An Energy-Efficient MAC Protocol for Underwater Wireless Acoustic Networks

Prof. Volkan Rodoplu
Min Kyoung Park
{vrodoplu, mkpark} @ece.ucsb.edu

Sep. 20, 2005

Dept. of Electrical and Computer Engineering
University of California Santa Barbara
Underwater Wireless Acoustic Networks (UWANs)

Underwater Environments:
- Energy limitations – battery operated sensor nodes.
- Long propagation delays – 1.5 sec / km (very high).
- Low data rates (~ several Kbytes).
- Difficulty of synchronization.

=> Novel, low-energy MAC protocol is needed.

Conductivity, Temperature, Density (CTD) data collected and then sent out on RF link to Internet.

Dockside acoustic/RF comm. And signal processing

Cabled hydrophone array

Wi-Fi or Wi-Max link

AquaNodes with acoustic modems/routers, sensors
Previous Approaches to Acoustic MAC layer

- SeaWeb 1998-1999 SeaWeb: FDMA
  - FDMA restrictive and inefficient in bandwidth utilization
- SeaWeb 2000: CSMA/CA
  - RTS/CTS handshake exacerbates end-to-end delays in networks
  - RTS/CTS + ARQ retransmission: increases energy consumption

- Xie & Gibson (2000)
  - Base station computes all the routes for underwater sensor networks
    - but scalability issues for large-scale underwater networks
  - CDMA codes used in topology establishment
    - but near-far problem needs to be addressed
Main idea of our proposed MAC protocol

- Use SLEEP MODE with low duty cycles to conserve energy
  (Rodoplu, Minimum Energy Networks, and Heidemann, S-MAC)
- WORKS UNDER long, unknown propagation delays and possible clock drift.
- No RTS/CTS handshaking.

![Diagram](image)

B knows when to wake up to listen to A, although neither knows the propagation delay.
Example network topology

- Each node keeps track of its 1-hop neighbors in the topology control layer.
INITIALIZATION and DATA TRANSMISSION phases

- All nodes LISTEN in initialization phase and decode cycle period stamps.
- Each node goes into the initialization phase periodically (e.g., every 10 cycles) or on demand.
DATA TRANSMISSION phase

- Packet structure

- Data Tx – actual information (data) being sent.
- Additional listen duration – listen to HELLO messages from newcomers or nodes who lost synchronization once.
- Missing – list of nodes from which a node can no longer hear.
- SYNC – modification of cycle periods.
- LISTEN period – to listen to any potential newcomers
Handling a newcomer (node F)
- Node F’s HELLO signal has a relative cycle period stamp.
Handling one-way loss of synchronization, and node failure

(a) One-way loss of synchronization (i can still hear from j)

- Scheduled wake-up time for i
- Missing : i
- Wake-up to listen to i

(b) Node failure

- Out of the energy
- Scheduled wake-up for i with i’s last cycle stamp $T_i$
- Missing : i
- Wake-up again to listen to i, no data: remove the wake-up schedule for i
Modification of Cycle Period

If B misses the cycle period modification signal, then it will use the "one-way loss of synchronization" procedure and advertise node A as a ‘missing’ node. If node A continues to wake up at B’s transmissions, it will send a HELLO signal to B and re-synchronize.
PERFORMANCE ANALYSIS: Probability of a collision

- **Assumptions:**
  - “Collision”: a receive-receive or a transmit-receive collision.
  - **For initial, analysis: Zero propagation delay.**
  - Uniformly, i.i.d transmission start time in \([0, T]\).

- \( \text{Prob}[\text{A's packet collides with B's}] = \frac{2\tau}{T} \)

- \( P[\text{A packet collides with at least one other }] \)
  \[ = 1 - P[\text{A packet does not collide with any other}] \]
  \[ = 1 - \left[ \left( 1 - \frac{2\tau}{T} \right)^{N-1} \right] \]
Simulation results – under zero propagation delay

Sleep Cycle: $T$, Tx duration: $\tau$, No propagation delay

- solid: theoretical analysis
- dotted: simulation

Fraction of energy wasted due to collisions

Number of nodes

- $\tau/T = 0.006$
- $\tau/T = 0.004$
- $\tau/T = 0.002$
Simulation results – Impact of long propagation delays

Sleep Cycle: $T$, Tx duration: $\tau$

- solid: with delay
- dashed: no delay

Fraction of energy wasted due to collisions vs. Number of nodes

- $\tau/T = 0.006$
- $\tau/T = 0.004$
- $\tau/T = 0.002$
Enhancement using a guard time duration

- Each node places a *guard time duration* $\tau_g$ on both sides of transmission duration to avoid receive-receive collisions.

- If $(\tau_1$ or $\tau_2) < \tau_g$, re-select its transmission start time satisfying that the time duration, transmission duration + $2\tau_g$ is not overlapped with any other wake-up times.
Simulation Set-up

- Deployment region: 500 meters * 500 meters; 20-30 nodes
- Only transmit energy is modeled (Sozer et. al’s 2000 paper):

\[ E_T = P_o T_p r^k a^r \]

- \( r \) = distance from source, \( T_p \) packet duration, \( k \) is path loss exponent
- \( a \): frequency-dependent absorption coefficient (Thorp’s expression)
- In our simulations: \( k = 1.5 \)
- Average duty cycle = 0.004.
- DATA transmission length = 10 * SYNC header
- Carrier frequency: 25 kHz
Simulation results – A dynamic network scenario

Sleep Cycle: $T$, Tx duration: $\tau$, $\tau/T = 0.004$

- - cycle 1
- - cycle 2
- - cycle 3

Data packets

average over 10 cycles

with guard time policy

SYNC packets only

No. of nodes:

Avg. no. of neighbors: 3
(derived result)
Conclusions and Future Work

- Conclusions
  - Our UWAN MAC protocol works for underwater wireless sensor networks which have unknown, long propagation delays.
  - It is distributed, scalable and robust as the network evolves.

- Future Work
  - For the operation of energy-limited sensor nodes in UWANs, we plan to combine this MAC protocol with topology control as well as energy-efficient routing protocol.
Simulation results – Self-configuration

Sleep Cycle: T, Tx duration: tau, \( \tau / T = 0.004 \)

5 new nodes added
Previous approaches to Terrestrial Sensor Networks

- **PEDAMACS**: an energy-efficient MAC protocol
  - Nodes are synchronized by a base station / TDMA access
  - But scalability issues for large-scale networks

- **S-MAC**: improves upon 802.11 DCF standard
  - Assumes that the propagation delay between nodes is small; cannot be used in underwater networks with large propagation delays
  - Recent improvements use a scheme that converges to a global schedule for entire network; but difficulty of synchronization underwater makes global schedules untenable.
Handling random propagation delays

\( \tau_e \): duration for early arrivals
\( \tau_l \): duration for late arrivals

actual wake-up times

scheduled wake-up times

\( \tau_c \): duration for early arrivals
\( \tau_l \): duration for late arrivals