An Adaptive Frame-based Age-aware Access Scheme for Time-Critical Satellite-IoT

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***Abstract*—Low earth orbit (LEO) satellite constellation provides a possible solution for remote real-time data gathering applications and timely updates of information can be efficiently transmitted through dynamic inter-satellite links. Recently, the freshness of status updates is characterized by age of information (AoI), a novel metric proposed to capture the freshness of status updates. In this paper, we propose a novel adaptive frame-based age-aware access (AFAA) scheme that prioritizes the transmission of devices experiencing consecutive frame failures. The proposed AAFA framework incorporates a new concept of control-AoI to differentiate the transmission probability of each device. In particular, higher control-AoI is given to the devices that manifest higher priority transmission requirements. Since obtaining the system control-AoI, which is the summation of all devices' control-AoI values, is challenging due to the lack of information about distributed devices, we enhance our AAFA scheme by integrating an estimation mechanism for the system control-AoI. Through comprehensive simulations, we show the effectiveness of this introduced estimation algorithm. The findings underscore that the AAFA scheme not only reduces average AoI but also achieves nearly optimal system throughput, which is appealing to LEO satellite IoT.**

***Index Terms*—Age of Information, random access, frame-adaptive, online estimation.**

I. Introduction

In the upcoming Internet of Things (IoTs), the spatial and environmental constraints sometimes limit their potential utilization within scenarios of encompassing maritime, remote expanses, disaster response, as well as wildlife tracking and identification. However, the expansive capabilities of satellite-IoT (S-IoT) can sufficiently compensate for the limitations of terrestrial IoT, thus paving the way for the comprehensive actualization of the overarching "Internet of Everything" paradigm. In contrast to geostationary earth orbit (GEO) satellites, low earth orbit (LEO) satellites offer advantages such as reduced signal delay, lower signal attenuation, and cost-effective deployment. The integration of LEO satellites into satellite-terrestrial networks holds the potential to deliver seamless coverage and enhance overall system performance.

The number of devices that are served by an LEO satellite in the coverage area is very large, which puts forward high requirements for the concurrent reception capability of the S-IoT. In the scenario of massive-device systems, random access protocol exhibits strong robustness and is capable of effectively reducing retransmission attempts, minimizing latency, and enhancing throughput. It can be stated that random access is an inevitable choice for achieving wide-area continuous access of massive IoT devices in satellite networks. Therefore, designing efficient and high-performance random access protocols that meet devices' service quality requirements within limited resources is of significant importance. Several related works have focused on optimizing the conventional performance metrics such as throughput and delay in S-IoT. In traditional satellite communication systems, slotted ALOHA was frequently used as the random access protocol [1], [2] while overcoming the effect of propagation delay in random access becomes the key challenge [3], [4].

While numerous studies have been presented for the random access in S-IoT, there is limited attention given to the issue of information freshness. For the applications which require feedback while retransmissions are accompanied, the cumulative propagation delay severely deteriorates the freshness of the received packets which may contain status updates. A new metric termed the age of information (AoI), was proposed to reflect the timeliness of status updates in early 2010s. The practical support of massive devices is one of the open challenges in the upcoming S-IoT while optimizing information freshness further increases the operational complexity. For S-IoT, [5], [6] proposed a grant-free age-optimal random access protocol to lower the average AoI by adjusting the number of access time slots in each transmission frame. Several reinforcement-learning (RL)-based approaches have also been proposed to reduce the average AoI in S-IoT. For example, [7] proposed a D3QN-based strategy for age-oriented access control problems in the GEO/LEO heterogeneous network and showed that it can improve the long-term AoI performance, especially in the case of high traffic load.

Nowadays, slotted ALOHA protocol has already become a part of S-IoT systems (such as DVB-RCS). It is applied for initial access, datagram requests, and signaling packet management. Despite its wide application, only a little attention has been paid for reducing the average AoI in S-IoT, particularly in scenarios involving massive devices.

Inspired by the aforementioned work, it is worth to design practical random access protocols capable of accommodating massive-device connectivity while ensuring information freshness with minimal message passing. In this paper, we propose a novel adaptive frame-based age-aware access (AFAA) scheme that assigns higher priority to the devices failed in transmissions for longer time. More specifically, we first

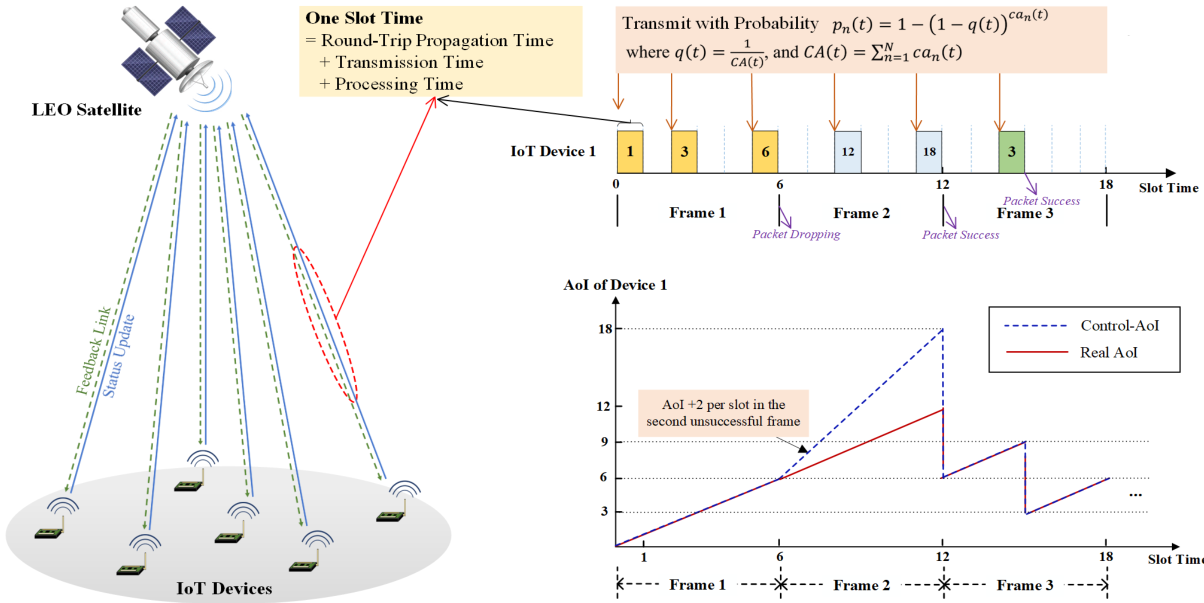

Fig. 1. System model.

propose a new concept of *control-AoI* as an amplification factor that is used for controlling the transmission probability, and the devices that have not successfully transmitted over multiple consecutive frames will have a larger instantaneous control-AoI. It is worth noting that when devices are active in a random manner, it is hard to know the system control-AoI, which is the summation of all devices' control-AoI values, due to the lack of information on the distributed devices.

The rest of the paper is organized as follows. Section II introduces the system model. Section III introduces our proposed adaptive frame-based age-aware access (AFAA) scheme and its estimation functionality. Section IV presents numerical results. Finally, concluding remarks are given in Section V.

II. System Model

We consider an uplink S-IoT network supported by a LEO satellite, and N IoT devices denoted by $D_1, D_2, \cdots, D_N$, aiming to to report their status to the satellite as timely as possible via a shared wireless channel.

Let T_F denote the duration of an access frame which consists of K slots of equal length while each slot corresponding to one packet transmission time for a status update. The IoT devices implement a slotted ALOHA-like random access protocol. Suppose that status packet arrivals to each device's queue in a Poisson process manner at the beginning of each frame. Let λ_n (packets/slot) denote the mean arrival rate to the n-th device. If a device has the status packets to transmit in one slot, it transmits the head-of-line packet according to an *age-aware transmission probability* which is denoted by p_n for the n-th device. It is notable that if multiple IoT devices transmit at the same slot, their packets will be collided, and the devices shall try the retransmissions in the remaining slots of the frame. At the end of the frame, those packets not successfully transmitted in the queue shall be dropped. We assume that all the devices are synchronized when accessing the satellite. The system scenario of the S-IoT is shown in Fig. 1.

In general, one slot consists of the packet transmission time, processing delay at satellite and device, and round-trip propagation delay [8]. We assume that LEO satellite operates at an altitude of 765 km which results in the round-trip propagation delay of 5.1 ms. We set the packet transmission time as 1 ms referring to [9]. As the processing delay is minimal compared to the propagation delay and the packet transmission time, we ignore the processing delay and assume it is 0. Consequently, the duration of each slot is determined as 7.1 ms [10]. For satellite links, when a contention timer can be set up to 50 ms [11], [12], the transmission frame is capable of accommodating 6 slots. Fig. 1 shows an example presenting three frames where at the beginning of each frame, one packet is generated at the n-th device. The device transmits the generated packet with probability p_n at each slot and the transmission trial continues until its successful transmission or the end of the frame. If the successful transmission does not occur until the frame end, i.e., the sixth slot, the packet will be dropped and the AoI of the n-th device continuously increases. When successful transmissions occur such as in slots 12 and 15 in the figure, the AoI decreases. The evolution of AoI as well as our proposed control-AoI will be introduced in detail in the next section.

III. The Proposed Adaptive Frame-Based Age-Aware Access (AFAA) Scheme

In this section, we first introduce a new concept "control-AoI" to control the transmission probabilities of the devices and explain the main difference between the conventional AoI and the control-AoI. Then, we propose a novel adaptive frame-based Age-Aware access (AFAA) scheme to prioritize transmissions from different devices and minimize AoI. It is worthy note that AFAA includes a Bayesian-based estimation functionality to estimate the system control-AoI.

A. Definition of Real-AoI and Control-AoI

For the n-th device, its AoI at slot t, $a_n(t)$, is defined as

$$a_n(t) = t - g_n(t),$$

where $g_n(t)$ denotes the generated time of the latest successful update packet transmission of device n. In general, AoI grows linearly along slots. If the device's update is successfully received by the satellite, the AoI will be reset to $t - g_n(t)$. We rename AoI by real-AoI to differentiate it from later control-AoI.

The underlining idea of AFAA is to make the devices with less successful transmission frames have a larger chance to update their status to the satellite. Consequently, instead of increasing one for each time slot when recording AoI, we increase c_n for the n-th device if the device has not transmitted successfully over c_n consecutive frames. The AoI recorded in such a way is defined as control AoI. Here c_n can be considered as an amplification factor, which is equal to the number of consecutive frames which do not contain successful transmissions for the device. Fig. 1 shows the evolution of control-AoI for the device whose c_n is set to 2. Specifically, in the first frame, the packet of device n fails in transmission, and the control-AoI will increase 2 by 2 in the second frame. When one success event occurs in the second frame, so in the third frame, the amplification factor c_n returns to one, i.e., $c_n = 1$.

The evolution of the control-AoI for the n-th device, ca_n can be expressed as follows.

$$ca_n(t) = \begin{cases} t - g_n(t), & \text{if } I_n(t) = 1 \text{ and } I_j(t) = 0, \forall j \neq n \\ ca_n(t-1) + c_n, & \text{otherwise.} \end{cases} \quad (1)$$

B. The Proposed AFAA

In minimizing the average AoI of the system, it would be better to make the device with no successful transmissions in more continuous frames have a higher transmission probability [13]. With this in mind, we control the n-th device's transmission probability $p_n(t)$ at slot t as follows.

$$p_n(t) = 1 - (1 - q(t))^{ca_n(t)}, \quad (2)$$

where $q(t) = \frac{1}{CA(t)}$ and $CA(t) = \sum_{n=1}^{N} ca_n(t)$ denotes the system control-AoI. Through the setting of (2), several interesting properties can be found:

- A larger instantaneous control-AoI $ca_n(t)$ yields a larger transmission probability $p_n(t)$.
- The probability that all the devices are idle in a slot can be obtained [13] as

$$\prod_{n=1}^{N} (1 - p_n(t)) = (1 - q(t))^{\sum_{n=1}^{N} ca_n(t)} = \left(1 - \frac{1}{CA(t)}\right)^{CA(t)}. \quad (3)$$

Algorithm 1 The Proposed AAFA Algorithm

1: Initialize $v_0 = 1$, N and do the following at each slot
2: **if** the current slot is *Idle* **then**
3: $\quad v_t \leftarrow \max(v_{t-1} - 1, 0)$
4: **else if** the current slot is *Busy* **then**
5: $\quad v_t \leftarrow \max\left(v_{t-1} + \frac{e^{-1}}{1+e^{-1}} - \delta, 0\right)$
6: **end if**
7: $v_t \leftarrow \max\left(v_t + \sum_{n=1}^{N} c_n, 1\right)$
8: $q = \min\left(\frac{1}{v_t}, 1\right)$
9: The AP broadcasts q to the devices.
10: Each device sets $p_n = 1 - (1 - q)^{ca_n}$, .

In particular, when the system control-AoI, $CA(t)$, is large, we have

$$\lim_{CA(t)\to\infty} \left(1 - \frac{1}{CA(t)}\right)^{CA(t)} = e^{-1}. \quad (4)$$

- The probability that the system has a success event in a slot, i.e., only one device transmits successfully, can be approximated by e^{-1} when $CA(t)$ is large enough as given below.

$$\begin{aligned} &\sum_{n=1}^{N} \left[\frac{p_n(t)}{1 - p_n(t)} \prod_{n=1}^{N} (1 - p_n(t)) \right] \\ =& \sum_{n=1}^{N} \left[\left(1 + \frac{1}{CA(t) - 1}\right)^{ca_n(t)} - 1 \right] \left(1 - \frac{1}{CA(t)}\right)^{CA(t)} \\ \geq& \sum_{n=1}^{N} \left[\left(1 + \frac{ca_n(t)}{CA(t) - 1}\right) - 1 \right] \left(1 - \frac{1}{CA(t)}\right)^{CA(t)} \\ \geq& \left[\frac{\sum_{n=1}^{N} ca_n(t)}{CA(t) - 1} \right] \left(1 - \frac{1}{CA(t)}\right)^{CA(t)} \\ =& \left(1 - \frac{1}{CA(t)}\right)^{CA(t)-1}. \end{aligned} \quad (5)$$

As can be seen from (2), in order to control the transmission probability, the IoT devices have to know the system control-AoI $CA(t)$. In the next subsection, we shall introduce an algorithm to estimate $CA(t)$ in real-time.

C. Algorithm Description

In order to make AAFA be practical, we further embed an estimation mechanism on $CA(t)$ into AAFA. In particular, the estimation is realized by observing the channel outcomes such as idle or busy in each slot. Algorithm 1 describes the whole proposed AAFA algorithm where v_t denotes the estimated system control-AoI at slot t. In addition, δ is the difference between the control-AoI and the elapsed time of the current frame if a successful transmission occurs and is 0 otherwise. Lines 3 and 5 correspond to the estimation of the system control-AoI depending on the channel outcomes such as idle and busy. In the following subsection, we shall introduce the underlying mathematical analysis to support these estimations. As each device's control-AoI increases by c_n in each slot, the

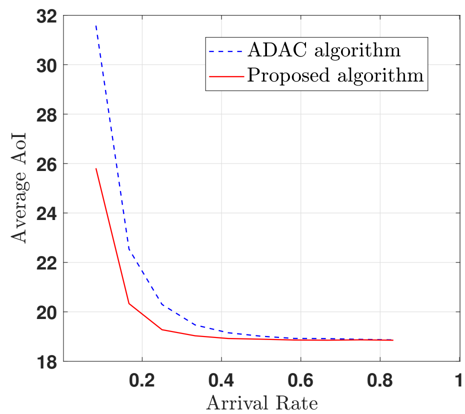

Fig. 2. Average AoI vs. Arrival Rate.

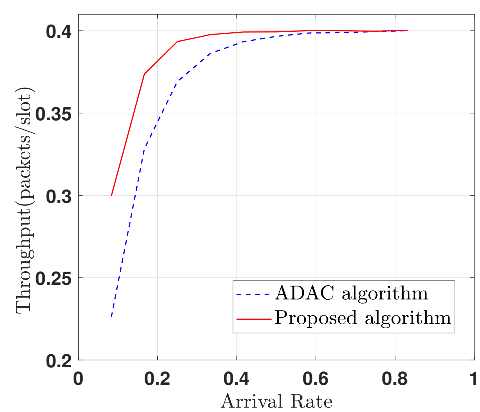

Fig. 3. Throughput vs. Arrival Rate.

system control-AoI increases by $\sum_{n=1}^{N} c_n$ which is also known by the receiver. Lastly, lines 8-9 correspond to the transmission probability shown in (2).

D. Estimation of the Control-AoI

In this section, we introduce how the estimation rules are obtained given the channel outcomes such as idle and busy events. We consider the Bayesian rule to estimate the system control-AoI. When applying the Bayesian rule, we assume the prior and posterior distributions have the form of Poisson which can be characterized by its mean. Suppose that at the beginning of a slot, the prior distribution of the system control-AoI, CA, has the mean μ. Then, we have the distribution as

$$P[CA] = \frac{\mu^{CA}}{CA!}e^{-\mu} = \Phi_{CA}(\mu). \tag{6}$$

Similar to [13], the update rule for the estimation of system control-AoI can be summarized as follows:

1) *Idle event*: An idle event $\mathcal{I}$ occurs in a slot when all the devices are idle. The mean v after the occurrence of an idle event can be derived as

$$E[CA|\mathcal{I}] = \sum_{CA=0}^{\infty} CA{\cdot}P[CA|\mathcal{I}] = \mu{-}\mu q = \mu{-}1, \tag{7}$$

where we applied the approximation of $\mu q = 1$.

2) *Busy event:* A busy event $\mathcal{B}$ occurs when there exists at least one device's transmission in a slot. As the busy event is the complement of the idle event, we have the mean CA after the busy event as

$$E[CA|\mathcal{B}] = \sum_{CA=0}^{\infty} CA \cdot P[CA|\mathcal{B}] = \mu + \frac{e^{-1}}{1-e^{-1}}. \tag{8}$$

Finally, (7) and (8) are the estimation rules shown in lines 3 and 5 in Algorithm 1.

IV. Numerical Results

In this section, we evaluate the performance of the proposed algorithm with computer simulations in terms of average AoI and throughput. For performance comparison, we also consider age-dependent activation control (ADAC) protocol [13] as the benchmark algorithm, which has similar transmission probabilities to ours but does not take into account the prioritized transmissions of devices. For the simulation scenario, we consider N IoT devices in the network.

In Fig. 2, we compare the average AoI performance of the proposed AAFA with that of the ADAC algorithm. We can clearly observe that our proposed algorithm can maintain a lower AoI compared to the existing ADAC algorithm. This confirms that all the IoT devices adopting AAFA co-exist in a harmonious way, and the effectiveness of the estimation capability.

Fig. 3 shows the system throughput performance over increasing packet arrival rate. The result shows that our proposed algorithm can achieve higher throughput than the existing ADAC [13] algorithm, especially when the packet arrival rate is low.

V. Conclusion

In this paper, we proposed an innovative adaptive frame-based age-aware access (AFAA) scheme aimed at maximizing system throughput and minimizing the average AoI. This is achieved by prioritizing devices that have not achieved successful transmission over multiple consecutive frames. In AAFA, packets from each device arrive randomly following a Poisson process, and the latest status is transmitted using an adaptive transmission probability. This approach enhances the likelihood of successful transmission for devices that have experienced prolonged update intervals. The AAFA algorithm encompasses the estimation of the system control-AoI for effective transmission probability control. The results show that the proposed AAFA scheme enhances overall system performance while also showcasing superior adaptability within the context of S-IoT.

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