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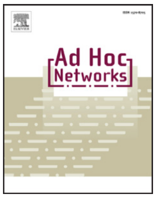

Performance analysis of Block ACK-Based Slotted ALOHA for wireless networks with long propagation delay[☆]

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ABSTRACT

Recently, many variants of Slotted ALOHA (S-ALOHA) have been proposed to solve a problem of performance degradation in wireless networks with long propagation delay. However, they do not consider the effect of retransmission, which also largely degrades performance, and do not provide any analytical model that considers the effect. In this paper, we design a variant of S-ALOHA to support retransmission and derive analytical models that do consider its effect. The designed scheme has a framed structure that starts with a coordinators beacon. The beacon consists of a coordinators timestamp and Block ACKnowledgment (B-ACK). Using the timestamp, a node estimates propagation delay to the coordinator (*PDC*) in order to reduce guard time while transmitting a packet. Moreover, B-ACK is used to report the results of all transmissions attempted in the previous frame at once. As a result, the designed scheme can largely reduce the number of feedbacks and waste of guard time. Even if there is no analytical model that considers the long propagation delay and retransmission simultaneously, we choose the existing analytical models that consider a framed structure and B-ACK as reference models. However, they are not fully mathematical and partially use simulation results because of high computational complexity. Moreover, these models only analyze stability and throughput as performance metrics. On the other hand, our analytical models are fully mathematical models and can analyze all metrics, such as stability, throughput, and packet delay. We expect our analytical models to be a foundation for deriving fully mathematical models for variants of S-ALOHA using a framed structure and B-ACK.

1. Introduction

Slotted ALOHA (S-ALOHA) is one of the most widely used random access protocols originally designed to enhance ALOHA throughput. While all the nodes in an ALOHA network transmit a packet immediately after it is generated, the nodes in an S-ALOHA network first wait until the start of the upcoming slot to transmit the packet. Thus, S-ALOHA can provide higher throughput than ALOHA because of reduced packet collision probability.

However, this is not valid when the propagation delay of a network is not negligible. In such network, there are collisions caused not only by time uncertainty, but also by long propagation delay. This is called the space-time uncertainty [1,2]. To prevent collisions caused by the long propagation delay, a guard time is required. In [3], simulation result shows that ALOHA and S-ALOHA without guard time provides almost equal throughput because S-ALOHA without guard time suffers from collisions caused by not only

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time uncertainty but also long propagation delay. After all, the throughput of S-ALOHA can be degraded. In [2], S-ALOHA with guard time is considered to resolve the space-time uncertainty. However, the results show that the guard time can be a waste and degrades throughput of S-ALOHA. In [1,4], analytical model for normalized throughput of S-ALOHA is given. Under the assumption that a packet arrival from infinite nodes follows Poisson distribution and retransmission is not considered, normalized throughput of S-ALOHA is given by $Ge^{G(1+\alpha)}$, where G is the offered load and α is the ratio of a guard time length to a packet transmission delay.

We define a *long propagation network* as the network with non-negligible α and different propagation delays between a coordinator and any nodes. In the long propagation network, normalized throughput of S-ALOHA is degraded and even lower than that of ALOHA when α is greater than one [1].

Recently, many variants of S-ALOHA have been proposed to solve the problem of throughput degradation in long propagation networks [1–3,5–8]. In [5], Improved Synchronized Arrival Slotted ALOHA (ISA-ALOHA) provides a time alignment mechanism where a node adjusts the start time of transmission in order to allow a packet to arrive at the start time of a slot at the coordinator. The time alignment mechanism can prevent collisions caused by different propagation delays. Thus, ISA-ALOHA can provide higher throughput than S-ALOHA. In [6], the modified Receiver Synchronized S-ALOHA (mRSS-ALOHA-uw) also performs time alignment mechanism to reduce the guard time. Moreover, it also considers the imperfect propagation delay information owing to the irregular underwater signal propagation speed. Thus, various guard time lengths are used. However, both ISA-ALOHA and mRSS-ALOHA-uw require the assumption that all nodes know their *propagation delay to coordinator* (*PDC*), even if the PDC is not accurate. In [1], Beacon-Based Slotted ALOHA (BS-ALOHA) does not require such assumption. Instead, it provides a framed structure to estimate *PDC*. At the start of every frame, the coordinator broadcasts a beacon with its timestamp. After receiving the beacon, all nodes estimate *PDC* periodically. Then all nodes can perform time alignment with the *PDC*. After all, BS-ALOHA can improve normalized throughput without the assumption of both ISA-ALOHA and mRSS-ALOHA-uw. More variants of S-ALOHA are surveyed and categorized in [7,8,16].

However, existing schemes, such as BS-ALOHA and ISA-ALOHA, have limitations. First, these schemes do not consider retransmission, although it can largely degrade performance. If these schemes support retransmission, sending a feedback, ACKnowledgment (ACK), requires non-negligible guard time again. However, this guard time cannot be reduced by the time alignment mechanism proposed in [1,5]. Thus, we need to provide a method for minimizing the effect of sending feedback when we consider a retransmission in S-ALOHA. Second, there is no adequate analytical model that considers the effect of retransmission in long propagation networks. Moreover, a new variant of S-ALOHA may have a framed structure as BS-ALOHA. Then, the analytical model should additionally consider not only the framed structure, but also the effect of retransmission in long propagation networks. However, there is no such analytical model yet.

More specifically, there are several analytical models for S-ALOHA that consider retransmission. In [9,10], S-ALOHA supports retransmission with an immediate ACK. In a slot, a sender transmits a packet and the receiver immediately sends an ACK if it receives the packet successfully. These models were constructed using a Markov chain whose state is defined as the number of backlogged nodes. The state can be changed individually by slot. In [11,12], S-ALOHA has a framed structure and supports retransmission with a delayed ACK. In [11], if a receiver obtains a packet successfully, it sends an ACK after several slots. Thus, ACK corresponds to a packet. On the other hand, in [12], ACK is different from that of [11] because this reports the results of all transmissions attempted by all nodes in the previous frame at once. Thus, this ACK is called Block ACK (B-ACK). At the beginning of every frame, B-ACK is sent to all nodes in the network. In [11,12], a system was designed using a Markov chain whose state is the number of backlogged nodes, similar to [9,10]. However, the difference is that the number of backlogged nodes can be decreased by more than one because the state in [11,12] can be changed individually by frame, not by slot. Thus, there are many cases of the change of the number of backlogged nodes and the computational complexity of the state transition probability grows exponentially fast with the number of nodes. Because of high computational complexity, both Markov chain models [11,12] partially use simulation to obtain the state transition probability, instead of mathematical analysis. To the best of our knowledge, there are no fully mathematical models for analyzing stability, throughput, and packet delay when S-ALOHA uses a delayed ACK.

In this paper, we simply design a variant of S-ALOHA, namely Block ACK-Based Slotted ALOHA (BAS-ALOHA), by modifying BS-ALOHA [1]. Similar to BS-ALOHA, our BAS-ALOHA has a framed structure to estimate *PDC* periodically, and provides a time alignment mechanism to reduce guard time. The framed structure consists of a time period for beaconing and a group of multiple time slots for random access. The difference is that a beacon of BAS-ALOHA additionally includes B-ACK to report the results of all transmissions attempted in the previous frame at once. Thus, at the start of every frame, all the nodes that receive the beacon can recognize whether their transmission of the previous frame was successful. BAS-ALOHA can largely reduce retransmission overhead using B-ACK, instead of multiple immediate ACKs. However, to design BAS-ALOHA is not main contribution. As mentioned above, to the best of our knowledge, there are no fully mathematical models for analyzing stability, throughput, and packet delay when S-ALOHA uses a delayed ACK such as B-ACK. Therefore, the main contribution of this paper is to construct the fully mathematical models for BAS-ALOHA. First, the analytical model for stability is constructed based on [12] because of the similar retransmission method using B-ACK. Thus, the analytical model for BAS-ALOHA is also constructed using a Markov Chain whose state is defined as the number of backlogged nodes. However, as mentioned before, in order to obtain the state transition probability, simulation is used in [12]. On the other hand, we construct fully mathemat-