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**

- **RTR**: Request-to-receive
- **ATS**: Available-to-send
- **ORDER**: Order packet
- **REPEAT**: Repeat packet
- **DATA**: Data packet
- **ACK**: Acknowledgement

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

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

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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

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Collaborative spectrum sensing (2)

\( S_x: \) cyclic cross periodogram \( \alpha: \) normalized cyclic frequency \( f: \) normalized frequency

Next: Spectrum decision …
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

Channel gain follows Rayleigh distribution

Mean value of channel gain

Transmission power

$Pr[R_{nk}^t > C_{nk}^t] \leq \beta_{nk}$

$C_{nk}^t = a_{nk}^t B_n \log_2 (1 + \frac{p_{nk}^t |h_{nk}^t|^2}{N_0 B_n a_{nk}^t})$

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

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

$a_{nk} = \begin{cases} 
1, & \text{channel } n \text{ is assigned to user } k \\
0, & \text{otherwise}
\end{cases}$
Joint **power** and **frequency band** allocation for RISM

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

\[
L = \int_0^{T_r} \left( \sum_{n=1}^{N} \sum_{k=1}^{K} B_n R_{n,k}^t \right) dt
\]

To Minimize

\[
\max \left( \sum_{n=1}^{N} \sum_{k=1}^{K} B_n R_{n,k}^t \right)
\]

**Optimization Problem:**

\[
\text{Prob.1} \quad \arg \max_{\substack{p_{n,k}^t > 0 \atop c_{n,k}^t \in \{0,1\}}} \sum_{n=1}^{N} \sum_{k=1}^{K} R_{n,k}^t,
\]

where

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

s.t.

\[
\text{C1: } \sum_{k=1}^{K} a_{n,k}^t = 1, \quad n \in \{1, \ldots, N\},
\]

\[
\text{C2: } \sum_{n=1}^{N} p_{n,k}^t \leq P_k, \quad k \in \{1, \ldots, K\},
\]

\[
\text{C3: } a_{n,k}^t = 0, \quad \text{if } c_{n,k}^t = 1, \quad n \in \{1, \ldots, N\}, k \in \{1, \ldots, K\}
\]

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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
Performance evaluation – Results (1)

- Scenario: three senders
- Optimal: \( a_{n_k}^t \in [0,1] \)
- Suboptimal: \( a_{n_k}^t \in \{0,1\} \)
- Random: Channel \( n \) is randomly allocated to user \( k \)

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