Leveraging Random Access Techniques for Finite Horizon Uncoordinated Status Sensing

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***Abstract*—This study explores the minimization of age of information from multiple sources in a low-complexity scenario without centralized management. Multiple nodes transmit without coordination to a common sink with the objective of reporting status information about a monitored area (e.g., a forest, a greenhouse, or a field) for a finite horizon time window. We show how, although the problem is prone to high inefficiency in the solution, the exploitation of techniques inspired by random access at the multiplexing level of wireless networks, in particular introducing carrier sense over predefined operational points, enables considerable improvements. Further, we explore the sensitivity of these approaches to parameters such as the contention interval, the processing time, and the available offset over the schedule.**

***Index Terms*—Age of information; Sensor networks; Game theory; Precision agriculture.**

I. Introduction

Agriculture absorbs a significant portion of the workforce in most populations worldwide. It can guarantee economic and food stability to countries, whereas its poor management may cause population impoverishment, and possibly turmoils or famines [1]. However, the agriculture sector is particularly dominant in developing countries, so that, with the advent of improved life conditions, a substantial share of the population is likely to move towards other sectors in the future [2]. This reduced availability of working personnel can be balanced by technological advancements revolving around the Internet of things (IoT) [3], [4].

In particular, similar to what happens in many "smart" or "IoT-related" scenarios such as smart cities, precision medicine, or industrial IoT, ambient intelligence can be applied for managing farms and plantations through IoT devices and AI-powered control [5]–[7]. This provision of services by requires a timely delivery of status updates from sensors deployed on the (literal) field, to gain information about humidity, temperature, moisture, nutrients, presence of pollutants or parasites, and more, for the crops under monitoring.

In this scenario, data freshness is essential for proper system control [8]. Although on different time scales, all monitoring systems obey to the same principle of requiring up-to-date information for proper functioning, for which many contributions show the benefits of considering a reference metric called age of information (AoI) [9], due to its analytical character.

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At time t, the instantaneous AoI is defined as $A(t) = t - \sigma(t)$, where $\sigma(t)$ is the instant of the last reception of an update [10]. In a sensing context, AoI may be useful to express not only the obsolescence of measurements, but also that devices that are constrained, e.g., in terms of energy or computation, ought to make the most out of the few opportunities to exchange data they have when monitoring the remote area such as a plantation or a forest [11]–[13].

Yet, most investigations of AoI scenarios focus on single link communications as opposed to a network of scattered sensing devices, as typical of precision agriculture or medicine [14], [15]. This is why the control actions performed in an atomic system, where all the decisions are made in the same unit, would not work in scenarios where achieving complete coordination is deemed expensive as it requires full awareness of the network topology and possibly lengthy exchanges of control messages for coordination and feedback [16]. Conversely, in most sensing scenarios deployed in areas with low-human impact, such as a field or a forest, the topology has little planning and minimal supervision [17], [18].

Therefore, our analysis focuses on low-cost distributed management, under the assumption that the individual control of each device is able to operate on its own with rational deduction. For this, the instrument of choice is game theory, which is successfully applied to many wireless communication problems [19]–[21]. We seek for achieving an efficient medium access through the choice of the individual sources acting in the absence of a pre-established transmission pattern to simplify their management, which is modeled as an anti-coordination game of complete information.

It turns out that a native uncoordinated medium access pays a high price of anarchy [22]. The idea presented in this paper is to adopt a solution inspired by medium access techniques [23], specifically, incorporating carrier sense over predefined operational points. This can be shown to significantly enhance the AoI performance, without causing too much a burden to the network [24]. We therefore discuss the resulting performance and the dependence on parameters such as the processing time, resulting in the vulnerability interval of the carrier sense, and the time window for contention.

The rest of this paper is organized as follows. In Section II, we discuss related work. Section III presents the system model. Numerical evaluations are discussed in Section IV. Section V concludes the paper.

II. Related work

While the analysis of this paper is general and does not necessarily refer to agriculture monitoring systems, it is worth mentioning that two key characteristics are present in this kind of scenarios that are particularly relevant to our contribution. The former is, IoT networks for agriculture are expected to have extremely low power consumption [17], possibly due to the need for long operation without battery replacement or possibly under energy harvesting through solar panels [13]. Implied by this, and also by the fact that the IoT devices used for crop monitoring or similar activities are likely to be low cost and unable to perform heavy computation tasks, it is also convenient that they can use some forms of distributed management [5], [8].

These characteristics are specifically explored in some related papers that apply the AoI paradigm to evaluations in sensing agricultural networks. For example, [25] considers a combined minimization of AoI and energy expenditure, for a system where sensors transmit status updates to a central mobile node in an agricultural field. Reference [16] considers a centralized optimization and discusses the role of feedback, which is another component that is hard to get in agricultural networks, where feedback packets can be lost due to channel errors or periodic sleep schedule of the nodes [26].

In [11], the specific feature of agricultural networks considered is that of data correlation, since this is a kind of system where multiple information flows coexist and can possibly refer to similar or even the same quantity under monitoring.

However, none of the aforementioned papers take a game theoretic stance, which is instead the focus of other contributions such as [24], [27]. In these studies, multiple sources are generally considered, each transmitting different data and therefore having a differetn objective, i.e., the AoI value related to their measured content only. In this case, it was shown in [28] how correlation among multiple sources may be beneficial, since it enables a reduction in the frequency of transmissions, alleviating possible system congestion episodes.

On the other hand, the problem we consider in this paper takes an opposite perspective, in that we assume that all the sensing devices transmit the same information content, so correlation is actually maximal [11], yet they are interested in achieving diversity in their transmission instants, so as to avoid to waste opportunities for updating the receiver. Thus, as in [29] the problem lies in choosing the best transmission instants for an efficient schedule. Yet, this last paper considers a centralized approach, whereas ours is distributed, and identifies the main problem in erasures; conversely, our channel access is collision-free, but choosing identical transmission instants causes inefficiencies because of the redundant transmission.

Our approach is inspired by not only game theory, but also certain aspects of random protocols for medium access, specifically carrier sense. For this, game theoretic studies exist [23], but mostly focusing on tuning the parameters of protocols. For example, [19] investigates the setup of the contention window and the backoff rule via game theory. Further, [30] analyzes the stability of a random access protocol through Gale-Shapley theorem from game theory. However, our paper is the first where this technique is used in a game-theoretic sense towards improving AoI.

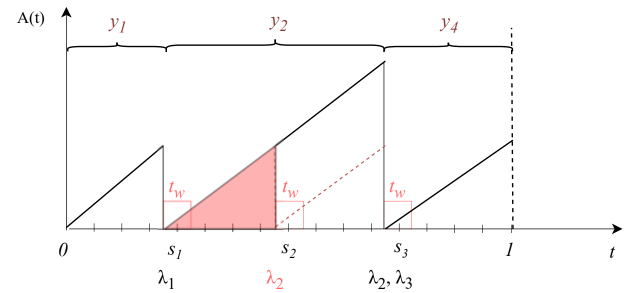

Fig. 1. Timeline of AoI evolution

III. System Model and Analysis

We consider a scenario with multiple IoT nodes transmitting data within the same network. All nodes are similar to each other and contain identical information that they forward to a common destination [28]. Since they operate in the same environment, they strive to keep the destination always supplied with the freshest information. As in [22], we focus on the optimal sending of updates within a defined time interval, given that many IoT networks face limited energy capacities [13]. Therefore, we take into account an energy consumption constraint. More precisely, the nodes have only one opportunity to update during the restricted time horizon, which is normalized to $[0, 1]$.

We assume that transmissions can only occur at specific time instances called *milestones*, which are ideally evenly distributed and denoted as s_i, where $s_i = i/(N+1)$, for all $i \in \{1, 2, \dots, N\}$. The transmission pattern is shown in Fig. 1, where we also consider the option to add a contention window t_w after each milestone, to be discussed later.

Complete coordination of the nodes is not possible without central control, and if the nodes transmit completely randomly, unfavorable scenarios occur more frequently, leading to an increase in the average AoI, which represents our objective function [9]. Similar to many studies focused on system information freshness, we use the average value of AoI as a freshness metric. Specifically, whenever data transmission occurs, the instantaneous AoI resets to zero [24], and the average AoI Δ is computed as the integral over the finite horizon normalized to $[0, 1]$, that is,

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

If two or more nodes propose similar times for their updates, scenarios with duplicate transmission of the same data can occur, thereby reducing the system efficiency and increasing AoI. For example, Fig. 1 shows the effect of two nodes transmitting simultaneously in the third milestone and skipping the second one.

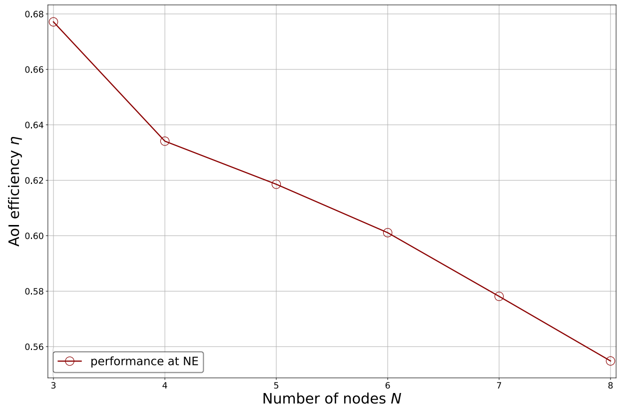

Fig. 2. Inefficiency due to uncoordinated transmissions of multiple nodes

This event can be avoided in the perfect case of full coordination, where all nodes transmit at different intervals, but such a finely tuned coordination is unachievable in real scenarios. On the other hand, letting the nodes to choose independently at random is risky because it leads to low system efficiency, which becomes even worse when the number of nodes increases, as can be seen from Fig. 2. This figure displays the ratio between the minimum possible AoI value under centralized control, and the AoI at the NE, which is an equilibrium in mixed strategies. Formally,

$$\eta = \frac{\Delta(\text{coordinated case})}{\Delta(\text{equilibrium in mixed strategies})}. \quad (2)$$

The reason is the lack of coordination among independent sources, leading to repeated transmissions that do not represent collisions as in [24], but rather lost opportunities for transmission in other intervals.

However, we allow for a transmission to occur within certain boundaries of the precise value of s_i, allowing independent sources to transmit slightly before or after the scheduled transmission, limiting the transmission opportunity to a time window t_w of a certain size. Each source is given the ability to specify when within the allowed window it would like to transmit, whether earlier or later. Based on the provided values, a schedule is chosen that is the earliest compared to all possible proposals [29].

Our focus is to investigate the impact of the size of the time window, within which we can shift the scheduled transmission. We also examine the case where transmission can only occur immediately after the scheduled time.

The model is framed as a static anti-coordination game [21], [22], where equilibrium arises from players selecting different strategies, represented by various time slots, within a framework of complete information $\mathcal{G} = \{\mathcal{N}, \mathcal{A}, \mathcal{U}\}$. Here, the players are distinct nodes belonging to the player set $\mathcal{N}$, with each representing an independent information source. Action set $\mathcal{A}$ comprises the available choices for the sources, denoted as $\mathcal{A} = \{1, 2, \dots, N\}$, reflecting that each source commits to one of the N milestones for its data transmission. Precisely, when source i selects action $(a_i = k)$, where $(1 \leqslant i, k \leqslant N)$, it indicates a specific transmission time $(t_i = s_i)$. The payoffs within the utility set $\mathcal{U}$ are contingent upon the actions made by the players. In this context, all sources converge on a mutual objective aimed at minimizing the average AoI Δ, which is a common goal shared across all nodes [23].

We define the transmission time of the ith source as t_i. Due to the lack of coordination among the sources, transmission times t_is can be out of order. To address this, we introduce vector $\boldsymbol{\lambda} = (\lambda_1, \dots, \lambda_N)$ as the re-ordered sequence obtained by arranging the times in increasing order. Here, λ_i represents the ith smallest transmission time, not necessarily corresponding to the choice made by the ith source.

The resulting AoI can be derived from the λ_i values [29] or, alternatively, from the $N+1$ transmission intervals $y_j = \lambda_i - \lambda_{i-1}$, where $\lambda_0 = 0$ and $\lambda_{N+1} = 1$. This leads to

$$\Delta(\mathbf{y}) = \sum_{i=1}^{N+1} \frac{{y_i}^2}{2}. \quad (3)$$

Here, $\mathbf{y} = (y_1, y_2, \dots, y_{N+1})$ represents the vector containing the resulting transmission intervals.

IV. Contributions and Evaluation

We first consider in Fig. 3 a scenario with perfect carrier sense, which results in all nodes choosing different milestones, even though there may be a slight delay in the transmission time to resolve the contention.

It is possible to see that, under this assumption, our model approaches complete coordination even though the schedule is not precisely in the milestones but a bit off. Thus, the results are similar to those in the case of perfect coordination and, as argued in [31] the effect of this delay is almost negligible and can be accounted for with minor modifications to remove it entirely.

As is also expected, the smaller the window during which transmission can occur, slightly earlier or later than planned, the closer the value of the average data freshness to the ideal scenario. However, since instantaneous carrier sense never occurs in practice, we kept into account the channel propagation through a parameter δ, as will be explained next, to basically represent a vulnerability interval due to propagation delay.

As all sources listen to the same channel and independently decide when they would like to transmit, the winner is the one that chooses the earliest transmission time, which represents our window for the planned milestone shift. We introduce the parameter δ, which signals to the other sources that the transmission has already taken place and that the channel remains locked for other transmissions within the interval from the actual milestone plus the propagation time. However, a redundant transmission will occur if some of the other sources have a sending time within this interval that is smaller than the δ parameter. Contrary to an ALOHA scenario [4], this repeated transmission does not represent a collision but only a lost opportunity for a new update possibility.

This model eliminates the state without transmission and also attempts to limit the possibility of multiple transmissions

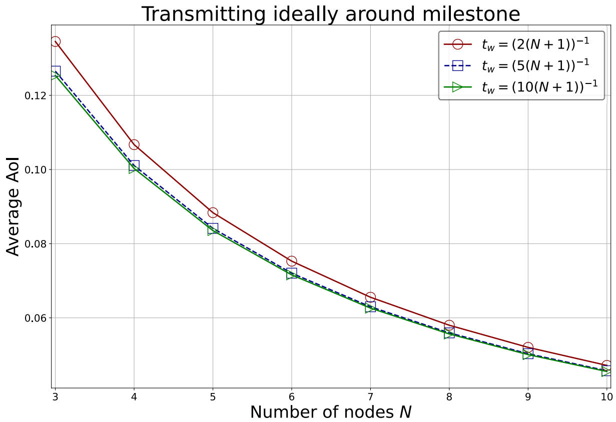

Fig. 3. Ideal scenario with fully coordination transmitting around scheduled milestone with different transmission time windows

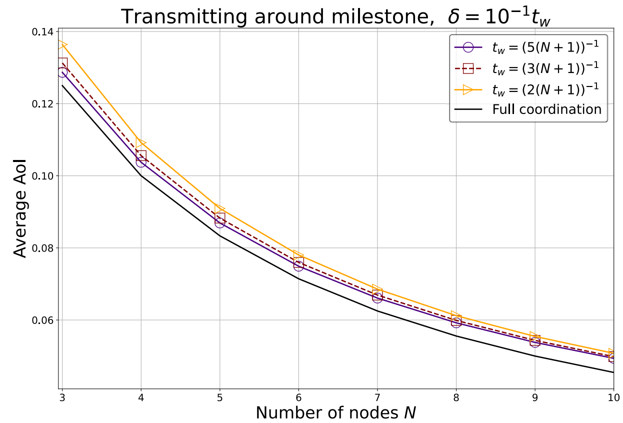

Fig. 5. Effect of time window size on the average value of AoI when δ is fixed to $\delta = \frac{1}{10t_w}$

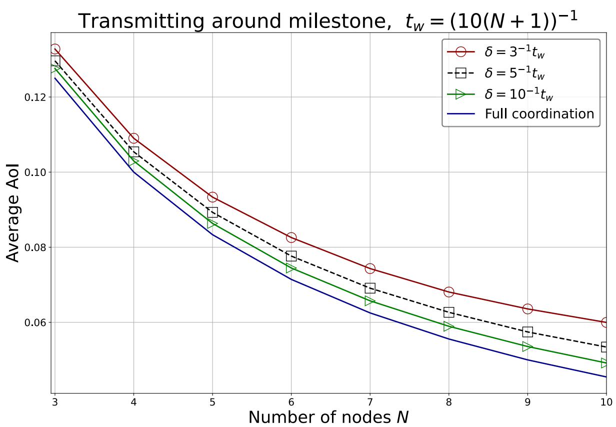

Fig. 4. Transmitting around scheduled milestone with window size equal to $t_w = \frac{1}{10(N+1)}$ with different δ values

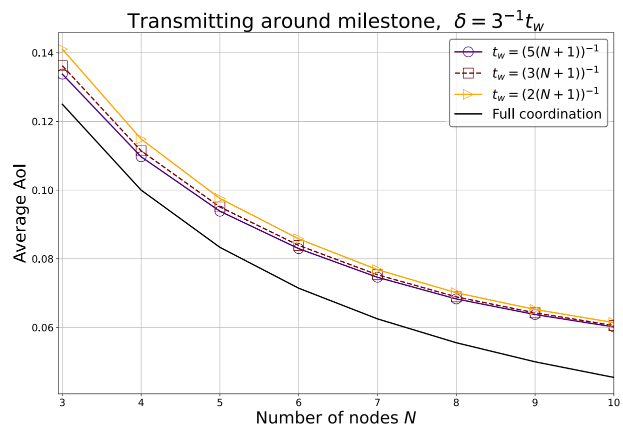

Fig. 6. Effect of time window size on the average value of AoI when δ is fixed to $\delta = \frac{1}{3t_w}$

by adjusting δ. Therefore, if the time window within which transmission can occur is narrow, the average data freshness will be close to perfect coordination, as visible from Fig. 4. However, depending on the value of δ, which determines whether an additional redundant and therefore useless transmission can occur, the value of the average information age will be either closer to or further from the ideal case.

The best value is achieved when δ is as small as possible, thereby minimizing the chance for repeated transmission. It can be concluded that with a larger number of sources, the difference in the achieved average AoI compared to a smaller number of nodes becomes more noticeable.

However, when δ is fixed, for example, to $\delta = \frac{t_w}{10}$, we can conclude that the size of the window is not as critical. It is more important if a smaller number of sources participate in the transmission; although the average values in the examined scenarios do not fluctuate significantly, see Fig. 5. In contrast, with a larger number of nodes, we can see that the differences are negligible if the propagation time is very short.

Fig. 6 considers a larger δ; for a higher number of sources, the different widths of the chosen transmission windows converge and move further from the ideal case of complete coordination. In contrast, for a smaller number of nodes, the window size plays a more significant role when the delta value is fixed and is closer to the ideal case of coordination.

Finally, in Fig. 7 we consider the case where the contention window starts at the uniform milestone, therefore the transmission instants can be only postponed after the initial planned time. Even in this case, the changes in δ do not play a significant role for a small number of sources. However, for a larger N, adjusting δ can significantly oscillate towards or away from the ideal case. Thus, for a larger number of sources, when the time window size is fixed, the processing and propagation speed must be as low as possible.

For situations where the window size is fixed, systems with a smaller number of nodes transmitting the same information are less affected by processing and propagation times. Conversely, when the δ parameter is fixed, for systems with a larger number of nodes transmitting identical information, the window size does not play a significant role. These systems converge to a point closer to the ideal scenario if the processing and propagation times are lower ($\delta \to 0^+$).

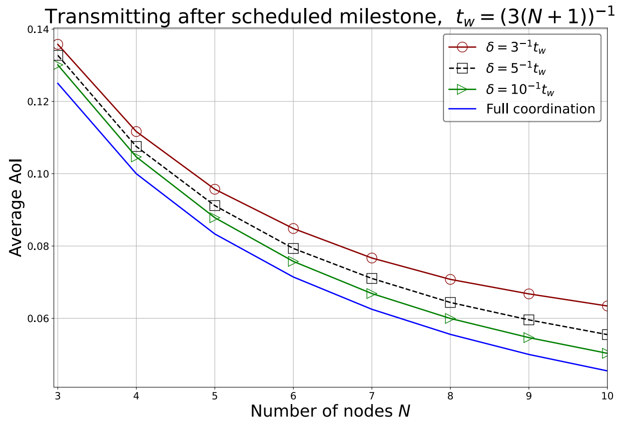

Fig. 7. Transmitting after scheduled milestone with window size equal to $t_w = \frac{1}{3(N+1)}$ with different δ values

V. Conclusions and Future Work

We presented a game-theoretic approach to minimize AoI in uncoordinated status-sensing networks, such as precision agriculture scenarios, where nodes transmit without centralized management. Our model, inspired by random access techniques [4], [19], allows for transmission around predefined milestones and improves data freshness compared to purely random transmissions. The results show how tuning of parameters like the contention window and processing delay can enhance performance, especially in scenarios where coordination is impractical or costly [24]. Our framework offers a solution for distributed IoT networks by balancing efficiency with implementation simplicity.

Future research can explore several extensions to the current model. A promising direction is the application of dynamic games that involve multiple stages, where nodes can adapt their strategies based on network conditions [23]. Further investigation into scenarios with heterogeneous nodes, transmitting different data types, may reveal new optimization strategies for AoI reduction [20]. Finally, expanding the framework to imperfect feedback and error-prone channels would make it more suitable for real-world implementations of large-scale agricultural monitoring systems [6], [15].

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