Sparse Satellite Constellation Design for LoRa-based Direct-to-Satellite Internet of Things

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Juan A. Fraire*†, Santiago Henn‡, Fabio Dovis§, Roberto Garello§, Giorgio Taricco§
*CONICET - Universidad Nacional de Córdoba, Córdoba, Argentina
†Saarland University, Saarland Informatics Campus, Saarbrücken, Germany
‡Comisión Nacional de Actividades Espaciales (CONAE), Argentina
§Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy

***Abstract*—A global Internet of Things is possible by embracing constellations of satellites acting as orbiting gateways in a Direct-to-Satellite IoT (DtS-IoT). By removing the dependency on ground gateways, DtS-IoT enables a direct service on the regions illuminated by the passing-by satellite. After an in-depth overview of relevant experiments and candidate technologies, we discover that specific configurations of the Long-Range (LoRa) network protocol specification are particularly appealing to realize the DtS-IoT vision. Specifically, we profit from the maximum clock drift permitted on LoRa devices to propose the sparse satellite constellations concept. This approach significantly reduces the in-orbit DtS-IoT infrastructure at the expense of latency anyway present in resource-constrained IoT networks. We then introduce a novel algorithm comprising specific heuristics to design quasi-optimal topologies for sparse IoT constellations. Obtained results show that LoRa-compatible DtS-IoT services can already be provided world-wide with 10% and 4% of the satellites required for a traditional dense constellation, in different configurations.**

***Index Terms*—Direct-to-Satellite Internet of Things, LEO Satellite Constellations, LoRa**

I. Introduction

We are evolving into an era of unprecedented pervasive connectivity between machines and objects, where millions of devices are expected to be connected to the Internet of Things (IoT) in the near future [1]. Although a plethora of short, medium and long-range protocols are part of the IoT family [2], the ambitious but rewarding objective of achieving a global IoT service is already attracting the attention of the industrial and academic communities.

In this context, a constellation-grade satellite segment can be the game changer [3]. In particular, the so-called Direct-to-Satellite IoT (DtS-IoT) paradigm constitutes the holy grail of IoT. The core idea is to succeed in connecting constrained devices on ground directly to Low-Earth Orbit (LEO) satellites without relying on intermediate gateways [4]. Remarkably, the recent in-orbit demonstration of the LacunaSat-1 nano-satellite proved the feasibility of this concept, so far only addressed by experiments [5] and scientific studies [6]–[9]. Indeed, the power-efficient LoRa modulation [10] and the supporting LoRaWAN network specification [11] are emerging as appealing candidates for realizing the DtS-IoT vision.

In spite of the unquestionable spaceborne IoT momentum, a persistent coverage of a global IoT service would require hundreds of orbiting gateways. For example, LacunaSat-1 is the first in a planned constellation of 240 nodes. Although based on affordable nano-satellite platforms, the deployment of such a dense constellation requires significant economic resources, menacing the survival of the small companies developing the technology. On the other hand, it is not fully clear up to which point a DtS-IoT can be materialized without major modifications of standard IoT protocols. A seamless interoperability with gateways already operating on ground would ensure the success of a true worldwide IoT connectivity.

This paper throws light on these DtS-IoT concerns by means of two specific contributions. (*i*) After presenting a survey-class overview of the state-of-the-art of DtS-IoT and LoRa capabilities, we are able to derive a novel vision of a *sparse constellation* for DtS-IoT. By allowing coverage gaps of 2 hours –bounded by the class-B mode defined in the LoRaWAN specification– the approach can significantly reduce the required in-orbit infrastructure at the expense of higher data delivery latency. A properly designed sparse constellation would comply with standard LoRaWAN protocol modes, indicating that space-terrestrial IoT integration can be achieved with less resources. (*ii*) We introduce a novel gradient descent methodology to efficiently derive quasi-optimal orbital parameters for sparse IoT constellations. The technique exploits specific ad-hoc heuristics to accelerate the convergence towards the minimum satellite fleet size that provides a maximum coverage gap of 120 minutes. Our results show that LoRa-based DtS-IoT can be already provided in a global scale with only 9 satellites deployed in the right topology. We finally analyze and compare the sensitivity of the produced configurations in an appealing set of parametric case studies.

The remaining of this paper is organized as follows. A thorough revision of DtS-IoT and related LoRa protocol developments is presented in Section II. Section III introduces the concept of sparse constellation and the optimization technique to design them. Obtained results are analyzed and compared in Section IV. Conclusions are summarized in Section V.

II. Background

A. Direct-to-Satellite IoT

The IoT ecosystem is broad (see Fig. 1-a). It embraces short and medium-range (1-10 km) cellular and sensor networks providing both high and low data rate services (0.1-100 Mbps) [12]. Moreover, and in accordance with the connectivity trend, Low Power Wide Area (LPWA) technologies are

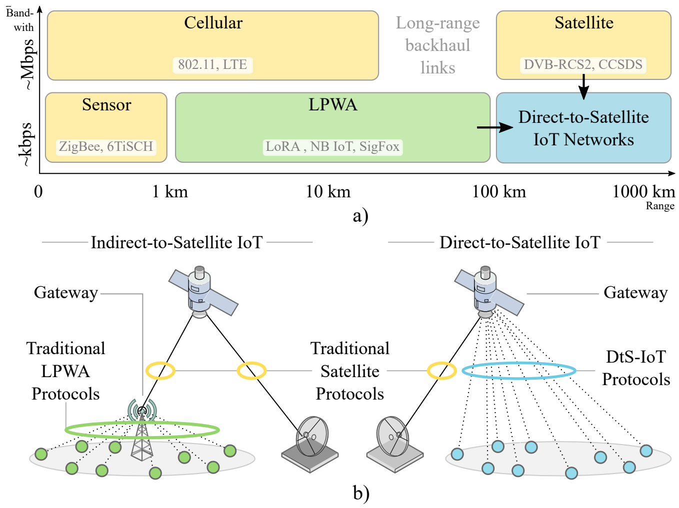

Fig. 1. a) The IoT protocol ecosystem. b) Direct-to-Satellite vs. indirect IoT.

also a crucial component of IoT capable of connecting applications that only need to transmit small amounts of information from long distances (100 km, at <50 Kbps) [13]. These applications range from agriculture to smart grid, environmental monitoring, emergency management, and others [14].

In order to further augment IoT coverage to provide a true global connectivity, satellite systems are natural candidates [3]. Compared with geostationary satellites, Low-Earth Orbit (LEO) satellites, orbiting below 1000 km height, can establish links with devices on the surface at reduced power budgets and round trip time delays [15]. However, the dynamics of near-Earth orbits demands for constellations of several LEO satellites to achieve a continuous coverage [16].

Existing LEO networks such as Iridium and Orbcomm originally deployed to provide voice and data services, were already adapted to transport machine-to-machine data traffic [16]. Upcoming mega-constellations such as OneWeb and Starlink will also include IoT services in their product portfolio [17], but recent bankruptcies indicate a stressed business model. On the other hand, new start-up companies such as Kepler, Astrocast and Lacuna are deploying specific satellites constellations for IoT [18]. Because of the low-power and small IoT messages, nano-satellites are a great fit, enabling lower costs than traditional satellites and lower risk deployments. This concept has attracted the attention of both the industrial and academic community [19].

One approach to global IoT services is to use satellites as a backhaul, to transport information from gateways deployed on ground that indirectly relay data from nearby IoT devices [20] (see Fig. 1-b, left part). A more appealing but challenging architecture implies a Direct-to-Satellite IoT (DtS-IoT), where the IoT device directly transmit data to the passing-by satellite [4], [21] (Fig. 1-b, right part). Unlike the indirect approach, DtS-IoT motivates research on custom ground to space link protocols [22], [23]. However, leveraging features from existing LPWA protocols would not only profit from the growing IoT market potential, but can also favor seamless interoperability with existing ground IoT infrastructure.

B. *LoRa and LoRaWAN*

Among LPWA technologies, Long Range (LoRa) is a chirp spread-spectrum modulation technique [10] particularly appealing for satellite as it provides the very low power consumption and large link margin [13]. LoRa operates within the unlicensed Industrial, Scientific and Medical (ISM) frequency bands, which can also be an advantage in terms of meeting otherwise complex worldwide frequency regulations [24]. The deployment of LacunaSat-1, the first LoRa nano-satellite by Lacuna in 2019, is compelling evidence of the feasibility of DtS-IoT, as expressed in related experiments [5] and scientific work including long-range evaluations [6], modulation enhancements for LEO links [7], Doppler effects assessments [8] and adaptations for LoRa-based space links [9].

Running on top of the LoRa modulation, LoRaWAN is the specification responsible for the network layer service, enabling data handling over asynchronous bidirectional link protocols [11]. LoRaWAN is based on a star topology where gateways act as single-hop data concentrators bridging LoRa devices and a centralized network server in the Internet [25].

The specification render data rates from 0,3 kbps to 50 kbps via three classes of services, or device classes. (*i*) Class-A is the *baseline*, mandatory, and most power-efficient mode where the device turns the radio on for the exact time needed to perform a frame transmission. This is an asynchronous pure ALOHA-based protocol [26]. Reception is supported by a receive window opened two times exactly 1 s and 2 s after the end of the device transmission. (*ii*) Class-B devices, typically equipped with batteries, allow gateway-triggered downlinks and uplink by periodically listening to so-called *beacons* (and *pings* in-between beacons) that synchronizes and coordinates reception and transmission episodes. This is a synchronous mode [27]. (*iii*) Class-C devices, assumed with external power source, operate in *continuous* reception mode.

To the best of authors knowledge, the evaluation of LoRaWAN service classes has not yet been properly conducted in the context of DtS-IoT networks.

III. Sparse DtS-IoT Constellations

The immediate approach towards a LoRaWAN DtS-IoT is to deploy a LEO constellation with enough satellites to continuously cover the surface of interest, potentially the whole planet. This approach would mimic the presence of at least one LoRaWAN gateway to every device on ground. Any of the LoRaWAN device classes can be applied to such a *dense constellation*, whose orbital topology design does not differ from those currently providing voice and data service. In this work, we introduce an alternative vision: a *sparse constellation* based on LoRaWAN IoT service classes.

A. *Sparse LoRaWAN Constellations*

Being the basic and mandatory mode, the asynchronous class-A LoRaWAN has received most of the community atten-

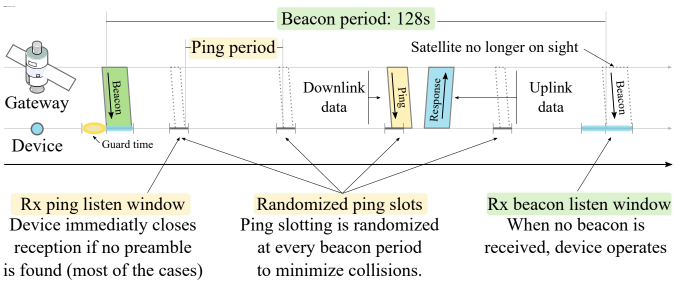

Fig. 2. Class-B mode operating in a LoRaWAN DtS-IoT.

tion [27]. However, there is no energy-efficient way for class-A devices to effectively synchronize with satellites. Instead, we claim that devices implementing the synchronous class-B mode can exploit the network initiated downlink to become aware of the availability of a passing-by satellite. In practice, this occurs when the beacon can be successfully decoded (see Fig. 2). LoRaWAN gateways would fly on the satellites, which can be provisioned with approximated location information of the IoT devices to coordinate the uplink access by means of the standard beacon and ping mechanisms. Uplink collisions, a notable issue for satellites illuminating hundred of thousands of devices, can thus be conveniently controlled by the LoRa gateway scheduler in orbit [28]. Furthermore, broadcast messages can be timely transmitted to many LoRa devices, when on sight, via the so-called multicast groups [11].

When the beacons are no longer received (satellite no longer on sight), the LoRaWAN specification indicates a so-called *beacon-less* operation mode. In this mode, devices rely on their own clock to keep timing. However, due to the low-quality (low-cost) nature of IoT electronics, clocks are expected to quickly drift from the time reference. In this situation, the LoRa specification states that compatible devices should be able to maintain beacon-less mode up to 120 minutes (2 hours) [11]. During this period, devices progressively increases their beacon listening window to compensate the drift. Before the end of the period, another (or the same) satellite must rise in the horizon in order to correct any timing drift and reset the receive slots duration.

The beacon-less coverage gap sits at the core of the proposed sparse IoT constellations paradigm. Instead of forcing a continuous visibility to a dense satellite constellation, IoT devices could be left unserved and drifting up to 2 hrs without detaching from the orbiting LoRaWAN network. Since most IoT applications are by definition asynchronous, they can tolerate delivery delays that would be prohibitive in traditional voice and data services. As a result, the number of satellites in a sparse constellation could be safely and significantly reduced, while still compliant with a flight-proven standardized DtS-IoT protocol, also widely adopted in ground systems.

In the next section, we present an appealing approach to design an optimal orbital topology for sparse DtS-IoT constellations.

TABLE I
PARAMETERS AND VARIABLES

Independent variables (parameters)	
g_{max}	Maximum allowed coverage gap (for all satellites)
h	Orbital height (km over the sea level for all satellites)
s	Antenna swath (field of view for all satellites)
$\{\mathcal{L}\}$	Set of (i, j) latitude/longitude locations served
T	Time horizon
Dependent variables (search space)	
$\mathcal{S}$	Number of satellites (minimization objective)
$\mathcal{P}$	Number of planes
$\mathcal{I}$	Orbit inclination (for all satellites)
$\mathcal{G}_{i,j}$	Maximum beacon-less gap at location (i, j)

B. Sparse LoRaWAN Constellation Design

In order to materialize the sparse DtS-IoT constellation vision, the adequate orbital parameters of the satellites need to be derived. This is not a trivial constraint-programming optimization problem where (*i*) the maximum beacon-less gap $\mathcal{G}_{i,j}$ must be kept under a given maximum value g_{max} in the T interval for a collection of ground latitude/longitude locations (i, j) in a set $\{\mathcal{L}\}$, and (*ii*) the size of the satellite fleet $\mathcal{S}$ arranged in $\mathcal{P}$ orbital planes carrying $\mathcal{S}/\mathcal{P}$ satellites per plane shall be minimized. We are also interested in finding the inclination $\mathcal{I}$ of the orbits. Therefore, the search space is composed of tuples $(\mathcal{S}, \mathcal{P}, \mathcal{I})$, and we want to find those that lead to $\mathcal{G}_{i,j}$ in which all points render coverage times lower than g_{max} ($g_{max} = 120$ min in LoRa class-B). Table I summarizes the parameters and variables of the sparse constellation design problem.

For the sake of simplicity, we assume that all satellites share the orbital elements and parameters (inclination, height, swath). Furthermore, we assume circular orbits (eccentricity $e = 0$), equally distributed orbital planes (in terms of ascending nodes), homogeneous distribution of satellites on each plane (satellite anomaly), and a plane phasing equal to the ascending node shift divided by the number of satellites per plane. After presenting relevant considerations, we introduce an algorithm to tackle the problem.

a) Grid $\{\mathcal{L}\}$ Considerations: In order to bound the (i, j) latitude/longitude grid resolution, the maximum coverage g_{max} value can be leveraged. Let $d_g^{P_1}(l)$ be distance that any point P_1 on the surface at latitude l shifts according to the rotation of the Earth in g_{max} time. There is no added information in measuring the coverage gap $\mathcal{G}_{P_2}$ of an intermediate point P_2 between the first and second location of P_1. Thus, the longitudinal step of two points in $\{\mathcal{L}\}$ shall be no smaller than $d_g^{P_1}(l)$ computed based on g_{max}[1]. Furthermore, in the latitude dimension, the grid density can be adjusted by the cosine of the latitude to account for the increased density of points as they become closer to the poles [29].

[1] Assuming an Earth rotation speed of 460 meters per second at the equator and a LoRa beacon-less gap $g_{max} = 120$ minutes, the minimum grid step at 0° latitude results 3312 km. This is 12 points along the equator for a perimeter of 40075 km, and is the $\{\mathcal{L}\}$ configuration assumed in this paper.

b) Inclination $\mathcal{I}$ Considerations: Satellite coverage is known to be dependant of the inclination parameter [30]. In particular, Fig. 3 presents the coverage that different inclinations i can offer at different latitudes. We leverage this information to bound the inclination possibilities that can actually serve a given grid $\{\mathcal{L}\}$. For example, for a grid $\{\mathcal{L}\}$ for which all points $P \in \{(i,j)\}$ are below 80° latitude, it makes no sense to consider inclinations lower than 60°, which should be removed from the search space (note that this relation depends on the swath of the antenna, which is assumed $s = 127^\circ$ in the figure). To deal with the general case, we manipulate the equations in [30] on which Fig. 3 is based to obtain equal coverage percentages for the grid points in $\{\mathcal{L}\}$. In particular, by equalizing the coverage metric at the equator and the highest latitude point in $\{\mathcal{L}\}$ we obtain

$$1 - \frac{2}{\pi}\ acos\left(\frac{sin(\lambda)}{sin(i)}\right) = \frac{1}{\pi}\ acos\left(\frac{-sin(\lambda)+cos(i)sen(L)}{sin(i)cos(L)}\right), \quad (1)$$

where L is the maximum latitude among all points in $\{\mathcal{L}\}$, i is the orbital plane's inclination, and λ is the maximum off-track ground angle ($\lambda = s/2$). This expression can be solved for i through numerical methods (we use the bi-section method), and it delivers a suitable lower-bound inclination that can be used to initialize the following search heuristic.

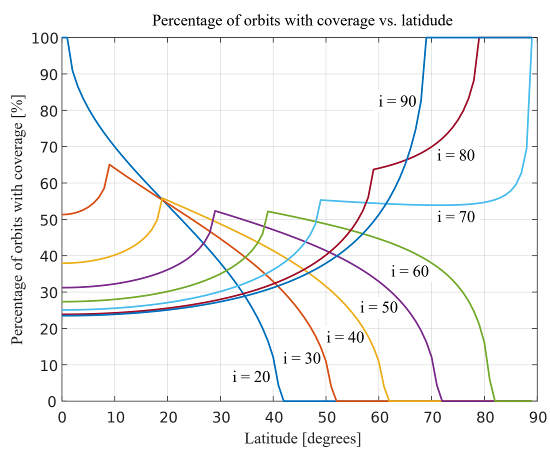

Fig. 3. Coverage as a function of latitude and inclination (i) for a LEO satellite at 700 km height and 5° elevation threshold (antenna swath $s = 127^\circ$) [30].

c) Complexity-Progressive Gradient Descent Algorithm: Based on the former parameters, assumptions, and considerations, we develop a gradient descent search algorithm that approximates the minimal $\mathcal{S}$ that can guarantee $\mathcal{G}_{i,j} \leq g_{max}\ \forall i,j \in \{\mathcal{L}\}$. To compute $\mathcal{G}_{i,j}$, each step of the algorithm calculates the orbit propagation of the constellation and the subsequent access evaluation to all points in the grid $\{\mathcal{L}\}$. Since this can be a compute-demanding process, we care to preemptively discard non-compliant scenarios. We achieve this objective by making quick evaluations over shorter time horizons ($T_0 \ll T$), and progressively testing each topology over $\{\mathcal{L}\}$ with increasing resolutions. In other words, simpler versions of the scenario are solved in an incremental fashion, and discarded as soon as the criteria is not met. The flow

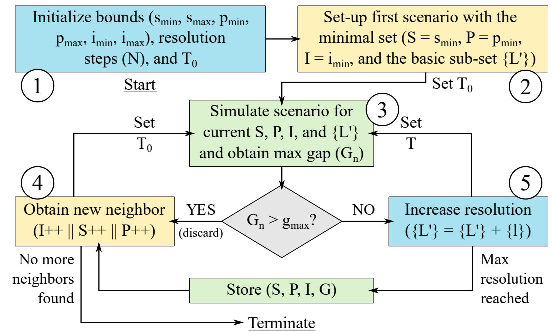

Fig. 4. Complexity-progressive gradient descent algorithm for sparse DtS-IoT constellation design.

diagram of the proposed algorithm is presented in Fig. 4. Step by step, the algorithm runs as follows.

① *Initialize:* The algorithm takes as input (see Table I): antenna swath (s), satellite height (h), latitude bounds (grid $\{\mathcal{L}\}$), maximum coverage gap (g_{max}), and the maximum time horizon (we find that $T = 1$ week is a suitable parameter). A solution space bound is then computed, comprised of (*i*) the possible number of satellites $[s_{min}, s_{max}]$ and planes $[p_{min}, p_{max}]$, where $p_{max} \leq 360^\circ/s$, and (*ii*) an allowed inclination range $[i_{min}, i_{max}]$, where i_{min} is obtained by solving equation (1)[2], and $i_{max} = 90^\circ$ as we disregard retrograde orbits. Based on $\{\mathcal{L}\}$, the steps N on which the input grid resolution will be approximated is determined. The shortened time horizon T_0 is computed as $T_0 = g_{max} + A_{max}$, where A_{max} is the longest visibility period between a passing-by satellite and a point on ground, which can be computed by $A_{max} = (s \times \pi\sqrt{a^3/\mu})/180$, where a is the semi major axis of the circular orbit, and μ is the Earth's gravitational parameter[3] (e.g., for 700 km height and $s = 120^\circ$, $T_0 = 131.6$ minutes).

② *Set-Up:* The first scenario is populated with the computed inclination $\mathcal{I} = i_{min}$, the minimum number of planes $\mathcal{P} = p_{min}$ and satellites $\mathcal{S} = s_{min}$. A new $\{\mathcal{L}'\}$ set is populated with a sub-set of the points in $\{\mathcal{L}\}$ comprised of only three rings: (*i*) maximum latitude ($L_{max} = max(lat\ \forall\ P \in \{\mathcal{L}'\}$), (*ii*) zero latitude, and (*iii*) half latitude ($L_{max}/2$). Furthermore, the first scenario is initially evaluated in a time horizon T_0. We find that the reduced grid expression combined with the minimum time T_0 enables the direct elimination of most non-compliant scenarios ($g_{n=1} > g_{max}$) quite efficiently. Table II presents evidences on this regard based on the executions analyzed in Section IV.

③ *Simulate:* The scenario is simulated for a time lapse T or T_0 for every first scenario for the tuple $(\mathcal{S}, \mathcal{P}, \mathcal{I})$. Orbits are propagated using the Simplified General Perturbations 4 (SGP4) algorithm [31] and accesses are computed for each of the points in the sub-set $\{\mathcal{L}'\}$. The new maximum gap G_n is computed from the obtained gap intervals among all P points in the grid ($G_n = max(G_n^P | P \in \mathcal{L})$). If the condition is met ($G_n > g_{max}$), the resolution of the scenario is augmented;

[2] i_{min} can also be bounded by the launch site location.

[3] $\mu = 3.986 \times 10^{14} \frac{m^3}{s^{-2}}$

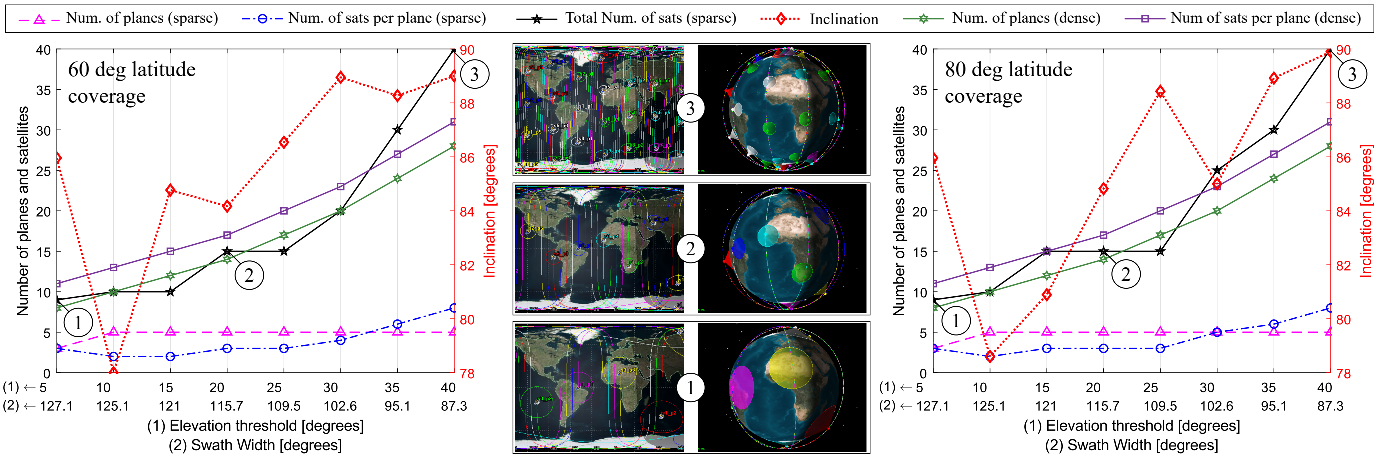

Fig. 5. Simulation results obtained for a 700Km height constellation for $\pm 60°$ and $\pm 80°$ of latitude coverage in sparse and dense constellations.

TABLE II
DISCARDED SCENARIOS AT N_n STAGES FOR EXECUTIONS IN FIG. 5

Latitude	N_0 (T_0)	N_1 (T)	N_2 (T)	N_3 (T)
$\pm 60°$	5838 (99.1%)	43 (0.7%)	7 (0.1%)	3 (0.1%)
$\pm 80°$	3260 (98.6%)	26 (0.8%)	10 (0.3%)	9 (0.3%)

otherwise, the tuple $(\mathcal{S}, \mathcal{P}, \mathcal{I})$ is discarded and a new neighbor is allocated from the solution space as follows.

④ *Obtain New Neighbor:* If the scenario was discarded, a new neighbor is obtained. The first criteria is to increment inclination on steps of one degree. If $\mathcal{I} = i_{max}$, then the next criteria is to increase the number of satellites per plane by one ($\mathcal{S} = \mathcal{S} + \mathcal{P}$). Else, if $\mathcal{S} = s_{max}$, the final neighbor search criteria es to increment $\mathcal{P}$ by one. Else, if $\mathcal{P} = p_{max}$, the search over the complete search space is concluded. The increasing scenario complexity as the search advances avoids overshooting good quality solutions. If no more neighbors can be found, the algorithm terminates.

⑤ *Increase Resolution:* If the scenario maximum gap was lower than $G_n > g_{max}$, the resolution and complexity of the scenario is increased. First, if the time horizon was set to T_0, it is now extended to the full T simulation time. Next, the resolution of $\{\mathcal{L}'\}$ is increased in the latitude dimension: new rings are included by splitting the already evaluated intervals in two. In particular, latitudes are separated by $\delta = L/(2^n)$ steps where $n = 1, 2, 3, ..., N$ is the current iteration number ($n = 1$ represents the initial set of points, including latitudes 0, $L/2$ and L). Note that previously evaluated rings already complies with $G_n > g_{max}$ and do not need to be simulated again. If the target resolution of $\{\mathcal{L}'\}$ is reached (i.e., $\{\mathcal{L}'\} = \{\mathcal{L}\}$), it means the current scenario fulfills the required coverage gap and the corresponding generating tuple $(\mathcal{S}, \mathcal{P}, \mathcal{I})$ is stored.

It is indeed possible that several tuples comply with the coverage gap condition with the same number of satellites $\mathcal{S}$. In this case, we honor those with the least number of planes $\mathcal{P}$ (which are related with deployment cost), and then, in the last place, lower inclinations $\mathcal{I}$.

IV. ANALYSIS

We implemented the sparse DtS-IoT constellation design algorithm in a specific Java-based application[4] that includes an SGP4 propagator released by the United States Department of Defense (DoD), and improved as reported in Vallado's Revisiting Spacetrack Report number 3 [31]. Some tools of the Orekit open-source libraries were also leveraged [32]. Access intervals obtained by the implementation were contrasted against AGI's System Tool Kit (STK) software, rendering negligible differences of less than 200 ms in access times.

Extensive simulations were performed for constellations with different values of elevation threshold in-between 5° and 40°, which map to antenna swath $s = 127.1°$ and $s = 87.3°$ respectively. We are also interested in studying maximum resolution $\{\mathcal{L}\}$ grids for which coverage is evaluated up to latitudes of 60° and 80°. All considered satellites are in a 700 Km height, circular orbit, positioned in symmetrically distributed planes, RAAN and mean anomaly in each plane. We let the solution space to include 1 to 5 planes with 1 to 8 satellites per plane (retrograde orbits not allowed). Obtained results are shown in Fig. 5. In order to compare sparse and dense constellations, the plots include information on the number of planes and satellites required to achieve a complete Earth coverage using *streets of coverage* (a well-known constellation pattern design for polar orbits [30]).

In general, results confirm that the number of satellites increases with the reduction of the antenna swath, both for sparse and dense constellations. However, the difference between both is noticeable: when 9 satellites are sufficient for sparse IoT systems, $8 \times 11 = 88$ are required for a dense configuration ($s = 127°$), and when 40 are enough for sparse, dense constellations demands $28 \times 31 = 868$ satellites ($s = 87°$). To keep an adequate scale of the plot in Fig. 5, dense constellations are expressed in number of satellites per plane and number of planes, thus the multiplication to obtain the total satellites. Indeed, dense constellations can operate

[4] Public repository: https://github.com/santiagohenn/astrotools/

with only 10% and 4% of the in-orbit infrastructure required for the announced mega-constellations, at the expense of a latency of $g_{max} = 120$ minutes in the worst case.

Results also showed that the approach is rather insensible to the maximum latitude. In particular, constellations ①, ② and ③, illustrated in the center of Fig. 5 to give an intuition on the topology, are the best solution found for the same swaths in 60° and 80° maximum latitude values in $\{\mathcal{L}\}$. Inclination, on the other hand, proved to be a more sensitive parameter to the maximum latitude, as already discussed in Section III-B-b). Specifically, the plots show that higher inclinations tend to be required to cope with smaller swaths, while some specific satellite fleets can meet the objective with exceptionally lower inclination values (e.g., $s = 125°$ with $i = 78°$ and $i = 79°$). As a final comment, plotted results correspond to orbital heights of 700 km, but we also evaluated other cases, not presented due to space limitations. The outcome of this campaign proved that altitude is also quite insensitive. For example, the same $\mathcal{S}$ is obtained for all altitudes in the 400-1000 km range ($s = 127°$).

V. Conclusions

We have open the field for IoT-compliant reduced space infrastructure to connect objects on a world-wide scale. Sparse constellations can realize the vision of DtS-IoT with only 4% to 10% of the traditional in-orbit platform. We provided sound technical motivation based on LoRa standards and an appealing algorithmic support to design optimal sparse DtS-IoT constellations, which rendered a full-stack assessment of the concept.

Future work includes further technical analysis on the LoRa specification such as the integration of orbiting and ground gateways and a delay-tolerant interface of the network server to a sparse space segment. Algorithmic-wise, we will pursue more capable search heuristics to generalize the presented assumptions (circular orbits, equal spacing, etc.).

References

[1] A. Osseiran, J. F. Monserrat, and P. Marsch, *5G Mobile and Wireless Communications Technology*. Cambridge University Press, 2016.

[2] J. Dizdarević, F. Carpio, A. Jukan, and X. Masip-Bruin, "A Survey of Communication Protocols for Internet of Things and Related Challenges of Fog and Cloud Computing Integration," *ACM Computing Surveys (CSUR)*, vol. 51, no. 6, pp. 1–29, 2019.

[3] M. De Sanctis, E. Cianca, G. Araniti, I. Bisio, and R. Prasad, "Satellite Communications Supporting Internet of Remote Things," *IEEE Internet of Things Journal*, vol. 3, no. 1, pp. 113–123, Feb 2016.

[4] J. A. Fraire, S. Céspedes, and N. Accettura, "Direct-To-Satellite IoT - A Survey of the State of the Art and Future Research Perspectives," in *ADHOC-NOW 2019: Ad-Hoc, Mobile, and Wireless Networks*, Luxembourg, Luxembourg, Oct. 2019, pp. 241–258.

[5] The Things Network Global Team, *LoRa World Record Broken: 832km using 25mW*, 2020 (accessed May 29, 2020). [Online]. Available: https://www.thethingsnetwork.org/article/lorawan-world-record-broken-twice-in-single-experiment-1

[6] S. Demetri, M. Zúñiga, G. P. Picco, F. Kuipers, L. Bruzzone, and T. Telkamp, "Automated Estimation of Link Quality for LoRa: A Remote Sensing Approach," in *Proceedings of the 18th International Conference on Information Processing in Sensor Networks*. Montreal: ACM, 2019, pp. 145–156.

[7] Y. Qian, L. Ma, and X. Liang, "The Acquisition Method of Symmetry Chirp Signal Used in LEO Satellite Internet of Things," *IEEE Communications Letters*, vol. 23, no. 9, pp. 1572–1575, 2019.

[8] A. Doroshkin, A. Zadorozhny, O. Kus, and V. Prokopyev, "Experimental Study of LoRa Modulation Immunity to Doppler Effect in CubeSat Radio Communications," *IEEE Access*, vol. PP, no. c, p. 1, 2019.

[9] G. Colavolpe, T. Foggi, M. Ricciulli, Y. Zanettini, and J. Mediano-Alameda, "Reception of LoRa Signals From LEO Satellites," *IEEE TAES*, vol. 55, no. 6, pp. 3587–3602, 2019.

[10] L. Vangelista, "Frequency Shift Chirp Modulation: The LoRa modulation," *IEEE Signal Proc. Letters*, vol. 24, no. 12, pp. 1818–1821, 2017.

[11] LoRa Alliance Tech. Committee, *LoRaWAN™ 1.1 Spec.*, Oct. 2017, v1.1.

[12] M. R. Palattella, N. Accettura, X. Vilajosana, T. Watteyne, L. A. Grieco, G. Boggia, and M. Dohler, "Standardized Protocol Stack for the Internet of (Important) Things," *IEEE Communications Surveys Tutorials*, vol. 15, no. 3, pp. 1389–1406, Third 2013.

[13] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A Survey on LPWA Technology: LoRa and NB-IoT," *ICT Express*, vol. 3, no. 1, pp. 14 – 21, 2017.

[14] N. Zhang, M. Wang, and N. Wang, "Precision Agriculture—a Worldwide Overview," *Computers and Electronics in Agriculture*, vol. 36, no. 2, pp. 113 – 132, 2002.

[15] D. Minoli, *Building the Internet of Things with IPv6 and MIPv6: The Evolving World of M2M Communications*, 1st ed. Wiley Pub., 2013.

[16] Z. Qu, G. Zhang, H. Cao, and J. Xie, "LEO Satellite Constellation for Internet of Things," *IEEE Access*, vol. 5, pp. 18 391–18 401, 2017.

[17] J. Huang and J. Cao, "Recent Development of Commercial Satellite Communications Systems," in *Artificial Intelligence in China*. Springer, 2020, pp. 531–536.

[18] J. van't Hof, V. Karunanithi, S. Speretta, C. Verhoeven, and E. Mc Cune Jr, "Low Latency IoT/M2M Using Nano-Satellites," in *70th International Astronautical Congress (IAC), Washington DC, United States, 21-25 October 2019*. IAC, 2019.

[19] V. Almonacid and L. Franck, "Extending the Coverage of the Internet of Things with Low-Cost Nanosatellite Networks," *Acta Astronautica*, vol. 138, pp. 95–101, 2017.

[20] M. R. Palattella and N. Accettura, "Enabling Internet of Everything Everywhere: LPWAN with Satellite Backhaul," in *2018 Global Info. Infra. and Networking Symposium (GIIS)*. IEEE, oct 2018, pp. 1–5.

[21] I. Bisio and M. Marchese, "Efficient Satellite-Based Sensor Networks for Information Retrieval," *IEEE Syst. J.*, vol. 2, pp. 464–475, Dec. 2008.

[22] Y. Kawamoto, H. Nishiyama, Z. M. Fadlullah, and N. Kato, "Effective Data Collection Via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things," *IEEE Sensors Journal*, vol. 13, no. 10, pp. 3645–3654, Oct 2013.

[23] T. Ferrer, S. Céspedes, and A. Becerra, "Review and Evaluation of MAC Protocols for Satellite IoT Systems Using Nanosatellites," *Sensors*, vol. 19, no. 8, p. 1947, apr 2019.

[24] N. Accettura, E. Alata, P. Berthou, D. Dragomirescu, and T. Monteil, "Addressing Scalable, Optimal, and Secure Communications over LoRa networks: Challenges and Research Directions," *Internet Technology Letters*, vol. 1, no. 4, p. e54, jul 2018.

[25] A. Lavric and V. Popa, "Internet of Things and LoRa Low-Power Wide-Area Networks: a Survey," in *2017 International Symposium on Signals, Circuits and Systems (ISSCS)*. IEEE, 2017, pp. 1–5.

[26] G. Ferre, "Collision and Packet Loss Analysis in a LoRaWAN Network," in *2017 25th European Signal P. Conf. (EUSIPCO)*, 2017, pp. 2586–2590.

[27] C. E. Fehri, M. Kassab, N. Baccour, S. Abdellatif, P. Berthou, and I. Kammoun, "An Uplink Synchronization scheme for LoRaWAN Class B," in *2019 International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2019, pp. 47–52.

[28] J. Finnegan, S. Brown, and R. Farrell, "Evaluating the Scalability of LoRaWAN Gateways for Class B Communication in ns-3," in *2018 IEEE Conf. on Stdrs. for Comms. and Net. (CSCN)*, Oct 2018, pp. 1–6.

[29] J. R. Wertz, "Mission Geometry: Orbit and Constellation Design and Management: Spacecraft Orbit and Attitude Systems," *Space technology library, 13, Kluwer Academic Publishers*, 2001.

[30] J. R. Wertz, D. F. Everett, and J. J. Puschell, *Space Mission Engineering: the New SMAD*. Microcosm Press, 2011.

[31] D. Vallado, P. Crawford, R. Hujsak, and T. Kelso, "Revisiting Spacetrack Report 3: Rev," in *AIAA Astrodynamics Specialist Conference*, 08 2006.

[32] L. Maisonobe, V. Pommier, and P. Parraud, "Orekit: an Open-source Library for Operational Flight Dynamics Applications," in *ICATT 2010*, 2010.