A Comparison Between the Tone-Lohi and Slotted FAMA MAC Protocols for Underwater Networks

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Abstract—**In this paper, we present a comparative evaluation among two MAC protocols specifically proposed for underwater acoustic networks, namely Slotted FAMA and Tone-Lohi. Both protocols are based on random access and regulate transmissions by either four-way handshaking (Slotted FAMA) or contention resolution procedures (Tone-Lohi). Our comparison is carried out by means of analytical models, which are used to capture the behavior of a node that acts according to either protocol. We focus on throughput, delay and energy performance, studying the pros and cons of each approach. Our results highlight relevant design tradeoffs that can be exploited in order to properly tune protocol performance.**

Index Terms—**Acoustic telemetry and communication, underwater networks, MAC protocols, performance analysis, Slotted FAMA, Tone-Lohi.**

I. Introduction and Related Work

Research on underwater acoustic networks is gaining momentum, as progressively greater interest arises around a widespread use of these networks for a number of tasks. In principle, underwater networks should serve to assist in surveillance, monitoring, as well as any environment-related task. It is also a common viewpoint [1], [2] that these networks will operate according to the ad hoc paradigm already known in radio networks, whereby wireless nodes autonomously organize themselves into a network, set up communications, and perform link maintenance to ensure connectivity. To this end, the design of protocols that provide efficient Medium Access Control (MAC) becomes a task of primary importance. Furthermore, underwater acoustic communications bear challenging issues to deal with, namely long propagation delays, distance- and frequency-dependent attenuation, non-white noise and very high transmit powers, which come in addition to propagation models usually unseen in radio [3]–[5]. These factors represent the main reasons why wireless networking protocols that have been proposed for terrestrial radio networks cannot be straightforwardly ported to underwater networks. New MAC and routing protocols should be designed with the aforementioned propagation effects in mind, in order to be applicable to underwater scenarios.

Currently, some steps have been moved in this direction. For example, [1] contains a discussion on basic deterministic access methods such as Frequency-, Time-, and Code-Division Multiple Access (FDMA, TDMA, CDMA), as well as a preliminary evaluation of clustered underwater networks. Since clustering is an interestingly feasible option for underwater communications, other papers present further investigations into this subject, e.g., by evaluating and comparing different combinations of deterministic access schemes as applied to intra- and inter-cluster communications [6], or by presenting the tradeoffs that arise due to the peculiar underwater propagation. For example, [7] discusses the tradeoff between the frequency reuse level and the maximum user density per unit area that can be supported while guaranteeing a given minimum signal to interference ratio to any transmission.

A number of distributed MAC protocols have also been proposed that either adapt ideas for radio ad hoc networks to underwater scenarios or present novel approaches. For instance, ALOHA and a collision avoidance-based scheme have been compared in [8]. The effects of long propagation delays and the related "spatio-temporal uncertainty" in ALOHA and slotted ALOHA have also been considered and evaluated in [9]. The protocols described in [10]–[15] are more specifically tuned for underwater networks. Slotted FAMA (S-FAMA) [10] and PCAP [11] try to save energy by avoiding collisions through handshaking and carrier sensing. S-FAMA achieves this by having all nodes in the network share a common slot synchronization and by allowing to initiate Request-To-Send/Clear-To-Send (RTS/CTS) handshakes only at the beginning of a slot. While this approach is very effective in reducing collisions, it severely limits throughput, because of the guard times required between subsequent slots in order to accommodate for the maximum propagation delay within a given coverage radius. PCAP, on the other hand, pursues similar objectives by making the duration of an RTS/CTS handshake fixed, hence predictable. To this end, the receiver defers the transmission of the CTS so that the receiver will hear the CTS packet only after exactly one maximum round-trip time. With this approach, all neighbors know when transmissions will take place, and can schedule their tasks accordingly, e.g., by exploiting protocol idle times. UWAN-MAC [14], [16] also has the objective of regulating multiple access by limiting contentions, but pursues this in a different manner. Namely, UWAN-MAC has neighboring nodes broadcast awake/sleep schedules to one another, so that each node can infer when to wake up to communicate to (or to receive transmissions from) any given neighbor. Like S-FAMA, UWAN-MAC's performance suffers from the constraints posed by long propagation delays, which tend to limit throughput. Better multiple access performance can be achieved by trying to limit collisions, instead of avoiding

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them completely. To this end, the protocol in [13] adds a warning message to the usual RTS/CTS handshake, so that receivers can warn transmitters of any detected concurrent access that is likely to cause collisions. Transmitters can defer communications themselves when detecting specific message patterns that are indicative of likely collisions. This approach can be shown to be more effective than S-FAMA in certain scenarios [10]. In order to leverage on the advantaged offered by both scheduled (collision-free) and random access, a hybrid approach is presented in [15]. There, the authors show that it is possible to tune the working point on the efficiency-throughput tradeoff by varying the fraction of time reserved to scheduled communications as opposed to random access. The authors in [17] perform a first investigation on the efficient management of idle sensor time, by exploiting the lower power consumption required to receive an acoustic signal, as opposed to the power required for transmission [18]. Tone–Lohi [12] also exploits this fact and proposes to avoid collisions by sending very short busy tones to signal that the channel is being used.

Despite the effort spent to propose suitable protocol solutions for underwater networks, an in-depth comparison between different approaches is still lacking, starting from the MAC level. Such a comparison is important and serves a twofold purpose: first, it would found MAC design on solid ground, through a clear understanding of the pros and cons of different protocols, as well as of the network parameters that yield the best performance for each protocol. Secondly, this comparison would help design new protocols that blend the best properties of current approaches, and perhaps outperform them through novel mechanisms.

In this work, we move some first steps in this direction by deploying analytical models for two distributed MAC protocols, Slotted FAMA [10] and Tone-Lohi [12], and compare their performance by varying key factors, such as the traffic intensity, node density per unit area, and transmission coverage radius. In our study, we explicitly account for the underwater propagation model [3] in order to show the interplay between communication rate, transmission reach and overall protocol performance. This allows to give some guidelines for the design of MAC protocols for underwater networks.

The rest of this paper is organized as follows. In section II we provide a brief overview of the underwater channel and related link budget equations. In section III we give a detailed description of Slotted-FAMA and Tone-Lohi, before introducing our analytical models in section IV. Section V presents the results of our performance evaluation, whereas section VI concludes the paper.

II. Overview of Underwater Propagation

In this section, we briefly summarize the basic characteristics of underwater acoustic propagation and give some details about relevant link budget relations employed in the sequel.

First of all, acoustic waves propagate in salted water at a slow speed $c \approx 1500$ m/s. This speed is actually dependent on environmental variables such as depth, temperature, and water salinity: however, for the evaluation of protocol performance it suffices to approximate it as constant.

One of the most important features of the underwater acoustic channel is the dependence between bandwidth and transmission distance [3]. More precisely, the available bandwidth decreases with increasing distances because of attenuation- and noise-related effects, which are frequency-dependent. In fact, the attenuation incurred by a tone at frequency f as a function of the distance d can be modeled as [19]:

$$A(d, f) = d^k a(f)^d \,, \qquad (1)$$

where k is the spreading coefficient, and models the geometry of the propagation. For example, in deep water, propagation is nearly spherical, hence $k = 2$. Conversely, shallow water horizontal links experience cylindrical propagation whereby $k = 1$. In the following, we will take $k = 1.5$ to model the so-called "practical" propagation [3]. The factor $a(f)$ in (1) is the absorption loss, and models the conversion of acoustic pressure into heat. This factor can be approximated by Thorp's formula [3], [20]. From the above equations, we observe that the attenuation increases with frequency and that the exponential term $a(f)^d$ makes the dependence of attenuation on distance much stronger than in radio channels.

The noise power spectral density (psd), $N(f)$ depends on the frequency as well, and is usually modeled as the superposition of four contributions, namely turbulence, shipping and other human activities, wind, and thermal noise in the receiver circuitry. Because it can be seen that $A(d, f)$ increases with frequency, whereas the noise psd $N(f)$ decreases (for frequency values typical of underwater communication systems), there exists an optimal frequency where a pure acoustic tone should be transmitted, in order to undergo minimal combined attenuation and noise effects. This is observed in [3], where the average SNR of a tone transmitted at a frequency f and traveling a distance d is defined as

$$SNR(d, f) = \frac{P_T(d)/A(d, f)}{N(f)\Delta f} \,, \qquad (2)$$

where $P_T(d)$ is the transmit power employed to cover the distance d and Δf is a narrow band around f. In (2), the factor $[A(d, f)N(f)]^{-1}$ is the frequency-dependent term, and can be shown to have a maximum for some frequency $f_0(d)$, which decreases for increasing communication distance. Note that $[A(d, f)N(f)]^{-1}$ is proportional to the SNR, which is thus maximum at $f_0(d)$ as well. An important observation that arises from this discussion is that the bandwidth available for transmission tends to decrease significantly for increasing distance. Figure 1 shows the dependence on distance of both the optimal communication frequency $f_0(d)$ and the bandwidth $B(d)$, defined as $B(d) = \{f : SNR(d, f) \geq SNR(d, f_0)/2\}$. Since the actual frequency and bandwidth values are obtained by lengthy numerical integrations, in the following we will employ a piece-wise log-linear approximation for both $f_0(d)$ and $B(d)$, in line to what is devised in [3]. The accuracy of these approximations is shown in Figure 1.

Based on the previous equations and considerations, the acoustic power that needs to be radiated in order to meet prescribed link quality objectives at the receiver depends on distance. In order to keep link budget calculations simple, in the sequel we will assume that the attenuation $A(d, f)$ and

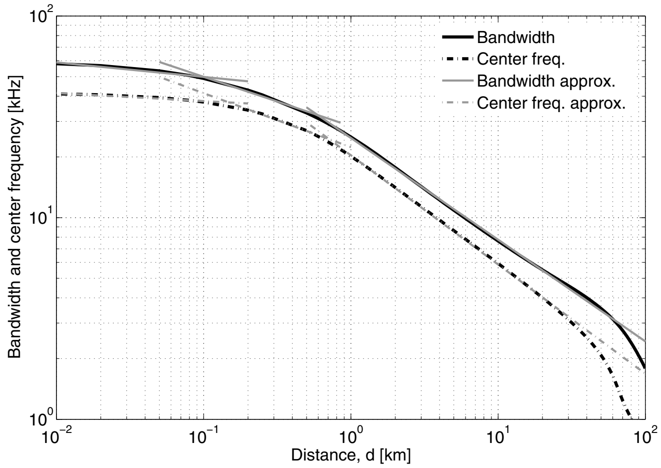

Figure 1. Piece-wise log-linear approximation of $B(d)$ and $f_0(d)$ as a function of distance (see also [21]).

the noise psd $N(f)$ are constant over the optimal transmit bandwidth for a given link distance d. More specifically, we will assume $A(d, f) = A(d, f_0(d))$ and $N(f) = N(f_0(d))$.[1] Assume now that we want the packet error rate (PER) at the receiver to be smaller than some target value α. Given a modulation format (say, BPSK) and under the assumption of independent and identically distributed channel errors, the PER over a link of distance d can be found as

$$PER(d) = 1 - \left(1 - \frac{1}{2}\text{erfc}\sqrt{\sigma SNR(d)}\right)^L , \qquad (3)$$

where L is the packet length and σ is a scaling factor used to account for signal processing inefficiencies [15]. After substituting (2) in (3), the error equation above can finally be inverted to find the transmit power $P_T(d)$ as a function of the distance to cover, d:

$$P_T(d) = B\big(d\big)N\big(f_0(d)\big)A\big(d, f_0(d)\big)\text{erfc}^{-1}\big(2 - 2(1-\alpha)^L\big) . \qquad (4)$$

III. Description of Slotted FAMA and Tone-Lohi

In this section, we provide an accurate description of the two protocols we compare in this study, Slotted FAMA and Tone-Lohi, before introducing our analytical models in section IV.

A. Slotted FAMA

Floor Acquisition Multiple Access [22] is a reservation-based MAC protocol which prescribes the exchange of RTS/CTS messages. In its original version, FAMA makes nodes communicate transmission requests and grants through RTSs and CTSs, transmit data and wait for a confirmation of correct reception (ACK). In case no CTS is received in response to an RTS, the transmitter backs off and reschedules a later attempt. The protocol also includes error control over the data packet by means of stop-and-wait ARQ with infinite retransmissions. FAMA also assumes that, in order to save energy, nodes are deaf during backoff intervals and that nodes transmit RTSs without listening to the channel. Let τ_{max} be the propagation delay required to reach the maximum coverage radius of a node, which is taken to be equal to R_{max}. Two necessary conditions for collision avoidance are defined: i) the duration of the RTS packet must be longer than τ_{max}, and ii) the duration of the CTS packet must be longer than the duration of RTS plus $2\tau_{max}$.

For underwater communications, these two conditions pose a number of problems, as the very long propagation delays usually incurred in underwater scenarios would require the transmission of very long control packets, with a dramatic loss of efficiency and a useless increase in power consumption. Moreover, recall that transmit power is significantly higher than receive or idle power in typical underwater modems hardware [18]: this fact discourages long transmission times, severely limiting the use of the original version of FAMA in underwater networks.

A solution to this problem is proposed in [10], where the authors suggest to make nodes share a global time synchronization and divide time into slots, forcing any transmission to be initiated only at the beginning of a slot. In order to avoid collisions between this transmission and any neighboring network activity, the minimum duration of a slot, T_s must include a guard interval, whose duration is at least the maximum propagation time within a given coverage range. Therefore, $T_s = T_{sig} + \tau_{max}$, where T_{sig} is the duration of a control packet.

With this "slotted" version of FAMA (S-FAMA hereafter), a node which has a data packet to send waits for the beginning of the next slot and transmits an RTS packet, which is received by all neighbors. In case the intended destination is not busy in other communications, it replies with a CTS packet at the beginning of the following slot. After a further time slot, if the source has received the CTS correctly, it starts to transmit the data packet, and backs off otherwise. The duration of the backoff is chosen to be a random number of slots uniformly chosen in the interval $[1, S_{max}]$, where S_{max} is the number of slots that are required on average to transmit the packet correctly. Once the data packet has been sent, the source waits for the corresponding acknowledgement (ACK) to arrive in the following slot and applies stop-and-wait ARQ for error control as said before. If no ACK is received, the node re-transmits the whole data packet.

During idle periods, the node is constantly listening to the channel. Depending on neighboring communications, any of the following messages may be received: i) an RTS addressed to itself, ii) an RTS addressed to another node, or iii) a CTS addressed to another node. In case i) the node starts receiving procedures according to the above handshake description; otherwise, in cases ii) and iii), it refrains from transmission to allow ongoing communications to be completed correctly.

B. Tone-Lohi

Tone-Lohi (T-LOHI) [12] is a reservation-based protocol like S-FAMA, featuring a simpler handshake and contention

[1]It should be noted that this only holds as an approximation. However, our results show that it has very limited impact on the MAC protocol performance evaluation presented in Section V, and does not qualitatively change our results.

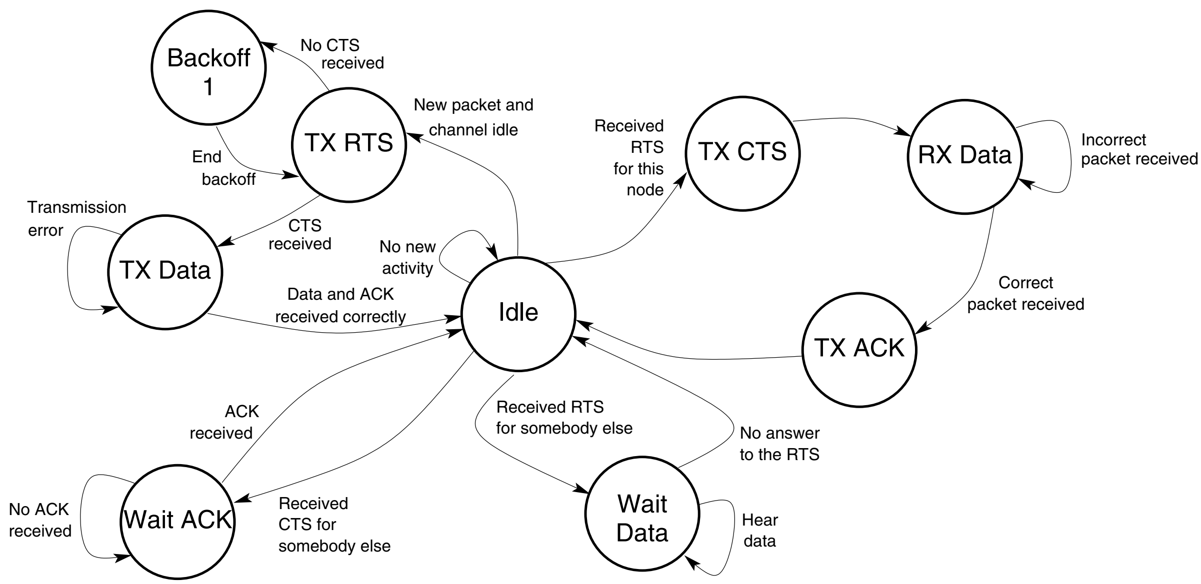

Figure 2. State-transition diagram for Slotted FAMA.

resolution in case of concurrent channel access. With T-LOHI, time is divided in frames; each frame consists of two portions, namely the reservation period and the data period. The reservation period is further partitioned into contention rounds. In order to carry out a fair comparison with S-FAMA, we consider here a modified version of T-LOHI, where all nodes share a global time synchronization. In view of this assumption, each contention round lasts $T_{tone} + \tau_{max}$, where T_{tone} is the duration of the tone transmission. As for S-FAMA's slots, T-LOHI's contention rounds are long enough to accommodate a maximum propagation delay, so that a tone transmitted within a round can potentially reach all nodes within R_{max}. Moreover, a tone transmission can take place only at the beginning of a round. Any node that wishes to send a data packet transmits a tone first. If no other tone is received from any neighbor, the node has been successful in reserving the channel, and can start transmitting the data packet. In order to pursue a fair comparison, we assume in the sequel that T-LOHI employs stop-and-wait ARQ with infinite retransmissions like S-FAMA.

In case the node hears other tones during the current contention round, a contention resolution procedure is started, whereby each contender backs off for a random number of rounds, uniformly chosen in the interval $[0, N]$. The node listens to the channel for the whole duration of this backoff. During this phase, if a node is the only one to choose the earliest round to transmit another tone among all contenders, it is called the *winner*, and is allowed to start data transmissions immediately. If more than one nodes choose the earliest contention round simultaneously, they are called *competitors* and continue to contend for channel access, by repeating the above procedure. If a node hears one or more tones before attempting to access the channel again (i.e., one or more competitors chose a shorter backoff time), it is called a *loser* and exits the contention phase. All losers start listening to channel activity until both the contention and the data transmission phases end, after which they go back to idle mode.

C. *Qualitative comparison*

Both the S-FAMA and the T-LOHI are random access MAC protocols based on channel reservation by means of signaling messages (S-FAMA) or tones (T-LOHI). The main difference between the two protocols resides in the presence of a contention phase in T-LOHI (which is absent in S-FAMA). Furthermore, we highlight that, in S-FAMA, nodes enter a backoff state whenever some activity is overheard on the channel, in order to allow concurring handshakes to complete. In T-LOHI, the backoff is only necessary to drive the contention phase, so that a single transmitter is granted channel access.

IV. Overview of Analytical Models

In order to evaluate and compare the performance of S-FAMA and T-LOHI, we have deployed two semi-Markov models [23], which capture the behavior of a single node as it operates according to one of these two protocols. A semi-Markov model is composed of i) an "embedded" Markov chain, whose states and transition probabilities models the evolution of the node behavior as it reacts to network events, and ii) by a time matrix that associates to each transition the time that is required on average to complete that transition. In the following we overview the two models we developed for S-FAMA and T-LOHI and how they can be used to derive relevant network metrics such as throughput, transmission delay and energy consumption.[2]

A. *Model for S-FAMA*

The Markov chain that models the behavior of S-FAMA is depicted in Figure 2. Let us start its description from the

[2]In this paper, we omit the complete characterization of transition probabilities and times due to space constraints. The interested reader is referred to [24] for a more detailed discussion.

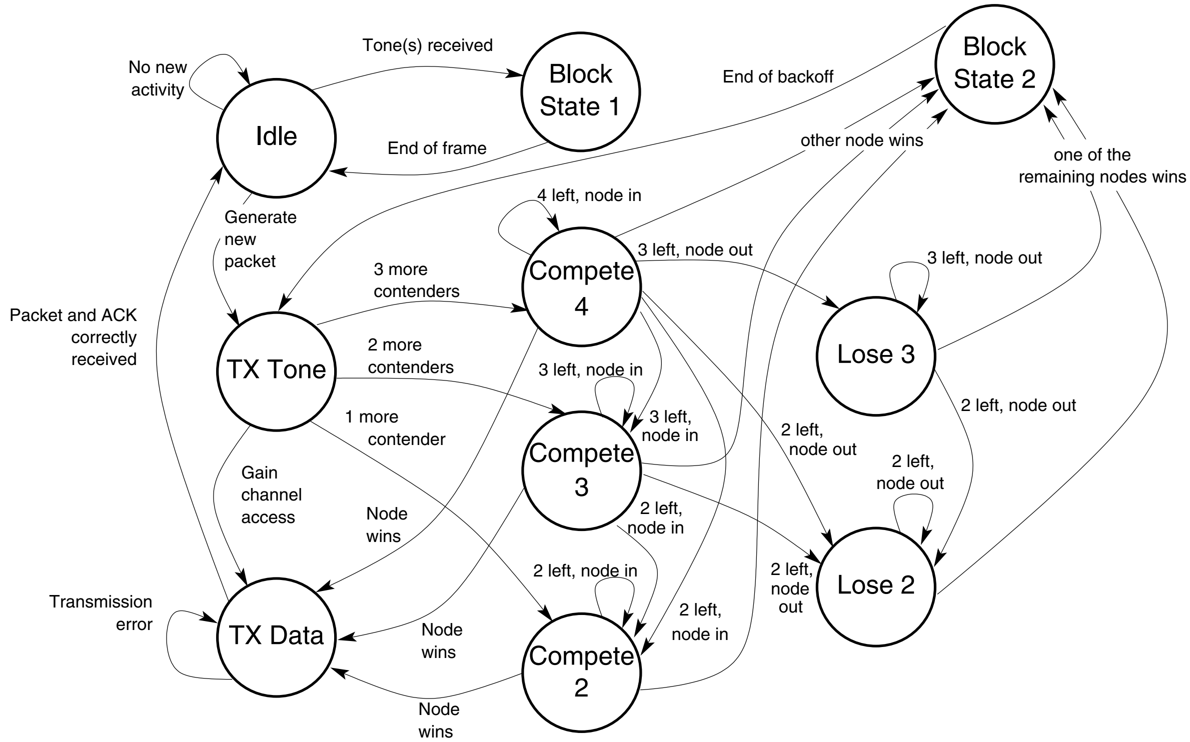

Figure 3. State-transition diagram for Tone-Lohi for $N = 3$ neighboring nodes.

Idle state. If a node generates one or more packets while in this state, it sends the RTS at the beginning of the next slot and moves to the TX RTS state. If it receives the CTS from the addressed node it goes to the TX Data state and sends the packet. The node stays in TX Data, until it eventually receives the ACK, and then returns to the Idle state. If no CTS packet is received, then the node backs off (state Backoff 1) and reschedules a later attempt.

If the node, while in Idle, receives a RTS meant for itself, it transmits the CTS at the beginning of the next time slot (TX CTS state) and goes to RX Data, where it stays until a correct data packet is received. At this point, the node transmits an ACK (TX ACK state) and then goes back to the Idle state. If the node hears an RTS directed to another node, it waits for the packet to be sent (state Wait Data). If no packet transmission is heard, it means that the handshake initiated by the neighbor has not been successfully completed, so that the node can return to the Idle state. Otherwise, the node stays in Wait Data until the data transmission and all required retransmissions have been carried out.

If the node, while in state Idle, hears a CTS addressed to another node, it goes to Wait ACK and waits for the ACK to be sent. If no ACK is received, it means that a packet error has occurred: the node hence stays in this state until the data transmission has been correctly completed. As soon as the node detects the ACK, it goes back to Idle.

B. Model for T-LOHI

The Markov chain that models T-LOHI is depicted in Figure 3. Starting from state Idle, if the node hears any tone, it goes to Block state 1, and keeps listening to the channel until the end of the current frame, after which it returns to Idle. Whenever the node generates one or more packets, it moves to state TX Tone and sends a tone. If it is the only one that tries to access the channel it goes to TX Data state, during which the node forwards the data packet and retransmits until it is correctly received. Otherwise it goes to one of the Compete k states, $2 \leq k \leq N$, where N is the average number of neighbors in coverage. From any of the Compete k states, the node observes the following behavior:

- if the node chooses the earliest contention round along with other n competitors, it moves to state Compete n, $2 \leq n \leq k$, and keeps contending after a backoff interval as discussed in section III-B;
- if the node hears one or more tones, it moves to state Lose n, $2 \leq n \leq k-1$, where n is the number of other nodes that are currently competing;
- if the node chooses the earliest contention round, and is the first and only to transmit a further tone, it gains channel access, and thus goes to state TX Data;
- if one of the other competitors gains channel access, the node goes to Block state 2.

From Lose n the node tracks the contention by recording the number of nodes that are still competing for the channel. Correspondingly,

- the node moves to state Lose p, $2 \leq p \leq n$, if p competitors choose the earliest contention round altogether, and $n-p$ exit the contention, having chosen a later round (in other words, a longer backoff time);
- if one of the current competitors gains channel access, the node moves to Block state 2.

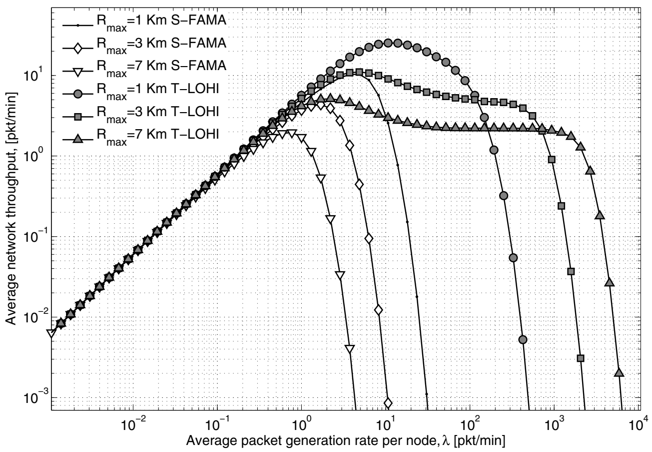

Figure 4. Average throughput as a function of offered traffic for varying values of R_{max}.

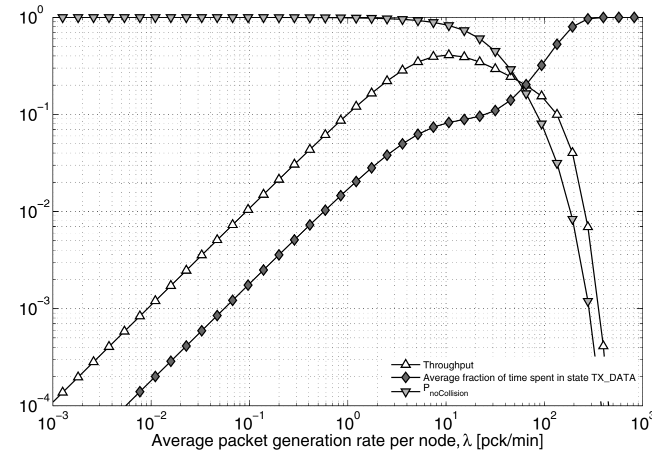

Figure 5. T-LOHI: throughput, time spent in state TX Data and probability that no collision affects a data transmission as a function of traffic, $R_{max} = 1$ km.

During Block state 2, the node receives the data packet being sent by the contention winner, in case it is its intended destination; otherwise, it discards the packet. After that, it goes back to state TX Tone to perform another transmission attempt (recall that the node entered Block state 2 after having lost the preceding contention).

C. Metrics used for the comparative study

To compare S-FAMA and T-LOHI, we are mainly interested in evaluating throughput, energy consumption and packet delay. The semi-Markov model described in the previous subsection allows to compute all such metrics, by means of the theory of renewal reward processes [23]. First of all, let $\pi = [\pi_1, \pi_2, \ldots]$ be the stationary distribution of the embedded Markov chain of either protocol. Let also T_i be the average time spent in state i. This time can be obtained by computing the weighed average of transition times for all transitions leaving state i, where the weights are represented by the respective transition probabilities. The average fraction of time Π_i spent in state i can then be derived as

$$\Pi_i = \frac{\pi_i T_i}{\sum_j \pi_j T_j} \, . \tag{5}$$

Assume now that a reward equal to 1 is collected every time a packet successfully reaches its destination. Therefore the average aggregate throughput of the protocol can be found as the average reward collected per unit time by all nodes within a circle of radius R_{max}, i.e.,

$$(N+1)\frac{\pi_{\text{TX Data}} P[\text{TX Data} \longrightarrow \text{Idle}]}{\sum_j \pi_j T_j} \, , \tag{6}$$

where we recall that N is the average number of neighbors of a node. Analogously, by assuming that the reward accumulated during a certain transition is given by the energy consumption related to that transition, we can compute the average energy consumption over time. Finally, the packet delay, defined as the time that elapses from the first RTS (tone) transmission up to the beginning of the packet transmission that is completed correctly, can be obtained for S-FAMA (T-LOHI) as the time required to go from state TX RTS (TX Tone) back to state Idle, minus the transmit times of a data and an ACK packet.

V. Results

A. Assumptions and Common Model Parameters

In the following comparative evaluation, we assume that nodes generate traffic according to a Poisson process of rate λ packets per second per node. We also assume that all nodes transmit at the same rate, within the same bandwidth, and using the same transmit power. In order to account for the bandwidth-distance relationship exhibited by the acoustic channel, we fix the transmission coverage radius, R_{max} and consequently scale the transmit rate to match the channel bandwidth equations (see section II). The transmit power is computed so as to achieve a target error rate of 0.01 for a packet of $L = 1000$ bits at a distance equal to R_{max}. Note that, with this target error rate, it is feasible to assume that ACK packets are received correctly, as they are usually much shorter than data packets. We assume that neighbors are distributed within the coverage area of a node according to a Poisson process of rate μ nodes per unit area, and scale μ so that, on average, $N = 5$ nodes are found within a circle of radius R_{max}. We finally assume that the network is not backlogged, or in other words, any node, other than the one being tracked by the Markov chain, is assumed to behave according to the steady-state distribution of the chain itself.

B. Comparison between S-FAMA and T-LOHI

The aggregate throughput achieved by S-FAMA and T-LOHI as a function of the traffic generation rate is depicted in Figure 4. Recall that both protocols are slotted (transmissions can take place only at the beginning of a slot). Since the duration of a slot is mainly determined by the propagation delay, both S-FAMA and T-LOHI offer the same throughput performance for low traffic. As traffic increases, however, the slope of the throughput curves progressively decreases until the a maximum throughput value is reached. After that, the

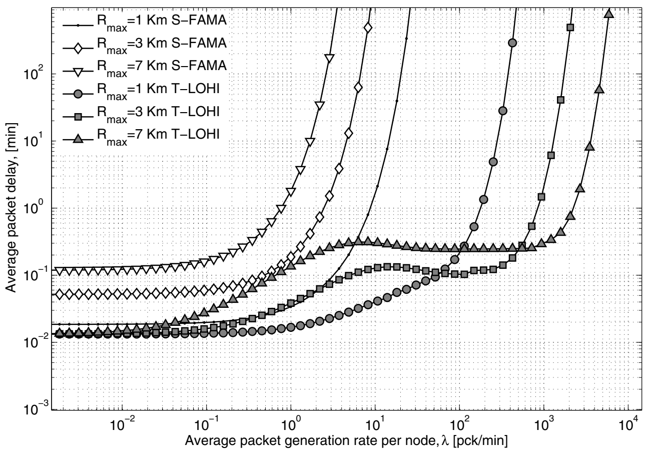

Figure 6. Average transmission delay as a function of offered traffic for varying values of R_{max}.

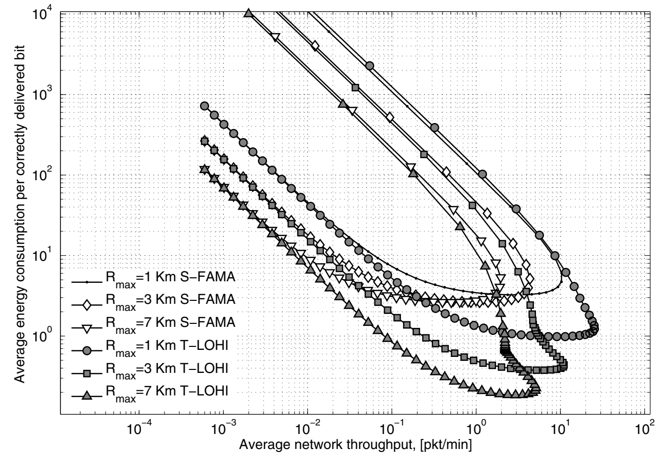

Figure 7. Average normalized energy consumption per correctly delivered bit against throughput for varying values of R_{max}.

curves tend to decrease with increasing traffic due to network congestion. T-LOHI reaches a higher throughput, on average, for all considered values of R_{max}, ad its lighter handshake procedure allows throughput to remain more stable for higher traffic values, before congestion causes it to drop. However, the only drawback of the absence of an explicit CTS in T-LOHI is that no check is carried out to see if the intended receiver node is in fact available to receive the transmission (it may be involved in the reception of other packets), so that the whole contention phase for channel access could end up with a winner, but no node available to receive. Furthermore, the absence of a CTS leaves the receiver unprotected from hidden terminals: therefore, any tone sent in the proximity of a receiver could potentially disturb the reception. Figure 5 supports these observations by plotting the throughput, the probability to gain channel access and the probability that a transmission collides with concurrent channel activity as a function of traffic, for $R_{max} = 1$ km. From this figure we see that, as traffic increases, the probability that no collisions disturb the reception of a packet decreases causing the protocol throughput to decrease as well.

Figure 6 shows a comparison of S-FAMA's and T-LOHI's transmission delay performance as a function of traffic, and is in line with the above discussion. Interestingly, T-LOHI's lighter channel access technique allows for a shorter access delay, on average. From this figure, we also observe that T-LOHI's delay remains quite stable until collisions increase (see figure 5): at this point, the effect of repeated retransmissions on delay and the high probability that a node loses contentions and backs off tend to increase delay considerably. However, it should be noted that this happens at a higher traffic generation rate than for S-FAMA.

By looking at the previous pictures, we can also infer some further information. For example, Figure 4 suggests that congestion is very critical for S-FAMA, as the throughput tends to decrease very steeply at high traffic. This indicates that S-FAMA would be best used in conjunction with some congestion control mechanism, assuming that the packet generation rate can be controlled by the nodes. Conversely, T-LOHI exhibits a smoother trend around the maximum throughput value, hence a better resilience to temporary or local congestion situations.

The importance of traffic control is further confirmed by looking at Figure 7, which depicts the average energy consumption per correctly delivered bit against throughput. Here, we have normalized energy to the amount spent by a node that stays idle for the duration of a time slot (a contention round for T-LOHI). Note that, in this case, curves are spanned in a counter-clockwise direction by increasing traffic. Moreover, recall that as traffic increases, throughput first increases up to a maximum point, and then decreases, which explain why the curves fold back. Besides confirming that energy tends to increase very rapidly as the network becomes congested, Figure 7 shows that there exists an "optimum" value of the traffic generation rate for which the best energy and throughput performance is jointly achieved: more specifically, this traffic value corresponds to the point on the curves that is closer to the bottom-right corner of the graph. Such a point exists for both S-FAMA and T-LOHI curves, and depends on network parameters such as R_{max} and the average number of neighbors N. Finally, Figure 7 suggests that T-LOHI's performance is more sensitive to the choice of a suboptimal traffic generation rate (the curves show a steeper change in the throughput-energy tradeoff for varying traffic.

VI. Conclusions

In this paper, we have presented a comparison among the Slotted FAMA and Tone-Lohi MAC protocols for underwater acoustic networks. We have developed two semi-Markov models that capture the evolution of a node's behavior according to either protocol, and have employed them to extract relevant network metrics such as throughput, energy consumption and packet delay. Our results suggest that while the four-way contention of Slotted FAMA yields a greater degree of protection against hidden terminal effects, it also considerably lowers throughput, especially in the presence of long coverage ranges, thus long maximum propagation delays. We also observed that Tone-Lohi provides better resilience against congestion and more convenient working points on energy-throughput tradeoff curves. These results allow to understand which protocol is more suited to a given network setting, and are expected to be of help in designing novel protocols that possibly outperform currently available solutions. Future directions of this work include, in fact, the extension of this study through the application of the same analysis methodology to other MAC protocols, the comparison of analytical results with simulations, and the design of a novel protocol based on the insight provided by our analysis.

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