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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 contention resolution mechanism that exploits space-time uncertainty and high latency to detect collisions and *count contenders*, achieving good throughput across all offered loads. Lohi uses 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, and that Lohi achieves good channel utilization, within 30% utilization of the theoretical maximum. We also show that Lohi is stable and fair under both low and very high offered loads.**

I. Introduction

Networks with shared media require access protocols (MACs) to control access of the shared channel. Compared to wired MAC protocols, wireless MACs face several unique challenges, such as lacking the ability to detect collisions and inconsistent views of the network as seen in the hidden and exposed terminal problems. In underwater sensornets (UWSN), a shared *acoustic* medium adds more challenges [1], [2]. Acoustic communication magnifies wireless bandwidth limitations, transmit energy costs, and variations in channel propagation. Control algorithms of MAC protocols are significantly changed by acoustic propagation latencies that are five orders of magnitude greater than radio.

The focus of this paper is to design an energy and throughput efficient MAC protocol for short range, acoustic sensor networks. Recently several innovative acoustic modems have been proposed [3], [4], but no MAC protocol is widely available to support dense networks—a requirement for sensornet-style embedded sensing. We will show that the challenges of high latency also enable new MAC techniques and solutions that provide good throughput across varying application requirements (Section II-A3).

Many applications will require long-term deployments, making energy-efficient design an important goal. While some researchers have suggested many underwater networks will be mobile, making communications power negligible [2], we see several important categories of application where energy-efficiency remains critical. A first category is the static sensing applications such 4-D seismic sensing of oilfields [1]. Gliders and low-energy mobility platforms represent a second category. The third category is applications such as water-life tagging [5], where mobility is parasitic and consumes no energy from the sensor system. Compared to radio communications, energy-efficient design is challenging for UWSN, as transmit energy costs are high [2], idle time is long, and battery replacement is difficult or impossible.

We propose a new class of medium access protocols called *Tone Lohi* ("Lohi" means *slow* in Hawaiian). Besides being energy and throughput efficient, Tone Lohi (T-Lohi) provides flexible, fair, and stable medium access for acoustic networks. Rather than customize the protocol to a specific type of application [6], we design for general underwater applications.

This paper presents three novel contributions: First, although implicitly considered by prior MAC protocols, we are the first to *fully describe space-time uncertainty* and deafness (Sections II-A and II-B). Second, we exploit this effect to provide *contender counting*, and to show how contender counting can improve fairness and stability under heavy load (Section II-A3). Finally, we propose Lohi, a new class of MAC protocols designed for underwater acoustic networks to exploit these effects (Section III).

We evaluate our protocols through detailed simulation (Section IV). Results show that their energy efficiency is within 3–9% of optimal, and that they achieve good channel utilization, which is within 30% utilization of the theoretical optimal. We also show that our protocols are stable and fair under both low and very high offered loads (Section IV-B2). These results are promising and suggest that evaluation in multi-hop conditions and an implementation are promising future directions.

II. Challenges and Opportunities

Prior work has studied the challenges inherent to underwater acoustic communications [1], [2]. 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, and so must be handled explicitly (for example, in time synchronization [7]). Most current underwater communication targets distances of several kilometers, but short-range communication (less than 500m) may simplify propagation characteristics and allow simpler and cheaper designs [1].

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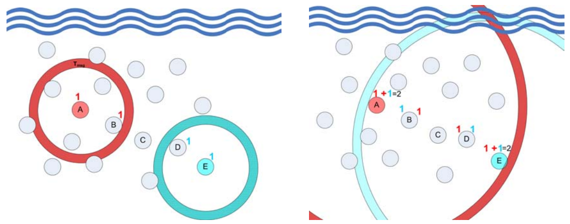


(a) Collision uncertainty (b) Contender detection and counting

Fig. 1. Spatio-temporal uncertainty in acoustic medium access.

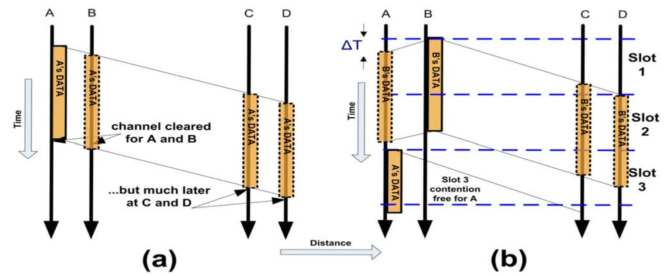


Fig. 2. Spatial Unfairness: (a) Transmitter and close neighbors have channel cleared earlier. (b) In slotted access, close neighbor A can attempt in slot 3 while C and D can not.

The energy consumption of acoustic hardware also differ significantly from terrestrial sensornets. With underwater acoustic communication, transmission is often 100 times more expensive than reception [2]. 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) [3], while short-range radios for sensornets generally provide ratios around 1:1.5 [8].

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.

A. Space-Time Uncertainty

Channel state in short-range RF networks can be estimated quickly since 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*. Although prior underwater work implicitly considers this uncertainty [9], we present a systematic description of this principle and its impact on contention based medium access. We next give an example of this principal, but separately investigate its impact on ALOHA protocols in detail [10].

Consider Figure 1(a): the two concurrent transmissions from A and E are received separately at nodes B and D but will collide at node C. This shows that collision and reception in slow networks depend on both transmitter *time* and receiver *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 where latency is 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.

1) Clear Channel Assessment: Clear channel assessment (CCA), sampling the medium for detecting activity, is an essential component of all CSMA-based MACs. Performing CCA before transmitting data prevents nodes from colliding with concurrent transmissions. While a transmission can be almost immediately detected by receivers in a short-range RF network, space-time uncertainty greatly reduces CCA effectiveness in acoustic networks. A modified CCA would synchronize transmission time and sense the channel for the duration of the worst case propagation delay. 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.

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 [11]. 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's arrival 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.

With slotted media 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 (Section III-B).

3) Contender Detection and Counting: Although latency increases uncertainty, we next show that it can also be exploited for *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.

Nodes in our protocol detect contenders by listening to the channel after sending *short* reservation tones that are analogous to RTS messages. Unlike low-latency wireless protocols, large propagation delays mean that nodes can observe tones sent concurrently because they may arrive after their own transmissions complete. Contender detection depends on relatively short tones and a long listen period. In addition to detecting contenders, if tones are short enough (we formalize shortness in Section II-B), nodes can further *count* the number of contenders, since tones from different transmitters arrive

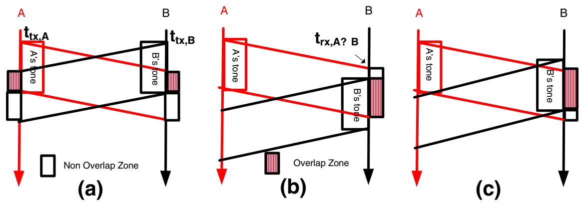


Fig. 3. The three cases where deafness can occur. (a) Bidirectional deafness. Unidirectional deafness at B with A's tone reaching B (b) before B starts transmitting, (c) after B starts transmitting.

at different times due to varying propagation latencies. An example is shown in Figure 1(b), where nodes A and E send short tones. At nodes where the tones do not collide, such as nodes A, E, B, and D, they can count the number of contenders. Even if the tones collide on some nodes, *e.g.*, node C, they can still detect the presence of contention. The capability of contender counting (CTC) is not generally possible for RF-based networks due to short propagation delays, although concurrent with our work, some researchers have begun to use game theoretic approximations of contender counts [12]. We exploit CTC in our MAC design in Section III. Others have proposed flow-level contention counting for multi-hop 802.11 networks [13]; our work differs by focusing on single-hop contention as applied to MAC protocols.

B. Deafness Conditions

Wireless transceivers normally work in half-duplex mode, and thus on a single channel a node that is transmitting cannot receive another packet at the *same* time. Therefore, a node becomes *deaf* to another transmission in this situation. We employ special low-power wake-up tone hardware [4] for sending contention tones (Section II-A3). The tone detection mechanism requires energy accumulation over a minimum duration, denoted as T_{detect}, larger than the data symbol duration. Thus while transmitting a node will be unable to *hear* a tone with a probability proportional to T_{detect}.

We next identify the relation between the latency of tone detection and deafness conditions. Three different circumstances can result in deafness; they are shown in Figure 3. In Figure 3(a), the deafness is *bidirectional*, as neither node A nor B can detect the other's tone. Figure 3(b) and (c) are two different scenarios that lead to *unidirectional* deafness, where only node B cannot detect A's tone.

We posit that the deafness conditions can be generalized if we make the convention that node A transmits its tone before B. (Detailed derivation of the conditions in each scenario is in our technical report [14]). We define *TDT* (Time Difference of Transmission) as $t_{tx,B} - t_{tx,A}$ ($t_{tx,B}$ is the global tone transmit time of B), and *TDL* (Time difference of Location) as $T_{A,B}$ ($T_{A,B}$ is the propagation delay between A and B). Then the *Generalized Deafness Condition* (***GDC***):

$$|TDT - TDL| < T_{detect} \quad (1)$$

GDC emphasizes that deafness is not affected by the tone length, but only by tone detection time (for equal length tones). 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). In Section III-C, we explore the impact of deafness condition on our MAC protocol.

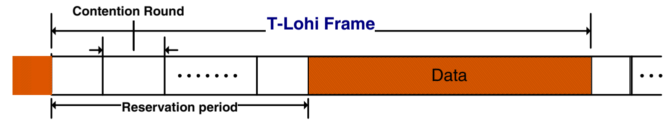


Fig. 4. The Tone-Lohi protocol frame

Algorithm 1 Pseudocode for the T-Lohi protocol

```
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 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
```

III. Tone-Lohi MAC Protocol Design

Tone-Lohi (T-Lohi) is a contention-based protocol where data reservation uses short wake-up tones. Its reservation process is fully distributed, and it is rapid and energy-efficient by employing short tones and a low-power receiver. This section describes T-Lohi in detail and discusses the motivation and design tradeoffs behind different flavors of T-Lohi.

A. Overview of T-Lohi

The primary objective of 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.

1) Tone-Based Reservation: In T-Lohi, nodes contend to reserve the channel to send data. Figure 4 shows this process: each frame consists of a *reservation period* (RP) followed by a data transfer. Each RP consists of a series of *contention rounds* (CRs) until one node successfully reserves the channel.

Contention requires that nodes first send a *short tone* and then listen for the duration of the *contention round* (CR). If a node receives no tones by the end of the CR, it wins the contention, and therefore ends the RP. It will then start sending data. If multiple nodes compete in a CR, each of them will hear the tones from other nodes, and thus will back off and try again in a later CR (perhaps the next), which effectively extends the RP. The CR is long enough to allow nodes to detect (CTD) and count (CTC) contenders.

Pseudocode for the T-Lohi protocol is shown as Algorithm 1. As shown in line 7, when nodes detect contention,

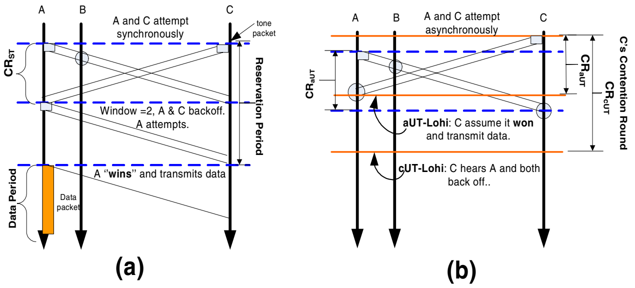


Fig. 5. Overview of (a) ST-Lohi, (b) UT-Lohi

they will randomly back-off according to the number of contenders being counted. Random backoff promotes fairness, while the window size equal to contender count allows quick convergence based on current load.

2) Data Transfer: To conserve energy, we keep the modem's data receiver and the host CPU off as much as possible (the default mode), and activate them only when a tone is detected by the low-power wake-up receiver. Thus our reservation depends only on wake-up tones.

We also precede any data with a wake-up tone, thus making 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, unless they are the destination, go back to sleep.

We also suppress additional transmissions from a successful sender to reduce spatial unfairness (Section II-A2). The exact duration of this quiet time depends on the T-Lohi variants to be discussed in Section III-B.

3) Tone Implementation: Next we describe how we implement tone as a contention indicator. T-Lohi uses our custom, low-power, wake-up tone receiver to conserve energy [4]; that shares the channel with data transmissions, but listening for a tone consumes 1/100th the energy of listening for data. The core of our protocol is still applicable without the wake-up receiver if we replace tones with short data packets. In our simulations, all nodes will spend at least a third of their time idle listening; our wake-up tone hardware effectively eliminates this cost. However, other aspects of our protocol, including utilization, throughput, and fairness, would remain unchanged.

Finally, we briefly consider the impact of false tone detection, given that the acoustic channel may often have periods with large amounts of noise [15]. 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. The energy impact of these false detections will be minimal due to the low energy cost for reservation. A more detailed discussion on design alternatives is in our extended technical report [14].

B. 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 IV-E we also vary the backoff mechanism.)

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

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

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. This duration of contention round is $CR_{ST} = \tau_{max} + T_{tone}$, where τ_{max} is the worst case one-way propagation time and T_{tone} is the tone detection time. Figure 5(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.

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 II-B). 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.

Synchronization also provides information about 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 (ΔT in Figure 2(a)). We use ΔT to compute a *spatial advantage index*, $\mathit{SAI} = 1 - \frac{\Delta T}{CR_{ST}}$. Nodes also maintain a boolean variable *didCntd* which is set based on whether a contention attempt is successful or not.

Algorithm 2 shows ST-Lohi's backoff algorithm using 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 II-A2 and Figure 2(b)).

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

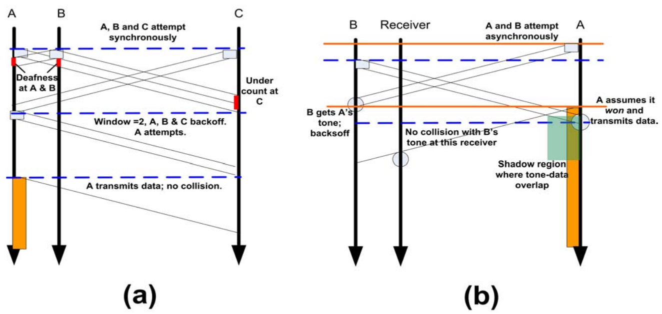


Fig. 6. Benefit of (a) Higher contention, (b) Aggression and asynchrony.

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. In order to provide the same contention detection guarantee as ST-Lohi, cUT-Lohi must observe the channel for $CR_{cUT} = 2\tau_{max} + 2T_{tone}$. Consider Figure 5(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 an asynchronous view of a contention round and defaults to just the quite period of a single CR after each transmission.

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 $CR_{aUT} = \tau_{max} + T_{tone}$.

The purpose of the long listen in 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: B's tone will not be heard by A within CR_{aUT}, so A will assume it has acquired the channel and transmit data at $t_{tx,C} + CR_{aUT}$. B's tone and A's data transmissions will collide at a node located within the *shadow region* near A (a tone-data collision), but be received separately at other nodes. Also, node B will hear A's tone and backoff. We describe these scenarios in more detail Section III-C1, arguing that the conditions that result in data collisions are quite unlikely. Simulation results in Section IV-D verify the low probability of such events with few packet losses for aUT-Lohi.

C. Discussion on Protocol Correctness

T-Lohi avoids packet collisions through a reservation mechanism. However, deafness and aggressive contention can cause the reservation mechanism to fail and lose packets. We next define conditions that lead to incorrect reservation, *i.e., protocol incorrectness*, which can cause packet loss. These cases include tone-data collision, data-data collision and persistently incorrect reservation. We also discuss how higher-level contention can alleviate these problems.

1) Tone-Data Collision: As described above in Section III-B3, tone-data collision can occur in aUT-Lohi because contenders listen for only τ_{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:

$$TDT < (TDL + T_{tone}); \qquad TDL \geq \frac{\tau_{max}}{2} \tag{2}$$

The first equation states that the interferer B (refer to Figure 6(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 6(b)) for an actual tone-data collision. This additional condition makes tone-data collision less likely to occur; (also supported by the very small number of tone-data packet losses in simulations in Section IV-D). 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.

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 reserving nodes are within D_{deaf}—this is a necessary and sufficient condition for data-data collisions. (D_{deaf} is quite small for our T_{detect}; in simulations with random node placement only 0.14% of node pairs are bidirectionally deaf.) Data-data collisions can also occur in aUT-Lohi when *pseudo-bidirectional deafness* occurs, that is when both tone-data coexistence conditions (Equation 2) and deafness condition (Equation 1) are met. This collision occurs as one node of the pair will assume data reserved because of its aggressive round length, while the other will do the same due to deafness. Such collisions need to be handled at a higher layer using back off and retransmission.

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.

Figure 6(a) illustrates this effect for ST-Lohi, where contending nodes A and B are within each other's deaf region. In this case, bidirectional deafness would normally cause both nodes to send data packets that would then collide. However, addition of a third 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.

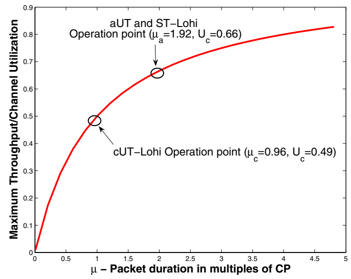
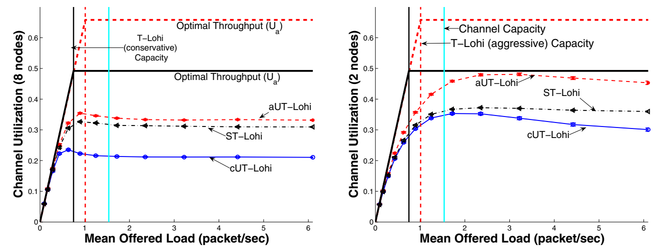


Fig. 7. Maximum theoretical utilization for T-Lohi protocols as μ varies, showing the operational points in our simulations.



(a) Eight Node Network (b) Two node network

Fig. 8. Channel utilization of three T-Lohi flavors. The vertical lines show the channel capacity and the protocol capacities, in packets/s.

IV. Performance Evaluation

We next evaluate T-Lohi performance through simulation. We look at the design tradeoffs between its three flavors. We also evaluate important medium access metrics such as throughput, energy efficiency, and fairness. Simulation results show that T-Lohi achieves better throughput (34 to 50%) than published results (22%) for comparable throughput efficient underwater MAC protocols [16], [9], while maintaining energy efficiency comparable to UWAN-MAC [6]. Finally, we quantify the impact of the unique characteristics in acoustic medium access, such as deafness and contender counting, on performance.

A. Simulation Methodology

We develop a custom acoustic network simulator based on a prior model for underwater time synchronization [7]. (The simulator and simulations are available for download from the authors' website.) We do not currently model packet loss due to channel noise and multi-path to focus on protocol behavior. Exploration of these effects of is an important direction for future work.

We perform simulations with the following parameters, unless otherwise noted. We randomly deploy nodes in a 300×400m area for a fully connected network with acoustic transmission 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 the mean and 95% confidence intervals for each statistic. (In almost all cases confidence intervals are barely visible.) We model traffic as a Poisson arrival process, with each node having a single packet transmission buffer.

B. Network Throughput

In this section our goal is to understand the impact on throughput in terms of offered load, network density, and protocol choice. 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.

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 a shorter CR caused by 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 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, given network saturation, becomes:

$$TH_{max} = \frac{\mu}{(\mu + 1)} \tag{3}$$

Figure 7 shows how this best possible performance varies with μ. Our simulations send a fixed amount of data (650B/packet), but since the duration of the contention round varies by protocol, aUT- and cUT-Lohi have different achievable performances. This figure shows the operational points we use in our simulations with a fixed data size; other points on this curve could also be used. For these data sizes and contention durations, the best possible utilization, U, is U_a= 0.66 for ST- and aUT-Lohi, and U_c=0.49 for cUT-Lohi.

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. However, we expect T-Lohi to be more stable because it can detect and count contenders.

Figure 8(a) shows channel utilization (throughput normalized by bandwidth) as a function of aggregate offered load. The figure also shows two theoretical limits while operating at μ_a and μ_c. First, the vertical lines show limits on the offered load due to channel and protocol capacities. Second, we also plot the optimal utilization curves for T-Lohi as the load varies.

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

Second, as offered load approaches the practical capacity (0.5–1 packet/s), we see T-Lohi reaches about 50% of maximum utilization. This decrease is due to greater contention, as the length of reservation period (RP) doubles during this region (more details in [14]).

Finally, as offered load exceeds practical capacity (more than 1 packet/s), we observe that T-Lohi throughput remains stable. The stability is a result of the nearly constant length of the average reservation period, due to back-off influenced by contender counts. We validate that the average reservation period length is constant in our technical report [14].

3) Impact of Protocol Choice on Throughput: To observe how different protocol design choices (Section III-B) affect channel utilization, we next compare the three T-Lohi flavors.

Figure 8 shows the channel utilization of T-Lohi flavors at two different network densities. We fist observe that cUT-Lohi has saturation capacity about two-third of aUT-Lohi, primarily because of its longer CR length. Although cUT-Lohi has a contention round that is twice that of aUT-Lohi, its capacity is not halved. This disparity is due to the non-linearity of achievable utilization as predicted by Equation 3.

A more interesting observation is that aUT-Lohi always achieves higher utilization than ST-Lohi (slightly higher with 8 nodes and much better with only 2 nodes). This is due (except at low densities, which we explain next) to the slotted access in ST-Lohi that delays all access attempts to the start of the next slot. When both have the same CR ($CR_{aUT} = CR_{ST}$), this delay (on average half CR) results in greater reservation latency for ST-Lohi. 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) Other Factors Affecting Throughput: We next explore how network density and packet length affect T-Lohi's throughput. The throughput of traditional wireless MACs degrades with density, but we expect T-Lohi to remain stable based on the results from Section IV-B2. We further expect packet length to increase throughput, and examine how close it can approach the maximum throughput.

Comparing Figures 8(a) and 8(b), we observe that utilization is significantly lower for aUT-Lohi and cUT-Lohi in denser networks (compared to a 2 node network). In fact the decrease by nearly 15% is evident even at 4 nodes (not shown here) and does not vary significantly for higher densities. Utilization of ST-Lohi, however, does not show such dependency on network density. We have separately evaluated T-Lohi throughput at higher densities (16 and 32 nodes), but we observe no significant differences in throughput curves there.

The higher throughput with two nodes is explained by a combination of asynchrony and the mechanism to handle spatial unfairness. With two nodes and asynchronous access, the quiet period after successful transmission (Section III-B), allows the two nodes to repeatedly swap the channel with just a single CR per frame. However, the similar effect does not often occur in ST-Lohi because of slotted transmission times. In Figure 2(a), only node A contends in slot 3, since B remains quiet in slot 3 to promote fairness. Nodes that are further away, such as C or D, start contending in slot 4 (not shown in figure) along with B whose quiet period would have ended.

With more than two nodes, this channel swapping is not possible with either flavor of Lohi, since more than one CR will be required. Thus the throughput of T-Lohi is insensitive to network density except for the two-node network.

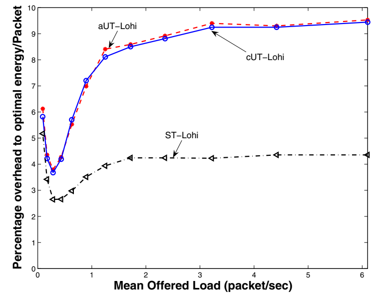


Fig. 9. Relative energy overhead for T-Lohi for an 8 node network

We also varied μ using longer packet length, and observed (details are in [14]) that the throughput increases monotonically with packet length or μ. Furthermore, under all operating regimes the utilization achieved by T-Lohi remains within 35% of the theoretical optimal given from Equation 3.

C. Energy Efficiency

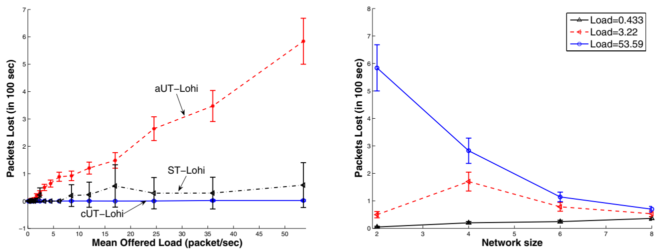
Since underwater sensornets are often energy constrained, we next consider the energy efficiency of T-Lohi under varying loads. We expect T-Lohi to be energy efficient because wake-up tone detection reduces the energy cost of long data reservation periods. The modem power values used are: 2W transmit, 20mW data receive, and 0.5mW for the wake up tone reception. These parameters roughly match the power consumption of a proposed modem with hardware support for wake-up tone reception [4].

Figure 9 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. 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 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. For lower network density (4 nodes) 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.

D. Protocol Correctness: Impact of Deafness and Aggression

We now evaluate the impact of deafness and aggressive contention on T-Lohi protocols. As discussed in Section III-C,



(a) 2 node network (b) aUT-Lohi with > 2 nodes

Fig. 10. Packets lost in a fixed duration as offered load is varied

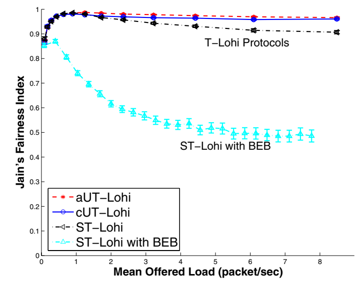


Fig. 11. Jain's fairness index for T-Lohi that can *count* contender vs. a MAC that can only *detect* contenders and uses BEB.

deafness and aggressive contention can cause protocol incorrectness, where multiple nodes believe they have reserved the channel. We quantify the impact of these factors by measuring packet loss over a fixed interval as offered load varies.

Figure 10(a) allows us to make several interesting observations for a *two node* network. 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. Analysis of packet loss for aUT-Lohi shows that the majority of the lost packets are due to data-data collision. The reason is that aUT-Lohi *guarantees* data-data collisions when pseudo-bidirectional deafness occurs (Section III-C). Since the probability of both coexistence and deafness conditions being met increases with offered load, the packet loss in aUT-Lohi increases as well.

The results of packet loss for both cUT-Lohi and ST-Lohi show very little variation over all network densities (details in technical report [14]). The impact of increasing the number of contenders on packet loss in aUT-Lohi is more profound. Figure 10(b) shows that both the mean and variance of the lost packets decrease as more nodes contend, since with more nodes it is easier to break the pseudo-deafness conditions necessary for data-data collision. These results show that under high contention, the impact of both deafness and aggression (in aUT and ST-Lohi) becomes negligible. Meanwhile, cUT-Lohi provides the most robust and reliable data transfer, especially for sparse and low traffic networks.

E. Impact of Contender Detection and Counting

T-Lohi leverages space-time uncertainty to provide contention detection (CTD) and contender counting (CTC). Here we separate these capabilities and observe throughput to quantify the impact of contention detection, and access fairness to observe the benefit of contender counting.

To evaluate the benefits of channel observation we compare T-Lohi with contender counting to a modified version that can only detect (but not count) contention and thus uses binary exponential backoff (BEB). We observe similar channel utilization curves for both MACs (figure omitted due to 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 [17].

In MAC protocols that depend only on CD (such as Ethernet), channel capture is a known potential problem. 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 only considered the number of successfully sent packets by a node.

We used Jain's fairness index defined as $\frac{(\Sigma x_i)^2}{(n \cdot \Sigma x_i^2)}$ where x_i is the number of packets sent by a node, and n represents the number of nodes in the network. Figure 11 shows the result for an experimental setup consisting of eight nodes run for 500s 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 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.

V. Related Work

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

Recent work on sensor networks has raised the importance of energy efficiency. Both scheduled contention in S-MAC and low-power listening (LPL) in B-MAC [8] requires significant changes due to large propagation delays in acoustic networks. S-MAC's listen interval needs to be increased due to large and location-dependent propagation delays to a receiver, greatly reducing its energy efficiency. With the cost of transmission two orders of magnitude higher in underwater networks, B-MAC's long preamble becomes energy inefficient. In contrast, T-Lohi exploits an ultra low power tone receiver to achieve excellent energy efficiency. There are other protocols, such as BTMA [18] and DBTMA [19], that use *busy tones* to deal with the hidden terminal and exposed terminal problems. These protocols, however, assume separate channels for tones and data, and do not consider large propagation delays as they are designed for RF networks.

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 [20]. Alternatively, a centralized MAC can be easily implemented. In comparison, T-Lohi is fully distributed protocol that does not rely on any special topology and is energy efficient.

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 [21]), resulting in low throughput. The other work employs CDMA by developing code distribution techniques [22], which has high energy cost. Rodoplu and Park extend S-MAC's schedule synchronization to sender-receiver pairs in UWSN [6]. 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 [9]. 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 [16]. These recent efforts do not minimize energy consumption. Their throughput is also relatively low (less than 20%), although these results are obtained in multihop networks whereas our results are restricted to a fully connected network. In such a network, T-Lohi offers energy efficiency, good and stable throughput with flexibility for all types of applications. Extending T-Lohi to multihop networks is our future work.

VI. Conclusions and Acknowledgments

In this paper we leveraged the opportunities in acoustic medium access 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 and carry out extensive simulations to evaluate their performance. The results show that all flavors are within 3–9% of optimal energy efficiency, and that our protocols achieve good channel utilization, within 30% utilization of the theoretical maximum.

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