

# An Analytical Analysis of Propagation Delay in Underwater Wireless Sensor Networks

Ramesh K<sup>#1</sup>, Kannan V<sup>#2</sup>

<sup>#Research Scholar</sup><sup>1</sup>, St.Peter's University, Dept. of ECE, Chennai, India

<sup>#Principal</sup><sup>2</sup>, Jeppiaar Institute of Technology, Chennai, India

**Abstract** - Underwater Wireless Sensor Networks (UWSN) is adapted to the intrinsic properties of underwater environments, such as long propagation delays, limited time width, and refractive properties of the medium, rapid time variation, low data rates and difficulty of synchronization. Although several time synchronization protocols have been developed, most of them tend to break down when implemented on mobile underwater sensor networks. However, optimality of the number of access slots with respect to the system performance parameters, such as system utilization, blocking probability, and delay, were not thoroughly studied. Besides, the effect of propagation delay uncertainty, which predominantly happens in underwater communications are yet to be addressed. Long propagation delays and low bit rates of underwater sensor networks make these systems fundamentally different from the packet radio networks. As a consequence, many of the network protocols designed for radio channels are either not applicable, or have extremely low efficiency over underwater acoustic channels. These facts necessitate a dedicated design of protocols for an underwater sensor networks. In this paper, we propose an analytical analysis of propagation delay tolerant ALOHA protocol proposed recently for underwater sensor networks. In this scheme, guard-times are introduced at each slot to reduce collisions between senders with different distances to the receiver. We prove some interesting properties concerning the performance of this protocol and show how it varies with key application and protocol parameters such as propagation delay, traffic load, and the guard-time. As well as simulations to show the performance of ALOHA protocol in the underwater environment. Our results show that long propagation delay of acoustic signals prohibits the coordination among nodes.

**Keywords** - Propagation delay, Guard – times, Collisions, ALOHA protocol.

## I. INTRODUCTION

Underwater Sensor Networks are networks composed of nodes with sensor, communication and processing abilities that operates underwater. This environment brings new challenges, such as radio-frequency (RF) electromagnetic waves, except those of very low frequencies (30 - 300 Hz), decay very rapidly in water, underwater networks need to adopt acoustic transmissions instead in most cases. However, the acoustic transmission introduces many kinds of problems so that a lot of high technologies developed for the RF transmission are stumbled in this environment. Ocean covers about two thirds of the earth surface. Those areas are uninhabited and largely unexplored. Through the advance of technology and use of sensor networks it is now possible to construct networks with many applications. In underwater sensor networks, the predominant physical layer technology is acoustic signals. In fact, radio waves propagate at long distances through conductive sea water only at extra low frequencies (30 to 300 Hz). Optical waves do not suffer from

such high attenuation but are affected by scattering. Thus, links in underwater networks are based on acoustic wireless communications [1].

The acoustic channel has large signal propagation delay. Usual network communication is based on electromagnetic waves travelling at the speed of about  $3 \times 10^8$  m/s. The speed of sound is roughly  $1.5 \times 10^8$  m/s. The difference in speed propagation can have a great impact on how a protocol works. We also have to look at narrow time width with high attenuation. Current time width and length product is about 40kbps x km [2]. Due to this low time width the frequency division multiple access (FDMA) scheme is not suitable. The acoustic transmission also has the large propagation delay which makes contention-based protocols relying on carrier sensing and handshaking an appropriate. It also hampers the use of time division multiple access (TDMA) scheme because TDMA then requires the long time guards. Therefore, the design and analysis of new approaches are required for different layers, including medium access.

In this paper, we discussing about ALOHA protocol, the guard-time in each slot are designed in order to relieve collisions between packets of different senders transmitted in consecutive time slots. Increasing the guard-time reduces collisions, but it also increases the length of each time slot, potentially reducing the throughput. Thus the selection of the appropriate guard-time length to get the maximum throughput can be formulated as an optimization problem. We analyze mathematically the throughput of the ALOHA protocol given a guard time, a traffic load, and the maximum propagation delay. Then, we investigate its maximum throughput over the guard times and the traffic loads given the maximum propagation delay. Although it turns out to be difficult to derive an exact expression for the maximum throughput, we propose simple approximate expressions which are very close to the maximum throughput calculated through numerical methods. We also prove a number of interesting and useful properties concerning the performance of the ALOHA protocol. The rest of the paper is organized as follows, section 2 discussing literature reviews. Section 3 define the ALOHA protocol. Section 4 follows an analytical analysis of propagation delay. Performance analysis of UWSNs discussed in section 5. Finally, section 6 concludes this paper.

## II. LITERATURE SURVEY

Underwater Wireless Sensor Network (UWSN) is a novel networking paradigm to explore aqueous environments. The characteristics of UWSNs, such as low communication time width, large propagation delay, floating node mobility, and

high error probability, are significantly different from ground based wireless sensor networks [4] and that directly affect how the protocols works. As shown that ALOHA in underwater is affected by propagation delay, the slotted ALOHA, that uses discrete time slots, exhibits the same utilization as non- Slotted ALOHA. Identified and validated the analytical model of ALOHA in multi-hop UASNs. The expected network throughput and average end-to-end delay in string topology underwater networks. The above analytical models are based on pure ALOHA protocol which the node's transmission has higher priority than the node's reception. It is very inefficient, since a node will simply transmit a packet whenever it has anything to send, regardless of whether it is currently receiving a packet [5].

There are many literatures which have studied on the throughput of ALOHA protocols in the underwater networks [9]. Investigated the impact of the large propagation delay on the throughput of selected classical MAC protocols and their variants through simulations [18]. Compared the performance of ALOHA and CSMA with RTS/CTS protocols in underwater wireless networks. And [16] has studied on the throughput of PDT-ALOHA through simulations producing rough idea of the performance. While these works are mainly based on simulations we approach the problem from the theoretical view point. Analyzed the performance of ALOHA in a linear multi-hop topology [8]. However, these works do not consider the guard time to relieve the negative effect of the large propagation delay have taken consideration of the guard time for the slotted ALOHA protocols in their analysis. The main difference from their problem is that nodes are located on the ground approximately same distance away from the satellite in their problem so that the propagation delay is more or less same for each node. But, the distance to the receiver can vary greatly from node to node in underwater wireless sensor networks.

### III. ALOHA

ALOHA is a class of MAC protocols that do not try to prevent packet collision. The protocol works as follow. Every computer that has data to send, sends the data. If two systems transmit packets at the same time, a collision occurs. In that case, a retransmission occurs. ALOHA can be improved by having discrete timeslots. A computer can no long send packets at anytime, but just at the beginning of a timeslot, and thus chances of collisions are reduced. This version is referenced as Slotted ALOHA. In this paper, we focus on the impact of long propagation delay of acoustic signals on those protocols. ALOHA in ground communication, one can see that a packet sent at time  $t$  will collide with other packets sent in time  $[t-1, t+1]$ . This can be visualized in Figure 1. The figure shows three stations that have sent packets. The first packet after time  $t - 1$ , the second at time  $t$  and the third before time  $t + 1$ . Since all the packet overlap with part of another, no transmission was successful. In underwater acoustic communication we can look at ALOHA using a similar approach. The transmission of a packet is successful if the

packet does not collide with another packet at the destination. To emphasize the difference that propagation delay can cause, we will look at an intuitive example. It is based on the same transmission explained in Fig 1. After time  $t - 1$ , the first node sends a message. At time  $t$ , the second node sends a message. Also, the first message keeps propagating. Both signals will eventually meet, forming constructive and destructive waves. After that, the signals will keep going in that direction. At time  $t + 1$ , the signal sent by node 2 will continue to propagate and the signal from message sent by node 1 will reach node 2. Since the message reaches node 2 without collision, the message is considered to be successful. Note that if it were radio signals, this would result in a collision.

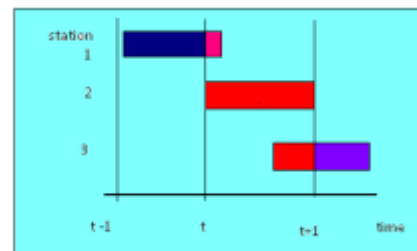


Fig. 1 Collision ALOHA

#### A. SLOTTED ALOHA

Slotted ALOHA is a modified version of ALOHA which introduced discrete time slots. Time is divided into equal length slots. A message is sent only on the beginning of a time slot. Instead of giving a formal proof, here we present an intuitive explanation of the performance of Slotted ALOHA in UW context. Assuming that there is a way to synchronize the nodes so that they could implement Slotted ALOHA. Again, we have to consider the propagation delay. Instead of looking at the time the packet was sent, we have to look at the time the packet is received at each node. Although the nodes sent the messages in pre-defined time slots, there is no guarantee that they will arrive in time slots. Therefore, Slotted ALOHA in underwater has no effect different from ALOHA except the cases where the propagation delay is a multiple of the time slot interval. In other words, the distance between nodes, when divided by the sound speed, results in an integer of time slots. The probability that all nodes are randomly place in this scenario is zero.

#### IV. ANALYTICAL ANALYSIS OF PROPAGATION DELAY

In this section we analyze the throughput of the ALOHA protocol. Space-time uncertainty can be handled by the addition of extra guard time beyond the transmission time in time slots. These guard times are added to ensure a single slot overlap at the receiver, thus tolerating the large propagation delays. Let us first look at the time slot. Each time slot consists of a transmission time and a guard time following the former. Since the guard time of the size of maximum

propagation time  $\tau_m$  would eliminate all the collision between different time slots, it does not make sense to have the guard time whose size is more than  $\tau_m$  only decreasing the throughput without any gain. In our modification to slotted ALOHA, nodes still transmit only at the start of globally synchronized slots.

Global time synchronization can be achieved using underwater time sync protocols such as [10, 11]. Hence, we use the normalized factor  $\beta$  s.t.  $0 \leq \beta \leq 1$  in expressing the size of guard time. The slot duration, however, is increased from  $T$  to  $\beta \cdot \tau_m$ , where  $\beta$  represents the fraction of maximum propagation delay ( $\tau_{max}$ ) that nodes wait after finishing their transmission as shown in the Fig 2. Hence,  $\beta \tau_{max}$  is the guard time, and  $\beta$  can be considered as the normalized guard time. Choosing  $\beta = 1$  ensures that no overlap at the receiver occurs unless packets are transmitted in the same slot, the guarantee that slotted ALOHA was originally designed to achieve when delay is not important. However this value of  $\beta$  results in a long wait time after each packet that will increase packet transmission latency and bandwidth overhead. With  $\beta < 1$  there remains the possibility that some node pairs still have the vulnerability interval of two slot durations. Therefore, reducing  $\beta$  value lowers the bandwidth overhead, but increases collision probability. Based on the intuition that the distance between node pairs is often smaller than the maximum propagation delay, we vary  $\beta$  to evaluate the tradeoff between bandwidth overhead and collision probability.

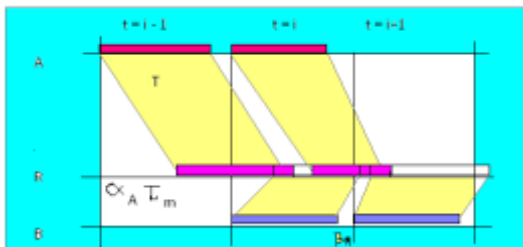


Fig. 2 Time diagram of packet transmission

The propagation speed of communication is a positive finite constant regardless of the location in the network, so that the maximum propagation time is the propagation time  $\tau_m$  from the receiver to the farthest transmitter. The transmission rate is constant for every transmitter. The packet size is constant so that the transmission time for a packet is constant. Only a proper scaling is needed for some parameters, particularly  $\tau_m$ , in order to cope with the general transmission time. Hence, the normalized maximum propagation delay  $a$  to the transmission time is  $a = \frac{\tau_m}{\text{transmission time}} = \tau_m$ .

A. SLOTTED ALOHA

In order to analyze the throughput we first derive the expected number of successful packet receptions in a time slot. We use the linearity of expectations and conditional probabilities to calculate the expected number. Let the indicator variable  $I_i$  denote whether or not the receiver receives the packet from  $i$ -th transmitter successfully in the time slot.

$$I_i = \begin{cases} r, & \text{if successful reception} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Where  $r$  denotes receiving packets

$$N = \sum_i I_i \quad (2)$$

$$E|N| = \sum_i^n E|I_i| = \sum_{i=1}^n Pr \{I_i = 1\} \quad (3)$$

$$E|N| = n \cdot p \Pr\{NC |n_i\} \quad (4)$$

Where  $N$  denotes random variable of the successful reception.  $NC |n_i$  denotes the event that no collision occurs given that  $i$ -th sender transmits.

B. No Collision Probability

The collision depends not only on the temporal uncertainty, but also on the spatial uncertainty. If more than one node transmit packets in the same time slot, the packets collide with each other regardless of the locations of their transmitters (when  $a < 1$ ). But, collisions can occur even if two packets are transmitted in different time slots, depending on their sender's locations. We call the former collision intra-timeslot collision, and the latter inter-timeslot collision. It turns out that the system can have at most three collision regions for each and every transmitter; one for the intra-timeslot collision and two for the inter-timeslot. In order to identify the regions, let us suppose an arbitrary transmitter  $n_i$  which has the normalized time distance of  $\alpha$  (Definition 1).

Then, the first collision region is the region such that a packet sent from  $n_i$  would collide with a packet if it is sent in the previous consecutive time slot by a node in the region. Similarly, the packet from  $n_i$  would collide with a packet sent in the same time slot by another node in the second region, and the third region is for the collision with a packet in the next consecutive time slot. We denote the three collision region by  $R_p(\alpha), R_c(\alpha), R_n(\alpha)$ , respectively, noting that each region depends on the distance of the interested transmitter from the receiver. Moreover, they also depend on the normalized guard time ( $\beta$ ).

Consider a simple network with two senders  $A$  and  $B$ , and one receiver  $R$ .  $A$  locates right next to  $R$  while  $B$  is very far from  $R$ , and the size of guard time is small enough. Then, if  $B$  transmits in the  $i$ -th time slot,  $R$  would receive last part of the packet in the beginning of the  $(i + 1)$ -th slot, which would produce collision with the packet transmitted in the  $(i + 1)$ -th slot by  $A$  although the two packets are sent in different time slots. The time diagram in Fig. 3 visually shows this situation, where  $\alpha_i$  is the normalized propagation time distance of  $i \in \{A, B\}$  from  $R$  defined by Definition 1, the normalized guard time size  $\beta$  is less than 1, and  $\alpha_A > \alpha_B + \beta$ . However, if  $\alpha_A = \alpha_B$  there is no collision between packets in different time slots. Therefore, we can see that the collision depends on nodes' locations and two packets transmitted in different time slots can experience collision between each other.

**Definition 1:** The propagation delay of sender  $X$  from the receiver is the propagation time from the receiver to  $X$  divided by the maximum propagation time  $\tau_m$  in the network. i.e.  $\tau_m/d$ , where  $d$  is the distance between sender and receiver.

The probability of no collision given a packet sent by an arbitrary  $i$ -th sender  $n_i$  is then as follows conditioning on the  $n_i$ 's normalized time distance  $\alpha$ , Note that, after calculation, the regions can be expressed in terms of normalized time distance and guard time. The region  $Rp(\alpha)$  is where the normalized time distance from the receiver is at least  $\alpha + \beta$ , but no more than 1. That is,  $Rp(\alpha) = \{p | \alpha + \beta \leq \partial(P) \leq 1\}$ , where  $\partial(P)$  denotes the normalized time distance of the point  $P$  from the receiver. Similarly, we have  $Rc(\alpha) = \{p | 0 \leq \partial(p) \leq 1\}$ , and  $Rn(\alpha) = \{p | 0 \leq \partial(P) \leq \alpha - \beta\}$ . Figure 3 visually presents the regions.

$$\begin{aligned} Pr\{NC/n_i\} &= \int_0^1 Pr\{NC/n_i \text{ transmits}, \partial(P_i)\} \\ &= \alpha \cdot f_{\partial(P_i/n_i)}(\alpha) d\alpha \end{aligned} \quad (5)$$

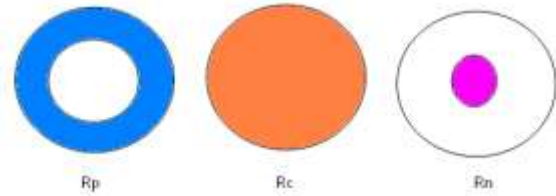
$$= \int_0^1 2 \alpha Pr\{NC/\alpha\} d\alpha \quad (6)$$

where  $P_i$  is the location of  $n_i$ ,  $f_{\partial(P_i/n_i)}(\alpha)$  is the probability density function of the normalized time distance of  $n_i$  from the receiver given that  $n_i$  transmits, and  $NC/\alpha$  is the abbreviated representation of the event that no collision occurs given  $n_i$  transmits and its normalized distance from the receiver is  $\alpha$ . The last equation holds because the location of a node is independent of the packet transmission the probability of no collision of a specific packet does depend on the location of its sender. The three collision regions as shown in the Fig. 3 areas affect the probability. we can get the equation.

Fig. 3 Network Collisions

$$Pr\{NC|\alpha\} = \sum_{(x,z):x+z \leq n-1} Pr\left\{ \left\{ \begin{array}{l} NC|\alpha, N_n = x, N_p = z, \\ N_c = n - 1 \end{array} \right\} \right\} \quad (7)$$

Where  $N_n$ ,  $N_c$ , and  $N_p$  denote the number of other transmitters in the collision regions  $Rn(\alpha)$ ,  $Rc(\alpha)$ ,  $Rp(\alpha)$  respectively. Note that (i)  $N_c = n - 1$  because the intra timeslot collision region  $Rc(\alpha)$  is the



whole area in our assumption; and (ii) there are  $(n - 1)$  other transmitters in total because we focus on one specific transmitter's success. The conditional probability of no collision turns out to involve the binomial series as follows

$$\begin{aligned} Pr\{NC|\alpha\} &= \sum_{z=0}^{n-1} Pr\{NC|\alpha\}, N_p = z, \\ &N_c = n - 1, \\ &N_n = 0\} \cdot Pr\{N_p = z|\alpha\} \quad (8) \\ &= \sum_{z=0}^{n-1} \binom{n-1}{z} (1-p)^z (1-p)^{n-1-z} \\ &\cdot (1-(\alpha + \beta)^2)^z ((\alpha\beta)^2)^{n-1-z} \quad (9) \end{aligned}$$

$$Pr\{NC|\alpha\} = (1-p)^{n-1} (1-p + p(\alpha + \beta)^2)^{n-1} \quad (10)$$

Substituting equation (10) in to equation (6) we can obtain the expression for the probability of no collision which can be evaluated easily with the numerical method. Thus the expression for probability of no collision does not involve the maximum propagation delay  $\tau_m$  implying the probability is independent of  $\tau_m$  so that the success rate is also independent of  $\tau_m$ . Suppose a network of nodes with fixed spatial locations of nodes, a fixed transmission probability  $p_i$  in a time slot for each node  $i$ , and a transmission time  $T$  for a packet. Then, the success rate  $f$  is independent of the maximum propagation time  $\tau_m$  in the network as long as  $0 < \tau_m \leq T$ . In other words, it is independent of the propagation speed  $v_p$ . The number of nodes in each of  $Rn, Rc$ , and  $Rp$  is constant regardless of the speed of propagation, and so the probability of no collision of the  $i$ -th transmitter is constant. Therefore,

$$f = \sum_i p_i Pr\{NC/n_i\} = \text{cons. w.r. t. } \tau_m \quad (11)$$

V. PERFORMANCE ANALYSIS OF UWSNS

The network has one receiver and 200 nodes of transmitters which are deployed in the 2-D disk area with the measurements of  $5 \times 5 \text{m}^2$ . The receiver locates at the center of the disk area, and the transmitters are deployed uniformly at random in the area, maximum transmission range is 30m long. And transmitter power is -20dbm. The propagation speed of communication is positive finite constant regardless of the location in the network, so that the maximum propagation time from the receiver to the farthest transmitter is a positive finite constant  $\tau_m$ . The transmission rate is constant for every transmitter i.e. 250Kbps. The packet size is constant so that, along with the constant transmission rate, the transmission time for a packet is constant  $T$ . The traffic in the network is I.I.D. Bernoulli so that a transmitter sends a packet to the receiver with probability  $p$  in each time slot. The transmission time  $T$  is no less than the maximum propagation time  $\tau_m$ . In this paper we consider the throughput  $S$  in packets per packet length. Because the expected number of successful packet receptions  $f(n, \beta, p)$  in a time slot is independent of the propagation time as long as it is positive finite,  $S$  can be expressed as follows after introducing a new variable  $t = \tau_m/T$  the ratio of the maximum propagation delay to the transmission time of a packet. Node transmission data rate taken as 19.2kbps

$$S(n, \beta, p, t) = \frac{f(n, \beta, p)}{1 + \beta t} = \frac{npPr\{NC|n_i\}}{1 + \beta t} \quad (12)$$

Using the numerical evaluation of Equation (12), Fig. 4 shows the characteristics of the throughput depending on the size of guard band  $\beta$  in Figure 4(a) the relative maximum propagation delay  $t$  is fixed, but the number of nodes  $n$  is varying from 20 to 100 with the interval of 20. In Fig. 4(b)  $n$  is fixed but  $t$  is varying from 0.2 to 1sec with the interval of 0.2sec. These plots show how the throughput responds to the variables, the optimizer  $\beta$  values are similar for one case, but different in the other case.

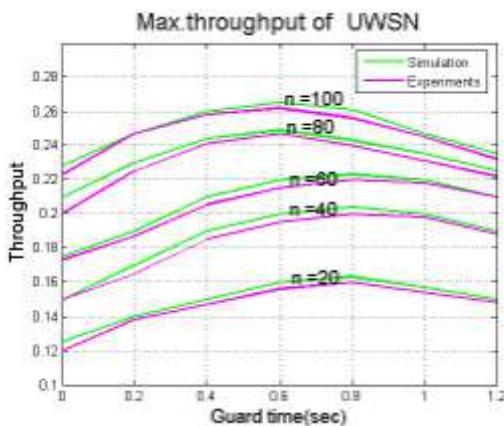


Fig. 4(a) Max. Throughput of packets

As we see results from both simulation and analysis complement each other. Both results show that throughput capacity of a network can be increased by using propagation delay -ALOHA and that the benefit of the guard time is highly correlated to its size and the delay regime in which the network is operating. We also observe two trends as  $\beta$  increases.

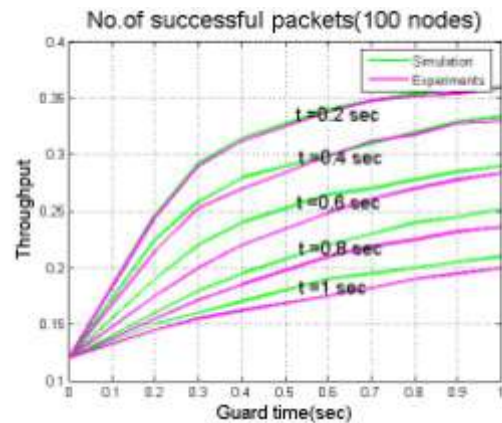


Fig. 4(b) Number of Successful packets

First, with very small  $a$  (e.g. 0.02 in simulation results) we see the throughput increases (approaching the optimum) as larger guard time is used due to a decreased inter-timeslot collision probability. Conversely, with large  $a$  (e.g. equal to 1 when the propagation delay equals transmission time) the throughput becomes insensitive to the use of guard time. Furthermore, simulation results (not shown here for clarity) show that for any value of  $a$  beyond 1, the benefit of choosing additional guard time diminishes. Thus, choosing a packet length that normalizes the propagation delay to an appropriate value is essentially to yield the benefits of propagation delay - ALOHA.

For vary  $a$  to observe how the throughput capacity is affected by propagation delay in propagation delay-ALOHA. Fig. 5(a) shows throughput capacity as a function of the normalized maximum propagation delay  $a$  when the guard time  $\beta$  is given and fixed. They are obtained for  $n = 50$  maximizing in equation (7) over  $p$  with given  $\beta$  and  $a$ . For comparison, we have the same plot generated from simulation results in Fig. 5(b). We plot the response using different values of  $\beta$ . It can be seen that a fixed value of  $\beta$  might lead to a suboptimal throughput. When  $\beta = 0.5$ , propagation delay - ALOHA is closest to the  $\beta$ -optimal curve when  $a$  is near 1 but the gap increases as  $a$  goes to 0. Conversely, for  $\beta = 1$  propagation delay - ALOHA is closest to the  $\beta$ -optimal curve for smaller values of  $a$  but becomes inefficient as  $a$  approaches 1. Although the throughput decreases monotonically with

increasing values of  $a$ , we observe very little sensitivity to  $a$  with smaller  $\beta$  values. This insensitivity is due to limited collision prevention provided by shorter guard time. Also the monotonically decreasing slope increases with  $\beta$  causing throughput to become more sensitive to  $a$ . Fig. 5 shows that propagation delay -ALOHA can achieve about 17% (when  $a = 1$ ) improvement on throughput. Fig. 5 shows the normalized throughput in terms of the maximum propagation delay  $a$ . Next, let us look into how the maximum throughput changes in terms of the guard time  $\beta$ . Our analytical and simulation results also show higher throughput can be achieved by using guard time for lower values of  $a$ .

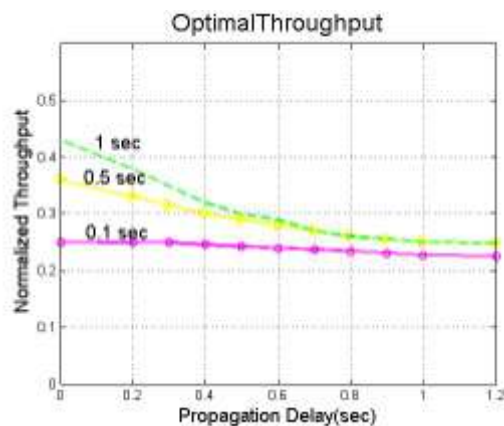


Fig. 5(a): Analytical results

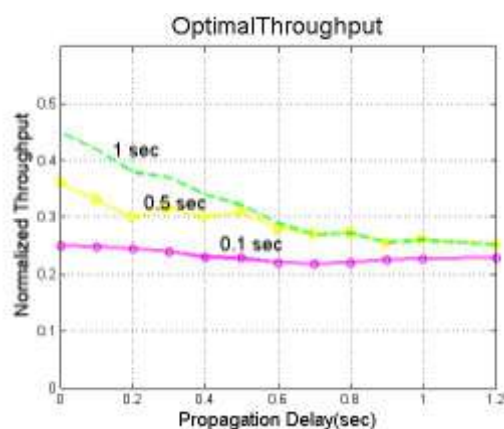


Fig. 5(b): Simulation results

## VI. CONCLUSIONS

We investigate different metrics of performances, expected number of successful packet receptions in a guard time slot, throughput and maximum throughput. We obtain exact expressions for the number of receptions and throughput in terms of well-known functions. Although the exact expressions are quite complicated, it is fairly fast to

numerically calculate them with given parameters. We have shown that for the optimal throughput capacity the value of optimal guard time changes based on operating delay regime. Our results indicate a significant throughput benefit when shorter communication links are used. However, this work focuses on capturing the impact of latency on ALOHA-like protocols and understanding the mechanics of underwater medium access.

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#### AUTHOR'S PROFILE



Mr. K. Ramesh was born in Odugathur, Tamil nadu, India on 10<sup>th</sup> June 1966. He received his Bachelors of Electrical and Electronics Engineering from Anna University in the year 2007. Masters Degree in VLSI Design from Sathyabama University in the year 2011. He is currently a Ph.D., student of St Peter's University, Chennai. Majoring in Electronics and Communication Engineering. He has presently working as Asst. Professor. His current research focuses on wireless sensor networks and VLSI design. He has five Research publications in International Journals and Conferences to his credit.



Dr. V. Kannan was born in Ariyalore, Tamil nadu, India in 1970. He received his Bachelor Degree in Electronics and Communication Engineering from Madurai Kamarajar University in the year 1991, Masters Degree in Electronics and control from BITS, Pilani in the year 1996 and Ph.D., from Sathyabama University, Chennai, in the year 2006. His interested areas of Research are Optoelectronic Devices, VLSI Design, Nano Electronics, Digital Signal Processing and Image Processing. He has more than 200 Research publications in National / International Journals / Conferences to his credit. He has 22 years of experience in teaching and presently working as Principal in Jeppiaar Institute of Technology, Sriperumpudur, Chennai, India, He is a life member of ISTE.