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MEDIUM ACCESS CONTROL IN UNDERWATER SENSOR NETWORKS: A COMPARISON BETWEEN THE STANDARD JANUS AND AD-HOC ENERGY-EFFICIENT MAC PROTOCOLS

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ABSTRACT

The development of MAC protocols for UWSNs is a challenging task due to energy limitations, long propagation delays and low data rates. In fact, acoustic communication suffers from latencies five orders of magnitude larger than radio communication. Therefore, a naive carrier-sense-multiple-access (CSMA) MAC protocol would require a very long listen time resulting in low throughput and poor energy efficiency. Efforts have been made to define MAC protocols based on contention-free and contention-based techniques. The JANUS protocol defines a MAC protocol that has been proven to be effective in multiple conditions but few studies have investigated its energy efficiency with respect to other underwater MAC protocols. To this end, the aim of this research is to provide an experimental comparative study of several types of MAC protocols, including the one defined in the JANUS standard, in terms of energy efficiency, fairness, and throughput.

Keywords: *underwater sensor networks, medium access control, back-off, throughput, fairness.*

1. INTRODUCTION

Underwater sensor networks (UWSNs) are becoming increasingly attractive in various domains for their increasingly large use in relevant underwater applications. Major applications of UWSNs include ocean monitoring [1], marine surveillance [2], offshore wind monitoring [3], and other environmental-related tasks. The general view [4, 5] is that these networks will operate according to the same paradigm in use in wireless networks, in which wireless nodes organize themselves autonomously in a network, establish communications, and perform link maintenance to ensure connectivity. However, unlike terrestrial wireless sensor networks, which rely primarily on radio waves for communication, underwater sensor networks use acoustic waves, which are a much harsher environment for both the physical and data-link layers, featuring long propagation delays, distance- and frequency-dependent attenuation, and non-white noise. Moreover, very high transmit powers are required, which are added to the propagation models not normally encountered in the radio [5, 6]. These factors are the main reasons why the wireless network protocols proposed for terrestrial radio networks cannot be straightforwardly ported to underwater networks.

The power consumption of acoustic hardware is also significantly different from that of terrestrial sensor networks. For underwater acoustic communications, the transmission is often 100 times more expensive than the reception [7]. For these reasons, access to the shared medium is particularly critical to avoid packet collisions and thus retransmissions. Ideally, MAC protocols for submarine networks must be able to handle high propagation delays while providing high throughput and low collision

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rates. In the early days of development, performance in terms of delay and throughput of UWSNs was the main concern in the design of MAC layer protocols. Later, energy efficiency requirements became increasingly important, as sensor nodes are generally powered by batteries that can be recharged less frequently.

Tone-Lohi (T-Lohi) [8] is a contention-based protocol based on a fully distributed reservation process. It was developed with the idea of promoting efficient channel usage, stable throughput, and low energy consumption by using short wake-up tones for channel reservation. A Back-off tuning scheme for ALOHA-based protocols was proposed in [9]. In this work, the ALOHA scheme is used with the Back-off technique for transmitting packets to achieve better throughput. The scheme is simple to implement and applicable to more complex protocols. The authors show that the proper setting of the Back-off parameter can significantly reduce the collision rate of packets and increase the throughput of the whole system.

The NATO STO Center for Maritime Research and Experimentation (CMRE), in collaboration with academia and industry, has developed a simple and robust signaling mechanism as the first standard for underwater digital communications. The proposed protocol, named JANUS (after the Roman god of transitions, gateways, and portals), was developed over a period of nearly ten years and promulgated as the NATO standard [10] on March 24, 2017. The JANUS standard also defines a MAC component introduced specifically to minimize the risk of collisions between JANUS and the Underwater Telephone Standard [11, 12]. The Janus MAC protocol is contention-based that uses carrier-sensing techniques to detect ongoing UT packets and avoid transmissions. In [13], the protocol was tested in a real-world application that demonstrated its effectiveness in combination with UT communication. However, to the best of our knowledge, there are few studies on the performance of JANUS MAC in terms of energy efficiency, throughput, and fairness compared to ad hoc protocols for underwater sensor networks.

Based on the above considerations, this paper reports the results of an experimental comparison between the JANUS MAC protocol and two other protocols: the first is obtained by replacing the standard Janus Back-off mechanism with the one proposed in [9], and the other the well-known T-Lohi protocol. The main focus of the research is to evaluate the performance differences in terms of throughput and fairness.

The paper is organized as follows: Section 2 presents the selected protocols and highlights their advantages and disadvantages, and Section 3 provides the results of field trials, describing both the experimental setup, the hardware characteristics and configurations. The last section provides some concluding considerations.

2. PROTOCOLS DESCRIPTION

This paper proposes a comparison between the JANUS-embedded MAC protocol and two other underwater network ad-hoc protocols. The first one, named Tone-Lohi [8], is based on the ALOHA strategy, while the other [9] makes use of an enhancement of the Back-off mechanism to improve throughput and collision rate.

2.1 JANUS

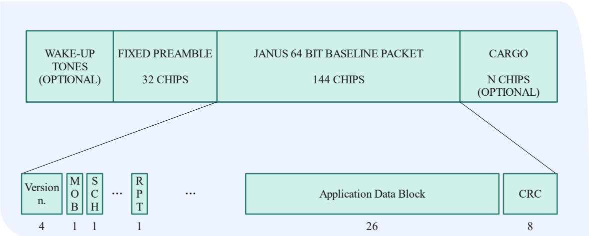


Figure 1. JANUS transmission.

JANUS is a signaling method that uses orthogonal frequency-division multiplexing (OFDM) to transmit digital data as a sequence of tones. A graphical representation of the components that define a JANUS transmission is given in Fig. 1. Four essential blocks can be recognized:

- An optional sequence of three "wake-up" tones, which are used to bring the underwater modem out of "sleep mode". This feature addresses directly the energy-efficient requirement. In fact, actual transmission can be acquired immediately after wake-up, without the need to constantly scan the channel and hence, waste the battery's power;
- A preamble, consisting of 32 tones/chips used for both transmission detection and synchronization;
- A message header that identifies the actual "baseline JANUS Packet" of 64 chips carrying information about control and transmission specifications, as well as user and application requirements. Before being transmitted, the header is coded and fed to an interleave process to reduce the Inter Symbol

Interference (ISI). At the end of the encoding algorithm, the actual tones transmitted are more than doubled (i.e. twice 64 data chips plus 8 dummy chips required by the encoding/decoding procedures).

- An optional Cargo of variable length (specified in the header).

As already mentioned, JANUS embeds a Medium Access Control (MAC) component that was specifically introduced to minimize the risk of collisions between JANUS and legacy technologies operating in the same band (such as the analog UT). The task of the JANUS MAC is to measure the energy in the band while keeping track of the background noise level. More specifically, when a transmission is requested, the acoustic power in the band is compared with the background acoustic power in the band. If the measured power exceeds the estimated one over then $3dB$ then the channel is considered busy and the transmission is delayed according to a Binary Exponential Back-off algorithm. Thus, in the case that other energy sources are detected in the occupied band, precedence is always offered to these sources. To facilitate the transmission of long-lasting messages, a node can also reserve the channel for a defined time window. The channel reservation feature can be enabled by setting the appropriate bits in the baseline JANUS packet, i.e. scheduling bit (Sch) and repetition bit (Rpt). Following the given specifications, the JANUS MAC layer protocol can be rephrased in Algorithm 1.

Algorithm 1: JANUS MAC PSEUDO-CODE

```
When the application requests packet $p$ transmission
 1: if channel is reserved then
 2:     wait for the end of the reservation period $T_{res}$
 3: end if
 4: compare the measured $\mathcal{S}_m$ and estimated $\mathcal{S}_e$ power in band
 5: if $\mathcal{S}_m - \mathcal{S}_e > 3dB$ then
 6:     compute $T_{BEB}$ (Binary Exponential Back-off)
 7:     wait for the end of $T_{BEB}$
 8:     goto 4
 9: end if
10: transmit packet $p$
```

It is important to specify that a maximum number of transmission attempts can be set. If the maximum number is reached, then the transmission is aborted. More details about the JANUS MAC protocol can be found in [10]. When applied to UWSNs, a typical drawback of all CSMA protocols can be identified. Due to the slow speed of sound propagation, a JANUS transmitter, following the specification, could not detect a distant transmission started while probing the channel. In fact, the energy of the message could arrive at the JANUS transmitter only after it has started its transmission. This problem is generally referred to as space-time uncertainty because it is related to both the relative distances between nodes and the instant in which the transmission is requested.

2.2 T-LOHI MAC

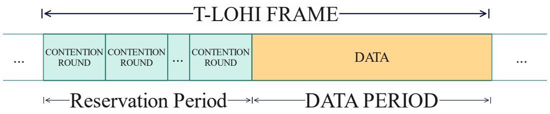


Figure 2. T-Lohi framing procedure.

In order to solve the problem of space-time uncertainty, a new class of CSMA-based MAC protocols, called Tone- Lohi (T-Lohi) has been proposed in [8]. Accordingly, nodes contend to reserve the communication channel to send data. Time is divided in frames TF (Fig. 2); each frame consists of two portions:

- the reservation period (RP);
- the data period (DP).

Each RP is further partitioned in a series of contention rounds (CRs). In order to carry out a fair comparison with the JANUS MAC, the unsynchronized version of T-LOHI, where nodes can start contending any time they know the channel is not busy, is considered. In particular, its aggressive formulation is exploited in which each contention round lasts $T_{tone} + \tau_{max}$, where T_{tone} is the duration of the tone transmission and τ_{max} is the propagation delay required to reach the maximum coverage radius of a node, which is taken to be equal to R_{max}. T-LOHI's contention rounds are defined in such a way as to be long enough to accommodate a maximum propagation delay. This ensures that a tone transmitted at the beginning of a round can potentially reach all nodes within a maximum known distance R_{max}, before the end of a CR takes place. The logic behind the T-Lohi MAC protocol is summarized in Algorithm 2. Any node that wishes to send a data packet transmits a tone first. If no other tones are received from any neighbor, the node has been successful in reserving the channel and can start transmitting the data packet.

Algorithm 2: T-LOHI MAC PSEUDO-CODE

```
When the application requests packet $p$ transmission
 1: if node labeled as loser then
 2:     wait for the end of frame $TF$
 3:     remove label
 4:     go to 1
 5: end if
 6: transmit contention tone
 7: listen for contention tones until the end of $CR$
 8: if the number of tones received $TR > 1$ then
 9:     compute $w$ uniformly in $[0, TR]$
10:     Back-off of $w \times CRs$
11:     if tone received while in Back-off then
12:         label node as loser
13:         go to 1
14:     else
15:         label node as competitor
16:         go to 6
17:     end if
18: else
19:     label node as winner
20:     transmit packet $p$
21: end if
```

In the case that the node hears other tones during the current contention round, a contention resolution procedure is started, whereby each contender randomly Back-off according to the number of contenders being counted. Random Back-off promotes fairness, while the window size equal to contender count allows quick convergence based on the current load [8]. The node listens to the channel for the whole duration of this Back-off. If one or more tones are detected before attempting to access the channel again, the node is labeled as 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. On the contrary, 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 node choose the earliest contention round simultaneously, they are called competitors and continue to contend for channel access, by repeating the above procedure. To reduce energy consumption, T-Lohi uses short wake-up tones as a means to communicate transmission intentions. In fact, tone reception is a task that can consume up to $1/100$th of the energy required for data reception [14]. Nevertheless, the core of the protocol is still applicable without using the wake-up tones defined by the T-Lohi protocol, but either exploiting the JANUS wake-up tones or short data packets instead. In this comparison, short ping tones are used in order to reduce the CR window and maintain the power consumption as low as possible.

2.3 Back-off Tuning Algorithm

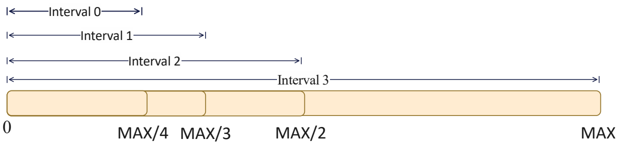


Figure 3. Back-off tuning subdivision.

A Back-off tuning scheme for ALOHA has been proposed in [9] to improve packet transmission and achieve better throughput. In fact, setting the Back-off parameter properly can greatly reduce the packet collision rate and increase the throughput of the whole system. In order to enhance the variability of the Back-off waiting time, the proposed algorithm introduces a new method to make the range of the Back-off interval variable among the nodes (Fig. 3). The maximum Back-off time, namely M_B, identifies the Back-off interval $[0, M_B]$. The idea is to define n overlapping inner intervals $[0, M_B/n]$, $[0, 2M_B/n]$, $\dots$ $[0,(n-1)M_B/n]$, $[0, nM_B/n]$, where n is the number of new sub-intervals. Each node of the network starts selecting the first/shorter interval $[0, M_B/n]$. When a node detects a collision, it selects the next interval and obtains a random value uniformly computed inside it. If the last range is selected while a collision occurs, the interval selection procedure restarts from the beginning.

In this paper, a modified version of the JANUS MAC protocol is achieved by substituting the JANUS standard Back-off algorithm with the aforementioned tuning scheme. According to the author's considerations, fairness should increase, promoting fewer collisions thanks to the higher randomness of the Back-off interval. In fact, when two nodes want to send packets that collide with each other, it is probable that the range in which their Back-off is computed is different, resulting in different waiting times.

The choice of the algorithm proposed in [9] is motivated by its simplicity and, more importantly, by the fact that it targets only the Back-off mechanism, which is of particular interest for this research. Indeed, different implementations of the Back-off mechanism can drastically change the performance of a MAC protocol. Furthermore, this tuning scheme can be easily implemented on available hardware without requiring any changes to the internal firmware or structure.

3. EXPERIMENTAL RESULTS

In the following comparative evaluation, the results of multiple on-field tests are presented to analyze the performance of the standard JANUS MAC protocol against the T-Lohi MAC protocol and the modified JANUS protocol with the tuned Back-off algorithm.

3.1 Experiment set-up

The experiments were conducted in a controlled underwater environment. More specifically, a basin measuring 5 by 8 meters and 2 meters deep was equipped with appropriate sensors to allow frequency analysis of the transmitted waves. In this way, it is possible to examine the propagation of the transmitted signals, monitor possible collisions and verify the correctness of the algorithms. The network consists of four nodes: Three transmitting nodes and one receiving/sink node. The first three nodes effectively compete for channel reservation, while the last is used to verify the integrity of the transmitted data. The nodes are arranged in a triangular pattern in the center of the pool such that each node is one meter away from the others.

Each node can receive/transmit data thanks to underwater acoustic modems. In particular, four JANUS compliant underwater acoustic modems [15], one for each node, were used. These modems, manufactured by AppliCon, a spin-off of the University of Calabria, are specifically thought for shallow water environments. Furthermore, their design is flexible enough to allow the implementation and testing of the three MAC protocols. In the following experiments, the changes in throughput, fairness of media access and energy efficiency are analyzed under different traffic loads. Specifically, throughput is defined as the ratio of the number of bits received by the sink node in a given time and the maximum number of bits potentially receivable in the same time if the channel were always available. The calculated throughput is then normalized in an interval from 0 to 1. When the throughput is 1, the channel is fully utilized. On the other hand, the fairness is calculated according to Jain's fairness index (FI) [16]:

$$FI = \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N \times \sum_{i=1}^{N} x_i^2},$$

where $N = 3$ is the number of transmitting nodes and x_i is the throughput relative to the ith node. The index ranges from $\frac{1}{N}$ (worst case) to 1 (best case), and it is maximum when all users receive the same allocation. The MAC protocols settings used during the experiments are listed in Tab. 1. Note that two different values ($1s$ and $0.5s$) are given for the *Contention Round*. In fact, two configurations of the T-Lohi protocol are tested to show the effect of the *Contention Round* length on the overall performance. Due to hardware limitations, it was not possible to further reduce the length of the *CR*.

Table 1. MAC protocols settings.

T-LOHI MAC	
CR	$1s$, $0.5s$
T_{Tone}	$0.025s$
τ_{max}	$0.0006s$
TUNED BACK-OFF	
M_B	$10s$
N	8

The energy consumption of each protocol was calculated as the average energy required by the Applicon modems to transmit all the packets of an experiment at each traffic rate. Specifically, the packets are transmitted at 8 watts of power. The energy consumption is strongly determined by the total number of packet conflicts. In fact, the most costly operation is the transmission of the packets and, in the event of a conflict, the retransmission. In this research, it is assumed that for each packet conflict, only one retransmission is required to deliver the packet safely.

Results for each traffic rate configuration were collected in a series of experiments ranging in number from 5 tests for low traffic rates to more than 10 tests for higher traffic rates. The experiments showed that the calculated averages were stable at low traffic rates with only a few tests, while more tests were required at higher traffic rates. The duration of each experiment is 3 minutes and the number of transmission attempts depends on the traffic

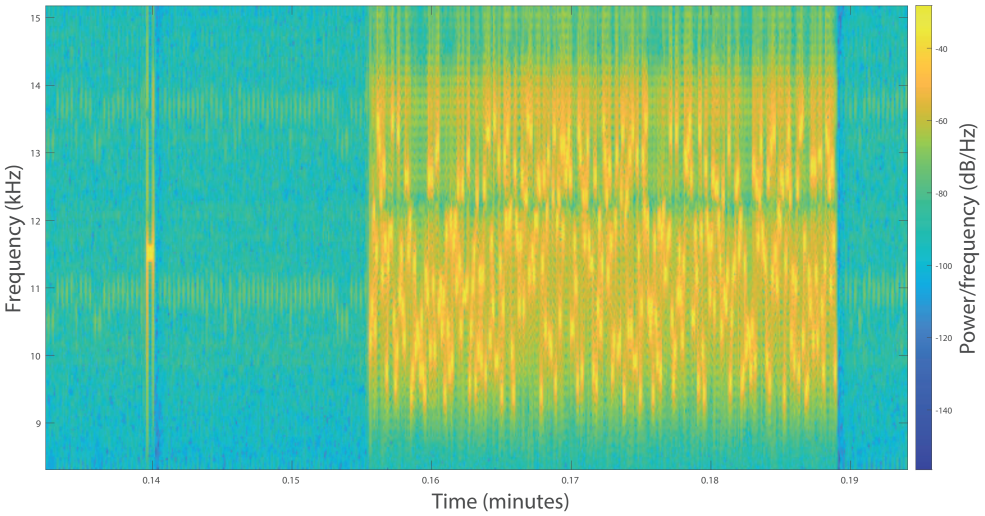
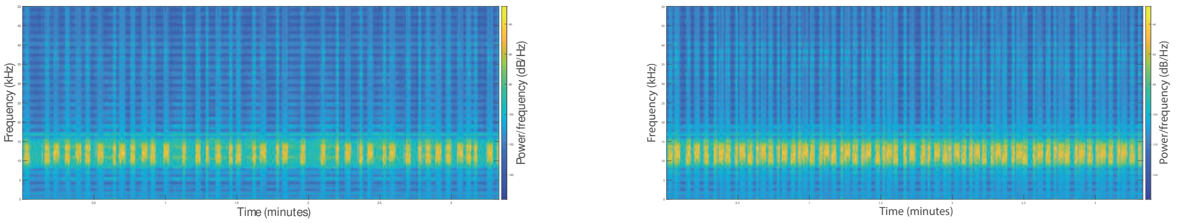


Figure 4. Example of a transmission with activated T-Lohi MAC.



(a) T-Lohi $1s$ CR.

(b) Tuned Back-off.

Figure 5. Multiple consecutive transmissions using T-Lohi $1s$ CR (Fig. 5(a)) and JANUS with Tuned Back-off (Fig. 5(b)) MAC protocols.

rate. It can vary from 100 attempts for low traffic rates to more than 600 attempts for higher traffic rates.

3.2 Analysis of the Results

In this section, all collected results are presented. Fig. 4 shows a time-frequency diagram, also known as a waterfall diagram, of a typical T-Lohi transmission. The X-axis of the diagram shows time from left to right. The Y-axis shows the frequencies from about 8 kHz to 15 kHz including the standard JANUS band (99440 Hz to 13600 Hz). The colors in the diagram represent the power carried by a frequency at a given time. At the beginning of the graph in Fig. 4, a contention tone is present. For simplicity, only one out of the three wake-up tones of the Janus standard was implemented. In particular, a tone frequency exactly in the middle of the JANUS band was used. Because no other contention tones were detected, the data transmission phase starts. Each JANUS symbol is visible as a yellow signal that has a duration of 6.25 milliseconds.

Initial considerations of throughput can be made by analyzing Fig. 5, which shows time/frequency plots of multiple successive transmissions. In this graph, a wider range of frequencies is represented. To remove unwanted noise, the signals were processed by a digital FIR bandpass filter. The effects of digital filter can be seen in Fig. 5, in which the power is reduced outside the JANUS frequency band. It is worth observing that the time among successive transmissions is significantly shorter when the Tuned Back-off algorithm is enabled (see Fig. 5(b)). Notice also that the splitting of the Back-off window in multiple overlapping intervals results into this behavior. As a consequence, the collisions are reduced and the nodes tend to access the channel more easily.

The above considerations are confirmed by analyzing the throughput data shown in Fig. 6. Each value displayed along with its 95% *Confidence Interval* (*CI*) is calculated as an average over a collection of measurements. At low traffic loads, similar values of the throughput can be observed. At higher traffic loads, the protocols settle to similar values, but the T-Lohi with $500ms$ CR achieves better throughput for almost any traffic rate. On the other hand, the T-Lohi's performance with 1 second CR is the worst overall. It is likely that listening to the channel for 1 second, before each transmission, is a too conservative approach, leading to harsh degradation of throughput. Both T-Lohi algorithms do not scale well at higher traffic rates. The Janus protocols based on ALOHA are close in overall performance, although the standard version is able to achieve better results with medium traffic loads.

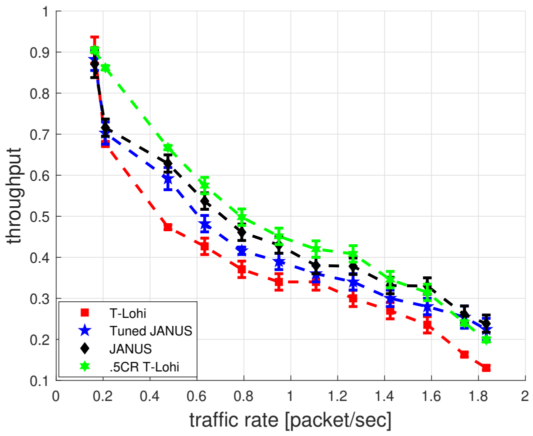


Figure 6. Average throughput values with 95% CI.

The performance differences in terms of fairness can be analyzed in Fig. 7. The T-Lohi with $0.5s$ CR is stable above 0.94 during all experiments. The other three protocols achieve similar results at low traffic loads. At higher loads (more than 1 packets per second), better results are achieved by the Tuned Back-off protocol, while the T-Lohi and standard JANUS protocols do not scale well. Overall, it is important to note that the fairness is always higher than 0.80.

Another important analysis aspect concerns the energy efficiency of the protocols. Fig. 8 shows energy consumption for each traffic rate. As expected, the T-Lohi protocol with $1s$ CR is the most efficient, but at the expense of throughput. The T-Lohi protocol with $0.5s$ CR is able to achieve better throughput while saving more energy than the JANUS-based protocols. This is possible because the number of collisions and consequently retransmissions is reduced. Among the JANUS-based protocols, the modified protocol is able to save more energy by reducing the number of retransmissions.

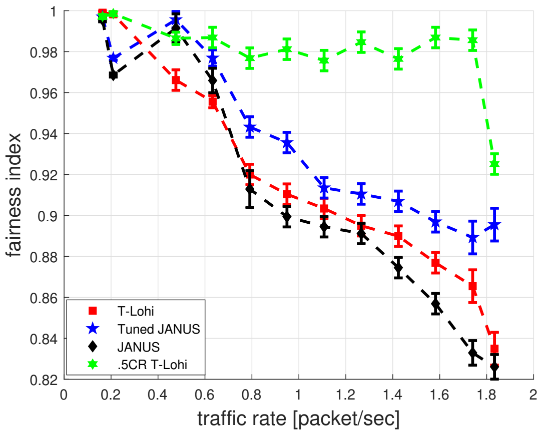


Figure 7. Average fairness values with 95% CI.

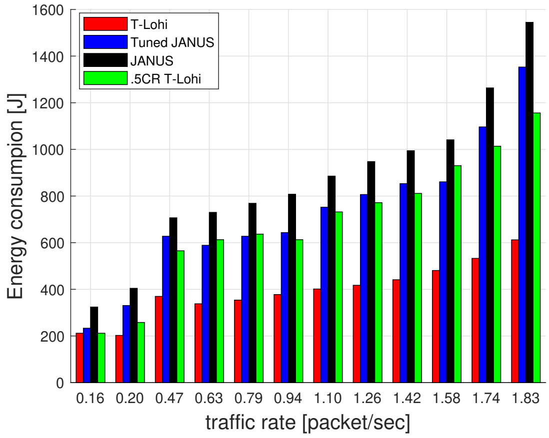


Figure 8. Average energy consumption.

4. CONCLUSION

This paper has presented comparisons between the JANUS MAC, the T-Lohi MAC and a modified JANUS MAC protocol with tuned Back-off algorithm. Several experiments with an underwater sensor network consisting of three transmitting nodes and one sink node were conducted. Relevant network metrics such as throughput, channel fairness allocation and energy efficiency have been extracted from the collected data. The results indicate that all three protocols exhibit a similar behavior in terms of throughput, with the T-Lohi protocol achieving better overall performance on medium/low traffic rates. For higher traffic rates, the protocols based on JANUS achieve better throughput at the cost of fairness and energy consumption. Applying the tuning Back-off mechanism to the JANUS protocol resulted in a small reduction in throughput, but a significant gain in fairness and energy efficiency. Future work will extend the results presented in this research with experiments conducted in larger areas, with sparser configurations and more advanced MAC protocols to address relevant issues such as propagation delays and hidden terminal effects.

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