DCCTA: Age of Information in Slotted ALOHA under Duty Cycle Constraints

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***Abstract*—Slotted ALOHA has been receiving renewed interest due to its suitability as a channel access scheme in low-overhead IoT and LP-WAN scenarios. Threshold ALOHA (TA) is a modification of slotted ALOHA where users only become inactive when the Age of Information (AoI) of their respective packet flows rises above a certain threshold. TA, as well as related algorithms (e.g., SAT, MiSTA) proposed in recent literature, control the access to the channel to communicate fresh rather than stale data, without loss of throughput with respect to ordinary slotted ALOHA. This paper was motivated by the fact that many low power wide area network (LP-WAN) scenarios where TA and its variants are useful are bound in practice by mandatory duty cycle constraints. We observe that under such constraints the previously proposed TA variants run into duty cycle violations, when in fact these may be avoidable without sacrificing throughput or freshness. We propose a modification of TA, referred to as Duty Cycle Compliant Threshold ALOHA (DCCTA), that obeys a given duty cycle constraint and analyzes its performance.**

***Index Terms*—Age of Information, AoI, Age-aware random access, IoT, Slotted ALOHA, Threshold ALOHA, random access, duty cycle, LoRa, LPWAN.**

I. INTRODUCTION

Internet of Things (IoT) use cases today come with a diverse set of timeliness requirements, from real-time or near-real-time applications in navigation or tracking to relatively sporadic data delivery in agriculture or environmental monitoring. However, in many IoT applications (especially those that make computations based on the current status of a measured process), stale data is obsolete, thus it is more efficient to make use of network resources to deliver data when it is fresh. The need for fresh data is influencing a re-evaluation of communication protocols with freshness-oriented objectives. Conventional metrics for the performance evaluation of communication networks such as throughput and delay do not directly address the freshness of information, which popularized the use of Age of Information (AoI) [1, 2] as a KPI in recent years.

The age $\Delta(t)$ of a packet flow at time t is the age of the freshest packet available at the destination of the flow at time t. More precisely, let $u(t)$ be the generation (sampling) time of the most recently generated sample that has already reached the destination by time t. Then $\Delta(t) = t - u(t)$. According to this plain definition, the $\Delta(t)$ rises linearly in time, in the absence of a sufficiently new update. Then, keeping the age low requires a sufficient influx rate (i.e., throughput) of new samples (that is, samples that have not already aged due to excessive delay in the channel). This means a good age performance requires controlling not only channel delay but also the rate at which packets are put out [3]. **In other words, optimizing age in a network ultimately requires relaxing the assumption of exogenous arrivals [4] and allowing the source to generate samples "at will".** Recently, in addition to analyses of AoI in multiple-access protocols [5], there have been proposals to modify these protocols to allow age optimization through the generate-at-will model [6, 7, 8].

A majority of age-aware protocols suggested in the literature adopted an IoT system model with many sources sharing a channel to a common access point. While these protocols have been optimized for data freshness, to the best of our knowledge, none to date have accounted for duty cycle constraints. However, in practice, frequency bands used for IoT applications are often subject to strict duty cycle regulations. For instance, in the ISM band used by prevalent IoT technologies such as LoRa$^{\text{TM}}$ and SigFox$^{\text{TM}}$ [9] a 1% duty cycle limitation is imposed in Europe, on the uplink [10]. Such a harsh limitation on the use of the channel by each node inherently introduces an age bottleneck, which can be significant. Therefore, duty cycle constraints can hardly be ignored when adapting age-aware channel access mechanisms to practical protocols.

This paper proposes a duty-cycle compliance modification to threshold ALOHA (TA), which was introduced in [6] and analyzed in [8]. We name this policy Duty-Cycle Compliant Threshold ALOHA (DCCTA). Each user implementing TA is forced to stay inactive for a fixed period after each successful or unsuccessful transmission. Closed-form approximations are derived for the time average and expected peak AoI of this system. We show that DCCTA avoids the duty cycle violations that other policies (such as TA, SAT[11] or MiSTA[12]) run into when operating at their age optimizing parameter settings. Moreover, we observe that DCCTA achieves roughly the same age and throughput values as TA under perfect channel conditions. A striking performance advantage of DCCTA with respect to TA is seen in lossy channel

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conditions, where packet losses can occur due to packet errors even in the absence of a collision.

Next, in Section II, the system model is described. In Sec. III, the DCCTA policy is defined and analyzed. A numerical study of DCCTA is presented and discussed in Section IV. In Sec. V, the impact of a duty cycle restriction on the gateway is discussed. We conclude the paper in section VI.

II. SYSTEM MODEL

We consider a single-hop wireless channel shared by n sources transmitting time-sensitive information to a single access point (AP). The purpose of each source is to keep its respective destination, reached via the AP, up-to-date with fresh information. The freshness of the information is captured with the AoI metric. Time is slotted, and all nodes are synchronized to the slotted time frame. The sources receive success feedback that AP sends as an acknowledgment after a successful transmission in a slot. The sources utilize the success feedback to keep track of their ages. We adopt the “generate-at-will” model for packet generation [3], where there are no packet re-transmissions. When a source decides to transmit, it generates a fresh packet. We do not utilize a collision resolution mechanism, hence there can be at most one successful transmission in a given slot and collisions result in packet loss.

We define the Age of Information (AoI) of source i at some time slot t as $A_i[t]$. By definition, $A_i[t]$ is equal to the difference between the current system time and the time-stamp of the freshest packet at the AP belonging to source i. In our slotted time system model with the generate-at-will assumption, this difference is equal to the number of slots since the last successful transmission by source i plus 1. As stated before, the sources utilize the success feedback to keep track of their ages. For this purpose, they increment the $A_i[t]$ value in each slot without success feedback and reset it to 1 when success feedback is received. Then, the time evolution of the age is given by:

$$A_i[t] = \begin{cases} 1, & \begin{array}{l}\text{successful transmission}\\ \text{at time slot } t-1\end{array} \\ A_i[t-1]+1, & \text{otherwise} \end{cases} \tag{1}$$

Then, we define the long-term average AoI of source i as

$$\Delta_i = \lim_{T\to\infty} \frac{1}{T}\sum_{t=0}^{T-1} A_i[t], \tag{2}$$

whenever the limit exists.

TABLE I: Notation to be used throughout the paper.

$A_i(t)$	AoI of source i at time t
Δ_i	Long-term average AoI of source i
n	Number of sources
τ	Transmission attempt probability in a slot
p	Probability of a transmission being successful
Γ	Age threshold
γ	Duty cycle threshold

In the analysis of Threshold ALOHA (TA) [8], it was shown that the utilization of a fixed AoI threshold alone already achieves significant age improvement: For a network of symmetric users, threshold ALOHA asymptotically reduces average age by almost 50%, while maintaining the throughput at the same level as ordinary slotted ALOHA. Other, more sophisticated policies with a dynamic threshold or a reservation-based mechanism can reduce age even further, however, we base the investigation in this paper on the simpler policy TA which will suffice to shed light on the impact of the duty cycle limitation.

While the suggested age-aware ALOHA protocols in the literature [7, 8, 12] have been motivated by large-scale IoT deployments, they do not specify any means to comply with duty cycle regulations. However, such regulations are present in many of the spectrum allocations used for prevalent IoT use cases, for instance, the ISM band. In the specific case of the ISM band duty cycle regulation, each transmitter has to be silent for some multiple of the on-air-time of their packets, after transmitting. Other duty cycle limitations may be defined in an average time-on-air sense, which may give more flexibility to the protocol designer. Nevertheless, in the rest, we will adopt a model consistent with the ISM band regulation in Europe, which enforces the source to strictly satisfy duty cycle regulation between any two periods of transmission.

III. DUTY CYCLE COMPLIANT THRESHOLD ALOHA

In this section, we describe the Duty Cycle Compliant Threshold ALOHA policy and analyze its performance in terms of information freshness. In the threshold ALOHA policy of [8], sources that make a successful transmission in a slot have to wait for Γ slots before making another transmission attempt. However, in a duty cycle constrained scenario, any source that makes a transmission, whether successful or not, has to wait for γ slots before the next transmission attempts to account for the duty cycle constraint. As a result, we shall assume that $\Gamma \geq \gamma$, to comply with duty cycle restrictions.

A source is defined as active if it does not have to wait for any of these two constraints, i.e. if it is free to make a transmission attempt in the next slot. Just as in regular slotted ALOHA, an active source will make a transmission attempt in the next slot with a probability τ. When a source makes a transmission attempt, the duty cycle counter (of length γ slots) will be initiated, regardless of whether the transmission was successful or not. If the transmission is not successful, the node is allowed to attempt again after this counter expires. If however, the transmission was successful, the source will continue to be inactive for additional $\Gamma - \gamma$ slots until the age threshold is crossed.

In our analysis, we make the approximation that at the steady state, the probability of any transmission being successful is p. Similar approximations have been made in the analysis of related random access schemes [13, 14, 15, 16]. This approximation may be justified as follows. Strong convergence of the ratio of active sources to the number of all sources to a constant in the large network limit was shown in [8]. As, in SA and TA variants, the probability of a transmission being successful at any time is a function of the attempt probability, τ, and the number of active users, the success probability also converges.

Following, we may characterise the interdelivery times between the consecutive successful transmissions from a source i as follows:

$$I = Y + \sum_{j=1}^{Z} X_j, \tag{3}$$

where Z is the random variable representing the number of transmission attempts until a successful transmission occurs and X_j is the time between the $(j-1)^{\text{th}}$ and j^{th} transmission attempts following the last successful transmission for $j \geq 2$. Note that, the source must wait for Γ time slots immediately after a successful transmission, as opposed to the waiting time of γ time slots after failed transmission attempts. In order to conserve the symmetry, we introduce the constant $Y = \Gamma - \gamma$ such that $Y + X_1$ represents the waiting time until the first transmission attempt occurs after the successful transmission. Then, $\{X_j\}_{j=1}^{\infty}$ sequence is IID and is independent of Z.

Proposition 1. *In the large network limit, at steady state, the mean and the variance of interdelivery times between the consecutive successful transmissions is as follows:*

$$\mu_I = \Gamma - \gamma + \frac{\gamma\tau + 1}{\tau p}, \tag{4}$$

$$\sigma_I^2 = \frac{(\gamma\tau+1)^2(1-p) + (1-\tau)p}{\tau^2 p^2}. \tag{5}$$

Proof. Conditional expectation and variance of I with respect to Z can be written as follows using (3):

$$\mathrm{E}[I \mid Z] = Y + \mu_X Z, \tag{6}$$

$$\mathrm{Var}(I \mid Z) = \sigma_X^2 Z. \tag{7}$$

Following, the mean and the variance of I may be obtained using the moments of other random variables, using the law of total expectation and total variance, respectively:

$$\mathrm{E}[I] = \mathrm{E}[\mathrm{E}[I \mid Z]] = Y + \mu_X \mu_Z, \tag{8}$$

$$\begin{aligned}\mathrm{Var}(I) &= \mathrm{E}[\mathrm{Var}(I \mid Z)] + \mathrm{Var}(\mathrm{E}[I \mid Z]) \\ &= \sigma_X^2 \mu_Z + \mu_X^2 \sigma_Z^2.\end{aligned} \tag{9}$$

Further, we note that $Z \sim Geom(p)$ and $X \sim Geom(\tau) + \gamma$ to obtain the statistics of X and Z:

$$\begin{aligned}\mu_Z &= \frac{1}{p}, \quad \sigma_Z^2 = \frac{1-p}{p^2}, \\ \mu_X &= \gamma + \frac{1}{\tau}, \quad \sigma_X^2 = \frac{1-\tau}{\tau^2}.\end{aligned} \tag{10}$$

Finally, (4) and (5) can be obtained from (8), (9) and (10). ☐

Proposition 1 allows us to evaluate the performance of a network with DCCTA policy in terms of the policy parameters and p. The throughput of the network is $\frac{n}{\mu_I}$, due to the homogeneity between the sources. The average AoI of a policy with IID interdelivery times is characterised by the following formula [17, Ch. 5]:

$$\Delta = \frac{\mathrm{E}[I^2]}{2\mathrm{E}[I]}. \tag{11}$$

In the following proposition, we unite Proposition 1 and (11) to express the average AoI of the DCCTA policy.

Proposition 2. *In the large network limit, at steady state, the time average AoI of any source, Δ, achieved under DCCTA with age threshold Γ and duty cycle compliance backoff time γ can be approximated as follows:*

$$\Delta = \frac{1}{2}\left(\mu_I + \frac{\sigma_I^2}{\mu_I}\right), \tag{12}$$

where μ_I and σ_I^2 are given in (4) *and* (5).

Corollary 1. *In the special case of $\gamma = 0$, the mean and the variance of the interdelivery times is found as:*

$$\mu_I = \Gamma + \frac{1}{\tau p}, \tag{13}$$

$$\sigma_I^2 = \frac{1}{\tau^2 p^2} - \frac{1}{\tau p}. \tag{14}$$

This special case is equivalent to a TA policy with age threshold Γ and attempt probability τ. As such, (13) *and* (14) *provide an alternative methodology to evaluate the performance of a TA policy, compared to [8].*

Corollary 2. *In the special case of $\Gamma = \gamma$, we obtain:*

$$\mu_I = \frac{\gamma\tau + 1}{\tau p}, \tag{15}$$

and can simplify the average AoI expression to derive:

$$\Delta = \frac{1}{2}\left(\frac{(\gamma\tau+1)(2-p)}{\tau p} + \frac{1-\tau}{\tau(\gamma\tau+1)}\right). \tag{16}$$

In this case, the behaviour pattern of the sources following a successful transmission and a failed transmission shall be identical, i.e. the outcomes of transmissions have no influence on the sources. DCCTA policy with this specification can be employed in networks where a duty cycle restriction is imposed and no feedback is available at the sources.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we discuss and compare our simulation results with the analytical results. We simulate a DCCTA policy that is compliant with a 1% duty cycle constraint, as in the ISM band channels used by LoRaWAN networks. We set $\gamma = 99$ to comply with a 1% duty cycle constraint.

To numerically illustrate the behaviour of DCCTA, we run simulations of DCCTA and three other related random access (RA) policies, namely threshold ALOHA, slotted ALOHA and SAT policy [11], with optimized parameters for all policies under varying network sizes. Note that the policies other than DCCTA are not designed to be compliant with duty cycle restrictions. In Fig. 1, we illustrate the proportion of transmission that violates the duty cycle limitations. In smaller networks, this violation rate is considerably high. As the network gets larger, optimal transmission probabilities in each of these RA policies decrease, resulting in a reduction in the duty

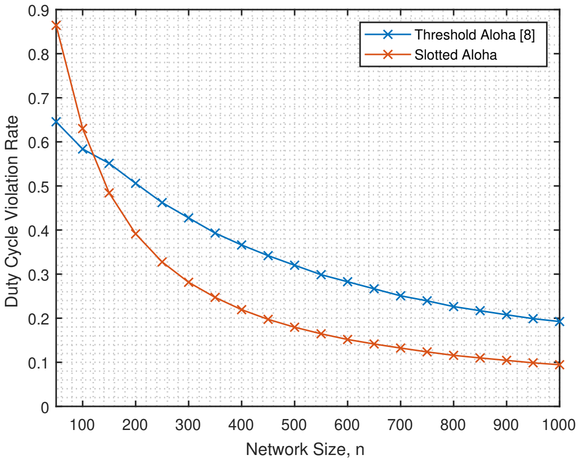

Fig. 1: The fraction of duty cycle limitation violating transmissions vs the network size under different random access policies.

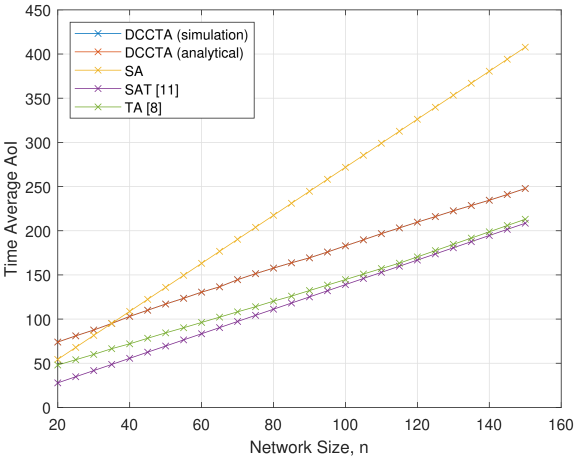

Fig. 2: The time average AoI vs n plot for Duty Cycle Compliant Threshold ALOHA (DCCTA), regular Threshold ALOHA (TA) and SAT[11] policies.

cycle violation rate. Note that, despite this decrease, these policies continue to violate the duty cycle constraints and therefore, cannot be deployed in an ISM band without modification.

In Fig. 2, we compare the average AoI of DCCTA with the other random access policies in smaller networks. The approximate analytical results derived for the DCCTA policy are seen to be consistent with the simulation results. In this region, we observe that p is very high and the number of active users is small (typically less than 5). This effect is caused by the strict duty cycle limitation compared to the network size. In the steady state, we observe that the majority of the time slots have no active sources that are eligible to make a transmission. This leads to a degradation in terms of throughput and average AoI. As a result, DCCTA with few number of users and high γ performs poorly compared to other random access policies in order to comply with duty cycle constraints.

In Table II, we compare the performance of DCCTA, Threshold ALOHA and slotted ALOHA in a network with 500 nodes. All three policies are optimized in terms of the average AoI. All three policies achieve nearly the same throughput of e^{-1} transmissions per time slot. Compared to slotted ALOHA, DCCTA and TA nearly halves the average AoI by reducing the number of active sources at the steady state. In threshold ALOHA policy, this results in a smaller group of sources making transmission attempts with a higher frequency following the failed transmission attempts and a higher duty cycle violation rate. By employing DCCTA policy, we may eliminate this adverse effect whilst preserving the benefit of having fewer number of active sources. In fact, we observe that DCCTA amplifies this effect to the point of achieving an even better average AoI than threshold ALOHA.

TABLE II: A comparison of Duty Cycle Compliant Threshold Aloha, Threshold Aloha and Slotted Aloha in a network of 500 nodes in terms of average AoI, throughput and duty cycle violation rate under optimized parameters.

	Avg. AoI	Throughput	DC Violation Rate
DCCTA	708.4	0.363	0
TA [8]	714.9	0.363	31.5%
SA	1359.6	0.368	18%

V. DUTY CYCLE CONSTRAINED GATEWAY

In TA, nodes expect an acknowledgement after each successful transmission in order to update their ages and compare with the age threshold. This acknowledgement can only come from the gateway. However, typically, duty cycle constraints apply to the gateway as well, which restricts the number of feedback messages it can send. For example, with 125 kHz bandwidth on the EU868 band when the spreading factor is 7, a packet with a 0-byte payload has a 46.3 ms time on-air time. Therefore, with a 1% duty cycle, the gateway can send feedback messages once every 4.63 seconds, which implies that time slots cannot be smaller than 4.63 seconds. If a node's payload is chosen to be 30 bytes with the same channel setting, it would have an 87.3 ms on the air time, hence allocating a 4.63 s time slot to a single user would correspond to excessive idle time. With this in mind, we consider the following two approaches to a network with a duty cycle constrained gateway:

Policy 1 (With Feedback): We create sufficiently large time slots so that each feedback can be received by the transmitter while complying with the DC restrictions. In this case, a TA policy can be deployed to improve the average age of information.

Policy 2 (Without Feedback): We can discard the availability of the feedback and let users assume their transmissions are successful (an assumption that will work well at optimum network load but will tend to lead to suboptimality as network size increases.) In this case, the transmissions are not acknowledged and slots do not need to be as long as in the previous policy. Even though the average age of information is higher with this approach in terms of time slots, the shorter slots can lead to lower

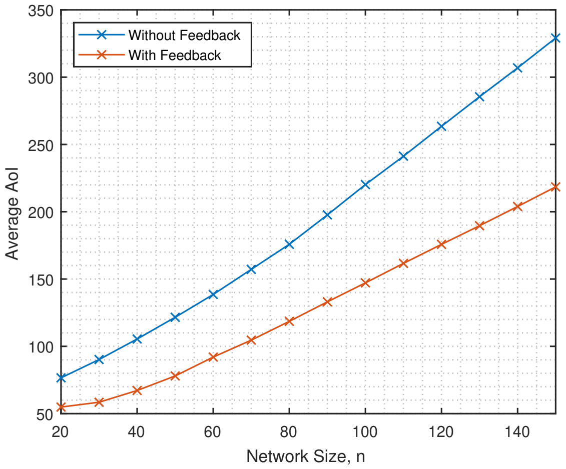

Fig. 3: Comparison of the two proposed policies to a network with a duty cycle constrained gateway in terms of the time average AoI (in time slots) vs network size.

average AoI in seconds. This policy can be considered to be a DCCTA policy in which Γ and γ are equal to each other.

In Fig. 3, we compare the two policies with varying sizes of networks. Utilizing the feedback reduces the average AoI by around 30% in time slots. The two slightly different regimes of the Policy 2 can also be observed in Fig. 3. In a scenario with fewer sources, the duty cycle constraint is the major factor in determining the optimal waiting times, *i.e.* Γ and γ shall be as small as possible while conforming with the duty cycle requirements. The impact of the duty cycle constraint is reduced greatly in a larger network, where we observe the ideal waiting times following a transmission to be approximately $\Gamma = \gamma \approx 1.2n$, based on the simulation results.

VI. CONCLUSION

In this paper, we have presented an Age of Information analysis for a duty cycle constrained Threshold ALOHA (TA) protocol. The duty cycle constraint has been added as an additional mandatory waiting time after each transmission, whether successful or not. In this system model, the sources wait for at least some γ slots after each transmission, and they wait for an additional $\Gamma - \gamma$ slots if the transmission is successful, where Γ is the AoI threshold and $\gamma \leq \Gamma$ is the duty cycle threshold. We adopted a *generate-at-will* model for the packet generation of a source that decides to transmit. Modeling the evolution of the network as a stochastic process, we obtained an average AoI expression that can be evaluated with policy parameters and p, the probability of a transmission being successful. From these expressions, we also found the average AoI for a duty cycle compliant slotted ALOHA policy by setting $\Gamma = \gamma$. We have also examined through simulation, the case of no feedback. It appears that this case is less affected by duty cycle limitations. Analysis of this case and proofs of convergence of the number of active users are among the topics for further work.

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