Towards Automated Design of MAC Protocols for Underwater Wireless Networks

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MAC Protocol Design Key to High Performance in Underwater Networks

- Many MAC protocols in past 4 years:
  - “R-MAC: Energy-Efficient MAC Protocol...” (Xie, Cui)
  - “A Propagation-Delay-Tolerant Collision Avoidance Protocol for Underwater Acoustic Sensor Networks” (Guo, Frater, Ryan)
  - “A MAC Protocol for Ad-Hoc Underwater Acoustic Sensor Networks” (Peleato, Stojanovic)
  - “When underwater acoustic nodes should sleep with one eye open...” (Harris, Stojanovic, Zorzi)

- Each protocol makes its own assumptions [propagation delay known to this node, to all nodes, not known at all.]

- Is there a way to place all MAC protocols in a single framework?
When Modem Specs Change, High-Performance MAC Protocol Changes

Modem # 1 Specs

<table>
<thead>
<tr>
<th></th>
<th>Tx</th>
<th>Rx</th>
<th>Idle</th>
<th>Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (mW)</td>
<td>2240</td>
<td>1350</td>
<td>1350</td>
<td>75</td>
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Modem # 2 Specs (WHOI modem)

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<tr>
<th></th>
<th>Tx</th>
<th>Rx</th>
<th>Idle</th>
<th>Sleep</th>
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<tbody>
<tr>
<td>Power (mW)</td>
<td>10000</td>
<td>3000</td>
<td>80</td>
<td>~0</td>
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UWAN MAC Protocol

- Initialization period of A
- Sleep for B
- Wake-up for B

Slotted-FAMA

- RTS
- CTS
- DATA
- ACK
- C defers its transmissions

: SYNC transmission
: data transmission
: SYNC reception from A
: data reception from A

\( \tau_s \ll T_o \)
We concentrate on Stage 1 and 2 in this talk.
What is an “Optimal” MAC Protocol?

➢ Currently, two paradigms:
  ▪ [Communications Community]: Scheduling assigns optimal schedules via a global scheduler.
    ▪ This cannot be an optimal “protocol” because control information exchange not modeled.
  ▪ [Networking Community]: Measuring and comparing the performance of different protocols eventually shows which one is best.
    ▪ This cannot guarantee optimality. Many protocols undiscovered.

➢ **Missing Key**: No way to model control information exchanges within an optimization framework.
Novel Concept I: General Form of Control Information

The most general form of a control packet for a MAC protocol has two parts:

1. A node’s entire “planned future” (e.g. its planned transmit-receive pattern in next M slots.)

2. A node’s entire “past” (e.g. ACKs of all receptions it has heard.)

Example:

- RTS/CTS:
  - Aims to reserve the next DataLength slots ("future")
  - ACK sent after DATA has been received ("past")
Novel Concept II: Model of the World

- At design time, we represent each node as having a behavioral model of others. This is the node’s “world”.

Within itself, A represents its world with a model

- Each node models how others would respond to control information sent by this node.
Optimization Example:
Max Throughput, N = 2, No Delay

\[ \max_{\tilde{x}_A, x_B} \mathbb{E} \left\{ \sum_{i=1}^{M} (w_A[i]z_B'[i] - \tilde{x}_A[i]z_B'[i] + z_B[i]w_A'[i]) \right\} \]

Subject to:
1. \( S_B[i] = \bigvee_{j=1}^{i-1} \tilde{x}_A[j]z_B'[j] \)
2. \( z_B[i] = (w_B[i]S_B'[i]) \lor (x_B[i]S_B[i]) \)
3. \( (\tilde{x}_A[i] = 1) \Rightarrow (w_A[i] = 1) \)
4. \( \sum_{i=1}^{M} w_A[i] \leq \frac{M}{2} + \varepsilon \)
5. \( \sum_{i=1}^{M} z_B[i] \leq \frac{M}{2} + \varepsilon \)
6. \( w \sim \varphi^* \)
“Butterfly pattern” is the optimal schedule for 2 nodes under propagation delay.
Throughput Maximization with Propagation Delay, $N = 2$

$$\max_{\tilde{x}_A, x_A, x_B} \mathbb{E} \left\{ \sum_{i=1}^{M+\tau_{\text{max}}} \left( x_A[i] z_B[i + \tau_{AB}] - \tilde{x}_A[i] z_B'[i + \tau_{AB}] + z_B[i] x_A'[i + \tau_{BA}] \right) \right\}$$

Subject to:

1. $S_B[i] = \bigvee_{j=1+\tau_{AB}}^{i-1} \tilde{x}_A[j - \tau_{AB}] z_B'[j]$  
   $z_B[i] = (w_B[i] S_B'[i]) \lor (x_B[i] S_B[i])$  
   $(\tilde{x}_A[i] = 1) \implies (x_A[i] = 1)$  
   $\sum_{i=1}^{M} x_A[i] \leq \frac{M}{2} + \varepsilon$

2. $5. \sum_{i=1}^{M} z_B[i] \leq \frac{M}{2} + \varepsilon$

3. $w \sim \varphi^*$

4. $6. z_B[M : M + \tau] = 0$

5. $7. x_A[M : M + \tau] = 0$

Optimal Transmission Waveform of node A ($x_{A}^{\text{Tx}}$)

Optimal Transmission Waveform of node B ($x_{B}^{\text{Tx}} | S_{B}$)
Energy Minimization

\[ N = 2, \text{ No Delay} \]

\[
\min_{\tilde{x}_A, x^H_A, x_B} E \left\{ \sum_{i=1}^{M} \left[ E^{TX} \left( x^{TX}_A [i] + z^{TX}_B [i] \right) + E^{RX} \left( x^{RX}_A [i] + z^{RX}_B [i] \right) \right] + \right. \\
\left. E^{ID} \left( x^{ID}_A [i] + z^{ID}_B [i] \right) + E^{SP} \left( x^{SP}_A [i] + z^{SP}_B [i] \right) \right\}
\]

- \[ x^{TX}_A [i] + x^{SP}_A [i] + x^{LI}_A [i] = 1 \]
- \[ z^{TX}_B [i] + z^{SP}_B [i] + z^{LI}_B [i] = 1 \]
- \[ z^{ID}_B [i] = z^{LI}_B [i] (x^{TX}_A [i])' \]
- \[ z^{RX}_B [i] = z^{LI}_B [i] x^{TX}_A [i] \]
- \[ \frac{1}{M-1} \sum_{i=1}^{M+\tau_{AB}} \left( z^{RX}_B [i] - z^{LI}_B [i] \tilde{x}_A [i] \right) \geq \beta \theta_{\min} \]

...(Constraints similar to 1-6)
Energy Minimization
N=3, Middle Node’s Program

\[ \min_{\{\tilde{x}_q, x^\mu_q\}_q \in H_B} E \left\{ \sum_{i=1}^{M+\tau_{\text{max}}} \sum_{l \in \{A,B,C\}} \left[ E^{TX} z^{TX}_l[i] + E^{RX} z^{RX}_l[i] + E^{ID} z^{ID}_l[i] + E^{SP} z^{SP}_l[i] \right] \right\} \]

1. \( z^{TX}_q[i] + z^{SP}_q[i] + z^{LI}_q[i] = 1 \)
2. \( z^{ID}_q[i] = z^{LI}_q[i](y^\phi_q[i])' \)
3. \( (z^{RX}_l)^q[i] = z^{TX}_l[i-\tau_{lq}]y^l_q[i] \)
4. \( z^{US}_q[i] = \bigvee_{l \in \{-q\}} z^{TX}_q[i-\tau_{lq}] \)
5. \( z^{RX}_q[i] = \bigvee_{l \in \{-q\}} (z^{RX}_l)^q[i-\tau_{lq}] \)
6. \( S^B_C[i] = \bigvee_{j=1+\tau_{BC}} \tilde{x}_B[j-\tau_{BC}] y^B_C[j] \)

<table>
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<th>( R_k ): Superior Set of ( k )</th>
<th>( H_k ): Union of ( F_k ) and ( {k} )</th>
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<tr>
<td>( F_k ): Inferior Set of ( k )</td>
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\[ q \in R_B = \{A\} \quad q = B \quad q \in F_k = \{C\} \quad 0 \quad I \leq i \leq \tau_{vq} \quad \max\{\tau_{vq} + 1, I\} \leq i \leq M + \tau_{\text{max}} \]

... (Constraints similar to previous slides)
Energy Minimization with Propagation Delay, $N = 3$
Energy Minimization
With Propagation Delay, N = 3

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Comparison with Random Access

- As $\theta_{\text{min}}$ increases, the gains of sending control over random access increases.
- Trade-off between complexity and performance: $M = 200$ suffices to achieve good performance.
Challenges Ahead: Incorporating Propagation Delay Estimation

- Incorporate the propagation delay estimation into the control packets via time stamps.
- Estimated delays appear as deterministic variables in the program; the distribution of random delays appears under the expectation.

\[
\max_{\tilde{x}_A, x_A, x_B} \mathbb{E} \left\{ \sum_{i=1}^{M+\tau_{\text{max}}} \left( x_A[i]z_B[i + \tau_{AB}] - \tilde{x}_A[i]z_B[i + \tau_{AB}] + z_B[i]x_A'[i + \tau_{BA}] \right) \right\}
\]
Conclusions and Future Work

- We proposed a framework for the automated design of MAC protocols for underwater networks.
- We showed how to write the protocol design problem by incorporating control into an optimization program.

Future Work:
- Model ACKs in optimization program.
- Model propagation delay estimation.
- Incorporate known as well as random propagation delays.
- Show how proposed MAC protocols are instances of this more general framework.