A Hybrid Medium Access Control Protocol for Underwater Wireless Networks

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September 14, 2007
WUWNet 2007
Introduction

- Underwater networks provide many challenges
  - Low signal propagation speed
  - Low data rates
  - Limited energy resources
- MAC protocols play important role in conserving energy
  - Controls when transceiver is operational
  - Transceiver consumes large amounts of energy
Introduction

Problem

- TDMA protocols achieve low efficiency with few active nodes and can not adapt to traffic conditions
- Random protocols achieve low efficiency with many active nodes through collisions

Proposed Solution

- Divide each frame into portions reserved for scheduled and unscheduled access
- Share state information during scheduled access to improve use of unscheduled slots
Hybrid MAC Protocol

- Divide frame into $N_S$ scheduled and $N_U$ unscheduled slots
- Share state information during scheduled slots
- Adjust unscheduled access based on state information
For an initial analysis, assume:

- $N = 10$ nodes surrounding a central receiver
- $T$ nodes are backlogged with many packets
- Packets are lost only through collision

Define the following:

- $E_{TX}$: Average energy to transmit a packet in a slot
- $E_{RX}$: Average energy to receive a packet in a slot
- $E_I$: Energy to remain idle in a slot
Protocol Energy Equations

- **TDMA**

\[
E_T = \frac{TE_{TX} + (N - 1)TE_{RX} + N(N_S - T)E_I}{N_S}
\]

- **Unscheduled**

\[
E_U = \frac{P_R N_U E_{TX} + (N - 1)P_R N_U E_{RX} + N(1 - P_R)N_U E_I}{N_U}
\]

- \(P_R\) is the probability of a successful reception in a slot

- **Hybrid**

\[
E_H = \frac{E_T N_S + E_U N_U}{N_S + N_U}
\]
Protocol Efficiency Equations

- **TDMA**
  \[ \mathcal{E}_T = \frac{T}{E_T N_S} \]

- **Unscheduled**
  \[ \mathcal{E}_U = \frac{P_R N_U}{E_U N_U} \]

- **Hybrid**
  \[ \mathcal{E}_H = \frac{(T + P_R N_U)}{E_T N_S + E_U N_U} \]
Abstract Protocol Efficiency

![Graph showing Efficiency vs. Reception Probability, P_R for different protocols and time slots (T=2, T=8). The graph compares Unscheduled, TDMA, and Hybrid protocols, with efficiency measured in bits/J.](image-url)

- **X** denotes Unscheduled protocol.
- **T=2** and **T=8** represent different time slots.
- **TDMA** and **Hybrid** are two types of protocols.
Concrete Random Protocol

- Random Protocol
  - Similar to Slotted Aloha
  - Packets are only backlogged
  - $P_T$ is the probability of transmitting in a slot

- Efficiency

$$\mathcal{E} = \frac{B(1, T, P_T)}{B(0, T, P_T)NE_I + \overline{E}_1}$$

where

$$\overline{E}_1 = \sum_{i=1}^{T} B(i, T, P_T)(iE_{TX} + (N - i)E_{RX})$$
Concrete Random Protocol Efficiency

The diagram illustrates the efficiency ($\text{Efficiency (bits/J)}$) as a function of the transmission probability ($P_T$) for different values of $T$ (transmission attempts). The curves are labeled as follows:

- $T=2$ (solid red line)
- $T=3$ (dotted blue line)
- $T=4$ (dashed purple line)
- $T=5$ (dotted-dashed black line)

The $x$-axis represents $P_T$ ranging from 0 to 1, while the $y$-axis represents efficiency ranging from 0 to 18 bits/J.

This graph likely shows how the efficiency of the protocol changes with varying transmission probabilities and different numbers of transmission attempts, highlighting the impact of $T$ on overall protocol efficiency.
Protocol Efficiency

The graph illustrates the efficiency of different protocols as a function of transmission probability, $P_T$. The x-axis represents the transmission probability, while the y-axis shows efficiency in bits/J.

- **Random** protocol is represented by red squares and shows a constant efficiency at 25 bits/J.
- **TDMA** protocol is shown with red crosses and varies with transmission probability, peaking near $P_T = 0.1$ before declining.
- **Hybrid** protocol with $T=2$ is indicated by blue crosses and peaks at a higher efficiency than the Random protocol but drops significantly with increasing $P_T$.
- **Hybrid** protocol with $T=8$ is shown with blue dotted lines, maintaining a higher efficiency than the Random protocol but also declining as $P_T$ increases.

The graph indicates that the Hybrid protocol with $T=8$ generally offers a higher efficiency compared to the other protocols, especially at lower transmission probabilities.
Simulation Introduction

- Device models
  - Ten devices in a circle around a central receiver
  - Underwater channel with practical spreading ($\alpha = 1.5$)
  - BPSK bit error model
  - $40 \text{ W } P_{TX}$, $3 \text{ W } P_{RX}$, $80 \text{ mW } P_I$

- Protocols
  - TDMA
  - Random – modified Slotted Aloha
  - Hybrid – combination of TDMA and Random
  - Aware Hybrid – nodes share transmission desire and nodes adjust transmit probability
  - Divider – nodes share packet queue length and divide unscheduled slots proportionally
Random Protocol Efficiency

Efficiency (bits/J) vs. Transmit Probability, $T_P$

- $T=2$
- $T=3$
- $T=5$
- $T=8$
Hybrid Protocol Efficiency

![Graph showing the efficiency of different transmit probabilities (TP) for various values of T (2, 3, 5, 8). The graph plots efficiency in bits/J against transmit probability. The x-axis represents the transmit probability (TP) ranging from 0 to 0.35, while the y-axis represents efficiency in bits/J ranging from 14 to 21. The graph includes lines for different values of T, with each line color-coded for easy identification.]
### Optimal Transmit Probability

<table>
<thead>
<tr>
<th>$T$</th>
<th>Random</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>0.155</td>
<td>0.145</td>
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<tr>
<td>4</td>
<td>0.11</td>
<td>0.095</td>
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<td>5</td>
<td>0.09</td>
<td>0.065</td>
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<td>0.025</td>
</tr>
<tr>
<td>10</td>
<td>0.04</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Protocol Efficiency for $T = 2$
Protocol Efficiency for $T = 8$
Protocol Efficiency for $T = 8$

![Graph showing network traffic rate vs. efficiency for different protocols: Random, TDMA, Hybrid, Aware Hybrid Divider. The graph compares efficiency (bits/J) against network traffic rate (pkts/sec).]
Protocol Efficiency as $T$ Varies

![Graph showing protocol efficiency as the number of transmitters varies. The graph plots efficiency (bits/J) against the number of transmitters ($T$) and includes lines for Random, TDMA, Hybrid, Aware Hybrid, and Divider.]
Message Latency for $T = 2$

Network Traffic Rate (pkts/sec) vs. Latency (s)

- Random
- TDMA
- Hybrid
- Aware Hybrid
- Divider
Message Latency for \( T = 8 \)
Low Power Protocol

- Stateful protocols require a higher transmit power than TDMA
- Allow nodes to adjust transmit power
  - Transmit packets to central receiver at low power (15 W)
  - Transmit packets with state information at high power (40 W)
Low Power Protocol Efficiency

![Graph showing efficiency vs number of transmitters for different protocols](image-url)

- Random
- TDMA
- Hybrid
- Aware Hybrid
- Divider

Efficiency (bits/J) vs Number of Transmitters, T
Bursty Traffic

- Hybrid protocols may adapt to changing traffic conditions
- Simulate a variable traffic load
  - All nodes transmit ($T = 10$)
  - Nominal rate of 0.02 packets/sec
  - Nodes randomly produce either 10 packets or one packet
Protocol Efficiency for Bursty Traffic

![Graph showing efficiency vs. burst probability](image_url)
Protocol Latency for Bursty Traffic

![Graph showing protocol latency for bursty traffic. The x-axis represents burst probability ranging from 0.1 to 0.5, and the y-axis represents message latency in seconds. The graph includes lines for Random, TDMA, Hybrid, Aware Hybrid, and Divider. Each line has different markers and colors representing the different protocols.]
Conclusions

- A Hybrid MAC may provide better performance
  - A higher efficiency except for heavily loaded networks with many transmitters
  - A lower and more consistent delay for a wider range of rates
  - Adaptability to bursts in generated traffic
- State information must be used judiciously
  - The Aware Hybrid protocol did not perform better than the Hybrid protocol in most cases
  - The Divider protocol performed very well
Thank You!

Questions?
Protocol Energy

![Energy vs Reception Probability Graph]

- Unscheduled
- Hybrid T=2, N_U=5
- Hybrid T=5, N_U=0
- Hybrid T=5, N_U=5
- Hybrid T=5, N_U=20
- Hybrid T=10, N_U=5