Dual Strategy Framework for Enhancing Information Freshness in Satellite-IoT Networks

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위성사물인터넷 네트워크에서의 정보 신선도 향상을 위한 이중 전략 프레임워크

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Abstract

In this paper, we propose a novel age-aware frame-based transmission and reservation (AFTR) scheme that reserves a time slot in advance for devices experiencing consecutive frame failures. The proposed AFTR framework incorporates a concept of threshold to distinguish devices that have failed to transmit for a long time. In particular, the device that fails to transmit multiple consecutive frames is prioritized, so the stale information can be transmitted in the reserved time slots to obtain higher information freshness. To facilitate this approach, we also develop the system AoI estimation algorithm based on observing the idle slots in an online manner. Through comprehensive simulations, the proposed AFTR scheme can reduce average AoI effectively, appealing to LEO satellite IoT networks.

Ⅰ. Introduction

The proliferation of the Internet of Things (IoT) has significantly increased the demand for efficient and reliable communication strategies, particularly in scenarios involving a large number of devices trans-mitting data to a centralized entity. In satellite-supported IoT (S-IoT) networks, ensuring the timeliness of the transmitted information is even more crucial due to the inherent latency and potential for transmission failures associated with satellite communications.

While numerous studies have addressed random access in S-IoT, the issue of information freshness has received limited attention. In applications requiring feedback alongside retransmissions, cumulative propagation delays can significantly degrade the freshness of received packets. To address this, a new metric, the Age of Information (AoI), is introduced to reflect the timeliness of status updates. Supporting a large number of devices is a key challenge, and optimizing information freshness adds another layer of operational complexity. To tackle this issue, Yang et al. proposed a grant-free age-optimal random access protocol aimed at reducing the average AoI by adjusting the number of access slots in [1], [2]. The average AoI in S-IoT is suggested to get lower according to the RL-based approach in [3]. The authors in [6] proposed a frame-based age-aware access (AFAA) scheme that prioritizes transmitting devices experiencing consecutive frame failures. Although it reduces the system AoI well, it also increases the operational complexity of the device itself.

In response to these challenges, this paper introduces an age-aware frame-based transmission and reservation (AFTR) scheme. The AFTR scheme is designed to address the issue of consecutive frame failures by reserving time slots. By incorporating a threshold mechanism, the AFTR framework identifies devices that have failed to transmit for an extended period, granting them higher transmission priority in the reserved time slots. This prioritization ensures that stale information is transmitted as quickly as possible. To implement this scheme effectively in the S-IoT, we developed an estimation algorithm. This algorithm provides real-time system AoI estimation. Through extensive simulations, we demonstrate the efficacy of the proposed algorithm in an S-IoT framework.

Ⅱ. Method

Suppose an uplink S-IoT network in which time is divided into slots of an equal length. We assume an LEO satellite is located at the center of the coverage area, and N IoT devices, aim to report their status to the satellite as timely as possible via a shared wireless channel.

We assume that the LEO satellite operates at an altitude of 765 km, a contention timer can be set up to 50 ms according to the 3GPP standards [4], [5]. Therefore, the transmission frame is capable of accommodating 6 slots. Each slot corresponds to one packet transmission time. At the end of each frame, some new packets arrive at the device under a Poisson process. The device transmits the head-of-line packet according to an age-aware transmission probability denoted by p_n for the n-th device. The collision will occur when multiple IoT devices transmit at the same slot, the devices will retransmit in the remaining slots of the frame, and packets will be discarded until the end of the frame.

For the n-th device, its AoI 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.

To optimize the average AoI of the system, it is better to assign a higher transmission probability to devices that have experienced consecutive unsuccessful transmissions over multiple frames [6], [7]. Bearing this principle in mind, we regulate the transmission probability p_n of the n-th device at time slot t as follows.

$$p_n(t) = 1 - (1 - q(t))^{a_n(t)},$$

Where $q(t) = \frac{1}{A(t)}$ and $A(t) = \sum_{n=1}^{N} a_n(t)$ which denotes the system AoI.

We aim to prioritize devices that have encountered fewer successful transmission frames, allowing them a greater opportunity to update their status to the satellite. Accordingly, we devise a frame-based time slot reservation scheme. Initially, we introduce the notion of a threshold, denoted as θ, which is employed to pre-allocate a time slot for devices that have failed to update their status successfully for multiple consecutive frames k. When the consecutive frame count k exceeds the threshold, the satellite allocates a time slot for a random device, ensuring that the device updates its status information with a probability of 1.

This dual strategy offers two priority transmission opportunities for devices that have experienced prolonged status update failures. Firstly, devices with higher AoI are afforded higher transmission probability p_n . Secondly, the satellite reserves a time slot specifically for devices with higher AoI, ensuring a dedicated opportunity for status updates.

To effectively implement this transmission probability, we introduce a Bayesian estimation rule by channel outcomes such as idle and busy events. Similar to [7], the update rule for the estimation of system AoI can be summarized as follows:

- Idle event: the mean value after an idle event:

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

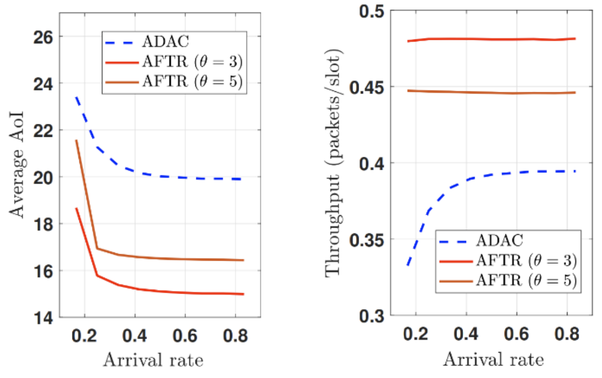
- Busy event: the mean value after the busy event:

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

Ⅲ. Numerical Result

In this section, we evaluate the performance of the proposed algorithm. For performance comparison, we also consider ADAC protocol [7] as the benchmark algorithm.

In Fig.1(a) and Fig.1(b), we compare the average AoI performance and throughput of the proposed AFTR with ADAC algorithm. Our results clearly demonstrate



(a) Average AoI (b) Throughput

Fig.1 Performance evaluation vs. arrival rate

that the AFTR scheme can achieves lower AoI and higher throughput. Furthermore, we observe that reducing the threshold value increases the likelihood of devices reserving time slots, consequently improving overall system performance.

Ⅳ. Conclusion

In this study, we present an age-aware frame-based transmission and reservation approach to ensure timely transmission of information in S-IoT networks. This approach demonstrates good performance primarily due to two key designs. Firstly, we establish the transmission probability to increase proportionally with the AoI. Secondly, we provide the reserved time slots for affording stale devices a heightened opportunity for transmission. This dual strategy ensures that devices with extended transmission failures are prioritized, enhancing their chances of successful status transmission.

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