Delay in Underwater Acoustic CSMA Networks

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***Abstract*—The paper considers the delay performance of an underwater acoustic multiple access network where bottom mounted sensor nodes transmit packets to an aggregation point. The focus is on Carrier Sense Multiple Access (CSMA) slotted Aloha. It is assumed that packets generated by the sensor nodes can be described by independent Poisson processes. The delay is investigated under the assumption that there is a pseudo-Bayesian stabilization of the considered CSMA network. Numerical examples are presented that illustrate the delay performance.**

I. Introduction

The interest in underwater acoustic networks has experienced a steady growth over the course of the past several years [1]–[3]. In particular, a significant amount of research effort has been aimed towards the investigation of various data collection appraches performed by underwater acoustic sensor networks [4] suitable for ocean monitoring applications [5]. These are networks where a number of sensor nodes perform sensing and collect data in an underwater environment which then needs to be communicated to, say, an aggregation point, through a shared undewater multiple access channel. This necessitates some kind of medium access control that would allocate the shared medium among the sensor nodes and facilitate the reception of collision free packets by the aggregation point.

Random access approaches have a general appeal in this regard as the sensor nodes are able to transmit whenever they have data to send to the aggregation point without the need for any scheduling overhead. Aloha and Carrier Sense Multiple Access (CSMA) are two random access approaches that have had a particular appeal as a number of their variations have been proposed and their performance has been investigated in many different settings [4].

The performance of a propagation delay tolerant Aloha protocol for underwater wireless networks has been considered in [6]. An Aloha modification that incorporated a random backoff time before transmission was shown to be suitable for small underwater acoustic networks [7]. Another approach considered slotted Aloha where the nodes transmission probabilities were assigned in a heuristic manner [8]. A traffic adaptive receiver synchronized MAC approach that adjusts the packet transmission time in a slot based on the distance between the transmitter and the receiver was studied in [9]. CSMA Aloha approach that senses the underwater channel for a random duration of time before transmission was investigated in [10].

The paper is organized as follows. Section II overviews Carrier Sense Multiple Access (CSMA) slotted Aloha. The focus is on an underwater acoustic network where multiple sensor nodes transmit packets to an aggregation point. The emphasis is on nonpersistent CSMA as a means to reduce the possibility of packet collisions at the cost of an increase in the delay. Section III considers the CSMA network delay performance. The delay is investigated under the assumption that there is a pseudo-Bayesian stabilization of the considered CSMA slotted Aloha network. Section IV presents numerical examples that illustrate the network delay performance. Section V concludes the paper.

II. Carrier Sense Multiple Access (CSMA)

We consider an underwater acoustic network where the sensor nodes are sufficiently close to the aggregation point that the propagation delay is less than the packet duration. That means that the time it takes to detect an idle channel due to the propagation delay is a fraction of the packet transmission time. This duration of time therefore represents a suitable length of an idle slot. It is denoted by β. Given the considered scenario, a nonpersistent Carrier Sense Multiple Access (CSMA) slotted Aloha network is appealing [11]. Without the loss of generality, we assume that the packet transmission time for all sensor nodes has been normalized to unity. This means that idle slots and packet transmission slots have different durations. It also means that sensor nodes obtain feedback from the aggregation point with a delay that is upper bounded by β. Packet transmission times are assumed to be synchronized. If two or more sensor nodes send packets at the same time a collision occurs. Collided packets need to be retransmitted during a subsequent slot. If only a single sensor node sends a packet to the aggregation point during a slot, that packet is assumed to be correctly received. This means that the packet losses occur solely due to packet collisions at the aggregation point. In this context, the consideration of nonpersistent CSMA emphasizes the reduction of the possibility of packet collisions at the cost of an increase in the delay. Nonetheless, a drawback of this approach is its potential instability. Therefore, a pseudo-Bayesian stabilization for CSMA slotted Aloha is assumed which can be achieved by varying the packet transmission probability based on the estimated backlog [11].

III. CSMA Network Delay Analysis

The focus is on an underwater acoustic network of bottom mounted sensor nodes that need to communicate their data to an aggregation point. It is assumed that the sensor nodes are spread around the aggregation point within some limited radius that describes the monitoring area, as shown in Figure 1.

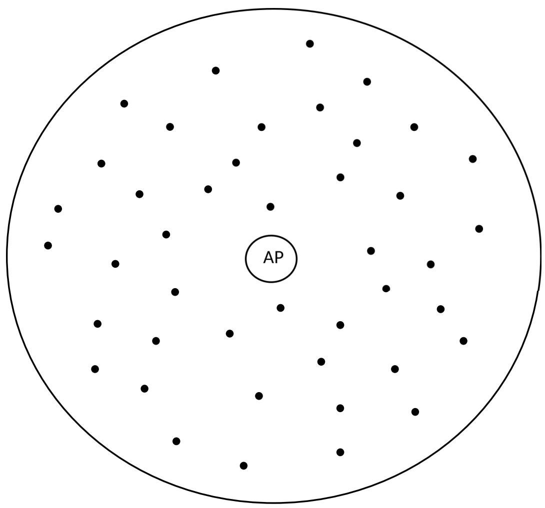

Fig. 1. Sensor nodes and an aggregation point.

Due to the proximity between the sensor nodes and the aggregation point, it is assumed that the sensor nodes can detect whether the channel is idle or busy within a fraction of the packet transmission time, denoted by β. The packet transmission time is simply the packet length in bits per packet divided by the transmission bit rate in bits per second. The packet transmission time is normalized to unity so that it matches the duration of the packet transmission slot. The multiple access network is therefore descibed as a nonpersistent CSMA slotted Aloha with packet transmission time slots of duration unity and idle slots of duration β. The nonpersistent transmission scenario where the sensor nodes sense the channel before the start of the packet transmission is aimed at reducing the possibility of packet collisions at the aggregation point. Due to the nonpersistent assumption, the packet transmission slot regardless of whether it results in a successful packet transmission or a packet collision is always followed by an idle slot.

It is assumed that the packets generated by the sensor nodes can be described by independent Poisson processes. Note that the retransmissions of collided packets are randomized due to the random backoff interval assumption of nonpersistent transmissions. The overall number of transmissions in a slot can then be approximated as a Poisson random variable. Therefore, a queueing theory approach could then be utilized in the analysis of the average delay. Of course, any analysis ought to also take into consideration the need to stabilize the CSMA slotted Aloha network. This is because an increase in the number of transmissions leads to an increase in the number of collisions which then diminishes the number of successful packet receptions at the aggregation point. For this reason, a pseudo-Bayesian stabilization of CSMA slotted Aloha is considered. This is achieved by varying the packet transmission probability based on the estimated backlog. The analysis is aided by the fact 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 that a packet collision occurred. Of course, this is also why the stabilization approach is referred to as pseudo-Bayesian [11], [12].

Given the considered scenario, the delay W_i from the generation of the i^{th} packet to the start of the i^{th} successful packet transmission can be modeled as [11]

$$W_i = R_i + \sum_{j=1}^{n_i} t_j + r_i \tag{1}$$

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, the delay W can be approximated as [11]

$$W \approx \frac{\lambda + 2\sqrt{2\beta}}{2[1 - \lambda(1 + \sqrt{2\beta})]}. \tag{2}$$

Note that it is assumed that the arrival rate λ is smaller than the departure rate, that is [11]

$$\lambda < \frac{1}{1 + \sqrt{2\beta}} \tag{3}$$

which ensures that even when the backlog is significant it decreases on the average.

IV. Numerical Results

The numerical examples illustrate the delay performance of the nonpersistent Carrier Sense Multiple Access (CSMA) slotted Aloha underwater network. The considered network model may represent a suitable scenario when a number of bottom mounted sensor nodes are used to monitor a given underwater coverage area, gather data, and communicate the data to an aggregation point over the shared multiple access channel.

The packet size is $L = 1000$ bits. The bit rate is $R_b = 1$ kbps. The packet duration is therefore unity, that is, $\frac{L}{R_b} = 1$ s. This means that β can be simply evaluated as the amount of time that it takes all sensor nodes to detect that the channel is idle at the end of the transmission. In other words, β is upper bounded in a straightforward manner by the propagation delay that it takes for sensor nodes to obtain feedback from the aggregation point. It follows that

$$\beta = \frac{d}{c} \cdot \frac{R_b}{L} = \frac{d}{c} \tag{4}$$

where d is the network diameter and c is the speed of sound propagation underwater. Note that $c = 1500$ m/s [13].

Figure 2 illustrates the nonpersistent CSMA slotted Aloha network delay performance when $\beta = \frac{1}{5}$. Note that given the considered parameters this corresponds to a network with a diameter of $d = 300$ m. It can be observed that for the most part the network delay is around 3 s.

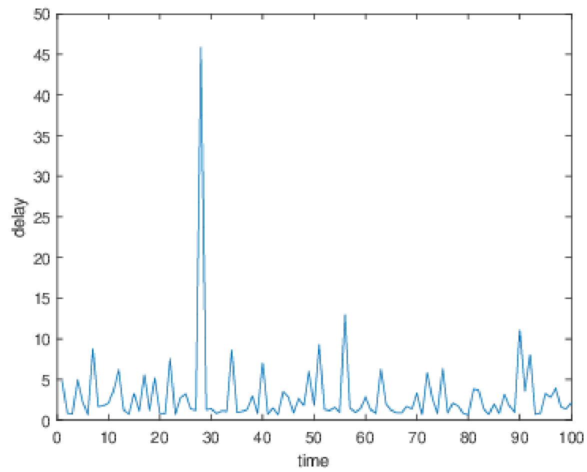

Fig. 2. Network delay when $\beta = \frac{1}{5}$.

Figure 3 illustrates the nonpersistent CSMA slotted Aloha network delay performance when $\beta = \frac{1}{3}$. Note that given the considered parameters this corresponds to a network with a diameter of $d = 500$ m. It can be observed that for the most part the network delay is around 4 s.

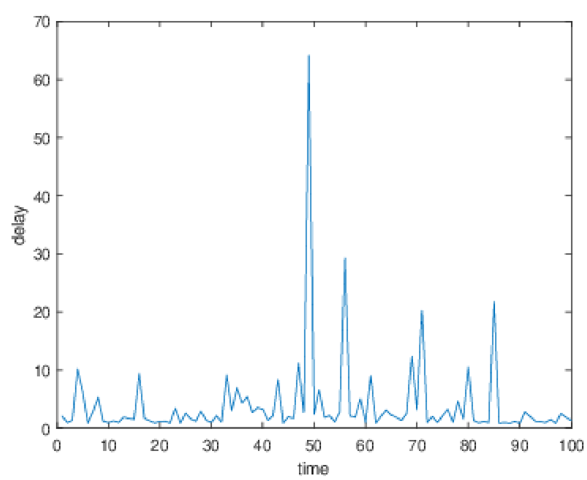

Fig. 3. Network delay when $\beta = \frac{1}{3}$.

V. Conclusions

The paper considered the delay in CSMA slotted Aloha underwater acoustic networks. The network consisted of bottom mounted sensor nodes that communicate the data to an aggregation point over the shared multiple access channel. Nonpersistent transmission was considered as it reduces the possibility of packet collisions at the cost of an increase in the delay. It was assumed that packets generated by the sensor nodes can be described by independent Poisson processes. The delay was investigated under the assumption that there is a pseudo-Bayesian stabilization of the considered CSMA network. The network delay performance was illustrated through numerical examples for scenarios where the sensor nodes obtain feedback from the aggregation point with a delay that is a fraction of the packet transmission time. Finally, note that the considered CSMA slotted Aloha network could potentially be a part of a hierarchical underwater network architecture [14] where the aggregation points themselves could be organized in an underwater acoustic network [15].

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