Low-Power Random Access for Timely Status Update: Packet-based or Connection-based?

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Abstract

This paper investigates low-power random access protocols for timely status update systems with age of information (AoI) requirements. AoI characterizes information freshness, formally defined as the time elapsed since the generation of the last successfully received update. Considering an extensive network, a fundamental problem is how to schedule massive transmitters to access the wireless channel to achieve low network-wide AoI and high energy efficiency. In conventional *packet-based* random access protocols, transmitters contend for the channel by sending the whole data packet. When the packet duration is long, the time and transmit power wasted due to packet collisions is considerable. In contrast, *connection-based* random access protocols first establish connections with the receiver before the data packet is transmitted. Intuitively, from an information freshness perspective, there should be conditions favoring either side. This paper presents a comparative study of the average AoI of packet-based and connection-based random access protocols, given an average transmit power budget. Specifically, we consider slotted Aloha (SA) and frame slotted Aloha (FSA) as representatives of packet-based random access and design a request-then-access (RTA) protocol to study the AoI of connection-based random access. We derive closed-form average AoI and average transmit power consumption formulas for different protocols. Our analyses indicate that the use of packet-based or connection-based protocols depends mainly on the payload size of update packets and the transmit power budget. In particular, RTA saves power and reduces AoI significantly, especially when the payload size is large. Overall, our investigation provides insights into the practical design of random access protocols for low-power timely status update systems.

Index Terms

Age of information (AoI), information freshness, low-power IoT networks, random access

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I. INTRODUCTION

The next-generation Internet of Things (IoT) network has been envisioned as a key enabler for emerging applications, such as connected vehicles in smart cities and cyber-physical systems in the industry. Empowered by IoT, billions of connected devices with sensing, monitoring, and communication capabilities operate collaboratively and intelligently to enable reliable real-time communication, interactions, and decision-making [1], [2]. In these applications, providing fresh status updates is of utmost importance. For example, periodic safety message exchange in vehicular networks should be delivered among vehicles as timely as possible to ensure safety [3].

Age of information (AoI) has been a key performance metric to measure information freshness [4]–[6], defined as the time elapsed since the generation time of the latest received information update at the destination. Specifically, suppose that the latest information update received by the receiver is the update packet generated by the source at time $t_0$, then the instantaneous AoI at time $t$ is $t - t_0$. Prior studies indicated that AoI depends on the data generation pattern and the transmission delay through the network [6]. Hence, AoI differs significantly from conventional metrics such as delay and latency [4]–[6] and has attracted considerable research interest, especially for IoT applications requiring timely data.

To achieve low network-wide AoI for large-scale wireless IoT systems, a fundamental design problem is how to schedule massive IoT devices to access the wireless channel, especially when these IoT devices are typically power-constrained, such as tiny sensors. Scheduled access protocols generally require centralized coordination and decisions, which can be restrictive for many IoT scenarios with a large number of low-cost sensors [7]. Hence, efficient random access protocols operating in a distributed and decentralized manner have been extensively studied, e.g., slotted Aloha and its variants were investigated in [8]–[10] to minimize the average AoI of the network. In random access, packet collisions often occur if multiple transmitters send packets concurrently due to a lack of coordination, resulting in high AoI and power wastage. Although multiple packet replicas could be sent so that advanced interference cancellation techniques can recover the original packets and improve the AoI performance [9], the transmission of multiple replicas leads to high power consumption. Considering low-power IoT sensors, we are interested in the following question:

*Given a maximum transmit power budget, can we achieve a low AoI by designing energy-
efficient random access protocols?

In conventional random access schemes, a transmitter contends for the channel by sending the whole data packet, referred to as packet-based random access [11], [12]. Typical packet-based random access schemes include slotted Aloha and the distributed coordination function (DCF) in WiFi networks [13]. Since all transmitters cannot have a successful update when more than one transmitter sends simultaneously, the time and transmit power wasted by a failed transmission is considerable when the duration of the data packet is long. In contrast to packet-based random access, connection-based random access allows a transmitter to send a short request frame to contend for the channel first (i.e., instead of sending the data packet directly) [12]. The transmitter can send the data packet only if it successfully receives an acknowledgment from the receiver. The request-to-send/clear-to-send (RTS/CTS) access mechanism in WiFi networks is a typical example of connection-based random access: a transmitter sends an RTS frame and waits for a CTS frame from the receiver to establish a connection before transmitting data packets [13]. Thanks to the established connection, the data packet transmission is usually collision-free. Consequently, transmission failures involve only the request frames, and the wasted time could be much shorter than a data packet. In other words, if the data packet is long enough, the transmission failure time and the wasted transmit power can be reduced, i.e., the cost of connection establishment is relatively small.

Developing AoI-aware random access schemes for timely status update systems that consider limited transmit power is crucial. In particular, the proper use of packet-based or connection-based random access protocols is of great practical importance. Intuitively, there should be a critical threshold for the duration of data packets so that it is beneficial to establish a connection, e.g., it should be longer than the request frames to a certain extent [12]. However, previous works have not investigated the AoI-aware characterization of such a threshold. This paper aims to fill this research gap. We present a comparative study of the average AoI of packet-based and connection-based random access protocols in the context of an average transmit power budget.

We first consider slotted Aloha (SA) and frame slotted Aloha (FSA) as representatives of packet-based random access protocols [11]. In every time slot of SA, each transmitter sends its packet with a fixed probability that can be optimized to minimize the average AoI. We extend the investigation of SA to FSA. In FSA, time is divided into frames, and each frame contains a fixed number of time slots. If a transmitter wants to send a packet in a frame, it randomly chooses one of the time slots to transmit. The closed-form average AoI and average transmit power
consumption of FSA with respect to the transmission probability are derived. Interestingly, our theoretical analysis indicates that although FSA and SA have the same average transmit power consumption, FSA has a lower optimal average AoI than SA, when the transmit probabilities are optimized for both schemes. This observation about AoI is different from previous studies where throughput was the system performance metric [11].

For the analysis of connection-based random access, we design a request-then-access (RTA) protocol motivated by FSA. The proposed RTA protocol consists of two phases. In the first phase, i.e., the request phase, transmitters contend and send update request frames to establish a connection with the receiver. In the second phase, i.e., the access phase, only transmitters that successfully contend in the request phase send update packets in a time division multiple access (TDMA) superframe, i.e., collision-free. The AoI analysis of RTA is more complicated than that of FSA. For example, the number of transmitters entering the access phase is random and depends on the probability of sending an update request during the request phase. More specifically, when the probability of sending an update request is too high or too low, the number of transmitters entering the access phase will be small due to high collision probability or low request update rate, which affects the average AoI. Moreover, if a large number of transmitters enter the access phase, the duration of the TDMA superframe will be long. In this case, the time required between two successful updates could also be long, which also affects the average AoI. Therefore, the probability of sending an update request in RTA should be carefully designed to minimize the average AoI. To this end, we derive the closed-form average AoI and the average transmit power consumption of RTA. Our derivations show that both high information freshness and high energy efficiency requirements can be satisfied by adequately adjusting the probability of sending an update request.

Our simulations show that whether to use packet-based or connection-based random access protocols mainly depends on the payload size of update packets and the transmit power budget of transmitters. When the payload size is large (e.g., 128 bytes), RTA should be adopted since it dedicates a connection establishment phase to help avoid collisions of data packets, thus saving power and reducing AoI. When the duration of an update packet and a request frame are comparable (e.g., 16 bytes), RTA should still be used when the power budget of transmitters is high enough; otherwise, FSA is a simple and effective solution.

To sum up, this paper has the following three major contributions:

(1) We are the first to compare packet-based and connection-based random access protocols in
low-power IoT status update systems with AoI requirements. Specifically, for a given trans-
mit power budget, we study different random access protocols to achieve high information fresh-ness.

(2) We use slotted Aloha (SA) and frame slotted Aloha (FSA) as representatives of packet-
based protocols and design request-then-access (RTA) as the connection-based protocol for theoretical analysis. Closed-form average AoI and average transmit power consumption formulas of different protocols are derived. Our study serves as a guideline for comparing packet-based and connection-based random access.

(3) We conduct comprehensive simulations to evaluate the performances of different protocols. The simulation results reveal that the favorability of connection-based random access depends mainly on the payload size of the update data packets (compared with the request frames), as well as the transmit power budget. Overall, our investigations provide insights into the design of random access protocols for low-power timely status update systems.

II. RELATED WORK

A. Age of Information (AoI)

AoI was first proposed in vehicular networks to characterize the timeliness of safety packets [14]. After that, it has been extensively studied under various communication and network systems; see the monograph [5] and the references therein for important research results. Most early studies of AoI focused on the upper layers of the communication protocol stack, i.e., above the physical (PHY) and medium access control (MAC) layers. For example, a rich literature analyzed the AoI performance under different abstract queueing models, e.g., single-source single-server queues [15], multiple-source single-server queues [16], etc. To lower the network-wide AoI, age-optimal scheduling policies among multiple transmitters are examined in [17]–[19], aiming at minimizing different AoI metrics at a common receiver, such as average AoI and peak AoI [1].

Moving down to the PHY and MAC layers, considering imperfect updating channels with interference and noise, the average AoI was analyzed in different network topologies, such as multi-hop [20] and multi-source [21] networks. Moreover, different age-oriented error-correction techniques were investigated to combat the wireless impairments, e.g., automatic repeat request (ARQ) [22] and channel coding [23], [24]. These works reveal that age-optimal designs are usually different from conventional delay/latency-optimal ones.
Energy is another crucial issue when designing AoI-aware status update systems, especially for low-power IoT sensor networks. For example, the AoI-energy characteristics of status update systems when using different ARQ protocols were discussed in [22], [25], [26]. These works showed an inherent tradeoff between the AoI and the average energy consumption at the transmitters, especially under the generate-at-will model. In other words, the transmitter needs to decide whether to send (or resend) a packet under the transmit power constraint [22]. In contrast to previous works, we do not consider ARQ in this paper. Instead, we study different MAC protocols in random access channels, aiming at reducing the average AoI given the average transmit power budget.

B. Random Access Protocols related to AoI

In the literature, different wireless access schemes on AoI were investigated, including scheduled access [7], [27] and random access [8]–[10]. Compared with scheduled access protocols, efficient random access protocols operating in a distributed and decentralized way have shown promising results in IoT networks [28]–[31]. Along this line, our work also focuses on AoI-aware random access protocols due to their importance and ease of implementation in distributed networks.

There has been rich literature on the modeling and performance analysis of AoI-aware random access protocols. In particular, slotted Aloha (SA)-like protocols have received the most attention from the literature. Despite being a relatively simple protocol, [28] showed the AoI effectiveness of SA in massive access networks. Moreover, successive interference cancellation (SIC) was applied to improve the AoI performance of SA when the number of transmitters is large (i.e., the collision probability is high) [9], [32]. Moving beyond SA, the AoI of carrier sensing multiple access (CSMA) and general random access protocols were analyzed in [33] and [34], respectively. Compared with the literature, this paper further investigates the average AoI of frame slotted Aloha (FSA), a generalization of SA. We show that FSA has a theoretically lower optimal average AoI than SA, given the same optimal throughput (see Section IV-B).

Prior random access works on AoI focused extensively on the packet-based random access [12]. To the best of our knowledge, the AoI performance of connection-based random access has not been investigated in the literature. This paper designs a request-then-access (RTA) protocol for the first time as the representative of connection-based random access. In the IEEE 802.11 standards, the payload size of data packets should exceed a threshold to activate the RTS/CTS
mechanism [13] so that the connection establishment facilitates higher network throughput. Unlike conventional 802.11 networks, our work uses AoI as the performance metric rather than network throughput. We examine how the request phase in RTA reduces transmission failure time and transmit power wastage to achieve timely and low-powered state updates.

III. AGE OF INFORMATION PRELIMINARIES

A. Age of Information (AoI)

We study a timely status update system in which $N$ sensors send status update packets to a common access point (AP) as shown in Fig. 1. At time instant $t$, the instantaneous AoI of sensor $u$, denoted by $\Delta_u(t)$, is defined by [4]–[6]

$$\Delta_u(t) = t - G_u(t)$$

where $G_u(t)$ is the generation time of the latest update packet received by the AP from sensor $u$. More specifically, the instantaneous AoI $\Delta_u(t)$ is a continuous-time continuous-value stochastic process [4]–[6]. A lower $\Delta_u(t)$ means a higher degree of information freshness.

With the instantaneous AoI $\Delta_u(t)$, we can compute the average AoI of sensor $u$. The average AoI $\bar{\Delta}_u$ is defined as the time average of the instantaneous AoI [4]–[6]

$$\bar{\Delta}_u = \lim_{T \to \infty} \frac{1}{T} \int_0^T \Delta_u(t) dt.$$
Fig. 2. An example of the instantaneous AoI $\Delta_u(t)$ of sensor $u$, where the $(j-1)$-th and the $j$-th updates occur at $t^{j-1}$ and $t^j$, respectively. We assume a generate-at-will model where a status packet is generated only when sensor $u$ has the opportunity to transmit. After a successful update, $\Delta_u(t)$ drops to $T_{pk}$ where $T_{pk}$ is the packet duration.

A low average AoI $\bar{\Delta}_u$ indicates that the update packets from sensor $u$ are generally fresh over a long period. Considering the whole system, the average AoI for all the sensors is $\bar{\Delta} = \frac{1}{N} \sum_{u=1}^{N} \bar{\Delta}_u$. Fig. 2 plots an example of the instantaneous AoI $\Delta_u(t)$ in which the $(j-1)$-th and the $j$-th successful updates occur at $t^{j-1}$ and $t^j$, respectively. Let $T_{pk}$ denote the transmission time of an update packet. In this paper, we consider the generate-at-will model, where a sensor can take measurements and generate a new update packet when it has the opportunity to transmit. The instantaneous AoI $\Delta_u(t)$ will drop to $T_{pk}$ when the AP successfully receives the update packet, e.g., at times $t^{j-1}$ and $t^j$ as shown in Fig. 2. To realize the generate-at-will model in practice, the communication layer of the sensor can “pull” a request from the upper application layer just when there is an upcoming transmission opportunity (i.e., the packet generation and transmission is goal-oriented). This ensures that the sampled information is as fresh as possible, e.g., a sensor reading is obtained just before the transmission opportunity [36].

This paper considers a collision model, where a packet/frame is successfully received when no other sensors’ packets/frames are sent at the same time; otherwise, simultaneous transmissions from multiple sensors lead to a collision [11]. Due to packet collision, sensor $u$ may send more than one update packet until the next successful update. As shown in Fig. 2, sensor $u$ sends four update packets after the last successful update at $t^{j-1}$, and only the last one is successfully received by the AP at $t^j$. If an update packet is not received successfully, the instantaneous AoI $\Delta_u(t)$ continues to increase linearly. In Fig. 2, we use $Z^j$ to denote the time taken for the
We next present a general method for computing the average AoI $\bar{\Delta}_u$ of sensor $u$. Let us consider area $\Sigma^j$ between the two consecutive successful updates in Fig. 2. The area of $\Sigma^j$ is calculated by

$$\Sigma^j = T_{pk}Z^j + \frac{1}{2}(Z^j)^2.$$  

Then the average AoI $\bar{\Delta}_u$ is computed using the renewal process theory

$$\bar{\Delta}_u = \lim_{W \to \infty} \frac{\sum_{w=1}^{W} \sum_{w=1}^{W} Z^w}{2E[Z]} = T_{pk} + \frac{E[Z^2]}{2E[Z]} = \left( \frac{1}{2} + \frac{1}{q(1-q)^{N-1}} \right) T_{pk},$$

where $\Sigma^w$ and $Z^w$ denote the $w$-th $\Sigma$ and $Z$, respectively. In the following subsection, we take the most common packet-based random access protocol, slotted Aloha (SA), as an example to detail the computation of average AoI.

**B. Slotted Aloha (SA) and its Average AoI**

SA divides time into orthogonal time slots. We assume that the duration of a time slot equals the duration of an update packet $T_{pk}$. In each time slot, suppose that each user independently becomes active and generates a time-stamped packet with probability $q$ to report its status. To compute the average AoI $\bar{\Delta}_u^{SA}$ of sensor $u$ in SA, let us denote by $X$ the number of time slots required between two consecutive successful updates. Then $X$ is a geometric random variable with a probability mass function (PMF)

$$P_X(X = x) = (1 - Q)^{x-1}Q, \ x = 1, 2, ...$$

where $Q = q(1 - q)^{N-1}$ is the probability that there is no collision between sensor $u$ and the other $N-1$ sensors (i.e., only sensor $u$ sends an update packet). The meaning of (5) is that sensor $u$ does not successfully send an update packet to the AP in the first $x-1$ time slots and finally sends an update packet in the $x$-th time slot. Thus, the duration between the two consecutive status updates is $Z = XT_{pk}$, and the average AoI of SA, $\bar{\Delta}_u^{SA}$, is computed by

$$\bar{\Delta}_u^{SA} = T_{pk} + \frac{E[Z^2]}{2E[Z]} = T_{pk} + \frac{E[X^2]T_{pk}}{2E[X]} = \left( \frac{1}{2} + \frac{1}{q(1-q)^{N-1}} \right) T_{pk},$$

where $E[\cdot]$ denotes the expectation operator, $E[X] = \frac{1}{Q}$, and $E[X^2] = \frac{2Q}{Q^2}$.

We define the average number of update packets per unit time in the SA network by $L^{SA} = \frac{qN}{T_{pk}}$. In other words, if we normalize $T_{pk}$ to 1, $L^{SA}$ is the average number of sensors sending update
packets to the AP per time slot. It is easy to verify that the average AoI $\bar{\Delta}^{SA}$ achieves a minimum when $q = \frac{1}{N}$. That is, $L^{SA} = 1$ packet per time slot results in the minimum average AoI for SA.

We further consider the average transmit power consumption per user, which is defined as the ratio of the total energy cost to the total time consumed for the next successful update. Suppose that each sensor has a constant transmit power $P$. In each time slot, let $\Omega$ and $\bar{\Omega}$ denote the events that sensor $u$ does and does not send a packet, respectively; also denote by events $S$ and $\bar{S}$ that sensor $u$ does and does not have a successful update, respectively. We can compute the average transmit power consumption of SA, $\bar{P}^{SA}$, by

$$\bar{P}^{SA} = \lim_{W \to \infty} \frac{\sum_{w=1}^{W} E_w}{\sum_{w=1}^{W} Z_w} = \frac{\Pr(\Omega, \bar{S})T_{pk}(\mathbb{E}[X] - 1) + T_{pk}P}{\mathbb{E}[X]} = \left(\frac{\Pr(\Omega, \bar{S})}{\Pr(\bar{S})}(1 - Q) + Q\right)P = qP$$

where $\Pr(\Omega, \bar{S}) = q\left(1 - (1 - q)^{N-1}\right)$ and $\Pr(\bar{S}) = (1 - q) + q\left(1 - (1 - q)^{N-1}\right)$. $E_w$ is the total energy and $Z_w$ is the time consumed for the $w$-th successful update since the $w-1$-th successful update. Although intuitively $\bar{P}^{SA} = qP$ since a sensor always transmits with probability $q$ in a time slot, (6) can be considered as a general method to compute the average transmit power consumption (e.g., the same method used in FSA and RTA below).

It is well known that SA suffers from high collision probability when the number of sensors is large, and collisions cause power wastage. Therefore, in this paper, we are interested in the following question: **given a maximum average transmit power, can we reduce the average AoI by designing novel random access protocols?** In particular, from the perspective of information freshness, should we adopt a packet-based or connection-based random access protocol? In Section IV we first generalize SA to a frame slotted Aloha (FSA) protocol. We show that FSA lowers the average AoI compared with SA with the same transmit power consumption. Inspired by the FSA protocol, Section V further puts forth a connection-based random access protocol, referred to as the request-then-access (RTA) protocol, which significantly reduces the average AoI thanks to the connection-based mechanism.

### IV. Frame Slotted Aloha

This section presents the average AoI of the frame slotted Aloha (FSA) protocol, a packet-based random access protocol generalized from SA. We first describe the details of the FSA protocol and then compute its average AoI in Section IV-A. After that, Section IV-B compares the average AoI between FSA and SA.
Fig. 3. An example of the frame slotted Aloha (FSA) protocol. Each frame consists of three time slots. In every frame, each sensor sends an update packet with probability $\omega$ and randomly chooses one of the $k$ time slots to transmit.

A. The Average AoI of Frame Slotted Aloha (FSA)

Like SA, FSA is a packet-based random access protocol in which sensors contend the wireless channel to send their update packets to the AP. As the name implies, time in FSA is divided into frames. As shown in Fig. 3, there are $k$ time slots in a frame for the sensors to contend and send update packets. Specifically, in each frame, a sensor sends an update packet with probability $\omega$; if a sensor has an update packet to send, it randomly chooses one of the $k$ time slots with equal probabilities (i.e., with probability $1/k$ for each time slot). It is easy to figure out that in FSA, the average number of update packets per unit time is $L_{FSA} = \frac{\omega N}{k T_{pk}}$. We note that the average number of update packets per unit time in SA and FSA is also known as the system load in the random access literature [9], [11].

Fig. 3 shows the number of time slots per frame when $k = 3$. In frame $i$, four sensors send update packets to the AP. In particular, sensor 1 and sensor 2 select the same time slot, leading to a packet collision. The AP successfully receives the update packets from the remaining two sensors, sensor $u$ and sensor $N$. In frame $i + 1$, three sensors send update packets to the AP without packet collision, i.e., all update packets are received by the AP. In the rest of this paper, we refer to a frame as a round. In SA, a round is just a time slot, i.e., SA is a special case of FSA with a frame size $k = 1$.

Since each sensor randomly chooses one of the $k$ time slots in a frame, let $D$ denote the time slot index that sensor $u$ chooses to send its update packet. Then $D$ has a PMF

$$\Pr(D = d) = \frac{1}{k}, \quad d = 1, 2, \ldots, k.$$
In Fig. 3, for example, we see $D = 1$ and $D = 3$ for sensor $N$ in frame $i$ and frame $i + 1$, respectively. As in SA, let $Z$ represent the duration between two consecutive successful status updates, e.g., the $(j - 1)$-th update and the $j$-th update. Also, let $D^{j-1}$ and $D^j$ denote the time slot index of the packet in the $(j - 1)$-th update and the $j$-th update, respectively. We now use $X$ to represent the number of rounds (frames) required for the next successful update. Thus, $Z$ is computed by

$$Z = (kT_{pk})X + (D^j - D^{j-1})T_{pk}.$$  

(8)

To compute the average AoI of FSA by (4), we need to compute $E[Z]$, where

$$E[Z] = kT_{pk}E[X] + E[D^j - D^{j-1}]T_{pk} = kT_{pk}E[X].$$  

(9)

where $D^{j-1}$ and $D^j$ have the same distribution, i.e., $E[D^j] = E[D^{j-1}] = E[D]$. Similarly, the second moment of $Z$, $E[Z^2]$, is computed by

$$E[Z^2] = E[(kT_{pk})X + (D^j - D^{j-1})T_{pk})^2] = (kT_{pk})^2E[X^2] + E[(D^j - D^{j-1})^2]T_{pk}^2$$

$$= k^2T_{pk}^2E[X^2] + 2(E[D^2] - E[D]^2)T_{pk}^2.$$  

(10)

Computation of $E[X]$ and $E[X^2]$: In (9) and (10), we need to compute $E[X]$ and $E[X^2]$. In FSA, event $S$ (i.e., sensor $u$ has a successful update in a round) occurs when sensor $u$ sends a packet (i.e., event $\Omega$) and there is no collision with other sensors’ packets in the chosen time slot. Let $B$ denote the number of the other $N - 1$ sensors which send an update packet. Then $B$ has the following PMF

$$Pr(B = \beta) = \binom{N-1}{\beta} \omega^\beta (1 - \omega)^{N-1-\beta}, \beta = 0, 1, ..., N - 1.$$  

(11)

Given $B = \beta$, the probability that sensor $u$ successfully transmits an update packet, denoted by $\eta_\beta$, is

$$\eta_\beta = Pr(S|B = \beta, \Omega) = k \times \frac{1}{k} \left(1 - \frac{1}{k}\right)^\beta \left(1 - \frac{1}{k}\right)^\beta.$$  

(12)

Then the probability of event $S$ is

$$Pr(S) = \sum_{\beta=0}^{N-1} \eta_\beta Pr(B = \beta|\Omega) Pr(\Omega) = \omega \sum_{\beta=0}^{N-1} \left(1 - \frac{1}{k}\right)^\beta \binom{N-1}{\beta} \omega^\beta (1 - \omega)^{N-1-\beta}$$

$$= \omega \left(1 - \frac{\omega}{k}\right)^{N-1},$$  

(13)
where \( \Pr(B = \beta | \Omega) = (N-1) \omega^{\beta}(1-\omega)^{N-1-\beta} \). Since each frame (round) is independent, \( X \) is a geometric random variable with a parameter \( \Pr(S) = \omega(1 - \frac{\omega}{k})^{N-1} \). Thus, with the properties of geometric distributions, we have

\[
\mathbb{E}[X] = \frac{1}{\Pr(S)}, \quad \mathbb{E}[X^2] = \frac{2 - \Pr(S)}{(\Pr(S))^2}.
\]

**Computation of \( \mathbb{E}[D] \) and \( \mathbb{E}[D^2] \):** We next compute \( \mathbb{E}[D] \) and \( \mathbb{E}[D^2] \) for (10). It is easy to figure out that

\[
\mathbb{E}[D] = \sum_{d=1}^{k} d \Pr(D = d) = \frac{1}{k} \sum_{d=1}^{k} d = \frac{k+1}{2},
\]

\[
\mathbb{E}[D^2] = \sum_{d=1}^{k} d^2 \Pr(D = d) = \frac{1}{k} \sum_{d=1}^{k} d^2 = \frac{(k+1)(2k+1)}{6}.
\]

Now we can calculate the average AoI of FSA, \( \bar{\Delta}_u^{FSA} \), by

\[
\bar{\Delta}_u^{FSA} = T_{pk} + \frac{\mathbb{E}[Z^2]}{2 \mathbb{E}[Z]} = T_{pk} + \frac{\mathbb{E}[X^2]k^2 T_{pk}^2 + 2 \left( \mathbb{E}[D^2] - \mathbb{E}[D]^2 \right) T_{pk}^2}{2k T_{pk} \mathbb{E}[X]}
\]

\[
= T_{pk} + k T_{pk} \frac{2 - \omega (1 - \frac{\omega}{k})^{N-1}}{2 \omega (1 - \frac{\omega}{k})^{N-1} + T_{pk} \frac{\omega (1 - \frac{\omega}{k})^{N-1} (k^2 - 1)}{12k}}.
\]

**B. Comparison between FSA and SA**

In this subsection, we present some preliminary simulation results to compare the average AoI performance between SA and FSA. A detailed comparison will be presented in Section VI. For FSA, we compute the average transmit power consumption \( \bar{p}_{FSA} \) following the same method as in SA, which is given by

\[
\bar{p}_{FSA} = \frac{\Pr(\Omega | \bar{S}) T_{pk} (\mathbb{E}[X] - 1) + T_{pk} P}{k T_{pk} \mathbb{E}[X]} = \frac{\Pr(\bar{S} | \Omega) \Pr(\Omega | \bar{S}) (\mathbb{E}[X] - 1) + 1}{k \mathbb{E}[X]} P = \frac{w P}{k}.
\]

To compare FSA and SA, we assume that the number of users is \( N = 10 \) and the frame size is \( k = 5 \) for FSA in this simulation. Fig. 4(a) shows the average AoI versus the system load (i.e., the average number of update packets per time slot) for the two protocols. We normalize the time slot duration to one so that the unit of the average AoI is the number of time slots. We see that the average AoI reaches a minimum when the system is loaded with one packet per time.
Fig. 4. Comparison of average AoI between FSA and SA: (a) the average AoI versus the average number of update packets per time slot (system load); (b) the minimum achievable average AoI versus the maximum average transmit power budget.

In both protocols, the access probability per time slot in SA is $q = 0.1$, while the access probability per frame in FSA is $\omega = 0.5$. Since FSA is frame-based and each sensor has only one transmission opportunity per $k$ time slot, the successful update probability in FSA is significantly higher compared with SA. In particular, the successful update probability per frame in FSA is 0.1937, while the successful update probability per time slot in SA is 0.0387. This is the primary reason why FSA outperforms SA in average AoI when both schemes have a system load of one packet per time slot, even though FSA has only one update opportunity every $k$ time slots. Interestingly, one can also verify that FSA and SA have the same optimal throughput $1/e$ packets per time slot [11]. However, the two schemes have different average AoI, indicating the difference between throughput and information freshness.

It is easy to figure out that FSA and SA have the same average transmit power consumption when they have the same system load. Now we consider the minimum achievable average AoI $\bar{\Delta}_{\text{min}}(\bar{P})$ of both protocols, given the same maximum average transmit power consumption $\bar{P}$. Fig. 4(b) plots $\bar{\Delta}_{\text{min}}(\bar{P})$ versus $\bar{P}$, where $\bar{P}$ has a unit of the transmit power $P$. We see that $\bar{\Delta}_{\text{min}}(\bar{P})$ first decreases as $\bar{P}$ increases, and finally to a constant, i.e., the minimum average AoI. This indicates that the sensors do not need to increase the transmit power further (i.e., increase the transmit probability) to reduce the average AoI, even if a higher power budget is possible. In Fig. 4(b), FSA has a lower $\bar{\Delta}_{\text{min}}(\bar{P})$ for the same $\bar{P}$. For example, when $\bar{P} = 0.1P$, FSA reduces $\bar{\Delta}_{\text{min}}(\bar{P})$ by around 8% compared with SA. This suggests that FSA is a preferable low-power solution over SA regarding information freshness.
In FSA, we notice that when more than one sensor chooses the same time slot, all the sensors cannot have a successful update, and it is a power waste for them to send the whole update packet, especially when the duration of an update packet is long. To avoid power wastage, intuitively, we can let the sensors send a short control frame to contend for the channel (e.g., a request-to-send frame in the IEEE 802.11 standards [13]) instead of sending a long data packet directly. Afterward, only the successfully contended sensors can access the channel and send update packets. As the length of a request frame is typically smaller than that of a data packet, the transmission failure time can also be reduced. Motivated by this idea, we put forth a request-then-access (RTA) random access protocol, described in the next section. The proposed protocol is connection-based and consists of two phases. In the first phase, sensors contend and send update requests to the AP to establish a connection. In the second phase, only the sensors that successfully contend in the first phase (i.e., the sensors which have successfully established a connection with the AP) send update packets to the AP in a TDMA manner. We show that both high information freshness and high energy efficiency requirements can be satisfied by adequately adjusting the probability of sending an update request in RTA.

V. REQUEST-THEN-ACCESS PROTOCOL

This section details the request-then-access (RTA) protocol. Section V-A first presents the protocol details, including the operation of the request phase and the access phase. Afterward, we analyze the average AoI of the RTA protocol in Section V-B. In addition, the average transmit power consumption is analyzed.

A. REQUEST-THEN-ACCESS (RTA) PROTOCOL DESCRIPTION

Similar to FSA, time in the RTA protocol is divided into a series of rounds. While a round in FSA is a frame, a round in RTA consists of two phases, namely the request phase and the access phase, as shown in Fig. 5. We explain the two phases in detail as follows.

REQUEST PHASE: This is a contention-based random access phase for the sensors to send update requests. In the request phase, the AP first broadcasts a synchronization frame at the beginning of a round to synchronize the time of different sensors. We omit the duration of the synchronization frame in the calculation of AoI because it is much shorter than the duration of a round. After that, there are \( k \) request slots for the sensors to send a request frame. Specifically, in each round, a sensor transmits a request frame with probability \( \pi \). As in FSA, if a sensor has a request frame
Fig. 5. The Request-Then-Access (RTA) protocol: in the request phase, a contention-based random access protocol is used by the sensors to send update requests to the AP; in the access phase, only the sensors that successfully contend in the request phase send update packets to the AP in a TDMA manner.

Specifically, sensor 1 and sensor 2 choose the same request slot, and their simultaneous request frames cause a collision. The AP successfully receives the request frames from the remaining two sensors (sensor \(u\) and sensor \(N\)), so they are admitted to the subsequent access phase. We use \(T_r\) to denote the duration of a request frame. In summary, the purpose of the request phase is to let the sensors contend for the channel. The successfully contended users establish a connection with the AP for sending data packets in the subsequent access phase.

**Access Phase:** This is the update packet transmission phase for the sensors that contend successfully in the request phase. At the beginning of the access phase, the AP sends a polling frame to notify the successful sensors to enter the access phase. The polling frame includes identifying the sensors and their order of sending update packets in the subsequent TDMA superframe. When calculating the AoI, we also omit the duration of the polling frame because it is short compared with the duration of a round.

For simplicity, this paper assumes that the order in which update packets are sent in the TDMA superframe is random. Let \(M\) be a random variable representing the number of sensors entering the access phase, and \(D_M\) denote the time slot index of a particular sensor sending its update...
Fig. 6. An example of the instantaneous AoI in the request-then-access (RTA) protocol.

packet, given that $M$ sensors are allowed to enter the access phase. Then the PMF of $D_M$ is

$$
\Pr(D_M = d) = \frac{1}{M}, \quad d = 1, 2, \ldots, M. \quad (18)
$$

In Fig. 5, two sensors, sensor $u$ and sensor $N$, are allowed to enter the access phase, so

the access phase (i.e., the TDMA superframe) consists of two access slots. Each sensor has a

probability of $\frac{1}{2}$ to send in the first access slot (i.e., $M = 2$). In this example, sensor $u$ samples

and sends a new update packet first, followed by sensor $N$. After both sensors send their update

packets, the current round ends, and a new round begins.

B. Average AoI of the RTA Protocol

We now analyze the average AoI of the RTA protocol. Fig. 6 shows an example of the

instantaneous AoI $\Delta_u(t)$ of sensor $u$ in RTA, where the first successful update occurs in round

1 and the second successful update occurs in round 4. Compared with FSA, the difficulties in

analyzing the average AoI of RTA are as follows:

(1) The duration of a round in RTA is random. In particular, the duration of the access phase

depends on the number of sensors $M$ in the access phase, i.e., the sensors that contend

successfully in the request phase. As shown in Fig. 6, $M = 2$ in round 1 while $M = 5$ in

round 4. In contrast, in FSA, the duration of a round is always $k$ time slots.

(2) Since the number of sensors, $M$, in the access phase is random, $D_M$ is also random and

depends on $M$. In Fig. 6, we use the random variable $D$ as in FSA to denote the time slot

index of the packet in the access phase, e.g., $D = 2$ in round 1 while $D = 1$ in round 4.
(3) After a successful update, suppose we use $X$ to denote the number of rounds spent until the next successful update. This means that sensor $u$ failed to update in the first $X - 1$ rounds and then successfully updated in the last round, i.e., $X = 3$ in Fig. 6 after the first successful update. We need to calculate the duration of the $X - 1$ rounds given that sensor $u$ failed to update (e.g., round 2 and round 3 in Fig. 6) and the duration of the last round given that sensor $u$ successfully updates (e.g., round 4 in Fig. 6). Furthermore, notice that a failed update could be due to a collision of the request frames or a sensor simply remaining silent during a round. 

As in FSA, let $Z$ denote the duration between two consecutive status updates, and $D_{j-1}$ and $D_j$ denote the packet index of the $(j - 1)$-th update and the $j$-th update in the TDMA superframe of the access phase, respectively. Then, $Z$ in RTA can be given by

$$Z = \Theta_F^1 + \ldots + \Theta_F^{X-1} + \Theta_S + (D_j - D_{j-1})T_{pk},$$ (19)

where $\Theta_F^v, v = 1, \ldots, X - 1$, is the duration of a round given that sensor $u$ fails to have an update and $\Theta_S$ is the duration of a round given that sensor $u$ has a successful update. To compute the average AoI of RTA $\bar{\Delta}_{u}^{RTA}$ by $\Delta$, $\mathbb{E}[Z]$ is computed by

$$\mathbb{E}[Z] = (\mathbb{E}[X] - 1)\mathbb{E}[\Theta_F] + \mathbb{E}[\Theta_S] + (\mathbb{E}[D_j] - \mathbb{E}[D_{j-1}])T_{pk} = (\mathbb{E}[X] - 1)\mathbb{E}[\Theta_F] + \mathbb{E}[\Theta_S].$$ (20)

The second equality is due to the fact that $\Theta_i^v, v = 1, \ldots, X - 1$, have the same distribution ($\mathbb{E}[\Theta_i^v] = \mathbb{E}[\Theta_F]$), and $\mathbb{E}[D_j] = \mathbb{E}[D_{j-1}] = \mathbb{E}[D]$.

Similarly, the second moment of $Z$, $\mathbb{E}[Z^2]$, can be computed by

$$\mathbb{E}[Z^2] = \mathbb{E}\left[\left(\Theta_F^1 + \ldots + \Theta_F^{X-1} + \Theta_S + (D_j - D_{j-1})T_{pk}\right)^2\right]$$

$$= \mathbb{E}\left[\left(\Theta_F^1 + \ldots + \Theta_F^{X-1}\right)^2\right] + \mathbb{E}\left[\Theta_S^2\right] + \mathbb{E}\left[(D_j - D_{j-1})^2T_{pk}^2\right] + 2\mathbb{E}\left[\left(\Theta_F^1 + \ldots + \Theta_F^{X-1}\right)\Theta_S\right]$$

$$= (\mathbb{E}[X] - 1)\mathbb{E}[\Theta_F^2] + \left(\mathbb{E}[X^2] - 3\mathbb{E}[X] + 2\right)\mathbb{E}[\Theta_F^2] + \mathbb{E}[\Theta_S^2]$$

$$+ 2(\mathbb{E}[X] - 1)\mathbb{E}[\Theta_F]\mathbb{E}[\Theta_S] + 2\left(\mathbb{E}[D^2] - \mathbb{E}[D]^2\right)T_{pk}^2$$ (21)

where $\mathbb{E}[X]$ and $\mathbb{E}[X^2]$ are the same as (14) except that $\omega$ in FSA replaced by $\pi$ in RTA, i.e., the number of rounds until the next successful update $X$ is a geometric random variable with a successful update probability $\Pr(S) = \pi(1 - \frac{\pi}{k})^{N-1}$. In the following, we compute the remaining components in (20) and (21).
Computation of $\mathbb{E}[\Theta_F]$ and $\mathbb{E}[\Theta_F^2]$: Since $\Theta_F$ is the duration of a round given that sensor $u$ fails to update, then $\Theta_F = kT_r + M_FT_p$, where $M_F$ is the number of sensors admitted to the access phase given that sensor $u$ fails to have a successful update. The PMF of $M_F$ is

$$
\Pr(M_F = m_F) = \Pr(M_F = m_F|\tilde{\Omega}) \Pr(\tilde{\Omega}) + \Pr(M_F = m_F|\Omega) \Pr(\Omega).
$$

(22)

The first term of the right-hand side of (22) is the probability of $M_F$ given that sensor $u$ does not send a request frame (i.e., event $\tilde{\Omega}$), and the second term is the probability of $M_F$ given that sensor $u$ does send a request frame (i.e., event $\Omega$).

We first consider the case where sensor $u$ does not send a request frame. Let $A$ denote the number of the remaining $N-1$ sensors which send a request frame. Given $A = \alpha$, the number of sensors that contend successfully has the following PMF

$$
\Pr(M_F = m_F|A = \alpha, \tilde{\Omega}) = \frac{(-1)^{m_F} k! \alpha!}{k^\alpha m_F!} \times \sum_{i=m_F}^{\min(k,\alpha)} \frac{(-1)^i (k-i)^{\alpha-i}}{(i-m_F)!(k-i)!(\alpha-i)!},
$$

$$
0 \leq m_F \leq \min(k,\alpha).
$$

(23)

Equation (23) can be derived from the well-known combinatorial problem of assigning balls to boxes [37]. In that problem, a number of balls are thrown into boxes. Each box is selected with equal probability. Our problem is to assign $A = \alpha$ sensors (balls) to $k$ request slots (boxes) and to calculate the probability that there are $m_F$ request slots with only one sensor in the $k$ request slots. For simplification in the rest of this paper, we use notation $\Pi(.)$ to denote the right-hand side of (23), i.e.,

$$
\Pi(m_F, \alpha, k) = \frac{(-1)^{m_F} k! \alpha!}{k^\alpha m_F!} \times \sum_{i=m_F}^{\min(k,\alpha)} \frac{(-1)^i (k-i)^{\alpha-i}}{(i-m_F)!(k-i)!(\alpha-i)!}.
$$

(24)

Considering all the possible $A$, the number of sensors contend successfully given that sensor $u$ does not send a request frame has the following PMF

$$
\Pr(M_F = m_F|\tilde{\Omega}) = \sum_{\alpha=m_F}^{N-1} \Pi(m_F, \alpha, k) \Pr(A = \alpha|\tilde{\Omega}), \quad 0 \leq m_F \leq \min(k, N-1).
$$

(25)

We next consider the case where sensor $u$ sends a request frame. Given $\alpha$ sensors sending request frames, let $\Phi_{\alpha}$ denote the number of sensors (among the $\alpha$ sensors) that do not choose the same request slot as sensor $u$. The PMF of $\Phi_{\alpha}$ is

$$
\Pr(\Phi_{\alpha} = \varphi_{\alpha}|A = \alpha, \Omega) = \binom{\alpha}{\varphi_{\alpha}} \left(\frac{1}{k}\right)^{\alpha-\varphi_{\alpha}} \left(1 - \frac{1}{k}\right)^{\varphi_{\alpha}}.
$$

(26)
Given $\Phi_\alpha = \varphi_\alpha$, the number of successfully contended sensors in the case where sensor $u$ sends a request frame but that is corrupted has a PMF

$$
\Pr(M_F = m_F|\Phi_\alpha = \varphi_\alpha, A = \alpha, \Omega) = \Pi(m_F, \varphi_\alpha, k - 1), \quad 0 \leq m_F \leq \min(k - 1, \varphi_\alpha).
$$

Equation (27) is to assign $\Phi_\alpha = \varphi_\alpha$ sensors to $k - 1$ request slots (a request slot is occupied by user $u$ and $\alpha - \varphi_\alpha$ sensors, which is a collision) and calculate the probability of having $m_F$ request slots with only one sensor in the $k - 1$ request slots. Considering all the possible $\Phi_\alpha$ and $A$, $\Pr(M_F = m_F|\Omega)$ can be computed by

$$
\Pr(M_F = m_F|\Omega) = \sum_{\alpha = m_F}^{N-1} \sum_{\varphi_\alpha = m_F}^{\alpha} \Pi(m_F, \varphi_\alpha, k - 1) \Pr(\Phi_\alpha = \varphi_\alpha|A = \alpha, \Omega) \Pr(A = \alpha|\Omega)
$$

$$
= \sum_{\alpha = m_F}^{N-1} \sum_{\varphi_\alpha = m_F}^{\alpha} \Pi(m_F, \varphi_\alpha, k - 1) \left( \alpha \left( \frac{1}{k} \right)^{\alpha - \varphi_\alpha} \left( 1 - \frac{1}{k} \right)^{\varphi_\alpha} \right)^{(N - 1)} \pi^\alpha (1 - \pi)^{N-1-\alpha},
$$

$$
0 \leq m_F \leq \min(k - 1, N - 1).
$$

Therefore, $\mathbb{E}[\Theta_F]$ and $\mathbb{E}[\Theta_F^2]$ are simply

$$
\mathbb{E}[\Theta_F] = kT_r + \mathbb{E}[M_F]T_{pk},
$$

$$
\mathbb{E}[\Theta_F^2] = (kT_r)^2 + T_{pk}^2 \mathbb{E}[M_F^2] + 2kT_rT_{pk}\mathbb{E}[M_F].
$$

**Computation of $\mathbb{E}[\Theta_S]$ and $\mathbb{E}[\Theta_S^2]$:** Since $\Theta_S$ is the duration of a round given that sensor $u$ has a successful update, then $\Theta_S = kT_r + M_ST_{pk}$, where $M_S$ is the number of sensors admitted to the access phase given that sensor $u$ has a successful update. Given $A = \alpha$ of the remaining $N - 1$ sensors sending request frames, the probability that all the $\alpha$ sensors do not choose the same request slot as sensor $u$ does is $\eta_\alpha = \left(1 - \frac{1}{k}\right)^\alpha$. Then the total number of sensors contend successfully given that sensor $u$ has a successful update has a PMF as

$$
\Pr(M_S = m_S) = \sum_{\alpha = m_S - 1}^{N-1} \Pi(m_S - 1, \alpha, k - 1) \Pr(A = \alpha|S)
$$

$$
= \sum_{\alpha = m_S - 1}^{N-1} \Pi(m_S - 1, \alpha, k - 1) \pi^\alpha (1 - \pi)^{N-1-\alpha} \left( \pi \left( 1 - \frac{\pi}{k} \right)^{N-1} \right),
$$

$$
1 \leq m_S \leq 1 + \min(k - 1, N - 1).
$$

The meaning of (31) is to assign $A = \alpha$ sensors to $k - 1$ request slots (a request slot is occupied by user $u$ only) and calculate the probability of having only one sensor in $m_S - 1$ request slots
among the remaining $k - 1$ request slots, finally adding up all possible $A$. Therefore, $\mathbb{E}[\Theta_S]$ and $\mathbb{E}[\Theta_S^2]$ are computed by

$$\mathbb{E}[\Theta_S] = kT_r + \mathbb{E}[M_S]T_{pk},$$
$$\mathbb{E}[\Theta_S^2] = (kT_r)^2 + T_{pk}^2\mathbb{E}[M_S^2] + 2kT_r T_{pk} \mathbb{E}[M_S].$$

(32)

Next, $\mathbb{E}[D]$ and $\mathbb{E}[D^2]$ can be computed using the probability mass function of $D$, considering all the possibilities of $M_S$, i.e.,

$$\Pr(D = d) = \sum_{m_S = d}^{\min(k,N)} \frac{1}{m_S} \Pr(M_S = m_S).$$

(33)

Now we have all the components to compute the average AoI of RTA. For a fair comparison with FSA and SA, since RTA consists of request slots and access slots and they have different slot durations, we define the average number of update requests per unit time for RTA as

$$L^{RTA} = \frac{N\pi}{\mathbb{E}[\Theta_S] \Pr(S) + \mathbb{E}[\Theta_F] \Pr(S)}. \quad (34)$$

That is, $L^{RTA}$ is the average number of request frames divided by the expected time duration of a round. SA and FSA are special cases where the request frame and the data frame are combined into a single update packet for accessing the channel. In Section VI, we use $L^{pro}$ to denote the average number of update requests per unit time for a particular protocol. We compare the average AoI under the same $L^{pro}$ in SA, FSA, and RTA using the real parameters defined in 802.11 standards [13].

Finally, we compute the average transmit power consumption of the RTA protocol $\bar{P}^{RTA}$. By definition, $\bar{P}^{RTA}$ is computed by

$$\bar{P}^{RTA} = \frac{\Pr(\Omega | \bar{S})(\mathbb{E}[X] - 1)T_r + (T_r + T_{pk})}{(\mathbb{E}[X] - 1)\mathbb{E}[\Theta_F] + \mathbb{E}[\Theta_S]} P, \quad (35)$$

where

$$\Pr(\Omega | \bar{S}) = \frac{\Pr(\bar{S}|\Omega) \Pr(\Omega)}{\Pr(\bar{S})} = \frac{\left(1 - \left(1 - \frac{\pi}{k}\right)^{N-1}\right)\pi}{1 - \pi + \left(1 - \left(1 - \frac{\pi}{k}\right)^{N-1}\right)\pi} = \frac{\pi - \pi \left(1 - \frac{\pi}{k}\right)^{N-1}}{1 - \pi \left(1 - \frac{\pi}{k}\right)^{N-1}} \quad (36)$$

is the probability that sensor $u$ sends an update request given that the update is not successful due to collision. In other words, only when the sensor sends a request frame will consume power in the request phase. Since it is difficult to establish a clear relationship between $L^{RTA}$ and the average AoI $\bar{\Delta}_u^{RTA}$ as well as average power $\bar{P}^{RTA}$, we explore the performance of RTA by simulations as detailed in the next section.
TABLE I

NETWORK SIMULATION PARAMETERS

| Parameter                                 | Values               |
|-------------------------------------------|----------------------|
| The number of sensors                     | 5, 10, 15, 20, 25, 30 |
| Payload of an update packet (bytes)       | 16, 64, 128          |
| Data transmission bitrate (Mbps)          | 6                    |
| PHY-layer header duration (μs)            | 20                   |
| MAC header + PHY pad (bits)               | 246                  |
| Signal extension time (μs)                | 6                    |
| Request frame (bits)                      | 160                  |

VI. PERFORMANCE EVALUATION

In this section, numerical simulations are presented to compare the performances between the packet-based random access protocols (SA and FSA) and the connection-based random access protocol (RTA). We conduct comprehensive simulations to evaluate the average AoI and the average transmit power consumption of different protocols. In particular, we will see how RTA improves the information freshness with a lower transmit power budget.

A. Average AoI and Average Transmit Power

We first consider a relatively large payload of an update packet, i.e., 128 bytes. The impacts of different payload sizes will be examined in the next subsection. We would like to verify the theoretical formulas derived in Section IV and Section V, i.e., we now prove the correctness of the theoretical average AoI and the average transmit power of SA, FSA, and RTA. Table I lists the network parameters of our simulations as defined in the IEEE 802.11 standards [13]. To compute the average AoI of each protocol in our simulations, we first collect the instantaneous AoI of the sensors according to their successful updates or failed updates in each time slot or round over a long time. After that, we compute the average AoI based on the instantaneous AoI. The computation of average transmit power consumption in our simulations follows a similar manner.

Fig. 7(a) plots the average AoI versus the average number of update requests per millisecond (ms) for different protocols, $L_{pr}^o$. Recall that SA and FSA are special cases where the request frame and the data frame are combined into a single update packet. In Fig. 7, the number of sensors is fixed to $N = 10$. The number of time slots per frame in FSA and the number of request slots in RTA are set to $k = 5$. We see that the simulation results corroborate the theoretical results
Fig. 7. Performance comparison among SA, FSA, and RTA: (a) average AoI and (b) average transmit power consumption versus the average number of update requests per millisecond (ms). The number of sensors is 10. The payload of an update packet is 128 bytes. The number of time slots per frame in FSA and the number of request slots in RTA are set to $k = 5$.

for both the average AoI and the average transmit power, thus validating our derivations in the previous two sections.

As in Fig. 4, Fig. 7(a) shows that the average AoI of FSA is lower than SA for the same $L_{pro}$ with the network and control parameters defined by the 802.11 standards. More importantly, the average AoI of RTA is significantly lower than that of FSA and SA in most scenarios. For example, when $L_{pro}$ is larger than two update requests per ms, RTA has the lowest average AoI among the three protocols, as shown in Fig. 7(a). The primary reason for the performance improvement of RTA is that the duration of a request frame is much smaller than that of an update packet. For example, when an update packet has a payload of 128 bytes, the duration of an update packet is around $238 \mu s$ while the duration of a trigger frame is around $52\mu s$. In this example, FSA wastes time when packets collide. Specifically, collisions among update packets waste the airtime and hence increase the average AoI. In contrast, by establishing a connection first, RTA resolves collisions with a much shorter time in the request phase (i.e., the total duration of the request phase is only $260 \mu s$ when $k = 5$), and only the sensors which contend successfully send update packets later in the access phase. This improves the channel utilization, which in turn improves the average AoI performance. Only when $L_{pro}$ is small, i.e., when the probability of sending an update request is small, FSA is slightly better than RTA, because there is not much traffic but RTA still has the extra request overhead caused by connection establishment.

Interestingly, we see from Fig. 7(a) that as $L_{pro}$ increases, the average AoI of RTA first
decreases substantially and then increases slightly, i.e., the optimal average AoI of RTA is achieved when $L^{pro}$ is not too high or too low. When $L^{pro}$ is too low, the average AoI suffers due to the low frequency of sending update requests (i.e., fewer update opportunities). When $L^{pro}$ is too high, the average AoI is also subpar due to the high collision probability of the request frames (i.e., the sensors cannot enter the access phase).

In addition, compared with FSA, the average AoI of RTA does not increase much when $L^{pro}$ becomes larger. This phenomenon is helpful in many practical scenarios in which the number of active sensors, $N$, could vary from time to time. In these time-varying scenarios, an online estimation of $N$ is required at the AP. When the AP is not able to estimate $N$ accurately, the probability of sending an update request/packet is not optimal, i.e., $L^{pro}$ is not optimal as well. Suppose the actual $L^{pro}$ slightly deviates from the optimal one. In that case, we see from Fig. 7(a) that the resulting average AoI of FSA differs significantly from the optimal one. On the contrary, RTA is more robust to the estimation error of $N$ (and hence $L^{pro}$) with a more stable average AoI. That is, a slight deviation from the optimal $L^{pro}$ has only a small change in the average AoI.

Fig. 7(b) plots the average transmit power consumption versus $L^{pro}$ for different protocols. Simulation results confirm that FSA and SA have the same average transmit power consumption using the network parameters defined in the 802.11 standards. Furthermore, the average transmit power consumption of RTA is lower than that of FSA and SA when $L^{pro}$ is large. That is, when the collision probability is high, RTA has the lowest transmit power consumption because the sensors send only a short request frame instead of a long data packet directly, as in FSA or SA.

### B. Minimum Average AoI Given A Maximum Average Transmit Power

We now evaluate the minimum average AoI of different protocols $\bar{\Delta}_{\min}(\bar{P})$, given a maximum average transmit power $\bar{P}$. Note that we only provide theoretical results herein as their correctness has been verified in the previous subsection.

We first consider the same network parameter setting as in Fig. 7. Fig. 8 plots $\bar{\Delta}_{\min}(\bar{P})$ versus $\bar{P}$ of SA, FSA, and RTA. We also vary $k$ to examine the average AoI of both RTA and FSA. We find that different $k$ have little effect on $\bar{\Delta}_{\min}(\bar{P})$, so we simply choose $k = 5$ for the rest of simulations, since the number of available time slots is typically fixed and smaller than the number of active users in random access scenarios. A fixed $k$ is also helpful for a time-varying
Fig. 8. Performance comparison among SA, FSA, and RTA: the minimum achievable average AoI versus the maximum average transmit power consumption. The number of sensors is 10. The payload of an update packet is 128 bytes. The number of time slots per frame in FSA and the number of request slots in RTA are set to \( k = 5 \). The small figure plots different \( k \) for RTA and FSA.

As shown in Fig. 8, for all the three protocols, as \( \bar{P} \) increases, \( \bar{\Delta}_{\text{min}}(\bar{P}) \) first decreases and finally reduces to the minimum average AoI. In Section IV, we have shown that FSA has a lower \( \bar{\Delta}_{\text{min}}(\bar{P}) \) than that of SA given the same \( \bar{P} \). Now we see from Fig. 7 that when the power budget is high, RTA has a substantial improvement on \( \bar{\Delta}_{\text{min}}(\bar{P}) \) over both FSA and SA. For example, when \( \bar{P} = 0.1P \), RTA reduces \( \bar{\Delta}_{\text{min}}(\bar{P}) \) by 40% and 45% compared with FSA and SA, respectively. Hence, RTA is a viable solution to achieve higher information freshness when there is enough transmit power budget.

From Fig. 8, we also see that RTA and FSA have almost the same \( \bar{\Delta}_{\text{min}}(\bar{P}) \) performance under a lower transmit power budget (e.g., when \( \bar{P} = 0.03P \)). To explore further, we plot \( \bar{\Delta}_{\text{min}}(\bar{P}) \) versus the number of sensors in Fig. 9 when \( \bar{P} \) equals (a) 0.1\( P \) and (b) 0.03\( P \). When the power budget is high, \( \bar{\Delta}_{\text{min}}(\bar{P}) \) usually equals the minimum average AoI of the corresponding protocol. Hence, we see from Fig. 9(a) that RTA gives the lowest average AoI when \( \bar{P} = 0.1P \). However, when the power budget is not high enough to achieve the minimum possible average AoI (e.g., \( \bar{P} = 0.03P \)), FSA and RTA almost have the same average AoI when the number of sensors is small (e.g., 5~10 sensors). In addition, Fig. 9 shows that RTA has a more stable average AoI than FSA.
under a different number of sensors. This indicates that even though \( k \) is not optimized for all the schemes, RTA can offer a more stable average AoI, thus significantly simplifying the system design.

**Impacts by payload sizes:** Notice that all our findings so far are obtained based on the fact that the duration of an update packet is much larger than that of a request frame. In practical IoT systems with short packets, the payload of an update packet can be as small as 128 bits (16 bytes) \cite{2}. Thus, we next investigate the effects of different payload sizes on the performances of different protocols.

Fig. \[10\] plots \( \tilde{\Delta}_{\text{min}}(\bar{P}) \) versus \( \bar{P} \) of FSA and RTA under different payload sizes, i.e., 16, 64, and 128 bytes, when the number of sensors is 10 (other numbers of sensors lead to similar phenomena, so we omit the results here). Since FSA generally outperforms SA in average AoI given the same transmit power, we only compare FSA and RTA in Fig. \[10\].

Previously in Fig. \[7\] we show that when the payload of an update packet is 128 bytes and \( \bar{P} = 0.1P \), RTA reduces \( \tilde{\Delta}_{\text{min}}(\bar{P}) \) by 40\% compared with FSA. When the payload size is reduced to 64 bytes (the duration of an update packet is 156 \( \mu s \)), the performance improvement of RTA over FSA becomes smaller, i.e., RTA reduces \( \tilde{\Delta}_{\text{min}}(\bar{P}) \) by 30\% compared with FSA. Furthermore, when the payload size is further reduced to 16 bytes, RTA still outperforms FSA by 6\%, when \( \bar{P} = 0.1P \). When the payload size is 16 bytes, the duration of an update packet is only 90\( \mu s \), which is comparable to the duration of a request frame (i.e., 52\( \mu s \)). Hence, when the average number of update requests, \( L^{pr} \), is large, collisions in request slots (of RTA) do not differ much from collisions in regular time slots (of FSA). More specifically, when collisions occur, both
Fig. 10. Performance comparison between FSA and RTA: the minimum achievable average AoI versus the maximum average transmit power consumption under different payload sizes. The number of sensors is 10. The number of time slots per frame in FSA and the number of request slots in RTA are set to $k = 5$.

waste almost the same amount of transmit power.

Assuming that the given power budget $\bar{P}$ is as low as $0.03P$, we see that FSA achieves better performance than RTA when the payload of the update packet is 16 bytes, as shown in Fig. 10. Specifically, FSA reduces $\Delta_{\text{min}}(\bar{P})$ by around 20% compared with RTA. Intuitively, if the power budget is tiny, sensors should reduce the number of update requests per unit time to save power, i.e., reduce $L_{\text{pro}}$. Since a lower $L_{\text{pro}}$ reduces the total traffic and the packet collision probability, a dedicated request phase for collision resolution with $k$ request slots in RTA wastes the airtime, resulting in a higher average AoI than that of FSA. This indicates that under extremely low-power conditions, the packet-based random access protocol, FSA, is a preferred solution over RTA, especially when the update packet has a tiny payload.

To summarize, in low-power status update systems, whether a packet-based or connection-based random access protocol should be used mainly depends on the payload size of update packets and the transmit power budget of sensors. When the payload size is large (e.g., 128 bytes), a connection-based random access protocol such as RTA should be adopted, because RTA dedicates a connection establishment phase to help avoid collisions of update packets, thus saving power and enhancing information freshness. When the payload size is small enough (e.g., 16 bytes) such that the duration of an update packet and a request frame are comparable, RTA should still be used if the power budget of sensors is high enough. Otherwise, packet-based
random access protocols (such as FSA) are a simple and effective solution, especially when the power budget is low.

VII. CONCLUSIONS

We have compared the average AoI performance of packet-based and connection-based random access protocols under a maximum transmit power budget. Specifically, we use slotted Aloha (SA) and frame slotted Aloha (FSA) as examples of packet-based random access protocols. Motivated by FSA, we design a request-then-access (RTA) protocol for the analysis of connection-based random access protocols.

AoI-aware and low-power random access schemes are crucial to IoT status update systems. In particular, the proper use of packet-based or connection-based random access protocols is of paramount importance in practical designs. Although prior works using throughput as the performance metric have shown that it is beneficial to establish connections (i.e., adopting connection-based random access) when the payload size of data packets exceeds a threshold, how to determine an appropriate threshold from an AoI perspective has not been studied yet. Furthermore, such an AoI characterization is much more complicated since AoI is generally related to the time elapsed between consecutive updates. Taking RTA as an example, when the probability of sending an update request is too high or too low, the number of sensors entering the access phase will be small due to high collision probability or low request update rate, possibly leading to a longer update interval. Moreover, if a large number of sensors enter the access phase, the time required between two successful updates could also be longer due to the use of a longer TDMA superframe, thus affecting the average AoI as well. Hence, the optimal probability of sending a request requires an in-depth analysis to minimize the average AoI. Besides, taking the transmit power consumption into account further complicates the problem.

We have derived the closed-form average AoI and average transmit power consumption of SA, FSA, and RTA. Our theoretical analysis and simulation results indicate that connection establishment reduces the average AoI when the payload size is large. Specifically, RTA reduces the average AoI by 40% and 50% compared with FSA and SA, respectively, when the update packet has 128 bytes. In contrast, FSA is a simple and effective solution when the power budget is low and the payload size is as small as 16 bytes. Our investigation on AoI can serve as a design reference for random access protocols with low-power and timely status update requirements.
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