Age of Information for Frame Asynchronous Coded Slotted ALOHA

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***Abstract*—The rapid growth of IoT applications in which a large number of devices need to deliver information to a central monitor in a timely fashion has focused attention on the age of information performance of random access protocols. This paper provides the first study of one such strategy, Frame Asynchronous Coded Slotted ALOHA (FA-CSA) Through detailed network simulations, we compare its performance to a benchmark in the field, namely Irregular Repetition Slotted ALOHA (IRSA). The results show that FA-CSA achieves fresher information on average compared to IRSA, especially at low to moderate channel loads. Additionally, the study sheds light on the implications of asynchrony in access protocols, particularly in the context of IoT applications with strict information freshness requirements.**

***Index Terms*—Slotted ALOHA, Age of Information, random access channel,**

I. Introduction

The rapid expansion of communication networks has led to the integration of Internet of Things (IoT) devices in various applications, including healthcare systems, agriculture, video surveillance, asset tracking, and more [1]. While current communication systems are reliable, they may fail to meet the needs of time-sensitive applications such as industrial control and remote sensing, where timely decisions should be taken. In such cases, the primary aim is to provide fresh information to the decision-maker at the appropriate time, rather than maximizing the spectral efficiency of the channel. This has drawn the focus on developing transmission policies which take into account the relevance, freshness and accuracy, rather than solely focusing on the technical aspects of communication [2]. The seminal concept in this field has been the Age of Information (AoI). First introduced in [3], [4] for vehicular networks, AoI measures the "staleness" of information at the receiver based on the time elapsed since the generation of last successfully decoded update. The metric depends on the frequency of update generation and the time required for it to be delivered, making it different from latency, which only considers the network time undergone by a packet.

AoI has been studied extensively for point-to-point communication channels [5]–[8]. However, research is still ongoing to characterize AoI in wireless networks, particularly in medium access policies, where multiple devices share a medium to transmit information to a common receiver. Optimal scheduling policies have been derived in [9]–[12] for such settings. However, a coordinated medium sharing is often infeasible in many IoT applications, where a massive number of low-power and low complexity devices generate updates in a sporadic and uncoordinated manner. In such settings, random access policies are commonly employed, e.g. in systems like LoRaWAN and Sigfox [13], [14]. Recent research, spanning various strategies [15]–[19], has highlighted the competitiveness of certain approaches in achieving efficient medium access control, particularly for large-scale IoT systems. Notably, advanced ALOHA-based protocols [20]–[22] have gained popularity due to their performance and manageable cost of overhead reaching performance comparable to coordinated schemes. For instance, Irregular Repetition Slotted ALOHA (IRSA), in which nodes transmit multiple copies of their packets independently over a frame of fixed length, was proposed in [23]. At the receiver end, Successive Interference Cancellation (SIC) is utilized to recover the information. Moreover, [24] introduced frame asynchronous coded slotted ALOHA (FA-CSA). improving packet loss rate and throughput by avoiding frame synchronism among users.

While the performance of these advanced schemes is well understood in terms of traditional metrics, limited contributions are available to characterize their behaviour in terms of AoI. In [25], an analytical formulation of AoI for the IRSA protocol was proposed to make it more appropriate for time-critical applications. An AoI-oriented enhancement of IRSA was also presented in [26], where a feedback signal from the receiver was used to implement a threshold-based transmission policy that prioritizes the access of nodes with higher AoI to the channel. This approach achieved an average AoI that was 50% lower than that of IRSA. The study in [27] focused on frameless ALOHA and demonstrated that setups of parameters aimed at achieving the highest throughput can lead to a decline in AoI performance. FA-CSA [28] presents a variant of IRSA in which the users will not wait for the start of the next frame to transmit their packet, and triggering a potential improvement in freshness. Taking the lead from this, we explore by means of extensive network simulationsthe AoI characteristics of FA-CSA.The study provides insights on

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how the asynchrony of the frame affects the AoI by comparing FA-CSA with IRSA.

II. Premilinaries and System model

Throughout this paper, we focus on a system with N devices that employ a shared wireless channel to communicate with a common receiver or sink. Each individual device activates intermittently and independently, attempting to transmit a status update containing time-stamped data related to a specific monitored physical process. The main goal of the system is to maintain a consistently up-to-date perception of the monitored processes at the receiving end.

For the rest of our analysis, we will consider time to be partitioned into uniform intervals, referred to as slots, and assume that all devices are slot-synchronized. The system operates over frames (i.e. group of consecutive time slots) of duration m slots. The system load, denoted by π, is defined as the average number of packets generated by the system per slot. The physical layer parameters have been configured so that the transmission of a packet fits a single slot. To ensure that the sink receives the latest information, we assume that a node in this scenario transmits only the most recently generated update, disregarding all the previously generated ones. Hence, not all generated packets will be sent to the channel. On the other hand, channel load (G) quantifies how busy the channel is and it is defined as the average number of packets transmitted per time slot. A higher channel load indicates that the channel is being used extensively, while a lower load suggests the opposite.

Based on a well established approach for slotted systems(e.g., [29], [30]), we focus on the collision channel model. As a result, when two or more packets are superimposed within a slot, the receiver cannot extract any meaningful information from them. However, when a data unit occupies a slot without any interference (i.e., a singleton slot), it is always correctly decoded. Furthermore, we assume that the sink has the ability to distinguish between idle, singleton, and collided slots.[1]

To increase the packet recovery probability, variants of ALOHA have been proposed that allow the terminals to transmit multiple copies of their data packet, while each copy includes a pointer to the slots where its counterparts have been transmitted. In this manner, if a packet is transmitted without collision, not only can it be decoded by the receiver, but also its contribution to other slots where its replicas are placed can be cancelled. This process has the potential to reveal additional singleton slots, which, in turn, facilitate the successful decoding of further packets. We focus, in particular, on two protocols which implement this principle.

A. Irregular Repetition Slotted ALOHA

When IRSA is employed, delivery of a packet can only be initiated at the start of a new frame. In this scheme, when a terminal has data to send, it transmits $\ell \in \{1, \dots, \ell_{max}\}$ copies of the packet, distributed randomly across the available m slots in the upcoming frame. Each replica embeds pointers to the positions where its counterparts are sent. The number of copies is drawn from a pre-defined distribution $\Lambda(x) = \sum \Lambda_\ell x^\ell$, where Λ_ℓ is the probability that a user sends ℓ copies of its packet. At the receiver side, SIC is performed every m-slots to resolve the collisions. Figure 1 provides an illustration of the proposed receiver operation. The scenario involves five users accessing a frame consisting of five slots. User 1 transmits three copies of its packet, while the other users send two replicas, resulting in the initial configuration depicted in Figure 1a. The receiver initiates the decoding process with user 3's singleton packet in slot 3, eliminating its contribution from slot 3, as shown in Figure 1b. At this stage, only the packet from user 1 remains in slot 4, which is successfully retrieved. Next, the corresponding replicas are removed from slots 1 and 5, leading to the configuration presented in Figure 1c. In this configuration, user 5's packet is decoded in the first slot. Thereafter, there would be no singleton slots and the SIC process can no longer be continued, as the packets of users 2 and 4 collide in a manner that renders them unrecoverable. These collision patterns are commonly referred to as stopping sets.

B. Frame-Asynchronous Coded Slotted ALOHA

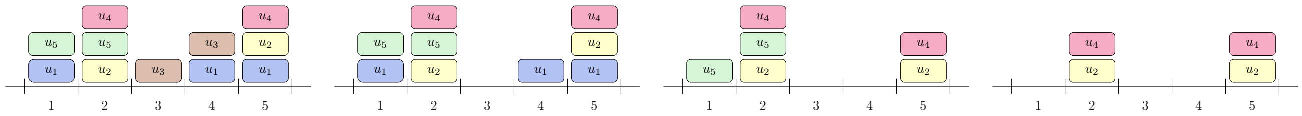
FA-CSA differs from IRSA in two key aspects. First, at the transmitter's side, when a new packet is generated at a node FA-CSA immediately transmits the first replica in the next available slot without waiting for the start of a new frame. We refer to a user as active during the transmission phase and idle otherwise. Note that with this terminology, IRSA synchronizes the activation period with the receiver's decoding window. However, in FA-CSA, the activation period operates independently of the receiver and is referred to as "virtual frames". During this period, the first replica of the packet is placed in the first slot of the virtual frame. and the remaining $\ell - 1$ replicas are uniformly distributed within its subsequent $m-1$ slots. If a user generates a new update while still active with a previous transmission, the virtual frame for the new update commences immediately after the conclusion of the ongoing virtual frame.

From the receiver's perspective, the asynchrony between virtual frames and receiver frames would require considering the system's entire history to capture all resolvable collisions. However, for practical reasons, the receiver employs a finite-size memory and retrospectively examines a limited number of recent frames, resulting in a sliding-window decoder. [2]

To illustrate these differences in the operation of the two protocols, consider the example shown in Figure 2. Here we focus on a single user and consider (virtual) frames of duration $m = 4$ slots. Brackets are used to indicate the decoding windows. In IRSA, shown in Figure 2a, the decoding window covers only the last frame. In contrast, as depicted in Figure

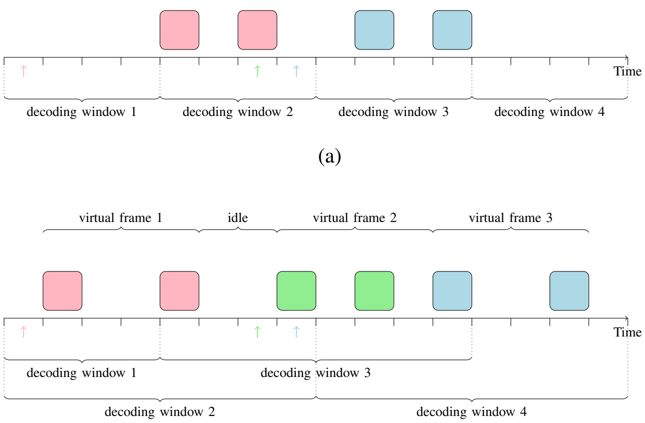
[1] This can be achieved, e.g. by using energy detection at the receiver.

[2] Performance gains are generally not observed by increasing the width of the sliding window beyond $5m$ [31].



(a) (b) (c) (d)

Fig. 1. Example timeline for the operation of IRSA at the receiver side. In the considered case, 5 users access a frame of $\mathsf{m} = 5$ slots. the receiver looks for collision-free slots to recover the uncollided packets and subsequently cancels the interference of their twins in other slots, potentially revealing more collision-free slots. This approach is iterated until there is no collision-free slot.



(a)

(b)

Fig. 2. Comparison between IRSA and FA-CSA operation. In both cases, $m = 4$. Dashed lines show the decoding moments. The arrows represent moments of update generation, with corresponding data packets shown as squares of the same colour as the arrows. In (a) the decoding window at every decoding moment spans only the recent frame, while in (b) it covers the past two frames.

2b, FA-CSA utilizes a decoding window spanning the last two frames, creating a sliding window decoding approach. In the example, each packet is sent twice over the channel, i.e. a regular degree distribution of order two is employed. Within the observed time span, the terminal generates three updates, distinctly indicated by arrows of different colours. Corresponding data packets are depicted as squares, sharing the same colour as their respective arrows.

For the first update shown in red, if transmitted using IRSA, the corresponding packets are sent during the second frame and both copies can be decoded at the end of the second frame. However, if transmitted using FA-CSA, its first replica is transmitted immediately after generation, and the second replica is placed randomly within the virtual frame that starts after its generation. The first replica can be decoded at the end of the first frame, and the second replica can be recovered at the end of the second decoding window.

The second update, denoted by the green arrow, is generated in the second frame. Under IRSA, it is discarded as only the latest update generated within a frame is transmitted. In this case, it is succeeded by the third update within the same frame, shown by the blue arrow. However, when operating under FA-CSA, the first replica corresponding to the second update is immediately sent through the channel, and the second replica is randomly placed within the remaining slots of the second virtual frame. Between the end of the first virtual frame and the start of the second virtual frame, the user is in an idle state. The third update is generated while the user is active, making it ineligible for immediate transmission. Instead, it must wait until the end of the second virtual frame. Subsequently, the third virtual frame begins, maintaining the user's active mode. During this frame, the first replica of the third update is sent at the start, while the second replica is randomly placed within that frame. The first replica falls within the third decoding window, allowing for potential decoding at the end of the third frame, followed by the recovery of its twin at the end of the fourth frame.

C. Throughput Performance

The throughput S of the considered schemes is represented in Figure 3. This figure shows the throughput (average number of unique packets decoded by the receiver per time slot) vs the system load π. In both schemes, the number of users is $N = 1000$, the frame duration is $m = 100$ slots and every user sends 3 replicas of its packets.When the system load is low, both schemes can recover most of the generated packets. In other words, the throughput is roughly equal to the system load. As the system load increases, collisions in the channel increase, leading to higher packet loss rates. This results in reduced throughput. However, the sliding window property of the FA-CSA enables it to improve over IRSA, reaching a higher throughput value [24]. In fact, this property provides the collided packets with more than one chance to be recovered. It is noteworthy to mention that the channel load in IRSA is lower than FA-CSA. This is due to the fact that when two updates are generated by a user in the same frame, the synchrony of the frames in IRSA leads to discarding the old updates generated in the same frame and only the last one is sent to the channel, while in FA-CSA the second update within a frame can be sent to the channel once the virtual frame of the previous update is over. This phenomenon was pronounced in the example in Figure 2 where the green update was discarded in IRSA, while it went through the channel in FA-CSA.

D. Age of Information

In order to evaluate the effectiveness of the considered protocols in preserving a fresh perception of monitored processes

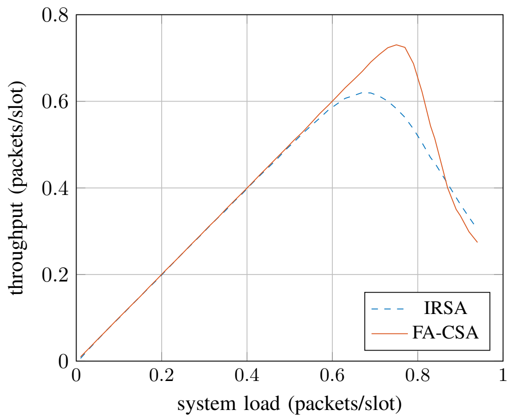


Fig. 3. comparison of throughput in IRSA and FA-IRSA. For both methods, frame width of m = 100 slots, N = 1000 users and $\Lambda(x) = x^3$ is considered.

at the destination, we leverage the age of information. It is assumed that all messages are of equal importance in the context of our study. The *instantaneous age of information* of each user i at the sink is defined as the duration between the present time and the time at which the latest information from user i was received, i.e.

$$\delta^{(i)}(t) := t - \sigma^{(i)}(t) \tag{1}$$

Here, $\sigma^{(i)}(t)$ represents the generation time of the most recent update received from node i at time t. Based on this, we introduce the average AoI for each node

$$\Delta^{(i)} := \lim_{t\to\infty} \frac{1}{t}\int_0^t \delta^{(i)}(\tau)d\tau \tag{2}$$

where we assume that the limit exists. Observe that in our setting $\Delta^{(i)}$ does not depend on the index i. Note also that, for a fixed probability of generating an update at a user, the AoI grows with N (the number of users in the system). Hence, we investigate the normalized average AoI (NAAoI) of the entire network

$$\Delta := \frac{1}{N}\Delta^{(i)}. \tag{3}$$

For IRSA, a tight approximation of (3) was derived in [25]:

$$\Delta_{\text{irsa}} \simeq \frac{1}{2N} + \frac{1}{S} + \frac{m}{N}. \tag{4}$$

On the other hand, no characterization of the AoI for FA-CSA is available. As the existence of memory across frames in the decoding process renders the problem difficult to be tackled analytically, we will resort to extensive network simulations.

III. Numerical Results and Discussion

In order to compare the protocols based on the network average AoI, it is common practice to study how the metric changes with varying channel loads. To perform this analysis, it is necessary to consider the relationship between channel load and variables such as packet generation probability, network size, and frame duration. We recall that the channel load is defined as the average number of devices accessing the channel per slot.

For IRSA, this is given by [25]:

$$G_{\text{IRSA}} = \frac{N(1-(1-\rho)^m)}{m} \tag{5}$$

where ρ is the packet generation probability, i.e. the probability that the node becomes active and generates a new status update in a slot. The above formula holds only if the user frames are synchronous. Another interpretation of the channel load is the mean rate at which the channel receives new packets. From this perspective, we calculate the expected value of the time elapsed between two consecutive updates from a user operating with FA-CSA. This time interval, which we denote by Y, is composed of m slots of activation period and potentially a silence period, X which can have a duration of zero slots if at least one update is generated during the activation period. The expected value for X is thus

$$E(X) = \sum_{x=1}^{\infty}(x(1-\rho)^{m+x-1}\rho) = \frac{(1-\rho)^m}{\rho} \tag{6}$$

leading to a mean inter-update time

$$E(Y) = m + E(X) = m + \frac{(1-\rho)^m}{\rho}. \tag{7}$$

Accordingly, the channel load with FA-CSA can be written as

$$G_{\text{FA}-\text{CSA}} = \frac{N\rho}{m\rho + (1-\rho)^m}. \tag{8}$$

If we denote the system load to be π, then $\pi = \rho N$, which is the expected value of the number of packets generated in the system per time slot. Accordingly, the channel load for these protocols can be re-written as:

$$G_{\text{IRSA}} = \frac{N}{m}\left(1-\left(1-\frac{\pi}{N}\right)^m\right) \tag{9a}$$

$$G_{\text{FA}-\text{CSA}} = \pi\left[\frac{m\pi}{N} + \left(1-\frac{\pi}{N}\right)^m\right]^{-1}. \tag{9b}$$

In turn, for large N

$$\sum_{i=0}^{m}\binom{m}{i}\left(\frac{\pi}{N}\right)^i(-1)^i = 1-\frac{\pi}{N}+O\left(\frac{1}{N^2}\right) \approx 1-\frac{\pi}{N} \tag{10}$$

so that for both schemes we get

$$\lim_{N\to\infty} G_{\text{IRSA}} = \lim_{N\to\infty} G_{\text{FA}-\text{CSA}} = \pi. \tag{11}$$

Put differently, although for an equal system load the synchronicity in IRSA results in a lower channel load compared to FA-CSA, when the number of users is sufficiently large, the channel load in the two protocols will tend to converge to the system load. In spite of this asymptotic convergence, we argue that the system load is a fairer ground for performance comparisons, as it is a good proxy for the energy consumed for the update generation since it does not disregard generated packets that are discarded due to the limitations of transmission schemes.

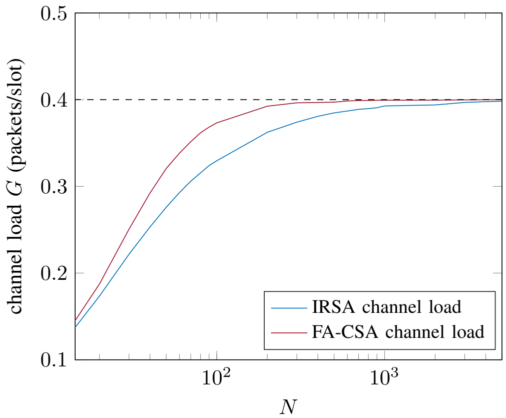


Fig. 4. Asymptotic channel load analysis. When the system load is fixed at $\pi = 0.4$ packets/slot, the FA-CSA has always a higher channel load compared to IRSA. However, the channel load of both protocols will converge to the system load from below as the number of nodes (N) grows large.

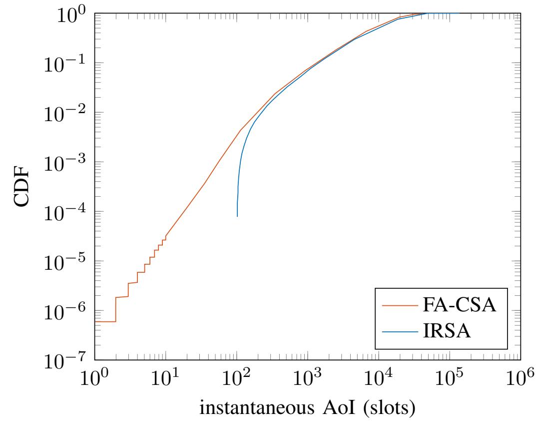


Fig. 5. Comparison of the two protocols' empirical AoI CDF.

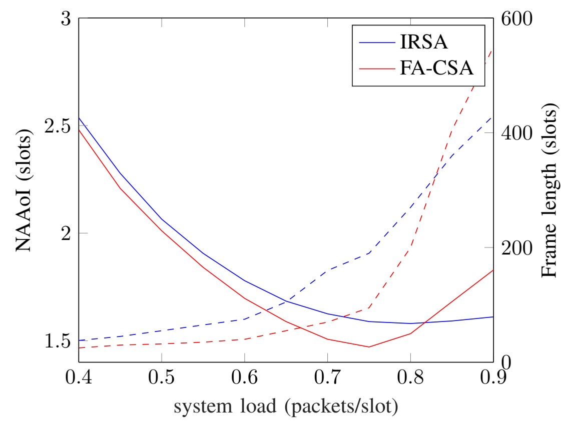


Fig. 6. Minimum normalized average age attainable (solid lines) and best frame length (dashed lines) for IRSA and FA-CSA with regular distribution $\Lambda(x) = x^3$ and $N = 1000$ users.

Fig. 4 depicts how the channel load varies with the change in the network size when the system load is kept constant at $\pi = 0.4$ (packets/slot). When the network size is small, the given system load stems from high packet generation probability of a few users. In both schemes many of the generated packets will be discarded and will not be sent through channel since they get succeeded by a newer generated packet in the same frame. It can be observed that under the same network size and system load, with FA-CSA, the channel will always experience higher load than with IRSA.

A. Age Violation Probability

Let us now focus on the age violation probability, i.e., the probability that the instantaneous age $\delta(t)$ exceeds a threshold. Figure 5 shows the empirical Cumulative Distribution Function (CDF) of the instantaneous AoI for the two schemes, when $N = 1000$ users contend to transmit packets, with uniform distribution of $\Lambda(x) = x^3$, and $m = 100$ slots. It can be inferred that while under IRSA protocol no terminal can have $\delta_i(t) < 100$ slots, in the FA-CSA there is a non-zero chance for them to have their instantaneous AoI reach the minimum possible, i.e. 1 slot. This happens thanks to the asynchrony of the frames between the receiver and transmitters, and also having the 1st replica transmitted always at the beginning of local frames. Furthermore, it can be viewed that the $F(x)$ curve for FA-CSA stands always on top of IRSA. This means that the probability that $\delta(t)$ surpasses a certain threshold is always lower in FA-CSA compared to IRSA, which makes the former superior when the objective is to minimize the age violation probability.

B. Impact of frame length and number of terminals

For both IRSA and FA-CSA, it is known that as the frame length increases, the packet loss rate decreases, leading to higher throughput [23], [28]. On the other hand, a large frame duration means that it takes a longer time to transmit all replicas. which might in turn hinder the age of information metric [25]. Thus, there exists a best frame duration for every channel load, beyond which the throughput increases at the cost of deteriorating the AoI. Figure 6 depicts the frame length providing the minimum average AoI for both IRSA and FA-CSA. In particular, the dashed lines indicate the frame duration that yielded the lowest average AoI in our simulations, whereas the solid lines provide the achieved average AoI. In both schemes, the higher system loads require larger frame lengths to minimize the average AoI. In the system load regimes that are typically of interest (i.e., for loads corresponding to moderate-low packet loss rates, e.g. $\pi < 0.7$ (packets/slot) for the considered schemes), the frame length is shorter in FA-CSA compared to IRSA. In the same system load regime, the NAAoI decreases as the system load increases. The figure confirms the superiority of FA-CSA, with a lower NNAoI exhibited for $0 < \pi < 0.8$.

An interesting trend in the NNAoI of IRSA and FA-CSA emerges in asymptotic scenarios $N \to \infty$, as shown in Fig 7. By the growth of network size, the NAAoI flattens in both schemes, reaching a limiting value that is numerically identical in both schemes. The limiting value is expected to

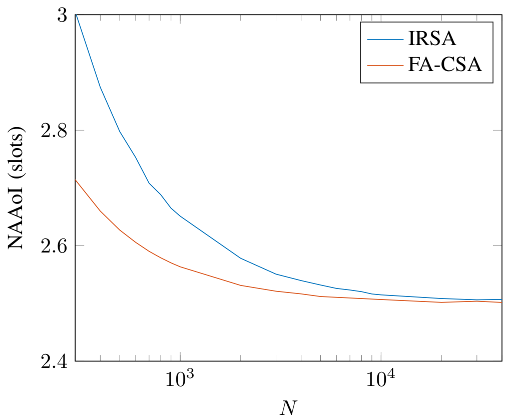


Fig. 7. Comparison of the two protocols' NAAOI when the network size grows. $m = 100$ slots and $\pi = 0.4$ packets/slot.

be influenced not only by the chosen frame size but also by the underlying protocol distribution $\Lambda(x)$. This trend shares similarities with findings in the literature concerning IRSA [26]. Notably, FA-CSA consistently achieves a lower NAAoI in comparison to IRSA. However, as the network size expands, the advantage diminishes. This trend stems from the dominant role of the number of users in contributing to the age metric, especially in large terminal sets.

IV. Conclusions

The paper investigated the performance of two random access protocols IRSA and FA-CSA in terms of AoI. By means of numerical simulations, we showed that FA-CSA consistently achieves a shorter AoI compared to IRSA, showcasing its superiority in preserving information freshness. These findings highlight the potential of FA-CSA as a more efficient and reliable random access scheme for massive IoT applications, ensuring real-time information updates for monitoring purposes. Future research involves the analysis of FA-CSA incorporating an age-threshold mechanism, along with comparative studies against methods like frameless ALOHA.

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