

# T-Lohi: A New Class of MAC Protocols for Underwater Acoustic Sensor Networks\*

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## Abstract

This paper introduces T-Lohi, a new class of distributed and energy-efficient media-access protocols (MAC) for underwater acoustic sensor networks (UWSN). MAC design for UWSN faces significant challenges. For example, acoustic communication suffers from latencies five orders-of-magnitude larger than radio communication, so a naive CSMA MAC would require very long listen time resulting in low throughput and poor energy efficiency. In this paper, we first identify unique characteristics in underwater networking that may affect all MACs, such as space-time uncertainty and deafness conditions. We then develop T-Lohi employing a novel tone-based reservation mechanism that exploits space-time uncertainty and high latency to detect collisions and *count contenders*, achieving good throughput across all offered loads. It employs our low-power wake-up receiver to significantly reduce energy consumption. Finally, we evaluate design choices and protocol performance through extensive simulation. The results show that the energy cost of packet transmission is within 3–9% of optimal, that our protocols achieve good channel utilization, within 30% of the theoretical maximum. We also show that our protocols are stable and fair under both low and very high offered loads.

## 1 Introduction

Networks with shared media require MAC protocols to control access of the shared channel. Design of the MAC protocol influences nearly every aspect of network performance, from channel utilization, latency, and fairness to metrics specific to sensor networks such as energy efficiency. Com-

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pared to wired MAC protocols, wireless MACs pose several unique challenges, including lack of the ability to detect collisions and inconsistent views of the network as seen in the hidden and exposed terminal problems.

In underwater sensor networks (UWSN), a shared *acoustic* medium adds to these challenges [10, 3]. Acoustic communication magnifies wireless bandwidth limitations, transmit energy costs, and variations in channel propagation. Control algorithms of MAC protocols are changed even more by acoustic propagation latencies that are five orders of magnitude greater than radio. We will show that these unique challenges reflect in novel problems, including space-time uncertainty, spatially-dependent fairness, and deafness conditions (Section 2.1).

The focus of this paper is to design an energy-efficient MAC protocol for short range, acoustic sensor networks. Recently several innovative acoustic modems have been proposed [32, 33], but no MAC protocol is widely available to support dense networks—a requirement for sensor network-style embedded sensing. We will show that the challenges of high latency also enable new implementation techniques (Section 2.1.3) and admit solutions that provide good throughput across varying application requirements.

Flexibility to application requirement and energy efficient design are important as we foresee many diverse applications for underwater sensor networks with a significant number requiring long term, energy efficient deployment. While some researchers have suggested many underwater networks will be mobile, making communications power negligible [17], we see several important categories of application where energy-efficiency remains critical. A first category is the static sensing applications such as 4-D seismic sensing of oil-fields [10]. Other such applications might be ecological observatories of biologically fertile locations like coral reefs. Gliders and low-energy mobility (for example, University of Washington's Seaglider [24]) platform that might even have marine energy harvesting mechanism represent a second category. The third category is applications such as wildlife tagging [1], where mobility is parasitic and consumes no energy from the sensor system. Energy-efficient design becomes even more important when transmit energy costs are high [17], idle times are long for underwater medium access [13], and when underwater deployment makes battery replacement difficult or impossible.

We propose a new class of medium access protocols

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**Table 1. Comparison of communication characteristics of wireless links**

Characteristic	Satellite	IEEE 802.11	Mica2 Radio	Short-Range Acoustic Modem	Benthos ATM-885
<b>Bit Rate</b>	155 Mb/s	11 Mb/s	20–50kb/s	1 kb/s	2.4Kb/s
<b>Typical BER</b>	$10^{-10}$	$10^{-5}$	$10^{-5}$	$10^{-5}$	$10^{-7}$
<b>Propagation Delay</b>	~120 ms	< 1 $\mu$ s	< 1 $\mu$ s	~300 ms	~6s
<b>Distance</b>	~ 42,000km	<3km	< .5km	< .5km	6–10km

called *Tone Lohi*<sup>1</sup>. Lohi provides an energy conserving, throughput efficient, fair, and stable medium access for acoustic networks. Rather than customize the protocol to a very specific application, we design for general underwater applications. We conserve energy in two ways: first, we use data reservations to ensure no data packets collide. Second, we employ wake-up tone hardware that resolves reservation contention with extremely low energy cost. We achieve stability and throughput efficiency by employing a mechanism that provides collision detection and contender count allowing the use of an intelligent back off mechanism that reduces the overall time for fairly reserving data.

The first contribution of this work is to identify several unique characteristics of high latency acoustic medium access. These include identifying the space-time uncertainty in ascertaining the channel state (Section 2.1) and defining some deafness conditions that prevent packet reception (Section 2.2). Second, we present the design of T-Lohi, a new class of distributed MAC protocols for UWSN, that employs a novel tone based reservation mechanism and exploits the space time uncertainty to detect and count contenders, achieving good throughput across all offered loads (Section 3). Finally, we perform detailed simulation analysis of our protocols (Section 4). The results show that the energy cost of packet transmission is within 3–9% of optimal, that our protocols achieve good channel utilization, within 30% of the theoretical maximum. We also show that our protocols are stable and fair under both low and very high offered loads.

## 2 Challenges and Opportunities

We next review the challenges particular to acoustic networks and how they relate to media access.

Prior work has studied the challenges inherent to underwater acoustic communications [3, 11, 10, 17]. Such challenges stem from the fundamental physical characteristics of the medium including low bandwidth, high BER, surface scattering, complex multipath fading, high propagation latency, and significant variation of these properties due to temperature, salinity, or pressure. The large propagation delay is especially harmful to protocols designed for radio networks, since it is so large that it becomes significant and so must be handled explicitly (for example, in time synchronization [27]). Most current underwater communication targets distances of several kilometers, but short-range commu-

nication (less than 500m) may simplify propagation characteristics and allow simpler and cheaper designs [10].

The power demands of acoustic hardware also differ significantly from terrestrial sensor networks. Table 1 compares short- and long-range RF and acoustic communications. With underwater acoustic communication, transmission is often 100 times more expensive than reception [17]. For example the typical receive power for the WHOI micro-modem is only 80mW, while the transmit power is 10W (a receive:transmit ratio of 1:125) [32]. While long-range RF also has relatively large ratios (1:40 or more), recent short-range radios for sensor networks generally provide ratios of 1:1.5 or so [25].

These unique characteristics, particularly propagation latency, create several new phenomena in MAC protocol design. We describe these phenomena next and show how they can be exploited to provide more information for MAC decisions.

### 2.1 Space-Time Uncertainty

Channel state in short-range RF networks can be estimated by considering just the transmit time, as the propagation delay is negligible. The large propagation delay of acoustic media makes it essential to also consider the locations of a receiver and potential interferers. Distance between nodes translates into uncertainty of current global channel status: *space-time uncertainty*.

Space-time uncertainty is illustrated in Figure 1. In Figure 1(a), nodes C and D have different estimates the channel as clear or busy, and in Figure 1(b) the two concurrent transmissions from A and E collide at node C but are received separately at nodes B and D. In general, these examples show that collision and reception in slow networks depend on both transmitter time and location. This space-time uncertainty can also be viewed as a duality where similar collision scenarios can be constructed by varying either the transmission times or the locations of nodes.

Although, in principle, this uncertainty occurs in all communication, it is only significant in acoustic communication where latency very high. While this property poses a new challenge, it also provides opportunities to detect and count contenders. We next evaluate both its impact and such opportunities. (Note: We have removed the section on the impact of space time uncertainty on ALOHA protocol in this updated technical report; a more focused analysis is present in our related publication [28].)

<sup>1</sup>“Lohi” means *slow* in Hawaiian, signifying slow propagation in acoustic medium access.

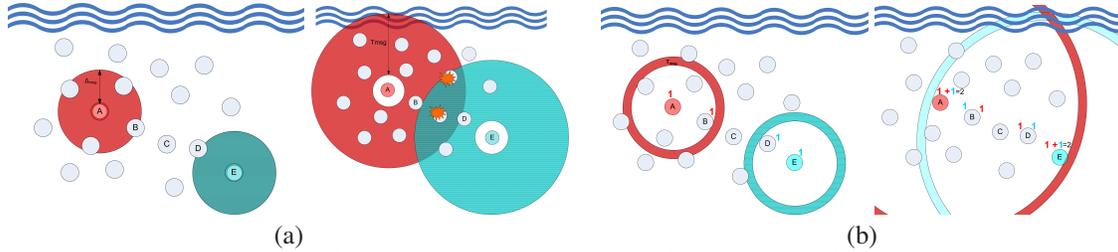


Figure 1. Spatio-temporal overlap of packet with (a) large message/packet transmission time (b) small message/short tone.

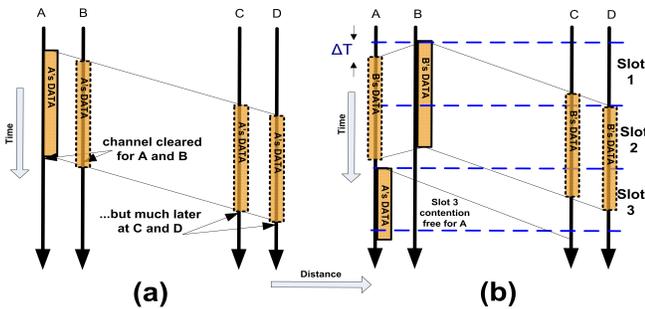


Figure 2. Spatial Unfairness: (a) Transmitter and close neighbors have channel cleared earlier. (b) In slotted access, close neighbor A can attempt in slot 3 while C and D can not. This can cause continuous exchange of channel between A and B.

### 2.1.1 Clear Channel Assessment

Clear channel assessment (CCA), sampling of the medium for activity, is an essential component of all CSMA-based MACs. Performing CCA before transmitting data prevents nodes from colliding with concurrent transmissions. While CCA is never perfect because of potential delay between measuring a clear channel and beginning transmission, the space-time uncertainty makes simple CCA much less effective.

Figure 1(a) shows one case where large propagation times imply that, even if A and E sensed their channel before transmitting, they would incorrectly assume the channel was clear and their transmissions would collide. One simple extension to CCA would be to synchronize nodes, dividing time into slots of length equal to worst-case propagation time. CCA would sample for an entire slot and send after a clear slot, resulting in collisions only when two nodes select the same slot. The cost of this approach is high latency, since propagation time is quite long at even moderate distances (330ms propagation delay at 500m), and collisions are still possible for nodes that select the same slot. These collisions will not only degrade the efficiency of the MAC but also result in significant energy loss (due to packet loss and retransmission). Furthermore sensing channel for that long also takes up idle/listen energy cost.

We will employ this concept of modified CCA to reduce uncertainty in our protocols, and will further discuss how to relax the requirement of slot synchronization. We also provide mechanisms to minimize energy overhead while stabilizing throughput.

### 2.1.2 Spatial Unfairness

Another significant impact of space time uncertainty is an inherent, location-dependent bias for medium access, which we term as *spatial unfairness*. Conceptually this unfairness is similar to classical unfairness in Ethernet channel capture and that described in MACAW [4]. However, there the reason for unfair access is the bias in the backoff counter value, in acoustic medium the unfairness stems entirely from spatial bias in estimating a clear channel.

Since a packet reception time is proportional to distance from transmitter, the channel becomes clear earlier at nodes closer to the transmitter. In Figure 2(a) transmitter A and its close neighbor B have a greater chance to recapture the channel after sending than nodes C and D that are far away. Two close nodes can therefore monopolize the channel, somewhat similar to how TCP throughput is inversely proportional to round-trip time [16].

In slotted medium access, where nodes are allowed to attempt only at synchronized times, spatial unfairness becomes more pronounced. In Figure 2(b), B's data ends in slot 2 for nodes A and B, but ends in slot 3 for C and D. Thus, even if the transmitter is prevented from immediately reacquiring the channel, nodes A and B can swap the channel back and forth. We handle spatial unfairness in our protocol design by employing a distributed backoff mechanism, as explained in Section 3.2.

### 2.1.3 Contender Detection and Counting

Although latency increases uncertainty, we next show that it can also be used to do *contender detection* (CTD) and *contender counting* (CTC). While some wired networks such as Ethernet provide CTD, but none has, to the best of our knowledge, the ability to directly count the number of contenders.

Contender detection in our protocol comes from listening to the channel after sending your tone. Unlike other wireless protocols, space-time uncertainty means that we can observe tones sent concurrently with ours because they may arrive after our transmission completes. The ability to detect depends on relatively short tones and a long listen period. In addition to detecting contenders, if tones are short enough relative to the contention round, we can further use time-space uncertainty to *count* the number of contenders (we formalize shortness in Section 2.2). An example is shown in Figure 1(b), where nodes A and E send short tones that are received at different times and counted separately by nodes B and D. The tones collide at node C, but it can still determine the presence of some tone if tones are not destructive.

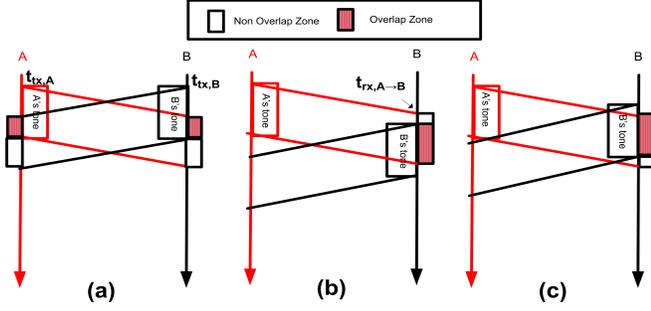


Figure 3. The three cases where deafness can occur. (a) Bidirectional deafness. Unidirectional deafness at B with A's tone reaching B (b) before B starts transmitting, (c) after B starts transmitting.

This ability to count the number of contenders is not generally possible for RF-based networks due to short propagation delay there, although concurrent with our work, some researchers have begun to use game theoretic approximations of contender counts [5]. We exploit CTC in our MAC design in Section 3.

## 2.2 Deafness Conditions

Wireless transceivers often work in half-duplex mode, and thus on a single channel a node that is transmitting cannot receive another packet at the *same* time. In the case of transmitting tones, a node will be unable to completely receive another tone with a probability that is proportional to the tone length. Therefore, a node becomes *deaf* to another transmission in these situations.

The following analysis is valid for any packet length that needs to be entirely received for contention detection. We employ the low-power wake-up tone hardware proposed by Willis et al. [33] for sending contention tones. Note that we assume that tones and data share the same channel: one transmitter but two receivers in the same channel. Such tone detection mechanism requires energy accumulation over a minimum duration, denoted as  $T_{detect}$ , larger than the symbol detection time for data on the same channel. This detection delay can lead to a node transmitting a tone failing to *hear* another tone — thus deafness occurs.

Our aim is to identify the conditions that will lead to deafness. Refer to three different circumstances in Figure 3, which can cause deafness at node B. We define the non-overlap zone (NOZ) as the non-overlapping region of two partially overlapping tones at B. Deafness will then occur if:

$$NOZ < T_{detect} \quad (1)$$

We take the first case, Figure 3(a), where both nodes are transmitting at the same instant. Here  $NOZ = T_{tone} - (t_{rx,B} + T_{tone} - t_{rx,A \rightarrow B})$ , A's transmission starts at  $t_{rx,A}$  while  $t_{rx,A \rightarrow B}$  is the global time at which B receives A's tone. If  $T_{A,B}$  is the propagation delay between A and B, then  $t_{rx,A \rightarrow B} = t_{rx,A} + T_{A,B}$ . With these definitions and noting that  $t_{tx,A} = t_{tx,B}$  we get a deafness condition specified by equation (1) as:

$$T_{A,B} < T_{detect} \quad (2)$$

If node transmissions are synchronized, then the deafness

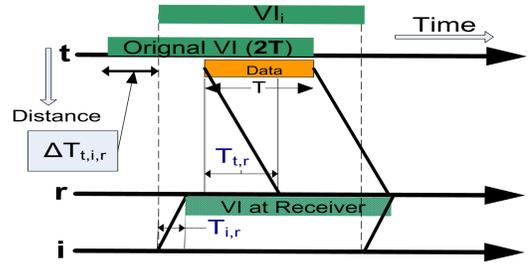


Figure 4. Vulnerability interval for ALOHA in high latency acoustic medium access.

condition is dependent solely upon the delay between the nodes, and thus with nodes spaced closer than the *deaf region*,  $D_{deaf} = T_{detect} * v_{sound}$ , causing *bidirectional deafness* where neither node can hear the other.

In the second case, Figure 3(b),  $t_{rx,A \rightarrow B} < t_{tx,B}$ , thus the  $NOZ = t_{tx,B} - t_{rx,A \rightarrow B} = t_{tx,B} - t_{tx,A} - T_{A,B}$ . Thus the deafness condition becomes:

$$(t_{tx,B} - t_{tx,A}) - T_{A,B} < T_{detect} \quad (3)$$

Similarly for the third case, Figure 3 (c), we get the following deafness condition

$$(t_{tx,A} - t_{tx,B}) + T_{A,B} < T_{detect} \quad (4)$$

Observe that in case (b) and (c) the deafness is *unidirectional*, *i.e.*, only node B is deaf to A's tone but A can still detect B's tone.

We can simplify all three deafness conditions above into a single generalized condition. We make the convention that node A transmits its tone before B. Then we can define the following time differences:

$$\text{Time Difference of Transmission (TDT)} = t_{tx,B} - t_{tx,A}$$

$$\text{Time difference of Location (TDL)} = T_{A,B}$$

With these definitions it is straightforward to see that all the three deafness conditions described above can be coalesced into a single generalized condition.

**Generalized Deafness Condition (GDC):**

$$|TDT - TDL| < T_{detect} \quad (5)$$

GDC shows that as long as all nodes transmit equal-length tones, the deafness condition in equation (5) is not affected by the tone length. This is because of the binary nature of information in a tone. The GDC also reflects the space time uncertainty by the dependence of deafness on both relative location (TDL) and transmit time (TDT).

## 3 Tone-Lohi MAC Protocol Design

T-Lohi is essentially a reservation based medium access protocol. Our reservation process is fully distributed, and by employing short tones the reservation is made in a rapid and energy-efficient way. This section describes T-Lohi in detail and discusses the motivation and design tradeoffs behind different flavors of T-Lohi.

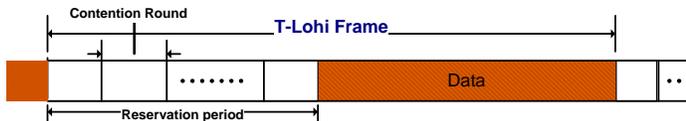


Figure 5. The Tone-Lohi protocol frame

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**Algorithm 1** Pseudocode for the T-Lohi protocol

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1: if you receive a contention tone (CTD) while idle
2:   set blocking state to true; unset at end of current frame
3: When application invokes MAC send
4:   if blocked; wait for end of frame and attempt in next RP.
5:   else transmit contention tone; wait for end of current CR.
6:     if (contender count (CTC) > 1)
7:       Compute  $w$  uniformly from  $[0, CTC]$ ; backoff  $w$  CR(s)
8:       if CTD; while in backoff
9:         set blocking state to true; unset at end of current frame
10:        wait for end of frame and attempt in next RP.
11:      else backoff ends; goto line 5 and repeat contention
12:     else contender count = 1; data reservation successful
13:     transmit data; when DP ends go to idle state

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### 3.1 Overview of T-Lohi

The main objective of Tone-Lohi (T-Lohi) is to provide a MAC protocol that has efficient channel utilization, stable throughput, and low energy consumption. The protocol is designed to be flexible for a range of applications, as it is not optimized for specific network topologies and traffic patterns.

We conserve energy in two ways; first we use reservation to prevent data packet collisions (or make them very unlikely), and second we employ a wake-up tone receiver that allows very low-power listening for wakeup tones. We will show that these two capabilities allow contender detection and counting (Section 2.1.3) and enable a MAC protocol that provides stability and good throughput (Section 4).

#### 3.1.1 Tone-Based Reservation

In T-Lohi, nodes contend to reserve the channel for the right to transmit data. Figure 5 shows this process: each frame consists of a series of contention rounds (CRs) that conclude with one node reserving the channel and sending data.

The contention procedure requires nodes to send a *short tone* and then listen for a duration called the *contention round* (CR) to decide if reservation is successful. If only one node competes in a CR, it wins and this ends the RP (*reservation period*); consisting of one or more CR) and it can then transmit data. If multiple nodes complete in one CR, they each detect contention, backoff, and try again in some later CR (perhaps the next), thus extending the RP.

The contention round is long enough to allow us to detect (CTD) and count (CTC) contenders. The RP continues until a successful channel reservation, much like the floor acquisition in FAMA [7]. However, instead of an RTS/CTS exchange we utilize the CTD ability to distributively acquire the channel. Pseudocode for the T-Lohi protocol is presented in Algorithm 1.

When multiple nodes contend in one round, they detect this and back-off (line 7). Random backoff promotes fairness, while we use the contender count to quickly converge

based on current offered load.

#### 3.1.2 Data Transfer

To conserve energy, we wish to keep the general modem receive circuits and host CPU off as much as possible. We therefore leave both off by default, activating them only when a tone is detected by the low-power wake-up receiver. Our reservation mechanism therefore depends only on wake-up tones.

We also precede any data with a wake-up tone. Since there are cases where all nodes will not be able to discern an end of reservation period as viewed by the transmitter, we make the transmitter responsible for waking up receivers. As a result, after receiving a wake-up tone each node needs to scan the data channel for a possible preamble, even during a reservation period. If no preamble is found, the tone is considered a contention indicator. Otherwise, nodes decode the data header and go back to sleep unless they are the destination.

We also considered shifting the complexity of ensuring data reception onto receivers. For this we can use a scheduled polling mechanism with all nodes polling the data channel a duration equal to the CR after receiving any tone, instead of just the transmitter forcing receivers to wake-up. We prefer to choose the first option as it results in T-Lohi being less sensitive to any synchronization errors, false tone detections and the switching cost from deep sleep.

Finally, we suppress additional transmissions from a successful sender to reduce spatial unfairness (Section 2.1.2). The exact duration of this quiet time depends on the T-Lohi variant to use the additional information in slotting.

#### 3.1.3 Tone Implementation

Next we describe how we implementation a tone as a contention indicator. T-Lohi employs the ultra low power tone receiver on the modem developed by Wills et al. [33]; in this modem tone and data share a common channel. The core of our protocol is still applicable if we send short data packets instead of tones, on a single channel. However sending data implies long idle periods leading to significant energy drainage; such cost can be minimized using the wake-up tone hardware.

Another possibility is to encode contention tone as a sequence of wake-up tones for better noise tolerance, but this approach leads to a much larger tone detection time. We therefore choose to treat the tone in a CR as a binary contention indicator, which retains this information even if multiple tones overlap at a receiver.

Finally, we briefly consider the impact of false tone detection, given that the acoustic channel may often have periods with large amounts of noise [21]. For low to moderate numbers of false detection, T-Lohi will work correctly, but efficiency will decrease. Noise will be taken as false contention and so will prolong the reservation period and lower throughput. While the energy cost of a longer reservation period is still minimal (nodes are sleeping almost the entire period and only the low-power wakeup receiver is on), listening on the data channel after each tone (as explained in section 3.1.2) may cause a perceptible energy loss.

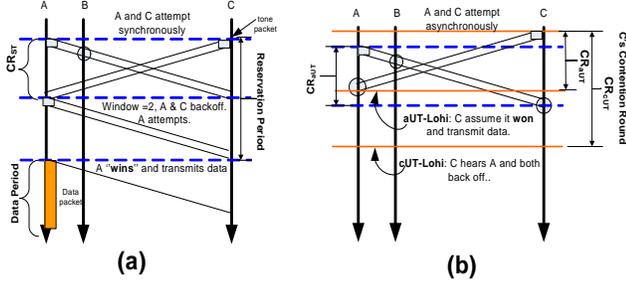


Figure 6. Overview of (a) ST-Lohi, (b) UT-Lohi

### 3.2 T-Lohi Flavors

The T-Lohi reservation mechanism deals with how nodes contend for the channel and make their decisions on channel acquisition by taking the space-time uncertainty into consideration. The backoff mechanism dictates the reaction to a failed contention round as well as the policy to start contention in a new T-Lohi frame, leveraging information about medium access such as CTC. We next define three flavors of T-Lohi that vary the reservation mechanism with different implementation requirements and performance results. (In Section 4.5 we also vary the backoff mechanism.)

#### 3.2.1 Synchronized T-Lohi (ST-Lohi)

We begin by assuming all nodes are time synchronized and present ST-Lohi. Synchronizing each contention round simplifies reasoning about protocol correctness, at the cost of requiring distribution of some reference time.

ST-Lohi synchronizes all communication (contention and data) into slots that last as long as each contention round. This duration is  $CR_{ST} = \tau_{max} + T_{tone}$ , where  $\tau_{max}$  is the worst case one-way propagation time and  $T_{tone}$  is the tone detection time. Figure 6(a) shows ST-Lohi in action, where two nodes contend in the first CR, one in the second CR, then the winner starts sending data in the third slot.

Slot-level synchronization helps ST-Lohi in two ways. Since tones are sent only at the beginning of each CR, we know that any tones must arrive before the end of the CR and will be detected assuming no bidirectional deafness (Section 2.2). Since bidirectional deafness happens deterministically based on node location (and only rarely when nodes are extremely close), ST-Lohi contention will always converge and provide collision-free data transfer.

Second, synchronization provides additional information that is used in deciding the backoff policy for the start of a new T-Lohi frame. All nodes learn the approximate number of nodes with data to send. We call this value the *first contender count* (FCC). FCC is updated if in any CR the CTC is greater than the current  $FCC$  and decremented after each frame. In addition, all nodes can estimate the distance from a transmitter by measuring the propagation delay relative to the start of the current slot ( $\Delta T$  in Figure 2(a)). We use  $\Delta T$  to compute a *spatial advantage index*,  $SAI = 1 - \frac{\Delta T}{CR_{ST}}$ . Nodes also maintain a boolean variable  $didCntd$  indicating if they attempted contention in a previous frame. This variable is reset every time node wins the frame and sends data.

Algorithm 2 shows ST-Lohi's backoff algorithm using

#### Algorithm 2 ST-Lohi Backoff(FCC,didCntd,SAI)

```

1: if  $didCntd = true$  then
2:   return  $\lfloor (random[0, 1] + SAI) \cdot FCC \rfloor$ 
3: else
4:   return  $\lfloor (random[0, 1] + SAI) \cdot 2^{FCC} \rfloor$ 
5: end if

```

this information. Nodes prioritize the channel access if they have already contended, thus reducing the medium access latency. Nodes with higher SAI are more likely to wait an extra slot thus handling the spatial unfairness that can result in channel exchange between neighboring nodes for slotted access (section 2.1.2 and Figure 2(b)).

#### 3.2.2 Conservative Unsynchronized T-Lohi (cUT-Lohi)

ST-Lohi is simple to reason about and we can exploit synchronization to estimate contender behavior. However, time synchronization is not free, and maintaining time synchronization adds run-time overhead and protocol complexity. We therefore next explore *unsynchronized* protocols.

In unsynchronized T-Lohi, nodes can start contending any time they know the channel is not busy. Each T-Lohi CR requires a node to determine who else is contending, so with cUT-Lohi we must observe the channel for  $CR_{cUT} = 2\tau_{max} + 2T_{tone}$ , twice as long as with synchronization to account for worst-case timing of tones. Consider Figure 6(b), where node C sends a tone at time  $t_C$ . In the worst case, the second contender A sends its tone at  $t_C + \tau_{max} + T_{tone} - \epsilon$  because it is as far from C as possible and sends just before hearing C's tone, and A's tone will arrive and be detected at C at  $t_C + 2\tau_{max} + T_{tone} - \epsilon$ . Unlike ST-Lohi, cUT-Lohi cannot estimate a variable similar to FCC because of asynchronous view of a contention round, it therefore defaults to just the quiet period of a single CR duration after each transmission. If nodes contend immediately once a frame ends, there attempt times will become synchronized. To break this synchronization, as it can lead to persistent deafness based on node location, non-transmitting nodes with data to send contend after an additional uniform backoff within a RECONTENTEND\_WINDOW that should be greater than  $T_{tone}$  (set to  $3 \cdot T_{tone}$  in our implementation to balance with access latency).

#### 3.2.3 Aggressive UT-Lohi (aUT-Lohi)

Although cUT-Lohi avoids the complexity of synchronization, its long contention time reduces throughput. Aggressive unsynchronized T-Lohi (aUT-Lohi) follows cUT-Lohi, but cuts the duration of its contention round to  $CR_{aUT} = \tau_{max} + T_{tone}$ .

Recall that the purpose of the long listen in cUT ( $CR_{cUT}$ ) was to account for worst-case timing of tones. In aUT-Lohi, worst-case timing results in either a tone detection (as before), or a *tone-data collision* or *data-data collision*, depending on the relative distances of the two senders and a receiver. Consider Figure 6(b) again: A's tone will not be heard by C within  $CR_{aUT}$ , so C will assume it has acquired the channel and transmit data at  $t_C + CR_{aUT}$ . A's tone and C's data transmissions will collide at a node located near C (a tone-data collision), but be received separately at B. Also, node A

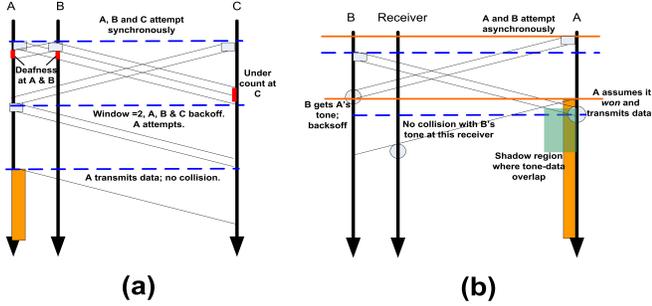


Figure 7. Benefit of (a) Higher contention, (b) lack of synchronization.

will hear C’s data and backoff. We describe these scenarios in more detail Section 3.3.1, arguing that the conditions that result in data collisions are quite unlikely. Simulation results in Section 4.4 verify the low probability of such events as there are few packet losses for aUT-Lohi.

### 3.3 Discussion on Protocol Correctness

T-Lohi avoids packet collisions through a reservation mechanism. However, there are occasional cases where the reservation mechanism can fail leading to *protocol incorrectness*. We next define problems that can lead to such incorrectness in T-Lohi. These cases include tone-data collision, data-data collision and persistently incorrect reservation. We also discuss how higher contention can lead to partially correcting these problems.

#### 3.3.1 Tone-Data Collision

As described above in Section 3.2.3, tone-data collision can occur in aUT-Lohi because contenders listen for only  $\tau_{max}$ . (It also occurs in very unlikely corner cases with cUT-Lohi and ST-Lohi.)

The necessary conditions for tone-data collision in aUT-Lohi are:

**Tone-Data coexistence conditions:**

$$\begin{aligned} TDT &< (TDL + T_{tone}) & (6) \\ TDL &\geq \frac{\tau_{max}}{2} \end{aligned}$$

The first equation states that the interferer B (refer to Figure 7(b)) transmits before A’s tone is detected by B, as tone detection precludes any contention attempt. This condition is actually a superset of the deafness condition, so if deafness occurs the first condition will be satisfied but not vice versa. The second equation represents the case that B is located far enough from A so that the CR at A ends before A can detect the tone sent by B.

However these conditions are not sufficient for tone-data collision. The overlap of tone-data must occur at the receiver (within the shadow region of A as shown in Figure 7(b)) for the protocol to behave incorrectly and result in tone-data collision. This additional condition makes tone-data collision less likely to occur; as supported by the very small number of packet losses in simulations in Section 4.4. In fact, if the receiver is not in the shadow region, a transmission in aUT-Lohi actually succeeds (because tone and data do not collide)

in situations where ST-Lohi and cUT-Lohi would extend the reservation period.

#### 3.3.2 Data-Data Collision

Data-data collisions can also occur in T-Lohi if two nodes believe they have won the reservation and so transmit simultaneously.

In ST-Lohi, data-data collisions occur only as a result of bidirectional deafness when nodes are too close together. As described in Section 2.2, bidirectional deafness occurs when two nodes are closer than  $D_{deaf}$ —this is a necessary and sufficient condition for data-data collisions. If nodes are stationary and transmission times are fixed (as in ST-Lohi), these collisions must be resolved at higher layers by attempting retransmission at different times. In addition,  $D_{deaf}$  is quite small for our hardware; in simulations with random node placement we see that only 0.14% of node pairs are bidirectionally deaf. Fortunately, unslotted transmissions imply that UT-Lohi contention attempts are uncoordinated and so this case is very unlikely there, and it will be resolved by normal MAC-level backoff should it happen.

Data-data collisions can also occur in aUT-Lohi. They occur when tone-data coexistence conditions of Equation 6 and the deafness condition of Equation 5 are both met, a combination of conditions we refer to as *pseudo-bidirectional deafness*. This is because one node of a pair will assume data reserved because of its aggressive round length, while the other will do the same due to deafness.

#### 3.3.3 Benefit of High Contention

Finally, although we describe collision scenarios above, presence of an additional contender solves these situations. In effect, an additional contender extends the reservation period.

We illustrate this effect for ST-Lohi, with contending nodes A and B within each others deaf region  $D_{deaf}$ , as shown in Figure 7(a). In this case, bidirectional deafness would normally cause both nodes to send data packets that would then collide. However, addition of another contender C causes both A and B to detect another contender. All nodes backoff and prevent an incorrect data reservation. If this backoff places A and B in separate CRs, then no collision will occur.

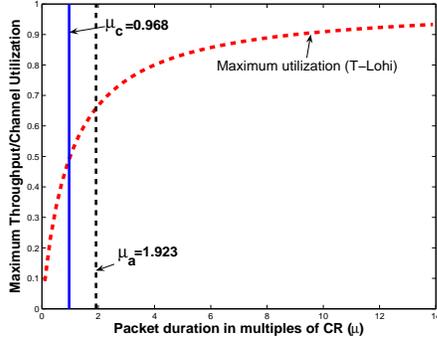
Similarly additional contenders also “break” the pseudo bidirectional deafness of aUT-Lohi and prevent packet collisions.

## 4 Performance Evaluation

We next evaluate T-Lohi performance through simulation. We look at the design tradeoffs between the three T-Lohi flavors. We also evaluate important medium access metrics such as throughput, energy efficiency, and fairness for T-Lohi. Finally, we quantify the impact of the unique characteristics in acoustic medium access, such as deafness and contender counting ability, on the performance of T-Lohi.

### 4.1 Simulation Methodology

Since we did not find an existing simulator that supports acoustic communication for MAC design with both data communication and wake-up tone detection, we developed our own simulator based on a prior model for underwater



**Figure 8. Maximum theoretical utilization for T-Lohi protocols as  $\mu$  is varied, with vertical lines showing the  $\mu$  used in our simulations.**

time synchronization [27]. Our simulator models the high latency in tone and data transmission, and captures collision at receivers both within and between overlapping tone or data transmissions. We do not currently model packet loss due to environment effects. We omit this primarily to focus on protocol behavior. Exploration of the effects of channel noise and loss is an important direction for future work.

We perform simulations with the following parameters, unless otherwise noted. We randomly deploy nodes in a  $300 \times 400\text{m}$  area for a fully connected network with acoustic modem range of 500m. The data rate for the acoustic modem is set to 8kb/s and packet length is 650 bytes, implying that packet transmission duration  $P_{Tx}$  is 650ms. Tone detection time is 5ms. We run each simulation 500 times, with each lasting 100s, and show mean and 95% confidence intervals for each statistic. (In almost all cases confidence intervals are barely visible.) We model the traffic with a Poisson arrival process, with each node having a single packet transmission buffer.

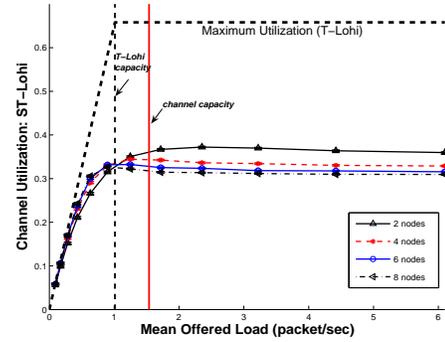
## 4.2 Network Throughput

In this section our goal is to understand the impact on throughput in terms of offered load, network density, and packet length. Understanding throughput performance is important as acoustic communication has very limited bandwidth and large latency. We will first look at the maximum theoretical throughput that T-Lohi is able to achieve. We then use this upper bound to compare with the practical throughput of T-Lohi with varying parameters.

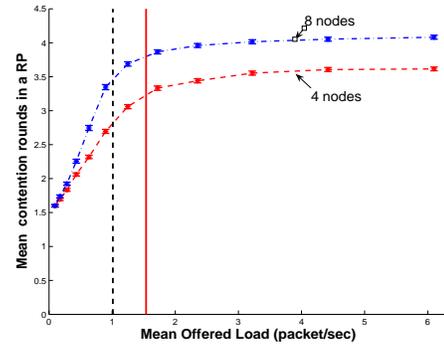
### 4.2.1 Maximum Throughput Analysis

Theoretically, T-Lohi achieves its maximum throughput when there is perfect scheduling. With perfect scheduling, there is only one contender per frame, and all T-Lohi frames will consist of a single contention round (CR) that is proportional to the worst case propagation delay. With just data packets contributing to throughput the maximum throughput measured as the percentage of channel utilization will be the ratio of data to frame length:  $P_{Tx}/(P_{Tx} + CR)$ .

The maximum utilization of T-Lohi thus *increases* with shorter CR (implies shorter communication range), lower bandwidth, or longer packet sizes. Since these variables vary for different modems and deployments, we combine them in a single parameter  $\mu = P_{Tx}/CR$ , the *packet transmission*



(a) Channel utilization for ST-Lohi



(b) Mean Reservation period per packet

**Figure 9. Throughput of ST-Lohi under varying load. The vertical solid and dotted lines represent the maximum load the channel and protocol can accept. The horizontal dashed line gives maximum utilization for T-Lohi as the load is varied.**

*time in multiples of contention rounds*, to divorce achievable throughput from a particular topology and hardware. With this parameter the maximum normalized throughput that T-Lohi protocols can achieve thus becomes:

$$TH_{max} = \frac{\mu}{(\mu + 1)} \quad (7)$$

Figure 8 shows how best possible performance varies with  $\mu$ . The vertical lines show operating points for our simulation as  $\mu_a = 1.923$  for aUT and ST-Lohi (same duration CR) and  $\mu_c = 0.968$  for cUT-Lohi. The maximum channel utilization achievable for ST-Lohi and aUT-Lohi is 0.66 while for cUT-Lohi it is 0.49.

### 4.2.2 Throughput as Load Varies

We first examine how the throughput of T-Lohi responds to varying offered load. Existing wireless MAC protocols all exhibit throughput degradation at heavy loads. We expect T-Lohi to be more stable to varying load because it can detect and count contenders.

To vary load we increase the Poisson arrival rate at each node. We start with ST-Lohi since, as we show in the next section, the other protocol flavors have similar throughput response to load.

Figure 9(a) shows channel utilization (throughput normalized by bandwidth) as a function of aggregate offered load

**Table 2. Acoustic Modem Power Draws**

Mode	Data	Wake-up Tone
<b>Transmit (Max)</b>	2W	2W
<b>Receive</b>	20mW	0.5mW
<b>Idle/Listen</b>	20mW	0.5mW

for different network densities. The figure also shows two theoretical targets while operating at  $\mu_a$ . First, the vertical lines show two limits on the offered load. The solid line represents the maximum channel capacity while the dotted line is practical capacity for a T-Lohi protocol. Second, we also plot the maximum theoretical utilization for T-Lohi as the load varies.

We have three observations from this simulation. First, ST-Lohi is very efficient at low offered load, where contention rates are low. For aggregate offered load less than 0.5 packets/s, ST-Lohi is very close to maximum theoretical utilization.

Second, as offered load approaches the practical capacity (0.5–1 packet/s), we see ST-Lohi reaches about 50% of maximum utilization. This decrease is due to greater contention, and as Figure 9(b) shows, the mean reservation period (RP) length doubles from 1.6 to 3.3 contention rounds. This longer RP leads to the 50% loss when compared to the best theoretical utilization at that load.

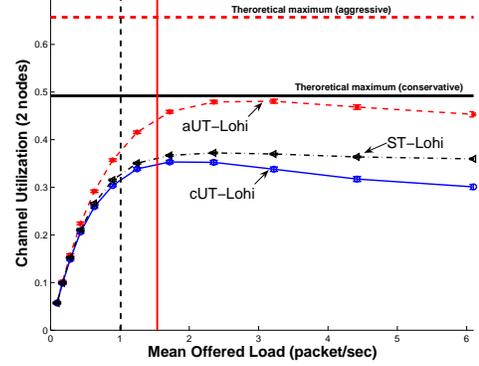
Finally, as offered load exceeds practical capacity (more than 1 packet/s), we observe that ST-Lohi performance remains stable. In other words, the throughput of ST-Lohi does not degrade at heavy load—a performance that cannot be achieved by existing wireless MACs. ST-Lohi’s stability is due to the near constant time taken to successfully reserve the channel, even under heavy load (Figure 9(b)). The constant reservation time is the result of T-Lohi’s capability to detect contention and backoff intelligently based on the number of contenders.

**4.2.3 Channel Utilization of Three T-Lohi Flavors**

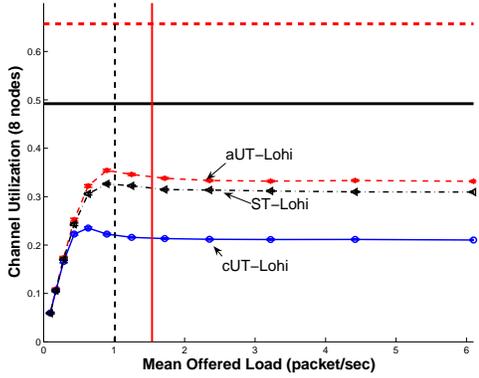
In order to observe how different protocol design choices (Section 3.2) affect channel utilization, we next compare the three T-Lohi flavors. We expect ST-Lohi and aUT-Lohi to have similar performance as they have equal length contention round (CR), while cUT-Lohi throughput should be significantly less because of its longer CR.

Figure 10(a) shows the channel utilization of T-Lohi flavors as the offered load varies in a two-node network, while Figure 10(b) shows that in an eight-node network. We observe three interesting aspects from these simulations. First, all protocol flavors have a similar throughput trend: efficient at low load and stable at high load. This similarity is due to contention detection and counting, which makes all three protocols adaptive to traffic. They all therefore allocate the channel quickly even at high contention.

The second observation is that cUT-Lohi always has saturation capacity; about two-third that of aUT-Lohi. The reduction is primarily because of its longer contention round:  $CR_{cUT} \simeq 2 \cdot CR_{aUT}$ . Although cUT-Lohi has a contention round that is twice that of aUT-Lohi, its capacity is two-third



(a) Two node network



(b) Eight Node Network

**Figure 10. Channel utilization of three T-Lohi flavors. The horizontal lines depict the maximum utilization for  $\mu_a$  (dashed) and  $\mu_c$  (solid).**

due to the non-linearity of achievable utilization as predicted by Equation 7 for a packet length twice  $CP_{aUT}$ .

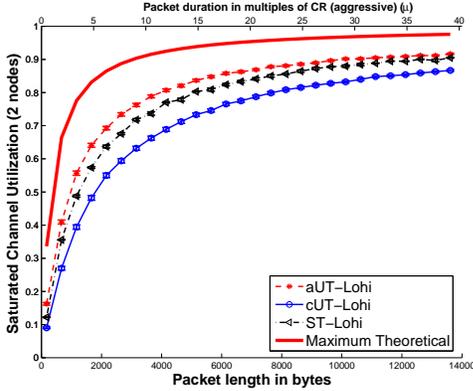
The last interesting observation is that aUT-Lohi utilization is always higher than ST-Lohi (slightly higher with 8 nodes and much better with only 2 nodes). There are two factors contributing to this effect. The first factor is the slotted access in ST-Lohi that delay all access attempts to the start of the next slot. With both having the same CR ( $CR_{aUT} = CR_{ST}$ ), this delay (on average half CR) results in greater reservation latency for ST-Lohi. Secondly, as described in Section 3.3.1 aUT-Lohi sometimes terminates the reservation period prematurely, but this decision only results in tone-data collisions based on node location. These simulation results suggest that such collisions are quite rare and aUT-Lohi’s aggression improves performance.

In summary, all the T-Lohi flavors have similar throughput behavior, but ST-Lohi and aUT-Lohi offer higher throughput than cUT-Lohi due to their smaller CRs.

**4.2.4 Impact of Network Density on Throughput**

Continuing with the simulations shown in Figure 10, we next explore how network density affects channel utilization. The throughput of traditional wireless MACs degrades with density, but we expect T-Lohi to remain stable based on the results from Section 4.2.2.

Comparing Figure 10(a) and Figure 10(b), we observe



**Figure 11. Channel utilization as  $\mu$  is varied by changing the packet length.**

that utilization is significantly lower for aUT-Lohi and cUT-Lohi in dense networks compared to that in sparse networks. In the two-node network (Figure 10(a)), aUT-Lohi and cUT-Lohi reach 50% and 35% utilization, respectively, versus the 35% and 23% in the eight-node network (Figure 10(b)). Although not shown here, this decrease by nearly 15% is evident even at 4 nodes, and densities larger than 8 do not further alter the utilization curves. Both protocols can reach within 30% of their maximum theoretical utilization (indicated by horizontal lines in Figure 10(a)) in the two-node network. Utilization of ST-Lohi, however, does not show such dependency on network density. Although its utilization can be slightly higher in the two-node network, it does not vary significantly (Figure 9(a)).

This density dependency can be explained by a combination of asynchrony and the mechanism to handle spatial unfairness. Recall that (Section 3.2) transmitters have a quiet period after a successful transmission to avoid channel capture. With two nodes and asynchronous access, this quiet period allows the two nodes to repeatedly swap the channel. However, similar effect does not occur as often in ST-Lohi because of slotted transmission times. Node A in Figure 2(a) can contend in slot 3 unopposed by node B as it remains quiet for slot 3 to enforce fairness. Nodes C or D, located further away can only start contending in slot 4 (not shown in figure) where B will also be able to contend as its quiet period would have ended.

When there are more than two nodes, all non-transmitting nodes have an equal opportunity for medium access, and thus the utilization decreases as multiple contenders require multiple CRs before the channel can be reserved. While this might suggest utilization will fall in proportion to density, T-Lohi’s ability to count contenders allows all densities converge quickly, and shows little additional reduction of utilization.

We thus conclude that the throughput of all T-Lohi flavors is insensitive to network density except for the two-node network.

#### 4.2.5 Maximum Practical Throughput

In the T-Lohi protocol, the fundamental physical limitation to throughput is a combination of propagation latency

and packet length. Propagation latency governs time spent coordinating, and packet length the time spent sending data. In Figure 8 we provided a theoretical bound on throughput, assuming an oracle could assist in reservation within a single contention round. We next explore how practical performance of our protocols compares with this bound, as a function of  $\mu$  (packet length normalized against CR that is proportional to the worst case propagation time).

To increase  $\mu$ , the ratio of packet transmission time to the length of contention round, we simply increase the packet size that gets sent in the data period. However, besides the obvious dependence of the utilization on application traffic, it is also constrained by the packet error probability that increases with the packet length. Several works quantify this impact [8, 14, 12], under different operating conditions, and optimize the packet length for different metrics. However, as suggested by Ye et.al., these effects can be mitigated by message passing, where related data is buffered and sent in fragments that can be more efficiently recovered [35]. To simplify our analysis we ignore the effect of packet loss, by assuming that it is mitigated with an efficient message passing mechanism. Based on work by Stojanovic that defines the optimal fragment size for any ARQ mechanism the efficiency of message passing can be optimized [26].

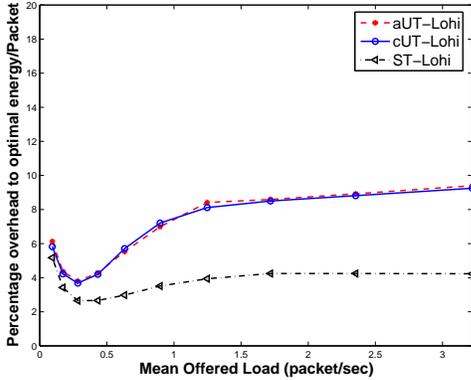
The channel utilization increases monotonically with packet length, under our simplifications, as shown in Figure 11, for all flavors of the T-Lohi protocol. We observe that at  $\mu = 5$  (packet length 1.6KB for our network characteristics) utilization of 64% and 58% for aUT-Lohi and ST-Lohi can be achieved respectively. Even cUT-Lohi at  $\mu = 5$  (not shown in the figure and achieved for 3.3KB packet) can achieve 64% utilization. In all cases the utilization achieved by our protocol remains within 35% of the theoretical limit for T-Lohi.

### 4.3 Energy Efficiency

Since underwater sensor networks are often energy constrained, we next consider the energy efficiency of T-Lohi under varying loads. We expect T-Lohi to be energy efficient because wake-up tone detection reduces the energy cost of long data reservation periods. We also expect ST-Lohi and cUT-Lohi to be most energy efficient, as they prevent any packet loss, while aUT-Lohi to be slightly less as it can cause packet losses.

The modem power characteristics used in our simulations are based on the values shown in Table 2. These parameters roughly match the power consumption of a proposed modem with hardware support for wake-up tone reception [33].

Figure 12 shows the energy overhead of T-Lohi in an eight-node network. We define energy overhead as the cost beyond the optimal energy per packet used in transmitting and receiving a single packet. All protocols are very efficient under all loads, with energy overhead at most 9% over the optimal cost (simply sending the data). ST-Lohi has a very low and nearly constant energy overhead (just 4% over the optimal) because it prevents any data collision. The overhead is solely due to the cost of sending and receiving tones during the contention rounds. The aUT-Lohi energy cost increases marginally at higher loads (9% over optimal at high



**Figure 12. Relative energy overhead for the three T-Lohi protocols for an 8 node network**

load versus 4% at low load) due to data collisions caused by its aggressive policy.

It is more interesting to observe that aUT-Lohi and cUT-Lohi have similar energy overhead. aUT-Lohi gets more packets through than cUT-Lohi, but cUT-Lohi has longer sleep periods during its operation, so the energy cost per packet becomes similar under the Poisson traffic model. Other experiments (not shown here) with a lower network density (4 nodes) show that cUT-Lohi is about 40% more energy efficient than aUT-Lohi. The reason can be explained from results in next section where we show that higher density reduces the probability of packet loss for aUT-Lohi.

Figure 10 shows that cUT-Lohi has lower throughput than aUT-Lohi, but as shown in Figure 12, its conservative behavior does not bring significant energy benefits. However, as the next section shows, cUT-Lohi does reduce any packet collisions, so it may be more energy efficient when sending a fixed amount of data, rather than sending over a fixed duration.

#### 4.4 Impact of Deafness and Aggression

We now evaluate the impact of deafness and aggressive contention on T-Lohi protocols. As explained in Section 3.3 both deafness and aggressive contention result in potentially incorrect data reservation, hence quantifying their impact allows us to examine the protocol correctness. We say the protocol is incorrect when it generates incorrect reservation leading to packet collisions.

The most important effect of incorrect data reservation is the loss of packets. Thus we quantify the impact of deafness and aggression by looking at how many packets are lost under similar offered load. Our observations in Section 3.3 are important to interpret these results: Unidirectional deafness can only cause a tone-data overlap which results in a single packet loss. Bidirectional or pseudo bidirectional deafness results in a data-data overlap, *i.e.*, the loss of two packets.

We look at protocol correctness for the three T-Lohi flavors, and then evaluate how it is affected by the node density.

##### 4.4.1 Correctness of T-Lohi Flavors

We quantify the correctness of the three flavors by measuring packet loss over a fixed interval in a two-node network as offered load varies. We expect that all three protocols

have minimal packet loss, but that aUT-Lohi have the most because of its aggressive contention.

The result of the simulation is shown in Figure 13(a). We make several interesting observations from these simulation results. First, cUT-Lohi experiences practically no collision at any offered load. ST-Lohi has very few packet losses but shows high variability, while packet loss for aUT-Lohi increases proportional to the network load.

As explained in Section 3.3 a long contention round allows cUT-Lohi to avoid collisions, even when unidirectional deafness occurs. However aUT-Lohi *guarantees* data-data collisions when pseudo-bidirectional deafness occurs. Analysis of packet loss due to only data-data overlap show that majority of the packet loss in aUT-Lohi occurs due to pseudo-bidirectional deafness. Since the probability of both incorrectness and deafness condition increase with offered load, we thus observe a load dependent increase in packet loss for aUT-Lohi. These results imply that the impact of unidirectional deafness in the two-node network is negligible (no collision for cUT-Lohi and very few tone-data collision for aUT-Lohi), but when combined with aggressive contention, it can cause packet loss. ST-Lohi shows packet loss whenever two nodes are placed too close to cause bidirectional deafness. Otherwise, packet loss never occurs with ST-Lohi; this bimodal response to deafness causes the higher variation in loss.

##### 4.4.2 Protocol Correctness and Network Density

We now want to observe the impact of density especially when more than two nodes contend. We expect that additional contenders will reduce the number of incorrect reservations as described in Section 3.3.3.

The results of packet loss for both cUT-Lohi (not shown here) and ST-Lohi show very little variation over all network densities. cUT-Lohi in fact remains robust with extremely low packet loss and low variance. ST-Lohi shows a few packets lost (mean of 1) for a 2 node density but with high variance because of topology dependent bidirectional deafness. However with more than two nodes the deafness conditions are broken by an extra contender and very few packets are ever lost (Figure 13(c)).

The impact of increasing the number of contenders on the packet lost by aUT-Lohi is more profound (Figure 13(b)). Figure 13(b) shows that both the mean packets lost and their variance decreases as more nodes contend.

These results show that under high contention, the impact of both deafness and aggression (in aUT and ST-Lohi) becomes negligible. cUT-Lohi meanwhile provides the most robust and reliable data transfer, especially for sparse and low traffic networks. These results also corroborate our decision to not actively handle persistent deafness (Section 3.3.2).

#### 4.5 Impact of Contender Detection and Counting

The T-Lohi protocols leverage space-time uncertainty of high-latency acoustic communication to provide contention detection and contender counting. Here we separate these capabilities and quantify their impact on T-Lohi performance. We observe throughput to quantify the impact of contention

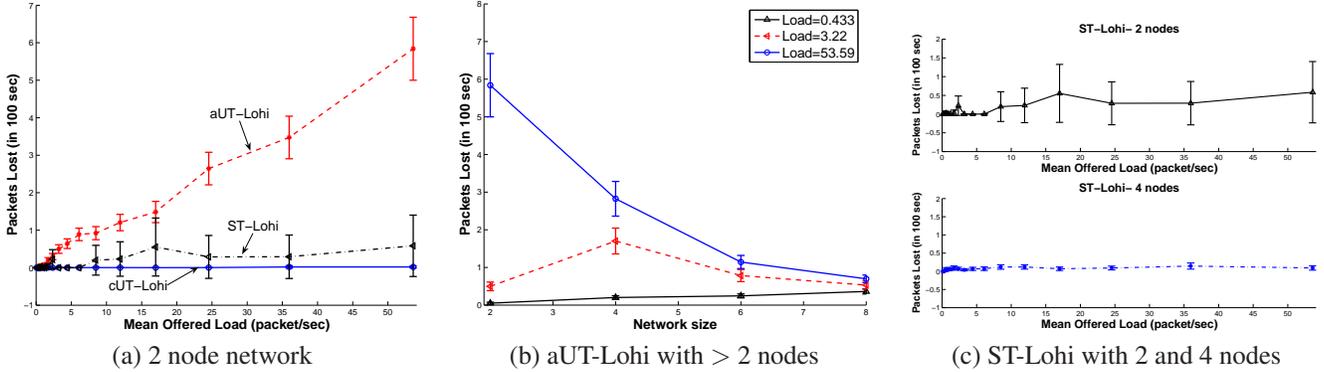


Figure 13. Packets lost in a fixed duration as offered load is varied

detection, while we look at access fairness to observe the benefit of contender counting.

To evaluate the benefits of channel observation we next compare ST-Lohi with standard CTC and a modified version that replaces CTC with standard binary exponential back-off (BEB). We observe similar channel utilization curves for both MACs (the figure is omitted for lack of space). Thus we conclude that that systems with collision detection capability exhibit stability even at high loads, as also shown in prior work for Ethernet [31]. What is interesting about T-Lohi protocols is that they possess collision detection ability in a single channel packet radio network.

However MAC protocols that depend only on collision detection, such as Ethernet, suffer from the *packet starvation* effect where under high load stations can not access the medium while a few capture it for long periods. This unfairness results from the backoff mechanism employed with insufficient (binary) information about the congestion. T-Lohi however provides accurate information about the number of contenders and allows for a traffic adaptive backoff mechanism (Algorithm 1). In order to compare the access fairness we looked at the number of packets that a node is able to send successfully. We used Jain’s fairness index defined as:

$$\text{Jain's Fairness Index} = \frac{(\sum x_i)^2}{n \cdot \sum x_i^2} \quad (8)$$

Here  $x_i$  is for the number of packets successfully sent by a node, and  $n$  represents the number of nodes in the network. Figure 14 shows the result for an experimental setup run for 500s and for an 8 node network to strenuously test protocol fairness.

We first observe that the T-Lohi protocols exhibit a high fairness index (0.9 and above) that remains nearly constant across all offered loads. In comparison the version employing BEB instead of using contention count for backoff shows an exponential decay in its fairness index. The reason for such traffic independent fairness in T-Lohi is again the ability to backoff based on an accurate view of the current congestion level.

This simulation shows that CTD is essential for stability of T-Lohi protocols, while CTC maintains high access fairness as it allows a traffic aware backoff.

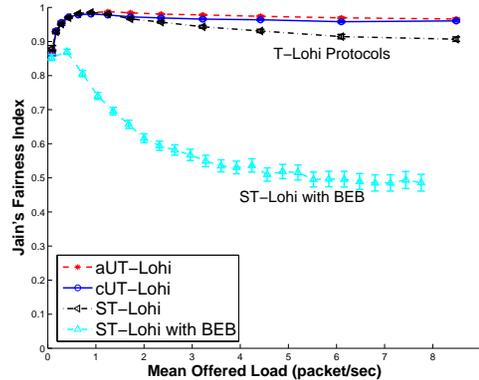


Figure 14. Jain’s fairness index for T-Lohi protocols that employ CTC vs. a MAC using CTC with BEB.

## 5 Related Work

There is a huge amount of work on media access control. Our work builds on prior work in sensor networks, particularly for energy efficiency, but such networks have quite low latencies. We also review satellite networks with high latency, and other underwater acoustic networks.

### 5.1 Terrestrial RF-based MACs

Packet radio networks pioneered two classes of wireless MACs: centralized protocols such as TDMA and distributed contention-based protocols such as ALOHA [2] and CSMA [29]. While these protocols are widely used in terrestrial wireless networks, they have significant performance loss when applied to high-latency acoustic networks.

Recent work on sensor networks has raised the importance of energy efficiency. Scheduled contention in S-MAC [35] and low-power listening (LPL) in B-MAC [20] and WiseMAC [6] are two major approaches to conserve energy. However, they also become less effective in underwater networks. S-MAC synchronizes the listen intervals of neighboring nodes to perform CSMA-based contention. In underwater networks, senders cannot start contention at the same time due to the large and location-dependent propagation delay to a receiver. A naive solution requires significant extension to the listen interval, and thus largely reduces its performance. LPL shifts the burden from receivers to trans-

mitters by using long preambles. However, in underwater networks, the cost of transmission can be two orders of magnitude higher than that in short-range radios. Moreover, LPL still uses a simple CCA approach in contention, which does not handle the space-time uncertainty (Section 2.1.1).

In contrast, T-Lohi uses a novel tone-based reservation mechanism that handles space-time uncertainty and efficiently resolves contention. It also exploits an ultra low power tone receiver to achieve excellent energy efficiency.

There are other protocols, such as BTMA [30] and DBTMA [9], that use *busy tones* to deal with the hidden terminal and exposed terminal problems. These protocols, however, assume separate channels for tones and data, but we only assume a single channel. They do not consider large propagation delays, as they are designed for wireless RF networks.

## 5.2 Satellite MACs

Satellite networks are an area where protocols do consider large propagation delays in the order of what UWSN experiences, for example, 125ms. However, the special, asymmetric topology in satellite networks largely simplifies their MAC design. Such a network usually consists of a satellite and many small nodes on the ground. The down link is a simple broadcast channel that requires no MAC. Although the uplink may involve many transmitters, there is only a single receiver, effectively removing the uncertainty in space. It therefore allows existing protocols such as ALOHA to handle contention in time [19]. Alternatively, a centralized MAC can be easily implemented. In comparison, T-Lohi is fully distributed protocol that does not rely on any special topology.

Another difference of satellite MACs to our work is that they do not consider energy efficiency, whereas T-Lohi explicitly optimizes this attribute in its design.

A common characteristic in sensor networks and satellite networks is that they usually have abundant bandwidth, so channel utilization may not be a big concern. However, the bandwidth in the underwater acoustic channel is very limited, and thus our protocol is designed to be very efficient in channel utilization.

## 5.3 Underwater Acoustic MACs

The most closely related work is the MAC protocols designed for underwater acoustic networks that also deal with high latency. Early work uses naive CSMA with RTS/CTS (Seaweb 2000 [22]), resulting in low throughput. The other work employs CDMA by developing code distribution techniques [34], which has high energy cost. Rodoplu and Park extend S-MAC's schedule synchronization to sender-receiver pairs in UWSN [23]. It allows energy-efficient operation, but lacks effective mechanism for contention. As a result, the protocol is only suited for applications that have extremely low traffic rates. S-FAMA uses an RTS/CTS exchange to prevent collisions, with an RTT penalty per packet attempt [15]. Peleato and Stojanovic extend this work using the fact that inter-node distance is seldom the maximum transmission range allowing less than RTT penalty per packet [18]. These recent efforts do not optimize for energy. The throughput that they achieve is also relatively low (<

20% normalized). T-Lohi protocols offers energy efficiency, good and stable throughput with flexibility for all types of applications.

## 6 Future Work

Our future work includes evaluating the design for multi-hop networks, exploiting the relative location information in ST-Lohi and contender count for greater throughput, adding data to contention tones for better handling of false positives and experimenting over a real acoustic testbed.

## 7 Conclusions

In this paper we explore acoustic medium access and identified its unique characteristics that allow detection and counting of contenders. We leveraged these opportunities along with low power wake-up tone hardware to design T-Lohi, a new class of energy efficient, stable and flexible MAC protocols for UWSN. We propose three flavors of T-Lohi representing different design choices. We carry out extensive simulation to evaluate their performance. The results show that ST-Lohi is the most energy efficient protocol, within 3% of the optimal energy. aUT-Lohi achieves the highest throughput (~50% channel utilization). cUT-Lohi provides the most robust packet delivery with almost no packet loss. All three flavors exhibit efficient channel utilization, stable throughput, and excellent energy efficiency.

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