Satellite Intermittent Connectivity and Its Impact on Age of Information for Finite Horizon Scheduling

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***Abstract*—Low Earth Orbit (LEO) satellite communications can provide real-time services with reduced latency, which makes them ideal for applications requiring timeliness, such as Internet connectivity, remote monitoring, and disaster response. In this paper, we study a problem of information freshness optimization for such a scenario. Usually, this is quantified through the age of information (AoI) metric, but the typical scenarios involve a homogeneous time horizon, where transmission can take place indifferently at any instant. In reality, LEO communication may be severely influenced by its intermittent connectivity, which is not present for long time windows where line of sight with the satellite system is absent. Thus, we consider a problem of AoI-minimal scheduling for a finite horizon, solved via dynamic programming, where intermittent connectivity is accounted for, and addressed through different approaches. Moreover, we quantitatively evaluate the impact of different parameters on AoI and derive practical considerations for empirical setups.**

***Index Terms*—Age of information; Satellite communications; Scheduling algorithms; Dynamic programming.**

I. Introduction

Prompt real-time monitoring is key to time-sensitive applications of many interconnected environments foreseen by the next generation of communication systems [1]. Satellite communications can play a fundamental role, especially for wide-area services, such as smart cities, ground/air traffic control, disaster response, environmental monitoring, or maritime surveillance to name a few [2]–[4]. Unfortunately, satellite links are also heavily affected by high delays [5] and LEO systems may also suffer from communication unavailability [6], which can undermine the reliability and latency of the data exchange.

In such a challenging environment, maintaining data freshness becomes even more essential than in traditional terrestrial networks, to ensure that transmitted information reflects the current state of monitored environments [7]. Timeliness of data can be quantified by age of information (AoI) [8], a metric computed as the difference between the current time and the last time an update was received. Formally, this is defined as:

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

where t is the current time index and $\sigma(t)$ is the instant of the last correctly received update at time t.

AoI quantifies timeliness of information, telling whether the exchanged messages are sufficiently up-to-date for an effective decision-making. In satellite-based systems, challenges such as long link distances and limited communication windows necessitate intelligent scheduling and data management strategies to control AoI [9]. In turn, the cost-effectiveness of the satellite network infrastructure can be justified if it is able to support real-time data analytics and automation in remote monitoring applications, which can be translated in the task of maintaining lower AoI. However, the information available at a device, exploited to plan its transmission schedule, ultimately impacts the resulting AoI. As shown in [10], [11], a transmitter that is oblivious to systematic surrounding conditions that may prevent a transmissions from being successful, and/or innovative over the current information, can experience significant increases in the resulting AoI.

This is exactly the problem faced by LEO satellite communications, which are heavily affected by the transit of satellites resulting in intermittent coverage. The specific impairing aspect we concentrate on in this paper is that line of sight to the satellite constellation may be absent for long time intervals, which may hinder successful timely updates. While the problem of AoI minimization under channel erasures has been addressed and often solved via dynamic programming [12], [13], an analysis that explicitly considers the impact of intermittent connectivity that is not just random, but rather persistent for a long window of non line of sight with a satellite constellation is still missing from the literature.

Therefore, in this paper we tackle the issue of AoI minimization for a satellite network over a *finite horizon*, where a limited number of transmission opportunities can be scheduled. For the sake of tractability, we will analyze this problem over a discrete time with dynamic programming, even though multiple alternative methodologies are also available. However, the crux of the analysis is that the network connectivity follows an ON/OFF pattern that spans across multiple time slots [14]. As we will argue, setting a proper way to translate this constraint in the scheduling policy can follow multiple avenues, which leads to a comparative analysis of the following different techniques, all considered in our investigation.

Agnostic scheduling. Introduced as a sort of benchmark, this policy considers a regular transmission pattern of updates simply neglecting that the data exchange will fail in the absence of the satellite link. While this may be the actual case for low-complexity devices that are only able to wake up at predetermined regular intervals [15], most realistically it can be seen as a bound to understand the degradation experienced by AoI in the worst possible case.

Scheduling with memoryless knowledge. This policy considers a dynamic programming framework [16], where the system state *includes* the current availability of the satellite network, but its further evolution is just assumed to follow a Markov chain with known transition rates corresponding to the actual values. Following such a strategy implies the ability to adjust the transmission schedule at run-time, i.e., postpone transmission if the satellite link is unavailable.

Scheduling with full knowledge. In this case, the dynamic program is obtained from the knowledge of the entire evolution of the connectivity throughout the entire time horizon. This would require that the communication leverages some positioning of the devices and constant control information of the satellite transits [17]. In this case, the best possible performance relative to channel knowledge is obtained.

In addition to comparing these approaches, our analysis also enables the capture the impact of multiple parameters. For example, we can consider error-free communication in the case of line of sight, or the case where further erasures, e.g., due to obstructions or other channel impairments, can be present with independent and identically distributed (i.i.d) probability [18]. We can additionally comparatively evaluate different durations of the transit windows, or the length of the entire horizon for the task under monitoring, as well as the number of transmission opportunities available within it.

All of these evaluations allow us to draw remarks which may be useful as practical guidelines in real-world contexts. Especially, the main finding is that an agnostic scheduling without any state information about the satellite transits performs very poorly, whereas a memoryless approach performs relatively close to a full knowledge scheduler, depending on the relative size of the connectivity periods.

The rest of this paper is organized as follows. In Section II, we review related work. Section III describes the system model, while Section IV presents the analysis of the resulting AoI minimization for the different policies under consideration. Numerical results are shown in Section V, and finally Section VI concludes the paper.

II. Related Work

AoI characterizes data exchange in networks and remote sensing from a semantic vantage point, transcending the traditional focus on individual packets. Unlike metrics that evaluate the instantaneous status of a single transmission, AoI encapsulates the temporal evolution of data freshness, with its value persisting and accumulating significance as time progresses [8].

For this reason, the recent scientific literature on communication networks has seen a proliferation of studies on AoI, often applied to exotic or non-conventional scenarios, such as underwater networks, disaster recovery, or molecular communications [2], [19]. Similarly, specific studies consider non-terrestrial networks (NTNs), where the focus ranges from multiple aspects such as longer delays, intermittent availability, and also energy consumption [7]. Of these, in this paper we specifically explore that connectivity is lost in the absence of satellite coverage, which is possibly the most severe impairment to timeliness. In this spirit, [6] already provided a first analysis of intermittent connectivity, even though the scenario of reference there is a multi-hop ad hoc network, where links are down for short periods, as opposed to long non line of sight windows experienced in satellite communications. Also, that reference considers a queueing theory based approach, whereas we analyze here the impact of packet scheduling, which implies a precise instantiation of transmissions.

The characterization of satellite links as alternating between active or inactive windows, i.e., where line of sight is present or not, respectively, is also the predominant aspect considered in the majority of the literature. We remark that the issues of energy efficiency are not specific to satellite communications and overall present across the entire literature on AoI, most often emphasized whenever the devices have specific features such as being powered by energy harvesting [20], [21].

Conversely, the role of a non-negligible transmission delay, which is indeed a remarkable property of satellite links, has been addressed by the authors already in [5], with the main conclusion that most of the times the scheduling problem is only slightly affected by extra delay terms, even though the resulting AoI is of course overall higher due to them. Moreover, we can argue that the link unavailability due to the satellite not having line of sight conditions can often last for up to to 10–15 minutes in LEO systems [22], which makes the propagation delay of few milliseconds (since distances can be up to 2000 km) to be negligible. In other words, the issues of intermittent connectivity, on which we focus here, or the propagation delay can certainly be considered for AoI analysis, but it is pointless to include them both in the analysis, as either of them is going to be ultimately relevant.

Still, our analysis has many points of contact with other papers appeared in the literature that considered a connectivity status alternating between active/inactive phases. For example, even though that analysis does not specifically focus on satellite links (and also not directly on AoI, since they consider query AoI), we argue that [23] hints at a possible application for a system with intermittent queries over a finite time horizon, which can ultimately lead to an analysis similar to ours. However, the Authors of that paper considered a long-term average minimization of information staleness rather than a finite horizon as we do here, and, as already mentioned, consider query AoI as their metric.

In [24], the impact of intermittent connectivity for LEO satellite networks is considered within a parametric analysis of the average AoI. However, the main focus is a statistical modeling of the duration periods for active or inactive transmission, based on practical NTN scenarios, and this is ultimately inserted in standard queueing theory evaluations of AoI, once again allowing for the computation of long-term averages, but not of localized scheduling.

The Authors of [25] analyze AoI in multihop connections with tributary traffic. Their main case study is indeed a LEO satellite system, represented as a network of queues, so that the computations leverage queueing theory [3], different from what done here, where we explicitly focus on scheduling of transmissions over a single connection.

In [26], the synergy between satellite networks and UAV is explored. In this paper, the comparison between the two kinds of sources just pertain to different surveillance areas, but there is no analysis of longer delays of satellite, nor their intermittent connectivity (conversely, the UAV are considered to be the sources with limited coverage). Reference [27] considers a problem of long-term AoI minimization, over an infinite horizon, subject to energy constraints. The solution is obtained via linear programming, nevertheless sharing a similar element with our analysis, namely, the unavailability of the satellite link under non line-of-sight conditions, which in this paper are foreseen in advance.

In general, long-term average AoI minimization is the most common setup in freshness-aware scheduling [9]. However, this formalization may be at odds with a satellite environment, where the spans of the connection/disconnection windows are considerably higher than the duration of a single transmission, which implies that a long-term average misses the locality of AoI evolution. Thereby, a finite-horizon scheduling would be more appropriate, as explored in [12], [13], [15], [16], [28]. However, none of these papers explicitly explore satellite networks and their specific characteristics.

Still, our analysis shares some similarities with the dynamic programming framework presented in [12] and [16], which performed a similar investigation of finite horizon scheduling. However, the latter paper investigates only the case of i.i.d channel errors and a correlated Gilbert-Elliot model, which is equivalent to applying one of our policies with memoryless knowledge, but ultimately different from studying the entire window. The former investigates instead the problem of unavailable *information* at the source, which is typical of industrial settings. In that case, timeliness is an important requirement to ensure that real-time control loops for machine operations or production line adjustments, are promptly executed over short time windows (of the order of seconds). In contrast, satellite communications operate over a much longer time span, where availability of information at the source's side is likely not an issue, but face limitations related to finite contact windows during orbital passes [22]. Thus, while industrial systems leverages schedule optimization for continuous responsiveness, satellite networks must leverage limited opportunities to ensure data freshness and relevance.

III. System Model

Throughout our discussion, we focus on a ground terminal aiming to deliver updates on a process of interest to a monitor center. Connectivity is achieved via LEO satellites covering the area and collecting data packets [3]. The terminal operates over a finite time horizon T, over which it can perform a limited number of transmissions m. The setting is inspired by practical IoT applications, where a remotely deployed node may wake up sporadically to operate for some time before going back to sleep, and channel access is constrained by duty cycle or energy saving/harvesting arguments [27], [29].

In turn, we model connectivity to be possibly intermittent, alternating periods of satellite illumination and time spans over which no link is available. This allows to capture the behavior of different LEO constellations, ranging from the ones offering continuous coverage, to smaller systems that leave areas without service for some time [22]. To this aim, we assume a slotted time and, without loss of generality, we take a unit duration for a slot. This implies that, in the following, we will use a discrete-time notation such as writing δ_n as opposed to $\delta(t)$.

We let the state of the channel in slot $n \in \mathbb{N}$ be captured by the random process C_n, taking values in $\mathcal{C} = \{0, 1\}$. Specifically, $C_n = 1$ indicates that the terminal is in visibility of a satellite, whereas $C_n = 0$ corresponds to a lack of coverage. The channel evolves at each step following a homogeneous Markov model [30], with one-step transition probabilities $q_{i,j} = \mathbb{P}(C_n = i \,|\, C_{n-1} = j)$, $i, j \in \mathcal{C}$. Accordingly, the transition probability matrix is

$$\mathsf{Q} = \begin{pmatrix} q_{0,0} & q_{0,1} \\ q_{1,0} & q_{1,1} \end{pmatrix}$$

and its element at row i and column j as $\mathsf{Q}[i, j]$. The stationary distribution of the process is readily given by $\pi_0 = q_{1,0}/(q_{1,0} + q_{0,1})$ and $\pi_1 = 1 - \pi_0$. Furthermore, we consider that a message sent by the terminal may be lost even when in satellite coverage with probability ε, due to obstructions or other channel impairments [15], [18].

Whenever accessing the channel, the terminal transmits a freshly generated message, containing a stamp σ_n denoting the current time (generate at will model [8], [9]). In case of successful reception at the LEO satellite, an error-free acknowledgment may be sent in response. In this setup, we are interested in evaluating the ability of different strategies to maintain an up-to-date knowledge at the monitor, captured by AoI as per (1). We assume that this metric is initialized to $\delta_0 = 0$ at the start of the time horizon, and that a successful message also resets it to 0. The latter assumption does not change the fundamental trends that will emerge in the evaluation, and boils down to neglecting transmission and propagation delays, as well as the time that the satellite may take to forward information to a ground gateway.[1] This typically happens in IoT settings where channel access is very sporadic, but even holds when these values are not small, but nevertheless have little variability. An example of AoI evolution over time is reported in Fig. 1.

In the remainder, we focus on the average AoI, defined as

$$\Delta = \mathbb{E}\left[\frac{1}{\mathsf{T}} \sum_{n=1}^{\mathsf{T}} \delta_n\right]$$

where the expectation is taken over all the random components that may affect the m transmissions performed by the terminal.

In this context, the rationale to obtain a scheduling strategy may vary significantly, depending on the availability, or lack

[1]For example, routing to the gateway via inter-satellite links may imply a negligible delay compared to other latency components.

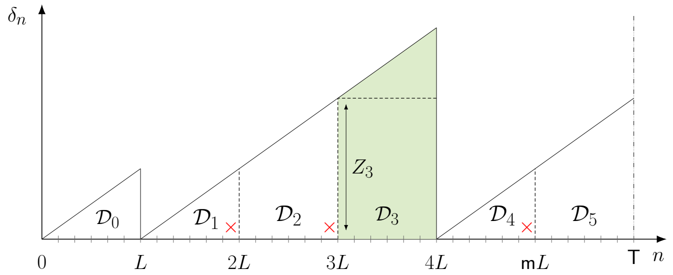

Fig. 1. Example of time evolution of the AoI $\delta(t)$. In this case, $\mathsf{m} = 5$ transmissions can be performed, and are equally spaced over the horizon. Red crosses (×) denote unsuccessful transmissions, either due to satellite unavilability or channel impairments.

thereof, of relevant information concerning connectivity aspects. For this reason, we consider three different approaches to derive our scheduling strategy, as discussed in Section I. These are classified as follows.

1) An *agnostic scheduling* that is not aware of the coverage status of the satellite link, nor of the outcome of the performed transmissions. For a finite horizon scheduling, this corresponds to an offline scheduler without feedback, where transmissions are performed even when the satellite link is unavailable (and in this case, they clearly fail). The strategy is relevant for IoT applications in which devices are not location aware and do not have any information regarding the ephemeris of the constellation available for connectivity. The lack of feedback may also by typical, as many practical systems foresee such operation mode to save energy [29].
2) A scheduling with *memoryless knowledge* of the evolution of the coverage state as well as of the outcome of transmissions. This means that the current state C_n is known, which trivially prevents from transmitting when the satellite is not in coverage, but every future value of the coverage state can only be predicted through the transition probabilities of Q. To derive this scheduling policy, a dynamic programming approach can be used [12], [16], [28].
3) A scheduling with *full knowledge* of the coverage state for the entire time horizon. In other words, all values of C_n are known throughout T in advance. The setting is inspired by solutions that currently employed for, e.g., NTN in 3GPP, where location-aware terminals can predict in advance when links will be available. From a modeling perspective, the aforementioned approach can also be followed, with the difference that the evolution of C_n is pre-determined and a dynamic program will obtain a scheduling policy that depends on it. There are actually other ways to analyze the system, for example, we validated our results of the dynamic program for the case of transmission without further erasures ($\varepsilon = 0$), in which case there is no randomness in the system evolution, through a constrained optimization formalization along the lines of [15].

As a side remark, we argue that the two last approaches allow for a gradient of intermediate cases depending on the actual distribution of the coverage times. Since the process, even when not entirely known in advance, is more realistically not fully memoryless either, i.e., practical distributions of these timing are not geometric, as argued in [24], one can leverage this aspect to plan a dynamic program with better predictions in the inductive step. However, besides not adding much insight to the analysis, we also remark that this approach of considering intermediate knowledge of the evolution is unnecessary whenever the performance of the schedulers with full or memoryless knowledge are found to be very close to each other, which happens oftentimes as will be shown by our numerical evaluations.

IV. Average AoI Characterization

In order to capture the performance of the considered transmission strategies, different modeling approaches can be followed, as highlighted in the following.

A. Agnostic case

In this case, the terminal has no knowledge of the current availability of a satellite connection. Accordingly, it performs the m transmissions at regular intervals over the time horizon, spacing them by $L = \mathsf{T}/(\mathsf{m}+1)$. For the sake of convenience, we denote by

$$p^{(k)}_{i\,|\,c_0} = \mathbb{P}(C_{kL} = i \,|\, C_0 = c_0) = \mathsf{Q}^{kL}[c_0, i]$$

the probability that the channel is in condition $i \in \mathcal{C}$ at the time of the k-th transmission attempt, given that it was in condition c_0 at the beginning of the considered time horizon. Following this notation, we will also lean on the probability distribution for the channel evolution between two successive transmission attempts, spaced by L slots, given by

$$p^{(1)}_{i\,|\,j} = \mathsf{Q}^{L}[j, i].$$

In this configuration, the average AoI can be conveniently computed as

$$\Delta = \mathbb{E}\left[\frac{1}{\mathsf{T}}\sum_{\ell=0}^{\mathsf{m}} \mathcal{D}_\ell\right]$$

where $\mathcal{D}_\ell$ is the area below the current AoI curve within the interval $[\ell L, (\ell+1)L)$, as illustrated in Fig. 1. By the linearity of expectation, we focus on $\mathbb{E}[\mathcal{D}_\ell]$, and notice that the area of interest can be expressed as

$$\mathcal{D}_\ell = \frac{L^2 - L}{2} + L Z_\ell \tag{2}$$

where Z_ℓ is the value of $\delta(t)$ at the start of the ℓ-th interval, i.e., after the ℓ-th transmission has been performed.

If we now introduce the r.v $S_\ell \in \{0, 1\}$ denoting the outcome of the ℓ-th transmission attempt, with 0 denoting failure and 1 success, we have readily

$$Z_\ell = \begin{cases} 0 & \text{if } S_\ell = 1 \\ L + Z_{\ell-1} & \text{if } S_\ell = 0 \end{cases} \tag{3}$$

with $Z_0 = 0$ due to the assumption $\delta_0 = 0$. Let us then consider the expected value of Z_ℓ, conditioned on having failed the ℓ-th attempt, and on having the channel in condition c_0 at the start of the time horizon. From (3), we can write

$$\mathbb{E}[Z_\ell \,|\, S_\ell = 0, C_0 = c_0] = L + \mathbb{E}[Z_{\ell-1} \,|\, S_{\ell-1} = 0, C_0 = c_0] \cdot \mathbb{P}(S_{\ell-1} = 0 | S_\ell = 0, C_0 = c_0) \quad (4)$$

In turn, the conditional probability in (4) can be computed by definition as the ratio of the joint probability of the event $\{S_\ell = 0, S_{\ell-1} = 0 \,|\, C_0 = c_0\}$ to that of the condition $\{S_\ell = 0 \,|\, C_0 = c_0\}$. The former is given by

$$\mathbb{P}(S_{\ell-1} = 0, S_\ell = 0 \,|\, C_0 = c_0) = p^{(\ell-1)}_{0\,|\,c_0} \left(p^{(1)}_{0\,|\,0} + \varepsilon \cdot p^{(1)}_{1\,|\,0} \right) + \varepsilon \cdot p^{(\ell-1)}_{1\,|\,c_0} \left(p^{(1)}_{0\,|\,1} + \varepsilon p^{(1)}_{1\,|\,1} \right). \quad (5)$$

Here, the first addend captures the probability that the loss of the $(\ell-1)$-th attempt was due to lack of connectivity ($p^{(\ell-1)}_{0\,|\,c_0}$), and accounts for the failure of the ℓ-th attempt due to either a still missing connectivity ($p^{(1)}_{0\,|\,0}$) or to channel impairments in the presence of a link ($\varepsilon \cdot p^{(1)}_{1\,|\,0}$). Similarly, the second addend in (5) covers the case of having a loss at the $(\ell-1)$-th attempt despite the satellite being in visibility, again considering the two possible failure conditions for the ℓ-th message. Following a simular reasoning, we also immediately get

$$\mathbb{P}\left(S_\ell = 0 \,|\, C_0 = c_0\right) = p^{(\ell)}_{0\,|\,c_0} + \varepsilon \cdot p^{(\ell)}_{1\,|\,c_0}. \quad (6)$$

Plugging the ratio of (5) and (6) into (4), we are then able to obtain the conditional expectation $\mathbb{E}[Z_\ell \,|\, S_\ell = 0, C_0 = c_0]$ for any $\ell \in \{1, \dots, \mathsf{m}\}$ in a simple recursive way, with initial condition $\mathbb{E}[Z_0 \,|\, S_0 = 0, C_0 = c_0] = 0$.

Leaning on this, we can then compute the expected contribution of the are $\mathcal{D}_\ell$ in (2) as

$$\mathbb{E}[\mathcal{D}_\ell] = \frac{L^2 - L}{2} + L \times \sum_{c_0 \in \mathcal{C}} \pi_{c_0} \, \mathbb{E}[Z_\ell \,|\, S_\ell = 0, C_0 = c_0] \, \mathbb{P}(S_\ell = 0 \,|\, C_0 = c_0)$$

where the summation removes the condition on the initial channel state C_0 resorting to the stationary distribution of the process. Finally, summing up all the contributions and using (6) leads to the sought expression of the average AoI for the agnostic strategy, reported in (7) at the top of next page.

B. Dynamic programming (memoryless/full knowledge)

The case where transmissions are scheduled explicitly taking into account the availability of the satellite link can be solved through a dynamic programming approach [16], [28], leveraging the binary variable C_n for the channel state in slot n. We remark that this procedure is already applied in the literature, typically to represent channel correlation within Markov decision processes, since C_n evolves through matrix Q. In our analysis, this would be the approach to derive a scheduler with "memoryless knowledge," i.e., only the value of C_n at present time is known and its evolution is only estimated through Q. However, we will also consider the case of "full knowledge," where the entire evolution of C_n for all slots from 1 to T is known.

The dynamic program is set by taking a state including variables δ_n and m_n, corresponding to the instantaneous AoI value and the number of transmission opportunities left available at time slot n, and possibly also C_n for the memoryless knowledge scheduler. Incidentally, note that the terminal has knowledge of δ_n by receiving the error-free feedback from the LEO satellite, informing on the outcome of a delivery attempt. A transmission can be performed if $m_n > 0$ and $C_n = 1$, and in this case m_n is decreased by 1 and δ_n is reset to 0. This is reflected by a binary control action u_n that represents the scheduling choice of whether a transmission happens in slot n; numerically, this can be represented by $u_n = 0$ or $u_n = 1$ for idle and transmission, respectively. The dynamic program also includes a noise component that includes two mutually independent and optional components: (i) the evolution of C_n (only for the case of memoryless knowledge, since the scheduler with full knowledge knows it already in its entirety) and (ii) the channel erasures that happen with probability ε.

Thus, the state variables evolve as:

$$\delta_{n+1} = \begin{cases} 0 & \text{if } u_n = 1 \text{ and } \texttt{rand} < 1-\varepsilon \\ \delta_n + 1 & \text{otherwise} \end{cases} \quad (8)$$

and

$$m_{n+1} = \begin{cases} m_n & \text{if } m_n \cdot u_n = 0 \\ m_n - 1 & \text{if } m_n \cdot u_n > 0 \end{cases}, \quad (9)$$

whereas the coverage state C_{n+1} also evolves as a Markov variable, the only difference between the two dynamic programs being that in the memoryless knowledge case it is a part of the state too, since only C_n is known and not its entire evolution.

The dynamic program derives the optimal policy $u_n = \mu_n(\delta_n, m_n)$ for any state value and $1 \leq n \leq \mathsf{T}$, minimizing the expected value of cost δ_n. Since we focus on a finite horizon, Bellman's conditions just follow from backward induction. The essence of the decision in policy μ is a threshold-based criterion between transmitting or not, based on the value of δ_n and the number of transmission opportunities available.

V. Results and Discussion

We evaluate the performance of the three considered transmission schemes discussing numerical results obtained following the approaches presented in Sec. IV. While the analysis can be applied to any parameters configuration, we target as example IoT applications, and tackle a reference scenario in which a terminal operates over a time horizon of $\mathsf{T} = 60$ minutes. Unless otherwise stated, we focus on the possibility to perform $\mathsf{m} = 5$ transmissions, corresponding to an average time between attempts of $L = 10$ minutes. A satellite is in visibility for an average of 10 minutes, whereas we vary

$$\Delta = \frac{1}{\mathsf{T}} \left[\frac{(\mathsf{m}+1)(L^2-L)}{2} + L \cdot \sum_{c_0 \in \mathcal{C}} \pi_{c_0} \sum_{\ell=1}^{\mathsf{m}} \left(p^{(\ell)}_{0\,|\,c_0} + \varepsilon \cdot p^{(\ell)}_{1\,|\,c_0} \right) \mathbb{E}[Z_\ell \,|\, S_\ell = 0, C_0 = c_0] \right] \tag{7}$$

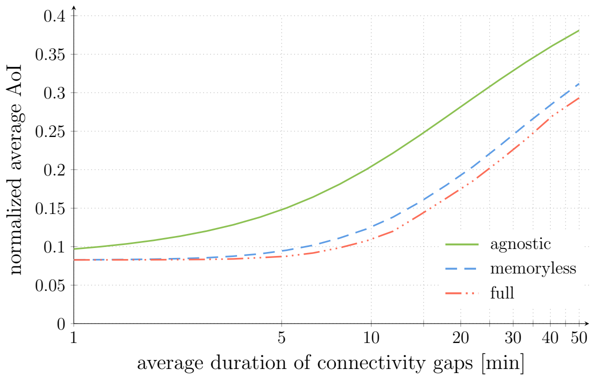

Fig. 2. Normalized average AoI vs average duration of connectivity gaps. A time horizon of 60 minutes has been considered, with 5 transmission opportunities. No losses in case of satellite visibility.

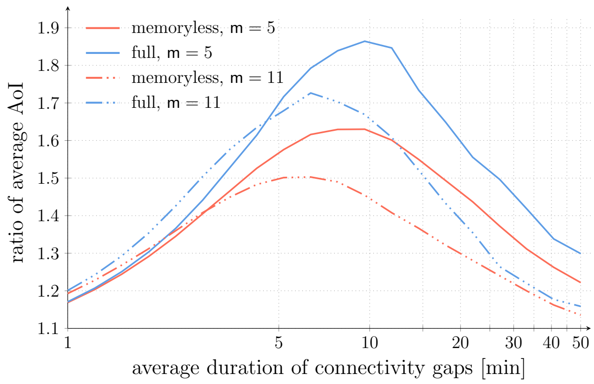

Fig. 3. Ratio of average AoI of the memoryless and the full-aware scheme to that of the agnostic approach, vs average duration of connectivity gaps. A time horizon of 60 minutes has been considered, with 5 (solid) and 11 (dashed lines) transmission opportunities. No losses in case of satellite visibility.

the mean duration of connectivity gaps.[2] We tune our model to these parameters by setting a slot duration of 6 seconds, thus having 600 slots within the time horizon. The choice, although arbitrary, provides sufficient granularity to optimize the placement of transmissions using the dynamic programming solutions, and captures well the evolution of satellite connectivity patterns.

We start our discussion assuming a perfectly reliable channel when available, i.e., $\varepsilon = 0$, and report in Fig. 2 the normalized average AoI Δ/T against the average duration of a connectivity gap for the three schemes. As expected, the longer the time spent without an available link, the higher the AoI, as the terminal enjoys larger portions of the horizon without the ability to deliver messages. More interestingly, a big gap emerges between the agnostic solution and its competitors. From this standpoint, performing blind transmissions suffers from the risk of missing many updates, sending data in the absence of a receiver. The effect becomes more detrimental when connectivity gaps are longer, as concentrating attempts whenever illuminated by a satellite becomes crucial. The plot also highlights a small difference between the full-knowledge and the memoryless approaches, which vanishes as unconnected times reduce (e.g., for gaps smallee than 5 minutes in the example). In this respect, detecting the presence of a link, combined with the knowledge of the current AoI attained by receiving feedback, suffices to properly schedule transmissions. The possibility to exactly predict future satellite availabilities only marginally improves performance, at the expense of an additional complexity (e.g., by means of location awareness and information on the constellation orbits).

[2]We recall that the average time of coverage and lack thereof are captured in the model as $1/q_{1,0}$ and $1/q_{0,1}$ slots, respectively.

To further delve into this aspect, we report in Fig. 3 the ratio of the average AoI attained with the agnostic benchmark to those achieved by the memoryless (red lines) and full-knowledge (blue lines) approaches. Solid curves show results obtained with $\mathsf{m} = 5$ transmission attempts, whereas dashed lines refer to the case $\mathsf{m} = 11$, i.e., an average transmission frequency of 5 minutes. For $\mathsf{m} = 5$, the trends of Fig. 2 are confirmed, with the agnostic approach exhibiting an average AoI up to $\sim$ 65% and 85% worse than the other solutions. Notably, the gain is maximum when the average duration of the connectivity gaps is of the same order as the transmission frequency (10 minutes). In fact, longer disruptions reduce the potential for a dynamic adaptation of the transmission pattern, as AoI unavoidably increases during link disruptions, whereas for very short interruptions in the satellite illumination a simple random placement of attempts suffices. A similar reasoning applies when $\mathsf{m} = 11$ attempt are available over the time horizon. In this case, the improvement over the agnostic approach is smaller, as the possibility to send more frequently provides a redundancy to link failures that favors the simpler solution. Once again, the highest improvements can be attained by dynamically leveraging knowledge on the link availability for connectivity gaps that are in the order of the transmission frequency.

The impact of operating over a longer time horizon is explored in Fig. 4. Here, we consider again the ratio of the average AoI of the agnostic scheme to that of the other two approaches, and focus on the settings $\mathsf{T} = 60$ minutes, $\mathsf{m} = 5$ (solid lines) and $\mathsf{T} = 120$ minutes, $\mathsf{m} = 11$ (dashed lines). In both cases, the average transmission frequency remains constant (i.e., one transmission on average every 10 minutes), yet the terminal may experiences more instances of satellite

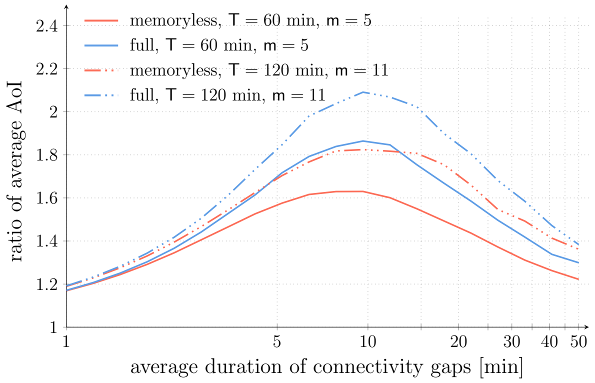

Fig. 4. Ratio of average AoI of the memoryless and the full-aware scheme to that of the agnostic approach, vs average duration of connectivity gaps. Time horizons of 60 minutes with 5 transmissions (solid lines) and of 120 minutes with 11 transmissions (dashed lines) have been considered. No losses in case of satellite visibility.

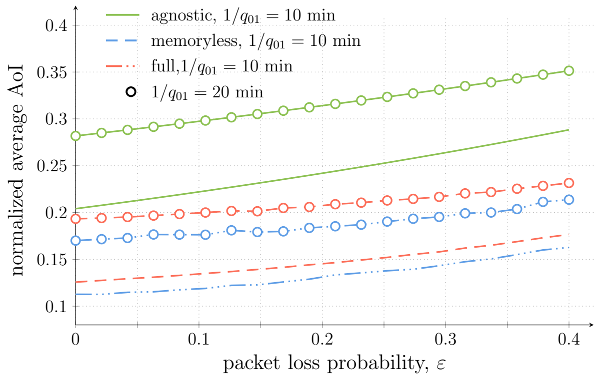

Fig. 6. Normalized average AoI vs error probability. A time horizon of 60 minutes has been considered, with $\mathsf{m} = 5$ transmissions. Lines without markers refer to an average duration of connectivity gaps of 10 minutes, whereas lines with markers to gaps of average duration 20 minutes

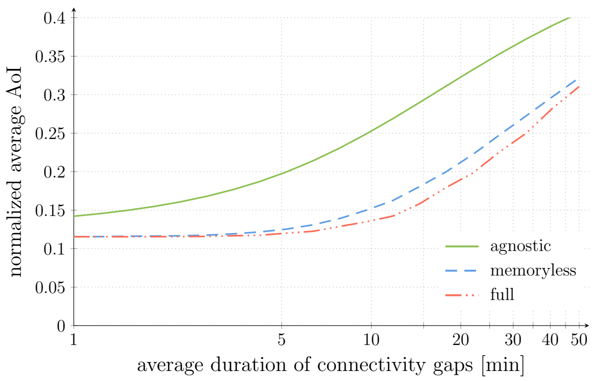

Fig. 5. Normalized average AoI vs average duration of connectivity gaps. A time horizon of 60 minutes has been considered, with 5 transmission opportunities. When in visibility of a satellite, a transmission fails with probability $\varepsilon = 0.25$.

coverage/absence. We can observe that, when operating with larger values of T, the benefit of the dynamic solutions becomes more evident, as, for instance, the AoI of the agnostic scheme is up to more than twice that attained with the fully aware solution. This stems from the smaller effect that very long periods of satellite unavailability play on the average performance. During such times, even full knowledge cannot prevent an AoI growth, and all strategies are affected in a similar manner. As the terminal can tune its behavior over a wider time-span, the potential of adaptive solutions emerges more.

To conclude, we study the performance of the transmission strategies when packets may be lost also in the presence of a satellite connection, due to channel impairments. As a preliminary step, we show in Fig. 5 the average normalized AoI of the policies against the average duration of satellite absence, assuming a packet loss probability of $\varepsilon = 0.25$. The plot is akin to Fig. 2, and the trends are similar. For all solutions the metric degrades due to the higher chance of losing packets. For very short connectivity disruptions, the effect is more pronounced for the agnostic scheme (AoI degradation of 50%) than for the memoryless and full-aware strategies (AoI degradation of $\sim$ 35%). This result highlights an advantage enjoyed by the more advanced strategies that goes beyond the knowledge of the link availability, i.e., the possibility to dynamically adapt the transmission schedule to channel losses leveraging feedback on the outcome of the transmission [15].

The role of packet losses is further tackled in Fig. 6, showing the normalized average AoI of all schemes against ε. Two cases are considered, focusing on a time horizon of 60 minutes with $\mathsf{m} = 5$ transmission opportunities: an average duration of satellite unavailability of 10 minutes (lines without markers) and of 20 minutes (lines with markers). In all situations, the performance degrades for higher loss rates, as well as for longer connectivity gaps. It is interesting to notice that the improvement offered by the dynamic schemes does not vary significantly as the packet loss probability increases, confirming that the critical factor in the setting under study is the tuning of the transmission to the availability of a satellite link. On the other hand, the most advantages are attained for average connectivity gaps of 10 minutes, i.e., comparable to the transmission frequency, in line with the remarks made for Fig. 3. Finally, the full knowledge of schedule also helps in lowering AoI in all cases compared to the memoryless solution, albeit with limited improvements. In this perspective, it is worthwhile noting that the additional knowledge on the satellite position may in turn allow to better tune transmission parameters. We disregard this aspect for the moment, and leave it as interesting part of future study.

VI. Conclusions

We investigated finite horizon scheduling towards AoI minimization over LEO satellite communications, explicitly taking into account the issue of intermittent connectivity, which may cause the link to be unavailable for long sequences of time instants, i.e., when satellite coverage is absent.

We considered different options to tackle this setting, namely, performing the scheduling decisions with full or just instantaneous knowledge of the coverage, or even without it. We found out that the information about link availability is necessary to avoid AoI surges, especially when the average duration of the periods with or without coverage is similar. Conversely, being fully aware of the evolution of the connectivity over the entire time horizon is often not necessary, as the optimal scheduler still obtains good performance even in a memoryless case. Moreover, we showed the impact of other parameters such as the packet loss probability or the total duration of the finite horizon, showing that full awareness of the satellite transits are more useful when erasures are more frequent and/or the transmission schedule covers a relatively short task window.

Future work may include the extensions of the results presented here to combine them with other AoI studies. For example, one can think of exploring hybrid communication strategies that combine satellite links with broader coverage but intermittent connectivity with terrestrial infrastructure that are limited in space instead of time to ensure continuous data flow [26]. Alternatively, the issue of exogenous content unavailability can be combined to channel errors as per [12]. Finally, the state of the satellite links themselves may be considered as a timely information to report, thereby making the issue of intermittent connectivity not only impacting on AoI but being the objective of status update as well.

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