Distributed Access by Multiple Sources for Age of Information Minimization Over a Finite Horizon

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***Abstract*—Age of information (AoI) quantifies the freshness of updates in real time applications, such as vehicular networking or road traffic monitoring and control. This study explores the optimization of AoI over a finite horizon for multiple IoT devices independently tracking the same process of interest and reporting status updates. In this setting, the efficiency of distributed policies where sources probabilistically report their measurements is not adequate. Even assuming pre-defined rendez-vous transmission instants, if the choice about which one to utilize is left to the individual source, lack of coordination may arise, causing simultaneous transmissions (redundant and therefore inefficient) at times, and, consequently, other intervals where no node transmits. We investigate practical solutions to this problem inspired by random medium access techniques. Firstly, we introduce a protocol where no transmission instant is deserted thanks to carrier sensing. If no nodes choose to transmit, they all sense the channel as idle, and randomly revise their decision until at least one transmits. Subsequently, we explore an uneven spread of the transmission instants to balance the resulting scheduling. We measure the effectiveness of these improvements compared to full coordination. These techniques are shown to improve distributed policies by more than 20%, and in general offer valuable insights for future research on sensing in multi-source autonomic environments.**

***Index Terms*—Age of information; Sensor networks; Game theory; Real-time applications; Vehicular networks.**

I. Introduction

The swift evolution of communication technologies has ushered in the era of the Internet of Things (IoT), marked by widespread connectivity among a diverse range of devices [1]. Among the many technological fields affected, the automotive industry is expected to be especially revolutionized, as the IoT facilitates the development of real-time applications that enhance vehicle efficiency and safety, and seamlessly blend the human factor in the resulting cyber-physical systems [2].

One key area is vehicle telematics, i.e., the use of IoT technologies to collect and transmit data from sensors and onboard systems within the vehicle to external monitoring platforms in real-time [3]. These data can include information such as vehicle diagnostics, location tracking, fuel consumption, driver behavior, and more. By leveraging this paradigm, advanced features such as assisted driving and predictive maintenance can be offered to users.

Furthermore, the IoT enables the implementation of connected cars, integrating vehicles with external networks and services [4]. Connected cars can communicate with the whole array of IoT elements, including other vehicles but also infrastructure and cloud, to realize a Vehicle-to-Everything (V2X) scenario, where elements exchange real-time information about traffic conditions, road hazards, weather updates, and more [5]. This enhances road safety, reduces traffic congestion, and improves navigation efficiency for drivers.

IoT technology also plays a crucial role in the development of driver assistance systems and autonomous driving technologies. The interconnection of onboard sensors, cameras, LiDAR/radar, allows the exchange of data for real-time monitoring of the vehicle's surroundings and detection of potential hazards [6]. Adaptive cruise control, lane departure warning, collision avoidance, and automated parking rely on real-time information to provide timely and accurate information to human drivers or autonomous driving systems [7].

Despite notable advancements, many challenges persist in managing resources to exploit the real-time information and make accurate control decisions [8]. A recent research trend has embraced age of information (AoI) as the preferred metric to represent the freshness of real-time content [9]–[11].

However, AoI is often studied in simple single-source contexts. The extension to a network scenario such as V2X or assisted driving requires a shift to multiple sources [12], which faces two main challenges. Firstly, energy and data link limitations may require avoiding persistent transmission, leading nodes to curtail their activity [13], [14]. Secondly, the management of multiple nodes often occurs in a distributed manner and without coordination, to meet scalability requirements in large scenarios [15]. In response to these challenges, a significant area of research focuses on minimizing AoI over finite horizons [16], [17], which is in line not only with the task-oriented nature of V2X applications but also with the common constraints of IoT devices, where the usage is limited over actual time windows and not just in the long run.

Researchers leverage various mathematical methodologies, including queueing theory and constrained optimization [18], [19], to analyze AoI. A recent line of research is focusing on

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game theory to optimize resource allocation in multi-source scenarios [20]. This approach allows for the integration of distributed management of multiple agents towards the common goal of AoI minimization. Specifically, in this paper, we tackle the problem of handling multiple equivalent distributed sources as an anti-coordination game [21].

Our paper contributes by integrating AoI within a multi-agent homogeneous game framework over a finite horizon, in line with IoT V2X networks. Our objective is to improve over the inefficient distributed allocation stemming from random selection of the transmission points that is found in [22]. To achieve this, we leverage the properties of medium access solutions in these scenarios, devising practical protocols that alleviate inefficiencies such as instances where nodes remain silent. Hence, we introduce protocols that, while still acting in a distributed fashion, yield more favorable solutions than a uniformly random allocation, thereby enhancing data freshness in the network.

The rest of this paper is organized as follows. In Section II, we review the most closely related papers to our analysis. In Section III, we present the system model and analysis. In Section IV, we discuss our proposed approach and show numerical evaluations. We finally conclude in Section V.

II. Related work

The problem of AoI minimization is studied by many papers in the literature with various methodologies, e.g., [9], [10], [17], but most of the times it relates to a single source-destination pair. Multiple agents are introduced in the analysis of [23] for independent sources each of which delivering their own information to the destination. Also, the generation by sources is memoryless and not scheduled. In a game theoretic context, an AoI minimization for this scenario would correspond to a competition among multiple agents over a scarce resource, i.e., the communication link. Nevertheless, the approach and the game theoretic hints of that paper are reminiscent of our analysis, especially when pointing out that the absence of coordination (which in our case corresponds to an anti-coordination of alternating transmissions) leads to inefficiency. More general multi-source queueing models are also used in [24].

Our analysis belongs instead to the studies of average AoI minimization by adjusting the sensor data transmission schedules in environments with multiple sources measuring the same parameters, and we approach the problem from a decentralized perspective. In this sense, our study is more similar to the analysis in [19], which extends the investigation to a controlled access, focusing on transmission scheduling AoI-minimizing policies. In that work, multiple sensors actively transmit unrelated data to a central monitoring system, which is fully able to coordinate the transmissions. As a result, the main focus is on the effect of channel impairments and how to counteract them through proper policies, but there is no common objective shared by the sources, nor a distributed interaction.

The observation that properly coordinated multiple sources can be beneficial to AoI is also common to many investigations [18], [25]. In particular, for IoT sensors used for autonomous driving or enviromental monitoring, a high degree of similarity between status updates from different sources is to be expected. In our analysis, this is pushed forward by considering interchangeable multiple sources, however each of them is limited in the number of updates they can send. This would require to achieve coordination, with decentralized means, towards an alternating schedule of transmissions.

We presented an analysis with similar premises in [16], where the main investigation pertains to the role of feedback to design optimal scheduling. This study is also the first one to consider a finite horizon, yet it has notable differences with the present investigation. First of all, it focuses on a single source only. Also, transmission impairments are considered as externalities, and do not result from lack of coordination among the nodes. One can consider instead the impact of collisions among multiple nodes transmitting with contention-based medium access, which is actually typical of V2X scenarios [5]. In this spirit, the extension discussed in [26] considers multiple sources, replacing channel losses with collisions. This phenomenon can be regarded as an inefficiency resulting from lack of coordination from the sources, even though the scenario is actually involving multiple sources once again with content unrelated to one another.

It is worth noting that V2X communications may also exploit vehicular beaconing as argued in [12]. In that paper, the minimization of AoI is pursued through a coordination technique achieved via slot reservation in a deterministic frame, which is however challenged by the highly dynamic network connectivity. Such a problem is not antithetical to ours, as a decentralized choice for the slot within the beacon would be akin to our challenge of distributed transmission instant selection. However, the cause of inefficiency in our scenario is more subtle and relates to the redundancy of the sources, which are all transmitting the same content [27]. As a result, multiple simultaneous updates are not lost; yet, their redundancy results in an inefficiency in the context of a finite horizon with limited resources since they prevent further updates to take place, which would further lower AoI.

A similar point is made in [28], which also uses game theory to evaluate the inefficiency of the uncoordinated transmission. Yet, that paper considers unscheduled random transmissions, infinite time horizon, and is limited to two sources only. Here, we take a different perspective, even though the reason for the inefficiency of uncoordinated transmissions is the same [22].

We also remark that [14] advocates the use of artificial intelligence engines through reinforcement learning to obtain efficient resource allocation towards AoI minimization in V2X networks. We argue that, especially in the case of multiple redundant sources, it may be preferable to avoid centralized data collection, since it is unlikely to allow for a true real-time interaction in extremely dynamic scenarios, not to mention further issues of energy consumption and privacy issues.

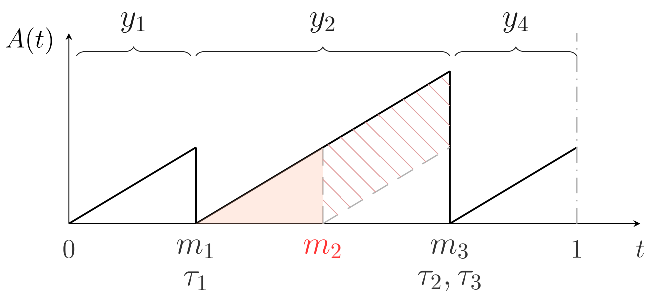

Fig. 1. Example AoI evolution. Planned updates by 3 sources are evenly spaced, yet sources are idling at the second milestone, and the third one is used by two sources. Thus, AoI increases as the dashed surface.

However, one can certainly apply this methodology with an approach based on federated learning, which is also studied in this context [29]. In turn, this would allow to improve the efficiency of the resulting equilibria and may be seen as a further extension to our analysis.

III. System Model and Analysis

We investigate a scenario involving $N > 1$ IoT nodes operating within a network, all transmitting data to a common destination. These nodes, acting as information sources, aim to enhance data freshness within the network environment. Our focus lies on devising an optimal update schedule within a defined time window [16]. In this timeframe, we assume that each of the N information sources can transmit only one update (though this process can be iterated across multiple segments for practical purposes) [30]. To facilitate numerical analysis, we normalize the finite timeframe to $[0, 1]$.

We consider the sources to be equivalent in terms of data they can generate, and all of them satisfying a *generate at will* property, so that each transmission, regardless of its position in the time horizon, resets AoI to zero [23], [26]. We compute the average AoI over the specified time interval as

$$\Delta := \int_0^1 A(t)\, dt \tag{1}$$

with an implicit normalization due to the unit time window. An illustrative example of the time evolution of the instantaneous AoI $A(t)$ is depicted in Fig. 1.

We denote the transmission time of the jth source as t_j. Since the sources are not coordinated, the t_j-s can be out of order, and therefore we consider vector $\boldsymbol{\tau}$ as the ordered version in increasing order of $\mathbf{t} = (t_1, \dots, t_N)$. This means that τ_j is the jth smallest transmission time, not the one chosen by the jth source. The resulting AoI value can be computed from the τ_j values, or equivalently, the $N + 1$ transmission intervals $y_j = \tau_j - \tau_{j-1}$, with $\tau_0 = 0$ and $\tau_{N+1} = 1$, which leads to

$$\Delta(\mathbf{y}) = \sum_{i=1}^{N+1} \frac{{y_i}^2}{2}, \tag{2}$$

where $\mathbf{y} = (y_1, y_2, \dots, y_{N+1})$ is the vector of resulting transmission intervals.

Under perfect coordination among the sources, the optimal choice for the transmission intervals is $y_j = 1/(N{+}1)$ for all $j \in \{1, \dots, N{+}1\}$. This means that the transmission instants happen at evenly spaced positions, which in the following will be referred to as *milestones*, denoted as $m_j = j/(N{+}1)$.

If the sources are managed independently by rational agents without communication, we assume they still opt to transmit at one of the milestones. However, due to the lack of coordination, a milestone may be missed while another experiences multiple (redundant) transmissions. For example, in Fig. 1, it turns out that $\tau_2 = \tau_3 = m_3$, which implies that no source transmits at milestone m_2. This causes an increase in the average AoI, due to the shaded orange area highlighted in the diagram.

We remark that, unlike a transmission failure as in [16], the AoI increase in our problem stems from multiple uncoordinated sources selecting the same milestone for transmission, leading to inefficiency due to redundancy. Consequently, fewer transmission opportunities are exploited, akin to an erasure [28], impacting AoI.

To formalize this scenario, we frame it as a static game of complete information $\mathcal{G} = \{\mathcal{N}, \mathcal{A}, \mathcal{U}\}$, involving multiple sources, belonging to the set of players $\mathcal{N}$, each corresponding to an independent source of information. Set $\mathcal{A}$ contains the available actions to the sources, denoted as $\mathcal{A} = \{1, 2, \dots, N\}$, since each source just decides one of the N milestones for its transmission. Formally, source j choosing action $a_j = k$, with $1 \leqslant j, k \leqslant N$, implies that $t_j = m_k$.

If we take a *mixed strategy* perspective, i.e., a probabilistic approach, we can characterize the decision of the jth source as a probability vector $\mathbf{p}_j = (p_{j,1}, p_{j,2}, \dots, p_{j,N})$, where $p_{j,k}$, $1 \leqslant k \leqslant N$, is the probability of source j transmitting at the kth milestone. Since mixed strategy $\mathbf{p}_j$ is a vector of N probability elements, a *joint strategy profile* by all sources is an $N \times N$ matrix $\mathbf{P} = \{\mathbf{p}_j\}_j$, with $j \in \{1, \dots, N\}$.

Finally, the payoffs in set $\mathcal{U}$ depend on the actions chosen by the players. In our scenario, all nodes share a common goal, which is, they all have the same objective of minimizing the average AoI Δ. Thus, we set the utility $u_j(\mathbf{P})$ of the jth source as identical to all other sources and equal to the expectation of the average AoI described by (1), i.e.,

$$u_j(\mathbf{P}) = \mathbb{E}_{\mathbf{P}}\left[\Delta(\mathbf{y})\right] , \tag{3}$$

involving both a time average in the definition of $\Delta(\mathbf{y})$ and a statistical expectation $\mathbb{E}_{\mathbf{P}}$ computed on all possible vectors $\mathbf{y}$ resulting from the joint strategy profile $\mathbf{P}$.

In this scenario, we search for Nash equilibria (NE) defined as a choice of the strategy profile $\mathbf{P} = (\mathbf{p}_1, \dots, \mathbf{p}_N)$ where no source can get unilateral improvement, i.e.,

$$\forall j \in \mathcal{N}, \forall \sigma \in \mathcal{S}: \qquad u_j(\mathbf{p}_j, \mathbf{p}_{-j}) \geqslant u_j(\sigma, \mathbf{p}_{-j})\,. \tag{4}$$

The specific game theoretic situation aligns with the concept of anti-coordination game [31], where strategic players are motivated to select different slots. With proper adjustments, this is equivalent to the pursuit of distributed coordination among multiple independent players. Nevertheless, since the players are not coordinated in reality, they might choose inefficiently. A simplistic approach to their decision-making would be to assign equal probability to all milestones, i.e., $p_j = 1/N$ for all j. Yet, this does not constitute an equilibrium point: the problem's structure implies that certain milestones are preferred, particularly those in the middle [22].

A more precise approach would lead to adjusting the p_j values so that all players adopt the same mixed strategy NE. This adjustment process relies on applying the *indifference theorem*, where players' decision probabilities are altered to render opponents indifferent among their available actions. This results in a mixed strategy NE $\mathbf{P}^*$, denoted as *symmetrical NE*, where all sources use the same probabilities to choose their milestone, i.e., $\mathbf{P}^* = (\mathbf{p}^*, \mathbf{p}^*, \ldots, \mathbf{p}^*)$, with $\mathbf{p}^*$ being an AoI-minimizer when all sources adopt it.

However, being akin to a coordination game, $\mathcal{G}$ admits multiple NEs, which opens up the subtopic of *equilibrium selection* in game theory [22]. Symmetrical solutions are known to be undesirable for (anti)coordination, and better working points can be found as *correlated equilibria* (CEs), basically corresponding to players deterministically choosing only one of the actions, but all in different ways. In our case, $\mathbf{P} = \mathbf{I}_N$, with $\mathbf{I}_N$ being the $N \times N$ identity matrix, is one such correlated equilibrium, but so are all permutations belonging to the *symmetric group* over $(1, 2, \ldots, N)$ so that exactly one source transmits at each milestone.

The usual game theoretic solution to this conundrum is to leverage *preplay communication* to establish a correlated equilibrium [32]. This approach can be matched to the standard reasoning of medium access techniques that leads to the implication of a time-division multiple access being better than an uncoordinated random access. Yet, the correlated equilibrium (i.e., a perfect time-division) can only be achieved by centralized approaches.

Inspired by this reasoning, we search for practical methods that improve AoI without explicitly requiring full coordination of the sources. In particular, we can actually leverage that wireless sensor nodes typically use *carrier sense*, i.e., they can listen to the channel and check if it is idle or busy [33]. However, unlike standard use of carrier sense for random access protocols [26], multiple transmissions in our scenario do not cause a collision, but just a redundant update. Still, we want to prevent this from happening as it corresponds to a wastage of resources [28]. Therefore, we are introducing two carrier-based protocols where sources can listen to the channel and prevent that sources are idling at some milestones.

IV. Contributions and Evaluation

The game of distributed choice of the transmission milestone within the finite horizon by multiple sources admits two types of equilibria. The exact number of equilibria is combinatorially high, as sources are all alike and therefore different yet equivalent equilibria can be obtained through permutations. Yet, as typical of (anti)coordination games, the game can lead to a pure strategy equilibrium where all sources choose different milestones; in practical scenarios, though, this would require full coordination to avoid overlapping choices. Alternatively, we can get a mixed strategy equilibrium, where all sources have the same probability distribution of choice of milestones. Note that the mixed equilibrium does not precisely correspond to a uniform selection of milestones (the selection is more biased towards the intermediate milestones, which get a lower average AoI). Nevertheless, for practical purposes the two approaches are very close, and both inefficient [22].

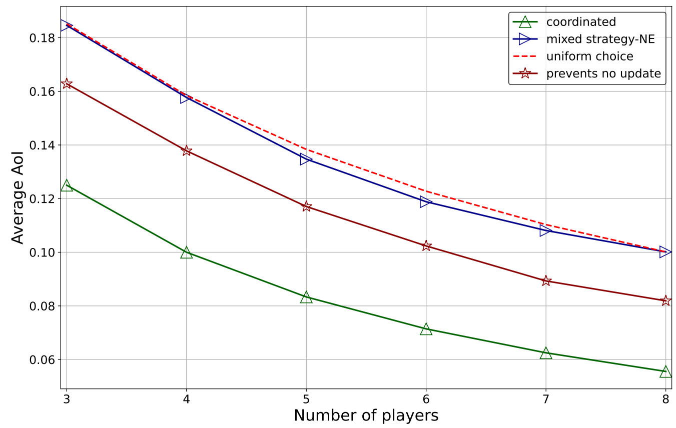

Fig. 2. Average AoI after preventing no update case

Fig. 2 reports a comparison of average AoI vs the number of sources obtained for the pure and mixed strategy equilibria (green and blue line, respectively). For comparison, the red dashed line corresponds to a uniform selection of milestones. Thus, it would be convenient to impose a CE that forces the sources to choose the coordinated case. This is generally possible through pre-play exchanges, but in our case this would directly correspond to assigning transmission instants in a round-robin fashion to the nodes, which requires a centralized control.

The aim of this paper is to introduce a practical approach to fill the gap between the two equilibria, at least partially, without resorting to centralized control. The intermediate red curve with star markers (in this and following figures) corresponds to one of such ideas, which are discussed in the following subsections.

A. Forcing transmission to prevent idling

As previously pointed out, it is reasonable to assume that the transmission of data takes place on a shared communication channel. For this to happen, we do not necessarily need to use a single full-duplex medium, which can also be prone to collisions [26]. We are simply considering that the sources are able to detect when another one sends information to the receiver (so a given milestone is chosen and utilized) thanks to some carrier sense mechanism.

We remark that in this case the ideal situation would be that each milestone is chosen by exactly one source. Two or more sources choosing the same milestone would be bad because of redundancy [28] and also because they leave at least another milestone uncovered. At the same time, having all sources idling during one milestone is also inefficient as the opportunity to lower AoI is lost. This situation resembles the study of random access for ALOHA networks (without the collisions).

Thus, the idea can be to use channel monitoring (i.e., carrier sense) to partially ameliorate this situation, at least for what concerns the latter inefficiency of skipped milestones. We propose a technique where all sources monitor the channel during a milestone (even if they chose not to transmit). Assume they are monitoring the jth milestone, which is chosen with probability p_j by all sources independently. If no transmission is detected, which happens with probability $(1-p_j)^N$, they are independently forced to reconsider they decision, i.e., they re-evaluate the binary choice of transmission/idle with probability p_j once again. This process is repeated until at least one source transmits.

Moreover, we allow the sources to adjust the schedule of subsequent milestones in case multiple transmissions occur. Assume for example that the first milestone is eventually chosen by $k > 1$ sources (this can happen immediately, or after a re-evaluation following a milestone that was initially neglected by all sources). The remaining sources will realize that $N-k$ of them are left to cover $N-1$ milestones. Thus, they better rearrange the transmission instants corresponding to the milestones as $N-k$ (instead of $N-1$) equally spread time instants until the end of the horizon.

We remark that this approach still makes only distributed decisions. Its resulting average AoI is reported in Fig. 2 as the black dashed line with intermediate performance. It is visible how this simple improvement manages to reduce the inefficiency by more than 50%.

B. Extension to non-evenly spread intervals

In addition to the previously outlined technique, a further improvement can be achieved by a different spacing of the milestones. Even though an even spreading would be optimal in the presence of independent failures [16], our modifications push sources to transmit more frequently, which justifies that the milestones are more distant at the beginning, and denser at the end of the time window.

To represent this, we introduce a *spacing factor*, denoted with α, to show that rather than employing evenly distributed intervals, we set each of them to be α times the previous one. Since we want them to be sparser at the beginning, we choose $\alpha \leqslant 1$. This means that the position of the jth milestone m_j is set as

$$m_j = \frac{1-\alpha^j}{1-\alpha^{N+1}} \,. \tag{5}$$

This can be easily verified to tend to the previous case of uniform spacing when $\alpha \to 1$.

Fig. 3 expands the previous findings with the feature of non-uniform milestones, with spacing factor α. A small improvement is visible, and can be better characterized by looking at the AoI efficiency defined as

$$\eta = \frac{\Delta(\text{coordinated case})}{\Delta(\text{compared technique})}. \tag{6}$$

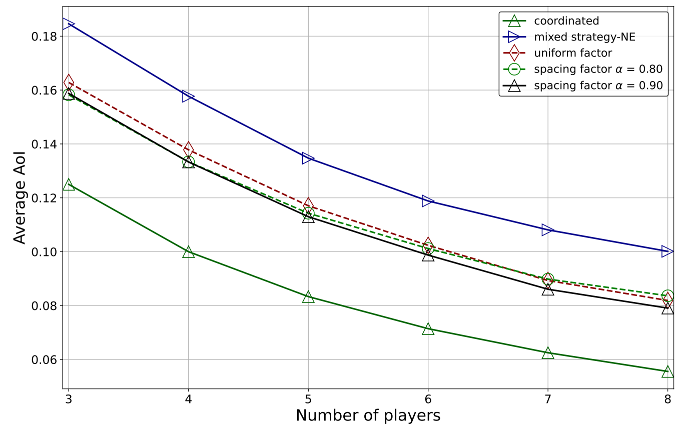

Fig. 3. Average AoI with spacing factor α

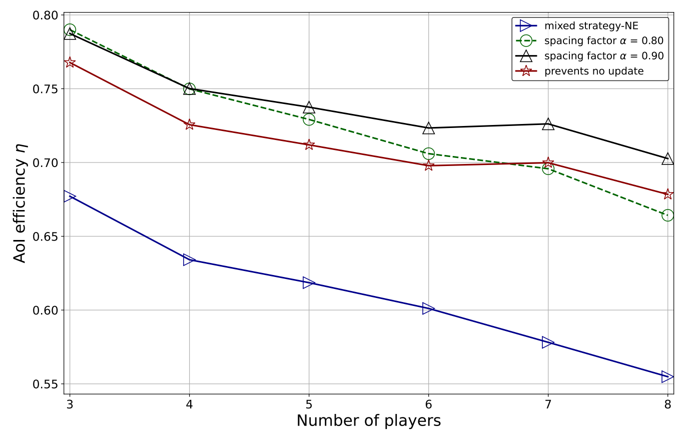

Fig. 4. AoI efficiency

Since the coordinated case is the one with lowest average AoI, the ratio is always less than or equal to 1. This value is plotted in Fig. 4, outlining how efficiency slowly decrease in the number of users. Yet, it seems that the proposed techniques make the descent less steep.

In addition, the value of $\alpha = 0.9$ represents an improvement over uniform spacing, whereas it is not always the case for $\alpha = 0.8$, especially when the number of sources increases, which seems to imply that 0.8 is too high a value. To better investigate this point, we also consider Fig. 5, where the efficiency of different values of α is investigated. It is visible that the best value of the spacing factor is around 0.9 but also depends on the number of sources. A further analytical characterization of this choice is left for future work.

V. Conclusions and Future Work

Our study delved into the potential for coordination enhancement to achieve AoI-optimal finite-horizon scheduling within networks consisting of N agents. Our primary aim was to differentiate between perfect coordination, a scenario seldom feasible in practical settings, and distributed decision-making following a mixed strategy NE, known for its inefficiency. We introduced two practical extensions based on

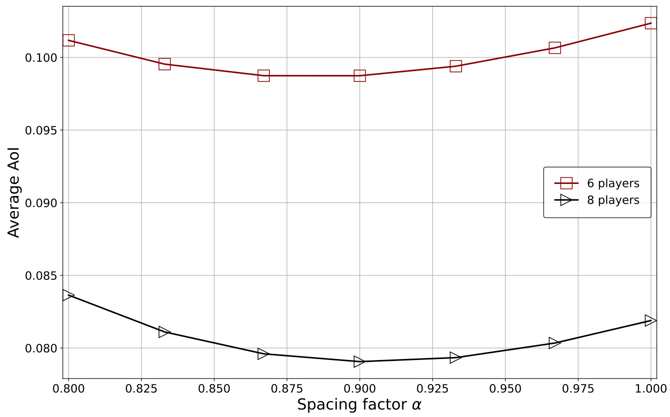

Fig. 5. AoI efficiency of different spacing factors

common features of wireless transmission protocols under multiple access. The effectiveness of our proposed solutions was evaluated using efficiency ratio metrics, compared against the ideal scenario of full coordination.

Future research efforts will be directed towards further enhancing the explored solutions to achieve higher efficiency, ideally surpassing the efficiency achieved with the discussed scenarios, and better mitigating redundant transmissions. Potential directions for future work include implementing additional strategies to break symmetry, leading to solutions closer to the anti-coordination paradigm.

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