Cyclic Intermittent Connectivity of Industrial Sensors Impacting Information Freshness

Lucrezia Rossi and Leonardo Badia
University of Padova, 35131 Padua, Italy
Email: lucrezia.rossi.2@studenti.unipd.it, leonardo.badia@unipd.it

***Abstract*—In industrial sensors, connectivity is often not persistent but subject to duty cycling for energy or multitasking reasons. The presence of off-periods impacts the freshness of the data reported. We present an analytical investigation of the delivery time achieved by a sensor that alternates connection and disconnection at regular intervals of the same duration. Although information staleness can locally increase due to the lack of connectivity during disconnection intervals, we found that its long-term behavior can be kept under control if these intervals are cyclic and of limited duration, which confirms the validity of freshness-based approaches for timely communication even in industrial scenarios without persistent links.**

***Index Terms*—Industrial Internet of things; Information freshness; Sensor networks; Intermittent connectivity.**

I. Introduction

Cyber-physical systems (CPSs) combine embedded intelligence in smart devices with wireless communication and control to manage the physical world from a networked virtual space [1]. While technological advancements in CPSs increase the potential offer of real-time applications, these often clash with strict requirements related to information freshness, particularly for industry-oriented applications, since the technologies used in the industrial Internet of things (IIoT) do not often scale for what concerns their performance in terms of latency and predictability [2], [3].

In addition, for industrial scenarios, sensor connectivity is critical for real-time monitoring and control, but is often subject to intermittent disruptions. One key reason is that industrial sensors are increasingly multifunctional [4]. Rather than dedicating their entire operational capacity to data transmission, they often perform tasks such as local signal processing, anomaly detection, or energy management [5], [6]. When resources such as processing power or communication bandwidth are reallocated for these secondary tasks, timely delivery of sensor data can be delayed or temporarily paused, leading to connectivity gaps.

Other common reasons for intermittent connectivity in industrial CPSs relate to the difficult and dynamically changing physical conditions typical of their settings. Wireless communication can be obstructed by metallic machinery, moving parts, and structural barriers such as walls and enclosures. These elements can cause signal fading, multi-path interference, or even complete signal blockage [7], [8]. In addition, technologies designed for the IIoT often lack a proper contrast to electromagnetic interference, which can be prevalent in industrial plants due to the presence of electric motors, welding equipment, and high-voltage power lines. Power constraints also play a role in connectivity intermittency. Many industrial sensors are battery-operated or energy-harvesting and often enter low-power or sleep modes to prolong their operational lifespan, at the cost of reduced or suspended connectivity [9]. Power saving strategies, while efficient, inherently reduce the frequency and consistency of communication [10].

For industrial sensors relying on Internet-driven services, network congestion can further exacerbate intermittent connectivity [11]. In environments with many sensors and devices that attempt to access the same communication bottleneck, the operational time windows may be reduced.

All of these phenomena may hinder tasks that are often relevant in industrial sensing, where timely status reporting is leveraged by smart applications for real-time system control. Especially, one may wonder where it is enough to just provide low latencies, or where the information about the system state also needs to be fresh to be useful. In the literature, the performance metric typically used to characterize freshness (or better, staleness) of measured data is the age of information, introduced in the seminal paper [12] and the subject of a fortunate line of research over the last 15 years [13]–[15].

In particular, in this paper we aim to investigate the impact of cyclic loss of connectivity on the sensing and reporting activity of an industrial measurement device. As we concentrate on a single link, information freshness can be directly associated with the termination time of a communication process. However, unlike most studies where channel impairments are sporadic and/or memoryless, we consider a periodic on/off cycle of known duration [16]. We show how the evaluation is actually complicated even in this simple model due to the presence of memory in the system, and we derive the increase in the termination time of data exchange, which directly reflects into information freshness.

Finally, we present numerical investigations from which one can see that, even though a periodic absence of connectivity implies stale information, this can be kept under control if the off period is relatively small compared to the expected transmission time [17]. As a result, we can assess the practicality of duty cycling in industrial settings and see whether it results in reasonably limited degradation of information freshness.

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II. BACKGROUND

The concept of information freshness, originally proposed for vehicular networks [12], has enjoyed widespread popularity in remote sensing scenarios aimed at real-time applications, and in particular industrial applications [2], [13], [14], [18]. For ambient monitoring, surveillance, automation, and any scenario where timely awareness of events is important, fresh information must be used to avoid errors [19].

However, most of the investigations related to this topic consider scenarios in which the communication channel is typically available in the long run. Whenever erasures [20] or collisions [15], [21] are considered, these are episodic events, possibly due to lack of coordination in the transmission, but are not structural to the environment. More recently, some studies have begun to consider the impact of persistent missing connectivity. For example, in [22], the authors consider information freshness from an intermittent link due to satellite flyby. Their scenario considers a scheduled transmission, as opposed to a memoryless one, as we study here, and the duration of satellite missing line of sight is modeled through a Markov chain. Other systems where a lack of connectivity may be present and structural to communications are vehicular communications, delay-tolerant networks, or multi-hop scenarios [17], [23]–[25].

These problems also affect the IIoT, but in this case the inherent lack of connectivity often exhibits typical characteristics of periodicity and limited duration. In fact, industrial systems cannot experience prolonged outages, which would invalidate the entire operability of the system, but at the same time can be subject to energy or multitasking constraints that prevent the link from being persistently available [26].

However, to our knowledge, a scenario with cyclic intermittent connectivity, where a periodic pattern is considered, has never been considered before, possibly due to the difficult tractability of deterministic time intervals. We can also observe that satellite communications also exhibit a similar pattern in that they have predictable off-times corresponding to the loss of line of sight in their orbits, yet the time scale of their cycle is significantly larger. Here, we focus on swift duty cycling due to energy recovery in harvesting devices and/or multitasking among different operations [5].

Thus, for the scenario at hand, all the existing evaluations considering memoryless state changes and/or Markov chains cannot be directly applied. Although they can certainly serve as an inspiration for our analysis, an explicit derivation of the computations is needed.

III. ANALYSIS OF INTERMITTENT TRANSMISSION

We investigate the behavior of an intermittent transmission process, where the transmitter alternates between active and inactive phases. We begin by analyzing the general asymmetric case, in which the durations of the active and inactive phases may differ, and then specialize our results to the symmetric case. Our analysis also accounts for scenarios where the process may start in an inactive phase and considers the effect of the duty cycle of the transmitter's activity. We characterize the finishing time F, i.e., the time required to successfully complete the process, for which we compute the pdf and the expectation $\mathbb{E}[F]$.

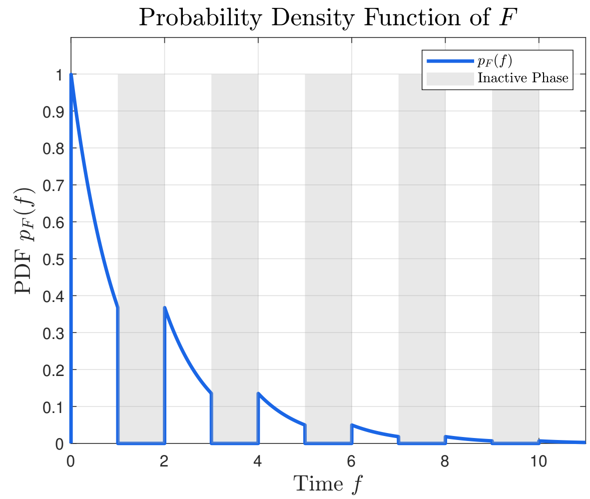

Fig. 1. Intermittent transmission of data to a receiver. The graph shows the pdf $p_F(f)$ of the delivery time F. No transmission occurs during inactive intervals.

A. Intermittent Transmission with Asymmetric Phases

The finishing time F is characterized by a piece-wise pdf as shown in Fig. 1, depending on the transmission phase. This means that the system operates through alternating phases:

- **Active transmission phase** (duration T_1): During this phase, the message can be successfully transmitted according to a memoryless process with rate m
- **Inactive phase** (duration T_2): No transmission

We denote with $T = T_1 + T_2$ the full cycle of an active and inactive phase.

The pdf of the finishing time F can be written as

$$p_F(f)=\begin{cases} me^{-kmT_1}e^{-m(f-kT)}, & f \in [kT, kT+T_1) \\ & \text{(active intervals)} \\ 0, & f \in [kT+T_1, (k+1)T) \\ & \text{(inactive intervals)} \end{cases} \tag{1}$$

We can also compute the expectation $\mathbb{E}[F]$, as

$$\mathbb{E}[F] = \sum_{k=0}^{\infty} \int_{kT}^{kT+T_1} f \cdot p_F(f)\, df = \sum_{k=0}^{\infty} I_k\,, \tag{2}$$

where we consider the contributions I_k from active intervals only. For each k, the term I_k corresponds to the integral:

$$\begin{aligned} I_k &= \int_{kT}^{kT+T_1} f \cdot me^{-m(f-kT)}e^{-mkT_1}\, df \\ &= \left(\frac{1-(1+mT_1)e^{-mT_1}}{m} + kT(1-e^{-mT_1})\right)e^{-mkT_1}\,. \end{aligned} \tag{3}$$

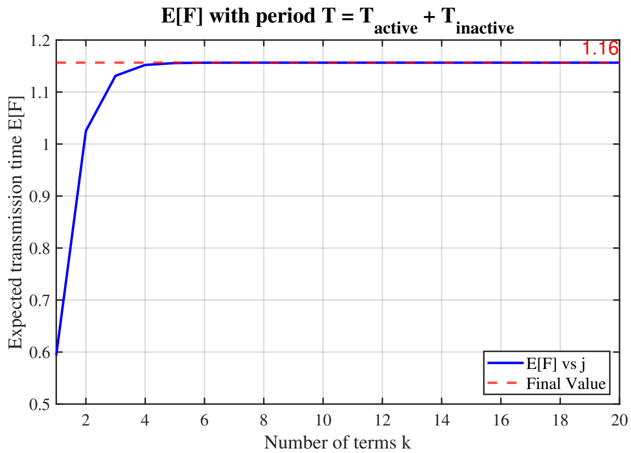

Fig. 2. Expected transmission time with $m = 1$, $T_1 = 2$, and $T_2 = 1$. Series-based computation and the analytical expression are reported as solid blue and red dashed lines, respectively.

Thus, the final expected value is given by the infinite summation:

$$\mathbb{E}[F] = \sum_{k=0}^{\infty} e^{-mkT_1} \left(\frac{1-(1+mT_1)e^{-mT_1}}{m} + kT(1-e^{-mT_1}) \right) \tag{4}$$

In Fig. 2 we can see how $\mathbb{E}[F]$ changes as a function of k. The transmission ends after approximately 4 steps, with an expected value of about 1.16. The final result of the analysis is compared with the approximation through a finite summation.

To determine the final value of $\mathbb{E}[F]$, we analyze the infinite sum and rewrite it as:

$$\begin{aligned} \mathbb{E}[F] &= \sum_{k=0}^{\infty} e^{-mkT_1} \cdot \frac{1-(1+mT_1)e^{-mT_1}}{m} \\ &\quad + \sum_{k=0}^{\infty} e^{-mkT_1} \cdot kT(1-e^{-mT_1}) \,. \end{aligned} \tag{5}$$

After defining auxiliary variables:

$$X = \frac{1-(1+mT_1)e^{-mT_1}}{m}, \quad Y = T(1-e^{-mT_1})$$

we get:

$$\begin{aligned} \mathbb{E}[F] &= X \sum_{k=0}^{\infty} e^{-mkT_1} + Y \sum_{k=0}^{\infty} k e^{-mkT_1} \\ &= \frac{X}{1-e^{-mT_1}} + \frac{Y \cdot e^{-mT_1}}{(1-e^{-mT_1})^2} \end{aligned}$$

After some simplifications, we obtain the final expression

$$\begin{aligned} \mathbb{E}[F] &= \frac{1-(1+mT_1)e^{-mT_1}}{m(1-e^{-mT_1})} + \frac{Te^{-mT_1}}{1-e^{-mT_1}} \\ &= \frac{1-(1-mT_2)e^{-mT_1}}{m(1-e^{-mT_1})} \end{aligned} \tag{6}$$

Figs. 3 and 4 illustrate how the expected transmission time $\mathbb{E}[F]$ varies as a function of the system parameters T_1 and T_2, respectively. These visualizations are obtained by evaluating the closed-form expression in (6) for different configurations.

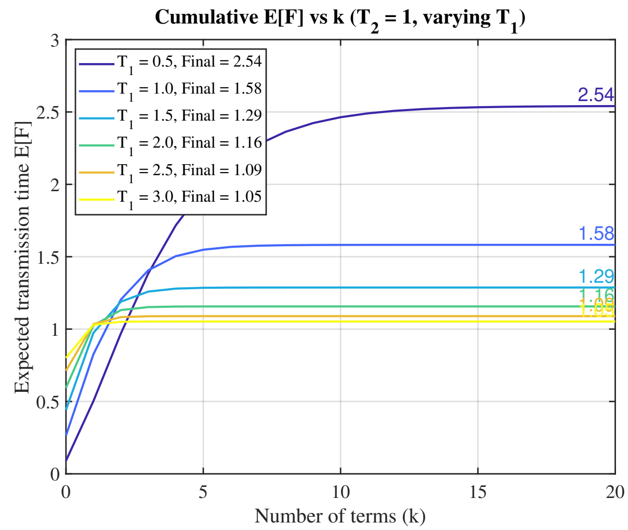

Fig. 3. Expected transmission time for $m = 1$, $T_2 = 1$, and different T_1 values.

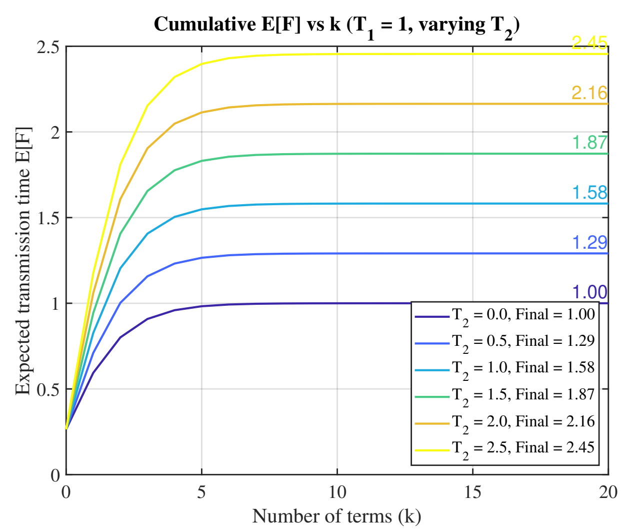

Fig. 4. Expected transmission time for $m = 1$, $T_1 = 1$, and different T_2 values.

The symmetric transmission scenario, where $T_1 = T_2 = T$, yields several simplifications and the expected transmission time reduces to the closed-form expression:

$$\mathbb{E}[F] = \frac{1-(1-mT)e^{-mT}}{m(1-e^{-mT})} \,. \tag{7}$$

Fig. 6 shows how the expected transmission time varies with the transmission rate m in this symmetric configuration. The inverse relationship shows how higher transmission rates lead to faster completion times. Similarly, Fig. 7 reveals the impact of phase duration T on system performance.

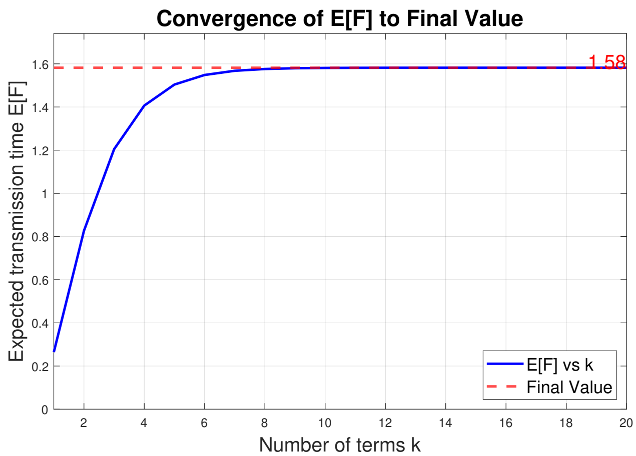

Fig. 5. Evaluation of $\mathbb{E}[F]$ for $m = 1$ and $T = 1$. The expected transmission time stabilizes around 1.58. Series-based computation and the analytical expression are reported as solid blue and red dashed lines, respectively.

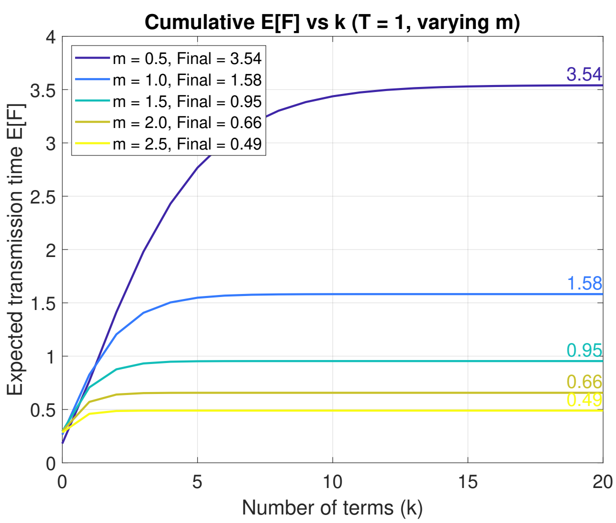

Fig. 6. $\mathbb{E}[F]$ vs. transmission rate m for fixed T. Higher m accelerates transmission.

The numerical evaluation in Fig. 5 confirms these predictions, showing the expected transmission time converging to approximately 1.58 for the baseline symmetric case with $m = 1$ and $T = 1$.

We can also remark that the limit for $T_2 \to 0$ obtains $\mathbb{E}[F] = \frac{1}{m}$, i.e., we converge to the case of uninterrupted transmission with exponential distribution.

We can also analyze a system that starts in an inactive phase and stays inactive for a time T_2 during all odd intervals, all followed by a duration of T_1 for the active phase in the even intervals. Since transmissions are only allowed during active intervals, the pdf of F becomes

$$p_F(f) = \begin{cases} 0, & f \in [kT, kT+T_2) \\ me^{-kmT_1 - m(f-(kT+T_2))}, & f \in [kT+T_2, (k+1)T) \end{cases}$$

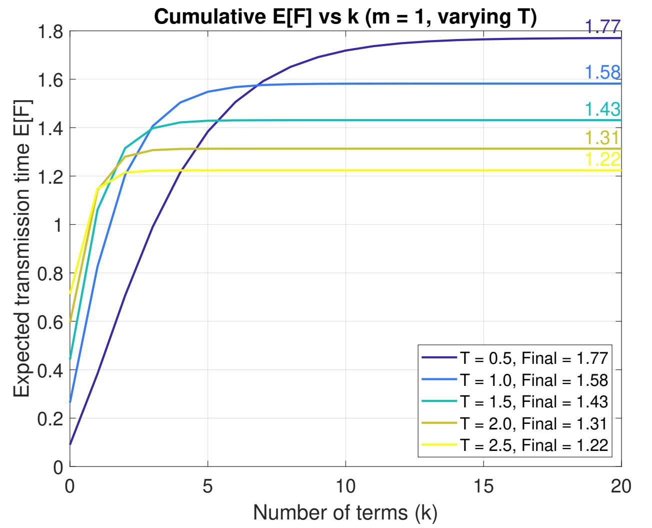

Fig. 7. $\mathbb{E}[F]$ vs. interval duration T for fixed m. Longer T reduces expected delay.

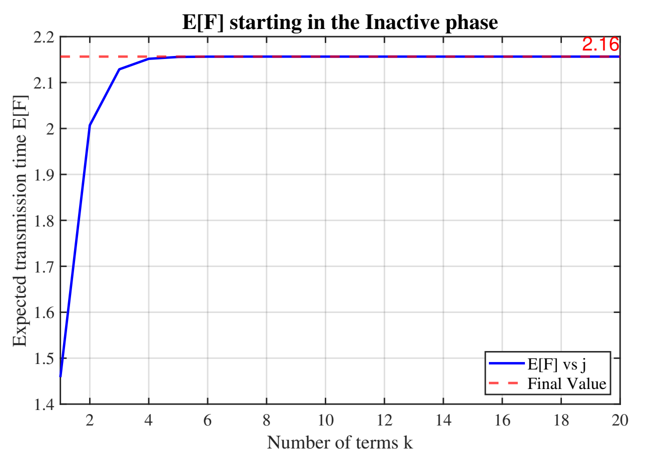

Fig. 8. Expected completion time for a system starting in the inactive phase, with parameters $m = 1$, $T_1 = 2$, and $T_2 = 1$. Series-based computation and the analytical expression are reported as solid blue and red dashed lines, respectively.

and repeating the analysis of (5) one gets

$$\mathbb{E}[F] = \frac{1 + mT_2 - e^{-mT_1}}{m(1 - e^{-mT_1})}. \tag{8}$$

Compared to the scenario where the system starts in the active state, an initial inactive phase introduces an additional delay T_2. Specifically:

$$\mathbb{E}[F]_{\text{inactive}} = \mathbb{E}[F]_{\text{active}} + T_2. \tag{9}$$

Still, when $T_2 \to 0$, the expected delay reduces to that of a memoryless exponential distribution $\mathbb{E}[F] = \frac{1}{m}$, and for the symmetric case where $T_1 = T_2 = T$, we obtain:

$$\mathbb{E}[F] = \frac{1 + mT - e^{-mT}}{m(1 - e^{-mT})}. \tag{10}$$

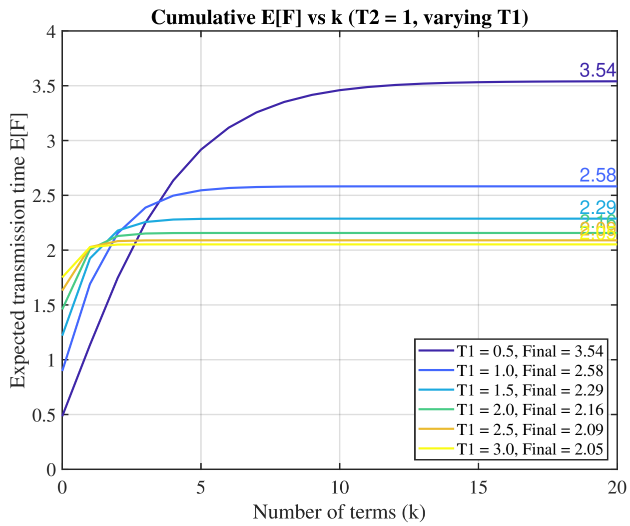

Fig. 9. Expected transmission time as a function of T_1, with $m = 1$ and $T_2 = 1$.

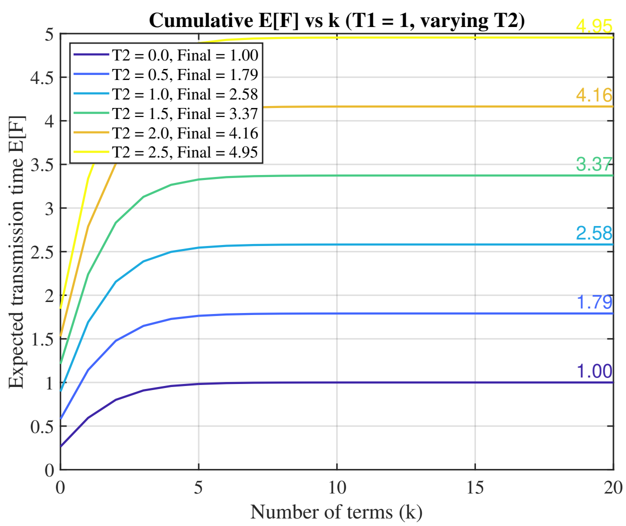

Fig. 10. Expected transmission time as a function of T_2, with $m = 1$ and $T_1 = 1$.

Figs. 9 and 10 show how the expected delay evolves with respect to T_1 and T_2, respectively.

B. Delay Expressions via Duty-Cycle Representation

We can also reformulate the analysis in terms of the *duty cycle* $D \in (0, 1)$, representing the fraction of time the system remains active, i.e.,

$$D = \frac{T_1}{T} = \frac{T_1}{T_1 + T_2} \tag{11}$$

The following expressions generalize the expected delay $\mathbb{E}[F]$ to duty-cycled systems, assuming an exponential transmission success process with instantaneous rate m.

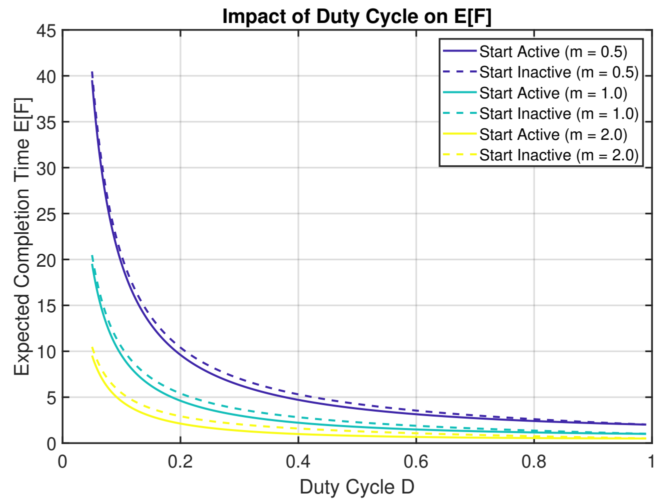

Fig. 11. Expected time $\mathbb{E}[F]$ versus duty cycle D, for various values of the success rate m. Results are shown for both initial conditions: system starting in ON (solid lines) and OFF (dashed lines) phases.

If the system starts in an active phase, transmission is immediately possible. The expected time to the first successful attempt is:

$$\begin{aligned}\mathbb{E}[F] &= \frac{1-(1-mT_2)\,e^{-mT_1}}{m\,(1-e^{-mT_1})} \\ &= \frac{1-(1-m(1-D)T)\,e^{-mDT}}{m\,(1-e^{-mDT})}.\end{aligned} \tag{12}$$

Conversely, if the odd intervals correspond to inactive phases, the system must wait for an active phase to being, first. The expected completion time becomes:

$$\begin{aligned}\mathbb{E}[F] &= \frac{1+mT_2-(1+mT)e^{-mT_1}}{m\,(1-e^{-mT_1})} \\ &= \frac{1+m(1-D)T-(1+mT)e^{-mDT}}{m\,(1-e^{-mDT})}.\end{aligned} \tag{13}$$

These expressions explicitly characterize how transmission delay depends on the duty cycle D, the cycle duration T, and the transmission rate m.

To illustrate the impact of the duty cycle on transmission delay, Fig. 11 shows numerical evaluations of $\mathbb{E}[F]$ for varying values of D, under both initial conditions (the first interval being an active or an inactive phase).

IV. Conclusions

Motivated by the cyclic patterns of connectivity (or lack thereof) in industrial sensors, we presented an analysis of information freshness for a periodic intermittent connection. We derived the expected time for the reception of updates for a sensor that alternates equally sized periods of connection and disconnection.

We also evaluated the parametric impact of the cycle duration and transmission rate. Our main conclusion is that cyclic unavailability of status update reporting increases information staleness but, if limited to short periods, does not totally hinder the implementability of real-time applications in the IIoT. The proposed analysis may indeed serve as a guideline about the expected impact on industrial scenarios and how to properly design the cyclic scheduling of sensor activities.

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