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Performance of IEEE 802.11 MAC in Underwater Wireless Channels

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Abstract

The future ubiquitous ambient systems will probably be incomplete without underwater wireless networks. In this paper we present an analytic model for the throughput of the IEEE 802.11 medium access control (MAC) protocol in underwater acoustic networks. Underwater acoustic networks suffer from long propagation delays and low bit rates. The IEEE 802.11 medium access control (MAC) protocol, designed for free space radio channels, faces difficulties in the underwater channel. This paper proposes a model to analyze the IEEE 802.11 throughput in underwater acoustic networks. The proposed model is verified with detailed simulations and is accurate for a continuous range of propagation delays from less than a microsecond to over a full second, making it suitable for a detailed throughput performance analysis of the 802.11 MAC protocol in underwater acoustic networks.

Keywords: medium access control, MAC, wireless networks, underwater networks, ad hoc networks

1. Introduction

Acoustic waves are the most popular communication media for underwater wireless networks. Radio frequency (RF) electromagnetic waves can only propagate significant distances through sea water at very low frequencies, on the order of several tens to hundreds of Hz, due to severe attenuation [1]. At these frequencies, the wavelength is several tens of meters, requiring the use of large antennae. Although electromagnetic waves in the optical range do not suffer from comparable attenuation, excessive scattering limits the effective range. The relatively low attenuation of sound waves as compared to electromagnetic waves in the underwater channel makes acoustic communications the only viable option for long range ($> 100m$) underwater wireless links [2].

Nonetheless, the underwater acoustic channel presents unique challenges to communication protocols. The speed of sound in water is approximately $1500m/s$, resulting in propagation delays $200,000$ times longer than those experienced by terrestrial radio communication networks. The attenuation increases with frequency and distance, limiting the available bandwidth to tens of kHz at less than a kilometer and less than 10 kHz at tens of kilometers [3]. Since an acoustic system operates at frequencies of a few Hz to a few tens of Hz, the system is wideband. Multipath dispersion creates frequency-selective signal distortion, and even moderate station motion creates significant Doppler effects [4].

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Medium access control (MAC) is a significant challenge in underwater acoustic networks. Multiple nodes share a common broadcast channel through the use of a medium access control protocol. The extreme conditions of the underwater acoustic channel make existing terrestrial MAC solutions unsuitable for these purposes [3]. As a result, efforts have been focused on the development of underwater MAC solutions [5, 6, 7, 8]. A review of MAC protocols for underwater acoustic networks can be found in [9]. In this paper, we analyze the performance of the IEEE 802.11 MAC protocol for underwater acoustic communications, considering the effects of long propagation delays and low bandwidth.

In the literature, performance evaluations of IEEE 802.11 MAC for terrestrial radio networks have been carried out, either through numerical simulations [10], or through analytical models [11, 12, 13]. In this paper we extend the analytic model in [13] to account for the excessive propagation delays in underwater acoustic communication networks and verify the new model through numerical simulations.

2. Underwater acoustic channel model

The focus of this work is on the consequences of the increased propagation delay and reduced bandwidth on the performance of IEEE 802.11 MAC in underwater acoustic networks. We assume that all communicating stations are within a single hop of each other, as assumed in [13].

2.1. Propagation Delay

The propagation velocity of acoustic waves in water is five orders of magnitude slower than electromagnetic propagation in air, and is dependent on environmental conditions such as temperature, salinity, and depth [14]. In this paper, we use the temperature dependent empirical formula found in [15]:

$$\begin{aligned} c \;=\; & 1.402385 \cdot 10^3 + 5.038813T - 5.799136 \cdot 10^{-2}T^2 \\ & + 3.287156 \cdot 10^{-4}T^3 - 1.398845 \cdot 10^{-6}T^4 \\ & + 2.787860 \cdot 10^{-9}T^5 \end{aligned} \tag{1}$$

for the velocity of sound in pure water, valid for $0 < T < 95\ ^\circ C$. The propagation delay is then

$$\delta = \frac{d}{c} \tag{2}$$

where d is the distance between the sending and receiving stations. Since we only consider scenarios where all stations are positioned at the same depth, the variation of the speed of sound with depth can be safely ignored.

2.2. Channel Bitrate

The available bandwidth of an underwater acoustic channel depends on both its signal frequency and transmission distance. The attenuation increases with frequency and distance. Moreover, at a given distance, there is an optimum frequency which maximizes the signal-to-noise ratio (SNR). We follow the analysis in [3] and adopt a heuristic 3 dB loss definition of bandwidth. The analysis relies on physical models of the attenuation and noise, which will be summarized below.

Assuming unobstructed line-of-sight acoustic transmission underwater, the attenuation $A(l, f)$ at a distance l for a frequency f is given by

$$A(l, f) = l^k a(f)^l \tag{3}$$

where k is the spreading factor and $a(f)$ is the attenuation coefficient, found using Thorp's formula [16]:

$$10 \log a(f) = 0.11 \frac{f^2}{1 + f^2} + 44 \frac{f^2}{4100 + f} + 2.75 \cdot 10^{-4} f^2 + 0.003 \tag{4}$$

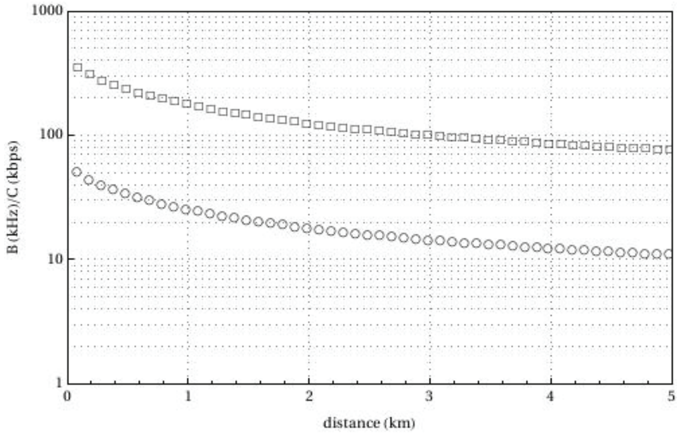

Fig. 1. Theoretical maximum bandwidth (B) and capacity (C) of an underwater acoustic channel

The noise is modeled in terms of a continuous power spectral density using empirical formulas that include noise due to turbulence, shipping activity, waves, and thermal noise:

$$\begin{aligned} 10\log N_t(f) &= 17 - 30\log f \\ 10\log N_s(f) &= 40 + 20(s - 0.5) + 26\log f - 60\log(f + 0.03) \\ 10\log N_w(f) &= 50 + 7.5w^{1/2} + 20\log f - 40\log(f + 0.4) \\ 10\log N_{th}(f) &= -15 + 20\log f \end{aligned} \tag{5}$$

where s is the shipping factor, with $0 \leq s \leq 1$, and w is the wind speed in m/s. The frequency is in kHz and the noise is units of dB re μ Pa per Hz. The total noise is then

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{6}$$

With the attenuation and noise defined, the SNR is given by

$$SNR(l, f) = \frac{P/A(l, f)}{N(f)\Delta f} \tag{7}$$

where P is the transmission power and Δf is the receiver noise bandwidth. At a given distance, there exists an optimum frequency f_0 that maximizes the factor $1/A(l, f)N(f)$, thus maximizing the SNR. Once f_0 found, the 3 dB bandwidth $B(l)$ is the range of frequencies that satisfy

$$SNR(l, f) > SNR(l, f_0)/2 \tag{8}$$

The minimum transmission power required to achieve a threshold SNR_0 at the receiver at a distance l is

$$P(l) = SNR_0 B(l) \frac{\int_{B(l)} N(f)df}{\int_{B(l)} A^{-1}(l, f)df} \tag{9}$$

Finally, the capacity is defined as

$$C(l) = \int_{B(l)} \log_2 \left[1 + \frac{P(l)/B(l)}{A(l, f)N(f)} \right] df \tag{10}$$

The bandwidth (lower plot) and capacity (upper plot) are shown in Fig. 1 for $SNR_0 = 20$ dB, $k = 1.5$, $s = 0.5$ and $w = 0$.

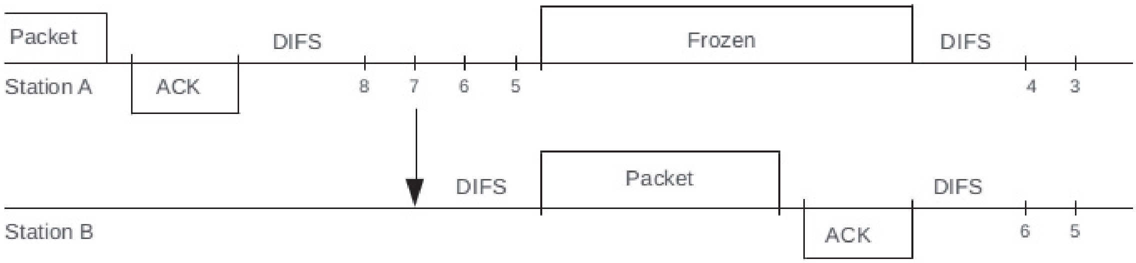

Fig. 2. Two stations access the same free-space RF medium using the distributed coordination function of the IEEE 802.11 MAC protocol. Station A has just transmitted a packet and has entered the backoff counter stage. Station B attempts to deliver its first packet, freezing Station A in the middle of a slot time. Upon completing the transmission, Station A resumes the countdown at slot 4, discarding the remaining time in slot 5. Since the propagation delay is negligible, this has the effect of self-synchronizing the time slots for stations.

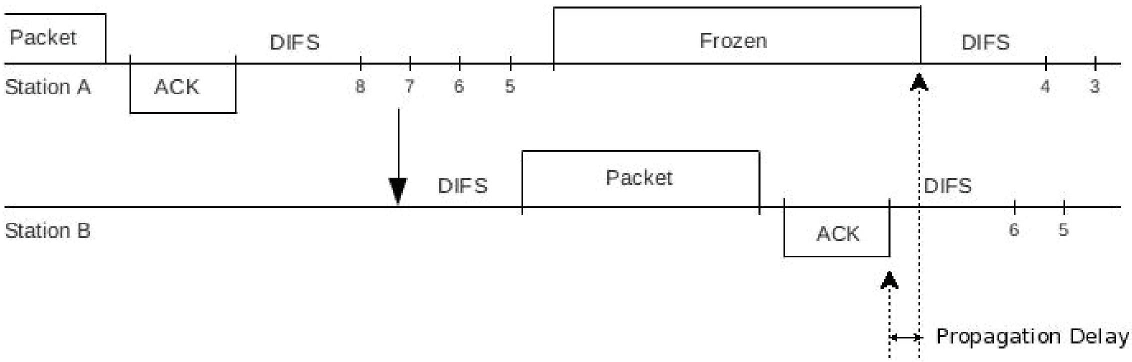

Fig. 3. Two stations access the same underwater acoustic medium using the distributed coordination function of the IEEE 802.11 MAC protocol. Station A has just transmitted a packet and has entered the backoff counter stage. Station B attempts to deliver its first packet, freezing Station A in the middle of a slot time. Upon completing the transmission, Station A resumes the countdown at slot 4, discarding the remaining time in slot 5. Since the propagation delay is not negligible, the time slots are not synchronized for stations after the completed transmission.

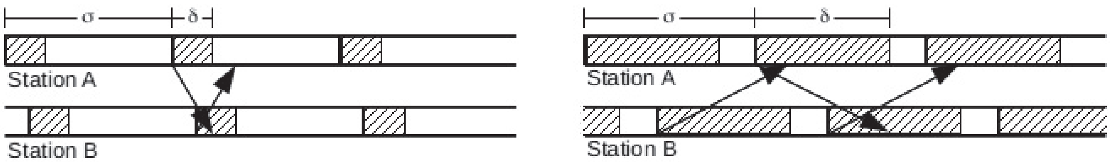

Fig. 4. The 802.11 standard defines the slot time as the sum of the propagation delay, RX-to-TX turnaround time, and energy detect time. The slot times of two stations are shown with the fraction due to propagation delay indicated as the shaded region. If the propagation delay δ is less than half of the total slot time σ, then there is only one slot time for Station B that can cause a collision given that Station A is transmitting (left). However, if the propagation delay constitutes over half of the total slot time, then there are two time slots for Station B that can cause a collision (right). Note that carrier sense prevents collisions for the other time slots.

3. Throughput Analysis

3.1. Probability of Packet Transmission

In [13], τ, the stationary transmission probability of a station in a generic sot time, is estimated under the assumption that all packets collide with a constant and independent probability p in a slot time, irrespective of the number of retransmissions that have already occurred. A bidimensional discrete-time Markov chain models both the backoff counter as well as the backoff stage, resulting in a closed form expression for the transmission probability [13]:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \tag{11}$$

where W is the minimum backoff window size and m is the maximum backoff stage, defined such that $W_{max} = 2^m W$. Since this expression is derived considering only the distributed coordination function (DCF) access scheme, it is independent of propagation delay and will therefore be used here without modification.

3.2. Throughput

The IEEE 802.11 standard defines the slot time σ as the time necessary to allow for the detection of the transmission of a packet from any station. Specifically, it is the sum of the RX-to-TX turnaround time, the energy detection time, and the propagation delay [17]. The slot time used in the standard for frequency hopping spread spectrum (FHSS) is $50\mu s$. For a network where the maximum distance between any two stations is $150m$, the maximum propagation delay is $0.5\mu s$, only 1% of the slot time.

In Fig. 2, the distributed coordination function (DCF) of the IEEE 802.11 MAC protocol is shown for two contending stations. Station A has just completed a successful transmission and after waiting a DIFS, starts a random backoff counter. During the countdown, Station B attempts to send its first packet. After waiting a DIFS, the packet is transmitted. Since the propagation delay is negligible with respect to the slot time, it is safe to assume Station A senses the transmission *immediately* and freezes the counter in the middle of slot time 5. Upon successful completion of the transmission, Station B starts a random backoff counter, while Station A resumes the countdown at slot time 4, discarding the remaining portion of slot time 5. The effect of discarding the remaining portion of frozen slot times is that after a successful transmission, previously unsynchronized stations become approximately synchronized in time slots.

The situation in the underwater acoustic channel, where the propagation delay accounts for a significant portion of the slot time, is much different. As shown in Fig. 3, a large propagation delay results in unsynchronized time slots for stations, even after a successful transmission, since stations cannot detect the same event in the network at the same time due to significant propagation delays. The analysis in [13] assumes all stations are synchronized - a reasonable approximation for the free-space RF medium. However, this assumption fails when the propagation delay is significant. In Fig. 4, the slot times for two stations are shown with propagation delays indicated as the shaded regions. Two cases are shown: (1) the propagation delay comprises less than half of the total slot time (left) or (2) more than half of the total slot time (right). In case (1), if Station A is transmitting in a given slot time, there is exactly one slot time in which Station B may transmit and cause a collision. In case (2) however, if Station A transmits in a given slot time, there are two slot times in which Station B may transmit and cause a collision[1]. Since at least one slot time will contribute to the probability of a collision, let μ be the number of additional slot times that will contribute to the probability of a collision. Then

$$\mu = \begin{cases} 0, & \delta/\sigma \leq 0.5 \\ 1, & \delta/\sigma > 0.5 \end{cases} \tag{12}$$

For n stations, the probability that a transmitted packet encounters a collision is given by the probability that at least one of the remaining $n-1$ stations is also transmitting in the same slot or any of the μ additional time slots:

$$p = 1 - (1-\tau)^{n-1}[(1-\tau)^{n-1}]^{\mu} \tag{13}$$

The additional time slot contributing to the probability of a collision is the result of the large propagation delay and the lack of synchronization among the stations. The probability that there is at least one transmission in a given time slot is

$$P_{tr} = 1 - (1-\tau)^n \tag{14}$$

[1] Note that carrier sense prevents collisions for the other time slots.

Table 1. Parameters Defined in the 802.11 Standard and Used in Numerical Simulations

packet payload	1024 bytes
MAC header	34 bytes
PHY header	16 bytes
ACK	14 bytes + PHY header
RTS	20 bytes + PHY header
CTS	14 bytes + PHY header
W_{min}	16
m	6
σ	$\delta + 50\mu s$
SIFS	0.56σ
DIFS	$2\sigma + SIFS$

Table 2. Propagation Delay and Bitrate Used in Simulation Trials

Distance	Propagation Delay	Bitrate
100 m	0.068 s	344 kbps
1 km	0.68 s	176 kbps
100 m	0.068 s	19 kbps
1 km	0.68 s	19 kbps

The probability that a transmission in a time slot is successful is given by the probability that exactly one station transmits in a given time slot and no stations transmit in μ additional time slots, conditioned on the fact that at least one station transmits:

$$P_s = \frac{n\tau(1-\tau)^{n-1}[(1-\tau)^{n-1}]^{\mu}}{P_{tr}} \tag{15}$$

We use the definition of the saturation throughput in [13], defined as the fraction of time the channel is used to successfully transmit payload bits:

$$S = \frac{P_s P_{tr} L}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \tag{16}$$

where L is the packet payload (assumed constant), T_s and T_c are the average time the channel is sensed busy because of a successful transmission and because of a collision, respectively. T_s and T_c depend on the access mechanism. For example, for the basic access mechanism of DCF,

$$T_s = H + L + SIFS + \delta + ACK + DIFS + \delta \tag{17}$$

$$T_c = H + L + DIFS + \delta \tag{18}$$

Note that if $\mu = 0$, as is the case for terrestrial radio networks, this model reduces to the one in [13].

4. Model validation

For radio frequency (RF) signals in free space, the propagation delay is less than $1\mu s$, or 2% of the total slot time (for distances of up to 300m), and thus $\mu = 0$ in the proposed model. However, for underwater acoustic networks - assuming the sum of the RX-to-TX turnaround time and energy detect time is $50\mu s$ - the

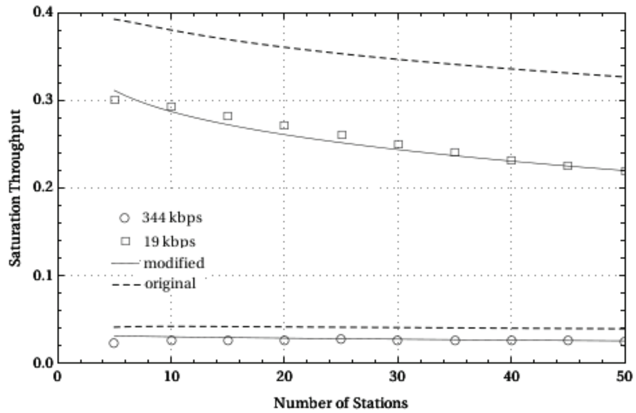

Fig. 5. Saturation throughput for a station separation of 100m for both the theoretical maximum bit rate (344 kbps) and a practical bit rate (19 kbps). The dots show the simulation results; the solid lines are the analysis presented here; the dashed lines are the model that neglects propagation delay.

propagation delay comprises the majority of the slot time (> 99%), and so $\mu = 1$. The 802.11 standard parameters listed in Table 1 are used for both the simulation and analysis. Simulations in ns-2 were conducted at distances of $100m$ and $1km$, using the channel model in Section II to find the propagation delay and bit rate at each distance. Additionally, simulations were conducted using practical bit rates achievable using currently available modems, such as the UWM1000 and UWM2000 manufactured by Ocean Innovations. These parameters are listed in Table 2.

In Fig. 5, the results of simulations are plotted along with the analytical model for station separation of 100m, showing that the analytic model is very accurate. The throughput is 20 to 30% for a transmission bit rate of 19 kbps, while for the theoretical maximum bitrate of 344 kbps, the throughput drops to below 5%. Fig. 6 shows the results for a distance of 1km. It is clear from these results that IEEE 802.11 MAC becomes extremely inefficient at long distances. It is also apparent that as acoustic modem technology continues to mature - allowing increased transmission bit rates - the 802.11 MAC also becomes less efficient, even at close distances.

5. Conclusion

In this paper, we have presented an analytic model that accounts for large propagation delay to analyze the performance of the IEEE 802.11 MAC protocol in underwater acoustic communication networks. The model is based on the fact that a large propagation delay results in un-synchronized time slots for stations and thus increases collision probability. The proposed model is compared to simulation results and found to agree with them very well.

The throughput performance of the IEEE 802.11 MAC protocol in the underwater acoustic channel is evaluated using the model proposed in this paper. We have shown that the protocol performs poorly in underwater acoustic networks, particularly when the communication bit rates are high or the communication distance is long.

Although it is generally agreed that the IEEE 802.11 MAC protocol is unsuitable for underwater acoustic communication networks, no detailed analysis has been performed. We have presented such an analysis in this paper, and have quantitatively confirmed the unsuitability of the IEEE 802.11 DCF for underwater acoustic networks.

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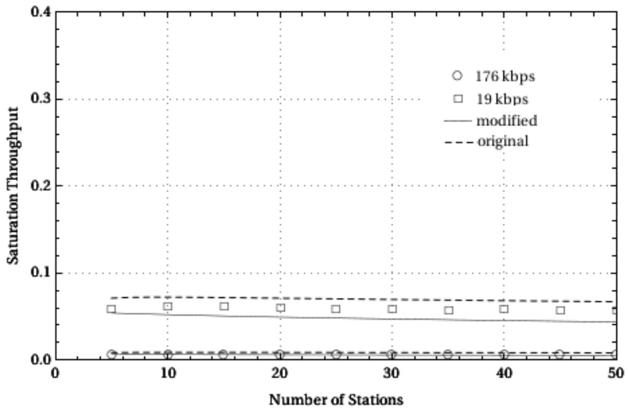

Fig. 6. Saturation throughput for a station separation of 1km for both the theoretical maximum bit rate (176 kbps) and a practical bit rate (19 kbps). The dots show the simulation results; the solid lines are the analysis presented here; the dashed lines are the model that neglects propagation delay.

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