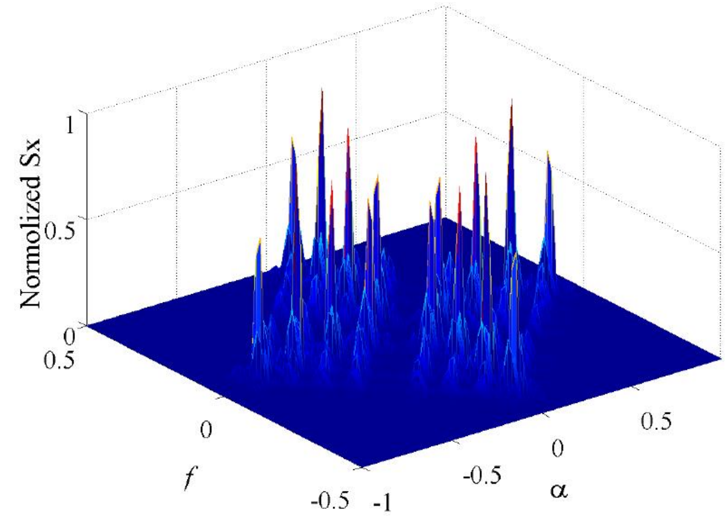
How to distinguish signals of **CA users** the **primary users**, like the marine mammals?

Solution: ***Cyclostationary*** based signal detection approaches

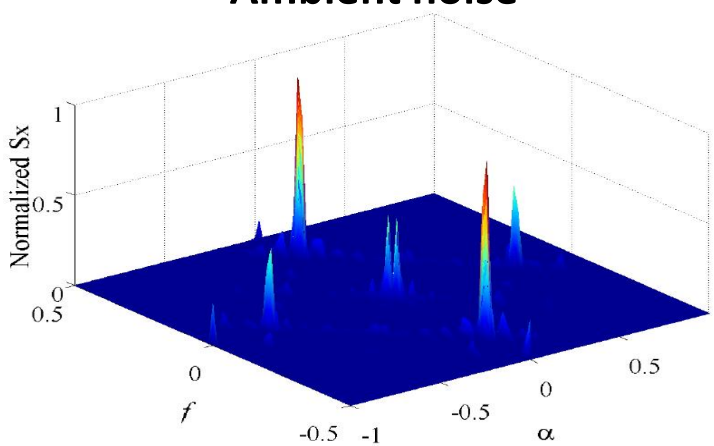
Collaborative spectrum sensing (2)



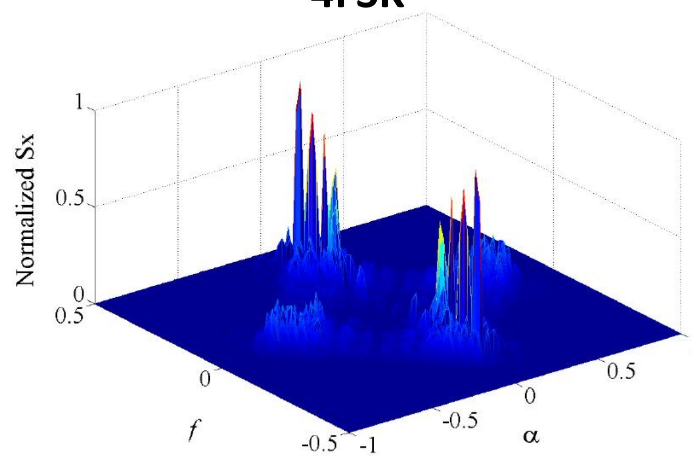
Ambient noise



4FSK



Blue dolphin



Minke

S_x: *cyclic cross periodogram* α: *nomolized cyclic frequence* f: *nomolized frequency*

Next: Spectrum decision …

Collision avoidance and spectrum decision (1)

Objective: Efficient and **collision free** channel and power allocation

Data rate of user *k* on channel *n* at time *t*

Channel capacity of user *k* on channel *n* at time *t*

Predetermined outage probability of user *k* on channel *n*

Shannon theorem

$$Pr[R_{nk}^t > C_{nk}^t] \leq \beta_{nk} \qquad C_{nk}^t = a_{nk}^t B_n \log_2(1 + \frac{p_{nk}^t |h_{nk}^t|^2}{N_0 B_n a_{nk}^t})$$

Channel gain follows Rayleigh distribution

$$f(|h_{nk}|^2, \lambda_{nk}) = \begin{cases} \frac{1}{\lambda_{nk}} exp\left(-\frac{|h_{nk}^t|^2}{\lambda_{nk}}\right), & |h_{nk}^t|^2 \geq 0, \\ 0, & |h_{nk}^t|^2 \leq 0. \end{cases}$$

Mean value of channel gain

Transmission power

$$R_{nk}^t \leq a_{nk}^t B_n \log_2\left[1 + \frac{p_{nk}^t \lambda_{nk} \ln(\frac{1}{1-\beta_{nk}})}{N_0 B_n a_{nk}}\right]$$

$$a_{nk} = \begin{cases} 1, & channel\ n\ is\ assigned\ to\ user\ k \\ 0, & otherwise \end{cases}$$

Collision avoidance and spectrum decision (2)

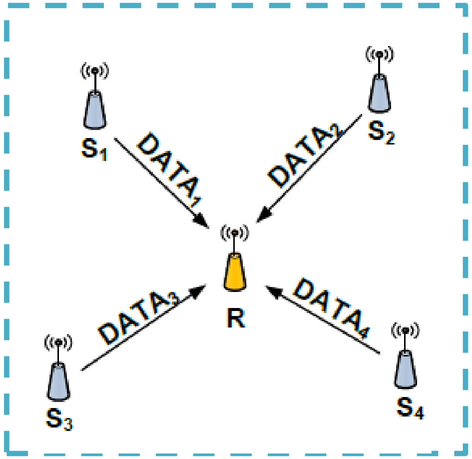
Joint **power** and **frequency band** allocation for RISM

Objective: **Minimize** the **total time receiving DATA packets** on receivers

To Minimize

Bandwidth

$$L = \int_0^{T_r} \sum_{n=1}^{N} \sum_{k=1}^{K} B_n R_{nk}^t \, dt \;\longrightarrow\; \max \sum_{n=1}^{N} \sum_{k=1}^{K} B_n R_{nk}^t$$



Optimization Problem:

Prob.1

$$\arg \max_{\substack{p_{nk}^t > 0 \\ a_{nk}^t \in \{0,1\}}} \sum_{n=1}^{N} \sum_{k=1}^{K} R_{nk}^t,$$

where $$R_{nk}^t = a_{nk}^t B_n \log_2 \left[1 + \frac{p_{nk}^t \lambda_{nk} \ln(\frac{1}{1-\beta_{nk}})}{N_0 B_n a_{nk}} \right].$$

s.t.

C1: $\sum_{k=1}^{K} a_{nk}^t = 1, \quad n \in \{1, \ldots, N\},$

Total transmission power of user k

C2: $\sum_{n=1}^{N} p_{nk}^t \le P_k, \quad k \in \{1, \ldots, K\},$

C3: $a_{nk}^t = 0, \text{ if } c_{nk}^t = 1, \; n \in \{1, \ldots, N\}, k \in \{1, \ldots, K\}$

Collision avoidance entry

Performance evaluation – Settings

Simulator: Aqua-Sim (ns-2 based)

Channel fading: Rayleigh model

Maximum transmission power: 20 watt

Maximum transmission range : 1.5 km

Average distance between neighboring users: 1 km

Bandwidth of whole frequency: 1 kHz – 31 kHz

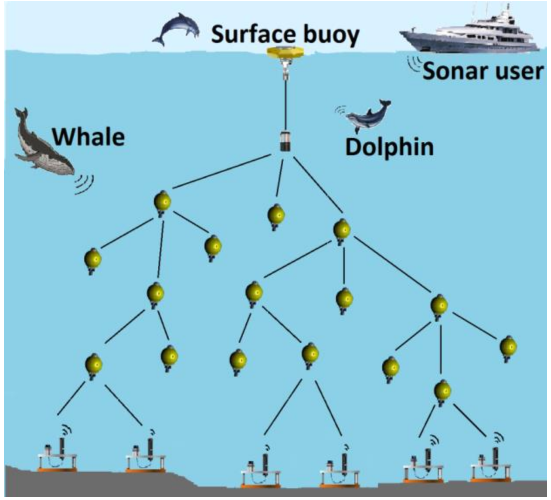
Common control channel: 1 kHz – 6 kHz

Bandwidth of each subset frequency: 5 kHz

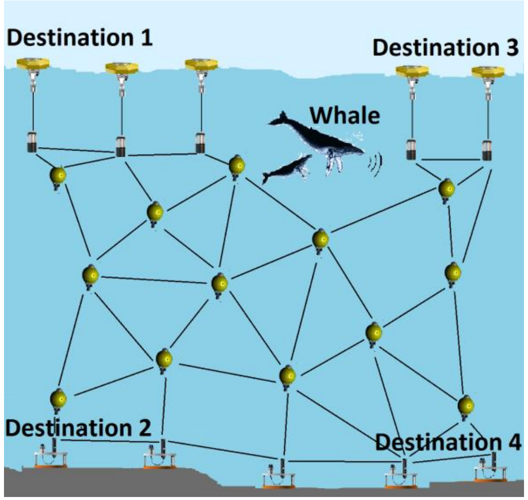
Routing protocol: Vector-based forwarding (VBF) routing

Two primary users randomly use one among five data channels for communications, and switch channel every **60 seconds**

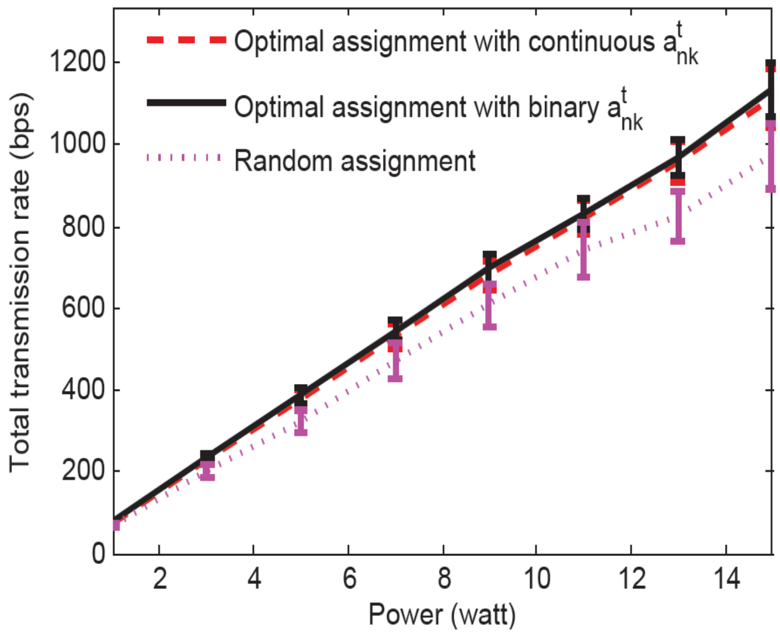
Tree topology

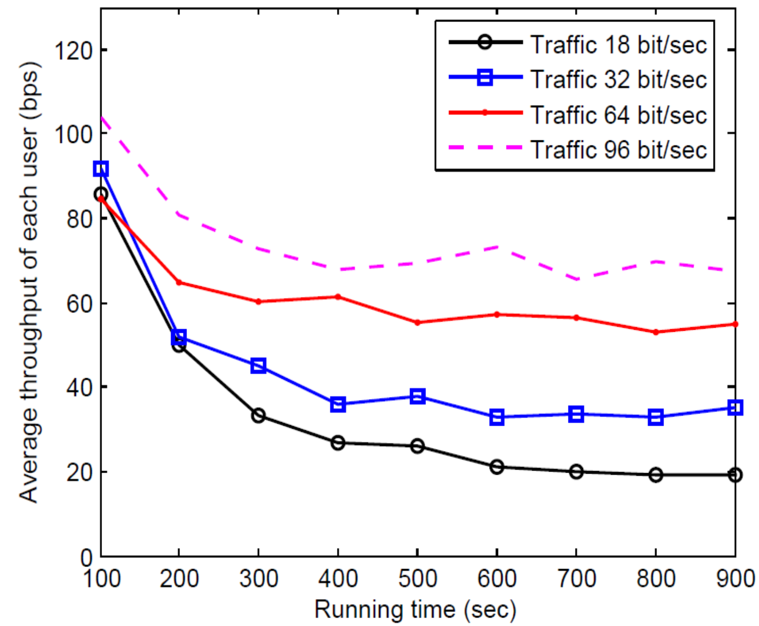


Mesh topology



Performance evaluation – Results (1)

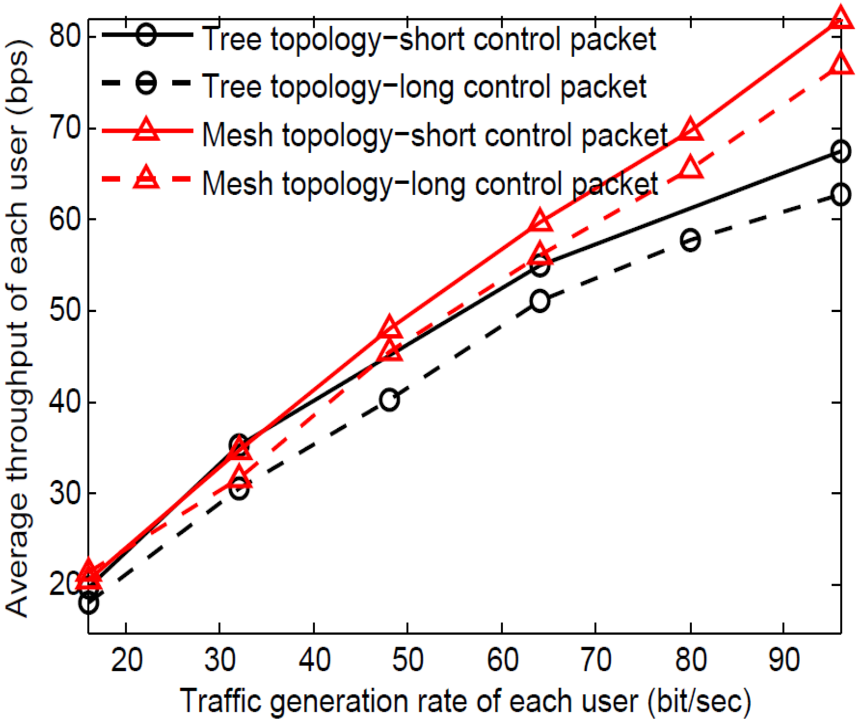


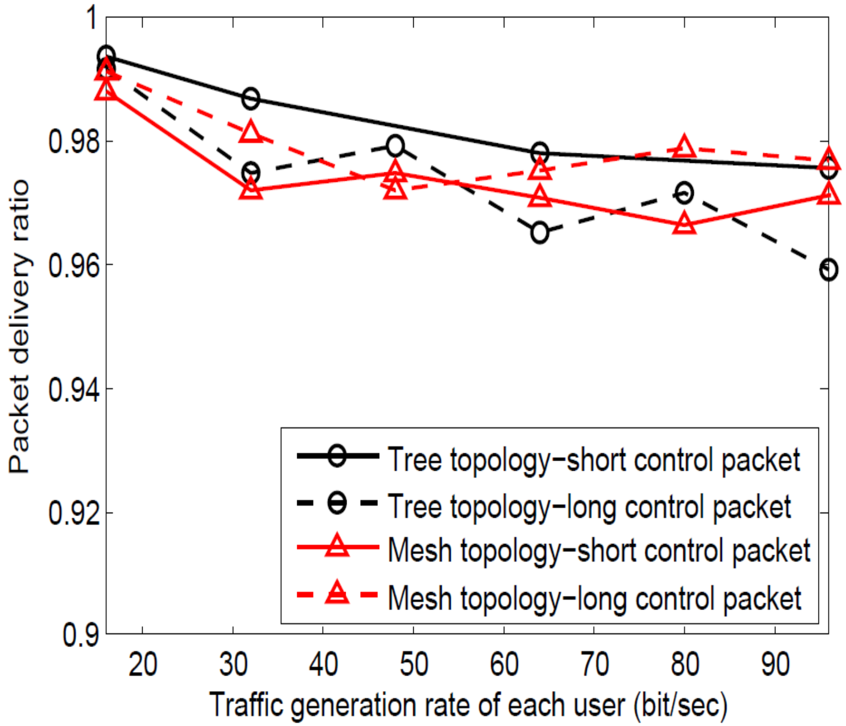


- Scenario: three senders
- Optimal: $a^t_{n\hat{k}} \in [0,1]$
- Suboptimal: $a^t_{n\hat{k}} \in \{0,1\}$
- Random: Channel *n* is randomly allocated to user *k*

- Scenario: tree topology
- High throughput at the beginning due to accumulative packets
- Throughput ≈ traffic generation rate in low traffic load situations (18, 32, 64 bps)

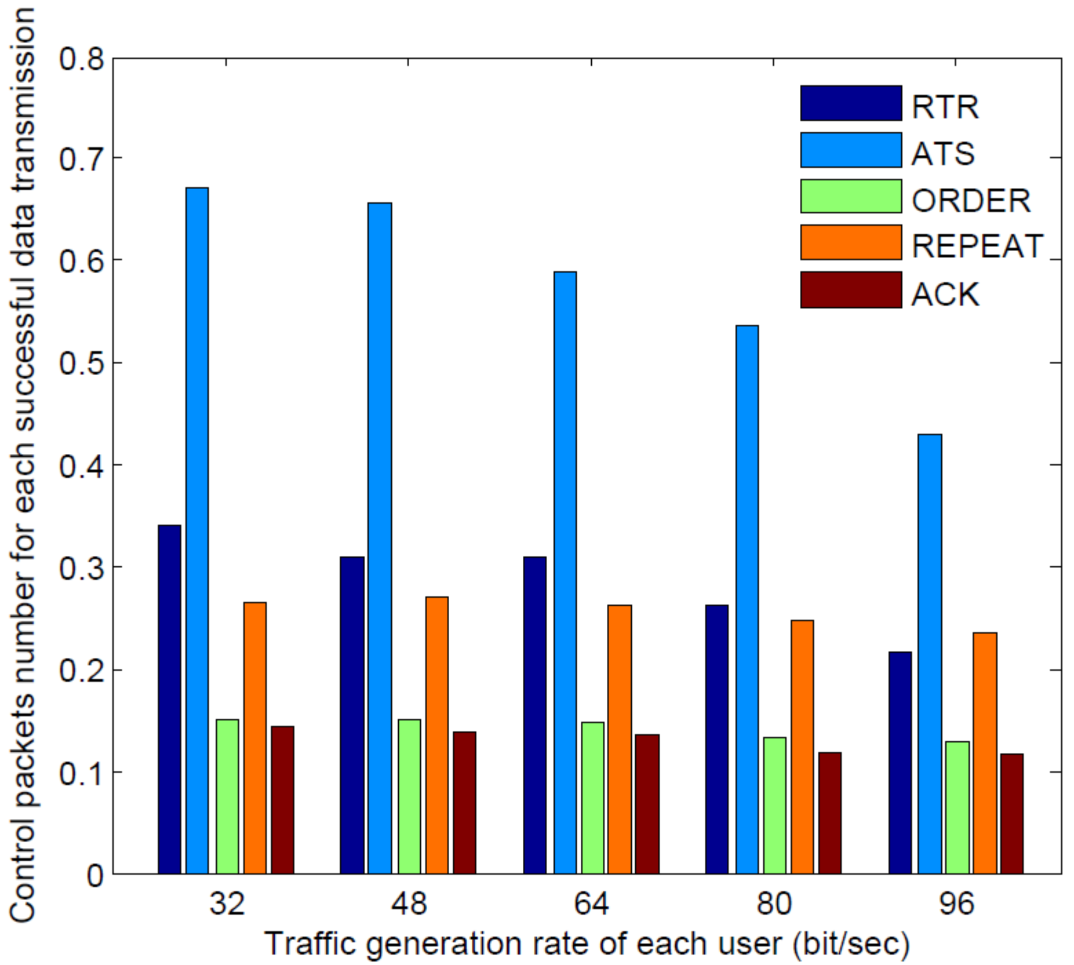
Performance evaluation – Results (2)





- Long control packet: RTR,ATS,ORDER,REPEAT and ACT : 0.2, 0.4, 1.0, 0.4, 0.2 seconds
- RISM has higher throughput in mesh than in tree topology
- RISM has high packet delivery ratio and low collision probability

Performance evaluation – Results (3)



- Number of control packets decreased with increased traffic generation rate

Conclusions

- **RISM for UCANs features**
  - **Reasonable overhead:** Collaborative spectrum sharing, spectrum sensing and spectrum decision
  - **Comprehensive optimization problem:** Power allocation, channel assignment and collision avoidance are considered
  - **High packet delivery ratio:** Over 95% sending packets can be successfully received
  - **Robustness:** The number of control packets does not increase with the traffic load, while the throughput keeps increasing with the traffic generation rate of CA users
- Can UANs be more environment-friendly?

Yes, UCAN!

Thanks and Questions

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