Delay in Underwater Acoustic Networks

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***Abstract*—The paper considers the delay performance of underwater acoustic networks. The focus is on the network delay when both the queueing delay and the propagation delay are considered. The queueing delay is evaluated for the case of general queues. General queues are of interest since the traffic in underwater acoustic networks cannot necessarily be modeled by a Poisson distribution. The propagation delay is of interest due to the low speed at which sound propagates underwater. Numerical examples are presented that illustrate the delay performance for various distances between the network nodes.**

I. Introduction

The interest in underwater acoustic networks has increased tremendously in recent years [1], [2]. This is due to the general desire to explore the Earth's oceans [3], [4], enhance our understanding and knowledge of the oceans [5], [6], improve awareness of maritime issues [7], [8], and expand the ocean research capabilities beyond the traditional seafaring research vessels and ocean platforms [9].

This means that in addition to the observation [10], monitoring [11] and sensing [12], [13] tasks there are additional considerations, such as, information processing [14] and communication of information [15]. The communication task is rather challenging since underwater acoustic communication experiences attenuation, or path loss, that depends not only on the distance between the transmitter and the receiver, but also on the carrier frequency [16]. Moreover, underwater communication is established by the transmission of acoustic signals, that is, a series of pressure waves [17], [18]. The low speed at which sound propagates underwater introduces transmission delays. These delays can become more pronounced as the distance between the transmitter and the receiver increases.

Several studies have focused on the evaluation of the delay in the case of specific routing protocols [19]–[22]. Nonetheless, there is still a need for a general analysis of the delay in underwater acoustic networks. The delay analysis of underwater acoustic networks needs to take into consideration both the sharing of information among the network nodes for information processing, as well as propagation delays experienced by transmissions between network nodes. We envision a regular topology (grid) network of bottom mounted network nodes that are equipped with sensors which over time take underwater measurements. The measurements are then communicated among the network nodes using multihop routing. The average number of routes per node is obtained based on a combinatorial approach. This is of interest since the average number of routes per node can then be used to evaluate the average traffic relayed by a node [23].

The paper is organized as follows. Section II reviews general queues. The emphasis is on the general G/G/1 queue. General queues are considered since the traffic in underwater acoustic networks cannot be modeled by a Poisson packet arrival process [24]. This means that an analysis based on memoryless queues is not really applicable. Section III considers the network delay performance. The network delay is investigated based on a queueing theory approach. The delay analysis considers both the queueing delay and the propagation delay. Section IV presents numerical examples that illustrate the network delay performance for various distances between the network nodes. Section V concludes the paper.

II. General Queues

We consider general queues. This is due to the fact that the traffic in underwater acoustic networks cannot necessarily be modeled by a Poisson distribution. Therefore, a straightforward analysis based on memoryless queues, such as the M/M/1 queue, where the interarrival times and the service times are described by an exponential distribution, is not applicable [24]. Instead, an analysis based on the G/G/1 queue may be more appropriate as it is characterized by a general distribution for the interarrival times and the service times. The first letter G indicates the general nature of the arrival process. In other words, the packet interarrival times are independent and are given by a general distribution. The second letter G indicates the general nature of the probability distribution of the service times. Note that the interarrival times and the service times are independent. The number 1 indicates that there is a single server, that is, a single communication link.

The average packet delay for the G/G/1 queue is upper bounded by [25]

$$T \leq \frac{\lambda\sigma^2}{2(1-\rho)} + \frac{1}{\mu}. \tag{1}$$

Note that λ is the arrival rate, μ is the service rate, $\rho = \frac{\lambda}{\mu}$ is the utilization factor, and $\sigma^2 = \sigma_a^2 + \sigma_b^2$ where σ_a^2 is the variance of the interarrival times, and σ_b^2 is the variance of the service times. The upper bound therefore only depends on the first two moments of the interarrival times and the service times, rather than a given distribution. The upper bound holds for $0 < \rho < 1$.

III. Network Delay Performance

We consider a regular topology (grid) network with N nodes. A regular grid node deployment may actually be the preferred option when compared to random deployment as it achieves better underwater coverage with a minimum number of nodes [26]. The improved coverage comes at an increased complexity of deployment which can be realized with the assistance of autonomous underwater vehicles [27].

The goal is to determine the average number of routes through an arbitrary network node, say, V. Let the source node be $S(i, j)$. The source node's distance to node V is i hops in the horizontal direction and j hops in the vertical direction. We refer to node V being in position (i, j) relative to the source node. The source node can select any other node in the network as the destination node. The source communicates with the destination using the route with the shortest number of hops. Note that there may be multiple options for the shortest path route between the source and the destination in which case one path is selected at random. The source node's distance to the destination node is x hops in the horizontal direction and y hops in the vertical direction. We refer to the destination node being in position (x, y) relative to the source node. This is illustrated in Figure 1.

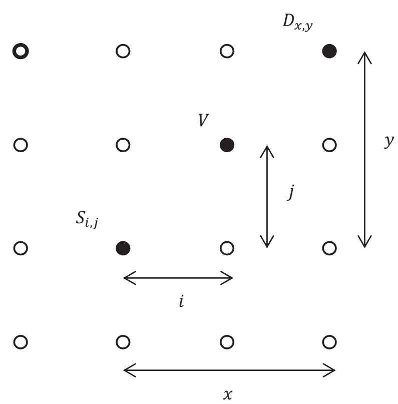

Fig. 1. Regular topology (grid) network.

The probability that node V is on a route of the source node $S(i, j)$ is [23]

$$P_{V_{i,j}} = \frac{(i+j)!}{i!j!(N-1)} \sum_{x=i}^{i_{\max}} \sum_{y=j}^{j_{\max}} \frac{(x+y-i-j)!x!y!}{(x+y)!(y-j)!(x-i)!}. \quad (2)$$

The average number of routes passing through node V follows as [23]

$$n_r = \sum_{\forall (i,j)} P_{V_{i,j}}. \quad (3)$$

Hence, assuming that each network node generates basically the same amount of traffic with an average rate λ_s, the average arrival rate is [23]

$$\lambda_{\mathrm{v}} = \lambda_s + \sum_{i=1}^{n_r} \lambda_s = (1 + n_r)\lambda_s. \quad (4)$$

The network delay can be evaluated as

$$T = \sum_{i=1}^{M} T_i \quad (5)$$

where M denotes the number of hops in the multihop route from the source to the destination. The network delay is the sum of the queueing delay and the propagation delay, that is [25]

$$T = \sum_{i=1}^{M} \left(\frac{\lambda_i \sigma^2}{2(1-\rho_i)} + \frac{1}{\mu_i} + \frac{d_i}{c} \right) \quad (6)$$

where d_i is the distance between neighboring network nodes and $c = 1500$ m/s is the speed at which sound propagates underwater [16].

IV. Numerical Results

The numerical examples illustrate the delay performance of underwater acoustic networks. We consider a regular topology (grid) network with $N = 16$ nodes. A multihop path across the network diagonal is considered. In other words, the source node is in the bottom left corner and the destination node is in the top right corner. The entries for the node's average rates are between 0 and 1. The service rates are assumed to be twice the respective arrival rates. Both the variance of the interarrival times and the variance of the service times are selected as unity.

Figure 2 illustrates the network delay performance as a sum of the queueing delay and the propagation delay. The distances between the network nodes are 1 km. This represents a scenario where all network nodes are placed in close proximity to one another. It can be observed that for the most part the network delay is around 30 s. Note that this is consistent with the average network delay obtained through simulations in the case of the shortest number of hops routing algorithm when the packet size is 500 bits and the bit rate is 1 kb/s.

Figure 3 illustrates the network delay performance as a sum of the queueing delay and the propagation delay. The distances between the network nodes are 5 km. This represents a scenario where all network nodes are placed farther apart from one another. Due to the low speed of sound underwater, the network delay is notably influenced by the propagation delay. It can be observed that for the most part the network delay is around 50 s. Note that this is consistent with the average network delay obtained through simulations in the case of the shortest number of hops routing algorithm when the packet size is 500 bits and the bit rate is 1 kb/s.

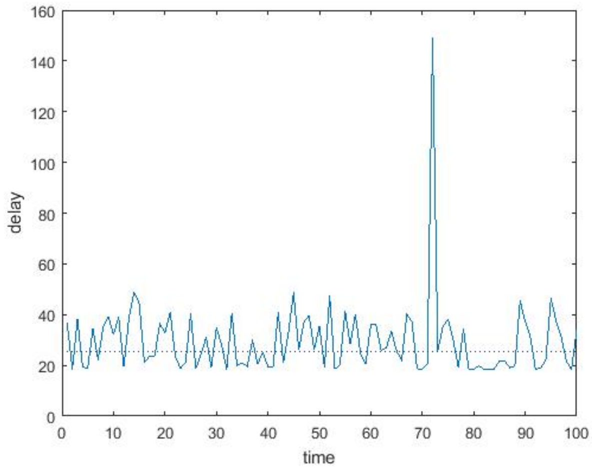

Fig. 2. Network delay when the distances between the nodes are 1 km.

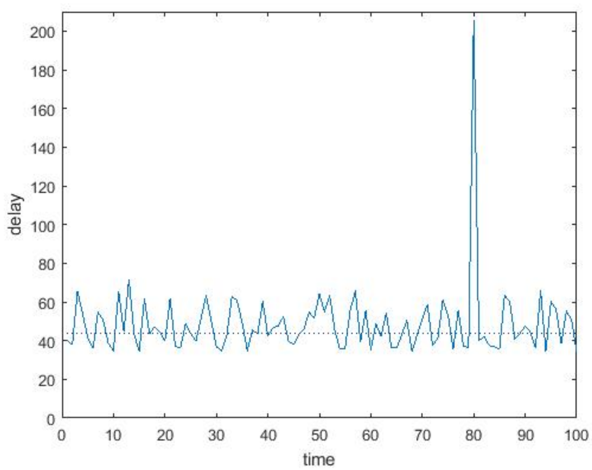

Fig. 3. Network delay when the distances between the nodes are 5 km.

V. Conclusions

The paper considered the delay in underwater acoustic networks. The network delay was investigated based on a queueing theoretic approach. Both the queueing delay and the propagation delay were taken into consideration. The queueing delay was evaluated for the case of general queues. General queues were of interest since a straightforward analysis based on memoryless queues was not applicable. A regular topology (grid) network of bottom mounted nodes was envisioned. Multihop routing based on the shortest hop route was considered. The average number of routes per node was obtained based on a combinatorial approach which was then used to evaluate the average traffic per node. The network delay performance was illustrated through numerical examples for various distances between the network nodes. It was observed that the delay became more pronounced as the distance between the network nodes increased.

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