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On the Scalability of Battery-Aware Contact Plan Design for LEO Satellite Constellations

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Summary

Size and weight limitations of Low-Earth Orbit (LEO) small-satellites make their operation rest on a fine balance between solar power infeed and power demands of supporting communication technologies, buffered by on-board battery storage. As a result, the problem of planning battery-powered inter-satellite communication is a very difficult one. Nevertheless, there is a growing trend towards constellations and mega-constellations that are to be managed using sophisticated software support. In earlier work, we have discussed how the effective construction of contact plans in delay tolerant satellite networking can profit from a refined model of the on-board battery behavior. This paper presents a profound study of the scalability of the approach, and discusses how to tailor it to the needs arising in the management of mega-constellations, together with a variety of improvements to the base approach. Results show that efficient mega-constellation operations are compromised, encouraging further research on the area.

KEYWORDS:
Satellite Constellations, Contact Plan Design, Delay-Tolerant Networks, Battery-Awareness

1 | INTRODUCTION

Large-scale Low-Earth Orbit (LEO) satellite constellations are in the spot. Big players such as SpaceX, Amazon, Boeing and OneWeb are part of a list comprising more than 17,000 satellites to be launched before 2027[1]. The purpose of these constellations is to provide world-wide connectivity and continuous awareness of our planet surface via real-time imaging[2]. Achieving such an ambitious objective will depend on the successful interaction between the space industry and state-of-the-art research on informatics. Among others, in-orbit satellites such as the GomX–4A and GomX–4B satellites from GomSpace are pioneering efficient space-terrestrial communication techniques based on extensive support from scheduling computation on ground[3,4,5,6].

The need for computation mainly arises from optimizing the utilization of energy resources enabling power-demanding tasks. Communications transponders, including Ground to Satellite Links (GSL) and Inter-Satellite Links (ISL)[7], are among the most demanding subsystems. Their power consumption cannot be sustained when operated continuously. Furthermore, even if an end-to-end path is present and enough electric energy is available for real-time access, ISLs can become a data rate bottleneck. In this context, Delay Tolerant Networking (DTN) has been leveraged in order to render a better utilization of communication opportunities by means of storing, carrying and forwarding data[8]. The DTN approach is particularly valuable for providing connectivity to (*i*) partially-deployed mega-constellations which cannot leverage traditional Internet routing before the complete topology is connected in orbit, and (*ii*) sparse constellations for Earth observation and high-latency data relay systems (i.e., IoT[9]). To fully exploit DTN, efficient contact plans need to be derived on ground in advance and timely provisioned to the constellation[10].

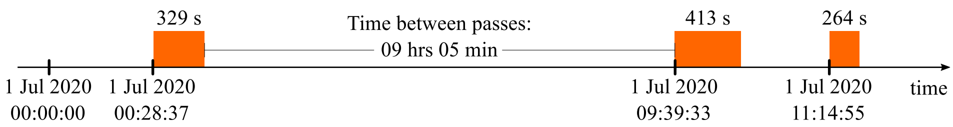


FIGURE 1 Time between passes example based on LEO and ground station parameters in Table 1 . Schedule computations have to be ready (validated and translated into commands) for provisioning before the next pass. For the sake or reliability, the schedule horizon is typically extended further into the future (we consider 48 hrs) and updated as necessary to guarantee autonomous connectivity even during unexpected satellite or ground segment outages.

Previous work extending DTN routing [11,12] towards considering energy availability focused on remote nodes during a path validation phase [13,14], where decisions are based on a pre-computed schedule of the communication resources, a.k.a., contact plan. The problem of computing resource-efficient contact plans based on fairness [15], routing [16], traffic [17,18] and mission-related tasks [19,20] was addressed to support the DTN data flow from ground. Moreover, recent work by the authors have introduced battery-awareness constraints [5,6]. Results showed that it is crucial to have detailed knowledge on how much power is drained for GSLs and ISLs, especially when in eclipse, where on-board batteries possibly end up in critically low states of charge [3,4]. Early versions of a Mixed Integer Linear Programming (MILP) model computed and designed optimal transponder's duty cycle for a LEO constellation of GomX–4 satellites [5,6].

In spite of the imminent deployment of mega-constellations, the scheduling complexity, in terms of required memory and computation time has been so far overlooked. In fact, we argue that obtaining accurate schedules guaranteeing a sustainable connectivity will likely compromise operations as computations are required to run to completion in between any two passes of satellites over the ground station (see Figure 1). In this paper, we study the scalability of the battery-aware contact plan design on a broad spectrum of increasingly complex LEO satellite constellations. We revisit the MILP modelling approach in [5,6] and adapt it to a series of more general and challenging settings, and while doing so present crucial enhancements to the model that further add to the scalability. The enhanced model improves by 60% the size of the problems that can be managed. Nevertheless, we present evidence that modern schemes are far from solving the problem for thousands of satellites. This asks for further research, to which we contribute with a valuable and realistic set of benchmarks.

This paper is structured as follows. Section 2 discusses the system under analysis and presents a benchmark of LEO satellite constellations in Section 2.1; relevant battery models in Section 2.2; and scheduling model enhancements in Section 2.3. Results are analyzed and discussed in Section 3 and conclusions are summarized in Section 4.

2 | SYSTEM MODEL

2.1 | Satellite Constellation Models

GomX–4A and 4B, launched on February 2017, are 6U CubeSats (20×30×10 cm cubic units nano-satellite) from GomSpace, commissioned by the Danish Ministry of Defense and the European Space Agency. The overall mission focuses on demonstrating miniaturized technologies, namely orbit maintenance, ISL, high speed downlink (HSL) and advanced remote sensing. These are considered key building blocks for a controlled deployment, operation and maintenance of a future CubeSat-based constellation known as Ulloriaq (the Greenlandic word for "star"). The concrete application context of the Ulloriaq mission is that of collecting observation and remote sensing data over the *Greenland* territory to deliver it to a ground station located in *Aalborg*, Denmark.

In this paper, we start off from an Ulloriaq space segment composed of 10 satellites equally spaced in the same sun-synchronous (quasi-polar) orbital plane flying in an along-track formation [5,6]. The constellation forms a *ring* around the Earth enabling a high revisit rate over Greenland territory, which in our model is represented by a centroid of a target area composed of 12750 boundary points, mimicking the mission sensing area. As in the GomX–4 mission, satellites are provisioned with two ISL antennas pointing to the front and back neighboring satellite. ISLs enable satellites to timely and cooperatively relay sensed data to the Aalborg ground station, while relaxing platform requirements as not all satellites need to be equipped with HSL downlink transponders.

Taking the Ulloriaq constellation as a base scenario, we explore more complex configurations and develop a benchmark set of LEO constellations designed to enable the evaluation of contact plan design schemes[1]. In particular, two families of flight segments are proposed: (*i*) *1-ring formation*, consisting of 10 up to 50 satellites in a ring, equally spaced in terms of true anomaly, and (*ii*) *2-ring formation*, based on two rings rotated 90° in Right Ascension of Ascending Node (RAAN), each with 10 up to 24 satellites, for a total of 20 up to 48 satellites in the constellation. The scenarios and

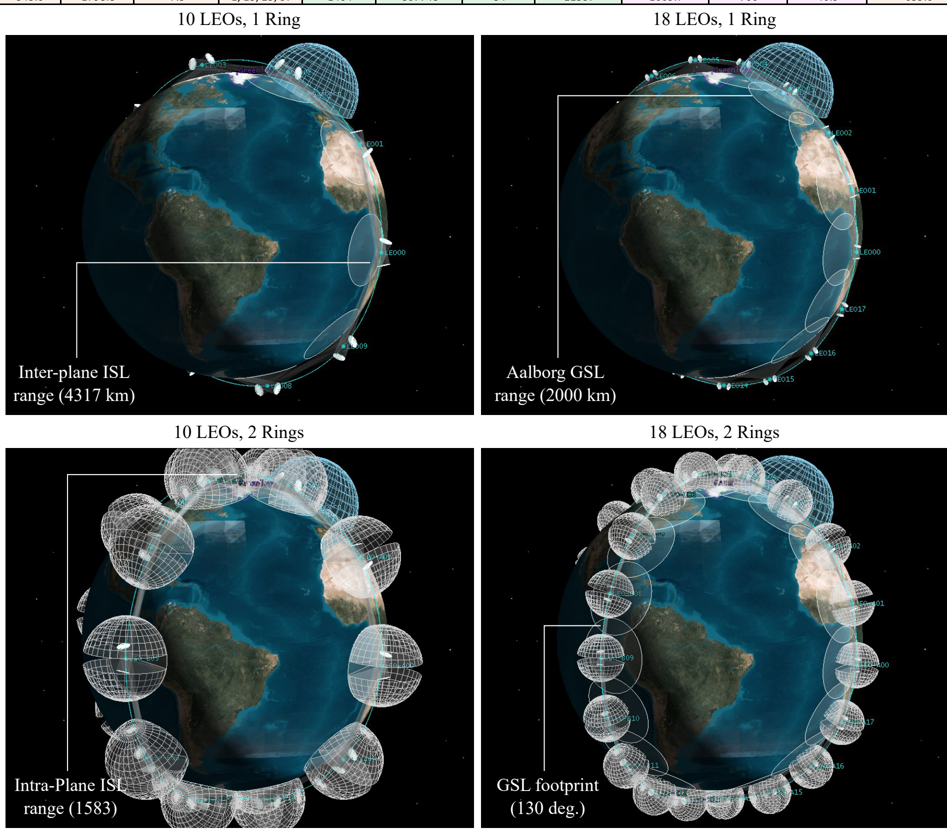
[1] The generated benchmark set can be visualized and is publicly available for downloaded at https://sites.google.com/unc.edu.ar/dtsn-scenarios

TABLE 1 Satellite Constellation Benchmark Parameters

Ground Segment	
Greenland location: 73.25 deg Latitude, -42.53 deg Longitude (defined by 12750 boundary points)	**Aalborg location:** 57.05 deg Latitude, 9.93 deg Longitude (34.53 m altitude)

1 Ring Flight Segment															Common features to all Segments Scenario epoch start: 1st Jul 2020 00:00:00 Scenario epoch end: 3 Jul 2020 00:00:00	
LEO sats/ring	Total LEO sats	T. anomaly [deg] first, step, last			ISL distance [km]	ISL elevation [deg]	LEO with HSL	Contacts to Greenland	UL Time to Greenland [s]	Contacts to Aalborg	DL Time to Aalborg [s]	UL Data vol [MB]	min DL rate [Kbps]	min ISL rate [Kbps]		
10	**10**	0.0	36.0	324.0	4317.2	18.0	1, 6	306	168687	17	5797	210.9	291	9.8	LEO sat height [km]	500
14	**14**	0.0	25.7	334.3	3083.7	12.9	1, 8	427	236162	17	5797	295.2	407	13.7	LEO sat Arg. Perigee [deg]	0
18	**18**	0.0	20.0	340.0	2398.4	10.0	1, 10	549	303658	17	5797	379.6	524	17.6	LEO sat inclination [deg]	97.03
22	**22**	0.0	16.4	343.6	1962.4	8.2	1, 12	672	371136	17	5797	463.9	640	21.5	LEO sat eccentricity	0
26	**26**	0.0	13.8	346.2	1660.5	6.9	1, 14	794	438658	17	5797	548.3	757	25.4	1 Ring RAAN [deg]	90
30	**30**	0.0	12.0	348.0	1439.1	6.0	1, 16	916	506114	17	5797	632.6	873	29.4	2 Ring RAAN [deg]	90, 180
34	**34**	0.0	10.6	349.4	1269.8	5.3	1, 18	1038	573610	17	5797	717.0	989	33.3	Greenland to LEO rate [kbps]	10
38	**38**	0.0	9.5	350.5	1136.1	4.7	1, 20	1160	641076	17	5797	801.3	1106	37.2	Intra-plane ISL beamwith [deg]	3
42	**42**	0.0	8.6	351.4	1027.9	4.3	1, 22	1282	708571	17	5797	885.7	1222	41.1	Inter-plane ISL beamwith [deg]	80
46	**46**	0.0	7.8	352.2	938.5	3.9	1, 24	1405	776047	17	5797	970.1	1339	45.0	LEO to Aalborg beamwith [deg]	65
50	**50**	0.0	7.2	352.8	863.4	3.6	1, 26	1527	843538	17	5797	1054.4	1455	48.9	LEO to Aalborg range [km]	2000

2 Rings Flight Segment																	
LEO sats/ring	Total LEO sats	T. anomaly [deg] first, step, last			ISL distance [km]	ISL elevation [deg]	LEO with HSL	Contacts to Greenland	UL Time to Greenland [s]	Contacts to Aalborg	DL Time to Aalborg [s]	UL Data vol [MB]	min DL rate [Kbps]	min ISL rate [Kbps]	Intra-Plane ISL range [km]	Inter-plane contacts	Inter-plane time [s]
10	**20**	0.0	36.0	324.0	4317.2	18.0	1, 6, 11, 16	611	336460	34	11537	420.6	292	19.5	1583.0	1830	173246
12	**24**	0.0	30.0	330.0	3597.6	15.0	1, 7, 13, 19	732	403927	34	11537	504.9	350	23.4	1319.1	2192	170990
14	**28**	0.0	25.7	334.3	3083.7	12.9	1, 8, 15, 22	854	471116	34	11537	588.9	408	27.3	1130.7	2558	169234
16	**32**	0.0	22.5	337.5	2698.2	11.3	1, 9, 17, 25	977	538492	34	11537	673.1	467	31.2	989.4	2922	167298
18	**36**	0.0	20.0	340.0	2398.4	10.0	1, 10, 19, 28	1097	605813	34	11537	757.3	525	35.1	879.4	3290	165390
20	**40**	0.0	18.0	342.0	2158.6	9.0	1, 11, 21, 31	1221	673144	34	11537	841.4	583	39.0	791.5	3654	163556
22	**44**	0.0	16.4	343.6	1962.4	8.2	1, 12, 23, 34	1342	740402	34	11537	925.5	642	42.9	719.5	4018	161624
24	**48**	0.0	15.0	345.0	1798.8	7.5	1, 13, 25, 37	1464	807748	34	11537	1009.7	700	46.9	659.6	4384	159724



their corresponding contact plans were generated using the System Tool Kit (STK) and the Contact Plan Designer plug-in [21]. It is worth noting that the constellation studied in [5,6] is an instance in this set corresponding to the 1-ring, 10 satellite configuration. In general, the more LEO satellites, the more connectivity, but also the more topological complexity.

Table 1 summarizes and illustrates the ground and flight parameters of the resulting constellations benchmark set, including connectivity metrics for a time period of 48 hours. On the one hand, it is assumed that on each ring, only two LEO satellites are equipped with HSL. As a result, 2-ring scenarios double the 1-ring downlink time to Aalborg, from 5797 up to 11537 seconds in a 48 hours time period. On the other hand, the uplink from Greenland depends on the scale of the flight segment, between 306-1527 contacts in the 1-ring topology and in between 611-1464 in the 2-ring scenario. While 1-ring LEO satellites are equipped with two high-gain intra-plane ISL (3° beam-width in the front and back), 2-ring satellite constellations additionally account for inter-plane ISL. As shown in Figure 2 , inter-plane connectivity occurs sporadically at the poles through wide beam-width ISL antennas (80°). As in [5,6], the uplink data rate is set to 10 Kbps, resulting in uplink data volume ranging from 210.9 up

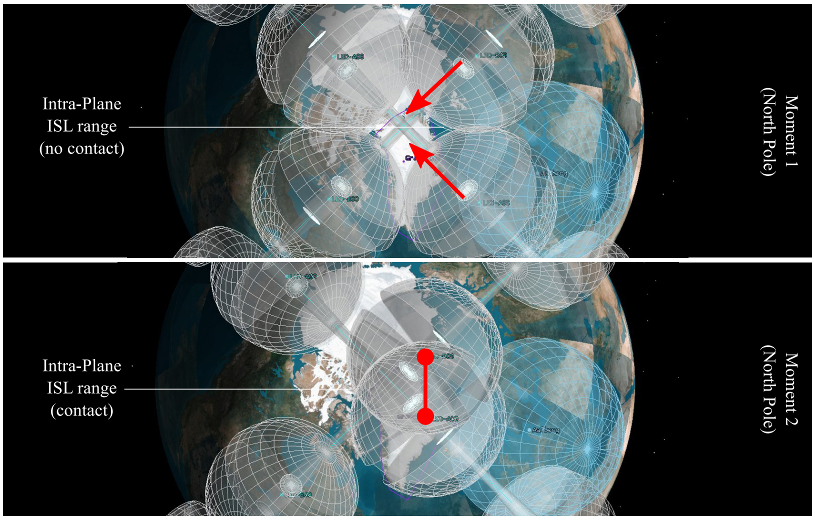


FIGURE 2 Intra-plane ISL is achieved via wide beam-width antennas in the pole areas, when satellites are in range (i.e., moment 2).

to 1054.4 MB in 1-ring and from 420 up to 1009.9 MB in 2-ring scenarios. The minimum ISL and GSL data rates shown in Table 1 are estimated in order to roughly accommodate and deliver such data volume to the ground station in Aalborg. The final data delivery metrics will indeed be dependent on the resulting contact plan schedule, which in turn will depend on platform specific limitations such as the power subsystem and the number of simultaneous interfaces the satellites can use.

In the work presented here, we will use the proposed benchmark set to study how battery-aware scheduling models could scale and provide valid contact plans. To properly decide how and when links should be used, battery utilization must be considered.

2.2 | Battery Models

To reason about the energy budget of CubeSat missions a faithful battery model is of central importance. In the majority of cases, Li-ion battery packs are used in CubeSat missions. Because of space limitations, we briefly review two important battery models already considered in [5,6], relevant in the context of this work. The interested reader is referred to [22] for a thorough comparison of state-of-the-art formal battery models.

Linear Battery Model (LiBaM)

This is the simplest model of electric energy storage. It is the standard model, e.g. visualized to smartphone users as a well holding liquid between 0% and 100%. Assuming it can be drained or refilled by a piecewise constant *load* function $\ell(t)$, the charge $e(t)$ evolves piecewise linearly over time t and proportionally to $\ell(t)$, where a positive (negative) load means discharging (charging). Any value of $e(t)$ below a *safety threshold* $c_{\min} > 0$ is considered critically low while the battery is full if $e(t)$ hits a value $c_{\max} > c_{\min}$ (where it needs to stay until discharging). Real-world batteries are inherently non-linear, thus the LiBaM is a rather simplistic model of energy storage.

Kinetic Battery Model (KiBaM)

This model can be thought of as two wells holding liquid that are connected at their bottom and where the flow between wells depends on the difference in their charge. Consequently, the KiBaM charge dynamics is non-linear, reflecting faithfully non-linear effects that can be observed in real batteries in-the-wild. Among them are the *recovery* and *rate-capacity* effect [23], not captured by the linear model.

We will work with one LiBaM model per satellite as part of the linear (MILP-based) scheduling model discussed below, while the KiBaM model (again one per satellite) serves as a means to validate the scheduling decisions under uncertainty with respect to the initial state of charge as well as load noise. For the latter we work with an extension of the KiBaM with capacity limits as well as stochastic perturbations [24]. This KiBaM validation step contributes negligibly to the overall computational requirements.

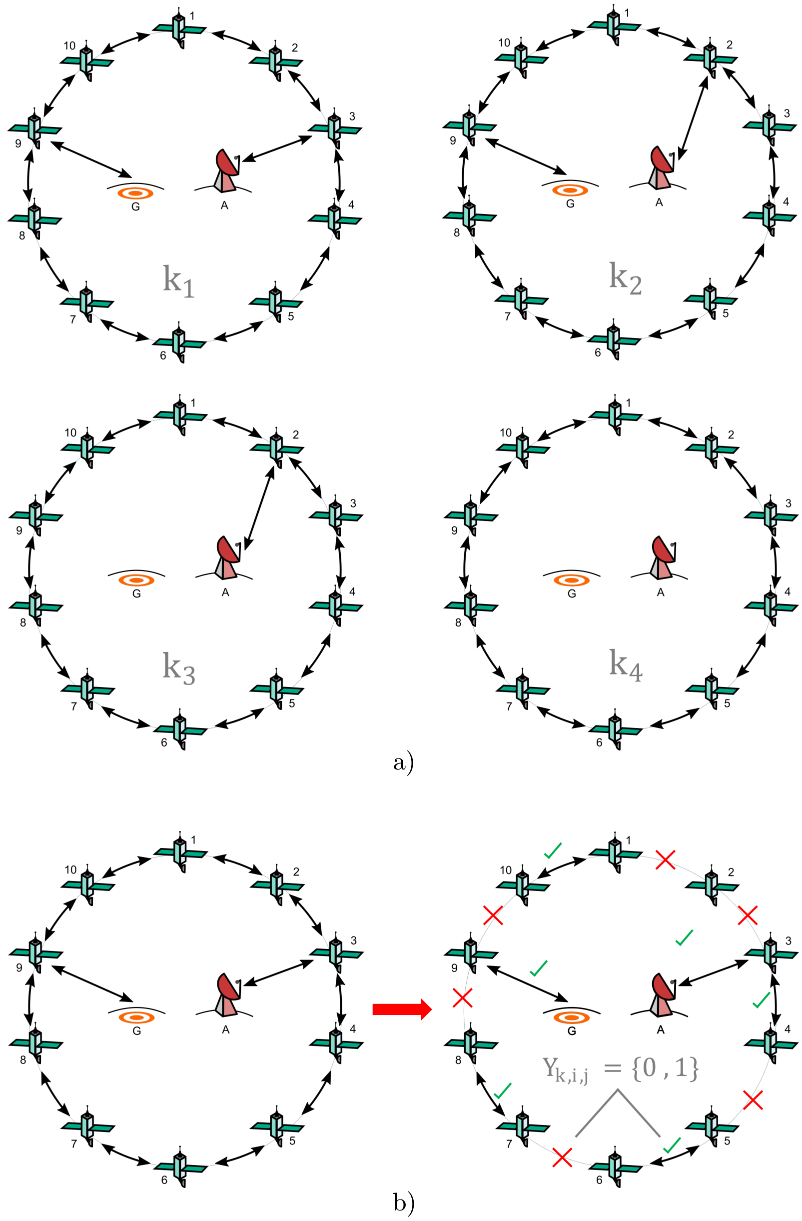


FIGURE 3 Time-evolving topology model based on discrete time episodes k_1, k_2, k_3 and k_4 in a). This model facilitates the scheduling of contacts on each of this episodes via $Y_{k,i,k}$ boolean variables as shown in b)[6]

2.3 | MILP Model

Topology model

In order to tackle the battery-aware link scheduling problem for DTN satellite networks, we consider an abstraction of the satellite constellation based on a discrete set of time episodes where the topology is considered stable and can be modeled by a temporary static graph. The approach is known as time-evolving graph and has been extensively used in previous works related with time-evolving networks[25,26,18].

In a time-evolving graph, a set of K states, each of them comprised of a static graph with N nodes valid during a specific period of time ($(t_k; t_{k+1})$), can be used to represent the time-evolving network connectivity. In other words, whenever a communication opportunity starts or ends, a new state is added to the topology to describe the new connectivity. This is illustrated in Figure 3 .

However, in a battery-aware model, a state change is also triggered by a change from sunlight exposure to eclipse, since it represents a transition from charging to discharging (and vice-versa) of the on-board batteries. Auxiliary coefficients such as contact capacity ($\{c_{k,i,j}\}$), buffer capacity ($\{b_i\}$) and traffic sources ($\{d_k^{i,j}\}$) can be used to complete the abstraction of the satellite constellation. It is worth noticing that in this work, data buffer limits are set high enough as we are not evaluating storage capacity in this opportunity. The modelling of data storage constraints is fully supported in the approach we use, and could be included if considered an important parameter, However, since modern on-board data storage are large enough (in the order of tens of GBs), we are marking this as a future research topic..

LiBaM battery coefficients are also included as part of the model, given by the minimum and maximum battery charge allowed ($\{c_{min,i}\}$ and $\{c_{max,i}\}$) as well as the initial charge ($\{c_{0,i}\}$). The battery is recharged whenever the spacecraft is exposed to sunlight, by the difference of the amount of solar infeed ($\{c^i_{rC}\}$) and the link activity (given by $\{c^i_{rT}\}$ and $\{c^i_{rB}\}$). As output variables we designate the traffic flowing through the network ($\{X^{y,z}_{k,i,j}\}$), the buffer occupancy as states evolve ($\{B^{y,z}_{k,i}\}$), link activity variables ($\{Y_{k,i,j}\}$), and the LiBaM state of charge at the end of each state ($\{C_{k,i}\}$).

Model parameters are illustrated in Figure 4 and summarized in Table 2 . The MILP is formalized as follows:

$$\text{minimize: } \sum_{k,i,j,y,z=1}^{N} w_t(t_k) \cdot X^{y,z}_{k,i,j} + w_y \cdot Y_{k,i,j} - w_c \cdot C_{k,i} \quad (1)$$

Subject to:

$$\sum_{j=1}^{N} X^{y,z}_{k,j,i} - \sum_{j=1}^{N} X^{y,z}_{k,i,j} = B^{y,z}_{k,i} - B^{y,z}_{k-1,i} \quad \forall k, y, z, i \neq y \quad (2)$$

$$\sum_{j=1}^{N} X^{y,z}_{k,j,i} - \sum_{j=1}^{N} X^{y,z}_{k,i,j} = B^{y,z}_{k,i} - B^{y,z}_{k-1,i} + d^{i,z}_{k} \quad \forall k, y, z, i = y \quad (3)$$

$$\sum_{y=1}^{N}\sum_{z=1}^{N} B^{y,z}_{k,i} \leq b^i_{max} \quad \forall k, i \quad (4)$$

$$B^{y,z}_{0,i} = 0 \quad \forall i, y, z \quad (5)$$

$$\sum_{y=1}^{N}\sum_{z=1}^{N} X^{y,z}_{k,i,j} \leq x_{k,i,j} \cdot i_k \quad \forall k, i, j \quad (6)$$

$$\sum_{k=1}^{K}\sum_{i=1}^{N} X^{y,z}_{k,i,z} - X^{y,z}_{k,z,i} = \sum_{k=1}^{K} d^{y,z}_{k} \quad \forall y, z \quad (7)$$

$$\sum_{j=1}^{N} Y_{k,i,j} \leq p_i \quad \forall k, i \quad (8)$$

$$\sum_{y,z=1}^{N} X^{y,z}_{k,i,j} \leq M \cdot Y_{k,i,j} \quad \forall k, i, j \quad (9)$$

$$C_{0,i} = c_{0,i} \quad \forall i \quad (10)$$

$$c^i_{min} \leq C_{k,i} \leq c^i_{max} \quad \forall k, i \quad (11)$$

$$C_{k,i} + i_k \cdot c^i_{rT} \sum_{j=1}^{N} Y_{k,i,j} \leq C_{k-1,i} + (c^i_{rC,k} - c^i_{rB}) \cdot i_k \quad \forall k, i \quad (12)$$

Non-Boolean alternative for Equation (12):

$$C_{k,i} + \sum_{j,y,z=1}^{N} \frac{c^i_{rT}}{x_{k,i,j}} X^{y,z}_{k,i,j} \leq C_{k-1,i} + (c^i_{rC,k} - c^i_{rB}) \cdot i_k \quad \forall k, i \quad (13)$$

Flow Constraints

These coefficients and variables induce a linear programming model as follows. Eq. (2) to (7) echo the constraints on a time-evolving statement of the multi-commodity flow problem originally developed for store, carry and forward satellite networks [18]. Specifically, eq. (2) and (3) capture the evolution of data as it either flows between nodes ($\{X^{y,z}_{k,i,j}\}$) or is kept in a local storage ($\{B^{y,z}_{k,i}\}$). Eq. (4) and (5) specify the maximum and initial status of each node's buffer. Eq. (6) specifies the maximum flow of data that can be sent over each contact. Eq. (7) sets the flow imbalance, or traffic demands ($d^{i,j}_k$) from all source to destination nodes. Given these constraints, the objective function in (1) aims at obtaining an optimal traffic

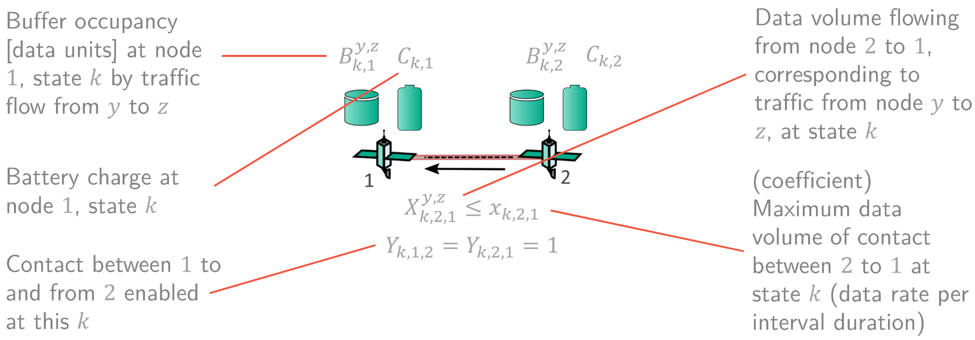


FIGURE 4 Traffic flow, buffer occupancy, battery charge and binary decision variables of the model.

TABLE 2 MILP Model Parameters

Input Coefficients	
N, K	Nodes and Topology states quantity
t_k, i_k	State k start time and duration ($1 \leq k \leq K$)
$x_{k,i,j}$	Data-rate of i to j contact at state k ($1 \leq k \leq K$ and $1 \leq i, j \leq N$)
$b_{max,i}$	Maximum buffer capacity at node i ($1 \leq i \leq N$)
$d^{y,z}_k$	Traffic from y to z originated at the beginning of k ($1 \leq k \leq K$ and $1 \leq y, z \leq N$)
p_i	Max. simultaneous links in node i ($1 \leq i \leq N$)
M	Big "M" coefficient for interface decision equations
$c_{min,i}$ $c_{max,i}$	Minimum and maximum battery charge at node i ($1 \leq i \leq N$) at all times
$c_{0,i}$	Initial battery charge at node i
$c^i_{rC,k}$	Battery recharge rate because of sunlight exposure at node i at k. Equals to 0 if on eclipse.
c^i_{rT}	Battery consumption rate because of transmission or reception system enabled at node i
c^i_{rB}	Battery consumption rate because of background load at node i

Output Variables	
$X^{y,z}_{k,i,j}$	Traffic from y to z at state k flowing in i to j edge ($1 \leq i, j, y, z \leq N$)
$B^{y,z}_{k,i}$	Node i buffer occupancy at the end of state k by the traffic flow from y to z ($1 \leq i, y, z \leq N$)
$Y_{k,i,j}$	Binary variable for link selection from i to j at state k ($1 \leq k \leq K$ and $1 \leq i, j \leq N$)
$C_{k,i}$	Battery charge at node i at the end of state k ($1 \leq k \leq K$ and $1 \leq i, j \leq N$)

flow assignment, where later flows are penalized by a cost function $w(t_k)$ that increases with time. The remaining equations capture limitations of the communication interfaces and of the batteries.

TABLE 3 Battery Model Parameters (GomX–4)

	Absolute	Relative
Total battery capacity	277056.0 J	100 %
Initial battery charge	221644.8 J	80 %
Minimal battery charge at all times	166233.0 J	50 + 10 %
Background consumption rate	4.630 J/s	0.001671 %/s
Tx/Rx consumption rate	13.651 J/s	0.004927 %/s
Recharge by sunlight exposure rate	15.472 J/s	0.005584 %/s

Interface constraints

Boolean variables $Y_{k,i,j}$ represent link (in)activity ($Y_{k,i,j} = 1$ whenever the link from i to j is active at state k, and 0 otherwise). Based on these variables, interface constraints are expressed in eq. (8) and (9). Based on the so-called "big M" approach [27], they provide a mechanism to bound the maximum quantity of simultaneous communications a node can establish at any moment, typically rooted in spacecraft architecture constraints [10]. The resulting formulation of the problem induces a MILP model with 0/1 integers. However, as we will discuss in Section 3, relying on Boolean conditions stresses the computation effort needed to solve models for large topologies.

Battery constraints

Equation (10) is used to set the initial state of charge, eq. (11) bounds the charge at all states and eq. (12) uses the LiBaM to model the evolution of charge in states, referring to Boolean variables $Y_{k,i,j}$. In order to be able to tackle larger satellites constellations, we introduce a new and actually more faithful formulation. We offer an alternative Equation (13) that replaces eq. (12). Instead of a qualitative representation of whether a link is active or not, we represent the utilization degree as a quantitative measure between 0 and 1 corresponding to the fraction of sent data per maximal link capacity. While the former model assumed a link being active throughout a state (thus overapproximating the link usage), the new version gives a more precise representation. This twist alone does not eliminate all Boolean variable occurrences (since interface constraints use them still), but we will see that replacing the battery constraints enables an increased capacity of solving larger schedules as sought in this paper. A last consideration on battery constraints concerns the usage and faithfulness of the model. Since the simplistic LiBaM model might not accurately reflect the real (non-linear) battery behavior, safety margins are to be considered. As an additional quality assurance and potential refutation mechanism, the contact plan synthesized with the LiBaM can be validated using the vastly more accurate stochastic KiBaM in a post-processing step with very low linear overhead [5,6].

The proposed MILP formulations are designed to provide optimal traffic assignments in terms of contact plans, enabling the best utilization of available communication resources in a constellation while minimizing battery exhaustion risk. In practice however this hinges on the ability to solve different configurations of such models in a timely manner, so as to comply with revisit periods of the constellation under study.

3 | RESULTS AND ANALYSIS

In this section, we evaluate the models in the 1-ring and 2-ring benchmark scenarios introduced in Section 2.1. In all scenarios, start and stop times are set to 1 Jul 2020 00:00:00 and 3 Jul 2020 00:00:00, spanning a schedule horizon of 48 hrs. Since LEO satellites typically visit a ground station two to four times a day, a 48 hrs contact plan leaves the network operator a reasonable margin to react to unexpected events or failures without losing network connectivity. However, we will also evaluate shorter scheduling horizons of 12, 24 and 36 hrs to study the variation of the computational effort required to solve them. The volume of data configured for each scenario (from Greenland to Aalborg) follows Table 1 , and is proportionally scaled down to 12, 24 and 36 hrs.

Table 3 summarizes the battery parameters for all satellites in all scenarios. It is worth noting that consumption values were extracted from the subsystems currently flying in GomX–4 satellites. As suggested in [5,6], a 10% safety margin is added to the minimal battery charge at all times in order to account for the idealistic linear nature of the LiBaM. All results analyzed in this section were successfully validated with KiBaM, proving that such a margin is an adequate parameter for the proposed models.

To study the scalability of the proposed models, we solve the 11 $\times$ 1-ring and the 8 $\times$ 2-ring scenarios, 4 times each (12, 24, 36 and 48 hrs schedule horizon), rendering a total of 76 scenarios under evaluation, each solved for 5 different configurations:

1. *LP-NIC*: the proposed model with No Interface Constraints (NIC, satellites can use all transponders simultaneously meaning no equations with Boolean variables appear in the MILP and therefore the model reduces to a pure LP model),

2. *MILP-2IC*: the MILP model allowing at the most one ISL and one GSL (2IC, two bidirectional interfaces),
3. *MILP-1IC*: the MILP model allowing only one active link (1IC, one interface, either one ISL or one GSL),
4. *MILP-1OI*: the MILP model allowing one Outgoing Interface (1OI, data reception is not constrained, mimicking a transponder that consumes power only while transmitting), and
5. *MILP-[56]*: the MILP model proposed in [5,6] using Equation (12) instead of (13) and restricted to one outgoing interface (as in 1OI).

For a total of 380 executions, we measure the memory utilization and computation time required to solve them. Data delivery metrics, for similar scenarios has been widely discussed in [5,6]. In this paper, we study the scalability aspect of the topic. The platform used is an Intel i7-7500 processor with 8 GiB of RAM running an Ubuntu 18.04.2 OS and the IBM ILOG CPLEX solver v12.8.0.0. Executions taking longer than 20 minutes are aborted and considered intractable.

Computation and memory metrics are plotted against the constellation size in Figure 5 . For each curve, results are shown for 1-ring and 2-ring topologies (1R and 2R). In particular, the *x* axis presents the amount of satellites in the constellation, which according to Table 1 can be of 10 up to 50 nodes in the 1-ring topology, and 20 up to 48 satellites in the dual ring case. Tractability limits are highlighted with a vertical line and a larger marker for models that cannot deliver a solution beyond a given constellation size.

In general, while memory consumption evidences an exponential increase with the number of satellites, processing time is rather erratic, but it is enough to show relevant tendencies and tractability limits. Validating the hypothesis, for the same number of satellites, 2-ring scenarios are more demanding because of a more complex connectivity pattern. This can be observed particularly in the memory consumption metric, which increases as a larger search space needs to be stored during the solving process.

On the one hand, the LP-NIC model provides the quickest and least memory-demanding computation. This was expected considering this is a pure LP model that can readily be solved via efficient Simplex algorithms [28]. However, when interfaces constraints are applied, the Boolean nature of the problem drastically increases the required effort to solve it. Solution approaches typically involve branch-and cut techniques that run several Simplex to solve the so-called *relaxation* of the problem [29].

Indeed, MILP-2IC and MILP-1IC turn intractable beyond 44 satellites even in the reduced 12 and 24 hrs schedule horizon. When implemented for the extended 36 and 48 hrs horizon, only 28 and 24 satellites can be scheduled in less than the 20 minutes time-frame. Although MILP-2IC and MILP-1IC present similar metrics, a slight advantage can be observed for MILP-2IC both in the 1-ring and 2-ring configurations. This difference can be explained by the fact that the more constrained the interfaces are, the smaller the search space, and thus, the less effort is needed to solve the problem.

On the other hand, the proposed MILP-1OI model consumes as much memory as the other MILP formulations for the four time-horizon variants. Nevertheless, the compute time is consistently lower, enabling the improved approach to schedule more satellites in less time. Indeed, relaxing the incoming flow restriction facilities the resolution, making MILP-1OI the only interface-constrained scheme able to terminate in the 48 hrs scenarios with 40 satellites. In all 1-ring topology cases, the MILP-[56] model with Boolean-based battery model is outperformed by the improved MILP-1OI.

It is worth mentioning, however, that the improvement is not so prevalent in the 2-ring topology, suggesting that scalability issues can still be present for larger topologies. Another fact from the results also support the latter statement: no battery-aware contact plan design scheme is able to provide a solution for constellations of 50 satellites with a time horizon of 48 hrs.

4 | CONCLUSION

The successful operation of upcoming mega-constellations will depend on the efficient application of state-of-the-art informatics. Solving complex schedules in bounded time horizons is particularly challenging as resulting commands will need to be provisioned timely to the network in a recurring fashion. The more realistic constraints are included in the underlying scheduling models, the quicker the scheduling problems become an operation bottleneck that puts the effective management of large satellites constellations at stake.

In this paper, we have provided an in-depth study in how far battery-aware contact plan design for delay-tolerant satellite networks is susceptible to variations in problem size and in problem characteristics. With the current technology, an upper bound in tractability appears to be reached for topologies in the order of 50 satellites. Although we have provided efficient and further improved MILP formulations, the day-to-day scheduling of mega-constellations of hundreds or thousands satellites does remain a challenge, to which we contribute a realistic set of benchmarks.

Future research efforts includes the exploration of data storage limitations reyling on the buffer modeling in the MILP formulation, the development of specialized heuristics for residing time-horizon scheduling, and their in-orbit validation in the GomX–4 mission in late 2019.

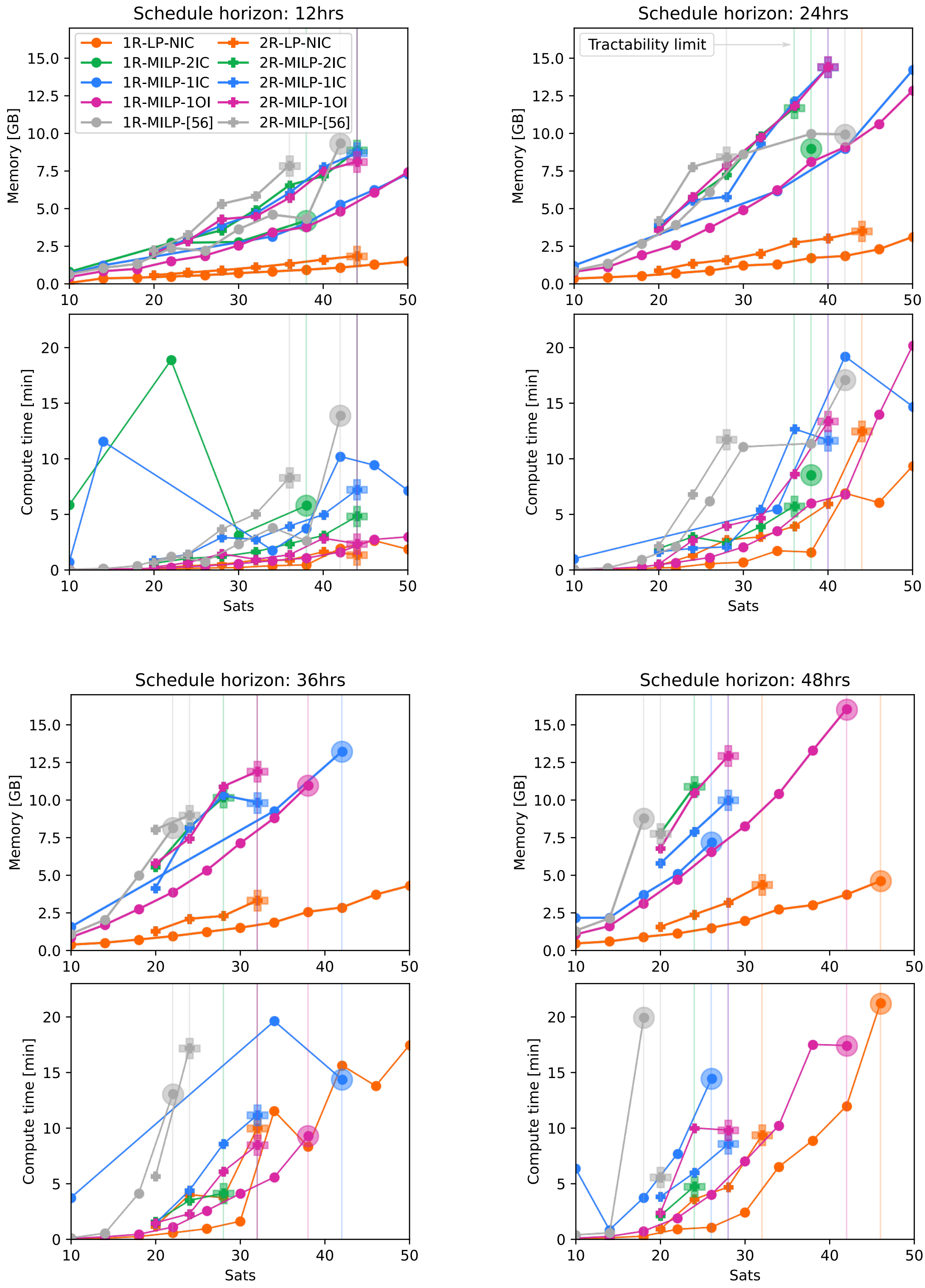


FIGURE 5 Metrics from solving LP-NIC (no interface constraints), MILP-1IC (1 interface constraint), MILP-2IC (2 interface constraint), MILP-1OI (1 outgoing interface constraint, new model) and MILP-[56] (1 outgoing interface constraint, old model) for the 1-ring (1R) and 2-ring (2R) benchmark scenarios. Tractability limits are highlighted with larger markers and vertical lines at the latest point where the models rendered a solution in less than 20 minutes. It is worth mentioning that the support for 1-ring configurations starts from 10 satellites while 2-ring topologies from 20 (10 satellites per ring).

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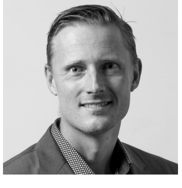

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