A Receiver Synchronized Slotted Aloha for Underwater Wireless Networks with Imprecise Propagation Delay Information

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Abstract

In a wireless network, where propagation delay is high but known, slotted Aloha (S-Aloha) is synchronized with respect to the receiver's time slots. Since the transmitter knows the propagation delay to its receiver, after a frame is generated, the transmitter introduces a suitable delay before its transmission, such that the frame arrives exactly in a slot at the receiver. However, in an underwater wireless network, due to significantly less signal propagation speed, the channel dynamics has a significant effect on the time dispersion of propagation speed. Due to this uncertainty in propagation speed, even if the transmitter-receiver distance is exactly known, it is likely that a perfect synchronization at the receiver is not possible.

In this paper, we first show that, even a little-less-than-perfect synchronization at the receiver reduces the throughput of receiver synchronized S-Aloha (RSS-Aloha) to that of pure Aloha. We modify the RSS-Aloha for underwater by accommodating the error in delay estimate while deciding the receiver-end slot size. Via probabilistic analysis, supported by simulations, we show that our proposed modified protocol offers a gradual increase in throughput as the propagation delay uncertainty decreases. We also show that the throughput of our proposed modified protocol is consistently higher compared to the transmitter synchronized S-Aloha when operating under the same propagation delay uncertainty. However, when the uncertainty is high, delay performance of the modified RSS-Aloha remains poorer than that of the transmitter synchronized S-Aloha in a system with smaller nodal communication range.

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1. Introduction

Short-range underwater wireless ad hoc networks (UWN) are aimed at remotely monitoring various aquatic activities, such as marine biological and zoological lives, geological changes, and underwater human activities. Despite some similarities in UWN and terrestrial radio frequency (RF) wireless sensor networks, such as, limited channel bandwidth, high bit error rate caused by the wireless channel, and limited battery power of sensor nodes, UWN performance is significantly different due to its sensitivity to propagation delay variations.

Underwater signal propagation speed $v(z, \xi, \theta)$ (in m/s) is modeled as [1]:

$$\begin{aligned} v(z, \xi, \theta) =& 1449.05 + 45.7\theta - 5.21\theta^2 + 0.23\theta^3 + \big(1.333 \\ & -0.126\theta + 0.009\theta^2\big)\,(\xi - 35) + 16.3z + 0.18z^2, \end{aligned}$$

where $\theta = \frac{\Theta}{10}$, Θ is the temperature in ^{o}C, ξ is the salinity in ppt, and z is the depth in km. From this expression it can be noted that the signal propagation speed is a function of the operating conditions. Besides, water current and turbulence may add to the variable signal propagation speed between different transmitter-receiver pairs. Thus, even if two transmitters have the same spatial separation from a common receiver in a possibly three-dimensional underwater environment, they are likely to encounter different propagation delays, however small it could be.

Generally, in centralized underwater wireless networks, the nodes deployed for sensing and communication purposes collect and send the field data to a gateway node, which further forwards them to the shore via wireless or wire-connected links. Communication from the field sensor nodes to the gateway is in the form of many-to-one access mechanism. This many-to-one connectivity and normally-sporadic sensed data from the field nodes suggest that some kind of random access protocol would be suitable for the field nodes to gateway communication. However, pertaining to the distinctly different signal propagation characteristics, RF multi-access communication protocols are not directly applicable [2, 3, 4, 5, 6].

Noting that the inter-nodal propagation delay in underwater communications is rather long, several variants of underwater access protocols have been proposed and studied in recent literature [7, 8, 9, 10, 6]. In context of receiver distance dependent propagation delay, pure Aloha and transmitter synchronized slotted Aloha (S-Aloha) performances have been studied, and different variants of conventional transmitter synchronized S-Aloha (which we call mTSS-Aloha-uw) have also been proposed and studied [11, 12, 13]. In [12] an optimum guard band for transmitter synchronized S-Aloha was analyzed, where it was called PDT-ALOHA. In [13], a different approach to finding optimum slot size in transmitter synchronized S-Aloha was analyzed, where the modified protocol was called mS-Aloha-uw. In this paper for consistency in nomenclature, the mS-Aloha-uw is called mTSS-Aloha-uw. It was noted in [13] that the performance of mTSS-Aloha-uw variants degrade as the propagation delay increases. Moreover, in all these studies the impact of propagation delay uncertainty on the protocol performance has not been investigated.

Our current work is motivated by receiver-initiated/ synchronized underwater wireless many-to-one multi-access communication protocol variants (e.g., [6, 14]). Note that, in practice Aloha protocol variants may not be used for actual data communication (because of its limited throughput), and some kind of (contention-free) reservation protocols may be more suitable. Yet, as demonstrated in the prior underwater multi-access protocol studies [15, 16, 9, 17, 18, 14], the initial communication phase for the resource reservation purpose is expected to be random-access (Aloha or S-Aloha) based.

We observe that, satellite to earth stations many-to-one multi-access communications also encounter a significantly large propagation delay, where, among several variants of random access protocols, receiver synchronized S-Aloha (which we call RSS-Aloha) was proposed [19]. This RSS-Aloha protocol works best as long as the synchronization at the receiver is perfect. The error in receiver-end time synchronization in RF based satellite communications may be insignificantly small, where the propagation delay uncertainty can be disregarded because of relatively very high electromagnetic signal communication speed. However, in underwater environment, perfect receiver-end synchronization is more difficult, as the temporal and spatial variation of underwater signal propagation speed cannot be insignificant. In fact, a few recent underwater communication studies have accounted for a finite uncertainty in inter-nodal signal propagation delay [20, 21, 22]. It may be pointed here that, to the best of our knowledge, the effect imperfect receiver-end synchronization on S-Aloha performance in satellite communications as well as in underwater networks and its remedies have not been studied before.

In this paper we investigate modified S-Aloha protocols for many-to-one underwater wireless environment with large and variable propagation delay, and aim at maximizing the system performance. Intuitively, to accommodate the error in synchronization, the slot size can be increased beyond the frame transmission time. For a given frame generation rate per unit time, this increase in slot size will reduce the inter-slot frame collisions, however at the cost of more intra-slot frame collisions. It needs to be studied how the trade-off between inter-frame collision and intra-frame collision vulnerability would work in case of receiver-end synchronized S-Aloha, and an optimum slot size would be of interest to achieve a higher system performance.

Our specific contributions in this paper are as follows:

(a) We investigate the impact of propagation delay estimation error on the RSS-Aloha performance and show that, a little error in delay estimate causes sharp degradation of RSS-Aloha-uw (RSS-Aloha for UWN) throughput to that of pure Aloha.

(b) We propose to improve the RSS-Aloha-uw protocol performance by optimally accommodating the propagation delay estimation error in deciding the receiver-side slot size. The proposed modified protocol is called modified RSS-Aloha-uw, or mRSS-Aloha-uw.

(c) With Gaussian approximation of propagation delay variation, we analyze and compare the mRSS-Aloha-uw with a transmitter synchronized modified S-Aloha (which we call mTSS-Aloha-uw), and demonstrate that mRSS-Aloha-uw performs better with respect to the mTSS-Aloha-uw in terms of throughput. Our results also show that, at a smaller communication range, the mRSS-Aloha-uw delay performance can be poorer compared to the mTSS-Aloha-uw, when the propagation delay uncertainty is high.

The remainder of the paper is organized as follows. Related works on propagation delay intensive many-to-one multi-access protocols and the synchronization related studies are surveyed in Section 2. Performance analysis of RSS-Aloha-uw is provided in Section 3. Our proposed mRSS-Aloha-uw is presented and its performance is analyzed in Section 4. Section 5 contains the throughput performance study of the modified TSS-Aloha-uw under propagation delay uncertainty. Delay performance of the modified S-Aloha protocols are formulated in Section 6. Numerical and simulation results are discussed in Section 7. In Section 8 we conclude the paper.

2. Related Work

Several variants of underwater MAC protocols have been proposed in recent literature. In this section we briefly survey the protocols that explicitly address the cluster or gateway based communications, and also the ones that address synchronization issues.

Different time synchronization protocols for underwater sensor network were studied in [23, 24, 25, 26]. In [23], synchronization was proposed using a two phase protocol. In phase I, clock skew of the nodes are adjusted with respect to the clock of the beacon node. In phase II, a two way handshake between a synchronized node and the beacon node is initiated. It was assumed that, during the short message exchange in phase I, propagation delay is fixed. In [24], time synchronization is initiated by the cluster head by broadcasting short packets to its local neighbors. These nodes reply to the reference packets with time stamps of receipt and their respective response instants. The cluster head then estimates the clock skew and clock offset of a node using linear regression. The approach in [25] uses a global node to initiate synchronization by transmitting multiple synchronization messages. Using the synchronization messages the local nodes estimate their clock skews using linear regression. The clock offsets are adjusted afterward by a two way message exchange. This protocol also considers the propagation delay is fixed during the short message exchange period. In [26], having a reference node is not necessary. Any node synchronizes its clock with respect to its neighbor nodes by short message exchanges. The frequency of a node's clock synchronization is decided by a profile manager, which checks if the number of messages from all neighbors are received with certain confidence limit.

The underwater multi-access protocol variants proposed in [15] use RTS/CTS (request to send/ clear to send) handshake, where the initial phase is Aloha based. Several other one-to-one underwater communication protocols in [16, 9, 17, 18, 14] also use some variants of handshaking that are Aloha or S-Aloha based. The gateway based many-to-one communication in [6] uses RTS from non-gateway nodes to gateway node through the control channel for resource reservation, and data channel is used for CTS from gateway to non-gateway nodes and for DATA from non-gateway nodes to gateway node.

The basic Aloha and S-Aloha protocol performances were studied and a guard time based variant of S-Aloha was proposed in [11]. Analytic performance evaluation of the Aloha protocols and different variants of transmitter synchronized S-Aloha protocol were independently studied in [12] and [13]. In these studies, the error in propagation delay estimate was not accounted. In [22], a TDMA based MAC protocol in single hop underwater sensor networks was proposed considering variability of propagation delay, where the optimal guard time is computed after every nodes communication.

In addition to the time-synchronization MAC protocols, CDMA (code division multiple access) based protocols have also been studied recently, some of which also have contextual similarities with Aloha protocols. In [27], a CDMA MAC protocol was proposed, which uses RTS-CTS for handshaking. In [28], transmitter controlled direct sequence CDMA distributed MAC protocol was proposed that incorporates closed loop distributed algorithm to set optimal transmit power and code length to minimize near-far effect.

In our present work, the proposed protocol is not a reservation based medium access scheme. Instead, we investigate the synchronization and optimal guard time allocation issues in the underwater S-Aloha protocols which can be used in the control (channel reservation) stage of the reservation based protocols. To this end, we take a re-look at the receiver synchronized S-Aloha concept in satellite-to-earth station communications [19]. Although the current study applies to gateway based many-to-one communication scenarios with propagation delay uncertainty, the proposed concept can be extended to one-to-one random access protocols as well.

3. Receiver Synchronized S-Aloha

In this section we study the performance of RSS-Aloha without as well as with propagation delay uncertainty, where slot size is the same as a (fixed size) frame transmission time. Before we proceed, the generic assumptions and definitions on the system and performance, that are used throughout the paper, are briefly mentioned.

Assumption: The transmitters are uniformly random distributed around the receiver's communication range R, and each node knows the distance to the receiver. Variability of underwater inter-nodal propagation delay, i.e., propagation delay uncertainty, is Gaussian distributed [20, 21].

Definition 1: Access performance is measured in terms of *normalized system throughput*, defined as the average number of successful frames in the network per frame transmission time.

Definition 2: Frame success rate is measured in terms of *delay per successful frame*, defined as the time taken to successfully deliver a frame.

3.1. Receiver synchronized S-Aloha without propagation delay uncertainty (RSS-Aloha)

In this case, perfectly synchronized reception is possible if the transmitter knows its distance to the receiver and waits appropriately before sending a frame. Thus, the frame will arrive exactly at a time slot, where the slot size is equal to the frame transmission time. The waiting time duration at the transmitter T_w can be defined as: $T_w = t_r - (t_a + T_p)$, where t_r is the start time instant of the nearest next time slot after time $(t_a + T_p)$, t_a is the frame arrival time instant at the transmitter, and T_p is the transmitter-to-receiver propagation delay which is known from the transmitter-receiver distance and the average speed of the underwater acoustic signal. The case of time synchronized

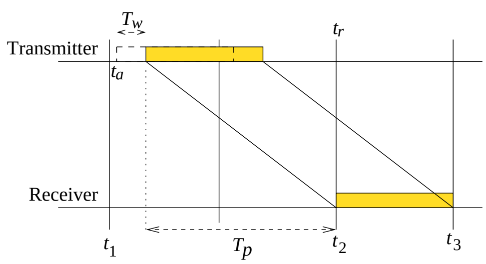

Figure 1: Frame transmission approach in RSS-Aloha.

reception depicted in Fig. 1, where $t_r = t_2$.

From the receiver's perspective this concept is depicted in Fig. 2. Consider, the number of

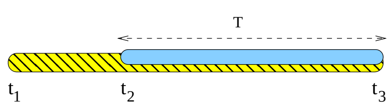

Figure 2: Collision vulnerability concept.

frames that arrive during $[t_2,\ t_3]$ is m and the total number generated during $[t_1,\ t_3]$ is n. Here the vulnerability duration is $|t_2 - t_3| = T = T_t$, frame transmission time. We have [29, Ch. 3]:

$$\Pr\Big[m \text{ out of } n \text{ frames arrive during } [t_2, t_3]\Big] = \binom{n}{m} p^m (1-p)^{n-m},$$

where $p = \frac{|t_2-t_3|}{|t_1-t_3|} = \frac{T_t}{|t_1-t_3|}$. Frame arrival rate in the system is $\lambda = \frac{n}{|t_1-t_3|}$. The window $|t_1 - t_3|$ can be increased arbitrarily so that $n \to \infty$ and $p \to 0$, keeping the product $np = \lambda T_t$ a constant. Thus, the above equation can be approximated as:

$$P_n(m) \approx e^{-np}\frac{(np)^m}{m!} = e^{-\lambda T_t}\frac{(\lambda T_t)^m}{m!}.$$

So the frame success probability is $P_n(0) = e^{-\lambda T_t}$, and the normalized system throughput is:

$$\eta_{\text{RSS-Aloha}} = \lambda T_t e^{-\lambda T_t}, \tag{1}$$

which is the same as the conventional S-Aloha throughput of a system with negligible propagation delay.

3.2. Receiver synchronized S-Aloha with propagation delay uncertainty (RSS-Aloha-uw)

In underwater wireless environment, due to significantly less signal propagation speed, the channel dynamics (caused by water current, temperature variation etc.) has a significant effect on the time dispersion of propagation delay, and the dispersion could be on the order of the average propagation delay. Due to this uncertainty in propagation delay, perfect synchronization at the receiver, i.e., receiving a frame exactly at a slot boundary, is not possible.

Looking from the receiver's perspective, as long as its frame reception duration does not overlap with any other frame arrivals, the frame will be successful. Thus, a frame of size T_t, whose reception starts at time $t + T_p$, will be successful if no additional arrival at the receiver occurs during the interval from $t + T_p - T_t$ to $t + T_p + T_t$, i.e., for the duration $2T_t$. Referring to Fig. 2, the vulnerability duration in this case is: $|t_2 - t_3| = T = 2T_t$.

Proceeding similarly as in Section 3.1, we have the frame success probability, $P_n(0) = e^{-2\lambda T_t}$. Hence, the normalized system throughput of RSS-Aloha-uw is:

$$\eta_{\text{RSS-Aloha-uw}} = \lambda T_t e^{-2\lambda T_t}, \tag{2}$$

which is same as the throughput of Aloha-rf or Aloha-uw. Thus, even due to a little imperfection in receive side synchronization, the S-Aloha performance degrades to that of pure Aloha.

4. A Modified Receiver Synchronized S-Aloha for UWN (mRSS-Aloha-uw)

In this section we propose to modify the slot size of RSS-Aloha-uw protocol to achieve an improved system performance. Consider, a frame reaches at the receiver at time t_r. The arrival instant is assumed Gaussian distributed [20, 21] as: $t_r \sim \mathcal{N}\left(t_g, \sigma^2(r)\right)$, where t_g is the start time of a time slot at the receiver and $\sigma^2(r)$ is the variance, which is a function of transmitter-receiver distance r.

We propose to increase the slot size of mRSS-Aloha-uw protocol as, $T_s = T_t + 2k\sigma(r)$, with $k \geq 0$ and $\sigma(r) \leq T_p^{(max)}$. k is termed as *slot size increment coefficient*, and $T_p^{(max)} = \frac{R}{v}$ is the maximum propagation delay to the receiver. $\sigma(r) \leq T_p^{(max)}$ is a practical assumption that the delay uncertainty is upper bounded by the maximum possible inter-nodal delay. The factor 2 on right hand side of the modified slot definition is to accommodate worst case errors due to jointly overshooting and undershooting a slot boundary.

By Gaussian approximation of arrival time uncertainty distribution, the success probability $P_s^{(mRS)}$ of a frame designated for slot i is primarily determined by the frames that are designated for slot $i \pm j$, where $1 \leq j \leq \left\lceil \frac{3\sigma(r)}{T_s} \right\rceil$. Clearly, for $k \geq 1$ and any value of $T_p^{(max)}$, $P_s^{(mRS)}$ in a slot will be governed by the designated frames that are its two-slot neighbors. If $0 \leq k < 1$, $\frac{3\sigma(r)}{T_s}$ can be greater than 2, and hence $P_s^{(mRS)}$ is affected by more than two-slot neighbors. In the following analysis of $P_s^{(mRS)}$, we consider only two-slot neighbor vulnerability, which is likely to introduce some error in analysis for $0 \leq k < 1$. However, as we will see from the numerical results in Section 7, the range $0 \leq k < 1$ is of less importance, as the optimum mRSS-Aloha-uw slot size is achieved only for $k \geq 1$. Considering vulnerability caused by up to two-slot neighbors, $P_s^{(mRS)}$

can be approximately written as:

$$
\begin{aligned}
P_s^{(mRS)} = \int_0^R \int_{(i-2)T_s}^{(i+2)T_s} & \left[\sum_{n_i=0}^{\infty} \text{Pr}\left(n_i \text{ arrival in slot } i\right) \prod_{i=0}^{n_i} \left\{1 - \text{Pr}\left(y - T_t \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_t\right)\right\}\right] \\
& \cdot \left[\sum_{n_{i_{p2}}=0}^{\infty} \text{Pr}\left(n_{i_{p2}} \text{ arrival in slot } i-2\right) \prod_{i_{p2}=0}^{n_{i_{p2}}} \left\{1 - \text{Pr}\left(y - T_t \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_t\right)\right\}\right] \\
& \cdot \left[\sum_{n_{i_{p1}}=0}^{\infty} \text{Pr}\left(n_{i_{p1}} \text{ arrival in slot } i-1\right) \prod_{i_{p1}=0}^{n_{i_{p1}}} \left\{1 - \text{Pr}\left(y - T_t \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_t\right)\right\}\right] \\
& \cdot \left[\sum_{n_{i_{n1}}=0}^{\infty} \text{Pr}\left(n_{i_{n1}} \text{ arrival in slot } i+1\right) \prod_{i_{n1}=0}^{n_{i_{n1}}} \left\{1 - \text{Pr}\left(y - T_t \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_t\right)\right\}\right] \\
& \cdot \left[\sum_{n_{i_{n2}}=0}^{\infty} \text{Pr}\left(n_{i_{n2}} \text{ arrival in slot } i+2\right) \prod_{i_{n2}=0}^{n_{i_{n2}}} \left\{1 - \text{Pr}\left(y - T_t \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_t\right)\right\}\right] \\
& \cdot \text{Pr}(\mathbf{y_i} = y)\, \text{Pr}(\mathbf{r_i} = r). \qquad (3)
\end{aligned}
$$

By the assumption of Gaussian delay distribution we have: $\mathbf{y_i}(r_i) \sim \mathcal{N}(iT_s, \sigma_i^2)$; $\mathbf{x_i}(r_i) \sim \mathcal{N}(iT_s, \sigma_i^2)$; $\mathbf{x_{i_{p2}}}(r_{i_{p2}}) \sim \mathcal{N}\left((i-2)T_s, \sigma_{i_{p2}}^2\right)$; $\mathbf{x_{i_{p1}}}(r_{i_{p1}}) \sim \mathcal{N}\left((i-1)T_s, \sigma_{i_{p1}}^2\right)$; $\mathbf{x_{i_{n1}}}(r_{i_{n1}}) \sim \mathcal{N}\left((i+1)T_s, \sigma_{i_{n1}}^2\right)$. $\mathbf{x_{i_{n2}}}(r_{i_{n2}}) \sim \mathcal{N}\left((i+2)T_s, \sigma_{i_{n2}}^2\right)$. Hence, for a uniformly random nodal distribution, the expression (3) becomes:

$$
\begin{aligned}
P_s^{(mRS)} = \int_{r=0}^{R} \int_{(i-2)T_s}^{(i+2)T_s} & \left[\sum_{n_i=0}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^{n_i}}{n_i!} \prod_{k=0}^{n_i} \{1 - \Pr\left(y - T_t \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_t\right)\} \right] \\
& \cdot \left[\sum_{n_{i_{p2}}=0}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^{n_{i_{p2}}}}{n_{i_{p2}}!} \prod_{i_{p2}=0}^{n_{i_{p2}}} \left\{1 - \Pr(y - Tt \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_t)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{p1}}=0}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^{n_{i_{p1}}}}{n_{i_{p1}}!} \prod_{i_{p1}=0}^{n_{i_{p1}}} \left\{1 - \Pr(y - T_t \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_t)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{n1}}=0}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^{n_{i_{n1}}}}{n_{i_{n1}}!} \prod_{i_{n1}=0}^{n_{i_{n1}}} \{1 - \Pr(y - T_t \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_t)\} \right] \\
& \cdot \left[\sum_{n_{i_{n2}}=0}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^{n_{i_{n2}}}}{n_{i_{n2}}!} \prod_{i_{n2}=0}^{n_{i_{n2}}} \{1 - \Pr(y - T_t \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_t)\} \right] \\
& \cdot \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y - i.T_s}{\sigma_i}\right)^2} dy \frac{2r\,dr}{R^2}. \qquad (4)
\end{aligned}
$$

In practice, the mean as well as variance of propagation delay are functions of transmitter-receiver distance [20, 21]. Accordingly, the frame arrival time at the receiver is also Gaussian distributed with distance dependent parameters. The arrival time of a frame destined to the receiver in slot i is Gaussian distributed as: $\mathbf{x_i}(r_i) \sim \mathcal{N}(iT_s, \sigma^2(r_i))$, where the variance is dependent on transmitter-receiver distance r_i. Using the arrival time distribution, the probability expressions in (4) can be simplified as:

$$
\begin{aligned}
\Pr\left(y - T_t \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_t\right) &= \int_0^R \Pr(y - T_t \leq \mathbf{x_i}(\mathbf{r_i} = r) \leq y + T_t) \cdot \Pr(\mathbf{r_i} = r) \\
&= \int_0^R \frac{1}{2} \left[\text{erf}\left(\frac{y + T_t - iT_s}{\sigma(r)\sqrt{2}} \right) - \text{erf}\left(\frac{y - T_t - iT_s}{\sigma(r)\sqrt{2}} \right) \right] \frac{r\,dr}{R^2} \triangleq P_1,
\end{aligned}
$$

$$
\begin{aligned}
\Pr\left(y - T_t \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_t\right) &= \int_0^R \Pr\left(y - T_t \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}} = r) \leq y + T_t\right) \cdot \Pr(\mathbf{r_{i_{p1}}} = r) \\
&= \int_0^R \frac{1}{2} \left[\text{erf}\left(\frac{y + T_t - (i-1)T_s}{\sigma(r)\sqrt{2}} \right) - \text{erf}\left(\frac{y - T_t - (i-1)T_s}{\sigma(r)\sqrt{2}} \right) \right] \frac{r\,dr}{R^2} \triangleq P_2,
\end{aligned}
$$

$$
\begin{aligned}
\Pr\left(y - T_t \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_t\right) &= \int_0^R \Pr\left(y - T_t \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}} = r) \leq y + T_t\right) \cdot \Pr(\mathbf{r_{i_{p2}}} = r) \\
&= \int_0^R \frac{1}{2} \left[\text{erf}\left(\frac{y + T_t - (i-2)T_s}{\sigma(r)\sqrt{2}} \right) - \text{erf}\left(\frac{y - T_t - (i-2)T_s}{\sigma(r)\sqrt{2}} \right) \right] \frac{r\,dr}{R^2} \triangleq P_3,
\end{aligned}
$$

$$\Pr\left(y - T_t \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_t\right) = \int_0^R \Pr\left(y - T_t \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}} = r) \leq y + T_t\right) \cdot \Pr(\mathbf{r_{i_{n1}}} = r)$$
$$= \int_0^R \frac{1}{2}\left[\operatorname{erf}\left(\frac{y + T_t - (i+1)T_s}{\sigma(r)\sqrt{2}}\right) - \operatorname{erf}\left(\frac{y - T_t - (i+1)T_s}{\sigma(r)\sqrt{2}}\right)\right]\frac{rdr}{R^2} \triangleq P_4,$$
$$\Pr\left(y - T_t \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_t\right) = \int_0^R \Pr\left(y - T_t \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}} = r) \leq y + T_t\right) \cdot \Pr(\mathbf{r_{i_{n2}}} = r)$$
$$= \int_0^R \frac{1}{2}\left[\operatorname{erf}\left(\frac{y + T_t - (i+2)T_s}{\sigma(r)\sqrt{2}}\right) - \operatorname{erf}\left(\frac{y - T_t - (i+2)T_s}{\sigma(r)\sqrt{2}}\right)\right]\frac{rdr}{R^2} \triangleq P_5.$$

For a known $\sigma(r)$, the above integrations can be solved to compute the frame success probability in (4). However, since the nature of distance dependence on $\sigma(r)$ is not known yet, for a closed form analytic solution on system throughput, below consider a special case of constant σ.

We consider $\sigma = aT_p^{(max)}$ a constant, where $0 \leq a \leq 1$. Thus, simplifying and using the identities: $\operatorname{erf}(x) = \int_0^x e^{-t^2}dt$, and $\int_a^b \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} = \frac{1}{2}\left[\operatorname{erf}\left(\frac{b-\mu}{\sigma\sqrt{2}}\right) - \operatorname{erf}\left(\frac{a-\mu}{\sigma\sqrt{2}}\right)\right]$, we have from (4),

$$P_s^{(mRS)} = \int_{r=0}^{R}\int_{(i-2)T_s}^{(i+2)T_s} e^{-\lambda T_s(P_1+P_2+P_3+P_4+P_5)} \cdot \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-iT_s}{\sigma}\right)^2} dy \frac{2rdr}{R^2}$$
$$= \int_{(i-2)T_s}^{(i+2)T_s} e^{-\lambda T_s(P_1+P_2+P_3+P_4+P_5)} \cdot \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-iT_s}{\sigma}\right)^2} dy.$$

Hence, the normalized system throughput is:

$$\eta_{\text{mRSS-Aloha-uw}} = \lambda T_t P_s^{(mRS)}. \tag{5}$$

Note that, for a given uncertainty in propagation delay (i.e., the standard deviation σ), the frame success probability, and hence system throughput can be optimized by suitably adjusting the slot size increment coefficient k.

5. Performance of Modified Transmitter Synchronized S-Aloha with Propagation Delay Uncertainty (mTSS-Aloha-uw)

We now evaluate the throughput performance of transmitter-end synchronized Aloha (which we call mTSS-Aloha-uw) protocol. In this case, a frame is transmitted at a slot boundary defined at the transmitters, and the transmitter-end slot size is optimally increased to accommodate the distance dependent propagation delays to the receiver [11, 12, 13] to maximize the system throughput.

The prior studies of the protocol performance [12, 13] however did not consider the propagation delay uncertainty, i.e., it was assumed that for a fixed distance away transmitter the propagation delay is constant.

We analyze the mTSS-Aloha-uw performance under the same assumption of Gaussian distributed propagation delay uncertainty as in mRSS-Aloha-uw. For mTSS-Aloha-uw with the transmissions governed by the transmitter-end slot boundaries and the maximum propagation delay to the receiver $T_p^{max} = \frac{R}{v} \leq T_t$, the slot size is modified as $T_s = T_t + \delta T_p^{max}$, where $0 \leq \delta \leq 1$. Note that, for $\sigma(r) = aT_p^{max}$ with $0 \leq a \leq 1$, always $\sigma(r) \leq T_t$. So, in this case the frame success probability in a slot will be governed by $\frac{3\sigma(r)}{T_s} \leq 3$ adjacent slots. Accordingly, the frame success probability can be calculated similarly as in (3) with the new integration limits for y as $(i-3)T_s$ and $(i+3)T_s$:

$$
\begin{aligned}
P_s^{(mTS)} = \int_{(i-3)T_s}^{(i+3)T_s} \int_0^R & \left[\sum_{n_i=0}^{\infty} \Pr\left(n_i \text{ arrival in slot } i\right) \prod_{i=0}^{n_i} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_t\right)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{p3}}=0}^{\infty} \Pr\left(n_{i_{p3}} \text{ arrival in slot } i-3\right) \prod_{i_{p3}=0}^{n_{i_{p3}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{p3}}}(\mathbf{r_{i_{p3}}}) \leq y + T_t\right)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{p2}}=0}^{\infty} \Pr\left(n_{i_{p2}} \text{ arrival in slot } i-2\right) \prod_{i_{p2}=0}^{n_{i_{p2}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_t\right)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{p1}}=0}^{\infty} \Pr\left(n_{i_{p1}} \text{ arrival in slot } i-1\right) \prod_{i_{p1}=0}^{n_{i_{p1}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_t\right)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{n1}}=0}^{\infty} \Pr\left(n_{i_{n1}} \text{ arrival in slot } i+1\right) \prod_{i_{n1}=0}^{n_{i_{n1}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_t\right)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{n2}}=0}^{\infty} \Pr\left(n_{i_{n2}} \text{ arrival in slot } i+2\right) \prod_{i_{n2}=0}^{n_{i_{n2}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_t\right)\right\} \right] \\
& \cdot \left[\sum_{n_{i_{n3}}=0}^{\infty} \Pr\left(n_{i_{n3}} \text{ arrival in slot } i+3\right) \prod_{i_{n3}=0}^{n_{i_{n3}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{n3}}}(\mathbf{r_{i_{n3}}}) \leq y + T_t\right)\right\} \right] \\
& \cdot \Pr(\mathbf{y_i} = y) \Pr(\mathbf{r_i} = r).
\end{aligned} \tag{6}
$$

Here, since all the transmitters transmit according to their own time slots, the mean of Gaussian distribution for the arrival slot i from an r_i distance away transmitter is $iT_s + T_p(r_i)$, where $T_p(r_i) = \frac{r_i}{v}$ is the propagation delay. In mTSS-Aloha-uw, the additional uncertainty is due to the random distance r_i to the receiver. Hence, accommodating the additional propagation delay to the receiver $T_p(r_i)$, the arrival time will be Gaussian distributed as: $\mathbf{x_i}(r_i) \sim \mathcal{N}(iT_s + T_p(r_i), \sigma^2(r_i))$, where $\sigma^2(r_i)$ is also a function of transmitter receiver distance r_i.

In (6), $\Pr(y - T_t \le \mathbf{x_i}(\mathbf{r_i}) \le y + T_t)$ can be written as:

$$P_1 = \Pr\left(y - T_t \le \mathbf{x_i}(\mathbf{r_i}) \le y + T_t\right) = \int_0^R \Pr\left(y - T_t \le \mathbf{x_i}(\mathbf{r_i} = r) \le y + T_t\right) \cdot \Pr(\mathbf{r_i} = r)$$
$$= \int_0^R \int_{y-T_t}^{y+T_t} \frac{1}{\sigma(r)\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-(iT_s+\frac{r}{v})}{\sigma(r)}\right)^2} dx \cdot \frac{2r dr}{R^2} \triangleq P_{11} - P_{12}.$$

This above equation can be derived for known values of $T_p(r)$ and $\sigma(r)$.

As in mRSS-Aloha-uw, since the nature of $\sigma(r)$ is unknown, by considering distance independent propagation delay uncertainty, a compact expression for system throughput can be obtained.

With constant σ approximation: $\sigma(r) = \sigma = \frac{aR}{v}$, with $0 \le a \le 1$, after simplification we have,

$$P_{11} = \left(\frac{\sigma\sqrt{2}}{T_p^{max}}\right)^2 \left[\frac{1}{4}\left\{\frac{2}{\sqrt{\pi}}\left(b_1 e^{-b_1^2} - a_1 e^{-a_1^2}\right) + \left(2b_1^2 - 1\right)\text{erf}(b_1) - \left(2a_1^2 - 1\right)\text{erf}(a_1)\right\}\right]$$
$$- \frac{\sigma\sqrt{2}}{(T_p^{max})^2}(y + T_t - iT_s)\left(b_1\,\text{erf}(b_1) + \frac{e^{-b_1^2}}{\sqrt{\pi}} - a_1\,\text{erf}(a_1) - \frac{e^{-a_1^2}}{\sqrt{\pi}}\right),$$

with $a_1 = \frac{y+T_t-iT_s}{\sigma\sqrt{2}}$, $b_1 = \frac{y+T_t-iT_s-T_p^{max}}{\sigma\sqrt{2}}$, and

$$P_{12} = \left(\frac{\sigma\sqrt{2}}{T_p^{max}}\right)^2 \left[\frac{1}{4}\left\{\frac{2}{\sqrt{\pi}}\left(b_2 e^{-b_2^2} - a_2 e^{-a_2^2}\right) + \left(2b_2^2 - 1\right)\text{erf}(b_2) - \left(2a_2^2 - 1\right)\text{erf}(a_2)\right\}\right]$$
$$- \frac{\sigma\sqrt{2}}{(T_p^{max})^2}(y - T_t - iT_s)\left(b_2\,\text{erf}(b_2) + \frac{e^{-b_2^2}}{\sqrt{\pi}} - a_2\,\text{erf}(a_2) - \frac{e^{-a_2^2}}{\sqrt{\pi}}\right),$$

with $a_2 = \frac{y-T_t-iT_s}{\sigma\sqrt{2}}$, $b_2 = \frac{y-T_t-iT_s-T_p^{max}}{\sigma\sqrt{2}}$.

Similarly $P_2 = \Pr\left(y - T_t \le \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \le y + T_t\right)$, $P_3 = \Pr\left(y - T_t \le \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \le y + T_t\right)$, $P_4 = \Pr\left(y - T_t \le \mathbf{x_{i_{p3}}}(\mathbf{r_{i_{p3}}}) \le y + T_t\right)$, $P_5 = \Pr\left(y - T_t \le \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \le y + T_t\right)$, $P_6 = \Pr\left(y - T_t \le \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \le y + T_t\right)$, and $P_7 = \Pr\left(y - T_t \le \mathbf{x_{i_{n3}}}(\mathbf{r_{i_{n3}}}) \le y + T_t\right)$ are found.

Now,

$$\int_{y=(i-3)T_s}^{(i+3)T_s} \int_{r=0}^{R} \Pr(\mathbf{y_i} = y)\Pr(\mathbf{r_i} = r) = \int_{y=(i-3)T_s}^{(i+3)T_s} \int_{r=0}^{R} \frac{e^{-\frac{1}{2}\left(\frac{y-(iT_s+\frac{r}{v})}{\sigma(r)}\right)^2}}{\sigma(r)\sqrt{2\pi}} dy \frac{2rdr}{R^2}$$
$$= \int_{y=(i-3)T_s}^{(i+3)T_s} \int_{r=0}^{R} \frac{e^{-\frac{1}{2}\left(\frac{y-(iT_s+\frac{r}{v})}{\sigma(r)}\right)^2}}{\sigma(r)\sqrt{2\pi}} dy \frac{2rdr}{R^2} = \int_{y=(i-3)T_s}^{(i+3)T_s} (I_{11} - I_{12})dy,$$

where the second equality is obtained by constant σ assumption. I_{11} and I_{12} are respectively:

$$I_{11} = \frac{\sigma\sqrt{2}\left(e^{-c^2} - e^{-d^2}\right)}{(T_p^{max})^2\sqrt{\pi}};\ I_{12} = \frac{(y - iT_s)\left\{\text{erf}(d) - \text{erf}(c)\right\}}{(T_p^{max})^2},$$

with $c = \frac{y-iT_s}{\sigma\sqrt{2}}$ and $d = \frac{y-iT_s-\frac{R}{v}}{\sigma\sqrt{2}}$.

After substituting and simplifying, $P_s^{(mTS)}$ in (6) can be written as:

$$P_s^{(mTS)} = \int_{y=(i-3)T_s}^{(i+3)T_s} e^{-\lambda T_s(P_1+P_2+P_3+P_4+P_5+P_6+P_7)} \cdot (I_{11} - I_{12})\, dy,$$

and hence the normalized system throughput is:

$$\eta_{\text{mTSS-Aloha-uw}} = \lambda T_t P_s^{(mTS)}. \tag{7}$$

6. Delay Performance

Consider that any transmitter will know the outcome of its transmission after a delay which is the round-trip propagation delay between the transmitter and the receiver. Since this propagation delay in underwater applications is large, we assume that the processing and decision making time is rather negligible, so as soon as the transmitter knows the outcome it will transmit or retransmit a frame immediately. With a uniform random distribution of nodes, the probability density function of transmitter-receiver distance is:

$$f_{\mathbf{r_i}}(r) = \frac{2r}{R^2}, 0 \leq \mathbf{r_i} \leq R$$

where R is the communication range of the nodes (assumed same for all nodes).

From (6), the average round trip propagation delay is computed as $\frac{4R}{3v}$, where v is the average propagation speed of underwater acoustic signal. So, the average delay per transmission can be written as:

$$D_1 = \frac{T_s}{2} + \frac{4R}{3v},$$

where $\frac{T_s}{2}$ is the average time a transmitter waits after a new frame is generated. Note, for example, $T_s = T_t + 2k\sigma(r)$ for mRSS-Aloha-uw, and $T_s = T_t + \delta T_p^{max}$ for mTSS-Aloha-uw, as defined in Sections 4 and 5, respectively.

Denote the probability of success of a transmission as p. $p = P_s^{(mRS)}$ for mRSS-Aloha-uw, where $P_s^{(mRS)}$ is given by (4), and $p = P_s^{(mTS)}$ for mTSS-Aloha-uw, where $P_s^{(mTS)}$ is given by (6). With no limit on the number of retries, the average number of transmissions per successful frame is, $N = \frac{1}{p}$.

So, the average delay per successful frame is given by,

$$D = D_1 N = \left(\frac{T_s}{2} + \frac{4R}{3v}\right)\frac{1}{p}. \tag{8}$$

7. Results and Discussion

For simulation based performance evaluation we considered a single cell scenario with one receiver and multiple transmitters at varying distances within the communication range of the receiver. Based on the estimate of propagation delay to the receiver, a frame transmission instant is deferred such that it arrives in a slot. But due to propagation delay uncertainty, the actual time of arrival of a frame at the receiver varies around the estimated arrival instant, which we have approximated as Gaussian distributed. To highlight the relative performance of different protocol variants at the MAC layer, the frame failure events were simulated only due to MAC level contentions, including that due to propagation delay uncertainty. Also, since the current analytical study does not involve other protocol layers, we chose to use our developed C based discrete event simulation model for creating a random network and verifying the analytical results. The analytical results were obtained in SCILAB using the expressions developed in Sections 4, 5, and 6.

In simulations, 200 randomly located nodes were taken around the receiving node. In each iteration, a randomly located transmitter was chosen, and the other neighboring transmitters' activities were controlled by varying the (Poisson distributed) frame arrival rate λ. Different values of delay variance σ^2 were taken to study its impact on a protocol performance.

Following the underwater modem specifications [30], the parameters considered are: channel rate 16 kbps, acoustic signal speed $v = 1500$ m/s, frame size $F = 40$ Bytes, and (unless otherwise stated) transmission range $R = 20$ m. We particularly chose to use very short frame size (as in RTS (36 Bytes or 44 Bytes) and CTS (38 Bytes)), as we anticipate that the proposed modified S-Aloha protocol could be useful for short (RTS/CTS or alike) control messaging purposes.

7.1. Performance of RSS-Aloha-uw

In Fig. 3, analytic and simulation based results on system throughput performance of RSS-Aloha with respect to frame arrival rate are shown. As observed in the analysis, with perfect

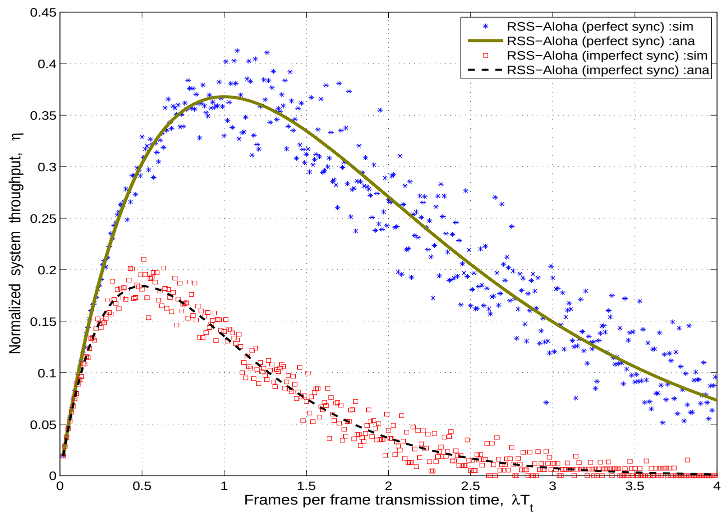

Figure 3: System throughput of RSS-Aloha with as well as without perfect synchronization. $T_s = T_t$. Propagation delay uncertainty in case of imperfect synchronization, $\sigma = 0.005T_t$. $R = 20$ m.

synchronization, i.e., without any propagation delay uncertainty, the system performs identically as in S-Aloha system without any propagation delay. Thus, as long as the propagation delay can be perfectly estimated, there is no impact of propagation delay on the S-Aloha performance. However, as shown in the second plot, when there is some uncertainty in the propagation delay estimation, the performance drops down to that of basic Aloha system. This result holds for any non-zero values of propagation delay uncertainty. Thus, the results verify that, without perfect synchronization the benefit of time slotting vanishes if the slot size T_s is the same as the frame transmission time T_t.

7.2. Graceful degradation of mRSS-Aloha-uw performance

In Fig. 4, throughput performance of our proposed mRSS-Aloha-uw is shown at different values of propagation delay uncertainty. In this study, to decide the slot size $T_s = T_t + 2k\sigma$, k was chosen 1.0. $\sigma = aT_p^{max} = nT_t$ where a is chosen such that $0 \leq n \leq 1$. The analytic

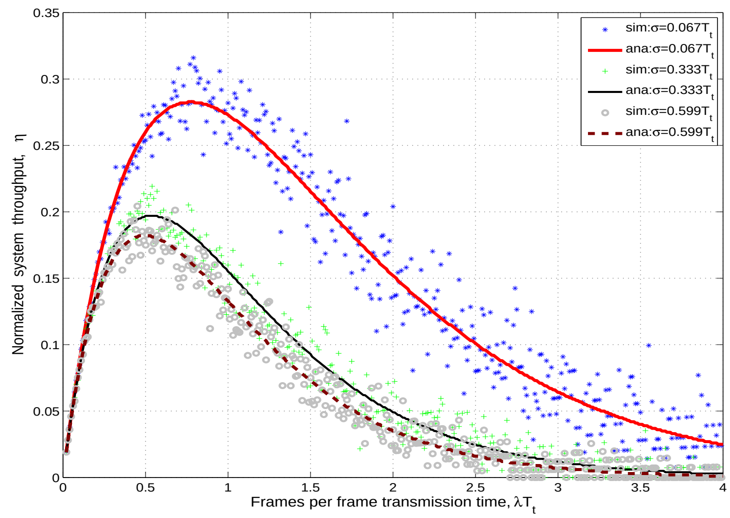

Figure 4: Performance of mRSS-Aloha-uw with $k = 1$ at different levels of propagation delay uncertainty. $R = 20$ m.

observations match well with the simulation results. The results also show that the throughput of mRSS-Aloha-uw at $a = 0.1$ (or $n = 0.067$) is more than the throughput at $a = 0.5$ (or $n = 0.333$), confirming a graceful degradation of mRSS-Aloha-uw performance as the propagation delay uncertainty increases.

Further, in Fig. 5, throughput performance of mRSS-Aloha-uw is shown with modified slot size $T_s = T_t + 2k\sigma$ and with $T_p^{max} \gg T_t$. Two different σ values ($\sigma < T_t$, and $\sigma > T_t$) were considered to verify if the analytic formulation of mRSS-Aloha-uw throughput holds good at a higher value of σ. The two numerical values are: $\sigma = 0.00075T_p^{max} = 0.005T_t$ and $\sigma = 0.45T_p^{max} = 3T_t$. The matched simulation results with both σ confirm that the simplifying assumption apparently does

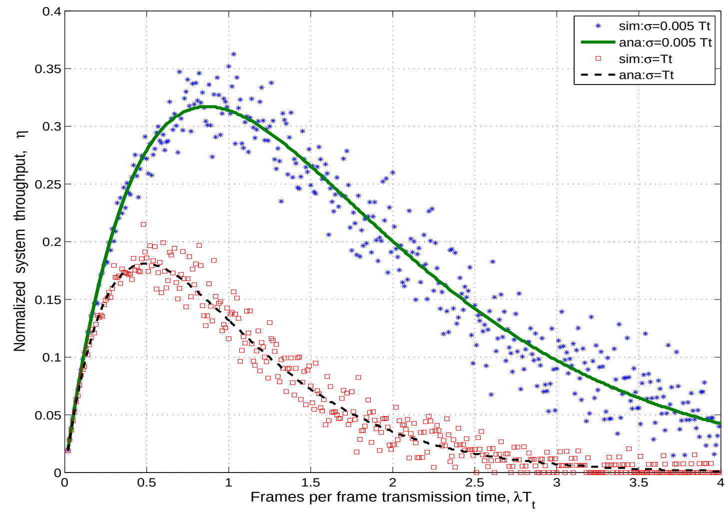

Figure 5: Performance of mRSS-Aloha-uw with $T_p^{max} > T_t$. $k = 1$, $R = 200$ m.

not have any bearing on the system performance. The plots also confirm that the throughput of mRSS-Aloha-uw is independent of the inter-nodal propagation delay.

7.3. Optimum slot size in mRSS-Aloha-uw

Fig. 6 shows the impact of slot size increment coefficient k on the maximum system throughput in mRSS-Aloha-uw at various values of σ. The results demonstrate that, with a larger σ a smaller k is required. This is because, when σ is large, a smaller k is able to increase the slot size sufficiently to accommodate the straying frames within a slot.

The results demonstrate further that, irrespective of the value of σ, at a very low value of k, i.e., when mRSS-Aloha-uw approaches to RSS-Aloha-uw, the system tends to behave as a pure Aloha system. Further, as k is increased, beyond a certain high value, the system performance actually decreases. This indicates that, some increase in slot size T_s is required to compensate the uncertainty of propagation delay, thereby reducing the inter-slot frame collisions. But, since the increase in T_s also invites additional waiting and hence more probability of overlapping arrivals in a slot (i.e., more intra-slot collision), beyond a certain large T_s, the gain from accommodating propagation delay uncertainty is superseded by the loss due to collisions. To quantify the maximum

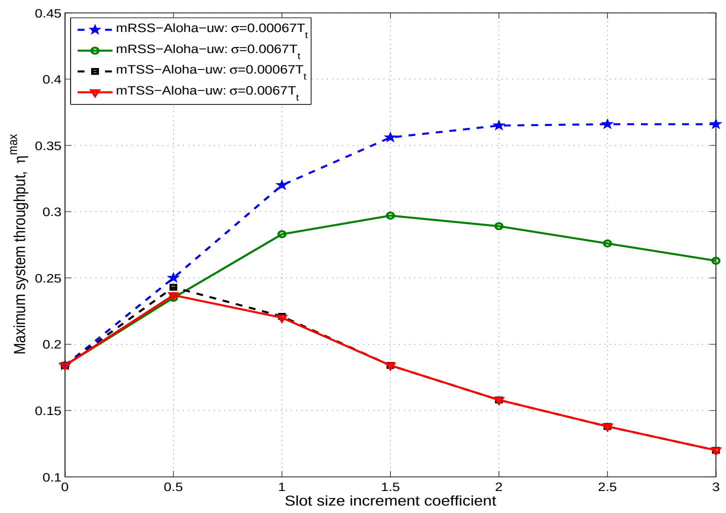

Figure 6: Relative performance of mRSS-Aloha-uw and mTSS-Aloha-uw at different slot size increment coefficient (k or δ). $R = 20$ m.

achievable gain associated with mRSS-Aloha-uw, let us define throughput gain as:

$$\text{Gain} = \frac{\eta^{\text{max}}_{\text{mRSS-Aloha-uw}} - \eta^{\text{max}}_{\text{RSS-Aloha-uw}}}{\eta^{\text{max}}_{\text{RSS-Aloha-uw}}} \times 100.$$

By inspection of the plots in Fig. 6, a higher gain is achieved in mRSS-Aloha-uw with respect to RSS-Aloha-uw at a smaller value of propagation delay uncertainty. For example, for $\sigma = 0.00067T_t$, a maximum gain of 98% is achieved at $k \approx 2$, whereas, $\sigma = 0.0067T_t$, a maximum gain of 61% is achieved at $k \approx 1.5$. The observation on throughput gain of mRSS-Aloha-uw with respect to RSS-Aloha-uw is more clearly demonstrated in Fig. 7.

7.4. Relative throughput performances of mRSS-Aloha-uw and mTSS-Aloha-uw

Relative throughput performance of mRSS-Aloha-uw with respect to mTSS-Aloha-uw at different slot size increment coefficient in Fig. 6 shows that, although at lower values of slot size increment coefficient both synchronization approaches have increasing trends of performance, mTSS-Aloha-uw has increasing lower throughput. At higher values of the coefficient, mTSS-Aloha-uw performance degrades fast, as the slot size increases in this case at a faster rate compared to that in mRSS-Aloha-uw. As a result, in mTSS-Aloha-uw intra-frame collision vulnerability overrides the

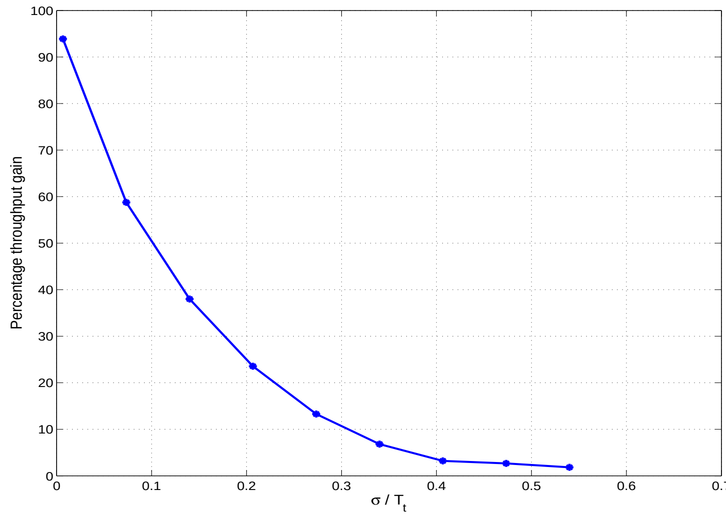

Figure 7: Maximum throughput gain in mRSS-Aloha-uw with respect RSS-Aloha-uw, as a function of standard deviation of propagation delay uncertainty (normalized with respect to T_t).

benefit of reduced inter-frame collisions.

Fig. 8 compares the maximum system throughput performances of mTSS-Aloha-uw and mRSS-Aloha-uw using (5) and (7), respectively. The plots clearly demonstrate that, when oper-

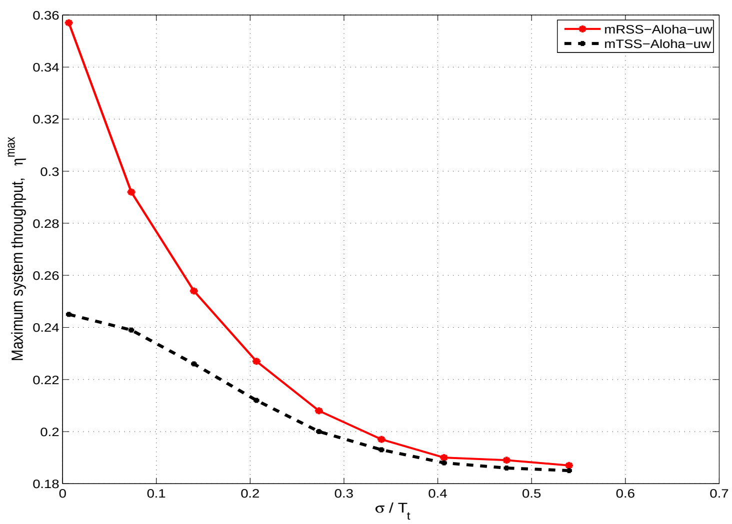

Figure 8: Maximum throughput comparison at different delay uncertainties.

ating in a propagation delay intensive communication environment, although transmitter-end synchronization with optimally increased slot size (mTSS-Aloha-uw) performs better than the case with $T_s = T_t$, receiver-end synchronization with an optimal slot size (mRSS-Aloha-uw) has a consistently higher throughput performance with respect to mTSS-Aloha-uw.

A comparative maximum throughput performance of mRSS-Aloha-uw and mTSS-Aloha-uw at a constant propagation delay uncertainty σ and different T_p^{max} (where $T_p^{max} \leq T_t$) in Fig. 9 shows that, beyond very small values of T_p^{max} mTSS-Aloha-uw performance degrades sharply below that of mRSS-Aloha-uw. The mRSS-Aloha-uw performance remains unaffected because the optimum

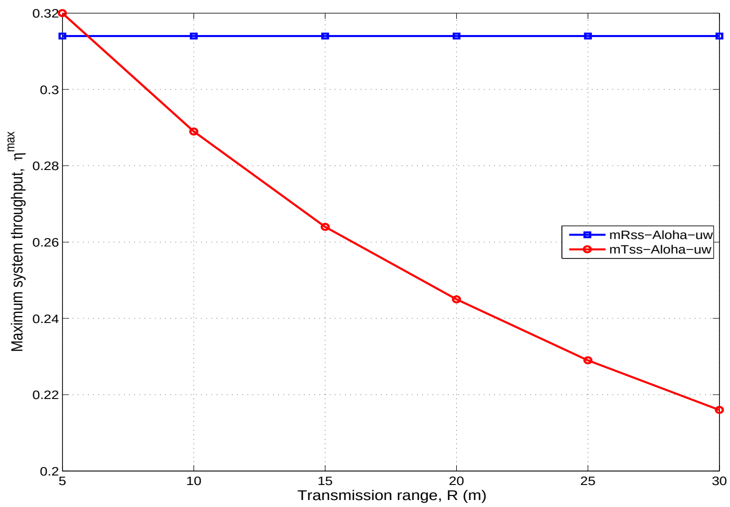

Figure 9: Maximum throughput comparison at different transmission ranges. $\sigma = 0.01T_t$.

slot size in this case is independent of T_p^{max}. This T_p^{max} independence of optimum slot size in mRSS-Aloha-uw also implies that, at very low T_p^{max} a fixed-σ dependent slot size is larger than T_p^{max}-dependent slots, and this larger slot does not help reduce inter-frame collisions compared to the increased intra-frame collisions. As a result, the throughput performance of mRSS-Aloha-uw is a little poorer than that of mTSS-Aloha-uw at very low T_p^{max}. Note that, the performance of mRSS-Aloha-uw at very low T_p^{max} can be improved if σ is an increasing function of T_p.

7.5. Delay performance

The delay performances of mRSS-Aloha-uw and mTSS-Aloha-uw per successful frame delivery, as developed in Section 6, are compared in Fig. 10. The results are based on maximum

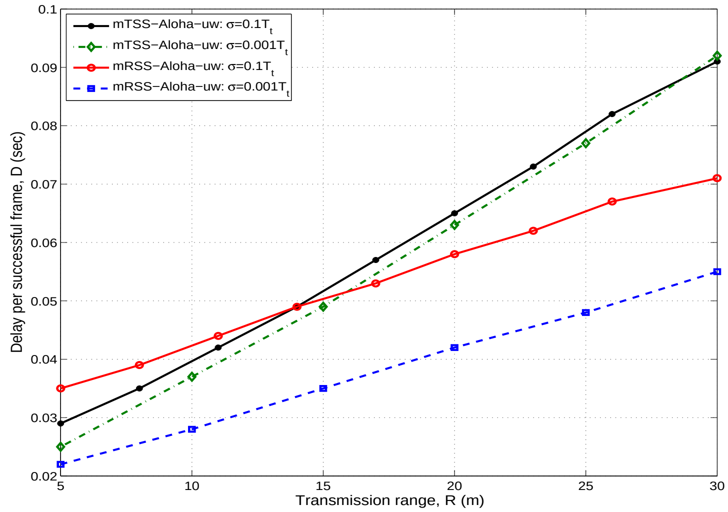

Figure 10: Delay comparison at different transmission ranges.

throughput (as expressed in (4) and (7)) for a given propagation delay uncertainty σ and with an optimum time slot increment coefficient k.

Two observations can be drawn from the plots. First, since the node deployment density is kept constant, with the increase in nodal communication range, the number of contending nodes (i.e., the overall frame arrival rate λ) increases, causing more collision vulnerability. Thus, irrespective of the propagation delay uncertainty, the delay per successful frame increases. The rate of increase of delay in mTSS-Aloha-uw is more because, the increase in T_p^{max} further contributes to the increase in slot size, whereas T_p^{max} does not have an impact in deciding the mRSS-Aloha-uw slot size. Second, while at a lower propagation delay variance σ^2 the mRSS-Aloha-uw always offers lower (better) delay performance, at a higher σ and for a shorter transmission range mTSS-Aloha-uw has an effectively lower delay performance. A similar trend was also seen in Fig. 9. This is because, although the average number of transmission attempt per success ($N = \frac{1}{p}$) in mTSS-Aloha-uw is always higher than that of mRSS-Aloha-uw (cf. Fig. 7), the slotting definitions of the two schemes dictate that the slot size in mTSS-Aloha-uw is lower (due to a small R) than that of the mRSS-Aloha-uw (due to a fixed σ).

8. Conclusion

In this paper, we have presented a theoretical framework for throughput performance computation of receiver synchronized S-Aloha in underwater wireless networks (RSS-Aloha-uw) with a random inter-nodal signal propagation delay and delay uncertainty. We have shown that, when using conventional slotting concept, if the propagation delay cannot be estimated perfectly, the performance of RSS-Aloha-uw degrades to that of basic Aloha. We have proposed and analyzed a modified RSS-Aloha-uw (mRSS-Aloha-uw) and have shown that, by optimally increasing the slot size, a graceful degradation of system performance can be achieved as the propagation delay uncertainty increases. Via analysis and simulations, we have further compared the proposed mRSS-Aloha-uw with a transmitter-end synchronized modified S-Aloha under a similar network environment setting, and verified that mRSS-Aloha-uw offers a consistently higher throughput performance. The delay performance studies have shown that, while at a lower propagation delay uncertainty mRSS-Aloha-uw always offers a lower (better) delay, when the uncertainty is high, the delay performance of mRSS-Aloha-uw can be poorer in a system with smaller nodal communication range.

Although the S-Aloha protocols may not be used for data communication phase because of low throughput, the reservation based random access protocols are normally preceded by S-Aloha based control message exchange phase. To improve the user experience as well as for resource efficiency, it is also important to maximize the control phase performance. Our proposed modified S-Aloha protocol is expected to be useful in such applications in uncertain propagation delay intensive environments.

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References

[1] R. J. Urick, Principles of Underwater Sound, McGraw-Hill, 1983.

[2] I. F. Akyildiz, D. Pompili, T. Melodia, Underwater acoustic sensor networks: Research challenges, Elsevier Ad Hoc Networks 3 (2005) 257–279.

[3] J. Partan, J. Kurose, B. Levine, A survey of practical issues in underwater networks, in: Proc. ACM Intl. Wksp. Under-Water Networks (WUWNET), Los Angeles, CA, USA, 2006, pp. 17–24.

[4] N. Parrish, L. Tracy, S. Roy, P. Arabshahi, W. L. J. Fox, System design considerations for undersea networks: Link and multiple access protocols, IEEE J. Selected Areas in Commun. 26 (9) (2008) 1720–1730.

[5] M. Stojanovic, Design and capacity analysis of cellular-type underwater acoustic networks, IEEE J. of Oceanic Engineering 33 (2) (2008) 171–181.

[6] L. T. Tracy, S. Roy, A reservation mac protocol for ad-hoc underwater acoustic sensor networks, in: Proc. ACM intl. wksp. wireless network testbeds, experimental evaluation and characterization (WuWNeT'08), San Francisco, CA, USA, 2008, pp. 95–98.

[7] P. Xie, J.-H. Cui, Exploring random access and handshaking techniques in large-scale underwater wireless acoustic sensor networks, in: Proc. MTS/IEEE Oceans Conf., Boston, MA, USA, 2006.

[8] N. Chirdchoo, W.-S. Soh, K. C. Chua, Aloha-based MAC protocols with collision avoidance for underwater acoustic networks, in: Proc. IEEE INFOCOM Minisymposium, Anchorage, AK, USA,, 2007.

[9] X. Guo, M. R. Frater, M. J. Ryan, An adaptive propagation-delay-tolerant MAC protocol for underwater acoustic sensor networks, in: Proc. IEEE OCEANS 2007 – Europe, Aberdeen, Scotland, 2007, pp. 1–5.

[10] A. Syed, W. Ye, J. Heidemann, Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks, IEEE J. Selected Areas in Commun. 26 (2008) 1731–1743.

[11] A. Syed, W. Ye, B. Krishnamachari, J. Heidemann, Understanding spatio-temporal uncertainty in medium access with ALOHA protocols, in: Proc. ACM Intl. wksp. Under-Water Networks (WUWNET), Montreal, Quebec, Canada, 2007, pp. 41–48.

[12] J. Ahn, B. Krishnamachari, Performance of propagation delay tolerant Aloha protocol for underwater wireless networks, in: Proc. Intl. Conf. Distributed Computing in Sensor Systems (DCOSS), Santorini Island, Greece, 2008.

[13] P. Mandal, S. De, S. S. Chakraborty, Characterization of Aloha in underwater wireless networks, in: Proc. Nat. Conf. Commun., Chennai, India, 2010.

[14] N. Chirdchoo, W.-S. Soh, K. C. Chua, RIPT: A receiver-initiated reservation-based protocol for underwater acoustic networks, IEEE J. Selected Areas in Commun. 26 (9) (2008) 1744–1753.

[15] S. Shahabudeen, M. N. Chitre, Design of networking protocols for shallow water peer-to-peer acoustic networks, in: Proc. MTS/IEEE Oceans Europe, Brest, France, 2005.

[16] M. Molins, M.Stojanovic, Slotted FAMA: A MAC protocol for underwater acoustic networks, in: Proc. MTS/IEEE Oceans Conference, Singapore, 2006.

[17] B. Peleato, M. Stojanovic, Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks, IEEE Communication Letters 11 (12).

[18] N. Chirdchoo, W.-S. Soh, K. C. Chua, MACA-MN: A MACA based MAC protocol for underwater acoustic networks with packet train for multiple neighbors, in: Proc. IEEE VTC2008-Spring, Singapore, 2008.

[19] S. S. Lam, L. Kleinrock, Packet switching in a multiaccess broadcast channel: Dynamic control procedures, IEEE Transaction of Communications 23 (9) (1975) 891–904.

[20] M. Stojanovic, Underwater Acoustic Communication. Encyclopedia of Telecommunications, John Wiley and Sons, 2003.

[21] D. Pompili, T. Melodia, I. F. Akyildiz, Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks, in: Proc. ACM intl. Conf. on MobiCom, Los Angeles, CA, USA, 2006.

[22] L. Hong, F. Hong, Z. Guo, X. Yang, A TDMA-based MAC protocol in underwater sensor networks, in: Proc. IEEE Intl. Conf. on WiCOM, Dalian, China, 2008.

[23] A. Syed, J. Heidemann, Time synchronization for high latency acoustic networks, in: Proc. IEEE INFOCOM, Barcelona, Spain, 2006.

[24] N. Chirdchoo, W.-S. Soh, K. C. Chua, MU-Sync: A time synchronization protocol for underwater mobile networks, in: Proc. ACM WuWNet, San Francisco, CA, USA, 2008.

[25] S. Maitra, K. Newman, Time synchronization protocol with minimum message communication for high latency networks, Springer Wireless Personal Communications.

[26] L. Liu, Y. Xiao, J. Zhang, A linear time synchronization algorithm for underwater wireless sensor networks, in: Proc. IEEE ICC, Dresden, Germany, 2009.

[27] H. Tan, W. K. G. Seah, Distributed CDMA-based MAC protocol for underwater sensor networks, in: Proc. IEEE conf. Local Computer Networks, Clontarf Castle, Dublin, Ireland, UK, 2007, pp. 26–36.

[28] D. Pompili, T. Melodia, I. F. Akyildiz, A CDMA-based MAC protocol for underwater acoustic sensor networks, IEEE Trans. Wireless Commun. 8 (4) (2009) 1899–1909.

[29] A. Papoulis, Probability, Random Variables, and Stochastic Processes, McGraw-Hill International Editions, 3rd ed., 1991.

[30] LinkQuest Underwater Acoustic Modems Data Sheet (2009).
URL http://www.link-quest.com/html/uwm_hr.pdf