Building Delay-Tolerant Digital Twins for Cislunar Operations using Age of Synchronization

Faheem Dustin Quazi*, Angeles Vazquez-Castro†, Dusit Niyato‡, Shiwen Mao§, and Zhu Han*
*Electrical and Computer Engineering Department, University of Houston, Houston, TX, USA
†Centre for Space Research (IEEC-UAB), Universitat Autònoma de Barcelona, Barcelona, Spain
‡School of Computer Science and Engineering, Nanyang Technological University, Singapore
§Department of Electrical and Computer Engineering, Auburn University, Auburn, AL, USA

***Abstract*—Digital Twins (DTs) provide a framework for building virtual representations of physically co-located or remote assets, and can be used by an end-user for command, control, and observation. These DT systems normally rely on high bit rate availability and minimal communication delay to accomplish their tasks. However, providing such resources may be challenging depending on the location of the asset, e.g., in a remote environment such as the lunar surface. In such cases, the ability to obtain information from the asset to maintain an up-to-date DT will be limited by the available data rate or by the propagation delay. This paper provides a novel scheduling paradigm for a remote asset to "synchronize" state with its DT over a tightly constrained network by combining the Age of Synchronization (AoS) metric with the Multi-Armed Bandit (MAB) mathematical decision framework. This provides a general weighted solution for scheduling data to minimize the Age of Information (AoI). Preliminary simulations were developed to validate this MAB-based AoS-Driven weighted scheduler against other scheduling paradigms. Experimental results show the MAB-based scheduler trades off priorities and AoS to create a delay-tolerant DT.**

***Index Terms*—scheduling, digital twins, age of synchronization, age of information, multi-armed bandit**

I. Introduction

Digital Twins (DTs) are becoming an increasingly popular way to represent physical entities in the virtual world. The DT becomes an intermediary for controlling physical assets, through which integration to internet-connected assets or large-scale Metaverses become simplified, and enables a method for DTs to interact with each other. However, the complexity of a DT can result in high computation, and communication bandwidth requirements to maintain an accurate and up-to-date state. For example, a light fixture may be simple to model as a DT, but the DT of a vehicle or robot will have magnitudes higher data and compute requirements for control and state manipulation. For a DT, maintaining a high level of synchronization ensures its usefulness in decision making processes.

DTs have been proposed for usage in a wide variety of industries, such as manufacturing [7] and healthcare [6]. Many existing works are applicable for highly populated locations on the Earth, where edge computing resources, high bandwidth, and low delay are available when attempting to synchronize a physical asset with its respective DT. Works such as [11] and [12] assume that sufficient resources exist and are readily available in order to support future advanced DT initiatives. However, such assumptions cannot be made in remote areas, hazardous locations, or environments beyond Earth such as the Lunar surface, where communication systems will be highly constrained, or a large physical delay is present due to the distance or method of communication. There are many works, such as [8] and [9], which approach the practical problem of human interaction with a physical entity through a digital twin, but these works do not consider the usage of their proposed technologies within a constrained communication environment. In the space realm, Ref [10] aims to reduce delay and utilize DTs for satellite route estimation, however it does not consider the tight constraint of bandwidth/bit-rate. Similarly, communication-specific works such as [13] directly constrain their problem space, but bandwidth/bit-rate and delay are generally not considered as part of their formulation. In such an environment, how can a remote DT controller reliably manipulate a DT to interact with a physical asset, or make decisions on the data it provides, when that asset is located in a tightly constrained environment? This work aims to fill the gaps in the aforementioned works by establishing the environment of the problem space with delay and bandwidth/bit-rate as constraints, specifically a cislunar communication system.

The scenario is as follows: There exists a physical asset (such as a robot) which is located on the moon. A remote user on the Earth intends to monitor the state of the asset using a DT, in order to make pseudo-real-time decisions related to the asset. This is visualized in Fig. 1. For the DT to represent the physical asset, it needs to obtain information across the vast physical distance, and over a highly constrained space network, equating to a high delay, and low bit-rate availability communication environment. Consequently, this becomes a scheduling and allocation problem. The objective is to send updates from the physical asset such that the state difference between the DT and the physical asset is minimized.

This work proposes to utilize the concept of Age of Synchronization (AoS) [2] and Multi-Armed Bandit (MAB) decision framework to create a weighted synchronization paradigm to solve the scheduling problem, where weights associated with information are used to determine what need to be sent. AoS provides a parameter which defines the Age of Information (AoI) as a function of update interval, and is

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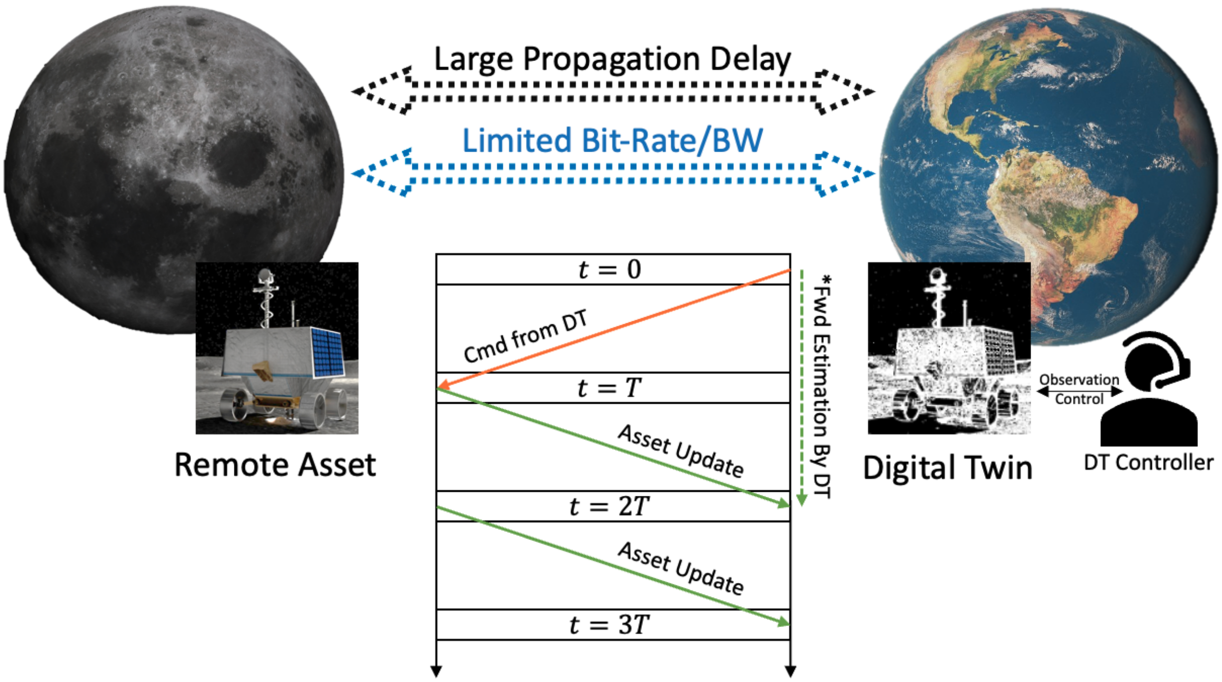

Fig. 1. Cislunar scenario showing an remote operator interacting with a DT of the remote asset on the lunar surface with a visualization of environmental constraints and the scheduling problem.

the primary criteria for synchronization. The MAB framework provides a function which can encapsulate priority, environmental constraints, and AoS, to make weighted decisions about the information which needs to be transmitted. Combined together, this system takes into account the available bit-rate, present delay, and priorities of the different data samples that need to be sent, in order to select items which will minimize the overall Age of Information (AoI) at the DT.

This paper is structured as follows: Section II introduces the system and working processes of the DT. Section III dives into the problem structure and details the scheduling methodology that will be used to address the aforementioned challenge. Section IV details the experiment setup and the general steps taken to compare the performance of the proposed algorithm against other methods, and discusses the experimental results. Finally, Section V concludes this paper.

II. Applying DTs to Cislunar Operations

As briefly described to in the previous section and visualized in Figure 1, the objective of the system is to synchronize the state of a physical asset on the lunar surface with a DT on Earth for use by a DT controller. In this cislunar scenario, the term “state” is used to represent the overall configuration of the physical asset on the Moon, and this state contains “items”, which are variables or data samples. In the context of a robot, the state includes items such as “position”, “speed”, “LIDAR”, “camera feed” - anything that is needed to accurately build and update the DT located on Earth, which the remote user will be utilizing for monitoring and decision-making.

For simplicity, the system will only synchronize data in one direction - from the physical asset to the DT. In the cislunar scenario, this enables the user to monitor the asset in near-real-time for informed decision-making. Therefore, the aim of this work is to optimize the scheduling of data being transmitted from the physical asset to the DT. It is assumed that this method can also be utilized in the reverse direction - DT to physical asset - for the purposes of command and control.

In addition, time is considered in discrete intervals (in the cislunar scenario, this represents a deterministic communication window), while relativistic effects are not considered. This enables the consideration of bandwidth and bit-rate allocation to be done in terms of a data size, where a finite amount of data is available to transmit per time-step.

As shown in Fig. 1, the DT exists on Earth, and is the primary interface the remote user (DT Controller) uses to interact with the physical asset. In an alternate but related scenario, the DT controller can also be an AI platform or ML-based system for autonomous control. Commands are sent by the DT controller to the robot, subject to the physical delay. Once the physical asset receives the command, it beings execution and transmits updates to the DT, subject to the physical delay and bit-rate/bandwidth limitations.

For this work, the focus is on the scheduled transmission of events and updates from the physical asset. In a future work, the DT will attempt to provide forward estimation of the command, and update the estimation based on the received results.

III. Delay-Tolerant Synchronization Problem Formulation

A. Quantifying States with Physical Constraints

At discrete time slot t, let $\Psi_R(t)$ be the state of the remote asset (robot) on the moon, $\Psi_D(t)$ be the current state of the DT on the Earth, and $\Psi_\Delta(t)$ be the state changes sent at t. "State change" is the set of items $\psi_i \in \Psi_\Delta(t)$ which are being sent, based on the updates generated by the physical asset. Each item ψ_i contains the following metadata, which is established as a result of the contents of each item:

$$\psi_i = \{T_{\psi_i}, P_{\psi_i}, S_{\psi_i}\} \; \forall \; \psi_i \in \Psi_{R,D,\Delta}(t). \tag{1}$$

- T_{ψ_i}: The time that the next update will be generated (Generation Time [2]), in seconds. This parameter is described in more detail in Section III-B.
- P_{ψ_i}: Time criticality of the item, a unit less value (higher value means higher priority).
- S_{ψ_i}: The bit-rate required to transmit the item, in Mbps (Translates to data size with duration of time slice).

The goal is to set $\Psi_\Delta(t)$ such that the difference in state between $\Psi_R(t)$ and $\Psi_D(t)$ is minimized *over time*. In the scenario, the physical distance between the twin on Earth and the remote asset, D_p, is assumed to be sufficiently large such that the propagation delay, $t_d = \frac{D_p}{c}$, is nontrivial. Incorporating these constraints, the following general expression can be established:

$$\Psi_D(t) = \Psi_R(t - t_d) + \Psi_\Delta(t). \tag{2}$$

This indicates that the state of the DT at time t is generally the state of the physical asset from t_d seconds in the past, with the state change observed at the current time overriding corresponding values (depicted as $+$). However, given the nature of long distance space communication, simply establishing expression (2) does not encompass the full problem space: Bandwidth is highly limited and continually varying depending on lunar and satellite positions, time-slice availability, etc. Therefore, it may not be possible to populate Ψ_Δ with the complete state difference between the physical asset and the DT.

To better quantify (2) under such constraints, let W_a be the amount of data which can be sent per-time-step as a function of the available bit-rate, and follow a random uniform distribution, namely $W_a = \mathcal{U}(0^+, W_{max})$. Since time is considered in discrete steps, the bit-rate that is available is simplified to an amount of data rather than a rate. This means that the size of the state change being sent is limited as follows:

$$\sum_{\psi_i \in \Psi_\Delta(t)} S_{\psi_i} \leq W_a. \tag{3}$$

In addition, direct transmission to the Earth may not be possible due to line-of- sight (LOS) obstructions, and so a number of relays may be incorporated to handle these gaps [1]; let t_r be the delay as a result of R hops in the communication path, which follows a random uniform distribution, namely $t_r = \mathcal{U}(0^+, t_d)$. Therefore, the instantaneous time delay T subject to the aforementioned constraints can be expressed as:

$$T = t_d + R \cdot t_r. \tag{4}$$

Finally, the following expression expands (2), and reestablishes $\Psi_D(t)$ to factor in the delay and bandwidth constraints:

$$\Psi_D(t) = \Psi_R(0) + \sum_{i=0}^{t} \Psi_\Delta(t_i). \tag{5}$$

The summation term in (5) represents the necessity for multiple update cycles, because the entire set of changes to be synchronized between Ψ_R and Ψ_D may not fit in a single transmission cycle as limited by W_a, and the difference may grow larger rather than shrink during each time-step. If full synchronization is reached (namely, $\Psi_R(t) = \Psi_D(t)$), due to a lack of changes across multiple time-steps, the update cycle can begin anew, as it was when $t = 0$ (i.e., reset time frame of reference).

B. Synchronization Problem

To facilitate efficient use of each time-step transmission, the concept of AoS [2] and the MAB decision framework are employed to establish a scheduling paradigm. AoS is formulated based on the Age of Information (AoI) concept [3] by associating a "Generation Time" parameter to each piece of information to be transferred, which describes when the next update should be received [2]. If time exceeds this value, then that information is considered out of sync, and the AoS value will increase with time until a new update is received. This implies that in a high-delay environment, an update for an item within the state of the system can be received which has a generation time in the past, leading to an AoS value which is still greater than zero. The MAB decision framework employs the concept of "exploitation" and "exploration" to determine if an item should be considered [4]. The goal of synchronization in the context of this problem is to minimize the mean AoI at the DT, using the AoS metric and MAB decision framework, such that the twin is up to date for decision making or monitoring of the physical asset.

For example, for the robot in the aforementioned scenario, it may be desired to have the "position" variable which is updated every time-step (1 second) and considered a high-priority item. Then, when an update is generated for that item, set $T_{\psi_i} = t + 1[s]$ and $P_{\psi_i} >> 1$; Additionally, the position of some object is typically represented by a set of X and Y coordinates, with a Z coordinate for elevation if needed, so the size of the item would be the total size of the three values: if they are each signed 32-bit integers, then $S_{\psi_i} = 12[B]/1[s] = 12[Bps]$.

With these criteria in mind, the AoS for an item ψ at time t is quantified as follows:

$$\text{AoS}(\psi_i, t) = (t - T_{\psi_i})_+, \tag{6}$$

Algorithm 1: MAB-AOS sync (as tested)

$t \leftarrow 0$;
$t_s \leftarrow$ update frequency (time step);
$T \leftarrow$ aggregate delay (e.g. environmental factors);
$MAB(\Psi)$: Return sync weights of Ψ elements via (7);
Initial Condition $\Psi_R(t) = \Psi_D(t)$ @ $t = 0$;
Suppose Updates generated: $\Psi_R \neq \Psi_D$ @ $t \geq t_{step}$;
while $\Psi_R(t) \neq \Psi_D(t)$ **do**
    $\Psi_C \leftarrow$ unsent updates in $\Psi_R(t)$ since $t - t_{step}$;
    $MAB_\Psi \leftarrow MAB(\Psi_C)$;
    $\Psi_\Delta \leftarrow$ items in Ψ_C sorted descending by MAB_Ψ;
    Truncate Ψ_Δ until $sizeof(\Psi_\Delta) < W_a(t)$;
    $\Psi_\Delta(t) \leftarrow \Psi_\Delta$: Transmit to DT;
    Update TX Count of Ψ_Δ items in $\Psi_R(t)$;
    Collect all computed Ψ_Δ since $t = 0$;
    Recompute $\Psi_D(t)$ via (5);
    $t \leftarrow t + t_{step}$; /* Increment time */
end

where $(\cdot)_+ = \max\{0, \cdot\}$ [2]. Note that AoS alone cannot fully encapsulate the problem space, as it does not have any method to factor in priority or constrain itself to bit-rate/bandwidth availability. Therefore, a system is needed to utilize AoS as a metric alongside the additional criteria of the problem. In this case, the upper confidence bound MAB mathematical decision framework is chosen to solve this problem.

C. MAB-based Formulation

Let $w_i(\psi_i, t)$ be the weight of any item $\psi_i \in \Psi_R(t)$ that can be synchronized under our delay-tolerant synchronization problem. This weight is defined as a sum of the so-called exploration and exploitation factors to determine if, in an overall sense, the item is worth transmitting:

$$\begin{aligned} w_i(\psi_i, t) &= Q_t(\psi_i) + c\sqrt{\frac{ln(t)}{N_t(\psi_i, t)}}, \\ Q_t(\psi_i) &= \text{AoS}(\psi_i, t), \\ c &= P_{\psi_i}, \\ N_t(\psi_i, t) &= \text{\# of times } \psi_i \text{ sent since } t = 0. \end{aligned} \tag{7}$$

In (7), Q_t uses AoS as the determining factor for "exploitation," the priority of an individual item scales the "exploration" factor, and N_t is the number of times the item in question has been sent since $t = 0$, which is used to further encourage less-transmitted items to be explored more over time.

With the MAB set up, the following formulation for $\Psi_\Delta(t)$ can be established to minimize the MAB weight of items within $\Psi_R(t)$:

$$\begin{aligned} \Psi_\Delta(t) = \underset{\psi_i \in \Psi_R(t), t}{\text{argmin}} \quad & \sum (w_i(\psi_i, t)) \\ s.t. \quad & \sum_{\psi_i} S_{\psi_i} \leq W_a. \end{aligned} \tag{8}$$

TABLE I
GLOBAL SIMULATION PARAMETERS

Parameter	Description	Value (min:step:max)
Time (t)	Execution Time and Resolution	0:0.1:60[s]
Delay (T)	Instantaneous Delay per time-step	2[s]
Bit-rate (W_a)	Used to establish data size [5]	4:4:20[Mbps]
Item Count	Size of $\Psi_{R,D}$	5:1:15

TABLE II
HAND-PICKED ITEM SETTING

Name	P_ψ	S_ψ [Mbps]	Generation Time t_s = One Time-Step
Photo	3	6	$10t_s$
Video	8	12	$2t_s$
Location	10	1	t_s
Stats	5	3	$5t_s$
LIDAR	9	12	$2t_s$

Functionally, this means the algorithm should iteratively (over time) select items with higher weights such that the overall weight of the system is reduced, and the size of items being sent is maximized for the bit-rate which is available. This acts as a method to schedule the data which is transmitted at each time step, ideally in a way which ensures the DT on the Earth is a stable (but delayed) representation of the remote asset on the Moon, and ultimately results in a lower mean AoI over time. A simplified version of this algorithm is described in Algorithm 1.

IV. EXPERIMENT

To analyze the proposed solution, a simulation model was developed based on the cislunar scenario[1]. A set of items will be generated for the physical asset state, which contains the parameters defined in (1), alongside additional simulation-specific content. Initially, the Moon state and the Earth state are synchronized (equal). Based on the configuration defined in Table I, the simulation executes and simulates a transmission system with a delay: During each time step, the scheduling algorithms under test will queue up the items it wants to transmit at that step, limited by the available bandwidth. Then, after the specified delay time generated at that time step has elapsed, the state of the items queued is applied to the DT (Earth) state. This repeats for the duration of the simulation.

This simulation is performed with the following algorithms:

- $MAB(AoS)$**:** The scheduling paradigm as defined in this work (Algorithm 1).
- $Max(AoI)$**:** Schedule items based on AoI value (descending sort).
- $First\text{−}Update$**:** Schedule items only if/when they update (first come first serve).

[1]See github.com/FaheemQuazi/DelayTwins-ICC2024WS. Experiment results generated in MATLAB notebooks

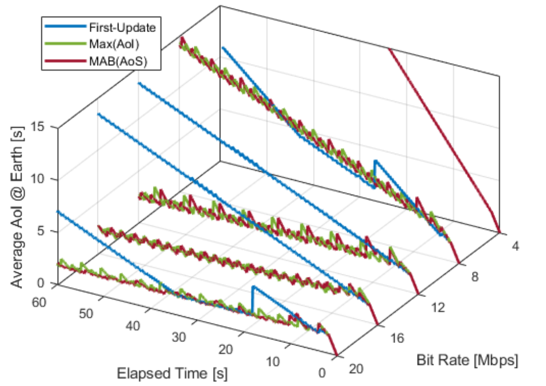

Fig. 2. Average AoI as a function of elapsed time and increasing bit-rate for three simulated algorithms.

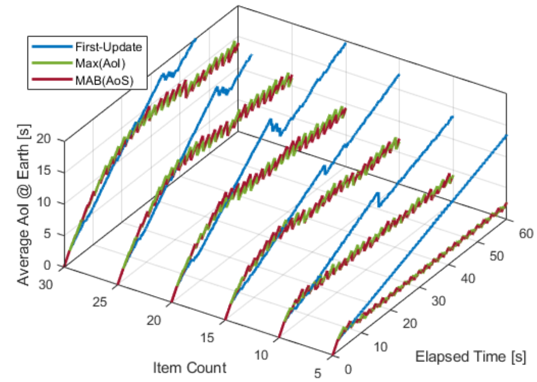

Fig. 3. Average AoI as a function of elapsed time and increasing item count for the three simulated algorithms (Bit-rate fixed at 16Mbps).

There are a few caveats to the simulation. First, if an item update occurs in between time steps, it is handled at the next step - This can be mitigated by increasing the resolution of the time steps, and separating transmission steps from update steps, but the results were not significantly different, so the chosen 0.1 sec. resolution was maintained. Second, five items were defined (Table II) based on the assumption that the remote asset is a robot - this was selected to match the cislunar scenario defined in Section II, however these parameters could be set to reflect any particular asset or task. Additional items are randomly generated to represent additional data that might be needed for a task, and follow the following criteria:

- P_ψ: $\mathcal{U}(0, 10]$;
- S_ψ: $\mathcal{U}(0, \text{Max Bit-Rate} \times 90\%]$;
- Generation Time: $\mathcal{U}[\text{TimeStep}, \text{TimeStep} \times 10]$.

Here "TimeStep" is the resolution of the simulation (the step value for t in Table I). Finally, the simulation generally does not take into account streaming transmissions, and transmission selection was executed in a round-robin fashion after the algorithms sorted the items; this was done to simplify the execution, whereas a more realistic simulation would show the total size of items being sent across multiple-time steps and with efficient data packing. In this way, items can be treated as "boxes" that can be loaded onto a "pallet" to be transmitted, independent of the efficiency of the data packing or transmission mechanism.

The first test executed analyzes the average AoI given a fixed number of items (listed in Table II), and increasing bit-rate constraint. As shown in Fig. 2, the $Max(AoI)$ and $MAB(AoS)$ algorithms were able to maintain a "stable" (non-increasing, minimum fluctuation) average AoI consistent with the physical delay over the course of the test. The $First-Update$ algorithm is "unstable" with an increasing AoI value. In all three cases, when the available bit-rate is reduced below the largest-sized item in the set (12Mb as specified in Table II), as expected, all three algorithms are unable to maintain a stable AoI value.

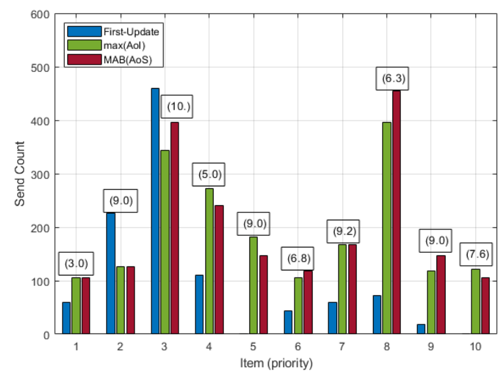

Fig. 4. Item transmission frequency (Bit-rate fixed at 16Mbps).

The second test executed was designed to analyze the Average AoI given a fixed bit-rate, but increasing number of items. A maximum bit rate of 16Mbps was selected, and the item count range begins from the five items in Table II, and increases up to 30 randomly generated items. As the results in Fig. 3 show, the increase in the number of items slowly increases the value where the AoI stabilizes for both the $Max(AoI)$ and $MAB(AoS)$ algorithms, and there is no improvement in the stability of the $First-Update$ algorithm.

The final test executed was designed to analyze the transmission *rate* of all the items in the set. For this test, two additional counters were added to each item: One to track the number of updates generated over the course of the test, and one to track the number of times the item was updated on Earth. A maximum bit rate of 16 Mbps was chosen and fixed, and an item count of 10 was chosen (Table II with five additional random items). Given the values in Table I, a maximum transmission count of 600 is expected.

As the results in Fig. 4 show, the $MAB(AoS)$ algorithm sent 3.5% more updates overall compared to the $Max(AoI)$ algorithm (2009 versus 1940, respectively), while the $First-Update$ algorithm fails to send some items with higher index values or larger size. The $MAB(AoS)$ algorithm sent some higher priority items less frequently than $Max(AoI)$, but this is traded off with the overall increase in updates, which demonstrates that $Max(AoS)$ ensures the DT as a whole may be a closer representation of the physical asset than with the $Max(AoI)$ algorithm. This shows potential for the $MAB(AoS)$ algorithm, and in future work, the algorithm will be iterated on to factor in other parameters to further improve the performance.

V. Conclusion

The $MAB(AoS)$ method as proposed provides a scheduling algorithm which factors in the priority of the item while maintaining a stable and low AoI Value. In all three tests performed, the proposed scheduling algorithm performed better than the alternative scheduling methods, quantified by having a minimized AoI against the scenario constraints, and providing the largest number of updates transmitted over time. In conclusion, this work provided a starting point for more efficient scheduling and data transmissions for cislunar assets to be replicated as DTs on the Earth, and proposed a novel solution for scheduling data transmissions given the distance, delay, and communication constraints.

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