Contention Analysis of MAC Protocols that Count

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ABSTRACT

The key aspect in the design of any contention-based medium access control (MAC) protocol is the mechanism to measure and resolve simultaneous contention. Generally, terrestrial wireless MACs can only observe success or collision of a contention attempt through carrier sense. An implicit estimate of the number of contenders occurs through repeated observation and changing back-off contention window. Recent work in underwater MAC protocols suggest there it is possible to directly *count* the number of contenders by exploiting the spatio-temporal uncertainty inherent to high-latency underwater acoustic medium. Prior work has shown how to use counting in underwater MACs, and how to optimize contention windows in radio MACs. In this paper, we quantify bounds to convergence time for MAC protocols employing exact contender counting. We show that perfect counting allows *contention to converge quickly*, *independent of network density*, with an asymptotic limit of *3.6 contention rounds* on average. We confirm this analysis with simulation of a specific underwater MAC protocol, and suggest the opportunity for the results to generalize for any radio-based MACs that estimate contenders.

Categories and Subject Descriptors

C.2.5 [**Local and Wide-Area Networks**]: Access schemes

General Terms

Verification, Performance

Keywords

Underwater acoustic sensor networks, Contention-aware MAC

1. INTRODUCTION

Media access and design of the MAC protocol influences nearly every aspect of network performance, from channel utilization, latency, fairness, and—of particular interest for sensor networks—energy efficiency. MAC protocols run over many different media, including shared, broadcast cables (original 3 and 10Mb/s Ethernet), switched point-to-point links (modern Ethernet), half-duplex radio-based wireless channels, and acoustic wireless channels. Acoustic wireless has been the medium of choice for underwater applications because of its long range (km compared to cm for underwater RF), but acoustic communications has limited bandwidth and propagation latencies five orders of magnitude longer than RF [11]. Underwater acoustics has been of interest for recent underwater sensor networks [8, 19].

Different physical media provide different kinds of information about contention. Radio communications are often half duplex and provide *no* information when transmitting a channel access request; radio protocols often sense the channel (Carrier Sense) before and after contention to detect concurrent use. Shared Ethernet provides the ability to detect concurrent contention requests (Collision Detect), providing more information. A third alternative is to avoid contention by using orthogonal channels, perhaps via CDMA (e.g., [13]), FDMA, or TDMA, although those approaches raise their own costs in coordination overhead, their full consideration must be outside the scope of the contention-based protocols we consider here.

While acoustic communication is challenging [11], recent underwater MAC protocols have shown that long propagation delays can be exploited as an *opportunity* [17, 6, 7, 12, 14]. A novel but simple way of exploiting propagation delay (or spatial uncertainty in packet reception [15], details in Section 2.1) is to use short packets, or "tones" to *count* the number of terminals contending for the channel. Counting is possible underwater because short contention tones, coupled with large acoustic propagation delays, mean that concurrent channel requests arrive at different times at different receivers with high probability. T-Lohi is a MAC protocol that uses tones to provide contention-based channel access in underwater acoustic networks [17]. Simulations show that T-Lohi provides stable performance over a wide range of loads and number of contenders while consuming little energy, but while these simulations suggest stability in the scenarios that were considered, they do not show *why* T-Lohi is stable, nor guarantee stability in other situations.

The contribution of this paper is to establish bounds on the convergence, or contention resolution, time for MAC protocols employing exact contender counting. Using Markov analysis, we show that perfect counting allows *contention to converge quickly*, and establish that medium access delay is *independent* of network load and density. This result identi-

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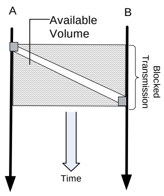

Figure 1: Space-Time Volume: Applying conservative methods in underwater medium access can waste the available "volume" for communication.

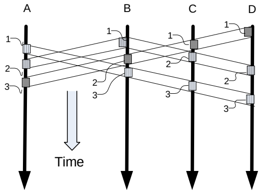

Figure 2: Contender counting: Nodes A, B, and D contest the medium; small tones and large delay allow each receiver count 3 contenders (count order shown).

fies the root cause of T-Lohi stability. We show that count-based contention can converge with an asymptotic limit of *3.6 contention rounds* on average. We confirm this analysis with simulation of T-Lohi, and suggest the opportunity for the results to generalize to radio-based MACs that estimate contenders. Our results apply wherever perfect counting is possible, but also provide a lower-bound on delay when counting accuracy falls, either due to collisions at high densities or the use of indirect measures.

Although the acoustic medium is unique in allowing an accurate count of contenders (with high probability), the concept of counting or estimating contenders applies more broadly. Satellite networks are high latency; although today they are mostly centralized and TDMA-based, alternative designs may consider a contention-based approach. Such a design may be well suited to extra-terrestrial networks such as at Mars, where terminals come and go over time and centralization may be undesirable. In RF MACs such as 802.11, contender counting is not done explicitly, but instead implicitly as collisions increase the backoff window. In a sense, 802.11's RTS/CTS provides an estimate of the number of contenders, sharing the contention window [1] effectively propagates the best estimate of concurrent contenders. Other research has used estimates of the number of contenders to optimize RF-based MACs, using idle-time between transmissions in [9], or the conditional collision probability in [5, 3]. These mechanisms are exploiting contender count by indirectly measuring it and thus our analysis, with an exact count, bounds them.

2. CONTENDER COUNTING: EMBRACING PROPAGATION LATENCY

We view the large propagation delay in acoustic networks as an opportunity. This unique perspective is a distinguishing characteristic of several new underwater MAC protocols [17, 6, 7, 12, 14]. We present an intuitive reason for this optimistic approach to acoustic medium access, and describe how it allows us to detect and count contenders. We then briefly describe, with an aim to help understand the ensuing analysis, the T-Lohi protocol as an example MAC protocol that explicitly exploits this capability.

2.1 Using Available Space-Time Volume

The interaction of large propagation latencies and access times results in an opportunity to exploit available *space-time volume*. Figure 1 illustrate this opportunity. When node A transmits its packet, a conservative approach to prevent any collision (used in traditional RF protocols) is to block transmissions while the packet remains in the medium. Such an approach is understandable for RF communications, where nano-second propagation latencies make the "blocked transmission" period short. With high propagation latency of acoustic networks, a large space-time volume is available for concurrent reception (observe the two triangular regions available for packet reception in Figure 1). While RF-based CSMA protocols would waste this volume, underwater MACs can coordinate and stagger collision-free packet reception in the unused volume. This approach has been employed, implicitly or explicitly, to exploit acoustic latency in recent underwater protocols [6, 7, 12, 14]. We next recap a simple but straightforward exploitation that allows us to detect and count contenders [17].

2.2 Counting Contenders

A key observation from Figure 1 is that smaller packet transmission allows greater available volume even for the same inter-node propagation delays. In the extreme case, sending a single information unit (in essence a bit) would yield us the largest unused volume. Since data packets generally are several bytes long (due to preambles, headers and CRC), sending data packets would mitigate such a benefit.

Therefore we propose sending short information units, or *tones*, that represents a node's intent to contest medium access (as in the T-Lohi MAC [17]). A tone reception, therefore, indicates contention. As a consequence of the available space-time volume for each transmit-receive pairing, tones will be received individually and, with a high probability, without collision at receivers. Tones allow each node to maintains a current count of contenders by simply incrementing a counter for each tone detection. While collisions might occur, they still trigger a detection (tones are non-interfering energy) leading to an undercount, but because tones arrive at different times at different receivers, others may get a correct estimate.

Figure 2 explains this process where three nodes A, B and D transmit tone packets. While individual tones overlap at certain locations, their small size increases the probability of not overlapping; thus independent detection of tones at all four receivers who can identify three concurrent contention attempts. This ability is unique in that it allows nodes to adapt their backoff strategies on the basis of an *exact* count of how much traffic exists in the network. Comparatively, half-duplex wireless MACs have to use carrier sensing and back-off to avoid collision. Thus collision backoff strategies are generally sub-optimal, with exponential backoff a conservative and unfair [9], but widely used, method for backoff.

In this paper, while we use T-Lohi as a concrete example of contender-aware distributed backoff, we believe that our model and analysis provides lower bounds for *any* counting-aware MAC protocol. Several such counting-aware protocols indirectly approximate the contender count by, for example, using conditional collision probability [5] or sensing idle-time intervals [9] and employ this count in a distributed backoff.

2.3 T-Lohi: A MAC that Counts

Tone-Lohi (T-Lohi) is a contention-based MAC protocol for underwater acoustic networks [17]. T-Lohi provides an energy efficient medium access mechanism by leveraging a

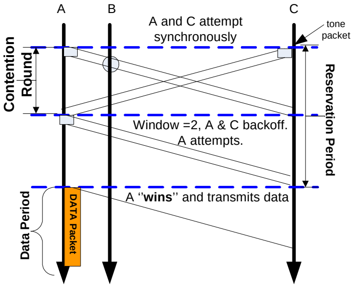

Figure 3: An example T-Lohi protocol contention exchange

sub-mW tonal energy detector [18] and using the contender count (as explained above) to reserve collision-free packet transmission. We now summarize this protocol to help develop an analytical framework in the next sections.

In T-Lohi, nodes contend to reserve data transmission. It requires that nodes first send a *short tone* and then listen for the duration of the *contention round* (a constant defined by communication range) to decide if reservation is successful. If only one node contends in a contention round, it wins, ending the *reservation period* and then transmitting its data. Since nodes can keep count of contenders (Section 2.2), additional detections in a round extend the reservation period by randomly backing-off within a window equal to this count. Figure 3 shows an example of this process: nodes A and C have data to transmit but first send tones indicating contention. At the end of the first contention round both A and C have a count of two and back-off to attempt uniformly in one of the next *two* rounds. If no other tone is detected in a given round (like A does not in round two), collision free data transmission occurs in the subsequent round.

In our earlier work our simulations show that, beyond channel saturation, the protocol shows very little load- and density dependence [17]. We postulated that a counting-aware backoff results in constant-time convergence. On the other hand, prior analysis of binary exponential backoff (BEB) shows that the medium access delay is linear in the number of active terminals [10]. We now follow up our prior assumptions with evidence for counting allowing constant access delay, by first providing basis for modeling the reservation period using super-rounds (Section 3) and then solving a Markov chain based analytic model of a counting-aware MAC's access delay (Section 4).

2.4 Generalizing to Non-Underwater Media

To our knowledge, to date, the only direct realization of contender counting is for underwater acoustic communications. Current wired and wireless networks handle contention through multiple rounds of contention and binary-exponential backoff. Researchers have also used approximations of contenders to optimize RF MAC operation [3, 9, 5]. We show that counting is advantageous; an open challenge is if exact contention count can be realized in RF networks. We speculate that it may be feasible in satellite networks where large propagation delay increases the contention volume, even at radio speeds. Exploration of these ideas is future work.

3. MODELING USING SUPER-ROUNDS

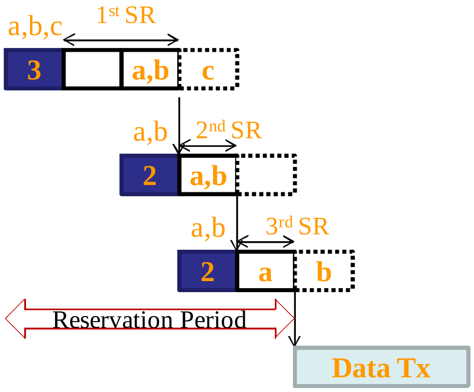

Figure 4: Super-Rounds: An example T-Lohi reservation period with three contenders, broken into conceptual super-rounds. Dashed contention rounds show chosen, but not used (due to contention detection), backoff round for a node.

We now analytically predict the the average duration of T-Lohi's reservation period (RP), which we define as its *convergence time*, in order to explain the throughput stability of counting-aware MAC protocols under high loads. This convergence time is essential in determining the bounds on T-Lohi's throughput and latency, as data transmission immediately follows the end of a RP. Moreover this analysis will also provide an analytic lower bound for the reservation delay for any counting-aware protocol. In this section we provide the framework to model a reservation period for a counting-aware MAC, like T-Lohi.

We first define the assumptions behind our model. Next, we introduce super-rounds that are conceptual sub-divisions of a reservation period. Finally, we estimate the average duration of a super-round to help us in finding the overall delay in transmitting packets.

3.1 Modeling Assumptions

To make our mathematical analysis we have made three assumptions. First, we consider only a synchronized and saturated network where all nodes simultaneously attempt contention at the end of data frame. Second, we are not concerned with fair access and ignore mechanism that enforces fairness (like those in T-Lohi). Lastly, we assume no tone collisions so that all nodes always have the same, and exact, contender count.

3.2 Super-Rounds: Subdivisions of Reservation Period

To help model T-Lohi, we conceptually divide a reservation period into *super-rounds*. These conceptual super-rounds, as we show next, can be tractably solved for their duration We then use super-round as a states of a Markov chain (Section 4) and solve the broader goal of finding the duration of a reservation period.

Super-rounds are characterized by the number of (contending) nodes when it starts. Thus an N-node super-round (SR) starts with N contending nodes, each already *aware* of the other $N-1$ contenders. The super-round ends when at least one node attempts contention by sending a tone.

In between the nodes backoff uniformly in a window of N contention rounds (CR). If M ($\leq N$) nodes simultaneously re-attempt a new SR starts with M nodes and the reservation period continues. Thus a reservation period consists of one or more super-rounds, ending when only a single contender remains at the end of a SR. To complete the length of a reservation period we need to add the first CR after data in which all nodes make an attempt (and were previously not aware of how many contenders exist).

Figure 4 explains the concept of a super-round for a saturated network with an example of three concurrently contesting nodes a, b, and c. Once a data transmission ends all three saturated nodes contend. After the first contention round all nodes backoff with a window of three contention rounds, thus starting the first, 3-node super-round (represented by the solid block). As an example scenario consider that both a and b choose the second contention round, but c chooses the third contention round. The first super-round thus spans two contention rounds (node c backs off transmitting in third round due to contention detection) at the end of which a and b have a window of two, thus starting a new 2-node super-round. This super-rounds ends (in this example) within one round as both a and b choose the first of two possible round starting a new, but still 2-node, super-round. Finally, in this third super-round, the contention ends with a and b choosing different backoff, and node a finally transmitting data as the only remaining contender. As our example shows, super-rounds can be of any length up to the size of the contention window (thus a 3 node SR can last 1,2 or 3 contention rounds).

3.3 Expected Duration of a Super-Round

We now compute the expected length of any super-round. This expected length will then be used to compute the duration of the complete reservation period. For this purpose we define a random variable X_N: the length of super-round with N nodes, measured in contention rounds (CRs). We can define the probability of this random variable being a particular value $i \in [1, N]$ as follows:

$$\begin{aligned} P(X_N = i) &= P(A_i^N \cap B_i^N) \\ &= P(A_i^N \mid B_i^N) P(B_i^N) \end{aligned} \tag{1}$$

In the above equation A_i^N represents the event that *at least* one node makes an attempt in the i^{th} CR and thus ending the super-round. B_i^N, on the other hand represents the event that *no* node has made an attempt in any of the prior $i-1$ contention rounds; otherwise the super-round would have ended earlier. Since a super-round ends once the *first* attempt has been made the event $X_N = i$ occurs when both these events occur together.

Since $P(B_i^N)$ represents the probability that no one has made an attempt in any previous CR, it is the compliment of the sum of events that $X_N = k$ where $k \in [1, i-1]$. Thus $P(B_i^N) = \left(1 - \sum_{k=1}^{i-1} P(X_N = k)\right)$. Also, given that no attempt has been made in the $i-1$ previous contention round, the probability is obtained by considering a uniform distribution over $N - (i+1)$. Thus $P(A_i^N \mid B_i^N) = 1 - (1 - 1/(N+1-i))^N$. Combining these two definitions into Equation 1 gives us a recursive solution for $P(X_N = i)$, where the termination condition is $P(X_N = 1) = 1 - (1 - 1/(N))^N$.

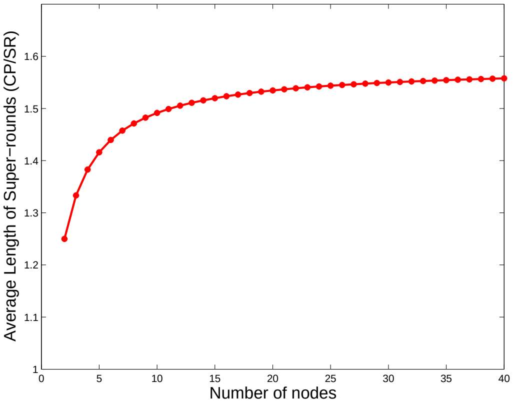

Figure 5: Average Length of Super-round (in number of contention rounds) as network density is changes.

$$\begin{aligned} P(X_N = i) = &\left(1 - \sum_{k=1}^{i-1} P(X_N = k)\right) \\ &\left(1 - (1 - \frac{1}{N+1-i})^N\right) \end{aligned} \tag{2}$$

Using Equation 2 we can now estimate the average duration of a super round.

$$E[X_N] = \sum_{i=1}^{N} i P(X_N = i) \tag{3}$$

We solve the expected duration of a super-round as defined in Equation 3 numerically. Figure 5 shows the result of plotting this expectation for different N (network density). It is apparent that the number of nodes starting a super-round has an exponentially (with respect to number of nodes) insignificant impact on the expected duration of a super-round. Thus having the exact count of contending nodes (using counting-aware capability in underwater MACs like T-Lohi) allows the super-round to end within an average of 1.5 contention rounds, even for very high density networks.

To generalize, while our super-round frame-work is meant to model the backoff process of a counting-aware MAC, we believe the concept is more general. Since it does not attempt to model a successful packet transmission, super-rounds are a natural building block to model general contention based backoff mechanism, such as binary exponential backoff (BEB) used in IEEE 802.11.

In the next section, we model the entire reservation period of T-Lohi as a Markov chain of states represented by super-rounds. We will then be able to use the result obtained from Equation 3 and Figure 5 to calculate the estimated length of this reservation period.

4. ANALYZING RESERVATION PERIOD

We now use the concept of super-round and its average duration (results from the previous section) to analytically compute the length of a reservation period.

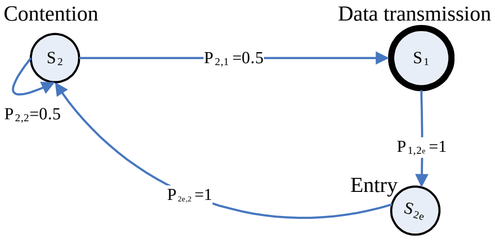

Figure 6: A special 2-Node model of the T-Lohi reservation process.

4.1 Markov Chain Model

This Markov chain model will provide a mathematical bound for T-Lohi's convergence time (or any counting-aware MAC in general) that we can compare with the simulation results present in a previous publication [17].

We start by representing each super-round as a state. Thus an N node super-round's state is S_N. In our Markov model of T-Lohi's reservation process, the network starts from a *special entry state* S_{N_e}. This entry state represents the first contention round where all the contending nodes necessarily collide. This is necessary to capture the initial contention round which is not part of any SR (Figure 4) Thus nodes transition from this entry state to a SR state in exactly one contention round. Each node then either stays in that state or transitions to a state with fewer number of nodes. The transitions between and within the contention states can happen with a variable delay based on the length of the super-round. For example in the first reservation period of Figure 4 the transition from a 3 node state (S_3 as per our definition here) can happen in two contention rounds (as shown) or also in three CR if all three nodes choose to attempt in the third round. Modeling such intricate transitions makes the model cumbersome; we instead approximate by assigning $E[X_N]$, the estimated length of for S_N (from Equation 3), as the transition delay from S_N to any other state. We will show, by comparing with simulation results, that this approximation has no significant affect on the accuracy of our model.

The reservation period ends when the transition is made to another special state S_1 that represents selection of one of the original N nodes for data transmission. Finally this special state returns to the original entry state to represent a saturated network where all N nodes start contending again. We purposefully ignore the data transmission time that must occur for this transition since that delay is not part of the reservation delay we are modeling here.

4.1.1 *Example for a two node network*

We first provide, for the purpose of clarity, an example of the Markov chain model in a relatively simple two node network to capture the essence of our modeling process.

Figure 6 shows the Markov chain model for a two node saturated network. The network starts in the special entry state S_{2e} in which both nodes contend simultaneously. After a single CR they transition to the super-round (SR) state of S_2, where each node chooses to backoff and reattempt within the next two contention rounds. Since its equally probable that the nodes choose the same or a different round, the transition to to S_2 or S_1 (data transmission) is equally likely. In order to model a saturated network (and make the Markov chain irreducible) we return to the special entry state S_{2_e}.

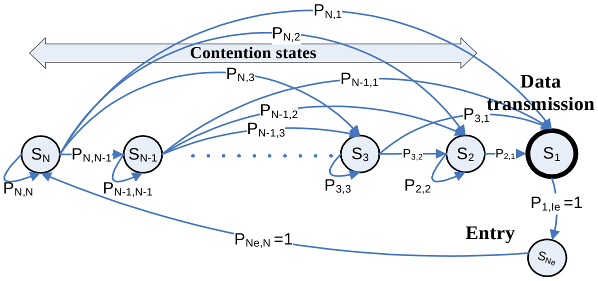

Figure 7: A generalized Markov chain model to analyze the convergence time of a T-Lohi reservation period.

We define the average duration of the reservation period as T_2: the time taken in going from state S_2 to S_1. Since we assume no time is spent in S_1 (where reservation has ended and data transmission starts), T_1 is by identity zero. We can therefore solve for the RP duration as follows:

$$\begin{aligned} T_2 &= P_{2,1}E[X_2] + P_{2,2}E[X_2] \\ &= (0.5)(1.25) + (0.5)(1.25) = 2.5 \end{aligned} \tag{4}$$

Adding the initial CR for the transition from S_{2_e} to S_2 we reach an average reservation period length of 3.5 contention round; this value is in agreement with both a 2-node closed form solution and simulation results for the two node network (for details about simulation parameters, see [16]). We will now generalize this very mechanism to solve a generalized Markov chain representing any network density, given perfect counting.

4.1.2 *Generalized Model*

We now expand our model to a general network topology. Figure 7 shows this general Markov chain model with a network of N saturated nodes. The chain starts in the entry state S_{N_e} depicting N saturated nodes at the start of every reservation period. We transition from this entry state to a corresponding super-round state S_N in a single contention round (the first of the reservation period) where each node discovers there are $N-1$ other contenders. Each state of the Markov chain either loops-back or goes to a lower value state with a certain transition probability. Thus state S_N can transition to any of the $N-1$ states where fewer number of nodes contend or loop-back.

We now need to define the transition probability $P_{N,j}$ between states S_N and S_j. Since the transition to state S_j can happen in any of the N possible contention rounds we define this probability in the following manner:

$$P_{N,j} = \sum_{i=1}^{N} P(C_{i,j}^N \mid B_i^N) P(B_i^N) \tag{5}$$

Here $C_{i,j}^N$ represents the event that exactly j nodes collide in the $i^{th} \leq N$ contention round of a super-round with N nodes. B_i^N is the same event defined in Section 3.2; the event that none of the N contending node made a contention attempt in any of the prior $i-1$ contention rounds. $P(C_{i,j}^N \mid B_i^N)$ therefore can be defined as the combined probability of $\binom{N}{j}$ possible event where j nodes choose the i^{th} round with probability $(\frac{1}{N+1-i})^j$ while the remaining $N-j$ choose not to with probability $(1-\frac{1}{N+1-i})^{N-j}$. Using the prior definition of $P(X_N = k)$ and $P(B_i^N)$ we get the following state transition probability:

$$P_{N,j} = \sum_{i=1}^{N} \left(1 - \sum_{k=1}^{i-1} P(X_N = k)\right) \binom{N}{j} \left(\frac{1}{N+1-i}\right)^j \left(1 - \frac{1}{N+1-i}^{N-j}\right) \tag{6}$$

We would like to point out that Equation 6 does not cover the transitions from the special state S_{Ne} and S_1. The transition to the state S_1 results in an immediate (incurring no time-cost in contention rounds) transition to the original entry state S_Ne . This transition is added to model a fully saturated network as explained previously. Also, we separately define that S_{Ne} transitions to S_N in one contention round to capture the first round not part of any super-round.

4.2 Solving for RP Duration

We now solve our Markov model of the reservation period to find its average duration in the number of contention rounds.

For this purpose we observe that, barring the special entry state, any state S_j is reached only from either itself or higher states (from S_i, $i \geq j$). Hence if we define T_i as the time duration it takes to transition from state S_i to S_1, we can use the above observation to solve the model as a simple recurrence. To find the length of the reservation period we thus need to find just T_N, which is solved as the following recurrence:

$$\begin{aligned} T_N &= \sum_{j=1}^{N} P_{N,j}(E[X_N] + T_j) \\ T_1 &= 0 \end{aligned} \tag{7}$$

Here we have assigned a duration of $E[X_N]$, the average number of contention rounds in a super-round from Equation 3, to any transition from state S_N to make analysis tractable. Equation 7 thus provides us with the average duration in terms of contention round(s) of going from the first contention state S_N of a generalized N node network to S_1 where the reservation period ends. By adding the initial single contention round transition from S_{N_e} to S_N we are therefore able to find the average duration of a T-Lohi reservation period for a saturated (and therefore the worst case) N-density network.

Equation 7 does not have an obvious closed-form solution. We numerically solve the equation for different network densities and show the result in Figure 8. We also compare with simulation results for a reservation process that meets all our analysis assumptions (full details of simulations are elsewhere [16]; essentially a saturated, synchronized T-Lohi, with no consideration for spatial fairness).

The simulated protocol captures the essential counting processes and represents exactly counting-aware MAC protocols. Separately, we have derived a closed form solution for a 2-node network [16]. That closed-form solution also reinforces our Markov model as it calculates a reservation period of 3.5 contention round which matches the result from our more general Markov model where T_2 equals 3.5 as well.

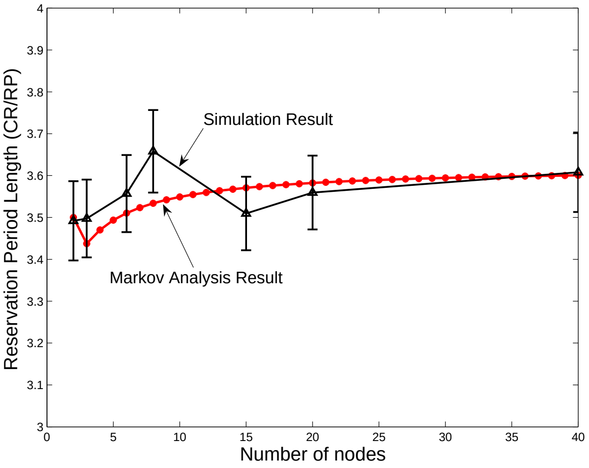

Figure 8: Average Length of reservation period (in multiples of contention rounds) for a varying network density as predicted by our model.

Figure 8 shows the results of our analysis as compared to simulation of just the contention process. The most important conclusion from this analysis is that MAC protocols with perfect counting converge quickly regardless of network density. Thus, going from 3 nodes to 40 nodes (an order of magnitude increase in density) the duration of a reservation period increases by only 5% (from 3.43 to 3.6). This result confirms our prior observations of T-Lohi stability and identifies counting as the key mechanism to provide stability.

Our model and result are for a saturated network (stations always have data to send). However, the model is general enough to extend for arbitrary load at any network density. Thus, a below-saturation load for a higher density network can be easily translated to a lower density, but saturated network to match the analysis shown in the paper. Thus our result also shows that counting-awareness leads to load-independent delay in contention resolution.

We next observe that our numerical results are consistent with our simulation results as they are within its 95% confidence interval. This corroboration between simulation and the numerical solution of our model validates our approximation in using expected values (and not the exact value) for each super-round duration (in Section 3.2).

In Figure 8 we also observe that the average duration of reservation period is lower for a 3- or 4-node case compared to the 2-node case. This initial decline—from 3.5 rounds to 3.43 rounds per RP—is explained by observing that the values of $P_{N,1}$ steadily increase from a lower-bound of 0.5 for $N = 2$. In other words, the probability of a single node making the first attempt, and therefore winning the right to channel access, increases with density (for example, it is 0.55 for $N = 3$ and 0.58 for $N = 40$). The average reservation length (refer to Equation 7), however, depends on the sum of all intermediate transitions that lead to the termination state. Since the two node case has no intermediate state, the duration is largely dependent on the direct transition to the termination state S_1. Going from two to three nodes, the increased probability of going directly to termination state coupled with a similar transition duration ($E[X_2] = 1.25$ and $E[X_3] = 1.33$) and very little contribution from the single intermediate transition, results in a shorter total duration than for two nodes. However with increasing number of nodes, the number of intermediate transitions become more-and-more significant and result in a monotonic increase in the duration of a reservation period.

We next discuss some interesting implication of our analytical results.

4.3 Discussion and Implication of Results

Now that we have modeled the reservation period of a fully counting-aware protocol (specifically the T-Lohi underwater MAC), we next discuss the predictions and implications of this model.

4.3.1 Differences with Published Results

As mentioned previously (Section 3.1) our model captures a simplified version of the T-Lohi protocol, without synchronization or fairness control. Our model shows a significant dip in the delay beyond two nodes (reason explained in previous section), however this result differs from our prior simulation results (Figure 8 in [17]) where a two node network show smallest delay that only increases with density. There we attribute this result to a combination of asynchronous access and the spatial fairness dominant at lower densities. Both of these factors, however, are ignored in our model that we have simplified to generalize for exact counting-aware MAC protocols. Thus, the throughput of real-world T-Lohi exceeds our analysis at lower network density (between 2–10 nodes) where these factors are dominant; we expect they converge as network density rises.

While we show that convergence time is independent of density, this claim assumes perfect counting. However, for a 200ms round and 5ms tone, even a 10 node neighborhood has a 29% chance for at least one collision (similar to Birthday Paradox), with collision guaranteed in neighborhood of > 40 nodes, We currently plan to look at incorporating this imprecise count into our analysis, but as T-Lohi does not require *exact* counts, we expect counting accuracy to degrade gradually at increasing densities with performance lower bounded by counting-assisted exponential backoff.

4.3.2 Deployment and MAC Design Implications

The example of T-Lohi suggests that counting MAC protocols are robust to network size, so they are especially well suited for high density networks where many terminals have data to send simultaneously. This need is common when multiple sensors observe the same event and need to coordinate their observations immediately, as in target tracking or beamforming. For such scenarios the performance of MACs with perfect counting would not degrade, for any network density, even with bursty traffic.

Our model also implies suitability of counting-aware protocols for delay-sensitive applications. For such applications, like voice and video communication, hard bounds on protocol delay are important to provide QoS guarantees. Although we report average-case performance, not hard, guaranteed bounds, our results suggest that count-based contention protocols may be suitable for cases where bounded performance with very high probability is sufficient.

A final implication of our model, points to a *memory-less* property for counting-aware protocols. Intuitively it would appear beneficial to remember the number of contender in a previous round. The reservation-time's independence on how many nodes eventually retry, however, reduces the advantage of retaining or propagating this information for MACs that can count contenders, because they can regenerate this information when needed.

5. RELATED WORK

There has been a great deal of work on performance analysis of wireless MACs that is similar to our work. We next review that, with work on counting-aware MAC protocols and underwater medium access.

Contention resolution and methods to measure contention are two key aspects that affect the performance (throughput, delay, and fairness) of MAC protocols. Modeling the MAC layer can both predict and bound performance, and also provide mechanism to optimize parameter selection. Several analysis of the IEEE 802.11 protocol have been performed, largely due to its wide-spread use. Initial capacity analysis for the protocol were performed by Calì *et al.* [4]. Bianchi provided a Markov chain based model of the 802.11 DCF [2]. Both these works show that throughput of 802.11 is highly dependent on number of contending nodes and its knowledge helps improve throughput. These conclusions naturally lead to the development of mechanisms that estimate the number of contenders leading to counting-aware (of which T-Lohi is an example), as opposed to just collision-aware, MAC protocols.

Several works have proposed mechanisms to estimate the contention count. Based on their 802.11 DCF model [2], Bianchi *et al.*provide a closed-form approximation that relates contender count to the probability of collision seen by a transmitted packet, or conditional collision probability [3]. They estimate this conditional collision probability using observations of transmissions on the channel in each slot. Using a Kalman Filter, they present a robust mechanism to estimate the contender count for 802.11 DCF. Idle-sense MAC extends the idea of estimating contenders indirectly by using local observations of idle-time between transmission to distributively decide a contention window [9]. They also show that a uniform CW allows for greater short-term fairness and their chosen CW maintains, using feedback, an optimal number of concurrent contending nodes. Another MAC protocol design infers the conditional collision probability by observation of collisions and then using a distributed gradient-play algorithm to define an appropriate contention window [5]. They use game-theoretic mechanisms to prove that their algorithm converges to a Nash equilibrium, and improves throughput (compared to 802.11 DCF) since now the CW is sensitive to the contender count. However, all the above work in wireless RF MAC protocols assumes partial or indirect knowledge of the contender count. We show instead that an exact knowledge of contender count allows protocols that converge in less than 4 contention rounds even with asymptotically many competing terminals, and demonstrate this result for an underwater MAC protocol, T-Lohi, where such count is possible.

The concept of space-time volume (Section 2.1) has implicitly been used in several of the most recent underwater acoustic MAC protocols [6, 7, 12, 14, 17]. Most of the MAC protocols, however, use the additional volume available to channel larger amounts of data, thus increasing protocol throughput. T-Lohi, however is unique in using the additional volume to provide the contention-counting capability, since it aims to jointly increase throughput *and* energy-efficiency. To the best of our knowledge, T-Lohi is the only wireless MAC protocol that is fully counting-aware, as it uses the propagation latency of underwater acoustic networks to exactly count the number of contenders.

6. CONCLUSIONS

This paper presented an analysis to find bounds on the delay in packet transmission for *counting-aware* MACs where the number of concurrent contenders can be determined. We demonstrate this principle using T-Lohi, a recently developed MAC for underwater acoustic networks, and we suggest how the results generalize to other high-latency RF media, or possibly can be approximated even in general RF media. We model the contention process by breaking it into conceptual *super*-rounds, which become states of a Markov chain. We solved the Markov chain numerically to show the reservation process as nearly independent of network density with only 5% increase in delay for an order magnitude increase in density. This result explains the load-stability shown by example counting-aware protocols like T-Lohi and also points to a unique memory-less feature for such MAC protocols. We believe our results will help spur interest in design of counting-aware protocols since they combine the flexibility of contention-based with the delay guarantees of TDMA-based MAC protocols.

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