New Reservation Multiaccess Protocols for Underwater Wireless Ad Hoc Sensor Networks

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Abstract

In a wireless network, where propagation delay is high and communications are sporadic, some kind of reservation protocol is generally used. Reservation access protocols were proposed earlier in earth stations-to-satellite communication with known propagation delay. 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.

In this paper, we first analyze the system performance in many-to-one multiaccess data transfer scenario in underwater wireless ad hoc sensor networks with fixed number of access slots and with the assumption of perfect propagation delay information. We propose two system state aware dynamic approaches to suitably adjust the number of access slots, and investigate the optimum slotting strategy to maximize the system utilization. Next, by accounting the propagation delay uncertainty, we re-look into the optimality criteria on the number of access slots, where we apply a modified receiver-synchronized slotted Aloha principle to maximize the access performance. Via mathematical analysis, supported by discrete event simulations, we show that the system utilization and blocking probability performances with our proposed dynamic reservation protocols are consistently better compared to the competitive reservation protocols with fixed as well as variable access slots. Further, we conduct NS3 simulations to study the protocol performances under more realistic channel and traffic conditions, which also demonstrate that the proposed optimized dynamic slotting offers a much better system utilization performance compared to a similar underwater reservation multiaccess protocol.

Index Terms

Underwater random access, receiver synchronized reservation protocol, propagation delay uncertainty, many-to-one communication

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I. INTRODUCTION

Short-range underwater wireless ad hoc sensor networks (UWSNs) are aimed at remotely monitoring various aquatic activities, such as marine biological and zoological lives, geological changes, and underwater human activities. Despite some similarities between UWSNs 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, UWSN 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, Chapter 5]:

$$v(z, \xi, \theta) = 1449.2 + 46\theta - 5.5\theta^2 + 0.29\theta^3 + \big(1.34 - 0.1\theta\big)\left(\xi - 35\right) + 0.016z,$$

where $\theta = \frac{\Theta}{10}$, Θ is the temperature in degrees Celsius, ξ is the salinity in parts per thousand, and z is the depth in meters. From this expression it can be noted that the signal propagation speed is a function of the operating conditions. Any fluctuation of underwater operating condition implies that the propagation delay between a transmitter-receiver pair can be different from that of another spatially separated pair, which is also true when two spatially apart transmitters are communicating to a single receiver.

Generally, in centralized UWSNs, 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 wired links. Communication from the field sensors to the gateway is in the form of many-to-one access mechanism. This many-to-one connectivity, significantly large and unpredictable propagation delay, and normally sporadic sensed data from the field nodes suggest that some kind of random access based reservation protocol would be suitable for the field nodes to the gateway communication. Although many-to-one multiaccess in RF communication has been extensively studied before, pertaining to distinctly different underwater signal propagation characteristics, the RF multiaccess control (MAC) protocols are not directly applicable [2]–[11].

Till date, a few reservation protocols have been proposed in the literature for UWSNs (e.g., [7], [10]–[14]) that use some Aloha variants in the reservation stage. The success rate of these random access protocols at the reservation stage are poor [15], [16]. To this end, receiver-initiated/ receiver-synchronized protocols (e.g., in [11], [12], [17]) are found to offer a higher throughput performance. However, the existing underwater reservation protocol approaches vary widely, and to our knowledge the overall utilization performance of the underwater reservation protocols in a many-to-one communication scenario has not been thoroughly studied yet.

In a bid to increase the system utilization in underwater many-to-one communications, we look into the reservation protocols in satellite-to-earth stations communications, which also encounter a significantly large propagation delay. Among several variants of random access protocols, receiver synchronized S-Aloha (which we call RSS-Aloha) concept was described in [18], [19]. Using this Aloha protocol variants, different reservation protocols were developed for satellite communication [20], [21]. While [22], [23] considered the network state dependence in the frame structure, these approaches did not study optimum variability of number of access slots or frame size that would maximize the network performance under varying traffic conditions.

A. Contribution and significance

We note that, time synchronization may be achievable in satellite communications, as the propagation delay uncertainty can be disregarded because of relatively very high RF signal propagation speed. In contrast, perfect synchronization is unlikely in underwater communication environment, as the temporal and spatial variation of acoustic signal propagation speed can be significantly large. In view of underwater propagation delay and its variability [24], [25], in this work we modify the RSS-Aloha based reservation protocol and propose optimized policies for many-to-one one-hop communication from the underwater field sensors to a gateway node.

Our key contributions are the following. (a) We first investigate the RSS-Aloha based reservation protocol performance with the assumption of perfect synchronization. With an aim to maximize the system utilization performance, we propose two variants of system state aware dynamic multiaccess reservation slotting policies, namely, traffic load aware policy (scheme I) and instantaneous occupancy aware policy (scheme II), which can work in satellite networks as well as in UWSNs. (b) To address the effect of imperfect synchronization due to propagation delay uncertainty, as prevalent in UWSNs, we apply a modified RSS-Aloha to maximize the random access throughput and re-look at the overall optimality criteria on system utilization. (c) Via mathematical analysis, supported by simulations, we show that, by optimally adjusting the access duration over a fixed sized frame in the proposed schemes, the system utilization performance can be significantly increased compared to the existing competitive schemes with fixed as well as dynamic access slots at any traffic load. Although the traffic load based adaptation (scheme I) is intuitive and performs a little better than scheme II at high traffic loads, its overall performance is poorer than the optimized access scheme II. (d) Via NS3 simulations with finite number of nodes, we demonstrate that channel utilization in the proposed scheme II is always higher than that in a competitive reservation channel MAC (RC-MAC) protocol.

The significant features of the work are: (a) It proposes two systematic approaches to dynamic reservation access protocols for long and uncertain propagation delay environments, such as in earth stations to satellite and many-to-one underwater network communication systems. In contrast, the existing approaches either do not consider system dynamics in deciding contention access period in a frame, or they are heuristically approached and do not provide optimal performance. (b) The proposed schemes are optimized with respect to system load as well as propagation delay uncertainty, which are unique with respect to the existing approaches. (c) The protocol performance studies have been based on solid theoretical foundation, supported by system simulations, which give a clear insight into the protocol design and optimization.

B. Paper organization

Outline of the rest of the paper is as follows: In Section II, prior works on underwater many-to-one communications are discussed, and reservation protocols in satellite as well as underwater communications are surveyed. Section III contains general assumptions on the reservation based access system and a summary of notations used in the paper. Section IV presents the RSS-Aloha based proposed reservation protocols with perfect synchronization assumption and their performance analyses. The effect of propagation delay uncertainty on the proposed protocols are investigated in Section V for optimality of system performance. Numerical and simulation based performance studies are conducted in Section VI. The paper is concluded in Section VII.

II. Related work

Due to low propagation speed of underwater acoustic signal, propagation delay varies appreciably with distance. So, before initiating a communication, synchronization between a transmitter-receiver pair is critical. Several synchronization schemes were proposed [26]–[29]. However due to spatio-temporal variation of underwater signal propagation speed, at the time of actual communication the available synchronization information may become stale.

Besides the added synchronization issue, UWSNs have the inherent problems of multiaccess systems. With the basic objective of reducing the collisions of data packets, there have been several request-to-send/clear-to-send (RTS/CTS) handshake based transmission schemes in the literature [11], [12], [30]–[32]. The multiple access collision avoidance with multiple neighbors (MACA-MN) protocol [12] operates via three-way handshake (RTS/CTS/DATA). In [11], on the other hand, the transmitter sends an RTS packet to a receiver with its suggested CTS and data reception windows. Upon successfully receiving the RTS, the receiver sends the CTS at an appropriate time and waits for the data packet at the designated interval. In these propagation delay aware handshake based reservation approaches, the data collision is reduced, but the initial RTS packet transmission is pure Aloha based, which has a low success probability.

In a receiver-driven reservation based one-to-one underwater communication approach [13], four-way handshake is performed, which involves ready-to-receive (RTR) broadcast, packet SIZE transmission by the ready transmitters, packet ORDER transmission by the receiver, and DATA transmissions. Here, since the receiver receives data in a sequence, unfair hogging network resource by some nodes is possible. Also in this protocol the delay is very high, since the transmitter needs to wait for the respective receiver's initiation to transmit its data. Another recent reservation protocol for UWSNs [14] is sender-initiated via Notice/Order/Data/Reply handshake. To avoid contention, 'Notice' message is spreading sequence based, which could limit the number of users in a cluster. Also, the issue of underwater propagation delay uncertainty has not been addressed here. In a gateway based many-to-one RC-MAC protocol [7], the whole bandwidth is divided into control and data channels. The nodes have the ability to transmit or receive simultaneously on the control and data channels. The field nodes reserve resource at the gateway via RTS on the control channel using pure Aloha. Gateway node responds with CTS in the data channel. Subsequently the field nodes transmit data using data channel. The unsuccessful nodes retry in subsequent frames according to the control channel rate communicated by the gateway.

Among other reservation based algorithms, in [33] each node learns the neighboring nodes' propagation delay information and their expected transmission schedule by overhearing packet transmission, so that the collision can be predicted and proactive action is taken. In [34], a transmitter oriented CDMA based MAC protocol was proposed, which uses RTS-CTS. In [35], a direct sequence CDMA distributed MAC protocol was proposed that incorporates closed loop algorithm to set optimal transmit power and code length to minimize near-far effect. A hybrid spatial reuse time division multiple access was proposed in [36]. Since the network may not be fully connected, spatial reuse TDMA is combined with CDMA. In cooperative underwater multichannel MAC protocol [37], multichannel hidden terminal, long propagation delay hidden terminal, and multi-hop hidden terminal problems were addressed. In a frame based underwater multiaccess protocol, called T-Lohi [10], flexible frame size was considered. A frame consists of variable number of contention rounds followed by data transfer. The number of contention rounds continues to increase until one successful access. There are three versions of synchronous/asynchronous T-Lohi, which differ mainly by the length of the contention round.

In satellite-to-earth stations communication, different reservation policies were proposed. In R-Aloha [20], a frame is divided into equal size slots, which are used for data transmission. A transmitter randomly accesses one of the free slots using S-Aloha protocol. If the random access is successful, the same slot in the subsequent frames is used by the same transmitter for data transmission purpose till the transmitter has data to transmit. In [21], a fixed sized frame is divided with equal-size slots. A few *fixed* number of slots in the beginning of a frame are further mini-slotted which are used for random access purpose. The transmitters that are successful in accessing a mini-slot get the chance to transmit their data sequentially over the data slots. In [22], a dynamic allocation of satellite channel capacity through packet reservation was proposed, where flexible frame size was considered. Each frame consists of a fixed number of access slots, followed by a variable number of data slots. In another policy, known as packet reservation multiple access with dynamic allocation (PRMA/DA) [23], fixed frame size was considered but the number of access slots was varied for different traffic classes, depending on the system load.

We observe that, in the existing underwater RTS/CTS based reservation protocols, the initial reservation part has been based on basic Aloha or transmitter synchronized S-Aloha, which has inherently low success rate [15]–[17]. While some of the frame based protocols considered the load dependent variability of access or data slots [22], [23], an optimum balance between the access and data periods at various system states has not been investigated. *Our current work aims at improving upon the prior frame based reservation protocol studies by suitably optimizing the access slots while accounting the propagation delay variability in UWSNs.* Here, the gateway and field nodes are assumed capable of full-duplex communication. This is a valid assumption since full-duplex communication is shown to be possible in underwater network [38], [39].

III. Reservation system model and general assumptions

For field nodes to the gateway multiaccess, the time is divided into fixed intervals as in [20], [21], [23]. Each interval encapsulates a frame of fixed size. The front end of the frame is sub-divided into a number of slots for contention based access request transmission of the field nodes, whereas the remaining portion of the frame is used for data packet transmission in first-in first-out (FIFO) order. To notify the successful access slots, gateway-to-field nodes downlink communication is carried out in a single (combined) access response to all contending nodes via a different channel. Clearly, here the multiaccess performance of interest is the uplink communication. The field nodes having data to transfer to the gateway node contend for randomly chosen access slots in a frame. The successful nodes transmit their data in the subsequent frames. The frame size is considered greater than the maximum round-trip propagation delay, so that a transmitter can receive the response to its access request within a frame duration. A pictorial representation of fixed size frame based reservation protocol is shown in Fig. 1.

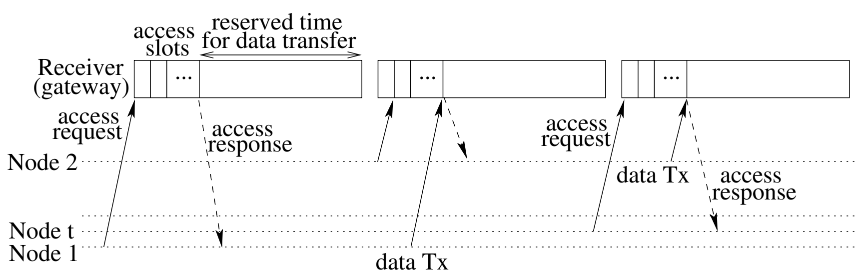

Fig. 1. Timing diagram of UWSN reservation-based many-to-one access protocol with a fixed frame length.

We consider the following simplifying assumptions for the performance analysis: (a) The system has finite but large number of users. Arrival rate per user is small, so that the probability of more than one arrival per user per frame is negligibly small. (b) To keep the data traffic arrival rate in the system same as the access request arrival rate, the new packet arrivals are not accumulated along with the message that is currently being transmitted. Instead, the new arrivals after a successful access request are backlogged for transmission after the next successful access request. Thus, the data message size is the sum of accumulated packets between two successful access requests. This message size is considered approximately exponentially distributed.

Beyond random access contention failures, access to the waiting queue at the gateway is limited by the maximum allowed pending data transmission requests.

We consider maximization of *system utilization* ρ, which is *defined as the fraction of a (fixed) frame duration actually utilized for data transmission*. The use of ρ is elaborated in Section IV.

A summary of notations used in the protocol performance analysis is listed in Table I.

TABLE I

SUMMARY OF NOTATIONS USED IN THE ANALYSIS

R	Nodal communication (transmit/receive) range (m)
v	Underwater acoustic signal propagation speed (m/sec)
N	Maximum allowed queued-up data transmission requests at the gateway
λ	Data transmission request arrival rate in the system per unit time (/sec)
$\lambda_a(n)$	Successful request arrival rate when the system state is n
$\lambda_s(n)$	Request arrival rate in the access part of a frame in the system state n
X_k	Message size of kth user, exponentially distributed with mean, $\overline{X} = \frac{1}{\mu}$ (sec)
$n_a(n)$	Number of access slots per frame when system state is n
T_a	Access slot duration (sec)
$T_a^{(m)}$	T_a in modified RSS-Aloha-uw
$T_s(n)$	Service time per frame when the system state is n (sec)
T_f	Fixed frame duration (sec)
$T_p^{\max}$	Maximum propagation delay
$\sigma(r)$	Propagation delay variance when transmitter-receiver distance is r
$P_a(i, n_a)$	Probability of i successful arrival of new requests in n_a access slots
$P_c(m, n)$	Probability of service completion of m requests in system state n
$P(i, j)$	State transition probability from state i to state j
$P_s(n)$	Probability of successful arrival in a slot when the system state is n
$P_s^{(m)}(n)$	$P_s(n)$ in modified RSS-Aloha-uw
k	Access slot increment coefficient in modified RSS-Aloha-uw
p_n	Steady state probability that the system state is n
ρ	System utilization factor

IV. RESERVATION PROTOCOL WITHOUT PROPAGATION DELAY UNCERTAINTY

Before we present our proposed protocols with dynamic access slots, we analyze the reservation protocol performance with a fixed number of access slots.

A. Reservation Protocol with fixed number of access slots

In this protocol, each frame consists of a fixed number of access slots and reservation time. Below, we study the reservation performance via discrete-time Markov chain (DTMC) analysis.

The system state n is defined as the number of successful data transmission requests from the field nodes that are queued up at the gateway, which is monitored at the beginning of every frame. Because the number of successful access slots in every frame is random and the size of data content per node is also random, n is a random variable varying between 0 and the maximum allowed number of queued up data transmission requests N at the gateway and the system state transitions form a DTMC. Since the number of access slots n_a is fixed,

$$\text{maximum number of successful requests in a frame } = \begin{cases} n_a, & \text{if } n + n_a \leq N \\ N - n, & \text{otherwise.} \end{cases}$$

The DTMC representation of system state with $n_a = 2$ is shown in Fig. 2. In this example, the

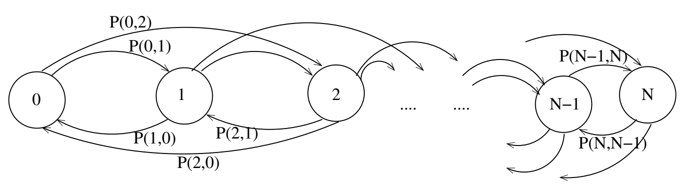

Fig. 2. System state transition diagram in reservation-based access with a fixed number of access slots per frame.

system state in a frame can be advanced by at most two states, whereas in the reverse direction the system state can reduce up to 0. Denote,

$P_s(n) = \Pr\{\text{successful access request in a slot when the system is in state } n\}$,

$P_a(i, n_a) = \Pr\{i \text{ successful arrival of new requests in } n_a \text{ access slots}\}$, and

$P_c(m, n) = \Pr\{\text{service completion of } m \text{ requests when the state of system is } n\}$.

$P_a(i, n_a)$ can be expressed as:

$$P_a(i, n_a) = \binom{n_a}{i} P_s^i (1 - P_s)^{n_a - i}, \tag{1}$$

where, by S-Aloha principle, $P_s(n) = \frac{\lambda T_f}{n_a} e^{-\frac{\lambda T_f}{n_a}} \equiv P_s$, i.e., independent of n in fixed reservation scheme. λ is the data arrival rate per unit time in the system, and T_f is the fixed frame duration.

Considering service time of the kth user X_k is exponentially distributed with mean $\overline{X} = \frac{1}{\mu}$, m being generally finite (small), the pdf of $X = X_1 + X_2 + \ldots + X_m$ is Erlang distributed as:

$$f_X(x) = \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} \quad x, \mu \geq 0.$$

If T_s is the service time in a frame, the probability of m nodes' service completion is given by:

$$\Pr\{X_1 + X_2 + \ldots + X_m \leq T_s\} = \int_0^{T_s} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx.$$

Hence, by using conditional probability principles, $P_c(m,n)$ can be expressed as:

$$P_c(m,n) = \begin{cases} \int_0^{T_s} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx - \int_0^{T_s} \frac{\mu(\mu x)^{m}}{m!} e^{-\mu x} dx, & \text{if } 0 < m < n \\ \int_0^{T_s} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx, & \text{if } m = n \neq 0 \\ e^{-\mu T_s}, & \text{if } m = 0,\ n > 0 \\ 1, & \text{if } m = n = 0 \\ 0, & \text{if } m > n, \end{cases} \tag{2}$$

with $\sum_{m=0}^{n} P_c(m,n) = 1$. Using (1) and (2), state transition probabilities can be obtained as:

$$P(n, n+i) = \sum_{m \leq N-(n+i)} P_a(i+m, n_a) P_c(m,n) + P_c(N-(n+i), n) \sum_{m > N-(n+i)} P_a(i+m, n_a), \tag{3}$$

$$P(n, n-i) = \sum_{m \leq N-n} P_a(m, n_a) P_c(i+m, n) + P_c(N-(n-i), n) \sum_{m > N-n} P_a(m, n_a). \tag{4}$$

Correspondingly, the state transition probability matrix $\underline{\mathbf{P}}$ is given by,

$$\underline{\mathbf{P}} = \begin{bmatrix} P(0,0) & P(0,1) & \cdots & P(0,N) \\ P(1,0) & P(1,1) & \cdots & P(1,N) \\ \vdots & & & \\ P(N,0) & P(N,1) & \cdots & P(N,N) \end{bmatrix} \tag{5}$$

with $\sum_{j=0}^{N} P(i,j) = 1$. Using (5) and the boundary condition $\sum_{n=0}^{N} p_n = 1$, the state probabilities $\underline{p} = \{p_0\ p_1\ \cdots p_N\}$ are found by solving $\underline{p}\ \underline{\mathbf{P}} = \underline{p}$. The system utilization ρ is obtained as:

$$\rho = \sum_{n=0}^{N} p_n \times \frac{\min\{T_s, n.\overline{X}\}}{T_f}. \tag{6}$$

The average number of pending requests at the gateway is $\overline{n} = \sum_{n=0}^{N} n p_n$. The blocking probability,

$$P_b = p_N \tag{7}$$

accounts for the cases when the system state in a frame interval is n (i.e., already n data transmission requests are queued up) and $N-n$ new requests are successful in the same frame.

B. Dynamic access scheme I: traffic load based

We observe from fixed access scheme that, the system's awareness to its state may be beneficial to its utilization. Here we propose a load based dynamic reservation protocol, where the number of access slots n_a at a system state n will be such that: (a) it tries to maximize the per-slot access request success rate, and (b) it does not occupy too much of time resource in a frame, thereby it allows sufficient room $T_s(n)$ for data transmission. The first constraint suggests that, at a given system load (request arrival rate λ) the allocated n_a fulfills the condition $n_a = \underset{n' \ (n'>0)}{\text{argmax}} \left\{P_s\left(n'\right)\right\}$, where $P_s\left(n'\right) = \frac{\lambda T_f}{n'} e^{-\frac{\lambda T_f}{n'}}$. The second condition is enforced by limiting the number of successful access slots to be no more than the maximum number of currently empty system states $N - n$, i.e., $n_a P_s\left(n_a\right) \leq N - n$. Combinedly, the scheme I operation can be defined as:

$$n_a = \begin{cases} n_a^{\max} & \text{if } n = 0 \\ \min\left\{ \underset{n' \ (n'>0)}{\text{argmax}} \left\{P_s\left(n'\right)\right\}, \ \underset{n'' \ (n''>0)}{\text{argmax}} \left\{n'' P_s\left(n''\right) \leq N - n\right\} \right\} & \text{if } 0 < n < N \\ 0 & \text{if } n = N. \end{cases} \quad (8)$$

With this modification, the variation of number of access slots $n_a(n)$ with system state n in Fig. 3 indicates that the number of access slots is increased with the system traffic load.

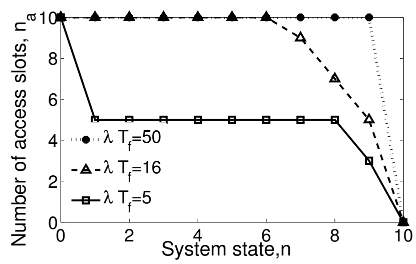

Fig. 3. Variation of access period with system state in scheme I. $n_a^{\max} = \frac{T_f}{T_a}$, $T_f = 0.2$ sec, $T_a = 0.02$ sec.

With the knowledge of $n_a(n)$, system state probabilities $\{p_n : \ n = 0, 1, \cdots, N\}$ can be computed using (1)-(5). Hence, the system utilization ρ is obtained as:

$$\rho = \sum_{n=0}^{N} p_n \times \frac{\min\{T_s(n), n.\overline{X}\}}{T_f}. \quad (9)$$

C. Dynamic access scheme II: parametric, system state based

To increase the system utilization, we propose another dynamic reservation protocol, where the number of access slots is adjusted per frame, based on the number of pending user requests, i.e., the system state n. If n crosses a certain lower threshold, the number of access slots n_a is decreased in that frame, which increases the service duration T_s. As a result, the data delivery rate to the gateway is increased. On the other hand, when the number of pending requests reduces, the number of access slots is increased so that more number of requests can be accommodated for their data delivery. Thus, n_a and as a result T_s are now functions of the system state n.

Unlike in scheme I, we propose a generic function to determine $n_a$as a function of n,

$$n_a(n) = n_a^{\min}\left(\frac{n}{N}\right)^{\alpha} + n_a^{\max}\left(1 - \left(\frac{n}{N}\right)^{\alpha}\right), \tag{10}$$

where $\alpha \geq 0$ is a tuning parameter that controls the sharpness of adjusting n_a as a function of n, $n_a^{\max}$ is chosen as $n_a^{\max} = \frac{T_f}{T_a} \leq N$, and $0 \leq n_a^{\min} \leq n_a^{\max}$, T_a is the duration of an access slot, and $n_a^{\min}$ and $n_a^{\max}$ are respectively the minimum and maximum number of possible access slots in a frame. The variation of n_a with n for different values of α is plotted in Fig. 4. A comparative look with respect to Fig. 3 indicates that, α-based tuning of n_a is more sensitive to n. Intuitively, at $n = 0$ the number of access slots should be the maximum, $n_a^{\max}$, whereas at $n = N$ it is the minimum $n_a^{\min}$. However, at the intermediate values of n how n_a should vary has to be optimally chosen, dictated by α, so as to maximize the overall system utilization ρ.

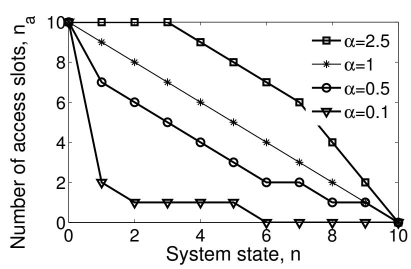

Fig. 4. Number of access slots n_a per frame versus system state n in scheme II, where the tuning parameter α controls the sharpness of variation of n_a. $T_f = 0.2$ sec, $T_a = 0.02$ sec, $n_a^{\min} = 0$.

Using the same method as described in IV-A, it is possible to find the steady state probabilities, $\{p_n :\ n = 0, 1, \ldots, N\}$. The corresponding system utilization can be obtained using (9).

Maximization of utilization: We note that, a right choice of α is needed to adjust the number of access slots with the system state – which is also a function of traffic arrival pattern. Below, we formulate an optimization problem to maximize ρ for the given values of $T_f,\ \lambda,\ \mu$, and N.

$$\begin{aligned}&\underset{\alpha}{\text{Maximize:}}\ \rho = \sum_{n=0}^{N} p_n \times \frac{\min\{T_s(n), n.\overline{X}\}}{T_f}\\ &\text{subject to: } \underline{p}\ \underline{\mathbf{P}} = \underline{p},\quad \sum_{i=0}^{N} p_i = 1,\ \text{and} \sum_{j=0}^{N} P(i,j) = 1,\end{aligned} \tag{11}$$

where $\{P(i,j):\ i,j = 0,\ 1,\ \cdots,\ N\}$ is obtained using (1), (2), (3), and (4).

Typically, in a given network setting, the quantities $T_f,\ \mu$, and N are system design parameters. So, the optimum α, denoted as α_{opt}, is a function of the arrival rate λ.

Access request blocking probabilities in dynamic access schemes I and II can be obtained using (7) with appropriately modified probability $P_s(n)$.

It may be noted that, the heuristic approach in [23] considered system state dependent access slot variation. However, as we will see in Section VI, compared to our proposed schemes, the utilization performance with the approach in [23] sharply deteriorates at high traffic load.

V. Reservation protocol for UWSNs with propagation delay uncertainty

Now that we have analyzed the dynamic reservation access protocols which work in general in systems with long propagation delay, in this section we address the propagation delay uncertainty, as in UWSNs. In particular, we derive the optimal access slot size as a function of propagation delay variance to minimize the access request failure probability.

Due to propagation delay uncertainty in UWSNs, perfect synchronization at the receiver is difficult to achieve. As a result, with the access slot size T_a, a reservation request packet of duration T_a is likely to be received in an access slot neighboring to the target slot. This lack of synchronization causes collision of the request packets, which is in addition to the collision due to more than one simultaneous transmission attempts in a receiver-end slot in the S-Aloha based access reservation. In this context, we adopt the modified RSS-Aloha (mRSS-Aloha) protocol in [17] (which was proposed to increase the throughput of RSS-Aloha), where the slot size at the receiver end is suitably adjusted as a function of delay variability to increase the success probability $P_s^{(m)}(n)$ of access requests. It may be recalled that, while mRSS-Aloha maximizes the S-Aloha performance by optimizing receiver-end slots, its performance is still quite poor, $< 37\%$, which deteriorates with the increased propagation delay uncertainty and packet size. Hence, mRSS-Aloha is used only for contention-based access control purpose with short packets.

Define modified access slot size as $T_a^{(m)} = T_a + 2k\sigma$, where σ (≥ 0) is the propagation delay variance and k (≥ 0) is the access slot increment factor. Note that, the computation of $P_s^{(m)}(n)$ is modified here to account for the definition of a successful request and net request arrival rate.

Since the propagation delay uncertainty would be small compared to the reserved time for data transmission, the effect of lack of synchronization on data message transmission would be negligibly small. In the following analysis, the delay variability issue for data transmission is not accounted. However, a similar modification as in case of access slots can be done to address synchronization in the reserved time frame for data transmission.

Following the approach in [17], the success probability of an access request from a r distance away field node that reaches the gateway at time y is given by:

$$
\begin{aligned}
P_s^{(m)}(n) = & \int_0^R \int_{(I-2)T_a^{(m)}}^{(I+2)T_a^{(m)}} \Pr\{\mathbf{y_p} = y\} \; \Pr\{\mathbf{r_p} = r\} \\
& \cdot \left[\sum_{i=0}^{\infty} \Pr\{(i+1) \text{ arrival in slot } I\} \prod_{p=0}^{i} \{1 - \Pr\{y - T_a \leq \mathbf{x_p}(\mathbf{r_p}) \leq y + T_a\}\} \right] \\
& \cdot \left[\sum_{i_{p_2}=0}^{\infty} \Pr\{i_{p_2} \text{ arrival in slot } I-2\} \prod_{p_2=0}^{i_{p_2}} \{1 - \Pr\{y - T_a \leq \mathbf{x_{p_2}}(\mathbf{r_{p_2}}) \leq y + T_a\}\} \right] \\
& \cdot \left[\sum_{i_{p_1}=0}^{\infty} \Pr\{i_{p_1} \text{ arrival in slot } I-1\} \prod_{p_1=0}^{i_{p_1}} \{1 - \Pr\{y - T_a \leq \mathbf{x_{p_1}}(\mathbf{r_{p_1}}) \leq y + T_a\}\} \right] \\
& \cdot \left[\sum_{i_{n_1}=0}^{\infty} \Pr\{i_{n_1} \text{ arrival in slot } I+1\} \prod_{n_1=0}^{i_{n_1}} \{1 - \Pr\{y - T_a \leq \mathbf{x_{n_1}}(\mathbf{r_{n_1}}) \leq y + T_a\}\} \right] \\
& \cdot \left[\sum_{i_{n_2}=0}^{\infty} \Pr\{i_{n_2} \text{ arrival in slot } I+2\} \prod_{n_2=0}^{i_{n_2}} \{1 - \Pr\{y - T_a \leq \mathbf{x_{n_2}}(\mathbf{r_{n_2}}) \leq y + T_a\}\} \right]. \qquad (12)
\end{aligned}
$$

Note, (12) accounts that the concerned packet is successful if no other arrival occurs in the time interval $[y - T_a, y + T_a]$. In addition to overlapping arrivals in the current slot, based on the typical data on underwater propagation delay variability [1], we consider a collision can be caused by the packets that are scheduled in the adjacent two slots on each side. Further, the range of r is $[0, R]$, which determines the second integration limits.

Denote, $\lambda_s(n) = \frac{\lambda T_f}{n_a(n) T_a^{(m)}}$ as the accumulated arrival rate per second in the access portion of a frame. With Poisson distributed arrival process, we have, $\Pr\Big\{i$ arrivals at a rate $\lambda_s(n)$ in a slot time $T_a^{(m)}\Big\} = e^{-\lambda_s T_a^{(m)}} \frac{\left(\lambda_s T_a^{(m)}\right)^i}{i!}$. For a uniformly random nodal distribution, $\Pr\{\mathbf{r_p} = r\} = \frac{2rdr}{R^2}$, where R is the communication range of the gateway node (receiver). In practice, the mean as well as variance of propagation delay are functions of transmitter-receiver distance. Accordingly, by the assumption of Gaussian delay distribution [24], [25], 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 access slot I is Gaussian distributed as: $\mathbf{x_p}(r_p) \sim \mathcal{N}(IT_a^{(m)}, \sigma^2(r_p))$, where the variance is dependent on transmitter-receiver distance r_p. With the above notations and considerations, the probability expressions in (12) can be simplified as:

$$\Pr\{y - T_a \le \mathbf{x_p}(\mathbf{r_p}) \le y + T_a\} = \int_0^R \Pr\{y - T_a \le \mathbf{x_p}(\mathbf{r_p} = r) \le y + T_a\} \cdot \Pr\{\mathbf{r_p} = r\}$$
$$= \int_0^R \left[\text{erf}\left(\frac{y + T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \text{erf}\left(\frac{y - T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{rdr}{R^2} \triangleq P_1,$$

$$\Pr\{y - T_a \le \mathbf{x_{p_1}}(\mathbf{r_{p_1}}) \le y + T_a\} = \int_0^R \Pr\{y - T_a \le \mathbf{x_{p_1}}(\mathbf{r_{p_1}} = r) \le y + T_a\} \cdot \Pr\{\mathbf{r_{p_1}} = r\}$$
$$= \int_0^R \left[\text{erf}\left(\frac{y + T_a - (I-1)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \text{erf}\left(\frac{y - T_a - (I-1)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{rdr}{R^2} \triangleq P_2,$$

$$\Pr\{y - T_a \le \mathbf{x_{p_2}}(\mathbf{r_{p_2}}) \le y + T_a\} = \int_0^R \Pr\{y - T_a \le \mathbf{x_{p_2}}(\mathbf{r_{p_2}} = r) \le y + T_a\} \cdot \Pr\{\mathbf{r_{p_2}} = r\}$$
$$= \int_0^R \left[\text{erf}\left(\frac{y + T_a - (I-2)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \text{erf}\left(\frac{y - T_a - (I-2)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{rdr}{R^2} \triangleq P_3,$$

$$\Pr\{y - T_a \le \mathbf{x_{n_1}}(\mathbf{r_{n_1}}) \le y + T_a\} = \int_0^R \Pr\{y - T_a \le \mathbf{x_{n_1}}(\mathbf{r_{n_1}} = r) \le y + T_a\} \cdot \Pr\{\mathbf{r_{n_1}} = r\}$$
$$= \int_0^R \left[\text{erf}\left(\frac{y + T_a - (I+1)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \text{erf}\left(\frac{y - T_a - (I+1)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{rdr}{R^2} \triangleq P_4,$$

$$\Pr\{y - T_a \le \mathbf{x_{n_2}}(\mathbf{r_{n_2}}) \le y + T_a\} = \int_0^R \Pr\{y - T_a \le \mathbf{x_{n_2}}(\mathbf{r_{n_2}} = r) \le y + T_a\} \cdot \Pr\{\mathbf{r_{n_2}} = r\}$$
$$= \int_0^R \left[\text{erf}\left(\frac{y + T_a - (I+2)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \text{erf}\left(\frac{y - T_a - (I+2)T_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{rdr}{R^2} \triangleq P_5.$$

For a known $\sigma(r)$, the above integrations can be solved to compute the frame success probability in (12). However, since the nature of distance dependence on $\sigma(r)$ is not known yet, for a closed form analytical solution of success probability, we consider a special case of constant

$\sigma = aT_p^{\max}$, where $0 \leq a \leq 1$. Thus, simplifying and using the identities: $\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$, and $\int_a^b \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} = \frac{1}{2}\left[\text{erf}\left(\frac{b-\mu}{\sigma\sqrt{2}}\right) - \text{erf}\left(\frac{a-\mu}{\sigma\sqrt{2}}\right)\right]$, we have from (12),

$$\begin{aligned} P_s^{(m)}(n) = &\int_{(I-2)T_a^{(m)}}^{(I+2)T_a^{(m)}} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-IT_a^{(m)}}{\sigma}\right)^2} \\ &\cdot \sum_{i=0}^{\infty} e^{-\lambda_s(n)T_a^{(m)}} \frac{(\lambda_s(n)T_a^{(m)})^{(i+1)}}{(i+1)!} (1-P_1)^i e^{-\lambda_s(n)T_a^{(m)}(P_2+P_3+P_4+P_5)} dy. \end{aligned} \tag{13}$$

With the knowledge of $P_s^{(m)}(n)$, the system state probabilities $\{p_n\}$ can be computed using (1)-(5) for a fixed n_a or different variants of dynamic $n_a(n)$ (respectively given by (8) and (10)). Hence the system utilization ρ is obtained using (6) (with a fixed number of access slots) or (9) (with a variable number of access slots).

Maximization of utilization: Following the approach in Section IV-C, for a given slot size increment factor k $(0 \leq k \leq 1)$, α_{opt} in access scheme II can be obtained. Further, since the factor k plays an important role in maximizing the system utilization, to find the optimum k, i.e., k_{opt}, we formulate an optimization problem as:

$$\begin{aligned} &\underset{k}{\text{Maximize:}}\ \rho = \sum_{n=0}^{N} p_n \times \frac{\min\{T_s(n), n.\overline{X}\}}{T_f} \\ &\text{subject to: } \underline{p}\ \mathbf{\underline{P}} = \underline{p}, \quad \sum_{i=0}^{N} p_i = 1, \text{ and } \sum_{j=0}^{N} P(i,j) = 1, \end{aligned} \tag{14}$$

where $\{P(i,j) : \ i,j = 0,\ 1,\ \cdots,\ N\}$ can be obtained using (2), (3), (4), and (13). The quantities $T_f,\ \mu$, and N are system design parameters. Therefore, like α_{opt}, k_{opt} is a function of the data transmission request arrival rate λ.

VI. Results and Discussion

System performance of the underwater reservation based protocol variants have been studied in SCILAB using the analytical expressions developed in Sections IV and V. The key numerical results have been verified by C-based discrete event simulation of a single-cluster (multiple randomly located field nodes to a gateway data transfer) scenario.

A. System performance criteria

Besides optimization of system utilization, user-end performance is measured in terms of access request blocking probability P_b – defined in (7), average access delay D_a – defined in

(15), and the average delay of data packets in the system D_s – defined in (16) that includes access, queueing, and service delays. For a given system capacity N and fixed frame size T_f, P_b and D_s are the measures of improved dynamic access protocol behavior and responsiveness to the user requests, which cannot be captured solely by the system utilization ρ.

With the system and traffic assumptions stated in Section III, the approximate average access delay is estimated as follows: Every new arrival comes with a constant packet size S_p (in seconds). Due to failure of access requests to grab an access slot, the packets are accumulated and the average message size $\overline{X}$ at the time of successful access is: $\overline{X} = N_t \cdot S_p$, where N_t is the average number of access request attempts for the first data packet of the message to successfully reach at the receiver. N_t is obtained as: $N_t = \frac{1}{P_s^{avg}}$, where P_s^{avg} is the average success probability of a request attempt to grab an access slot, and it is obtained as: $P_s^{avg} = \sum_{n=0}^{N} P_s(n) p_n$. Here $P_s(n)$ is the probability of success to grab an access slot when the system state is n, N is the maximum number of unserved access requests that gateway can queue, and p_n is the probability of n unserved access requests in the gateway queue.

The average access delay D_a is estimated as:

$$D_a = (N_t^{avg} - 1) \cdot \left\lceil \frac{(1/\lambda_u)}{T_f} \right\rceil \cdot T_f + \frac{T_f}{2} + T_p^{avg} + T_f, \tag{15}$$

where N_t^{avg} is the average number of access attempts per packet in the message (of length N_t packets), and it is related to N_t as: $N_t^{avg} = \frac{1}{N_t} \sum_{i=0}^{N_t - 1} (N_t - i) = \frac{N_t + 1}{2}$. That is, the first data packet in the message saw N_t access attempts, whereas the last data packet experienced only one access attempt. λ_u is traffic arrival rate (per second) per user. Out of the four additive terms on the right hand side of the expression for D_a in (15), the first term is due to $(N_t^{avg} - 1)$ times unsuccessful tries, the second and third terms together are due to the last (successful) try, and the last term is due to one frame delay in beginning data transmission after the successful access request.

The system delay D_s is expressed as:

$$D_s = D_a + \overline{n}\overline{X} + \left\lceil \frac{\overline{n}\overline{X}}{\overline{T}_s} \right\rceil \cdot \overline{n}_a T_a, \tag{16}$$

which is the time needed for complete service (including access, queueing, and service delay) of average number of unserved user requests $\overline{n}$ in the system. D_a is the access delay as defined in (15). In a system where continuous service is possible, the average number of user requests needed is $\overline{n}\overline{X}$ time units. Since the service of a message can be interrupted due to the access slots, the term $\left\lceil \frac{\overline{n}\overline{X}}{\overline{T}_s} \right\rceil \cdot \overline{n}_a T_a$ accounts for this in the system delay consideration.

B. System parameters considered for numerical and simulation results

The system performance with the different slotted access protocols are evaluated numerically in terms of frame utilization (average time of a frame actually used for data transfer), average system state (average number of user requests in the system), blocking probability (probability that an access request is successful but the data transfer service is denied, which can happen when the system is having maximum allowed number of service requests). 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.

To study the performance via simulation, the field nodes were uniformly random distributed around a gateway. The nodes with successful access requests are marked queued up list of nodes in the gateway for data transfer as long as the queue is not full. Data messages are served in FIFO order. The length of data message at a node, which is the accumulated data since its previous successful access request until the current one, is considered exponentially distributed.

Following the underwater modem specifications [40], the parameters considered for numerical and simulation studies are: channel rate 16 kbps, acoustic signal speed $v = 1500$ m/s, access request (control) message size 40 Bytes (which is on the order of RTS (36 Bytes or 44 Bytes) and CTS (38 Bytes) packet length), and correspondingly, the basic access slot duration is $T_a = 0.02$ sec. The average data message size is exponentially distributed with mean 286 Bytes, i.e., the service rate is $\mu = 7$ data messages/second. The frame length is considered fixed, $T_f = 0.2$ sec. The maximum communication range of the gateway node is $R = 100$ m, which corresponds to the round trip propagation delay $2T_p^{\max} < T_f$. The system capacity (the maximum number of queued up data transmission requests) is $N = 10$. The number of field nodes considered is 300.

C. Performance of the basic dynamic access schemes

Before presenting the relative performance of the protocols proposed in Section IV and PRMA/DA [23] we briefly explain the PRMA/DA protocol. Original PRMA/DA is not exactly applicable for the considered packet data communication in underwater networks. Due to long propagation delay in underwater applications, the actual data transmission is delayed from a successful access request by at least one frame duration. Additionally, in this work we consider only delay tolerant ABR (available bit rate) data traffic. So, the CBR (constant bit rate) and VBR (variable bit rate) data traffic in the original PRMA/DA protocol are not considered here; ABR data transmission is useful in the present context. The algorithm for dynamic allocation of the number of access slots in PRMA/DA-uw (PRMA/DA for underwater) can be stated as:

$$n_a^{(f+1)} = \begin{cases} \min\{\max\{(n_a^f - n_s^f), 2n_c^f\}, n_a^{\max}\}, & \text{if } n_a^f > n_s^f \\ 1, & \text{if } n_a^f = n_s^f \end{cases}$$

where, in a frame f, n_a^f is the number of access slots, n_s^f is the number of successfully accessed slots, n_c^f is the number of collision in the accessed slots, and $n_a^{\max}$ is the maximum allowed number of access slots.

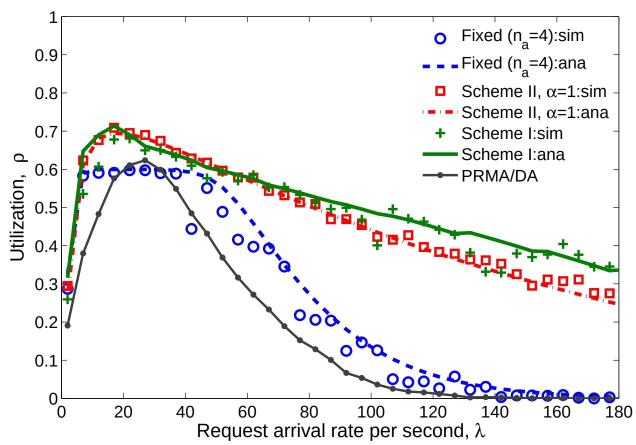

Fig. 5. Utilization comparison and verification of analysis via system simulations. $n_a^{\max} = N = 10$.

In Fig. 5, utilization performances of the competitive schemes are compared. The utilization of PRMA/DA-uw is low in general, but it is higher than in fixed assignment based reservation protocol over a small range of traffic arrival rate. The performance of PRMA/DA-uw is low at high traffic intensity, because at a high traffic intensity, to accommodate the negative effect of collisions the number of access slots per frame is increased to its highest value, which decreases the time available for service in a frame. As a result, most of the successful users do not get a chance to transmit their data, and therefore the system utilization decreases and the service delay increases. It is also observed that, while the performance with a fixed number of access slots ($n_a = 4$) peaks for certain values of traffic load, it drops fast on its other side. The schemes

I and II have more graceful decay in utilization performance with traffic load compared to the other protocols. Also utilization of schemes I and II are always higher than the fixed assignment scheme and PRMA/DA-uw. But with high load it is observed that load based scheme performs better than scheme II, as the load based scheme adapt itself with load.

The average system states in all the competitive protocols are plotted in Fig. 6. It shows,

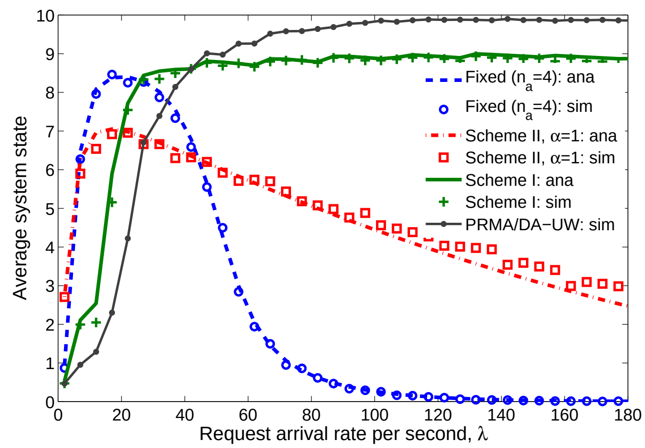

Fig. 6. Average system state versus traffic load. $n_a^{\max} = N = 10$.

PRMA/DA-uw system quickly saturates up to the system capacity as the traffic load is increased, which is because, in this protocol at high traffic loads the whole frame duration is used for the access purpose only. This is also the reason for a sharper decay in its system utilization (see Fig. 5). The system state in the proposed scheme I also increases sharply but saturates at a little lower than the system capacity, which is due to its awareness of the system state in deciding the number of access slots (see (8)). With a fixed number of access slots, the system moves into a higher non-blocking state at some values of arrival rate. After that, due to low success probability with increasing arrival rate, a less number of requests come into system for service, which results in a decreased system state. In dynamic scheme I, since the number of access slots is increased with the traffic load (see Fig. 3), the nodes get lesser chances to transmit their data. As a result, the average number of pending requests in the system increases with the traffic load. In the parametric dynamic scheme II, the system states are among the lowest ones, indicating a better balance between the number of access slots and the service time duration per frame.

Numerical and simulation-based access request blocking probability of all the protocols are compared in Fig. 7. The plots show, the blocking probability is highest for PRMA/DA-uw.

Clearly, the system state performance results in Fig. 6 is indicative to the blocking probability performance of this as well as other protocols. Fixed access scheme has some blocking probability

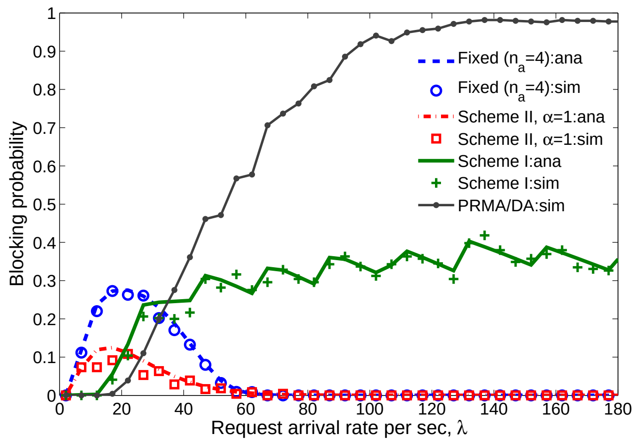

Fig. 7. Blocking probability comparison. $n_a^{\max} = N = 10$.

at lower values of traffic load. But it decreases with the increase of load, since a lesser number of users are successful in sending a reservation request. Blocking probability of the dynamic scheme I is also high at a higher value of arrival rate. There is a negligible blocking probability in the dynamic scheme II. In contrast with the blocking probability variation in scheme II, the saw-tooth type variation of blocking probability in scheme I is believed to be due to a nearly-discrete variation of $n_a(n)$ against the system state n, as observed in Fig. 3. In scheme II, the n_a maintained at a lower-than-saturated system state as well as its variation is smoother and more responsive to the system state, as shown in Fig. 4, resulting in a much less blocking probability with very little oscillations with system load variation. *It may be noted here that, a high access request blocking probability is undesirable and wasteful because, even after an access request is successful, the message could not be served due to a full service queue.*

In Fig. 8(b) the average access delay D_a of the access requests in different schemes are plotted. At very low request arrival rate λ, by the S-Aloha principle, the access request success probability P_s^{avg} is very low (shown in Fig. 8(a)). Combinedly with low P_s^{avg}, the average interarrival time being high at low λ, the D_a in all approaches are high. As λ increases, P_s^{avg} initially increases sharply, leading to the reduced D_a. At higher λ, the P_s^{avg} decreases sharply in fixed access scheme, leading to a sharp rise in D_a. In the other dynamic approaches, the moderately slow decay of P_s^{avg} combined with smaller interarrival times lead to slowly-varying D_a.

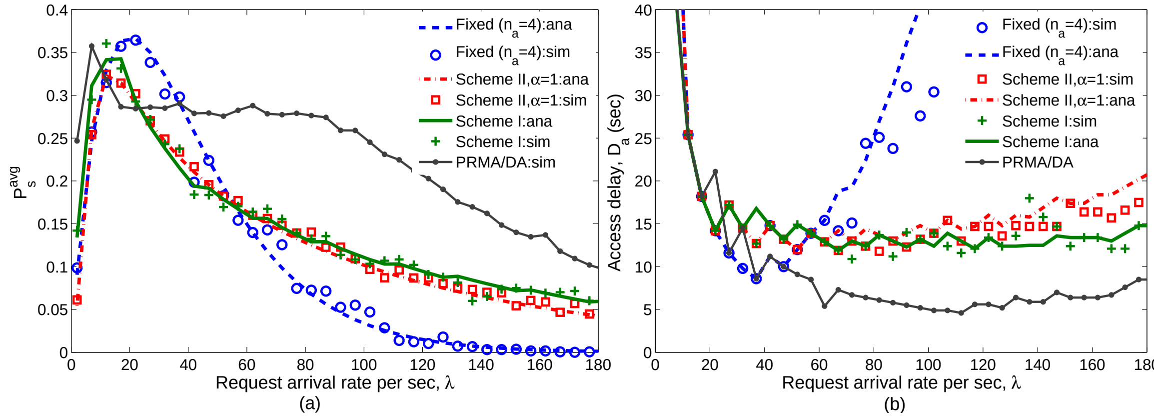

Fig. 8. Average probability of success to grab an access slot

In Fig. 9, the system delay of the reservation protocols are plotted. In PRMA/DA-uw, we argue

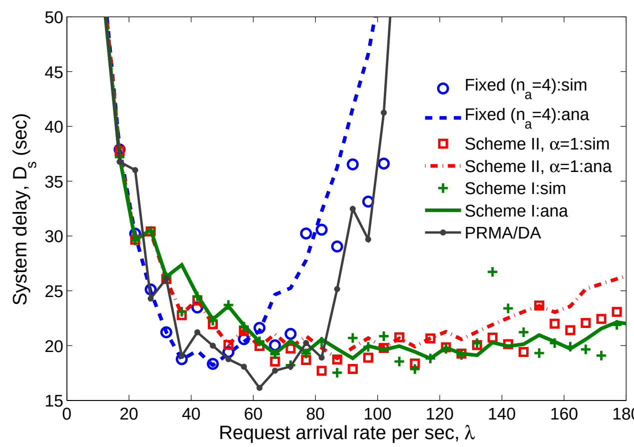

Fig. 9. System delay performance of the basic dynamic access protocols. $n_a^{\max} = N = 10$.

that, the dynamic adjustment of number of access slots based on the instantaneous number of successful/failed access slots, combined with a limited upper bound $n_a^{\max}$, lead to a reduced time to clear the backlogged requests in the system. The fixed access based as well as the dynamic scheme II is similarly governed by an upper limit of the number of access slots $n_a^{\max}$, allowing the system to incur a lesser system delay to clear the backlogged requests.

From the above results, the dynamic schemes I and II have been observed to perform good compared to the Fixed access and PRMA/DA-uw. *Though scheme I offers a little higher utilization and a lower system delay compared to the unoptimized scheme II, we pursue with scheme*

II further due to its low blocking probability and also for its additional parametric control capability – which has not been explored in the unoptimized scheme II.

D. Performance of the optimized dynamic access schemes II

To improve the system utilization in scheme II, we conduct parametric optimization (by controlling the parameters α). This optimized utilization performance are plotted in Fig. 10 along with scheme I, fixed assignment, and PRMA/DA-uw. The plots clearly show that, at any traffic

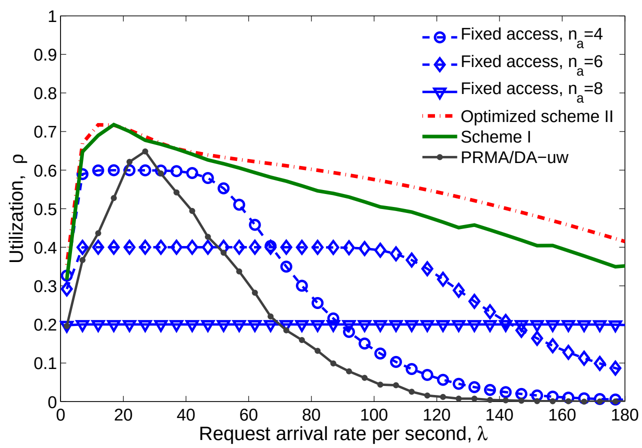

Fig. 10. Utilization performance with optimized dynamic access schemes. $n_a^{\max} = \frac{T_f}{T_a^{(m)}}$, $N = 10$, $n_a^{\min} = 2$.

load, the optimized dynamic scheme II has the overall best utilization performance compared to the fixed assignment scheme and dynamic scheme I. This is further emphasized by varying n_a in the fixed assignment scheme. Although the scheme II is a simpler one compared to the scheme I and its optimized performance is higher than that of scheme I.

Corresponding to the optimized utilization performance in the scheme II, the optimum value of the parameter α_{opt} is plotted against the system traffic load in Fig. 11. The Fig. 11 shows that,

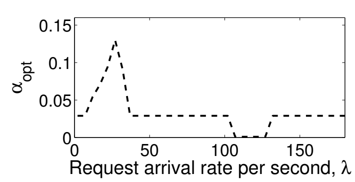

Fig. 11. α_{opt} versus traffic intensity in scheme II, with $n_a^{\min} = 2$.

an increased value of α is needed with the increase of traffic load till a certain value of traffic load. This is because, more traffic load implies a higher need for the access slots in α-based parametric dynamic scheme II. With further increase of arrival rate, if the number of access slots is decreased to achieve a higher utilization, as shown in Fig. 11.

E. Performance of reservation protocols in presence of delay uncertainty

We now study performance of the competitive reservation protocols in presence of propagation delay uncertainty. Since PRMA/DA-uw does not have better performance even with perfect delay information, we do not study it here. Utilization versus traffic load in Fig. 12 shows a good match between the analytic and simulation results, thus verifying validity of the analysis.

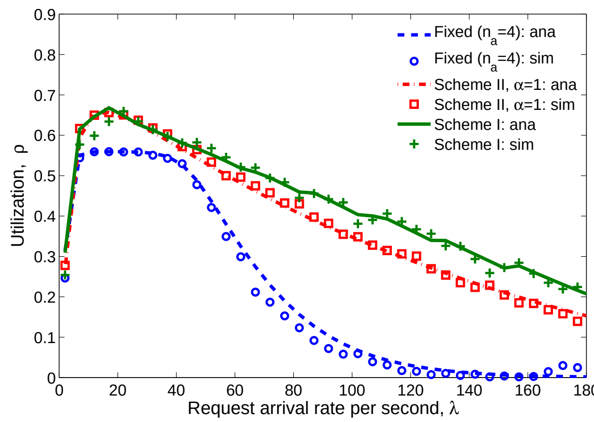

Fig. 12. Validation of analytical results on utilization performance. $n_a^{\max} = \frac{T_f}{T_a^{(m)}}$, $N = 10$, $T_a^{(m)} = T_a + 2k\sigma$, with $\sigma = 0.001$.

For the two dynamic schemes, we consider the optimized parameters that maximize the respective utilization performances. The primary focus in this part of study is therefore studying the effect on modified access slot size (in terms of the slot modification parameter k) on the protocol performances. In Fig. 13 we show the system utilization in mRSS-Aloha-uw [17], fixed assignment based, and the two proposed dynamic access schemes with propagation delay uncertainty, without as well as with the slot size modification. The utilization performance without delay uncertainty (i.e., $\sigma = 0$) is also shown in each plot for comparing the performance degradation with delay uncertainty. As observed in all the four cases, in presence of delay uncertainty, the utilization performance is very low without access slot modification, i.e., with $k = 0$, because in this condition very less number of users get into system for service. With the increase of access slot size, utilization increases in all the three protocols. Increasing the slot size

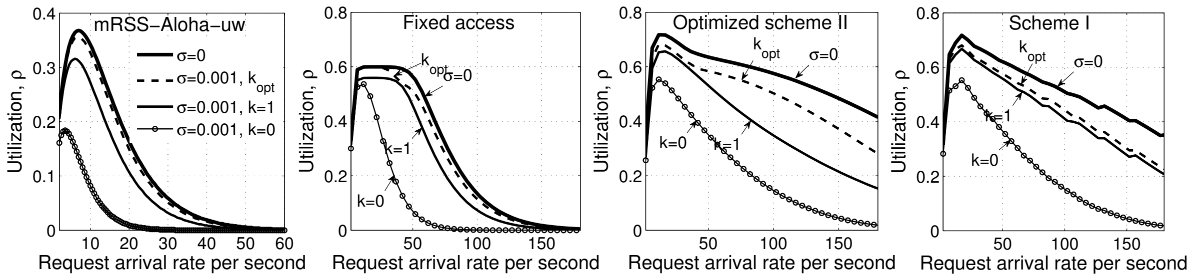

Fig. 13. Utilization performance without and with optimum parameters for the number of access slots (α_{opt} for scheme II) and the access slot size (k_{opt}). $n_a^{\max} = \frac{T_f}{T_a^{(m)}}$, $N = 10$, $T_a^{(m)} = T_a + 2k\sigma$, with $\sigma = 0.001$.

indefinitely would ensure progressively reduced delay uncertainty related collision, but it will also lead to the waste of frame time resource for actual data transmission, resulting in a reduced system utilization. The three sub-figures with the reservation based schemes indicate that the respective system utilization is maximized with an optimally chosen k, where the performances with an arbitrarily chosen k $(k = 1)$ are also shown. These results also show the importance of slot size optimization in the presence of propagation delay variability.

Fig. 14 shows the various inter-related system performance optimality versus propagation delay uncertainty. Fig. 14(a) shows the optimum acceptable request arrival rate at different delay uncertainties, which indicates two different trends. The fixed assignment based reservation and scheme II have somewhat constant trend of optimum λ. This could be because, as the delay uncertainty increases the slot size is decreased (to reduce the inter-slot request packet overlaps) (see Fig. 14(b)), which reduces the effective request arrival rate per slot. So, same λ is required to achieve a certain request success rate. This is not the case with the dynamic schemes I, initially the optimum λ is high and further increase of delay variability will cause the λ as constant which is same as in scheme II and fixed assignment.

The decreasing trends of access slot increment factor k in Fig. 14(b) for maximized utilization in all three cases is intuitive: Increased σ will itself increase the slot size. However, since increased slot size also would increased arrival rate per slot, decreased k_{opt} compensates to an optimal value to achieve the maximum utilization.

Fig. 14(c) shows the variation of maximum utilization with delay uncertainty. First, the decreasing trends in performance is because of more randomness (uncertainty) in the slotted arrival process and the associated effect of reduced data service portion in a frame. The plots

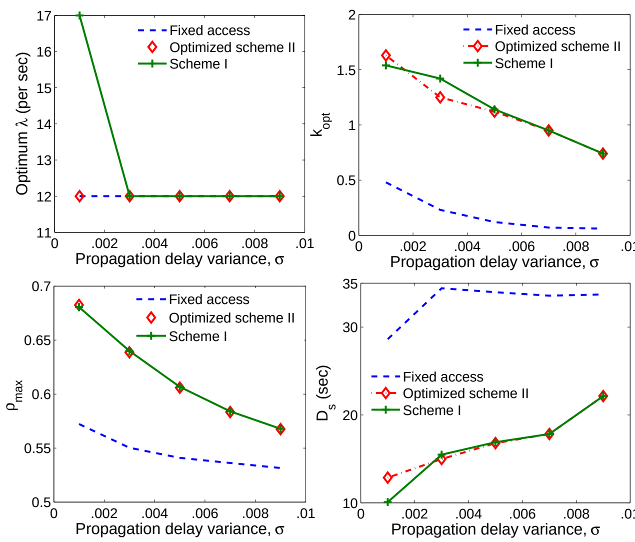

Fig. 14. Optimum system behavior at different propagation delay uncertainties: (a) request arrival rate; (b) access slot increment factor; (c) maximum achievable system utilization; (d) average system delay performance. $n_a^{\max} = \frac{T_f}{T_a^{(m)}}$, $N = 10$.

also indicate that, the dynamic schemes perform better than the fixed assignment for all the values of propagation delay uncertainty, showing robustness of the proposed approaches. For example, at $\sigma = 0.003$, there is an about 20% higher utilization performance in the dynamic schemes compared to the fixed assignment case.

Finally, the resultant effect on system delay is plotted in Fig. 14(d), which shows that dynamic schemes always offer lower delay than in fixed access reservation protocol. In fixed access scheme, the number of access slots does not change; the only adaptation is the increased access slot size with the uncertainty, which causes penalty in terms of more system delay. Reducing trends in the dynamic schemes is because of the system's tendency to keep the occupancy level at a low value. Also, by dynamically adjusting the number of access slots, the pending data transmission requests are cleared at a faster rate.

F. Overheads and implementation feasibility of the proposed schemes

In terms of overhead, both the proposed schemes do not put any extra load on the field nodes. In scheme I, the gateway needs to keep track of the system state n and $P_s(n)$, i.e. the fraction of access packets that are successful per frame. In scheme II, besides the system state information, the gateway requires the value of the optimization parameter α. As shown in Fig. 11, since α

does not vary significantly with traffic intensity, it can be computed offline, or at most at a slow time scale at the gateway. Additionally, in both the schemes the number of access slots n_a in the next frame needs to be communicated to the field nodes, which can be piggybacked with the common downlink (access response) message. So, the message overhead in the dynamic schemes should be quite nominal for practical implementation.

In scheme I, at every frame, given the system state n ($n \leq N$) and traffic load λ, the value of $n_a(n)$ is computed using the expression (8), which has the computation complexity $O(N)$. So, in scheme I the additional computational load with respect to the fixed access scheme linearly increases with the system capacity N. On the other hand, in scheme II, given the system state n, the number of access slots $n_a(n)$ is decided by (10), where α can be precomputed with respect to the system load, as discussed above. Thus, it has the computation complexity $O(1)$, which is only a constant additional overhead.

Since the performance of the optimized scheme II is better than scheme I in terms of utilization, system delay, as well as request blocking probability, while its run-time overhead is lesser, scheme II would be an overall better choice between the two proposed schemes.

G. Performance comparison with RC-MAC

Performance of the optimized dynamic reservation scheme II is further studied with more realistic traffic and system settings and compared with a competitive underwater reservation protocol, called RC-MAC, via NS3 simulations. The basic protocol was presented in [7], the modified RC-MAC protocol codes in NS3 are available in [41]. In modified RC-MAC protocol [41], total available bandwidth is dynamically divided between a data channel and a reservation channel. The bandwidth allocation is determined by the gateway node based on the system state. Nodes reserve time on the data channel via RTS packets on the reservation (control) channel using Aloha random access protocol. Then the gateway accumulates the successful RTS packets and sends a CTS packet to schedule the non gateway nodes for data transmission.

As in the RC-MAC protocol, finite number of field nodes was considered in the proposed protocol simulation. Data packets were considered of fixed size with transmit time T_d, and a field node is allowed to transmit only one packet per successful access to the system. Following the definition of system utilization in (9), in the simulation the utilization was calculated as $\rho = \frac{n_d T_d}{T_{sim}} \cdot \frac{1}{R_t}$, where n_d is the number of data packets received at the gateway over the total simulation time T_{sim}, and R_t is the data transmission rate.

The number of access slots in scheme II is varied as in (10), with N and $n_a^{\max}$ replaced by N_f, where N_f is the finite number of nodes in the simulation scenario. Note that, with a finite number of field nodes, the system capacity is now taken as N_f instead of N. With this modified (variable) system capacity constraint, to keep the minimum guaranteed service time $T_s^{\min}$ unchanged per frame at various system population the frame size is taken as $T_f = N_f T_a + T_s^{\min}$.

The total channel bandwidth in the simulations was considered 4096 bps. In RC-MAC, the control and data channel bandwidth is dynamically adjusted according to the system state. In the proposed scheme, instead, the forward channel (from the field nodes to the gateway) for access request and data transmission 3950 bps capacity is reserved, while for the access response communication in the reverse channel (from the gateway) 146 bps is reserved. This combination of rate splitting for the two channels were to ensure maximization of channel utilization while guaranteeing that the gateway response reaches up to the farthest away field nodes within the same frame of the corresponding access requests. Within the forward channel the resource for access requests and data transmission is dynamically time-shared.

In RC-MAC, there is no concept of frame duration, whereas in the proposed scheme $T_s^{\min}$ was taken as 10.9 sec. The transmission range of the nodes was taken 2000 m, and the data packets were of size 1000 Bytes. The access request packets for RC-MAC were of size 12 Bytes.

The simulation based relative system utilization performances of the dynamic scheme II and RC-MAC are shown in Fig. 15. To obtain 95% confidence intervals we repeated each simulation 15 times for a given value of field nodes. The utilization of scheme II is generated with $\alpha_{opt} =$

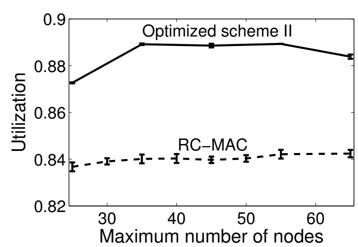

Fig. 15. Utilization performances of optimized dynamic scheme II and RC-MAC.

0.001 and $n_a^{\min} = 0$ at various values of maximum number of nodes in the system. As observed from Fig 15, at all node densities the utilization of scheme II is higher than that of RC-MAC.

RC-MAC uses Aloha for reservation contention, whereas scheme II uses mRSS-Aloha which offers a higher utilization. Further, unlike dynamic variation of control and data channels in RC-MAC, variation of the number of access slots in scheme II is expected to be a more practical approach. Note that NS3 implementation code for RC-MAC protocol does not work beyond 65 maximum nodes. Therefore we compared the scheme II performance with up to 65 nodes.

VII. Concluding Remarks

To sum up, in this work we have demonstrated that the system utilization as well as delay performance can be significantly improved by suitably accounting the traffic and system dynamics via adaptive reservation access protocol for delay-tolerant data transfer applications in UWSNs. Our proposed first dynamic reservation access protocol (scheme I) is system traffic load aware, whereas the second dynamic access protocol (scheme II) is system state adaptive and has an additional parametric control for adjusting sensitivity of the system state on variation of the access duration in a frame. The protocols are adapted to optimally accommodate the propagation delay uncertainty in UWSNs. While both protocols offer improved system utilization and delay performance compared to the conventional fixed reservation access scheme as well as a heuristically adaptive dynamic scheme (PRMA/DA), the performance gains are more prominent at higher system traffic loads. Our protocol performance studies have further demonstrated that the optimized scheme II has the overall best performance in terms of system delay, utilization, as well as keeping the system open to accommodate successful access requests. While both schemes are simple, scheme I has a linear ($O(N)$) complexity whereas scheme II has only a constant ($O(1)$) complexity added with respect to the fixed reservation scheme. A comparative study with respect to a competitive UWSN access protocol (RC-MAC) has shown the optimized scheme II to offer a much higher system utilization performance under similar network and traffic settings. The proposed protocol concepts can be useful in many-to-one long-distance RF network communications as well.

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