A new dynamic reservation protocol for many-to-one multi-access with long propagation delay

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***Abstract*—Reservation multi-access protocol is a natural choice in wireless networks with high inter-nodal propagation delay and sporadic communications. There have been some proposals in delay-intensive networks, such as satellite networks as well as underwater networks, that address the variability of system state for tuning the access window. In this paper, we propose a new parametric dynamic reservation access scheme with an aim to improve the system utilization. We first analyze the system performance in many-to-one multi-access with long propagation delay data transfer scenario with the assumption of perfect propagation delay information and with fixed number of access slots. We then investigate the proposed system state aware approach to suitably adjust the number of access slots and investigate the optimum slotting strategy to maximize the system utilization. Via mathematical analysis, supported by discrete event simulations, we show that the system utilization and blocking probability with our proposed modified reservation protocol is consistently better compared to the competitive reservation protocols with fixed as well as dynamic access slots.**

I. Introduction

In a wireless network, where propagation delay is high and communications are sporadic, some kind of reservation protocol is generally used. If the propagation delay to the receiver is exactly known a priori at the transmitter, the transmission of control/data packets can be suitably staggered at the transmitter, so that they can be received in a predetermined slot time. For a known propagation delay, as in the earth stations to satellite communications, fixed as well as variable number of reservation access slots have been proposed earlier. However, optimality of the number of access slots with respect to the system performance parameters, such as system utilization and blocking probability has not been thoroughly studied.

Like satellite network, in underwater network also propagation delay is high, where short-range communications are aimed at remotely monitoring various aquatic activities, such as marine biological and zoological lives, geological changes, and underwater human activities. In addition to the high propagation delay in underwater network, channel bandwidth is limited and error rate is very high. Also due to the limited battery power of sensor nodes, UWN performance is significantly different due to its sensitivity to propagation delay variations.

Generally, in centralized UWNs, the nodes deployed for sensing and communication purposes collect and send the field data to a gateway node, which further forwards them to the shore via wireless or wire-connected links. Communication from the field 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 many-to-one reservation protocol would be suitable for the field nodes to the gateway communication. Although many-to-one multi-access in RF communication has been extensively studied before, pertaining to distinctly different signal propagation characteristics, the RF multi-access communication protocols are not directly applicable [1]–[10].

Till date, a few reservation protocols have been proposed in the literature for underwater wireless networks (e.g., [6], [9]–[12]) that use either Aloha or modified transmitter-synchronized slotted Aloha (S-Aloha) in the reservation stage. The success rate of these random access protocols at the reservation stage are poor [13]–[15]. To this end, receiver-initiated/ receiver-synchronized reservation protocols, e.g., in [10], [11], [15], are found to offer a higher throughput performance. However, the existing underwater reservation protocol approaches vary widely, and to our knowledge the overall throughput performance of the reservation protocols in a many-to-one communication scenario has not been well-investigated. Moreover, the existing underwater reservation protocols may not be suitable when source-to-destination propagation delay is significantly larger than the packet transmission time.

In a bid to increase the overall network throughput in many-to-one communications with propagation delay, we look into the reservation protocols in satellite to earth stations communications, which encounter a significantly large propagation delay. Among several variants of random access protocols, receiver synchronized S-Aloha (which we call RSS-Aloha) was proposed in [16]. Using this Aloha protocol variants of random access, different reservation protocols were developed for satellite communication networks assuming perfect synchronization [17]–[19]. While [19], [20] have 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.

Also if the perfect synchronization is not possible in any network, then there is a need to increase the slot size to accomodate the imperfection issue.

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Our key contributions in this paper 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 network utilization performance, we propose system state aware optimal multi-access reservation slotting policy, which can work in satellite networks as well as in underwater networks. (b) Via mathematical analysis, supported by simulations, we show that, by optimally adjusting the number of access slots over a fixed size frame, the system performance can be significantly increased compared to the existing competitive schemes.

The rest of the paper is organized as follows: Reservation based multi-access system considered in this paper is presented in Section II. Section III presents the proposed RSS-Aloha based reservation protocols with perfect synchronization assumption and their performance analysis. The numerical and simulation based performance results are discussed in Section IV. The paper is concluded in Section V.

II. Reservation system model

For field nodes to the gateway multi-access, we divide the time into fixed intervals as in [17]–[19]. Each interval encapsulates a frame of fixed size. The front end of the frame is divided into a number of slots for contention based access of data transmission opportunity for the field nodes, whereas the remaining portion of the frame is used for data packet transmission in FIFO (first-in first-out) order. To notify the successful access slots, gateway-to-field nodes downlink communication is carried out via a different channel. Clearly, here the multi-access 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, that are notified through the downlink channel, get to transmit their data in the subsequent frames. A pictorial representation of fixed size frame based reservation protocol is shown in Fig. 1, where the maximum

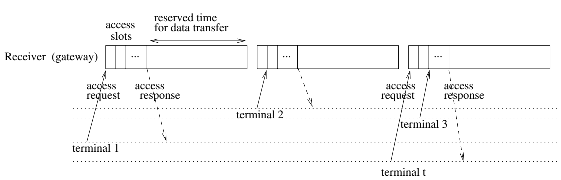

Fig. 1. Timing diagram of underwater reservation-based multi-access protocol with a fixed frame length for field nodes to the gateway data transfer.

propagation delay to the gateway node corresponds to the terminal t.

In Sections III, the system performance with a fixed number of access slots is investigated, and the system performance improvement is studied with the proposed variants of system state aware dynamically adjusted number of access slots with perfect knowledge of propagation delay from different field nodes to the gateway. As a simplifying assumption in the analysis, we consider the data transmission request arrival process in the system is independent of the system state. We consider infinite number of nodes, so every arrival is considered from a seperate node. Also to keep the arrival rate constant, we assume no retry for the unsuccessful access to the access slot. For a successful data transmission request, the data message length is considered 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.

For the system performance optimization, we consider maximization of system utilization ρ, which is defined as the fraction of a (fixed) frame duration used for actual data transmission. The utilization factor ρ will be elaborated in the ensuing Section III.

III. Reservation Protocol

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 of a random number of successful access slots at every frame and random size of data content per node, n is a random variable varying between 0 and the maximum allowed number of queued up data transmission requests N at the gateway, forming a DTMC. DTMC representation of system state with $n_a = 2$ is shown in Fig. 2. In this example,

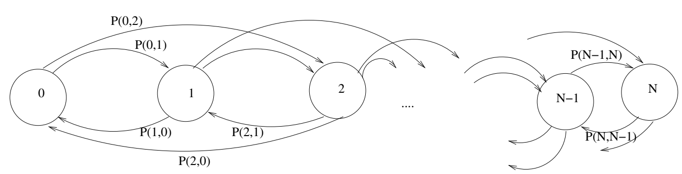

Fig. 2. System state transition diagram in reservation-based access protocol with a fixed number of access slots per frame

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

Denote,

$P_s = \Pr\{\text{successful access request in a slot}\}$,

$P_a(i, n_a) = \Pr\{i \text{ successful arrival of new request from } n_a \text{ access slots}\}$, 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

$$P_s = \frac{\lambda T_f}{n_a} e^{-\frac{\lambda T_f}{n_a}}, \tag{2}$$

λ is the data arrival rate per unit time in the system, and T_f is the fixed frame duration.

Assuming that the service time of the kth user X_k is exponentially distributed random variable with mean $\overline{X} = \frac{1}{\mu}$, the pdf of $X = X_1 + X_2 + \ldots + X_m$ is Erlang distributed.

Here, $P_c(m, n)$ can be expressed as:

$$P_c(m,n) = \begin{cases} \int_0^{T_s} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx & \\ -\int_0^{T_s} \frac{\mu(\mu x)^{m}}{m!} e^{-\mu x} dx, & \text{if } 0 < m < n \\ \int_0^{T_s} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx, & \text{if } m = n \neq 0 \\ e^{-\mu T_s}, & \text{if } m = 0,\ n > 0 \\ 1, & \text{if } m = n = 0 \\ 0, & \text{if } m > n, \end{cases} \tag{3}$$

with $\sum_{m=0}^{n} P_c(m, n) = 1$.

Using (1) and (3), state transition probabilities can be obtained as:

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

$$P(n, n-i) = \sum_{m \leq N-n} P_a(m, n_a) P_c(i+m, n) + P_c(N-(n-i), n) \sum_{m > N-n} P_a(m, n_a) \tag{5}$$

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

$$\underline{\mathbf{P}} = \begin{bmatrix} P(0,0) & P(0,1) & \cdots & P(0,N) \\ P(1,0) & P(1,1) & \cdots & P(1,N) \\ \vdots & & & \\ P(N,0) & P(N,1) & \cdots & P(N,N) \end{bmatrix} \tag{6}$$

with $\sum_{j=0}^{N} P(i, j) = 1$.

Using (6) and with the boundary condition $\sum_{n=0}^{N} p_n = 1$, the steady state probabilities $\underline{p} = \{p_0\ p_1\ \cdots p_N\}$ can be found by solving $\underline{p}\ \underline{\mathbf{P}} = \underline{p}$.

The system utilization, which is defined as the fraction of frame time actually used for data transmission, can be obtained as

$$\rho = \frac{\lambda_a(1-p_N)}{\mu} \frac{T_s}{T_f}. \tag{7}$$

λ_a is the successful request arrival rate at the gateway, given by $\lambda_a = \lambda P_s$, where P_s is obtained from (2). T_s is the fixed duration for data reception service in a frame duration T_f. The average number of pending data transmission requests at the gateway is $\overline{n} = \sum_{n=0}^{N} n p_n$. Note that, p_N is the access request blocking probability, since maximum N successful user requests can be queued up at the gateway. Thus, $\lambda_a(1-p_N)$ is the successful data transmission request arrival rate which are accepted at the gateway for service. For system stability, the service rate μ is such that $\frac{\lambda_a(1-p_N)}{\mu} < 1$.

B. System state based dynamic reservation

To increase the system utilization, we propose an enhanced reservation protocol, we use two parameters i.e α and β to control the number of access slots in all frames, it is adjusted per frame based on the number of pending user requests present in the system. The generic function to determine the number of access slots n_a in the system as a function of system state n so that the system utilization can be maximum is as,

$$n_a(n) = n_a^{\min} \left(\frac{n}{N}\right)^{\alpha} + \beta . n_a^{\max} \left(1 - \left(\frac{n}{N}\right)^{\alpha}\right) \tag{8}$$

Here $\alpha \geq 0$ and $0 \leq \beta \leq 1$ are the 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 $0 \leq n_a^{\min} \leq n_a^{\max}$.
With the knowledge of $n_a(n)$, system state probabilities $\{p_n :\ n = 0, 1, \cdots, N\}$ can be computed using (1)-(6), and hence the system utilization ρ is obtained as:

$$\rho = \frac{\sum_{n=0}^{N-1} \lambda_a(n) p_n \frac{T_s(n)}{T_f}}{\mu}, \tag{9}$$

where $\lambda_a(n) = \lambda P_s(n)$, and data service duration T_s is now a function of the system state n.

No we formulate the optimization problem to get the maximum utilization as:

$$\underset{\alpha,\beta}{\text{Maximize:}}\ \rho = \frac{\sum_{n=0}^{N-1} \lambda_a(n) p_n \frac{T_s(n)}{T_f}}{\mu}$$

$$\text{Subject to: } \underline{p}\ \underline{\mathbf{P}} = \underline{p},\quad \sum_{i=0}^{N} p_i = 1 \text{ and } \sum_{j=0}^{N} P(i,j) = 1$$

where $\lambda_a(n) = \lambda P_s(n)$, $P_s(n)$ is given by (2), $n_a(n)$ is given by (8), and $\{P(i, j) :\ i, j = 0,\ 1,\ \cdots,\ N\}$ are obtained using (1), (3), (4), and (5). Typically, in a given network setting, the quantities T_f, μ, and N are system design parameters. So, the optimum α, denoted as α_{opt}, and optimum β, denoted as β_{opt} are function of the arrival rate λ.

IV. Results and Discussion

System performance of the underwater reservation based protocol variants have been studied in SCILAB using the analytical expressions developed in Sections III.

A. System parameters considered for numerical and simulation results

In the simulations, to see the performance of our proposed (α, β) based enhanced dynamic reservation protocol, the frame utilization, blocking probability were simulated. Also, since the current analytical study does not involve other protocol layers, we chose to use our developed C based discrete event simulation model for creating a random network and verifying the analytical results. The plots were generated using MATLAB.

In simulations, to study the performance of these protocols randomly located large number of nodes were taken around the receiving node. Every arrival treated from a seperate transmitting node. Field nodes those are having data to transmit, first transmits control packets to access the access slots in frame at the receiver. Those nodes are successful to access the access slot, will be provided reserve time at any nearest frame by the server for transmission of data in FIFO order. If the access to the access slot is not successful then that arrival will not be retried, it will be marked as unsuccessful. In each iteration, a randomly located receiver was chosen, and the other neighboring transmitters' activities were controlled by varying the (Poisson distributed) frame arrival rate λ.

Following the underwater modem specifications [21], the parameters considered are: channel rate 16 kbps, acoustic signal speed $v = 1500$ m/s, control message size, 40 Bytes and average data packet size is exponentially distributed with mean 286 Bytes(i.e service rate 7 messagess/second). We are considering fixed frame size in all variant of reservation protocol. Also the frame size need to be more than the round trip propagation delay. We are considering frame size as 0.2 sec and the system capacity,$N = 10$. Transmission range is such that the maximum round trip propagation delay should be less than frame time.

B. Performance Comparison

Before comparing the performance of the protocols of section III and packet reservation multiple access with dynamic allocation(PRMA/DA) [19] we briefly mention the PRMA/DA protocol. Presently we are considering only ABR data traffic so PRMA/DA protocol for ABR data transmission will be useful in the present context. So we are using modified access slots allocation algorithm as:

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

Where

n_a^k is the number of access slots in frame k.
n_s^k is the number of successfully accessed slots in frame k.
n_c^k is the number of collission in the accessed slots in frame k.
$n_a^{\max}$ is the maximum number of access slots in a frame.

First we verify analytical utilization of our proposed enhanced reservation protocol and fixed assignment based reservation protocol with the simulated result as in Figure 3, where we also plot the simulated PRMA/DA protocol performance. This figure shows all the simulation results match well with the anslytical result. In Figure 3, we also compare the utilization of protocols as described earlier. For low load, utilization of PRMA/DA is higher than others, but decreases for higher value of arrival rate. Fixed assignment based reservation protocol, showing high utilization for a particular value of arrival rate, λ with fixed number of access slots($n_a = 4$) per frame. But our proposed (α, β) based enhanced protocol, showing overall high utilization, i.e for low as well as for higher arrival rate this protocol gives higher utilization.

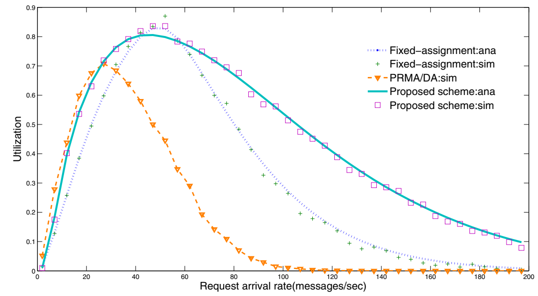

Fig. 3. Utilization comparison and verification with analysis: fixed assignment based, proposed scheme with ($\alpha = 1.06$, $\beta = 0.6$) and PRMA/DA. $n_a^{max} = N = 10$

In Figure 4, blocking probability compared for all the protocols, which shows blocking probability is highest for PRMA/DA, since in this protocol, with the increase of arrival rate most of the frame will be used for access purpose only. Fixed assignment based reservation protocol also has some blocking probability for low value of arrival rate, but blocking probability decreases with the increase of arrival rate, since less number of users get a chance to successfully access the access slots. There is negligible blocking probability for our proposed enhanced reservation protocol, since it has the less and lowest system state among all the protocols compared here.

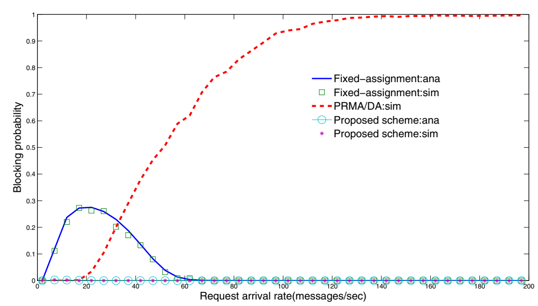

Fig. 4. Blocking probability comparison and verification with analysis: fixed assignment based, proposed scheme with ($\alpha = 1.06$, $\beta = 0.6$) and PRMA/DA. $n_a^{max} = N = 10$

C. Performance Comparison with proposed scheme with optimum tuning parameters

Maximum utilization of our proposed reservation protocol with optimum tuning parameters is compared with the utilization of fixed assignment based reservation protocol with fixed number of access slots($n_a = 4, 5$) and PRMA/DA as in Figure 5. Here if we consider a single value of number of access slots, n_a, for all arrival rate, that shows no single value of n_a exist for fixed assignment based reservation protocol, which can give high utilization for all arrival rate with respect to our proposed enhanced reservation protocol. Also it is not possible to get a n_a value corresponding to all the value of arrival rate with fixed assignment based scheme which will give higher utilization.

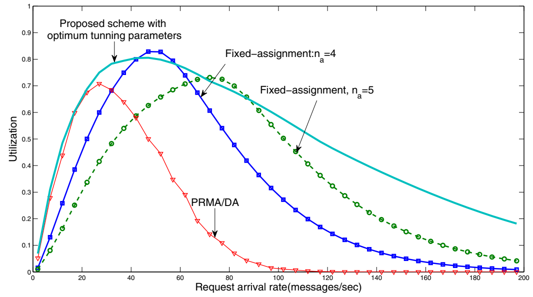

Fig. 5. Utilization comparison: fixed assignment based($n_a = 4$, $n_a = 5$), proposed scheme with optimum tuning parameters and PRMA/DA. $n_a^{max} = N = 10$

Further Figure 5, shows for low value of arrival rate our scheme closely matching with PRMA/DA and in some cases our protocols perform better than PRMA/DA. But for higher value of arrival rate our protocol performs always more better than PRMA/DA, e.g for arrival rate,$\lambda = 100$ there is a difference of 60% higher utilization with our proposed enhanced reservation protocol.

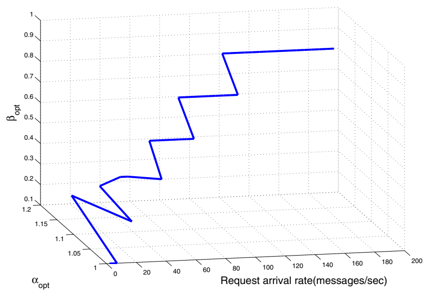

Fig. 6. α_{opt} and β_{opt} of proposed scheme corresponding to given request arrival rate, λ

In Figure 6, we plot the optimum value of $\alpha(\alpha_{opt})$ and $\beta(\beta_{opt})$ corresponding to the given arrival rate,λ, to get the maximum utilization as in Figure 5 which shows an increasing value of (α,β) need with the increase of arrival rate to increase the number of access slots.

V. Conclusion

In this paper we have presented a theoretical framework for utilization performance comparison for reservation based protocol. Also proposed a dynamic state based reservation protocol which perform better than existing similar protocols. We have found the maximum value of utilization for given arrival rate considering our proposed enhanced dynamic reservation protocol.

Our proposed modified protocol can be used in many-to-one like network. This protocol can be useful not only for underwater network but also be useful with little modification for RF network.

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