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Age-of-Information Dependent Random Access in Multiple-Relay Slotted Aloha

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“Nada se edifica sobre la piedra, todo sobre la arena, pero nuestro deber es edificar como si fuera piedra la arena...”

J.L.Borges

RESUMO

Com a chegada e rápida consolidação da Internet das Coisas (*internet of things*, IoT), múltiplas aplicações surgem com diferentes requisitos de desempenho, como a pontualidade da informação, que pode ser quantificada pela métrica da idade da informação (*age-of-information*, AoI). Em termos gerais, quanto menor a AoI de um dispostivo, mais fresca é a informação coletada, e melhor é seu desempenho. Ainda, permitir a coexistência de números massivos de dispositivos IoT de baixa complexidade é frequentemente desejável, e métodos de acesso aleatório modernos vêm sendo explorados como uma maneira de alcançá-la. Neste trabalho, o desempenho de uma rede com acesso aleatório em dois saltos com múltiplos *relays* é investigado, com foco na métrica AoI. A média de idade dos usuários na rede (AoI média da rede) é avaliada quando ela segue duas abordagens diferentes: *Age dependent random access* (acesso aleatório dependente da idade, ADRA) em múltiplos relays no *uplink* (ADRA-MRU), em que usuários comparam sua idade com a de um limiar pré-definido antes de realizar uma transmissão, e ADRA em múltiplos relays no *downlink* (ADRA-MRD), em que esta tarefa pertence aos relays. Como resultado, é mostrado através de métodos analíticos e numéricos que ADRA-MRU reduz consideravelmente a AoI média de uma rede seguindo o esquema de acesso aleatório com múltiplos relays (AIRA-MR) em mais de 60%, enquanto que o desempenho do ADRA-MRD é apenas ligeiramente melhor do que o do AIRA-MR. Além disso, são apresentadas ideias sobre o número ótimo de relays, bem como outros parâmetros que influenciam a AoI.

Palavras-chave: Internet das Coisas. Acesso aleatório. Redes com repetidores.

ABSTRACT

With the advent and rapidly consolidating of the Internet of Things (IoT), multiple applications arise with different performance requirements, such as the timeliness of information, which can be quantified by the age-of-information (AoI) metric. Generally, the lower an user's AoI is, the freshest is the information collected at the destination, and the better is the user's performance. Furthermore, allowing the coexistence of massive numbers of low-complexity IoT devices is often desirable, and modern random access methods have been explored as a way of achieving it. In this work, we investigate the performance of a random access two-hop network with multiple relays, focusing on the AoI metric. We evaluate the average age of the network under two age-dependent approaches, namely Age Dependent Random Access (ADRA) in Multiple Relays in the Uplink (ADRA-MRU), in which users evaluate their age against a threshold before transmitting, and ADRA in Multiple Relays in the Downlink (ADRA-MRD), where this responsibility belongs to relays. As a result, we show through analytical and numerical results that ADRA-MRU can considerably reduce the average AoI of an age-independent random access scheme with multiple relays (AIRA-MR) by more than 60%, while the performance of ADRA-MRD is slightly better than that of AIRA-MR. Moreover, we also provide insights on the optimal number of relays as well as other parameters that influence the AoI.

Keywords: Age-of-information, Internet of Things, Random Access, Relays.

RESUMO EXPANDIDO

Introdução

À medida que a Internet das Coisas (*Internet of Things*, IoT) se desenvolve, diversas aplicações surgem com demandas de sistema que podem não ser atendida s por tecnologias e abordagens clássicas. Por exemplo, em uma rede IoT com um número enorme de dispositivos de baixo custo equipados com sensores e um rádio, novos sinais de informação são transmitidos constantemente, de forma não sincronizada e imprevisível, em um único canal comum a todos. Esforços para coordenar estes dispositivos resultariam em um gasto com tempo de processamento e recursos que poderia inviabilizar completamente a solução. Neste sentido, políticas de acesso aleatório vêm recebendo nova atenção como uma forma viável de acomodar um número grande de usuários no mesmo canal. Recentemente, uma nova classe de métodos de acesso aleatório, chamados acesso aleatório moderno, vêm sendo explorados na literatura, sendo desenvolvidos normalmente com base no clássico esquema ALOHA, mas buscando resolver um de seus aspectos mais frágeis: a colisão de pacotes.

Métodos de acesso aleatório moderno geralmente dependem de técnicas de diversidade, principalmente com a adoção de retransmissões juntamente de técnicas de cancelamento de interferência sucessiva. Estas abordagens costumam superar métodos de acesso aleatório clássicos, mas também impõem uma complexidade maior ao sistema, especialmente aos receptores que devem ser capazes de executar algoritmos complexos. Por outro lado, diversidade também pode ser alcançada espacialmente, por exemplo, com diversos receptores espalhados espacialmente tentando coletar pacotes independentemente, posteriormente encaminhando-os a um destino comum. Esta topologia é chamada neste trabalho de “sistema com dois saltos e múltiplos retransmissores”. Tecnologias atuais comerciais, como LoRaWAN, aplicam este tipo de diversidade, por exemplo.

Inicialmente, os métodos de acesso aleatório moderno foram propostos para permitir o acesso descoordenado por múltilpos usuários. Porém, eles não necessariamente garantem atualizações (recebimento de novos pacotes de informação) pontuais. Algumas aplicações demandam que suas atualizações sejam tão recentes quanto possível, exigindo o desenvolvimento de outras técnicas e métricas de desempenho para garantir o funcionamento preciso do sistema. Neste sentido, a métrica de Age-of-Information (AoI) é apresentada como uma quantização do “frescor” da informação recebida, e caracteriza o tempo que passou desde a última vez que um dispositivo teve sua transmissão recebida com sucesso no destino.

Neste trabalho, a AoI de uma rede com diversidade espacial é caracterizada matematicamente e são propostas duas implementações de métodos de acesso aleatório moderno neste cenário. São realizadas simulações para validar o equacionamento desenvolvido, e é feita uma discussão sobre a seleção de parâmetros ótimos dependendo das características do sistema. É mostrado que, quando dispositivos têm informação de sua AoI, é possível reduzir em até 60% a AoI média da rede comparada ao caso agnóstico.

Objetivos

Esta dissertação tem como objetivo principal caracterizar a evolução da AoI de uma rede em um sistema com dois saltos e múltiplos retransmissores quando os dispositivos finais têm informação sobre sua própria AoI. Os objetivos secundários são: (i) obter equações fechadas para a AoI média da rede com os métodos de acesso aleatório propostos e validar o equacionamento por meio de simulações de Monte-Carlo; (ii) avaliar o desempenho das redes em função dos diversos parâmetros selecionáveis; (iii) encontrar tendências e ideias-chave para a seleção ótima dos parâmetros em diversos cenários.

Metodologia

Inicialmente, a métrica de AoI é apresentada e discutida, comentando sobre os métodos mais originais de se realizar o equacionamento. É apresentada uma breve revisão bibliográfica de trabalhos que exploraram esta métrica no contexto de acesso aleatório moderno. A principal referência para a AoI deste trabalho, He Chen *et al.* (2020), é apresentada em sequência, onde os autores propõem um método de acesso aleatório em que os dispositivos têm conhecimento de sua própria AoI e só transmitem a partir de um certo limiar, chamado *Age-Dependent Random Access* (ADRA). É detalhando o desenvolvimento e principais considerações dos autores.

Depois, é apresentado com detalhes o modelo do sistema e é demonstrado o motivo pelo qual é possível utilizar parte da estrutura apresentada por He Chen *et al.* (2020) para obter a AoI média também no modelo de sistema com múltiplos relays adotado neste trabalho. São propostas duas novas implementações de ADRA no contexto de múltiplos retransmissores: a primeira, em que os dipositivos têm conhecimento de sua AoI, chamada ADRA-MRU, e só transmitem após um certo limiar; e a segunda, ADRA-MRD, em que os dispositivos são agnósticos a sua AoI, transmitindo quando desejarem, mas os retransmissores detém este conhecimento, somente retransmitindo pacotes de usuários com AoI maior que o limiar. Para fins de comparação, também é apresentado o método em que nenhuma parte do sistema tem conhecimento sobre a AoI dos usuários, chamado AIRA-MR, e todos transmitem e retransmitem a qualquer momento. As expressões analíticas para a probabilidade de sucesso da transmissão nestes três esquemas são derivadas em seguida.

Resultados e discussão

Primeiramente, é avaliado o impacto de dois parâmeteros do sistema quando há $K = 3$ retransmissores disponíveis, a probabilidade de acesso ao meio dos dispositivos p e o limiar de AoI para início de transmissões/retransmissões δ. É feita uma busca bidimensional destes parâmetros nos dois métodos baseados no ADRA, e apenas do de p no caso do AIRA-MR, e algumas tendências interessantes são percebidas. Por exemplo, há pouco ganho de desempenho no ADRA-MRD, comparado ao AIRA-MR, quando ambos os parâmetros são ótimos. Por outro lado, com ADRA-MRU é possível atingir AoI quase 25% menor do que no caso AIRA-MR. Por fim, para valores baixos de p, todos os métodos se comportam de forma muito semelhante, uma vez que há poucas colisões e δ deixa de ser relevante.

Em seguida, os parâmetros p e δ são otimizados quando o número de retransmissores K varia entre 1 e 8. São avaliados dois cenários de condição de canal diferentes, e em ambos os casos, para todos os esquemas, o valor ótimo de K é 2. Apesar do valor ótimo de K ser baixo, para valores mais altos, o método ADRA-MRD apresenta um desempenho melhor do que dos outros métodos, mas ainda inferior ao ADRA-MRU com K ótimo. Nestes cenários, o valor de K ótimo baixo é explicado pelo ganho de diversidade suficiente para coletar ao menos um pacote por vez, ainda mantendo um tráfego baixo no segundo salto. Após esta análise, são considerados alguns pares de parâmetros da qualidade de enlace, e a mesma otimização tridimensional (p, δ, K) é realizada. É avaliado o ganho de desempenho que cada um dos métodos baseados em ADRA garante ao sistema comparado ao caso do AIRA-MR. O esquema ADRA-MRU resulta em um ganho de desempenho de até $63,5\%$, mostrando-se uma boa alternativa para implementação. Por outro lado, ADRA-MRD tem desempenho ótimo muito próximo do AIRA-MR, resultando em um ganho máximo de 5% quando as condições dos canais são muito ruins. Esta análise também revelou que o número ótimo de retransmissores varia conforme as condições dos canais variam, sendo necessário menos retransmissores quando as condições são boas, e mais conforme elas se deterioram.

Finalmente, para duas condições de canais distintas, os parâmetros são otimizados conforme o número de dispositivos aumenta. Em todos os casos, o valor de K não variou com o número de dispositivos, apenas com as condições do canal e esquema adotado. Novamente o método ADRA-MRU se mostrou superior aos outros dois, e o método ADRA-MRD provou-se pouco eficaz comparado ao método AIRA-MR, falhando em garantir bons resultados com o aumento da complexidade.

Considerações finais
Esta dissertação propõe duas possíveis implementações de métodos de acesso aleatório moderno dependentes da AoI de dispositivos em uma topologia de dois saltos e múltiplos retransmissores. Foi mostrado que o número ótimo de retransmissores também é uma variável sujeita a otimização, dependente dos parâmetros do sistema. Algumas tendências do comportamento dos métodos propostos são discutidas, e o método em que os dispositivos têm conhecimento de sua própria AoI consolidou-se como superior ao restante ao atingir desempenho até $63,5\%$ melhor. Uma relação de troca não trivial entre o número de retransmissores é observada, e a melhor utilização destes dispositivos pode ser investigada no futuro, aproveitando mais a diversidade fornecdia por eles.

Palavras-chave: Internet das Coisas. Acesso aleatório. Redes com repetidores.

LIST OF FIGURES

LIST OF ACRONYMS

AIRA-MR	Age Independent Random Access in Multiple Relays
AAoI	Average Age of Information
ADRA	Age Dependent Random Access
ADRA-MR	Age Dependent Random Access in Multiple Relays
AIRA	Age Independent Random Access
AoI	Age of Information
CSMA	Carrier Sensing Multiple Access
DTMC	Discrete Time Markov Chain
FDMA	Frequency Division Multiple Access
IoT	Internet of Things
IRSA	Irregular Repetition Slotted ALOHA
LEO	Low Earth Orbit
MIMO	Multiple Input Multiple Output
NOMA	Non Orthogonal Multiple Access
PAoI	Peak Age of Information
RA	Random Access
SA	Slotted ALOHA
SIC	Successive Interference Cancellation
TDMA	Time Division Multiple Access

LIST OF SYMBOLS

U_i	Particular user of index i
$\Delta_i(t)$	Instantaneous AoI of user U_i at time slot t
$\bar{\Delta}$	Average network AoI
q	Probability of a packet successfully reach the sink
δ	Age of Information threshold
p	Channel access probability of users
S_a	States of the DTMC that models the AoI
η	Probability of any user U_i to have $\Delta_i(t) \geq \delta$
ε_U	Erasure probability at the uplink
ε_D	Erasure probability at the downlink
$\bar{\Delta}_{\mathbf{I}}$	Average AoI of a network following policy AIRA-MR
$\bar{\Delta}_{\mathbf{U}}$	Average AoI of a network following policy ADRA-MRU
$\bar{\Delta}_{\mathbf{D}}$	Average AoI of a network following policy ADRA-MRD
K	Number of relays
N	Number of users
π_a	Stationary probability of DTMC to be at state S_a
$\bar{\Delta}^{(p)}$	Peak network AoI
t	Time slot index
$I_i(t)$	Delivery status of user U_i at time slot t
$\mathcal{T}$	Observation period in time slots
$T_{a,b}$	Transition probability from state S_a to state S_b of the DTMC
μ_a	Mean recurring time of state S_a
$\mathbf{P}$	Transition probability matrix of the DTMC
η_U	Probability of any user U_i to start a transmission following ADRA-MRU
n	Number of users starting a transmission concurrently with user U_i at time-slot t
m	Number of users with $\Delta(t) \geq \delta$ at time-slot t
$\hat{q}$	Probability of an user to have its packet delivered to the sink without considering collisions
$\tilde{q}$	Probability of any of m users to have their packets delivered to the sink without considering collisions

CONTENTS

1 INTRODUCTION

As the Internet of Things (IoT) develops, many applications arise with unprecedented requirements, which may not be attended by classical approaches (XU *et al.*, 2014; RAY, 2018; NGUYEN *et al.*, 2022). For example, in an IoT network with a massive number of low cost devices equipped with sensors and a radio, new small packets with information are constantly, asynchronously and unpredictably being generated to be transmitted over a common channel (RAZA *et al.*, 2017). Efforts to coordinate such devices would lead to impractical overhead for successful transmissions (CLAZZER *et al.*, 2019). In this context, Random Access (RA) policies have gained revived attention as a feasible way to accommodate all these users in the same channel. Recent investigations have been made on this topic, with a new class of modern RA methods being developed for these specific problems, many of them building upon the classic ALOHA scheme, while addressing one of its weakest aspects: packet collision (CLAZZER *et al.*, 2019).

Modern RA methods have generally relied on diversity techniques, by adopting retransmissions along with Successive Interference Cancellation (SIC) (CLAZZER *et al.*, 2019). In this scenario, users may transmit copies of the same packet multiple times, and, upon successfully decoding one of the copies, the receiver attempts to cancel out the interference caused by the decoded packet in the signal received with collisions. While this approach outperforms classic RA methods (CASINI *et al.*, 2007; TEGOS *et al.*, 2020), it also imposes additional complexity to the system, specially to receivers who must be able to perform advanced signal processing to retrieve the collided packets. Instead, spatial diversity may be an option (MUNARI *et al.*, 2021, 2019; OGATA *et al.*, 2017), for example, with multiple receivers, without significant modifications to either the transmitters or receivers. Note that this is a setup of practical relevance, as it represents current and envisioned IoT technologies, such as LoRaWAN and its star-of-stars topology (LORAWAN™. . . , s.d.), or Low-Earth Orbit (LEO) constellations with satellites working as receivers for transmissions sent by ground users (QU *et al.*, 2017). In this light, authors in (MUNARI *et al.*, 2019) evaluate a two-hop topology where a number of end-devices randomly transmit their packets to a set of relays, which, in turn, forward such packets to a common sink. This topology achieves spatial diversity while still maintaining implementation costs low from the end-devices perspective, since they are able to operate under regular ALOHA.

Initially proposed as enablers for uncoordinated access to the channel by multiple users, modern RA methods have not necessarily been designed to guarantee timely updates in the form of information packets. In deployments with well defined time requirements, not only information is expected to be received consistently, but it also must be *fresh*. In this sense, the Age of Information (AoI) has emerged as a metric to quantify the freshness of information (KAUL *et al.*, 2012; YATES, R. D. *et al.*, 2017). Essentially, the AoI characterizes the time elapsed since the generation of the last packet at the end-device. While it is possible to evaluate the AoI from several different perspectives, the average AoI (AAoI) provides useful insights in the design of timeliness-oriented communication systems, being often obtained through graphical analysis (YATES, Roy D. *et al.*, 2021).

In this work, inspired by recent literature, we reevaluate the performance of the two-hop relay-assisted network from (MUNARI *et al.*, 2019) under a freshness perspective, i.e., by adopting the AoI as performance metric. More specifically, we extend the ADRA scheme from (CHEN, H. *et al.*, 2020) to the aforementioned multirelay scenario, which imposes a different set of optimization parameters and trade-offs. Moreover, given the two-hop nature of the considered network, we analyze two different implementations of ADRA-based policies in Multiple Relays, namely ADRA-MRU, in which users evaluate their age against a threshold before transmitting, and ADRA-MRD, where this responsibility belongs to relays. We perform a number of experiments to obtain insights on the impact in the AoI of each of the tunable parameters, and present numerical results obtained from the expressions alongside Monte-Carlo simulations to confirm our formulations. We show that, compared to the age-independent case, it is always beneficial to evaluate the age threshold at the users side, while evaluating it at the relays provides only modest performance gains. Moreover, we show that the number of relays is also a variable subject to optimization in each policy, alongside the channel access probability and age-threshold, while the optimum number of relays increases as the quality of the channels deteriorate.

The rest of this work is organized as follows: we describe our system model in Chapter 2. We then devise the expressions used to obtain the AAoI in this system in Chapter 3, where we also present and discuss our analytical and simulation results. Finally, we conclude the work in Chapter 5.

2 AGE OF INFORMATION

The AoI metric was first introduced in Kaul *et al.* (2012) to characterize the freshness of information at the destination, being defined as the time elapsed since the generation of the most recent packet successfully delivered to the sink. For example, in an IoT network with N users, user U_i has instantaneous AoI $\Delta_i(t)$ at time t, and its AoI can increase or decrease depending on whether or not it has delivered new information to the destination at time $t' > t$. Formally, $\Delta_i(t)$ is defined as

$$\Delta_i(t) = t - r_i(t), \tag{1}$$

where t is the current time and $r_i(t)$ is the time when the last packet received was generated. The evolution of the AoI is illustrated in Fig. 1. In this illustration, two packets are generated at time t_1 and t_2, separated in time by the inter-arrival time Y_2. At time t_1', the packet is received at the destination, and the AoI is set to $\Delta_i(t_1') = T_1 = t_1' - t_1$. This process is repeated for the second packet generated at time t_2 and successfully received at time t_2'. At last, the packets are received with difference of Z_2. This metric can be evaluated from different perspectives, which provides different insight on the performance of a given system. Two main relevant approaches can be cited as AAoI and peak AoI (PAoI) (YATES, Roy D. *et al.*, 2021).

As its name suggests, the AAoI, $\bar{\Delta}$, is obtained by averaging the value of the AoI in a time interval $\mathcal{T}$, which can be solved by finding the area under the curve of $\Delta_i(t)$. Commonly, this value has been found through graphical analysis, specially in continuous time systems. These methods consist on decomposing the area under the curve into a sum of trapezoidal smaller areas. In Fig. 1, Q_2 is one of the decomposed trapezoidal

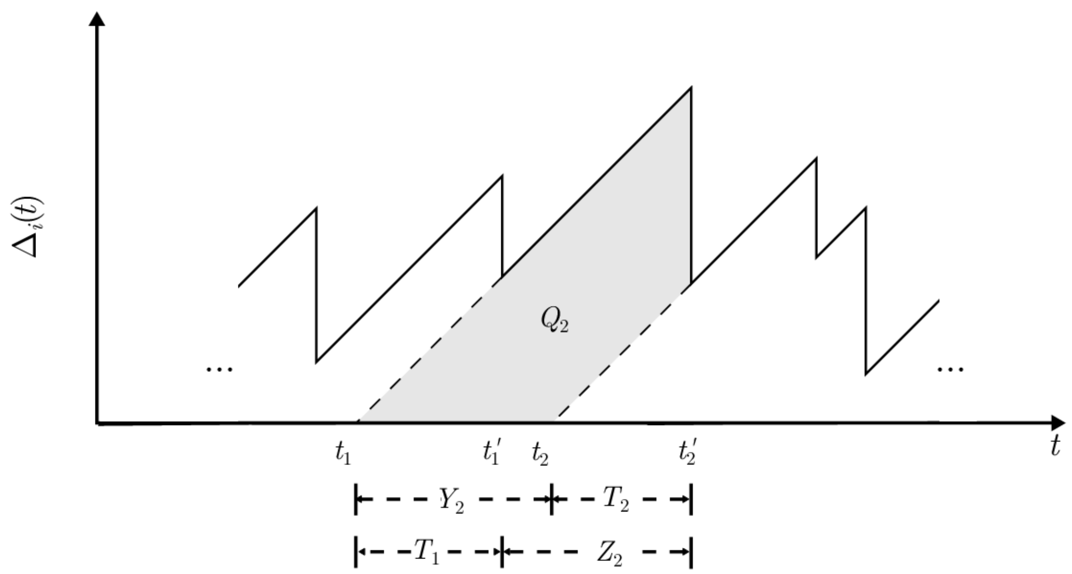

Figure 1 – Illustration of the evolution of the AoI in continuous time.

areas. When the inter-arrival time Y_n and the processing time T_n are stationary ergodic process, by letting $\mathcal{T} \to \infty$, the AAoI satisfies (YATES, Roy D. *et al.*, 2021)

$$\bar{\Delta}_i = \frac{\mathbb{E}[Q_n]}{\mathbb{E}[Y_n]} = \frac{\mathbb{E}[T_n Y_n] + \mathbb{E}[Y_n^2]}{2\mathbb{E}[Y_n]}, \tag{2}$$

and the performance of a system can be obtained by properly modelling T_n and Y_n. However, a common problem which arises in this approach is that, when the inter-arrival time is significantly high, the processing time tends to decrease. The result is Y_n and T_n being negatively correlated, which makes the evaluation of $\mathbb{E}[T_n Y_n]$ less trivial.

On the other hand, the PAoI emerges as a solution to the aforementioned problem by getting rid of the need of evaluating $\mathbb{E}[T_n Y_n]$. The PAoI, $\bar{\Delta}^{(p)}$, characterizes the average of the local maximum values of the AoI over $\mathcal{N}$ subsequent transmissions. Assuming ergodicity and $\mathcal{N} \to \infty$, the PAoI is characterized by (YATES, Roy D. *et al.*, 2021)

$$\bar{\Delta}_i^{(p)} = \mathbb{E}[T_{n-1}] + \mathbb{E}[Z_n], \tag{3}$$

where Z_n is the interval between the successful reception of packets. This approach gives more tractable expressions for complex systems and also properly characterizes the AoI.

Although the two previous methods of characterizing the AoI are relevant in their use-cases, many modern technologies work on discrete time systems. We continue our bibliographic revision in the next section by presenting a formal definition of the AAoI for the discrete time case.

2.1 DISCRETE TIME AGE OF INFORMATION

Consider a system in which time is divided in slots of equal duration and a single slot is sufficient for the complete generation, transmission, reception and processing of an information packet. Let $r_i(t)$ represent the generation time of the most recently packet from user U_i successfully received by the sink, at time slot t. The instantaneous AoI of U_i is then defined as the random process (YATES, R. D. *et al.*, 2017)

$$\Delta_i(t) = t - r_i(t), \tag{4}$$

which follows a staircase shape due to the discrete time-slotted model (CHEN, H. *et al.*, 2020; GRYBOSI *et al.*, 2022), as illustrated in Fig. 2. The time-averaged AoI of U_i is then (CHEN, H. *et al.*, 2020)

$$\bar{\Delta}_i = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} \Delta_i(t), \tag{5}$$

where $\mathcal{T}$ is the period of observation.

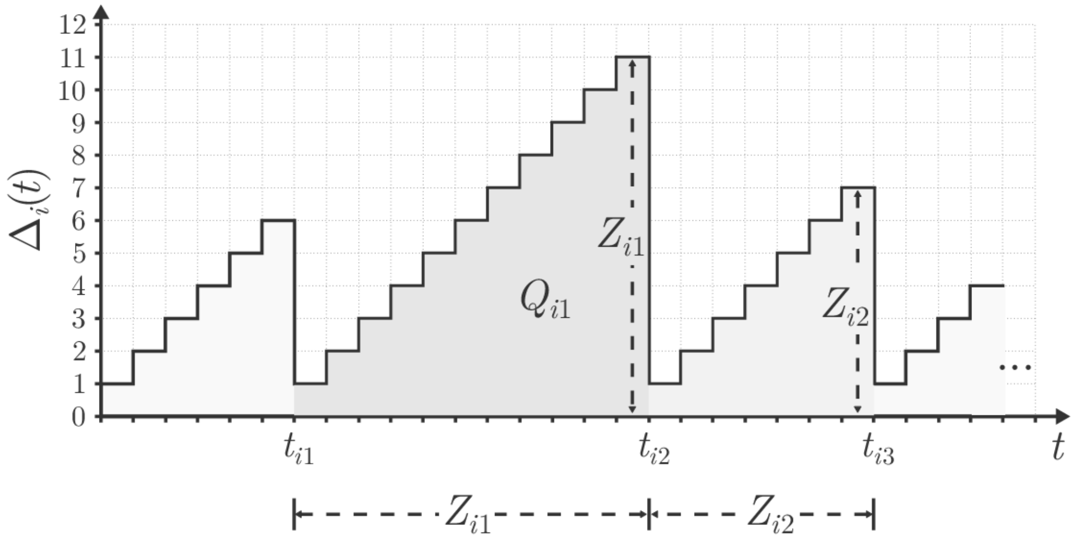

Figure 2 – Evolution of $\Delta_i(t)$ in time.

The AAoI from (5) can be obtained by calculating the area under $\Delta_i(t)$ (YATES, R. D. *et al.*, 2017). Such an area between the jth and the $(j+1)$th correctly received packets of U_i is represented by Q_{ij} (which is as highlighted in Fig. 2 for $j = 1$) and calculated as

$$Q_{ij} = \frac{Z_{ij}^2 - Z_{ij}}{2} + Z_{ij} = \frac{Z_{ij}^2 + Z_{ij}}{2}, \tag{6}$$

where Z_{ij} is the jth inter-packet interval for U_i. The average AoI is then

$$\bar{\Delta}_i = \frac{\mathbb{E}[Q_i]}{\mathbb{E}[Z_i]} = \frac{\mathbb{E}[Z_i^2] + \mathbb{E}[Z_i]}{2\mathbb{E}[Z_i]} = \frac{\mathbb{E}[Z_i^2]}{2\mathbb{E}[Z_i]} + \frac{1}{2}. \tag{7}$$

In a SA scheme, the inter-packet interval Z_i has expected values (YATES, R. D. *et al.*, 2017)

$$\mathbb{E}[Z_i] = 1/\varphi_i \qquad \text{(8)a}$$

and

$$\mathbb{E}[Z_i^2] = 2/(\varphi_i)^2 - 1/\varphi_i, \qquad \text{(8)b}$$

where φ_i is the probability of the packet from U_i to be successfully delivered (YATES, R. D. *et al.*, 2017). After substituting (8) in (7), it finally becomes

$$\bar{\Delta}_i = \frac{1}{\varphi_i}. \tag{9}$$

At last, in a network composed of N users, the overall AAoI of a network is given by the average of all users' AoI, as

$$\bar{\Delta} = \frac{1}{N}\sum_{i=1}^{N}\bar{\Delta}_i. \tag{10}$$

Meanwhile, the PAoI is obtained directly by determining the average age right before the collection of the packet. From the function $\Delta_i(t)$, it is clear that this is the average value of the inter-packet arrival Z_{ij}, or[1], (KHORSANDMANESH *et al.*, 2021)

$$\bar{\Delta}^{(p)} = \mathbb{E}[Z_i] = 1/\varphi_i. \tag{11}$$

For the symmetric scenarios we study in this work, we can drop the i subscript from now on when evaluating the AAoI and PAoI of the networks.

2.2 RELATED WORK

Several works have explored the AoI metric in IoT networks with modern RA. In this section we go over a selection of them, commenting on their contribution to the understanding of this metric in distinct setups.

The AoI under a modified Slotted ALOHA (SA) policy was investigated by Bae *et al.* (2022). The authors present expressions to evaluate the AAoI, PAoI and throughput, and show that allowing the channel access probability to be dependent on the success of previous transmissions help towards improving the performance of the system in terms of the AAoI and throughput. Furthermore, they also show that there exist optimal values of interval between transmissions that optimize either the AAoI or the throughput.

An analytical framework, as well as the development of a practical testbed, is presented by Kadota *et al.* (2021). The authors explore the AoI in both SA and Carrier Sensing Multiple Access (CSMA) policies, obtaining valuable insights on the impact of system parameters in the scenarios studied, as well as providing an approximation for the optimal parameter selection in, namely, the packet generation rate and transmission probability combined with the number of users in the network.

The performance of SIC-aided methods has been evaluated by Munari (2021), where the author characterizes the AoI in the irregular repetition SA (IRSA) scheme. Relying on Markovian analysis, closed form expressions are derived for the stationary distribution of the AoI in devices, then obtaining the AAoI in this scenario. The author presents the probability of the AAoI to be above a given threshold, proposing a metric referred to as the *age-violation probability*, which may provide valuable insight for time dependent systems. The performance of the IRSA scheme is evaluated and compared to the regular SA scheme, and trade-offs on parameter selection, such as the frame duration, are discussed.

Furthermore, Grybosi *et al.* (2022) proposed a frameless SIC-aided policy, namely AIRA-SIC, where the sink is capable of recovering more than a single packet in a time slot when there are collisions, as long as the strongest packet has significantly greater power than the others, so as to treat them as interference while decoding, later

[1] In this particular setup, the PAoI and AAoI expressions coincide. However, this is not the case in all setups, as is shown briefly in Section 2.3.3.

performing SIC to retrieve the remaining packets. They derive approximations for the optimal channel access probability dependent on the system parameters and show that the proposed method achieves lower AoI than both the regular SA scheme, as well as the age-aware policy from He Chen *et al.* (2020).

Ren *et al.* (2022) derive expressions for the AAoI for two orthogonal multiple access methods, namely, time division multiple access (TDMA) and frequency division multiple access (FDMA) schemes, as baselines for their proposed SIC-based non-orthogonal multiple access (NOMA) method. Similarly to AIRA-SIC, in SIC-based NOMA, the receiver can decode more than a single packet when collisions happen, as long as there is a signal that is sufficiently stronger than the other. The authors setup a simulation consisting of two users, and show that the SIC-based NOMA method outperforms both TDMA and FDMA methods as the difference between transmission power from users increases.

Exploring spatial diversity, Yu *et al.* (2021) evaluates the AoI on a grant-free RA scheme with massive Multiple Input Multiple Output (MIMO). They model the system and derive closed expressions to obtain the AAoI in a massive MIMO scenario, also studying the case with large number of antennas, where the access control parameters and pilot length are analyzed and an algorithm is proposed to optimize these parameters in order to obtain low AAoI. They show through numerical results that this algorithm has similar performance to the exhaustive search, while being much more efficient.

2.3 AGE-DEPENDENT RANDOM ACCESS (ADRA)

A natural extension of RA methods in the context of AoI are age-based policies, in which users stay idle for at least a pre-defined period of time after a successful transmission, and the proposal and study of these policies have also gained attention. While similar in the ideas and motivation, recent works (ATABAY *et al.*, 2020; CHEN, H. *et al.*, 2020; YAVASCAN *et al.*, 2021; CHEN, X. *et al.*, 2022) differ in their methodology of the analytical expressions for obtaining the AAoI. Atabay *et al.* (2020) showed empirically through simulations that this policy reduces the average AoI of compliant networks. Moreover, Yavascan *et al.* (2021) and Xingran Chen *et al.* (2022) worked on asymptotic analysis of networks following age dependent policies, deriving expressions and obtaining results which indicate that the proper selection of channel access probability and age threshold reduces significantly the AoI of these networks.

Independently, He Chen *et al.* (2020) show that the AAoI of a single-hop network decreases as users comply to an ADRA policy with an age threshold δ, as long as the threshold is correctly selected. They model the evolution of the AoI of each user as a DTMC, which is increased by one at the end of every time-slot without new updates at the sink, and is reset to one whenever fresh information is collected by the sink. Let $t = 1, 2, \ldots$ denote the index of time slots. Moreover, let the auxiliary function $I_i(t)$

indicate the delivery status of user U_i. Specifically, $I_i(t) = 1$ when user U_i has its packet successfully delivered to the sink at time slot t, and $I_i(t) = 0$ when it has not. From the discrete-time nature of the system, and the description of the AoI given above, it follows that $\Delta_i(t) = 1$ when $I_i(t) = 1$, and $\Delta_i(t) = \Delta_i(t-1) + 1$ otherwise. By taking the average of all values of $\Delta_i(t)$ over $\mathcal{T} \to \infty$ time-slots, the AAoI of user U_i is obtained from (7), such that the AAoI of a network is given by averaging the AoI of all devices as (10).

Let q denote the probability of user U_i to have its packet collected at the sink when it starts a transmission in a time slot. When users share an uplink channel, q depends, among other parameters, on the event of any other user transmitting simultaneously. When no age threshold is considered, q can be obtained straightforwardly. However, in an ADRA-like policy, q depends on the instantaneous AoI of all users, since their values determine whether or not these users can transmit, possibly colliding with the packet of interest. In He Chen *et al.* (2020), the authors adopt an approximation to decouple the evolution of the AoI of all users, by considering that the value of q is constant whenever a user starts a transmission. Thus, under such approximation q becomes independent of the instantaneous AoI of other users, but it is still a function of δ and the channel access probability p. With this in mind, all users follow the same state-transition process, which can be describe by a Discret Time Markov Chain (DTMC) characterized by δ, p and q.

2.3.1 The AoI Modeled by a DTMC

As in He Chen *et al.* (2020), consider a DTMC with an infinite number of states denoted by S_a, $a \in \{1, 2, \ldots\}$, for which the instantaneous AoI of an user is a. The transition probability $T_{m,n}$ is the probability of the DTMC to go from state S_m to state S_n, $m, n \in \{1, 2, \ldots\}$, in a single step. The channel access probability of user U_i is p when $\Delta_i(t) \geq \delta$, and 0 otherwise. Thus, (CHEN, H. *et al.*, 2020)

$$\begin{cases} T_{a,a+1} = 1, a \in \{1, 2, \ldots, \delta - 1\}, \\ T_{a,a+1} = 1 - pq, a \in \{\delta, \delta + 1, \ldots\}, \\ T_{a,1} = pq, a \in \{\delta, \delta + 1, \ldots\}. \end{cases} \tag{12}$$

Since all states in the DTMC are reachable from any other state after a number of steps, this DTMC is irreducible and, therefore, admits a stationary distribution. We denote by $\pi = \{\pi_1, \pi_2, \ldots\}$ the stationary distribution for of the DTMC. Each element π_a, $a = 1, 2 \ldots$ denotes the stationary probability of the AoI to be a. Let $\mathbf{P}$ be the state transition matrix of the DTMC,

$$\mathbf{P} = \begin{bmatrix} T_{1,1} & T_{1,2} & \cdots & T_{1,\delta-1} & T_{1,\delta} & T_{1,\delta+1} & \cdots \\ T_{2,1} & T_{2,2} & \cdots & T_{2,\delta-1} & T_{2,\delta} & T_{2,\delta+1} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ T_{\delta-1,1} & T_{\delta-1,2} & \cdots & T_{\delta-1,\delta-1} & T_{\delta-1,\delta} & T_{\delta-1,\delta+1} & \cdots \\ T_{\delta,1} & T_{\delta,2} & \cdots & T_{\delta,\delta-1} & T_{\delta,\delta} & T_{\delta,\delta+1} & \cdots \\ T_{\delta+1,1} & T_{\delta+1,2} & \cdots & T_{\delta+1,\delta-1} & T_{\delta+1,\delta} & T_{\delta+1,\delta+1} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} = \begin{bmatrix} 0 & 1 & \ldots & 0 & 0 & 0 & \ldots \\ 0 & 0 & \ldots & 0 & 0 & 0 & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & 0 & 1 & 0 & \ldots \\ pq & 0 & \ldots & 0 & 0 & 1-pq & \ldots \\ pq & 0 & \ldots & 0 & 0 & 0 & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}. \tag{13}$$

There exists π such that (PAPOULIS *et al.*, 2002)

$$\pi\mathbf{P} = \left[\pi_1, \pi_2, \ldots, \pi_{\delta-1}, \pi_\delta, \pi_{\delta+1}, \ldots\right] \begin{bmatrix} 0 & 1 & \ldots & 0 & 0 & 0 & \ldots \\ 0 & 0 & \ldots & 0 & 0 & 0 & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & 0 & 1 & 0 & \ldots \\ pq & 0 & \ldots & 0 & 0 & 1-pq & \ldots \\ pq & 0 & \ldots & 0 & 0 & 0 & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} = \pi. \tag{14}$$

Thus, $\pi_1 = \pi_2 = \cdots = \pi_\delta = pq\sum_{a=\delta}^{\infty}\pi_a$. Moreover, $\pi_{\delta+1} = \pi_\delta(1-pq)$, $\pi_{\delta+2} = \pi_\delta(1-pq)^2, \ldots, \pi_a = \pi_\delta(1-pq)^{a-\delta}$, $a > \delta$. Since $\sum_{a=1}^{\infty}\pi_a = 1$, we have

$$\begin{aligned} \sum_{a=1}^{\infty}\pi_a &= \sum_{a=1}^{\delta}\pi_a + \sum_{a=\delta+1}^{\infty}\pi_a \\ &= \delta pq\sum_{a=\delta}^{\infty}\pi_a + \sum_{a=\delta}^{\infty}\pi_a - \pi_\delta \\ &= \delta pq\sum_{a=\delta}^{\infty}\pi_a + \sum_{a=\delta}^{\infty}\pi_a - pq\sum_{a=\delta}^{\infty}\pi_a \\ &= (\delta pq + 1 - pq)\sum_{a=\delta}^{\infty}\pi_a = 1 \\ &\longrightarrow \sum_{a=\delta}^{\infty}\pi_a = \frac{1}{\delta pq + 1 - pq}. \end{aligned} \tag{15}$$

Therefore,

$$\pi_a = \begin{cases} \frac{pq}{\delta pq+1-pq}, a \in \{1, 2, \ldots, \delta\} \\ \frac{pq(1-pq)^{a-\delta}}{\delta pq+1-pq}, a \in \{\delta+1, \delta+2, \ldots\}. \end{cases} \tag{16}$$

2.3.2 Average AoI

The AAoI, $\bar{\Delta}$ is given by summing all possible values of AoI, weighted by the stationary probability of an user to have that AoI, or:

$$\bar{\Delta} = \sum_{a=1}^{\infty} a\pi_a. \tag{17}$$

This sum can be divided in two parts, in accordance to the formation law of π_a. For the interval $1 \leq a \leq \delta$ we have,

$$\begin{aligned} \sum_{a=1}^{\delta} a\pi_a &= \frac{pq}{\delta pq + 1 - pq} \sum_{a=1}^{\delta} a = \frac{\delta(\delta-1)pq}{2(\delta pq + 1 - pq)} \\ &= \frac{\delta(\delta-1)pq + \delta - \delta}{2(\delta pq + 1 - pq)} = \frac{\delta}{2} - \frac{\delta}{2(\delta pq + 1 - pq)}. \end{aligned} \tag{18}$$

Then, for $a > \delta$, we have

$$\sum_{a=\delta+1}^{\infty} a\pi_a = \frac{pq}{\delta pq + 1 - pq} \left[\sum_{a=\delta+1}^{\infty} a(1-pq)^{a-\delta} \right]. \tag{19}$$

With the substitution, $b = a - \delta$, we obtain

$$\sum_{a=\delta+1}^{\infty} a(1-pq)^{a-\delta} \xrightarrow{m=a-\delta} \sum_{b=1}^{\infty} b(1-pq)^b + \delta \sum_{b=1}^{\infty} (1-pq)^b = \frac{1-pq}{(pq)^2} + \frac{\delta}{pq}. \tag{20}$$

Thus,

$$\sum_{a=\delta+1}^{\infty} a\pi_a = \frac{pq}{\delta pq + 1 - pq} \left(\frac{1-pq}{(pq)^2} + \frac{\delta}{pq} \right) = \frac{1}{pq}. \tag{21}$$

And, finally,

$$\bar{\Delta} = \sum_{a=1}^{\delta} a\pi_a + \sum_{a=\delta+1}^{\infty} a\pi_a = \frac{\delta}{2} + \frac{1}{pq} - \frac{\delta}{2(\delta pq + 1 - pq)}, \tag{22}$$

which gives a compact framework for obtaining the AAoI of a network in which users respect a threshold δ, transmit with probability p, and are successfully received at the sink with probability q.

2.3.3 Peak AoI

The PAoI, $\bar{\Delta}^{(p)}$, can be obtained by solving the problem of finding the mean recurring time of state S_1, μ_1 that is, on average, in how many steps the DTMC returns to state S_1 after leaving it. As the DTMC is ergodic, we have (PAPOULIS *et al.*, 2002)

$$\frac{1}{\mu_1} = \pi_1. \tag{23}$$

Thus, the PAoI is readily given by

$$\bar{\Delta}^{(p)} = \frac{1}{\pi_1} = \frac{\delta pq + 1 - pq}{pq}. \tag{24}$$

2.3.4 The Value of q in single-hop ADRA

To obtain the probability of a user to have its packet successfully received by the sink, in the setup considered by He Chen *et al.* (2020), we must evaluate the probability of no other users to access the channel simultaneously with the user of interest. When no threshold is considered, this is simply given by the probability of all other users to not start a transmission, or, $q = (1-p)^{N-1}$.

However, q is not obtained so trivially when considering the ADRA scheme, as the instantaneous AoI of all users depend on the AoI of all other users, entangling the evolution of each users' DTMC in an overwhelming way. To solve this, the authors rely on and validate an approximation to decouple the evolution of the DTMCs by considering that, when a user starts a transmission, the probability of success is a constant. As this is a symmetric setup, if we consider the probability η of any user to have $\Delta_i(t) \geq \delta$ by summing the probability of occurrence of all states S_a, $a \geq \delta$, so that (CHEN, H. *et al.*, 2020)

$$\eta = \sum_{a=\delta}^{\infty} \pi_a = \frac{1}{\delta pq + 1 - pq}. \tag{25}$$

We have the probability of an user to start a transmission in this method $\eta_U = \eta p$, and a packet from user U_i is successfully received when no other user transmits simultaneously, each with probability $(1-\eta_U)$. We then obtain q as

$$q = (1-\eta_U)^{N-1} = \left(1 - \sum_{a=\delta}^{\infty} \pi_a p\right)^{N-1} = \left(1 - \frac{p}{\delta pq + 1 - pq}\right)^{N-1}, \tag{26}$$

which can only be obtained using numerical methods whenever $\delta > 1$. Once q is obtained, the AAoI is readily obtained relying on (22).

This derivation was validated by He Chen *et al.* (2020) by simulating the stationary distribution of states in an IoT network, and we present a reproduction of these results in Fig.3. Moreover, the authors also study the impact of the selection of the

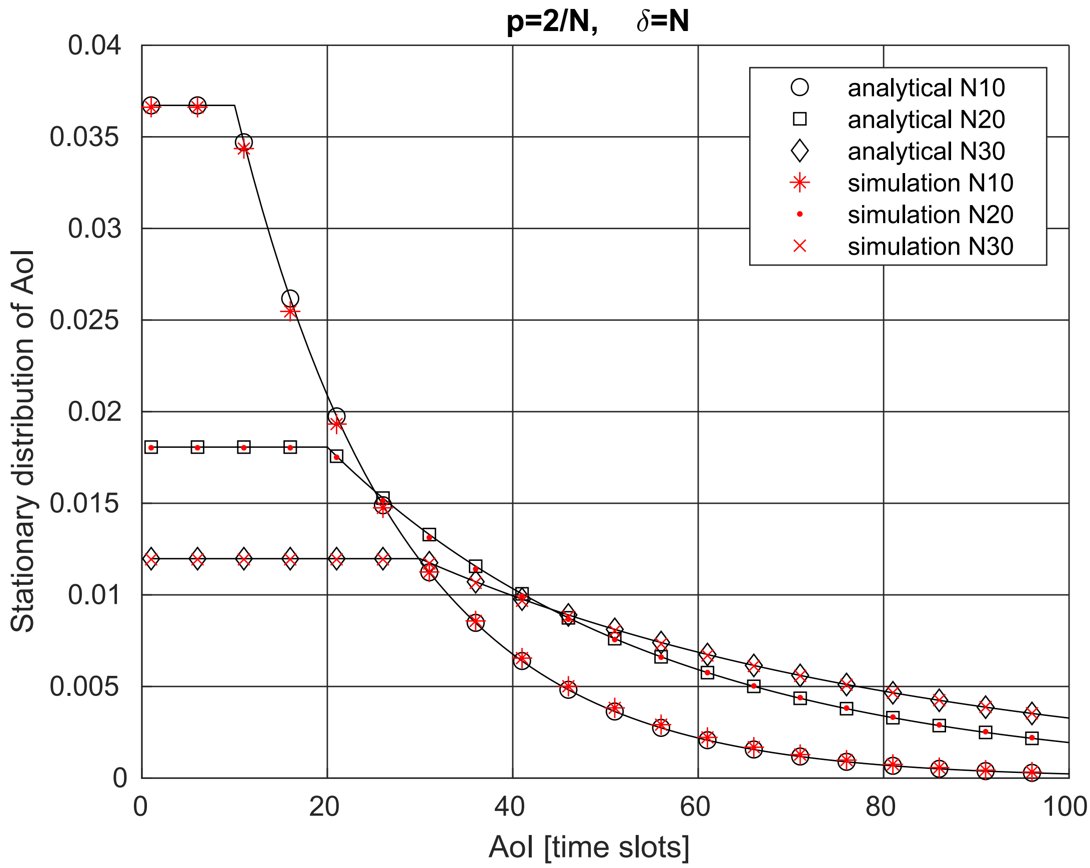

Figure 3 – Stationary distribution of the AoI for different setups. Reproduction of Fig. 3b, as in He Chen *et al.* (2020)

threshold δ on the AAoI, and show that there exist optimal values of δ depending on the network configuration. We have also reproduced these results and present them in Fig. 4. Note that Fig. 3 validates the approximation adopted by the authors, as the numerical and simulation results are mostly identical, showing that this framework can be adopted to quickly evaluate the AAoI performance of IoT networks. Moreover, Fig. 4 highlights the performance gain of ADRA when the age threshold is properly selected. At last, for illustration, in Fig. 5, we present the AAoI and PAoI as a function of δ in this scenario. An interesting remark is that the optimal value of δ for the AAoI is different from the PAoI, although, in this case, evaluating one when the other is optimized would not lead to a significant performance deterioration. Furthermore, in our experiments in Chapter 4, we focus on optimizing the AAoI, but also comment briefly on the PAoI in our setup.

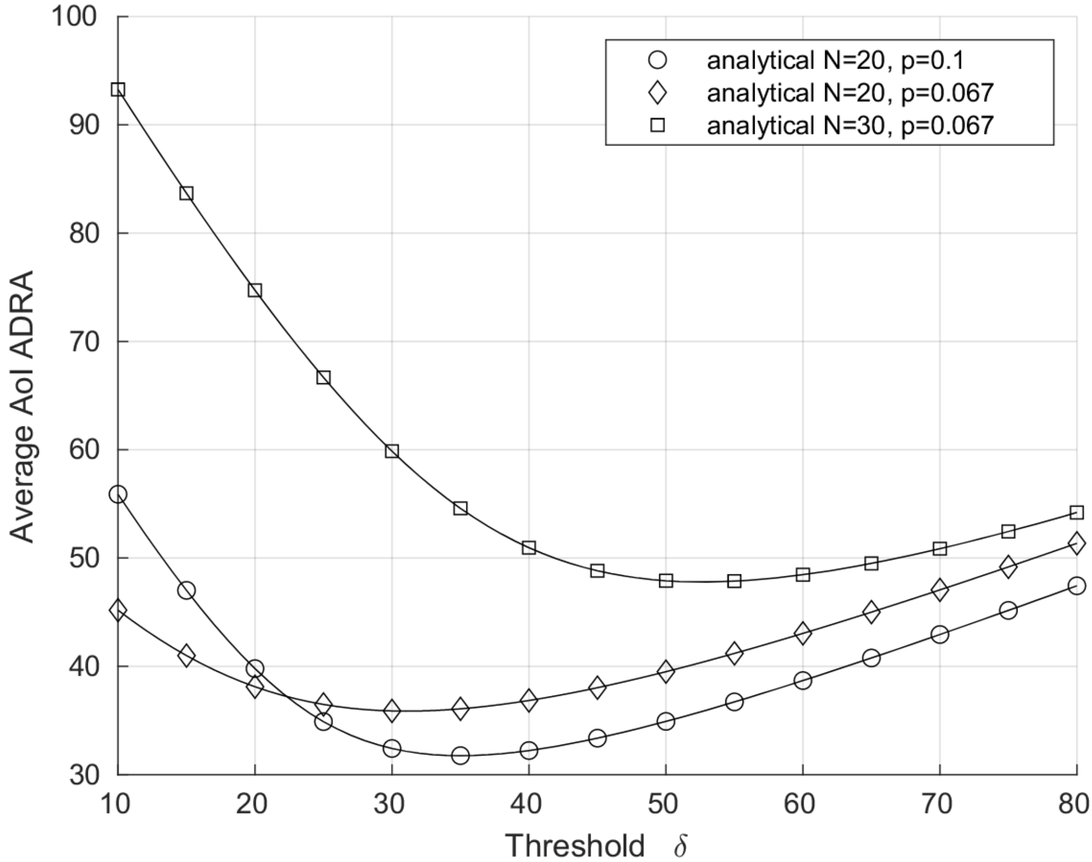

Figure 4 – The AAoI as a function of the threshold δ for different setups. Reproduction of Fig. 4, as in He Chen *et al.* (2020)

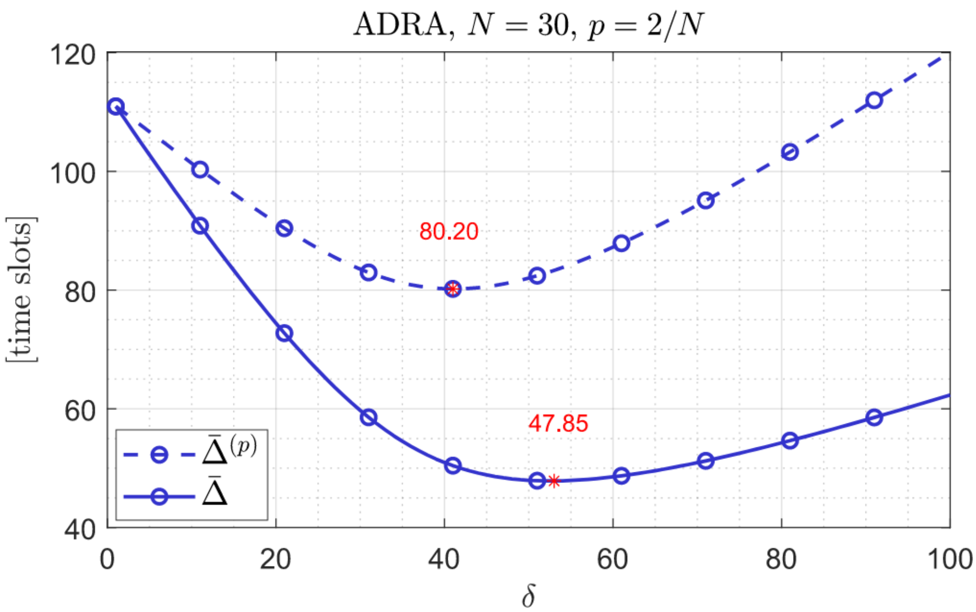

Figure 5 – The AAoI and PAoI as function of the threshold δ.

3 AGE DEPENDENT RANDOM ACCESS IN MULTIPLE RELAYS

In this chapter, we extend the works from He Chen *et al.* (2020) and Munari *et al.* (2019) by deriving expressions for the AAoI of networks in a two-hop multiple relays scenario. We start by describing the system model based on Munari *et al.* (2019), and then provide the analytical expressions to obtain the numerical value of the probability of transmission success q in this scenario as a function of its configuration parameters. This is then used to obtain the AAoI of networks relying on the framework provided by He Chen *et al.* (2020).

3.1 MULTIPLE RELAYS

We consider a network where N users U_i, $i \in \{1, ..., N\}$, have independent information to transmit to a common sink. However, following Munari *et al.* (2019), we assume that there is no direct link between users and sink, such that the communication is established in two-hops with the aid of K relays, which may represent, *e.g.,* LEO satellites or LoRaWAN gateways, as depicted in Fig. 6. The link between users and relays is referred to as uplink, where the users share the same wireless resources, transmitting randomly according to a generate-at-will policy (MUNARI *et al.*, 2019). Therefore, each user decides, at the beginning of each time-slot, whether or not to start a transmission with probability p, thus sampling data and generating a packet immediately upon making that decision. The downlink, in turn, corresponds to the link between relays and sink.

The wireless channels, either in the uplink or downlink, are characterized by an on-off fading model (PERRON *et al.*, 2003) with erasure probability ε, such that a packet is successfully received with probability $1-\varepsilon$, or entirely lost with probability ε[1]. Users transmit to relays in the uplink with erasure probability ε_U. After successfully receiving a packet, a relay forwards it to the sink through the downlink channel characterized by erasure probability ε_D. The uplink and downlink channels are orthogonal. A packet is only retrieved at any receiver (relays or sink) if it reaches them without being erased and without colliding with other packets.

While the work in Munari *et al.* (2019) evaluates the throughput of the aforementioned scheme, in this work we focus on the timeliness of information, by adopting the age-of-information (AoI) (KAUL *et al.*, 2012) as performance metric. Recall that the work in He Chen *et al.* (2020) considers a single hop star network. However, the state transition probabilities defined above still hold in the two-hop multirelay scenario considered in this work, as, for every state S_a of the DTMC of a given device in this

[1] The on-off fading model, apart from its simplicity, captures fundamental aspects of the channel, while keeping mathematical tractability. It has been widely used to derive closed form performance metrics, as in Munari *et al.* (2019).

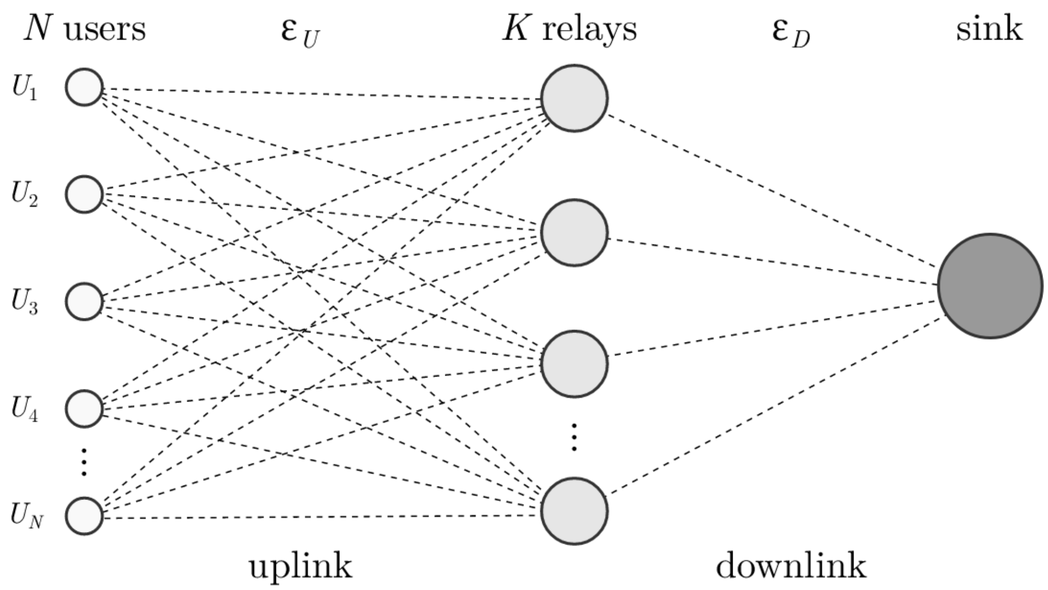

Figure 6 – System model adopted in this work, as in Munari *et al.* (2019).

network, there is only at most two reachable states in a single step, namely S_{a+1} and S_1, with probabilities $1 - pq$ and pq, respectively. Therefore, the framework derived by the authors can be used in this scenario, and, more than just leading to a different success probability q, the expanded network enables different ADRA policies. More specifically, the age-threshold can be enforced either at the users or at the relays. The performance and tradeoffs of the aforementioned policies are discussed in what follows.

3.2 ANALYTICAL EXPRESSIONS

In this section we extend the single-hop ADRA policy from He Chen *et al.* (2020) to the multirelay scenario in Fig. 6, proposing two implementations for an ADRA-MR policy. We refer to **ADRA-MRU** as the scheme where the users in the uplink are only enabled to transmit when their instantaneous AoI is above a given threshold δ, i.e., the ADRA policy runs at the users, which are responsible for keeping track of their AoI. On the other hand, in the so-called **ADRA-MRD**, the threshold is evaluated at the relays, which forward to the sink the packet received from a given user only if the instantaneous AoI of such user is above the pre-defined threshold.

The remainder of this section evaluates the age performance of both ADRA-MRU and ADRA-MRD, by presenting their success probability q respectively in Theorem 1 and Theorem 2. But first, let us introduce the following Lemma.

Lemma 1 *When user U_i and n other users transmit concurrently in a time-slot and $m \leq n+1$ of these packets are correctly recovered by at least one relay, the packet of U_i is correctly recovered by the sink with probability*

$$P_K(n, m) = K\hat{q}(1 - m\hat{q})^{K-1}, \qquad (27)$$

where $\hat{q}$ is given by

$$\hat{q} = (1 - \varepsilon_U)\varepsilon_U{}^n(1 - \varepsilon_D). \tag{28}$$

Proof: The probability of the packet from user U_i to be captured by one of the relays when n other concurrent users transmit at the same time is the probability of it not being erased on the uplink, i.e., $(1 - \varepsilon_U)$, while all other n interfering packets are erased with probability $\varepsilon_U{}^n$. Should the packet be captured by a relay, in order to reach the sink, it must resist the erasure of the channel, with probability $(1 - \varepsilon_D)$. Thus, across two hops, this user's packet is able to reach the sink with overall probability $\hat{q} = (1 - \varepsilon_U)\varepsilon_U{}^n(1 - \varepsilon_D)$ (MUNARI *et al.*, 2019). However, if any other packet reaches the sink simultaneously, including a different copy of the packet of interest arriving from a different relay, there is a collision on the downlink and the packet can not be successfully received. Let $\tilde{q}$ denote the probability of any of the m packets to reach the sink, where $m \leq n + 1$ is the number of packets that are able to be forwarded by the relays. When there is only one relay available, none of the m packets will reach the sink with overall probability

$$1 - \tilde{q} = 1 - \binom{m}{1}(1 - \varepsilon_U)\varepsilon_U{}^n(1 - \varepsilon_D) = 1 - m\hat{q}, \tag{29}$$

and, considering that erasure events at the relays are independent, a packet will not reach the sink from any of the remaining $K - 1$ relays with probability $(1 - \tilde{q})^{K-1}$. From the symmetry of the system (MUNARI *et al.*, 2019), any of the K relays can capture the packet from user U_i and successfully deliver it with the probability given in (27), concluding the proof. □

From Lemma 1, we can obtain an expression for q in each policy by determining the values of n and m in (27), and removing the condition on these variables by determining the probability with which each value occur.

3.2.1 The ADRA-MRU policy

When following an ADRA-MRU policy, users are only allowed to access the channel if their instantaneous AoI is equal to or greater than a defined threshold δ, at which point they may decide to start a transmission with fixed probability p. Under the assumption that a perfect feedback channel is available between sink and users, meaning that users know instantly when their packets are collected at the sink, one has that the success probability of the ADRA-MRU is given as presented in Theorem 1.

Theorem 1 *In an* ADRA-MRU *policy, the probability of a packet from user U_i to be successfully delivered to the sink when it decides to start a transmission is*

$$q = \sum_{n=0}^{N-1} P_U(n)\left[K\hat{q}(1 - (n + 1)\hat{q})^{K-1}\right], \tag{30}$$

if $\Delta_i(t) \geq \delta$*, and* $q = 0$ *otherwise, where* $P_U(n)$ *is given by*

$$P_U(n) = \binom{N-1}{n} {\eta_U}^n (1-\eta_U)^{N-1-n}, \tag{31}$$

and $\eta_U = \eta p$.

Proof: At any given time-slot user U_i decides to transmit, the integrity of its packet is threatened by the existence of $n \in [0, N-1]$ interfering packets transmitted by other users in the network. In a regular slotted ALOHA protocol, the number of simultaneous interfering packets being transmitted is given by a binomial distribution with parameters N–1 and p. However, when all users are required to verify their instantaneous AoI before transmitting, not all of them will be able to start a transmission. For sufficiently long observations, the probability η of an user U_j having $\Delta_j(t) \geq \delta$ is given by (25). Therefore, to start a transmission, any user U_j will have to decide to do so with probability p, and have $\Delta_j(t) \geq \delta$, with probability η, resulting in an overall probability

$$\eta_U = \eta p = \frac{p}{\delta pq + 1 - pq}. \tag{32}$$

Then, with this threshold, the number of interfering packets follows a binomial distribution with parameters $N-1$ and η_U, and the probability of exactly n interfering packets being transmitted is given by

$$P_U(n) = \binom{N-1}{n} {\eta_U}^n (1-\eta_U)^{N-1-n}. \tag{33}$$

Resorting to Lemma 1, since all packets that can be captured can also be forwarded, i.e., $m = n + 1$, we obtain the overall probability of user U_i to have its packet successfully delivered by taking the average of all possible n by their respective probabilities $P_U(n)$, or

$$q = \sum_{n=0}^{N-1} P_U(n) P_K(n, n+1). \tag{34}$$

□

However, similarly to its single-hop counterpart, the ADRA-MRU policy demands that users have constant feedback from the network server to update their own instantaneous AoI, which may be unfeasible in a number of applications. Moreover, even if a feedback channel is present, users would have to consume energy to listen to the response, and a latency of at least two time-slots (one for each hop) would be inserted into the system, possibly resulting in inaccurate instantaneous AoI estimates, which worsen if the feedback channel is also subject to delivery failure[2]. Thus, it becomes of practical relevance to consider a ADRA-MRD policy, where the age-threshold (and consequently the need to have feedback from the sink) is placed at the relays.

[2] In this sense, we have performed simulations considering a delay in the feedback. Considering no buffer or erasure events in this feedback channel, these results did not differ much from our perfect feedback assumption. Thus, it is reasonable to stick to the approximation we consider.

3.2.2 The ADRA-MRD policy

In ADRA-MRD, users start transmissions whenever they want to, but only those with instantaneous AoI above the threshold are forwarded by the relays. In contrast to ADRA-MRU, in this policy users are not required to keep track of their own AoI, with this task being delegated to the relays. Here, only a single hop is needed for the feedback channel, reducing energy consumption by users that will not have to wait for a response every time they transmit, as well as reduced latency since the feedback would be direct from sink to relays. On the other hand, one would expect that since users transmit at will with the same probability p, collisions in the uplink channel will likely be more frequent that in ADRA-MRD.

Theorem 2 *In an* ADRA-MRD *policy, the probability of a packet from user U_i to be successfully delivered to the sink when it decides to start a transmission is*

$$q = \sum_{n=0}^{N-1} P(n) \left[\sum_{u=0}^{n} P_D(u) K \hat{q} (1 - (u+1)\hat{q})^{K-1} \right], \tag{35}$$

if $\Delta_i(t) \geq \delta$, and $q = 0$ otherwise, where $P(n)$ is given by

$$P(n) = \binom{N-1}{n} p^n (1-p)^{N-1-n}, \tag{36}$$

and $P_D(u)$ is given by

$$P_D(u) = \binom{n}{u} {\eta_D}^u (1 - \eta_D)^{n-u}. \tag{37}$$

Proof: When user U_i decides to transmit at any given time-slot t, the number of interfering users transmitting in an ADRA-MRD network follows a binomial distribution with parameters $N-1$ and p, such that exactly n interfering users transmit simultaneously with probability

$$P(n) = \binom{N-1}{n} p^n (1-p)^{N-1-n}, \tag{38}$$

and any of them could be captured and forwarded by relays with the same probability $\hat{q}$ from (28). However, from the n interfering packets, only u of them will come from users who have their AoI big enough to be forwarded. From the symmetry of the system, any user U_j in the network has the same probability $\eta_D = \eta$ of having $\Delta_j(t) \geq \delta$ and exactly u users are allowed to be forwarded with probability

$$P_D(u) = \binom{n}{u} {\eta_D}^u (1 - \eta_D)^{n-u}. \tag{39}$$

Then, again resorting to Lemma 1, we obtain q by setting $m = u + 1$ in (27), and taking the average over all possible values of n and u, or,

$$q = \sum_{n=0}^{N-1} P(n) \sum_{u=0}^{n} P_U(u) P_K(n,u). \tag{40}$$

□

For comparison purposes, we also present the AIRA policy in multiple relays, AIRA-MR. Here, users transmit and relays forward at will, as a direct implementation of an slotted ALOHA RA policy. The value of q for AIRA-MR can be obtained by setting $\delta = 1$ in either ADRA-MRU or ADRA-MRD expressions for q.

Corollary 1 *An* AIRA-MR *policy is a special case for both* ADRA-MRU *and* ADRA-MRD *when* $\delta = 1$*, such that* q *becomes*

$$q = \sum_{n=0}^{N-1} P(n) \left[K\hat{q}(1-(n+1)\hat{q})^{K-1} \right]. \tag{41}$$

In the next chapter we provide numerical results for all three policies in a number of scenarios, also providing some discussion and insights about the optimal parameter selection that minimizes the AoI.

4 NUMERICAL RESULTS

In Fig. 7 we evaluate the impact of p and δ on the AAoI, presented as in the curves, by individually performing a 2-D search for the pair of parameters that minimizes the AoI of each policy. Here, we set N = 30 users and consider $\varepsilon_U = \varepsilon_D = 0.3$. One can note that the optimal values for each policy differ. For instance, ADRA-MRD achieves its minimum AoI, at slightly lower values of p and δ than its user-based counterpart. For this policy, since users tend to compete more for the uplink, it is reasonable to keep their access probabilities lower, while still maintaining some back-off in the downlink. For ADRA-MRU, users with larger AoI can be allowed to access the channel with a higher probability, as the selection of the threshold makes up for the congestion in the uplink that they would, otherwise, face. Interestingly, for lower values of p, both ADRA-based policies behave similarly to AIRA-MR regardless of the value selected for δ. Analytically, we notice that $\eta \to 1$ as $p \to 0$, thus both (30) and (35) simplify to (41). Conceptually, due to the lower number of users accessing the channel simultaneously being constantly small, collisions are less frequent in the uplink and there are less packets to be captured by most relays, thus the selection of the age threshold at the relays has little impact in the overall performance.

4.1 ON THE OPTIMAL NUMBER OF RELAYS

In this subsection we evaluate the effect of the number of relays in the AAoI. Unless stated otherwise, we set N = 30 users, and, for each value of K, we numerically optimize p and δ through a 2-D search[1].

Fig. 8 considers $\varepsilon_U = 0.5$ and $\varepsilon_D = 0.1$ with optimized values of p and δ. In general, increasing K favors the uplink, but on the other hand damages the downlink performance. As the number of relays increases, there is enough opportunity for packets to be recovered by at least one of them. Thus, the benefit of backing-off on the uplink is no longer relevant, making both ADRA-MRU and AIRA-MR indistinguishable for higher values of K. On the other hand, the back-off on the downlink is still relevant in this scenario. Specially when the number of relays is big, this back-off helps to avoid collisions at the sink. One can see from Fig. 8 that there exists an optimal value of K that minimizes the average AoI, which in this scenario is K = 2 regardless the scheme. This optimal number of relays along with the correspondent optimal values of p and δ makes ADRA-MRU to achieve an average AoI of approximately 60 time-slots, a considerable smaller value than the $\sim$ 75 time-slots achieved by AIRA-MR. In this scenario, ADRA-MRD behaves similarly to AIRA-MR.

[1] Although (YAVASCAN *et al.*, 2021) has tackled the problem of finding an optimal value for both p and δ, their system model is significantly different from ours, and directly applying their findings would not be meaningful in this scenario.

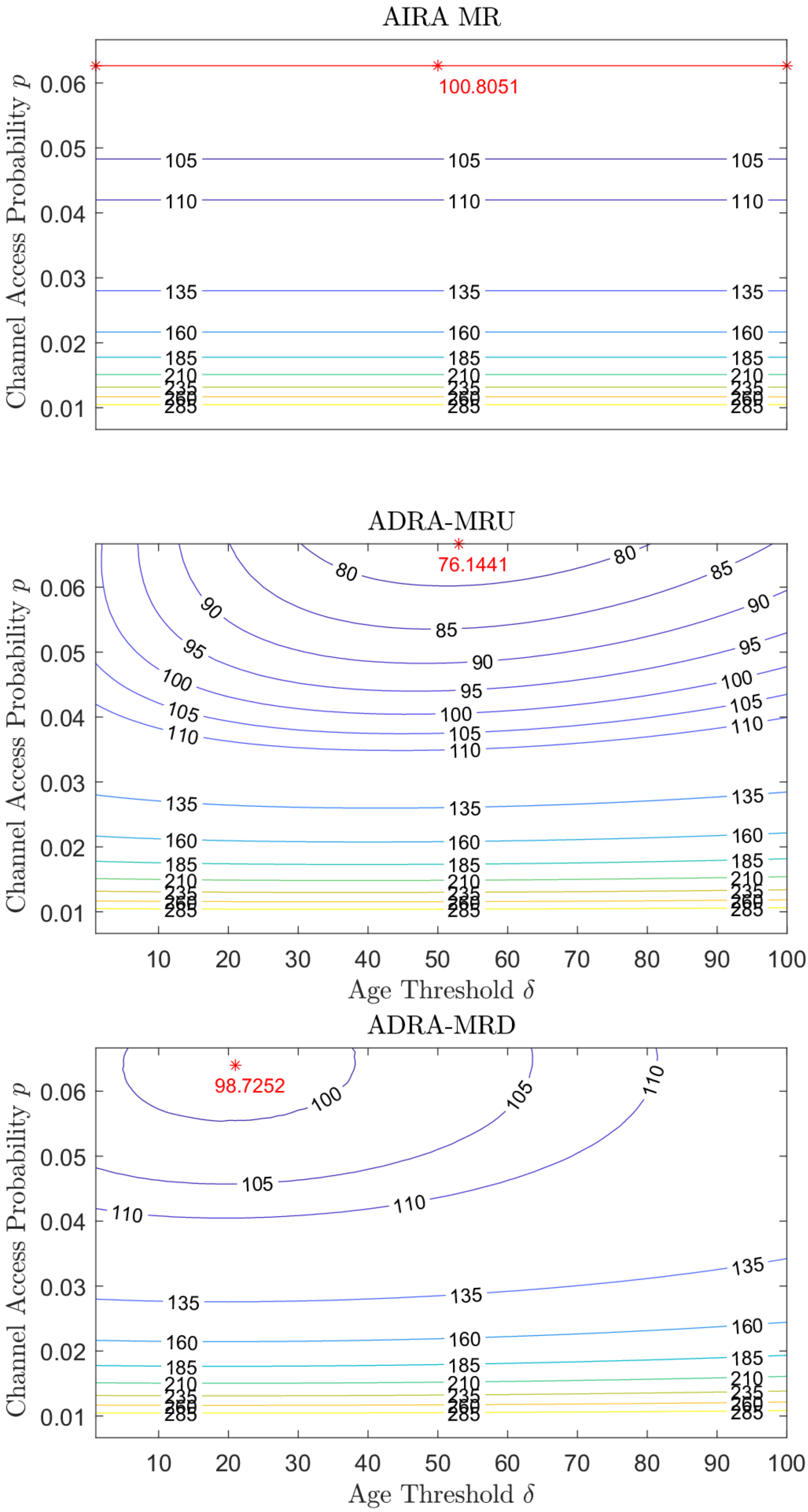

Figure 7 – Search for δ and p in a particular scenario with N = 30, K = 3 and $\varepsilon_U = \varepsilon_D$ = 0.3.

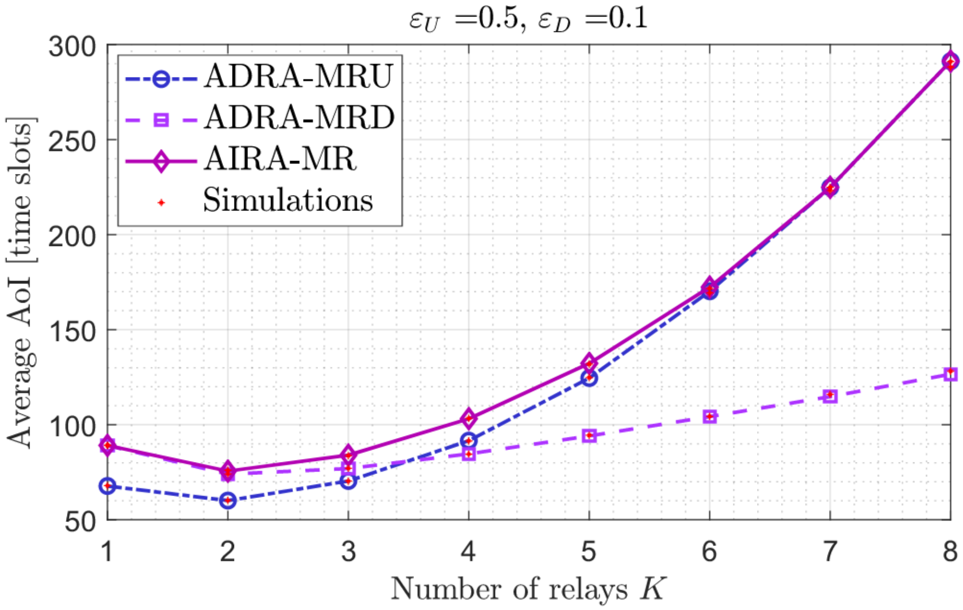

Figure 8 – AAoI $\varepsilon_U = 0.5$ and $\varepsilon_D = 0.1$.

A similar analysis is performed in Fig. 9, but for $\varepsilon_U = \varepsilon_D = 0.3$. All policies have similar trends as before for fewer relays, except for offsets in the AAoI. While the optimal values of p in the ADRA-MRU policy remain the same for all K in this scenario compared to Fig. 8, the optimal δ grows substantially to avoid collisions in the uplink, as they are now more frequent. An opposite effect is seen in the ADRA-MRD policy, where, comparing to the scenario depicted in Fig. 8, the optimal δ increases slightly for all K, but optimal values of p tend to decrease, with the network having to avoid collisions in the uplink, controlled by p, and in the downlink, controlled by δ. Similar to the previous experiment, as the number of relays increases, ADRA-MRU tends to a performance equal to that of AIRA-MR, while ADRA-MRD benefit of its backing-off on the downlink avoiding collisions at the destination. Again, the optimal number of relays is $K = 2$ in all policies, indicating that, even though the number of packets captured by the relays in the uplink increases with the addition of more relays, the congestion in the downlink is too high to be neglected, resulting in increasingly higher AAoI.

Finally, we extend the analysis of the influence of ε_U and ε_D in Fig. 10, when considering the optimized set of parameters. In such figure, we plot at the top the ratio between the average AoI of AIRA-MR and ADRA-MRU, which we refer to as $\bar{\Delta}_{\mathbf{I}}/\bar{\Delta}_{\mathbf{U}}$. At the bottom, we show the ratio between the average AoI of AIRA-MR and ADRA-MRD, namely $\bar{\Delta}_{\mathbf{I}}/\bar{\Delta}_{\mathbf{D}}$. A clear improvement is seen when comparing ADRA-MRU to AIRA-MR in every case, with remarkable improvements of up to 63.8% in the erasure pair $\varepsilon_U = 0.1$, $\varepsilon_D = 0.3$. Meanwhile, ADRA-MRD generally does not provide significant improvement to the AAoI, but outperforms the AIRA-MR policy by at most 5% in a region where erasure in the uplink and downlink are higher, although still performing worse than ADRA-MRU in all cases. As a complement, Figure 11 presents the optimal

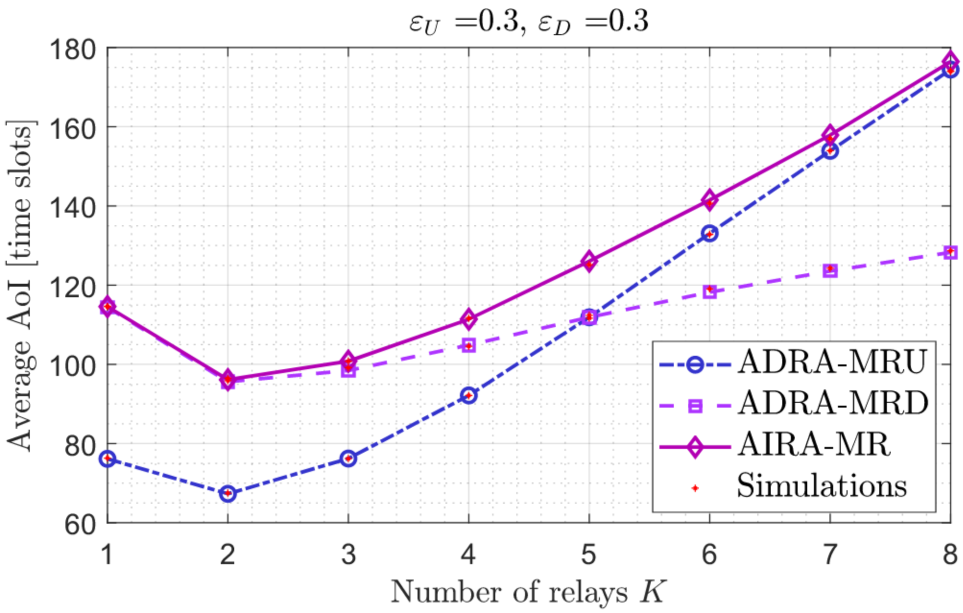

Figure 9 – AAoI $\varepsilon_U = \varepsilon_D = 0.3$.

number of relays for each pair of ε, which highlights the role of the number of relays, as they can be a tool to mitigate erasure events at higher erasure rates, but can also increase the number of collisions at the second hop at lower erasure rates. Therefore, when the erasure probabilities are low, relays may be unnecessary. However, when the quality of the channels degrades the optimum number of relays increases.

4.2 THE AOI VERSUS THE NUMBER OF USERS

In Figs. 12 and 13, we present the AAoI as a function of the number of users N when p, δ and K are optimized. As a result, one can see that the optimized set of parameters leads to considerable lower AoI levels, specially for ADRA-MRU, which, for instance, compared to a result obtained for fixed values of δ and p, decreases the AoI in approximately 30% for when $N = 100$, $\varepsilon_U = 0.3$ and $\varepsilon_D = 0.3$. On the other hand, these results indicate that the added complexity of making the relays keep track of the user's AoI in ADRA-MRD gives no significant improvement to the AoI compared to AIRA-MR.

4.3 THE PAOI IN MULTIPLE RELAYS

As an illustration of the difference between the PAoI and AAoI metrics, we perform a simple experiment where we focus on optimizing the threshold δ for a fixed set of parameters $N = 30$, $p = 2/N$ and $K = 2$ in the erasure pair $\varepsilon_U = 0.1$ and $\varepsilon_D = 0.5$. In Fig. 14, we present this search for the optimal values of δ for both ADRA-MRU and ADRA-MRD considering the PAoI and the AAoI. In this case, as expected from the previous results, ADRA-MRD performs at best as good as AIRA-MR, therefore

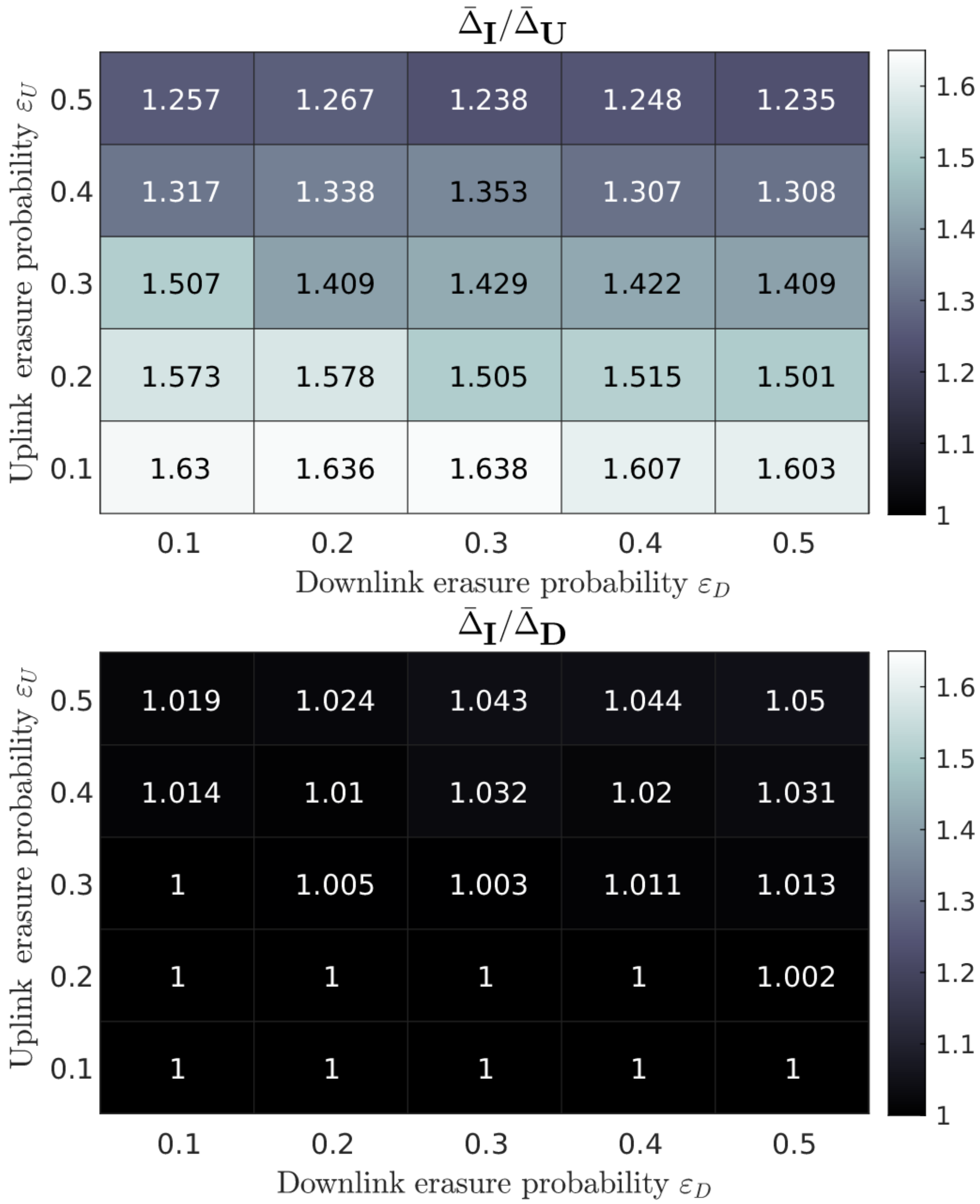

Figure 10 – AoI ratio for different values of ε_U and ε_D.

its optimal δ = 1 and the PAoI and AAoI are the same as this reduces to the regular SA policy. Meanwhile, ADRA-MRU is optimal in different values of δ for the PAoI and AAoI, showing that optimizing this parameter for one metric may result in sub-optimal performance for the other.

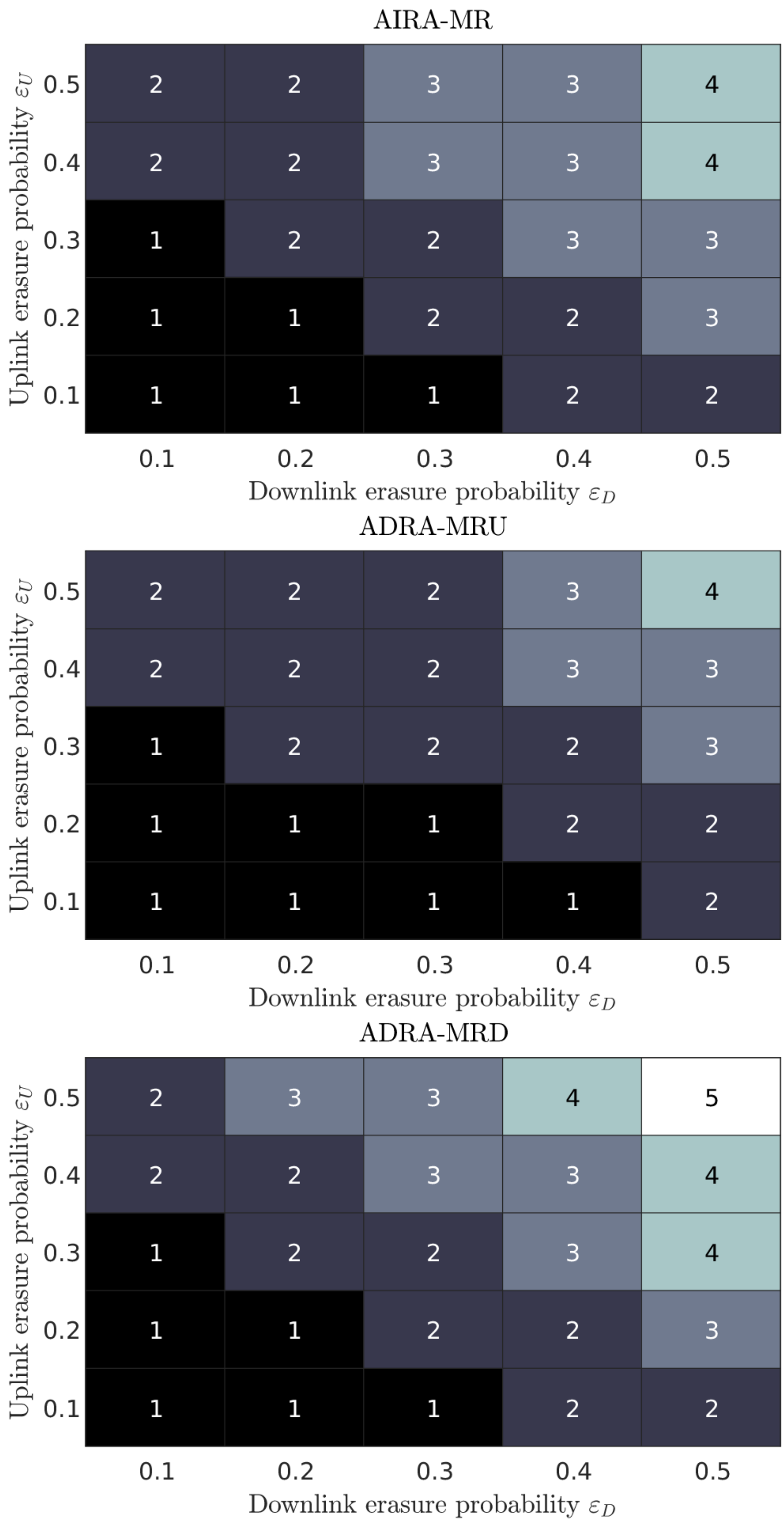

Figure 11 – Optimal number of relays K for different values of ε_U and ε_D.

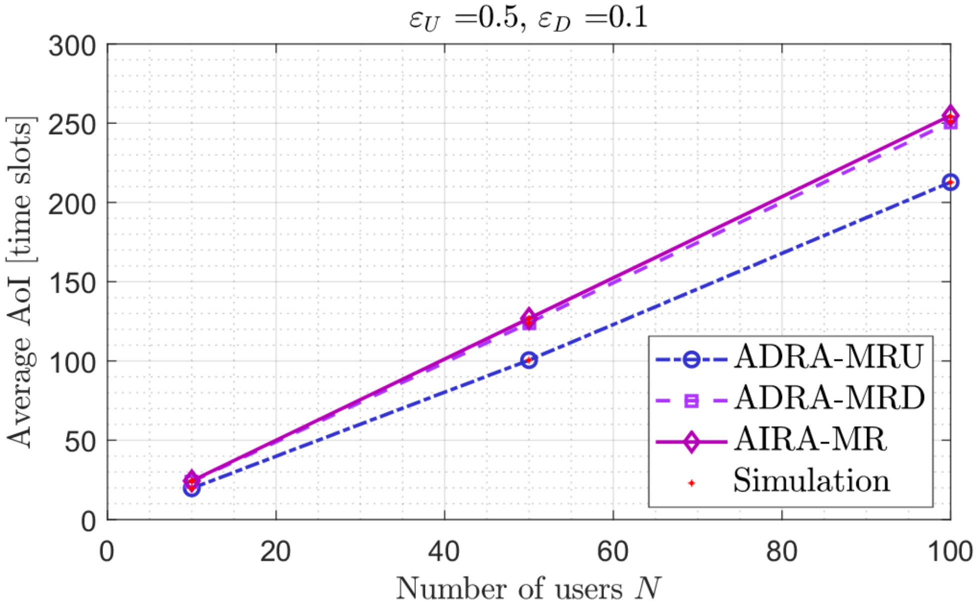

Figure 12 – AAoI versus N, for ε_U = 0.5, ε_D = 0.1, and numerically obtained optimal values of K, p and δ.

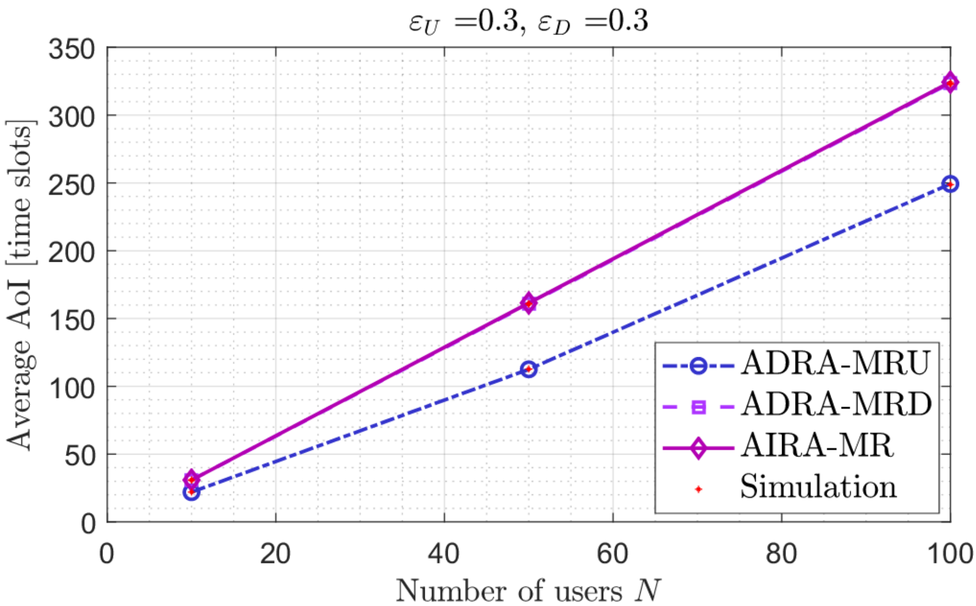

Figure 13 – AAoI versus N, for ε_U = 0.3, ε_D = 0.3, and numerically obtained optimal values of K, p and δ.

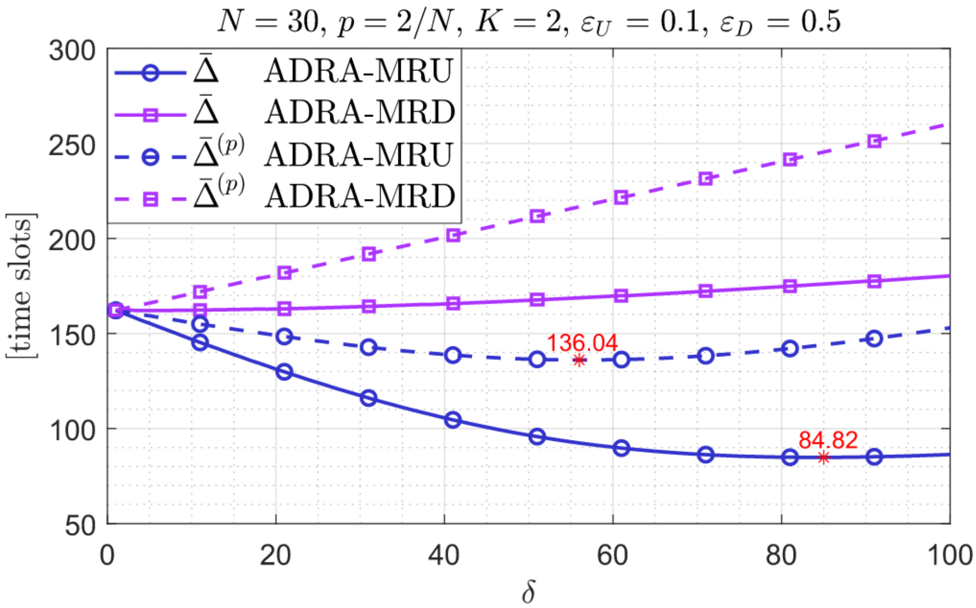

Figure 14 – PAoI and AAoI as function of δ with multiple relays.

5 CONCLUSIONS AND FUTURE WORK

In this work, we evaluated the performance of a multirelay network with random access under a timeliness of information perspective. More specifically, we adopt the AoI metric to evaluate the performance of the network when operating under two different age-dependent approaches, namely ADRA-MRU and ADRA-MRD. While in the former the threshold to define whether a given packet is allowed to be transmitted is implemented at the users, in the latter this responsibility belongs to the relays. As a result, we show through analytical and numerical results that ADRA-MRU can considerably outperform age-independent AIRA-MR scheme, while the performance of ADRA-MRD is slightly better than that of AIRA-MR, given that all parameters are optimized. Moreover, we also provide some insights on the optimal values of parameters that minimizes the AoI, highlighting the effect of properly selecting the number of relays in a given network as to avoid congestion in either of the hops.

One question which remains open is: what is the minimum AoI this types of networks can achieve once collisions on the downlink are extinguished? We have performed simulations considering a perfect downlink (no collisions or erasure events), which may serve as a minimum achievable limit of the systems. In Fig.15, we present the AAoI versus $K \in [0, 20]$ obtained in a simple setup where $N = 30$, $p = 2/N$ and $\delta = N$. Different to the results presented earlier in this work, as expected, the AAoI only decreases with the inclusion of more relays, as collisions are nonexistent.

For future works, such perfect downlink can be explored analytically for more precise and efficient analysis. Furthermore, viable attempts at achieving this perfect downlink can be explored. For example, in order to address the collisions on the downlink,

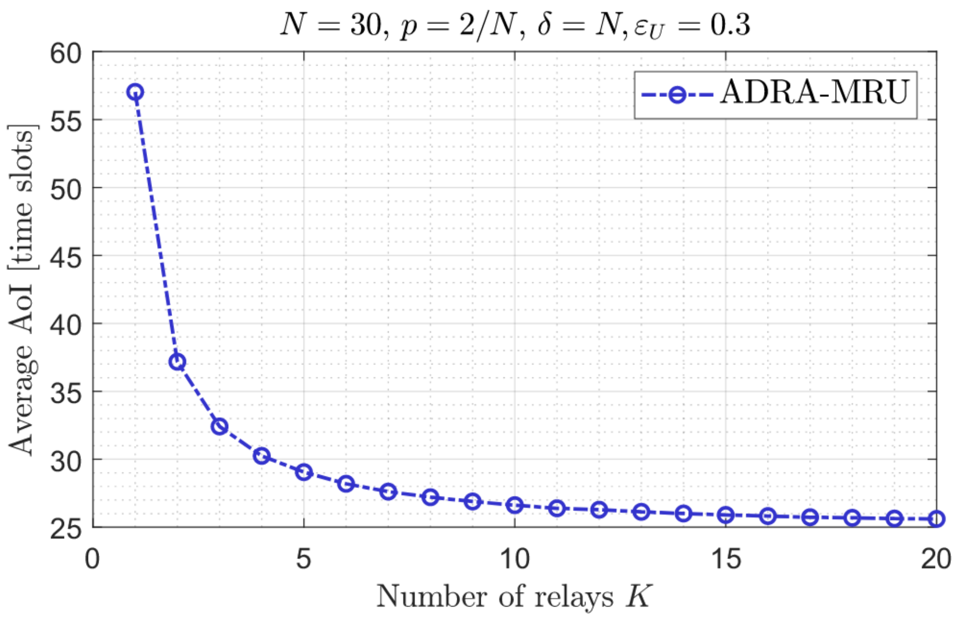

Figure 15 – Perfect downlink simulation.

different RA methods on the downlink can be applied and their respective expressions derived. In a classical approach, as the number of relays will be considerably smaller than the number of users, they could be synchronized using TDMA. On the other hand, aiming at modern RA methods, this could be done by exploring SIC on the downlink in a NOMA fashion, where collisions could be solved by removing stronger, easily decoded, packets from the signal.

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