Slotted Aloha Protocol Delay in Maritime Systems

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***Abstract*—The paper considers the delay of a maritime system that consists of a sea-to-shore radio network and an underwater acoustic random access network. First, the delay of the stabilized slotted Aloha protocol in the case of the radio network is evaluated by itself. Next, the overall delay for the stabilized slotted Aloha protocol in the case of the radio network and the stabilized CSMA protocol in the case of the underwater acoustic network is evaluated as well. Numerical examples are presented that illustrate the delay performance.**

I. Introduction

An effective sea-to-shore transmission of information represents a key aspect in the development of maritime systems [1]. It is an essential component in ocean monitoring [2] and coastal ocean observation [3] which are predicated on reliable collection and transfer of data [4]–[8].

We consider a scenario where underwater acoustic networks communicate with surface buoy stations. The underwater acoustic network is a random access network which consists of bottom mounted sensor nodes that collect data and transmit the data to a surface buoy station. The random access protocol is based on the stabilized carrier sense multiple access (CSMA) protocol [9]. It is assumed that the packets generated by the bottom mounted sensor nodes can be described by independent Poisson processes [10]. A property of the pseudo-Bayesian stabilized CSMA protocol is that the number of packets for transmission remains Poisson distributed given an idle slot or a successful packet transmission, or is well approximated as Poisson distributed given a packet collision [11]. It is therefore assumed that the packet arrival process at the surface buoy stations is also Poisson distributed. In the considered data collection scenario, the surface bouy stations use a radio network to transmit the gathered data to an on shore data center for further processing [12]–[14]. It is assumed that the radio network utilizes the slotted Aloha protocol. Note that the considered approach may represent an appealing solution for maritime systems due to the increased sensing and/or monitoring area provided by the deployment of multiple underwater acoustic random access networks which communicate the sensed data to their respective surface buoy stations.

The paper aims to analyze the delay from a queueing theory perspective [15]. The delay of the slotted Aloha protocol itself is considered first. This is then followed by an evaluation of the overall maritime system delay. The overall delay consists of the delay of the CSMA protocol in the case of the underwater acoustic network [9] and the delay of the slotted Aloha protocol in the case of the radio network.

The paper is organized as follows. Section II overviews the slotted Aloha protocol. Section III analyzes the delay performance of the stabilized slotted Aloha protocol in the case of the radio network between the surface buoy stations and the on shore data center. Section IV presents numerical examples that illustrate the delay performance for the stabilized slotted Aloha protocol itself, as well as the overall delay for the stabilized CSMA protocol and the stabilized slotted Aloha protocol. Section V concludes the paper.

II. Slotted Aloha Protocol

The Aloha protocol was developed by Abramson to establish a radio communication network among the campuses of the university of Hawaii [16]. The slotted Aloha protocol was introduced by Roberts [17]. In the slotted version of the Aloha protocol all transmissions are synchronized. Each packet requires a single slot for transmission. The packet duration is normalized to unity. It is assumed that the packet arrival process at all surface buoy stations is Poisson distributed. Let there be m such stations. The overall arrival rate is λ. The arrival rate per station is λ/m. It is assumed that packet losses are solely due to packet collisions. A collision occurs if two or more packets are transmitted in the same slot. A successful transmission occurs if only one packet is transmitted in a given slot. Each packet that has been involved in a collision needs to be retransmitted at a later slot. The retransmission takes place after some random number of slots. Further packet retransmissions may be necessary in subsequent slots, until the packet's eventual successful transmission. A station with a packet that requires retransmission is referred to as a backlogged station. Let there be n backlogged stations and $m-n$ nonbacklogged stations. The n backlogged stations retransmit packets with probability q_r. The $m-n$ nonbacklogged stations transmit newly arrived packets with probability q_a. Since the packet arrival process at each station is Poisson distributed with mean λ/m, the probability of a new packet transmission is $q_a = 1 - e^{-\lambda/m}$. Let $Q_a(i,n)$ denote the probability that i nonbacklogged stations transmit a packet in a given slot [15]

$$Q_a(i,n) = \binom{m-n}{i} (1-q_a)^{m-n-i} q_a^i. \tag{1}$$

Let $Q_r(i,n)$ denote the probability that i backlogged stations transmit a packet in a given slot [15]

$$Q_r(i,n) = \binom{n}{i} (1-q_r)^{n-i} q_r^i. \tag{2}$$

The probability of a successful packet transmission in a slot is [15]

$$P_{\text{succ}} = Q_a(1,n)Q_r(0,n) + Q_a(0,n)Q_r(1,n). \quad (3)$$

The probability of an idle slot is [15]

$$P_{\text{idle}} = Q_a(0,n)Q_r(0,n). \quad (4)$$

Let $G(n)$ denote the attempt rate, that is, the expected number of transmissions in a slot when there are n backlogged stations and $m-n$ nonbacklogged stations [15]

$$G(n) = (m-n)q_a + nq_r. \quad (5)$$

The approximation $(1-x)^y \approx e^{-xy}$ for small x is applicable if q_a and q_r are small. It follows that the probability of successful transmission is [15]

$$P_{\text{succ}} \approx G(n)e^{-G(n)}. \quad (6)$$

The probability of an idle slot similarly follows as $P_{\text{idle}} \approx e^{-G(n)}$ [15].

The slotted Aloha protocol as described tends to suffer from instability. Namely, if the backlog increases due to a series of unfortunate collisions, it becomes highly likely that subsequent packet transmissions will likewise result in collisions leading to an even greater backlog. It is therefore beneficial to consider a stabilized version of the slotted Aloha protocol. A simple and effective approach is the so-called pseudo-Bayesian algorithm [11]. The pseudo-Bayesian algorithm considers all new packet arrivals as immediately backlogged. There is a single packet transmission probability q_r for all packets. The probability of a successful packet transmission is simply $nq_r(1-q_r)^{n-1}$. The objective of the stabilization algorithm is to obtain an estimate of the backlog at the start of each slot and vary the packet transmission probability accordingly. Moreover, if the a priori probability distribution of the number of packets for transmission is Poisson, it actually remains Poisson distributed given an idle slot or a successful packet transmission, or is well approximated as Poisson distributed given a packet collision. Hence, the name pseudo-Bayesian stabilization [11]. Stability is achieved for all $\lambda < 1/e$ [15].

III. Slotted Aloha Protocol Delay Analysis

We evaluate the sea-to-shore delay in the context of the slotted Aloha protocol. This represents a scenario when there are a number of surface buoy stations that need to transmit packets to the on shore data center over the radio network. It may be of interest due to the increased sensing and/or monitoring area made possible by the deployment of multiple underwater acoustic random access networks which communicate with their respective surface buoy stations. Note that the propagation time over the radio communication channel is neglected.

The delay analysis assumes that the packet arrival rate λ is known. The probability of a successfull packet transmission is assumed to be $P_{\text{succ}} = 1/e$ when the backlog is $n \geq 2$ and $P_{\text{succ}} = 1$ when $n = 1$ [15].

The delay W_i from the arrival of the i^{th} packet to the start of the i^{th} successful packet transmission can be modeled as [15]

$$W_i = R_i + \sum_{j=1}^{n_i} t_j + r_i \quad (7)$$

where R_i is the residual time until the beginning of the next slot, t_j is the interval between the $(j-1)^{\text{th}}$ and j^{th} successful packet transmissions and r_i is the remaining interval until the start of the i^{th} successful packet transmission. After averaging, we obtain [15]

$$W = \frac{1}{2} + \lambda e W + (e-1) - \frac{(1-\lambda e)(e^{\lambda}-1)(e-1)}{\lambda[1-(e-1)(e^{\lambda}-1)]}. \quad (8)$$

The delay W follows as [15]

$$W = \frac{e-1/2}{1-\lambda e} - \frac{(e^{\lambda}-1)(e-1)}{\lambda[1-(e-1)(e^{\lambda}-1)]}. \quad (9)$$

The system delay is

$$T = W + 1. \quad (10)$$

IV. Numerical Results

The delay performance of the maritime system is illustrated by numerical examples. First, we illustrate the delay performance for the stabilized slotted Aloha protocol in the case of the radio network between the surface buoy stations and the on shore data center. The propagation time over the radio communication channel is neglected. The packet arrival rate is $0 \leq \lambda \leq 1/e$.

Figure 1 illustrates the delay performance of the stabilized slotted Aloha protocol in the case of the radio network. It can be observed that for the most part the delay is around 10 s.

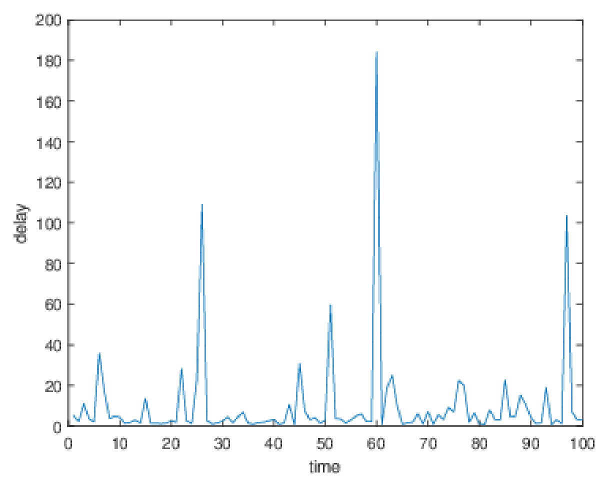

Fig. 1. Delay performance of the slotted Aloha protocol.

Next, we illustrate the overall delay performance for the stabilized slotted Aloha protocol in the case of the radio network and the stabilized CSMA protocol in the case of the underwater acoustic network. Note that the speed of sound propagation underwater is $c = 1500$ m/s [18].

Figure 2 illustrates the overall delay for the stabilized slotted Aloha protocol in the case of the radio network and the stabilized CSMA protocol in the case of the underwater acoustic network. The roundtrip distance between the bottom mounted sensor nodes on the perimeter of the monitored area and the surface buoy station is taken to be $d = 300$ m [9]. It can be observed that for the most part the overall delay is around 11 s.

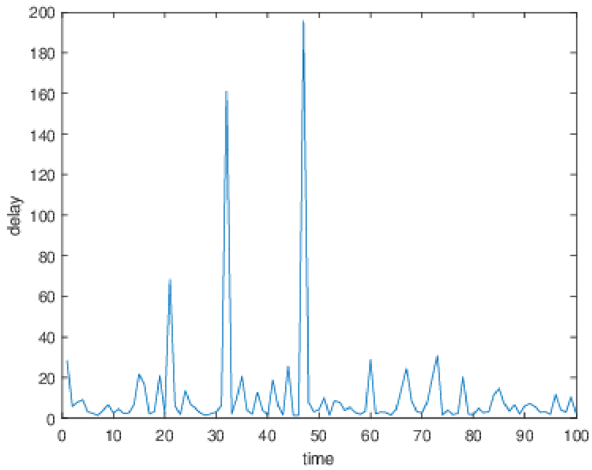

Fig. 2. An overall delay performance of the slotted Aloha protocol and the CSMA network with $d = 300$ m.

Figure 3 illustrates the overall delay for the stabilized slotted Aloha protocol in the case of the radio network and the stabilized CSMA protocol in the case of the underwater acoustic network. The roundtrip distance between the bottom mounted sensor nodes on the perimeter of the monitored area and the surface buoy station is taken to be $d = 500$ m [9]. It can be observed that for the most part the overall delay is around 12 s.

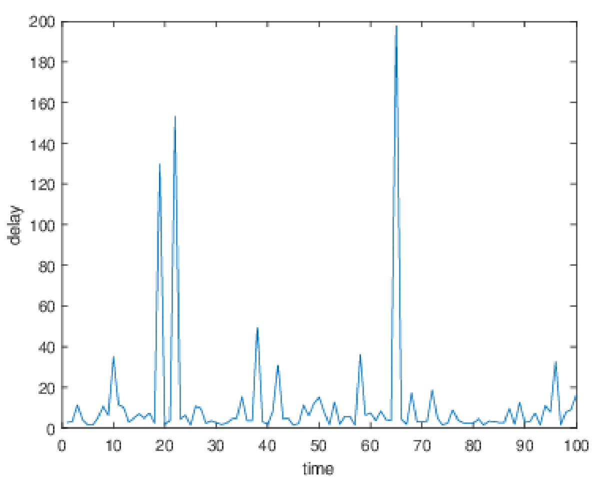

Fig. 3. An overall delay performance of the slotted Aloha protocol and the CSMA network with $d = 500$ m.

V. Conclusions

The paper considered the delay performance of a maritime system that consisted of a sea-to-shore radio network and an underwater acoustic random access network. The sea-to-shore radio network was between surface buoy stations and an on shore data center. The delay performance was evaluated in terms of the stabilized slotted Aloha protocol. The underwater acoustic random access network was between bottom mounted sensor nodes and a surface buoy station. The delay performance was evaluated in terms of the stabilized CSMA protocol. The delay of the stabilized slotted Aloha protocol in the case of the radio network was evaluated first. The overall delay was also evaluated. The overal delay considered the delay for the stabilized CSMA protocol in the case of the underwater acoustic network and the delay for the stabilized slotted Aloha protocol in the case of the radio network. The delay performance was illustrated by numerical examples.

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