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Performance Analysis of p-persistent Aloha for Multi-hop Underwater Acoustic Sensor Networks

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Abstract— Media Access Control (MAC) must be carefully considered in multi-hop Underwater Acoustic Sensor Networks (UASNs) due to limited bandwidth and large propagation delay. In particular, variable propagation delays in UASNs cause inaccurate time synchronization and therefore make reservation-based protocols less favorable. Large propagation delays limit the performance of carrier sense in predicting the status of the intended recipients, and therefore CSMA protocols show bad performance in UASNs too. Therefore, simple protocols, such as Aloha, show promise for UASNs. In this paper we consider the performance of a multi-hop *p*-persistent ALOHA protocol.

Keywords-Aloha; underwater; acoustic; sensor networks

I. INTRODUCTION

Multi-hop Underwater Acoustic Sensor Networks (UASNs) differ fundamentally from the packet networks depicted by Kleinrock and Tobagi in [1], since some of the assumptions do not necessarily hold. Nonetheless, a careful consideration of such protocols can yield significant value when selecting an appropriate MAC for use in particular applications like UASNs, especially when the differences and similarities of the employment environments are well understood. Such an analysis was undertaken for the ALOHA protocol within the context of UASNs in [2]. This paper complements that analysis by considering the implications of the multi-hop UASN topology on the performance of a variant of the ALOHA protocol that incorporates a persistence factor in the decision to transmit.

Random access protocols have long been used to avoid inefficient allocation of limited bandwidth to individual communicating entities with bursty traffic or to simplify the implementation of the communications infrastructures. Reservation-based protocols have never been successful in commercial products in the past 50 years due to many drawbacks, such as not being scalable or robust, etc. In particular, variable propagation delays in UASNs cause inaccurate time synchronization and therefore make reservation-based protocols less favorable [7-11]. Employing contention-based, distributed, medium access control (MAC), these protocols must address the potential for two or more hosts to access the medium such that their transmissions overlap in time at the intended recipient, thereby preventing

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successful reception of the traffic; especially since as the traffic intensity increases the performance of contention-based protocols diminishes. Successful contention-based protocols in commercial products such as CSMA/CD in Ethernet and CSMA/CA in IEEE 802.11 WLAN indicate the potential of contention-based protocols in commercial products due them being plug-and-play, simple, robust, and scalable.

The least complex of these protocols is the ALOHA protocol, as defined in [3], which makes no attempt to coordinate the access of the various nodes, resulting in a significant number of collisions as the composite traffic load increases. Several enhancements have been introduced to mitigate the impact of increased loads on this simple protocol.

By incorporating a global time reference, such that hosts could only begin transmission at the beginning of a time slot, the utilization was doubled under some assumptions. However, multiple hosts could still attempt to access the medium simultaneously. Another enhancement considered how voice conversations may coordinate access to the “shared medium” by listening to see if someone was already speaking before initiating a transmission.

However, neither of these protocols is well suited to the underwater environment due to the difficulty in managing a global timing standard and the significant propagation delay, as compared to transmission delay, that limit the value of using information regarding the local status of the medium to project the status at the intended destination. In other words, in UASNs, and other networks with large propagation delays, carrier sense does not work well for predicting the status of the intended recipients, and therefore CSMA protocols show bad performance too. Furthermore, the low speed of the signal’s propagation results in potentially large variations in propagation delays for relatively small differences in distances between nodes. Therefore, simple protocols such as Aloha should be considered for UASNs.

Naor and Levy [4] proposed a variant to the ALOHA protocol for use in satellite networks. Under this variant access to the medium is constrained by a persistence factor, *p*. Thus, it incorporated the simplicity of ALOHA with a means of limiting the potential for collisions as the composite load increases. It should be noted, however, that the trade-off for collision reduction is increased latency.

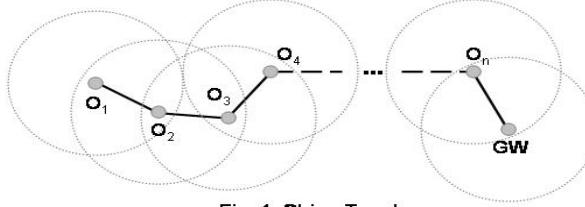


Fig. 1: String Topology

St

ring topology UASNs, as depicted in Fig. 1, are appropriate for moored sensors, such as those proposed to measure various off-shore water channel characteristics [5], or to monitor underwater structures, such as pipelines or entrances to ports. The key differences between these implementations and single-hop packet radio networks include very constrained bandwidth, potentially large normalized propagation delays, very limited numbers of hosts each connected to at most two other hosts, and unique traffic patterns where all traffic flows to a single host, or gateway node. The gateway (GW) is responsible for relaying all received traffic to a remote location over radio or wired links.

While the propagation delays are substantially larger, roughly 667 microseconds per meter, the bandwidth decreases as a function of the range, thereby increasing the frame transmission time. However, the normalized propagation delay increases non-linearly with increased hop-distance [6]. The combinations of non-negligible, increasing normalized propagation delays and limited bandwidth, which may rapidly result in relatively large offered loads, suggest that some form of low persistence variant may be suitable.

The remainder of this paper provides an analysis of the performance of a p -persistent ALOHA protocol as applied to multi-hop UASNs. We study multi-hop p -persistent Aloha in Section II. In Section III, we provide numerical results. Finally, we conclude our paper in Section IV.

II. P -PERSISTENT ALOHA ANALYSIS

Consider a network as shown in Fig. 1. Each sensor node is assumed to randomly generate a frame containing sensor data at an average rate of λ frames per second. The generation of samples is independent between sensors, both locally, should a node have more than one sensor, and between sensor nodes. It is assumed the frame generation for each sensor follows a Poisson distribution. We further assume a constant frame size and uniform transmission rate for all sensors, resulting in a constant frame transmission time, denoted by T . Therefore, the offered load (original frames) of each sensor node is λT .

A. Why Carrier Sense Does Not Work Well

In an underwater acoustic network characterized by large propagation delay, a carrier sense function will not be accurate at all. Typically, a range-rate product value is between 10 and 70 kbps-km, although for shallow water networks (horizontal networks up to 100 meters depth) the range-rate product is closer to 5 Kbps-km. Therefore, over 1.5 km one would expect a maximum of 3 kbps. Given a typical propagation speed of approximately 1500m/s and assuming the transmission rate is 3K bit/s, the sensor data is

64 bytes, and the distance between two directly communicating sensor nodes is 1500m, then the propagation delay is 1s while the transmission time is 0.1666667s. This yields a ratio of propagation delay to transmission time of 6. Normalizing the propagation delay to the transmission delay to restore some generality, in the above case, a device cannot hear the neighbor's transmission until 6 units of time later, but when it hears it, it assumes that the channel is busy, but in fact it will be only busy for 1 unit of time. The above example shows that carrier sense (CS) function does not work well for predicting the status of the intended recipient when the propagation delay is large as compared to the transmission delay.

B. P -persistent Aloha without Dropping Frames

Suppose that a node, O_i , has a frame ready to transmit. It transmits the frame with probability p_i , where we let p_i denote the persistence, p -value, of node O_i . If the frame is not transmitted, it backs-off an exponentially distributed random time and tries again. We refer to this access mechanism as p -persistent Aloha without dropping frames. We further adopt no acknowledgment mechanism: once the frame is sent it is removed from the transmit buffer by the source.

The success probability of O_i 's transmission, P_i , is the success probability of its frame's reception by O_{i+1} . More formally stated:

$$P_i = \Pr \left\{ \begin{array}{l} \text{successful reception at } O_{i+1} \\ \text{frame transmitted by } O_i \end{array} \right\} \quad (1)$$

Note p_i and P_i are different.

Given each node originates frames at the same rate, we have:

$$\lambda_1 = \lambda, \lambda_2 = \lambda(1 + P_1), \lambda_3 = \lambda(1 + P_1 P_2 + P_2), \dots,$$

$$\lambda_i = \lambda \left(1 + \sum_{k=1}^{i-1} \left(\prod_{h=k}^{i-1} P_h \right) \right), \dots, \lambda_{n-1} = \lambda \left(1 + \sum_{k=1}^{n-2} \left(\prod_{h=k}^{n-2} P_h \right) \right),$$

$$\lambda_n = \lambda \left(1 + \sum_{k=1}^{n-1} \left(\prod_{h=k}^{n-1} P_h \right) \right), \text{ respectively.}$$

In general, we have:

$$\lambda_i = \lambda \left(1 + \sum_{k=1}^{i-1} \left(\prod_{h=k}^{i-1} P_h \right) \right), i = 1, \dots, n. \quad (2)$$

Since the arrival process is assumed to be Poisson, we can prove the following (proofs are omitted due to limited space):

$$\begin{aligned} P_i &= e^{-2T(\lambda_i p_i + \lambda_{i+1} p_{i+1} + \lambda_{i+2} p_{i+2})}, i = 1, \dots, n-2 \\ P_{n-1} &= e^{-2T(\lambda_{n-1} p_{n-1} + \lambda_n p_n)} \\ P_n &= e^{-\lambda_n 2Tp_n} \end{aligned} \quad (3)$$

Note that when $p_1 = p_2 = \dots = p_n = 1$, the above is exactly the Aloha protocol [2]. As the purpose of the network is to forward sensor observations through the gateway to the external user, the utilization and throughput of the network can be viewed as the utilization and throughput of the final

link in the network, specifically, the link between O_n and GW . These values are, respectively:

$$U(n) = U_n = \lambda_n \cdot P_n \cdot T \quad (4)$$

We can vary the persistence value, $p_1 = p_2 = \dots = p_n = 1$, to determine how it influences the performance of the network in terms of utilization and throughput.

C. P -persistent Aloha with Dropping Frames

Suppose that the source node drops the frame if transmission is deferred rather than holding it and re-attempting access after a back-off period. In other words, if node O_i has a frame ready to transmit, it transmits the frame with probability p_i ; if the frame is not transmitted, it is dropped. We refer to this as p -persistent Aloha with frame drop. As above, p_i denotes the persistence, or p -value, of node O_i .

Thus, the offered load changes according to the value of p_i . To modify the load equation we only need to incorporate

the persistence into the load. Since the persistence is consistent across all nodes, the value distributes across all factors, yielding the following:

$$\lambda_i = p_i \lambda \left(1 + \sum_{k=1}^{i-1} \left(\prod_{h=k}^{i-1} P_h \right) \right), i = 1, \dots, n. \quad (5)$$

The formulation of $U(n)$ and P_i are unaffected.

III. PERFORMANCE EVALUATION

In this section, we numerically study the effect of varying p values on the performance of the two versions of p -persistent Aloha protocol. Without loss of generality, T is set to 1, i.e., the offered load at each sensor is simply λ . For brevity, most of the evaluation is done for an offered load of 0.01, i.e., each sensor generating an original data frame 1% of the time.

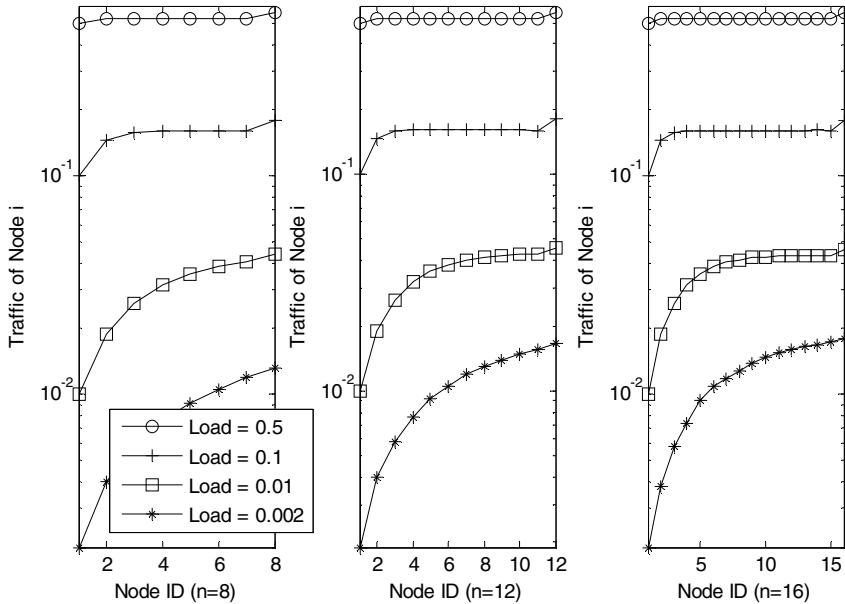


Figure 2. Node Traffic Load (λ_i) versus Node ID(i) for different string lengths (n)

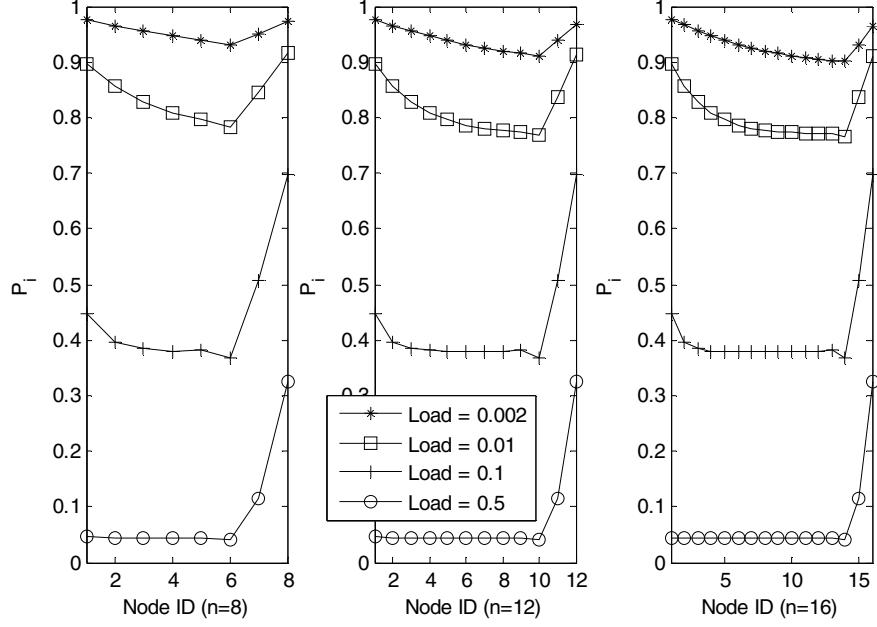


Figure 3. P_i versus Node ID (i) for string length(n)

Performance evaluation of multi-hop Aloha is shown in Figs. 2-5. As noted, we set T to 1. We let $\lambda = 0.002, 0.01, 0.1$, or 0.5 to vary the per-sensor load. Fig. 2 shows the aggregate traffic load of each node ($\lambda_i, i=1, \dots, n$) for different values of the string size n . When the load is small, λ_i increases when i increases, regardless of n . This observation matches our intuition as each node has to forward the frames received from the previous node to the next node. This tendency becomes weak when the load

increases. Evidently, when $\lambda=0.5$, λ_i becomes almost a constant regardless of i . This is because as more collisions occur due to higher traffic loads each node gradually reaches saturation status.

Then, we expect P_i decreases with i due to the increase of the traffic at each node. Fig. 3 shows that no matter what string size is chosen, P_i decreases except at the last two nodes due to their smaller contending node sets. When the load exceeds $\lambda = 0.5$ each node has reached its saturation status and P_i becomes flat.

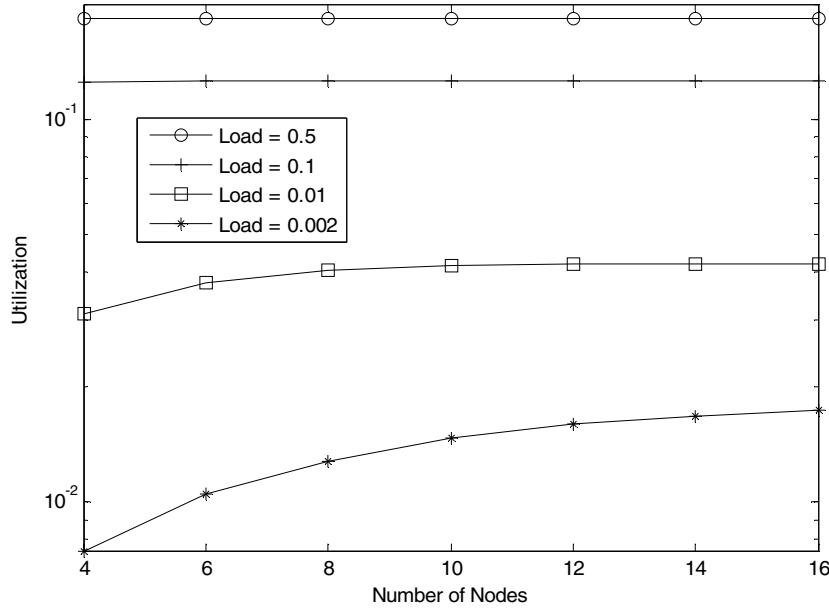


Figure 4. Utilization versus number of nodes at different load(λ)

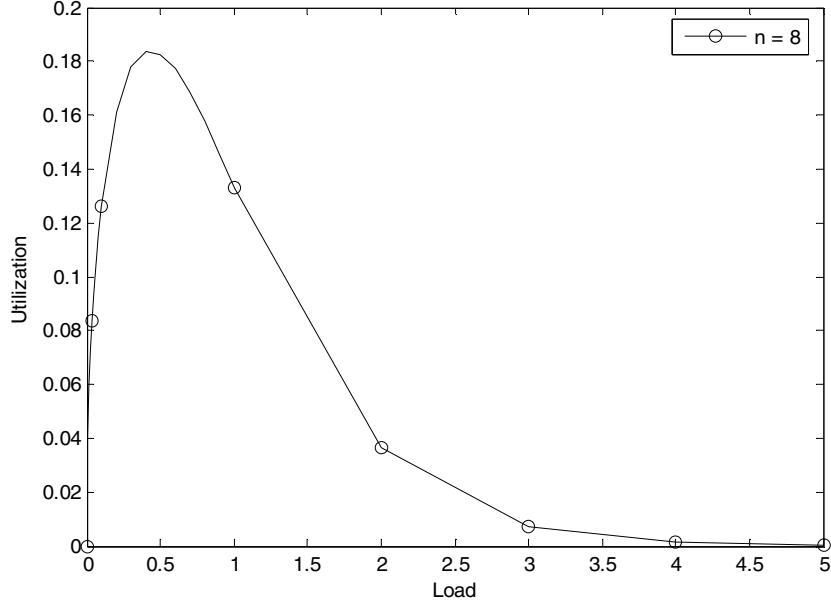


Figure 5. Utilization versus load(λ)

Fig. 4 shows that the network utilization increases with n when the per-sensor load is very small. We expect more frames arrive at the gateway as the string size increases as long as the nodes have not reached their saturation status. We also expect that when the string size becomes large, the nodes close to the gateway will become saturated. Then the utilization will no longer increase. This can be observed when $\lambda = 0.01$. When $\lambda = 0.1$ or 0.5 , all nodes are saturated, or almost saturated, and the utilization is flat regardless of the string size.

Fig. 5 shows the network utilization versus the load for a given string size of eight. Initially, as the per-sensor load increases, but before the nodes reach their saturation status, more frames arrive at the last node to be passed to the gateway. However, with the load surpassing a certain threshold, too many collisions occur, reducing the total number of frames arriving at the gateway. This is exactly what Fig. 5 shows. The utilization first increases with the load. It reaches the maximum when the load is about 0.5. After that, it starts decreasing because of the many collisions. This is precisely the performance characteristic of Aloha applied to single-hop networks.

Performance evaluation of p -persistent Aloha without frame drop is shown in Figs. 6-7. We let $p = 0.1, 0.5, 0.7$, or 1.0 to vary the persistence. Fig. 6

shows the probability of successful reception by each node ($P_i, i = 1, \dots, n$) for three different network sizes ($n = 8, 12$, or 18). When $p = 1.0$, the performance is the same as reported in [2], which is as expected. Note that the probability of successful reception decreases monotonically as traffic proceeds through the network until it reaches the final two nodes. These last two nodes contend with a smaller set of nodes and therefore experience fewer collisions resulting in an increased level of reception success. The three plots in Fig. 6 highlight the fact that when p is smaller, P_i is larger. This is because a smaller p value leads to a smaller subset of neighboring nodes on the average that may send frames concurrently. Therefore, fewer collisions occur and P_i increases. As the performance above is under a fixed $\lambda = 0.01$ it is recognized that if λ is a bigger or smaller value, the performance may be different.

Fig. 7 shows the aggregate traffic load of each node ($\lambda_i, i = 1, \dots, n$) for different values of the string size (n) and with $\lambda = 0.01$. For each p value, λ_i increases monotonically. When p is smaller, λ_i is larger. This observation matches our intuition that more frames are successfully received at each node when p is decreased due to a corresponding increase in P_i .

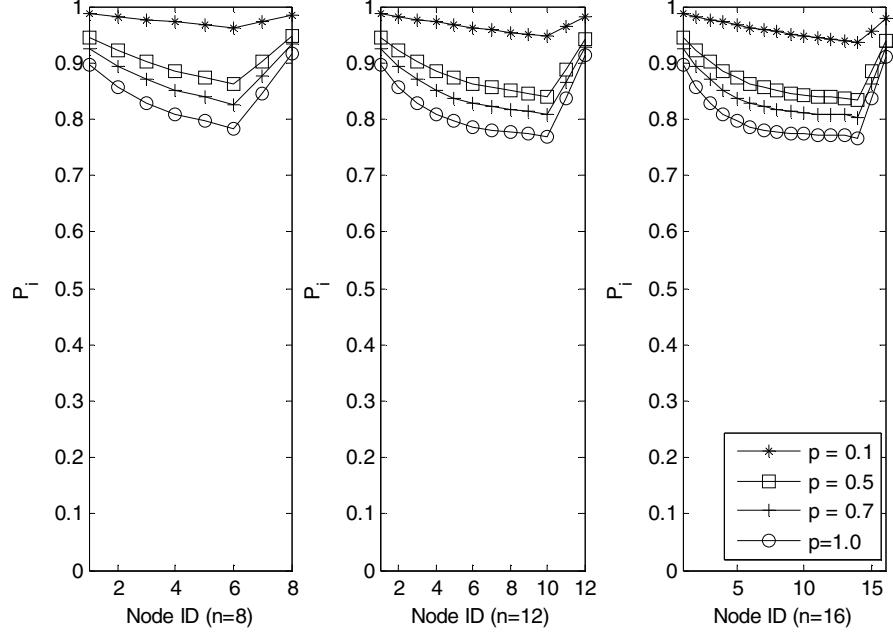


Figure 6. P_i versus Node ID (i) for different network lengths (n)

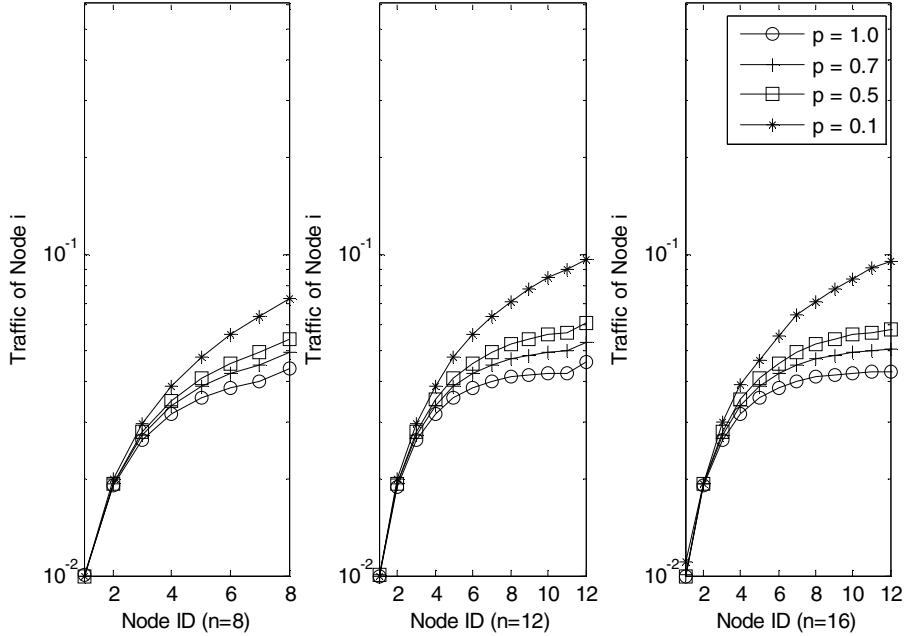


Figure 7. Node Traffic Load(λ_i) vs. Node ID(i) for different string lengths (n)

IV. CONCLUSIONS

In this paper we presented two variants of the classic ALOHA protocol to address the increasing likelihood of collisions as the network load increases. To determine the actual impact of those variants on the utility of the network one must consider the traffic being carried by the network.

We show that the p -persistent ALOHA without frame drop results in improved throughput as the load increases.

However, the latency of those messages that reached the gateway will increase significantly as each node along the path defers transmission in order to reduce the likelihood of collisions at its downstream neighbor. If the traffic is time-sensitive then this increased latency may be unacceptable, thereby limiting the benefit of the protocol to the user. If however, the traffic is not time-sensitive, then the increased latency is not an issue and the improved throughput will increase the utility of the network.

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