

Research paper

Architecting CubeSat constellations for messaging service, Part I

Ksenia Osipova^{a,*}, Adriano Camps^{a,b,c}, Alessandro Golkar^d, Joan A. Ruiz-de-Azua^e,
Lara Fernandez^a, Nicola Garzaniti^f

^a CommSensLab-UPC, Dept. of Signal Theory and Communications, Universitat Politècnica de Catalunya, Campus Nord, bld. D4, c/ Jordi Girona 3-1, Barcelona, 08034, Spain

^b Institut d'Estudis Espacials de Catalunya IEEC, c/ Gran Capità 2-4, bld. Nexus, 201, Barcelona, 08034, Spain

^c United Arab Emirates University, College of Engineering, PO Box, Al Ain, Abu Dhabi, 15551, United Arab Emirates

^d Chair of Pico-, Nanosatellites, and Satellite Constellations, Department of Aerospace and Geodesy, School of Engineering and Design, Technical University of Munich, Lise-Meitner-Straße 9, Ottobrunn, 85521, Germany

^e Space Communications Research Group, i2CAT Foundation, c/ Gran Capità 2-4, bld. Nexus, 2^a planta, Barcelona, 08034, Spain

^f School of Aerospace, Transport and Manufacturing, Cranfield University, College Road, Cranfield, MK43 0AL, United Kingdom

ARTICLE INFO

Keywords:

LoRa technology
Messaging service
Satellite communications
Internet of Things

ABSTRACT

In today's modern and globalized world, connectivity is a key factor for businesses, production facilities, sensor networks, and ordinary people. However, there are still populated areas which are not covered by ground-based telecommunications infrastructure. This is where telecommunication satellite constellations come in, as they can provide coverage to remote and uninhabited regions and fill existing connectivity gaps to ensure data transfer.

LoRa is one of the technologies designed for data transmissions over long distances with low power consumption. Alongside with other technologies of the Low-Power Wide Area Network family, it is widely used for Internet of Things applications. LoRa chirp spread spectrum modulation is robust against the Doppler frequency shifts encountered in low earth orbits, and it has already been used in IoT satellite communications. Due to the low transmitted signal power, the achieved data rate is not high, making it a suitable technology for telecommunications payloads on CubeSat platforms for messaging services. As compared to existing traditional communication satellite systems, CubeSat constellations are low-cost and may offer an affordable connectivity service to developing regions.

This study is divided in two parts. In Part I the demand model is built based on the population distribution not covered by cell towers. The LoRa link performance is analyzed, considering the impact of LoRa channel parameters variation, such as spreading factor and channel bandwidth, while satellite orbital height, transmission antenna beamwidth, and transmitter peak power have a direct impact on the payload mass. Among thousands of possible configurations, 73 feasible payload designs have been downselected. In Part II of the study, the satellite mass and the total system cost are estimated based on the payload parameters obtained. Messages transmission simulation via a constellation is conducted in order to identify optimal constellation architectures for messaging service, as well as the main drivers of the system economic profitability.

The presented analysis results provide a deeper understanding of LoRa connectivity advantages and limitations together with the performance drivers, which will support the optimization of future LoRa-based satellite communication systems and other IoT satellite constellations.

1. Introduction

1.1. Background and motivation

In recent decades, the way we exchange information has undergone a significant transformation, impacting industries, production processes, supply chains, scientific research, and even our daily lives.

The use of data-driven insights is giving rise to new possibilities in fields ranging from human resources and traffic management to business strategies and power station control [1].

Data exchange between people is crucial as well. It accelerates business processes, facilitates communication for travelers, or allows us to stay in touch with family and friends. Unfortunately, there are

* Corresponding author.

E-mail address: ksenia.osipova@upc.edu (K. Osipova).

<https://doi.org/10.1016/j.actaastro.2024.07.022>

Received 21 November 2023; Received in revised form 12 March 2024; Accepted 11 July 2024

Available online 15 July 2024

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still populated areas, which are not covered by ground-based telecommunication infrastructure, primarily in developing countries or rural areas.

Data transmission can be conducted wireless via cell towers, or using cables or optical fibers. However, in rural and remote areas deploying cell towers or laying cables is a quite complex task due to the geographical location, such as islands or mountains, and/or the absence of urban infrastructure like roads or electricity supply. To overcome this, satellites can act as “cell towers in space” or “space gateways”, providing broader coverage and enabling even individual users in isolated regions to connect.

Currently, the most widely spread ways of wireless connectivity between user terminals are technologies based on 3GPP standards [2]: from early generations such as GSM to the most advanced ones, such as LTE [3] and 5G NR [4]. However, these standards have several limitations for satellite communications for direct-to-handset services. This results in increased complexity and cost for both telecommunication payloads and satellites.

Several companies are working towards offering direct connectivity for regular smartphones using satellites. For example, Lynk Global [5] managed to send and receive an SMS message over their satellite Lynk Tower in 2020 [6] and conduct a voice-call in 2023 [7]. The requirement to establish the link and provide sufficient data rate for a 4G LTE signal from a 500-km orbit forced the satellite mass to reach 100 kg. In September 2023 AST SpaceMobile [8] accomplished a successful voice call through BlueWalker-3 satellite reaching a data rate of 14 Mbit/s [9]. BlueWalker-3 weighs 1500 kg, and it is equipped with a 64 m² deployable phased antenna array to shape multiple beams into cell coverage.

Technologies under the 3GPP standards use advanced modulation techniques. For instance, LTE leverages QPSK and QAM modulations, which require either high signal power or narrow signal bandwidth to demodulate the signal properly at the receiver. Another technical problem is the orbital velocity causing the Doppler frequency shift of a signal, which needs to be compensated at the user equipment (UE) or on the satellite side. Both cases require extra computational power to calculate the exact position of the UE and satellite or to implement Doppler frequency shift compensation algorithms [10,11].

Internet of Things (IoT) is another type of connectivity that New Space companies are focusing on. This technology is a part of the 5G service called massive machine-type communication (mMTC), which is suitable for applications requiring numerous device connections, such as smart cities, smart homes, digital agriculture, and remote facility control. IoT devices are affordable due to their low complexity and high energy efficiency, and they can function independently for up to several years [12].

IoT technologies can be standard or private. NB-IoT and LTE-M come from the LTE telecommunication standard and are maintained by the 3GPP community. LoRa and Sigfox are proprietary solutions owned by Semtech and Sigfox, respectively. According to Omdia LPWAN Market Report [13], LoRa and NB-IoT are currently the top contenders and are expected to make up to 87% of all LPWAN connections by 2028.

Sateliot [14] is a company that aims to provide seamless connectivity for IoT devices via satellites. Focusing on message transmission without voice calls allowed to reduce the satellite mass to 3U and 6U CubeSats. Sateliot employs NB-IoT, and it is participating in the development of new releases of the 3GPP standards regarding NB-IoT. In the latest Release 17 [15] the use of UE with GNSS functionality is suggested for Doppler frequency shift compensation. The drawback of this approach is an increase of an UE complexity and power consumption.

Lacuna Space [16] is constructing a system that utilizes LoRa technology to facilitate the integration of UE with terrestrial LPWAN networks through a satellite constellation. As of November 2023, there are 3 CubeSats on LEO and additional hosted payloads on larger satellites (e.g. OneWeb [17]) to enable beam hopping. The UE is an LS300

sensor and relay developed in collaboration with Semtech, the owner of LoRa technology. Lacuna Space has successfully sent and received LoRa messages to the Moon from the Dwingeloo radio telescope with a 25-meter antenna [18], demonstrating the vast potential of LoRa technology for space applications.

FOSSA Systems [19] is working with even smaller satellites of PocketQube's 2P form factor, which is $5 \times 5 \times 10 \text{ cm}^3$, or Ferox, which a proprietary form factor of $2 \times 2 \times 0.25$ units (1 unit is 1 cube of 10 cm side). Their goal is to provide LoRa connectivity with 3 UE types: industrial nodes (FOSSA-XL), medium independent nodes (FOSSA-M), and small nodes (FOSSA-S) connected with a satellite through FOSSA-XL, serving as a gateway. FOSSA Systems has launched a total of 12 satellites, and as of November 2023, three of them are active [20].

For both technologies, NB-IoT and LoRa, maximum transmitted powers are quite close: 22 dBm for LoRa, and 23 dBm for NB-IoT [21]. The channel bandwidths are also comparable, with NB-IoT at 200 kHz, and LoRa between 125 and 500 kHz. However, NB-IoT offers a much higher channel capacity of 250 kbps, almost ten times more than LoRa's capacity of 27 kbps. On the other hand, LoRa's spread spectrum modulation is capable to cope with the Doppler frequency shift without any additional techniques, while NB-IoT requires that the receiver compensates for the Doppler frequency shift, making UE more complex and expensive. These features make LoRa a promising technology for low-cost low data rate applications via LEO satellites.

Large terrestrial telecommunication players have declared their intention to jump into the satellite communications market as well. For example, technological giants as Samsung and Qualcomm have developed smartphone chip editions containing the functionality of direct phone-to-satellite connectivity [22,23]. Their main competitor, Apple, also launched a collaboration with Globalstar [24], aiming at providing SMS messaging service via the Globalstar constellation. Huawei is following the same trend, leveraging on the Beidou geopositioning constellation [25]. Finally, SpaceX has successfully tested text messaging for ordinary smartphones via Starlink constellation on January 6th, 2024 [26]. The company is targeting to start the delivery of voice and data connectivity to cell phones and IoT services in 2025 [27].

There is evidence of financial struggle in some IoT connectivity constellation projects. For example, Eutelsat released a plan of launching a 25 nanosatellites constellation for IoT [28] but put it on indefinite hold [29]. Sky-and-Space Global [30] was delisted by the Australian Stock Exchange and went through the bankruptcy procedure [31], as well as another IoT company, Hiber [32], providing remote monitoring of oil and gas assets [33]. These cases highlight the necessity of business model verification and a deeper analysis of the system performance from both, technical and financial points of view.

The scientific community has explored the potential of utilizing LoRa technology for messaging purposes. For instance, a recent proposal in [34] suggests the creation of an independent network composed of LoRa devices that can exchange messages with one another or relay them to a Telegram-bot through gateways equipped with LoRa modules connected to the Internet. These gateways are equipped with a LoRa module and an antenna, and initial tests have shown that messages can be transmitted in about 2 s. Another suggestion for LoRa technology is its use as last-mile data delivery, as proposed in [35]. This network consists of UEs with LoRa functionality which are connected to Internet Proxy server managers through LoRa gateways and repeaters. The network prototype was successfully tested at distances up to 400 m. Another well-known project is the network of ground stations for satellites, equipped with LoRa transceivers, signals reception and operation. It is called TinyGS [36] and consists of around 1400 stations over the world as of February 2024. 25 satellites are currently communicating with the Tiny GS network. Many of these satellites are created by universities. For example, Doppler effects on LoRs signal was studied during flight tests of 6U CubeSat NORBY [37] and proved the LoRa signal robustness for communication from LEO. In [38] LoRa signal was tested for image transmission from a CubeSat to the ground,

which became possible by applying Vista communication system for on-board data encoding, decoding on the ground, and on-board image processing.

This study proposes an end-to-end framework for architecting optimal constellations of communications satellites, and it has been applied to the particular case of a messaging service using LoRa technology. Part I focuses on the demand map estimation and the payload conceptual design, while Part II [39] deals with the constellation design itself, including economical and service performance optimization.

The suggested methodology stands out from other existing approaches because it implies parametric end-to-end modeling of the all main elements of a satellite constellation, including users traffic, communications channel, satellite sizing, messages transfer simulation, constellation architecting and profitability estimation in a single model. While existing ones are focused on one of the aspects like communication channel and coverage optimization [40], inter-satellite network architecting [41], or quality-of-service optimization. The study [42] is closer to an end-to-end modeling, since it includes demand traffic, satellite model, launch cost and financial evaluation. However, this model lacks some elements, which are considered in our suggested framework, such as geographical users distribution, several launch strategies, and service pricing. The presented approach facilitates not only an overall system optimization considering all the listed above elements, but also an analysis of the impact of single parameters on the overall system performance.

1.2. Research objectives

To reach the goals of Part I the following objectives are targeted:

1. To build a demand map of unserved users based on the databases of population density distribution, and cell towers locations, as the most spread communication infrastructure, to estimate the required data rate for serving the potential data traffic demand;
2. To compare LoRa technology and GSM standard applied to satellite communications;
3. To estimate LoRa performance for satellite messaging as well as the impact of channel parameters on the achievable channel capacity, and the maximum distance from which the link can be established;
4. To identify a set of feasible payloads for satellite messaging using LoRa technology, to be used later in the constellation design.

1.3. Structure of the paper

The remainder of the paper is organized as follows. In Section 2 the procedure to build the demand model is presented, and Section 3 describes the LoRa communication channel performance, as well as its dependence on the Spreading Factor, orbital height, and satellite antenna beamwidth. The antenna and transceiver parameters estimation approach is explained in Section 4. In Section 5 a downselection of the telecommunications payload architectures is conducted to reduce the number of feasible payloads for further consideration in the whole constellation optimization (Part II of the study). Section 6 discusses the results' significance and limitations, and Section 7 summarizes the obtained results.

2. Demand model

In this section, the demand model is built based on the population density distribution, that is not covered by cell towers. The model will be further used to estimate the required data rate to enable at least one message per user per day for the worst-case scenario, corresponding to the most densely populated areas in the world.

Previous demand models for constellations of communications satellites were suggested by different authors. For example, in [43] the

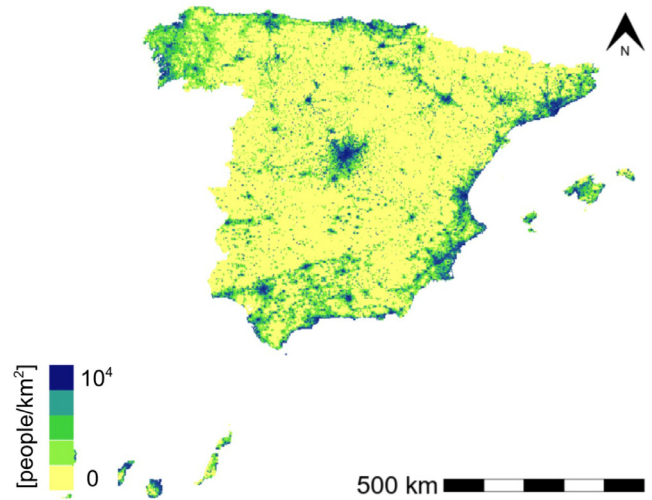


Fig. 1. Population density distribution of Spain in 2020.

model aiming to estimate the throughput for the optimization of mega-constellations (e.g. Starlink, OneWeb, Telesat), and ground stations (GS) is presented. In this approach, the link is modeled between a satellite and a GS, not directly with users. In order to estimate the demand size, a world population distribution map was used, and 10% of this population is considered as potential customers for a satellite connectivity service. Traffic simulation for satellite communication was described in [44] to optimize satellite antenna beam patterns. This model includes population density distribution, and flight and marine traffic databases, considering not only the spatial users distribution, but also the temporal fluctuations.

However, both models do not take into account whether this potential demand is already satisfied or not. In the demand model presented in this paper, the share of the population already covered by terrestrial infrastructure is estimated, and therefore not considered as potential users.

2.1. Map of the uncovered population

In this study, the part of the world population that is located outside of the radius of coverage of cell towers is considered as potential users of the satellite communication system.

In order to build this model, data from two databases have been used. The first one is the population density map for all countries, which was created by the WorldPop research program [45] by the School of Geography and Environmental Sciences at the University of Southampton. The database is peer-reviewed, and it contains data from the years 2000 to 2020. The mapping resolution is 30 arc-seconds (approximately 1 km at the equator) allowing us to build a very realistic users distribution over the Earth's surface. As an example, the population density distribution of Spain in 2020 is shown in Fig. 1.

The second database was created by the OpenCellid project [46], established by the world collaborative community, collecting GPS positions of cell towers from the whole world, as well as other tower characteristics, including cell tower range, and their capacity. For instance, the locations of the cell towers in Spain are represented in Fig. 2.

In order to generate the map of not covered users, for each grid cell with a population, collected from the WorldPop database, it is estimated if any cell tower taken from OpenCellid covers this population grid cell or not. As shown in Fig. 3, the grid cell is considered as covered by a cell tower if the distance between the grid cell center, and a cell tower is less than the cell tower range. If at least one cell tower



Fig. 2. Cell towers locations in Spain.

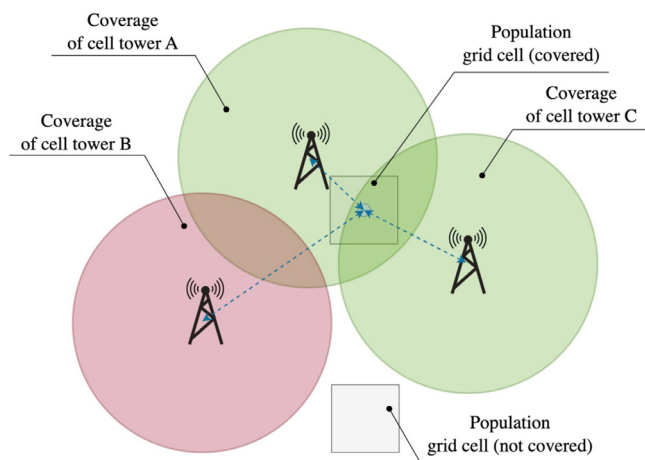


Fig. 3. Demand map unit coverage determination approach.

covers the population grid cell, this grid cell is considered as covered and removed from the database. After running the algorithm, it was obtained that 2.2 billion people or 28% of the world population is out of cell towers coverage. The highest amount of unserved users were identified in Asia and Africa, while the populations of the Americas, Europe and Australia are mostly covered by terrestrial infrastructure.

In the second step, scaling of the demand map of not covered population distribution is performed in order to decrease the demand map granularity and make the subsequent simulations less computationally intensive. In order to estimate an optimal target scale, a simulation of one satellite with maps of different granularities was firstly conducted. This simulation model itself is described in detail in Part II of the paper [39]. Varying Latitude/Longitude step from 5×5 degrees up to 40×40 degrees, it was found that the resulting satisfied demand did not change significantly for the different grid sizes considered (Fig. 4). On the other hand, there is the expected dependence of the simulation time on the granularity — the smaller the Latitude/Longitude step, the longer the simulation time. Despite the simulation time for a single satellite being at the order of tens of seconds, decreasing the simulation time is crucial for further simulations at the constellation level. The considered constellation size may reach up to 324 satellites (case of 18 orbital planes with 18 satellites per plane), and for this constellation simulation time reaches the order of hours. Moreover, for each constellation size, several simulations are planned to be done for different orbital heights and inclinations. Thus, a Latitude/Longitude

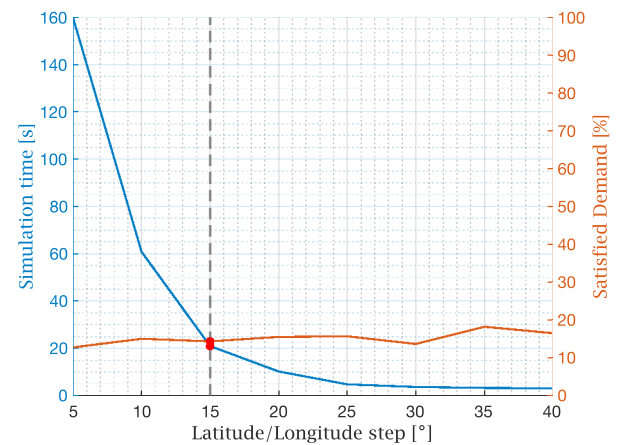
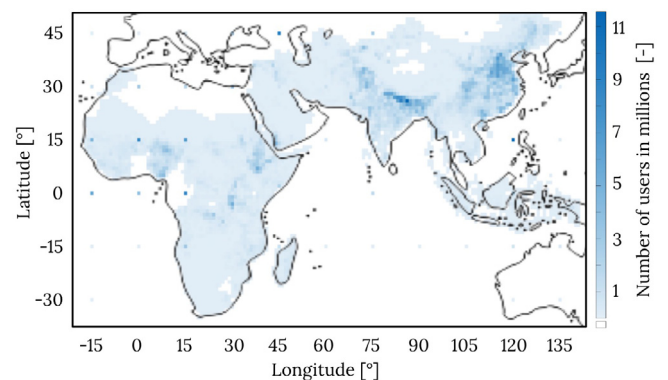


Fig. 4. Dependence of the simulation time and the satisfied demand on the Latitude/Longitude step size.

Fig. 5. Number of users that are not covered by cell towers (area with the highest users density (Asia and Africa) is enlarged, heterogeneous granularity: 1×1 and $15 \times 15^\circ$).

step of 15×15 degrees has been chosen, as a good compromise between accuracy and computational time.

In order to have the ability to model a realistic amount of messages per day, and avoid an overconcentration of the demand in a single grid cell, the Latitude/Longitude step in the areas with the highest amount of not covered users, i.e. Africa and Asia, is decreased down to 1×1 degrees. As a result, the demand map with heterogeneous granularity of 15×15 and 1×1 degrees is obtained, where some areas on the map, primarily Asia and Africa, are covered by adjacent cells, while the Americas, Europe, and Australia are primarily covered by separated cells, collecting all the surrounding users into one cell. The part of the map with the highest concentration of potential users is shown in Fig. 5.

The obtained demand model can be verified by the comparison of the results with the figures reported by other research institutions. For example, the GSM Association in its State of Mobile Internet Connectivity Report 2021 [47] stated that 3.8 billion people remained unconnected, but only 450 million lived out of the areas with mobile broadband coverage. So, the existing gap is not “the coverage gap”, but “the usage gap”. While in the developed demand model 2.2 billion are obtained as uncovered. The International Telecommunication Union declared that in 2021 2.6 billion people were offline, and 96% of them lived in developing countries [48]. Indeed, on the created demand map it is seen that the majority of unconnected users are located in Africa and Asia.

This difference can be explained by the incomplete database of cell towers locations which is created by the world’s collaborative community, thus cell towers data can be added by any user. That is

Table 1

Number of users in millions in a footprint centered in Beijing depending on an antenna beamwidth and an orbital height.

Antenna beamwidth [°]	Orbital height [km]			
	400	600	800	1000
30	16.85	48.26	77.71	104.74
50	58.54	113.06	194.20	250.49
70	118.67	211.29	313.15	385.47

why some data, especially regarding new towers, can be missed, which may explain the difference between the uncovered population, obtained with the suggested approach, and the unserved users according to GSMA or ITU. Despite this, the developed demand model may still be used because it represents the users distribution which is higher in developing countries, and lower in the developed areas as it is in reality. Also, “the usage gap” is close to the number of not served users obtained by the model (2.6 vs. 2.2 billion). So, this gap can be closed by satellite connectivity as a mobile connectivity competitor.

2.2. Required channel capacity

The area with the highest population density not covered by cell towers is located in the Beijing area in China. Therefore, the required parameters of the telecommunications payload have to ensure service in this area as the worst case.

Further analysis aiming at the determination of the required channel capacity is conducted for a footprint, whose center is located at latitude 35° and longitude 115°, where Beijing is. Depending on the antenna beamwidth and satellite orbital height, a different number of users will be located within the antenna footprint. From Table 1, it is clear that the larger the antenna beamwidth, and the higher the orbit, the more users will be in the antenna footprint. Consequently, having more users per satellite footprint leads to payloads with higher throughput to transmit the required amount of messages per unit of time.

In order to provide an opportunity to send at least one message per day for every user, a different data rate is required for each satellite footprint, which is determined by the combination of two parameters: the antenna beamwidth, and the orbital height. As a first approximation, the demand is assumed to be uniformly distributed during a day, and the message size is considered equal to 140 bytes, as stated in GSM standards for SMS messages [49]. The message size is increased by 10%, considering the addition of service information such as time stamps, message length, protocol ID, etc. The required channel capacity to provide at least one message per day for every user in a footprint is represented as a heat map in Fig. 6.

3. Communication technologies performance analysis

In this section, the GSM standard and the LoRa technology are compared by means of the achieved channel capacity and the required transmitted power. For the selected one a more detailed analysis is conducted, including uplink and downlink design, channel parameters discussion, and the estimation of the quality of service (QoS).

3.1. Theoretically achievable channel capacity

The required channel capacity characterizes the target performance that a payload has to provide to transmit at least 1 message per day per user in a footprint. In the next step, the data rates that can be provided by a satellite applying GSM and LoRa are analyzed and compared to the required ones.

The achievable capacity directly depends on the signal strength received by the UE. The higher the orbital height, and the larger the antenna half-power beamwidth, the weaker the received signal will be. Fig. 7 shows the values of the received signal strength for a UE with

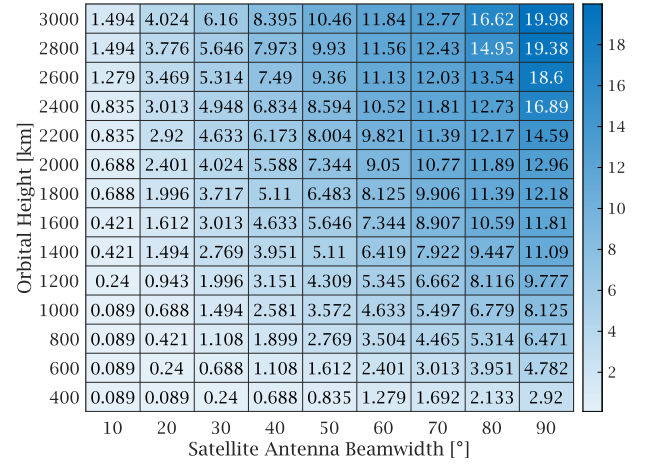


Fig. 6. Required channel capacity in Mbps, which telecommunication system has to provide for enabling at least 1 message per day for every user in a footprint centered in Beijing.

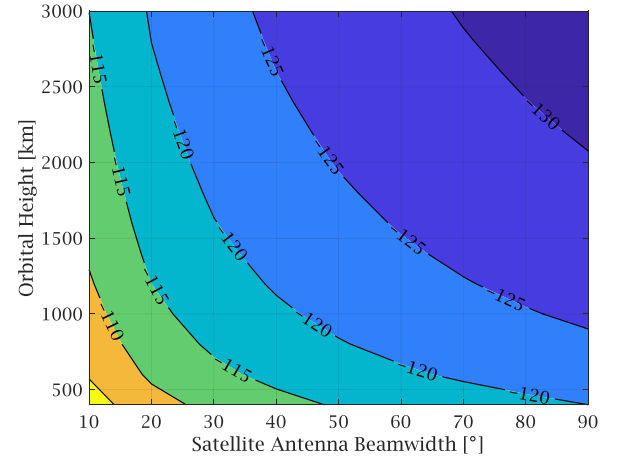


Fig. 7. Received signal power (in dB) by user equipment depending on an antenna beamwidth and orbital height ($P_{tr} = 2$ W, $G_r = 2$ dB, $G_{tr} = f(\beta)$).

a receiving antenna gain of 2 dB, and a satellite payload transmitting a peak power of 2 W. It is clearly seen from the graph that in order to keep the same received signal power in case of increasing one parameter, orbital height or antenna beamwidth, the second one has to be decreased and vice-versa. The transmitting antenna gain (G_{tr}) here depends on the antenna solid angle (Ω , Eq. (1)), which, for a pattern with rotational symmetry, can be approximated as the square of the antenna beamwidth (β) as $\Omega \approx \beta^2$, and the antenna efficiency, which is assumed to be 0.9:

$$G_{tr} = \frac{4 \cdot \pi}{\Omega} \cdot \eta_{tr} \quad [-] \quad (1)$$

The Shannon Limit [50] indicates the maximum theoretical data rate, which can be transmitted as a function of the signal-to-noise ratio:

$$\frac{R}{BW} = \log_2 \left(1 + \frac{S}{N} \right), \quad [\text{bps/Hz}] \quad (2)$$

where R is data rate in bit/s, BW – channel bandwidth in Hz, S – received signal power in Watts, and N – noise power in Watts. In our case, the 960–1164 MHz bandwidth is considered, which is allocated to the Aeronautical Mobile application for all Earth regions, according to ITU Radio Regulations [51]. As the first approximation, 26 MHz of total bandwidth around central frequency of 973 MHz is used, as the closest option to the ISM and GSM-900 bands. The channel bandwidth

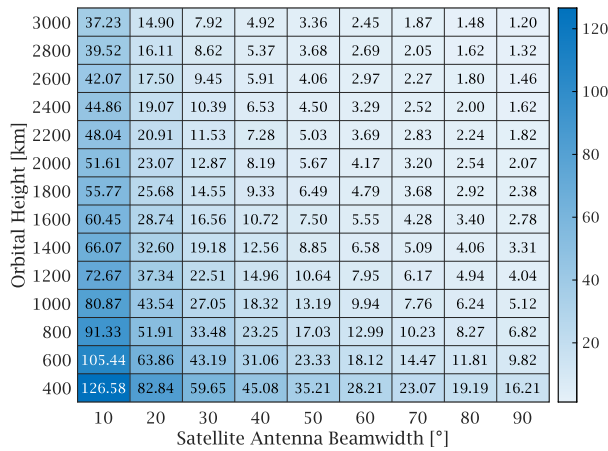


Fig. 8. Total maximum data rate for 208 channels of 125 kHz of bandwidth in Mbps, according to the Shannon Limit.

is assumed to be 125 kHz, which is the most commonly used for LoRa satellite communications, as it can compensate the Doppler frequency shifts, and it will be optimized in Section 5.

In order to compute the Shannon Limit, the received signal and noise powers must be computed. The received signal strength S equals to the product of transmitted power, transmitter and receiver antenna gains, divided by losses:

$$S = \frac{P_{tr} \cdot G_r \cdot G_{tr}}{L_s \cdot L_p \cdot L_a} \quad [\text{W}] \quad (3)$$

The free-space loss L_s , in logarithmic units is given by Eq. (4):

$$L_s = \left(\frac{4\pi}{c} \right)^2 \cdot R^2(h, \theta) \cdot f^2, \quad [-] \quad (4)$$

where f is the carrier frequency, $c = 299\,792\,458$ m/s is the speed of light in vacuum, and R is the propagation path length, which depends on the orbital height h and the satellite elevation angle θ . For the worst case scenario, the distance R is the largest distance between a satellite, and the footprint center on the Earth's surface, at the lowest elevation angle equal to 10° , considering that the antenna is pointing towards the target area center.

Polarization losses (L_p), account for the polarization mismatch between the transmitter and the receiver antennas, which is assumed to be equal to 3 dB (circularly polarized transmitter antenna, and linearly polarized receiver antenna). The attenuation losses (L_a) due to atmospheric effects and rain absorption are assumed to be 3 dB.

As system's noise temperature T_{sys} , a value of 1090 K is considered, based on the ITU recommendations regarding radio noise [52], which corresponds to the median man-made noise in a business area.

The noise power is calculated as follows:

$$N = k \cdot T_{sys} \cdot BW, \quad [\text{W}] \quad (5)$$

where k - is the Boltzmann constant, equal to $1.38 \cdot 10^{-23}$ J/K.

The values of the maximum total channel capacity (per 208 channels of 125 kHz bandwidth each one) as a function of the antenna beamwidth and the orbital height are represented in Fig. 8. As it can be seen, the lower the orbit, and the smaller the antenna beamwidth, the higher the data rate that can be achieved.

Real throughput is always less than the theoretical Shannon Limit due to other losses, modulation schemes, packet collisions, and how data packets are handled by the protocol. Further, GSM and LoRa technologies are analyzed to estimate their potential for the proposed space telecommunication system.

3.2. GSM vs. LoRa trade-off

This section compares the applicability of GSM and LoRa technologies for messaging via satellites. The comparison is done in terms of the provided data rate and required satellite transmitted power as the key figures of merit (FoM) for our use case.

3.2.1. GSM standard applicability

The GSM standard [53] was created to describe the protocols for the second generation of digital cellular networks, and it was optimized for full duplex voice telephony with the following adaptation for data transfer by packet data transport technology. In the case of GSM with a code rate of 1, the maximum possible data rate is achieved: 21.55 kbit/s per channel [54]. A GSM channel occupies a bandwidth of 200 kHz which ensures a total data rate of 2801.5 kbit/s for 130 channels within 26 MHz of total bandwidth. This data rate is higher than the required data rate in 40 considered target areas (Fig. 6).

According to the 3GPP standards [55], the reference sensitivity level for GSM-900 with a central frequency of 935 MHz is -102 dBm. To achieve this performance, the satellite payload has to transmit at least 64 dBm. Considering a 5 dB margin, possible combinations of payload parameters would be a transmitted peak power of 8 W, and the transmitting antenna gain of 27 dBi from an orbital height of 400 km. As a result, the GSM-900 standard could be able to satisfy the demand, but it requires a significant transmitted power of the satellite payload, and a large antenna in order to establish a communication link.

3.2.2. LoRa technology applicability

Another promising technology is LoRa [56], which was developed by Semtech [57] to establish low-volume data exchange between sensors located at long distances. LoRa has a programmable channel bandwidth around a programmable central frequency [58], and it allows the system to optimize the data rate versus power or sensitivity. LoRa modems that are currently available in the market have low mass and power consumption. These characteristics allow us to consider their use of as user terminal with limited power consumption for direct Earth-to-satellite connectivity.

LoRa technology is able to provide 18.75 kbit/s at 250 kHz channel bandwidth and a Spreading Factor (SF) of 6, which is the closest data rate per channel for GSM-900 (21.55 kbit/s). According to SX1261/2 radio transceivers datasheet [58], SNR has to be larger than -5 dB to ensure signal decoding for a SF of 6 (or even smaller for larger spreading factors, $SF \geq 7$), which can be achieved with 45 dBm of transmitted power from an orbital height of 400 km. This value is lower than the required one in the case of GSM-900 (64 dBm), which translates into a decrease of the mass, and cost of a payload, and the satellite itself. Taking into account the fact that this data rate is much higher than the required one for many footprint cases, the provided data rate can be decreased even more together with the corresponding savings in payload mass and cost.

Comparing GSM and LoRa technologies, LoRa requires a lower received signal power to establish the link with a comparable data rate as GSM. For this reason, the satellite constellation design and, in particular, payload sizing will follow the LoRa approach, aiming to low-cost constellation architecture configured specifically for messages transmission.

3.3. LoRa performance for messaging service

In this section, the LoRa channel parameters and their impact on the channel capacity are analyzed, as well as the uplink and downlink design. Also, their influence on the number of feasible combinations of antenna beamwidth and satellite orbital height is investigated.

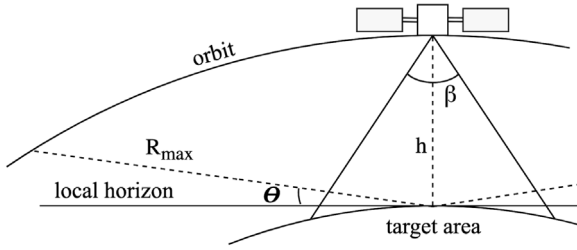


Fig. 9. Satellite position over a target area for LoRa link modeling.

3.3.1. LoRa channel capacity and number of packets

(a) Channel capacity

The maximum achievable channel capacity for LoRa technology is determined with the equation [59]:

$$C = \frac{SF \cdot RC \cdot BW}{2^{SF}}, \quad [\text{bps}] \quad (6)$$

where SF is Spreading Factor, and RC is Rate Code, calculated in its turn as follows:

$$RC = \frac{4}{4 + CR}. \quad [-] \quad (7)$$

Here CR is the coding rate, which may vary from 1 up to 4, and it is assumed to be equal to 1, as it corresponds to the lowest amount of redundant bits in the forward error correction code (FEC).

This capacity is the maximum value that the channel can provide at the physical layer, but the actual channel throughput will be lower due to the impact of the Medium Access Control, and the characteristics of the applied communication protocol, as well as the probability of packets collisions. For a preliminary estimation the maximum channel data rate is used, i.e. channel capacity. Additionally, a dynamic full-duplex system is considered, allowing the use of all the channels for both uplink and downlink.

As stated in Section 2, for the communication link modeling a target area with a center in the Beijing area and a “static” satellite over it are considered (Fig. 9). In order to estimate if the performance meets the existing demand, the relation of the total data rate (per 208 channels) provided by LoRa, and the required total data rate is calculated for different footprint sizes. For further analysis, $SF = 7$, and $BW = 125$ kHz will be assumed as they are often used for LoRa.

(b) Number of packets

The amount of transmitted messages is equivalent to the amount of transmitted LoRa packets, containing 1 message per data packet. In order to calculate it, the Time on Air (ToA), i.e. the amount of time required for the transmission of one LoRa packet has to be computed. A LoRa frame [59] consists of a preamble with a minimum size of 4.25 symbols ($N_{sym_preamble}$), a header of 20 symbols (N_{s_h}) for the explicit header as a default one, a Cyclical Redundancy Check (CRC) of 16 symbols (N_{bit_CRC}) and the payload, which is a message of 140 bytes (N_{byte_PL}). The message size is assumed to be the size of the SMS message. CR here is the number of redundant symbols for coding. The total amount of symbols per frame N_{symbol} is calculated as:

$$N_{symbol} = N_{sym_preamble} + a + 8 + (CR + 4) \cdot \text{ceil}\left(\frac{\max(8 \cdot N_{byte_PL} + N_{bit_CRC} - 4 \cdot SF + 8 + N_{s_h}, 0)}{4 \cdot SF}\right), \quad (8)$$

where “ceil” is the rounding operator to the next integer number, and parameter a equals 6.25 for $SF = 5$ and 6, and $a = 4.25$ for $SF \geq 7$, according to the Semtech documentation [59].

Then, the ToA for a frame containing a message is given by:

$$ToA = \frac{2^{SF}}{BW} \cdot N_{symbol}. \quad [\text{ms}] \quad (9)$$

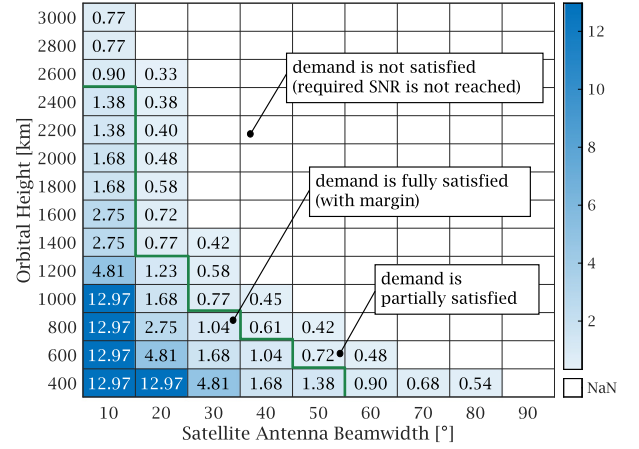


Fig. 10. Available number of messages per user per day with LoRa modulation for different footprint sizes centered in Beijing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Knowing the channel capacity and the ToA , the amount of LoRa packets containing messages can be calculated. The number of messages per user and per day that can be transmitted using LoRa for different footprint sizes is shown in Fig. 10. In the heatmap, the demand is fully satisfied, if the value is above 1. In this case, the satellite can provide even more than 1 message per day per user. On the other hand, if the value is less than 1, it means that the demand is partially satisfied — not all users can send at least 1 message per day. These two areas are separated by the green line in the figure. Empty cells mean that the provided signal strength is less than the required sensitivity, and therefore the communications link cannot be closed. So, it can be clearly seen that a sufficient amount of combinations of orbital height, and antenna beamwidth can satisfy the existing demand and provide capacity to transmit over 1 message per user per day.

3.3.2. Variation of LoRa channel parameters

In this section, two parameters having a significant impact on the LoRa channel data rate are discussed. They can be configured and optimized according to the communication system needs.

(a) Spreading Factor (SF)

One of the important parameters to consider is the Spreading Factor. SF controls the channel capacity, regulating how the signal is spread in frequency. This spread is adjusted by the number of raw bits that can be encoded per symbol. Thus, each symbol contains 2^{SF} chips in the Chirp Spread Spectrum modulation used by LoRa.

SF is a key parameter to tune the channel capacity and the minimum SNR required to demodulate the signal. The higher the SF , the more chips each symbol contains which increases the coding gain and leads to the decrease of the minimum required SNR, but at the price of a reduced data rate. However, lower SNR allows longer signal transmission distances, due to higher coding gain, and decreases telecommunication payload mass, thanks to smaller signal power or antenna directivity. In our case it also helps to increase the target area, covered by an antenna with a larger beamwidth, and to have more users in satellite visibility.

The described trade-off between the data rate and the target area size will be considered during the performance simulation at a constellation level in order to identify the optimal SF values. In the Semtech documentation [58], SF values range from 5 to 12, while the minimum SNR required to demodulate LoRa signal is specified only for values of SF from 6 to 12. Thus, to analyze all possible cases, we consider cases with SF only from 6 to 12.

Fig. 11 shows the impact of the SF on the performance of the messaging case. For larger SFs , the channel capacity decreases, leaving

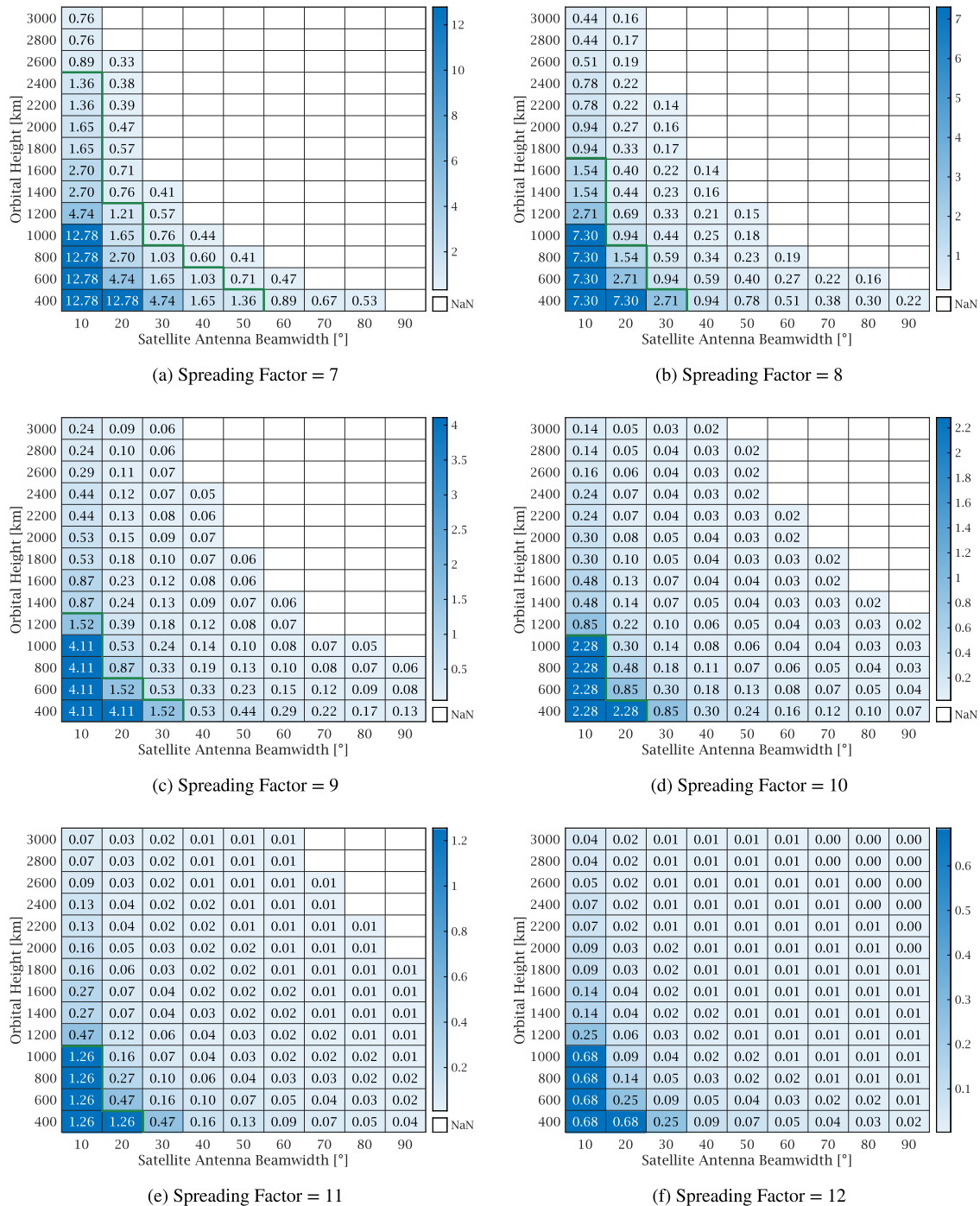


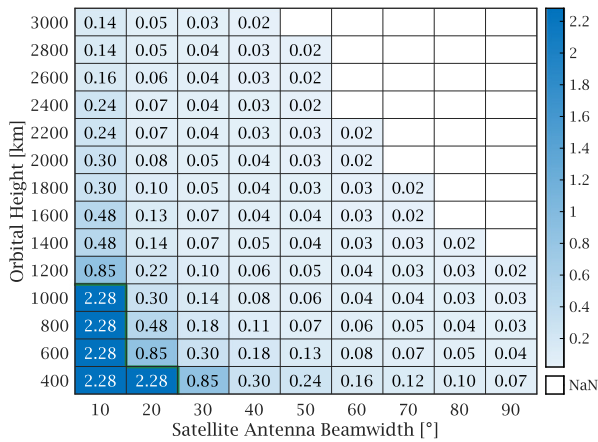
Fig. 11. Relation of the required data rate and the provided data rate (per 208 channels) with LoRa technology for different spreading factors.

fewer cases of fully satisfied demand, but on the other hand, the number of cases where the link can be established increases due to the decrease (i.e. improvement) of the minimum required SNR. The channel BW in this case is fixed at 125 kHz.

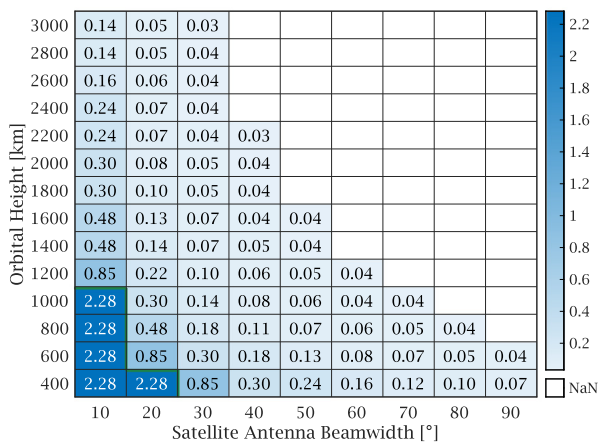
(b) Channel Bandwidth

Another parameter to consider is the channel bandwidth. The bandwidth values applicable to LoRa technology vary from 7.81 up to 500 kHz, while the most widely used one equals 125 kHz. For the case of satellite communications the set of available values decreases due to the Doppler frequency shift. According to [59] the maximum allowed frequency offset between transmitter and receiver which is

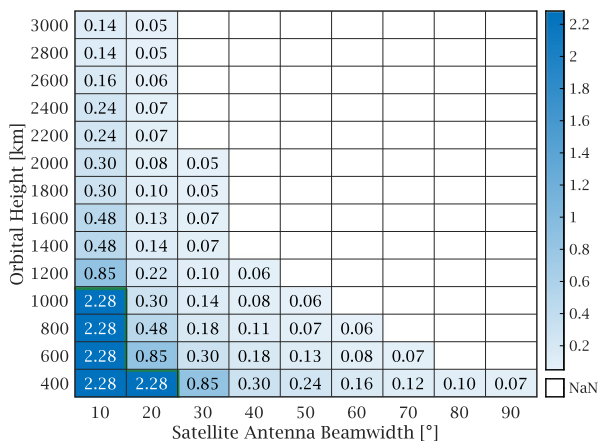
not causing sensitivity degradation is 25% of channel bandwidth. The Doppler frequency shift at an orbital height of 400 km is the largest one among the orbital heights considered because the largest orbital velocity corresponds to the lowest orbit. At this orbit Doppler frequency shift equals 24.9 kHz, which is around 20% of channel bandwidth of 125 kHz. Thus, for the case of a satellite constellation, channel bandwidths of 125, 250, and 500 kHz can be considered as valid options allowed by LoRa design from one side, and able to compensate for the Doppler frequency shift from another side. To use a narrower channel bandwidth of 62.5 kHz, the orbital height has to be increased up to 10,000 km, where the Doppler shift equals 15.63 kHz.



(a) Channel Bandwidth = 125 kHz



(b) Channel Bandwidth = 250 kHz



(c) Channel Bandwidth = 500 kHz

Fig. 12. Relationship between the required data rate and the provided data rate (per 208 channels) with LoRa technology for different channel bandwidths ($SF = 10$).

In our model, the channel capacity does not depend on the bandwidth change because by reducing the bandwidth, the number of channels in the total bandwidth increases by the same amount. The same effect is observed in the ToA parameter. For larger bandwidths, the ToA is smaller, so more LoRa packets can be transmitted per unit

Table 2

Downlink budget for one of the architectures, providing the highest channel capacity.

Parameter	Value	Units
Orbital height	1000	km
Range at 10° elevation	2764	km
Central frequency	973	MHz
Transmitter peak power	2	W
Transmitting antenna beamwidth	20	°
Transmitting antenna gain	18.1	dBi
Receiving antenna gain	2	dBi
Polarization losses	3	dB
Attenuation losses	3	dB
Free space losses	161.0	dB
Noise	−117.3	dBm
Received signal power	−113.9	dBm
Signal-to-noise ratio	3.3	dB
Min required signal-to-noise ratio	−5	dB
Min margin	5	dB
Channel bandwidth	125	kHz
Coding rate	1	–
Spreading factor	7	–
Achieved data rate per channel	5.5	kbit/s
Time on Air	0.2	s
Total bandwidth	26	MHz
Number of channels in the bandwidth	208	–
Total data rate per all channels	1137.5	kbit/s

of time and per channel, but the reduced amount of channels cancels out this effect. In reality, gaps have to be introduced between channels because of the frequency roll-off of the band-pass filters, which will lead to a reduction of the available number of channels. Thus, a wider bandwidth is preferable because the number of gaps introduced will be smaller. As a drawback of this approach, due to the wider bandwidth and reduced SNR , the channel will suffer from a higher noise level, which can be compensated by either a higher transmitted signal power, or to some extent, by improving the noise figure of the receivers' low-noise amplifiers.

Fig. 12 shows the impact of the bandwidth change on the number of cases when the communication link can be established. With the growth of the channel bandwidth, the amount of payload architectures able to transmit reduces, because the larger data rate requires a higher SNR to demodulate the signal. For comparison purposes the SF is fixed at 10, and the transmitted power at 2 W.

In addition, channel throughput has to be taken into account as well. It depends on coding schemes and messages transmission protocol. However, as the first approximation, the ideal case of a 100% of channel efficiency is considered. The QoS (i.e. collisions probability) will be discussed in Section 3.3.4.

3.3.3. Link budget

Taking into account all the parameters discussed above, the link budget can be calculated. Table 2 presents the results for one of the cases, providing the highest channel capacity. The satellite is located at an orbital height of 1000 km, and the transmitting antenna beamwidth equals 20°.

Following the assumption that UE has restricted capabilities, comparable to an ordinary mobile phone, it is required to analyze the uplink, and the downlink as well. In general, network operators use adaptive power control to keep phones transmitting with a power no higher than what is necessary to meet the required sensitivity to avoid extra noise. This power is dynamically adjusted depending on various parameters, such as the distance from the cell tower, surround noise level, and the presence of physical obstacles, which introduce additional losses. In [60] authors measured the output power of mobile devices in different area types: rural, small urban, suburban, and city areas. According to their results, the highest output power level registered at the frequency of 900 MHz equals 2 W. The frequency selected for our case study, 973 MHz, is located quite close to 900 MHz, so it is relevant

Table 3

The corresponding uplink budget.

Parameter	Value	Units
Orbital height	1000	km
Range at 10° elevation	2764	km
Central frequency	973	MHz
Transmitter peak power	2	W
Transmitting antenna gain	2	dBi
Receiving antenna gain	18.1	dBi
Polarization losses	3	dB
Attenuation losses	3	dB
Free space losses	161.0	dB
Noise	−123.0	dBm
Received signal power	−113.9	dBm
Signal-to-noise ratio	9.1	dB
Min required signal-to-noise ratio	−5	dB
Min margin	5	dB
Channel bandwidth	125	kHz
Coding rate	1	–
Spreading factor	7	–
Achieved data rate per channel	5.5	kbit/s
Time on air	0.2	s
Total bandwidth	26	MHz
Number of channels in the bandwidth	208	–
Total data rate per all channels	1137.5	kbit/s

Table 4

Inputs for Erlang B formula.

Original parameters	Analogues	Values
Number of calls per minute	Number of messages per minute	33 510
Average handling time	LoRa packet duration (ToA)	0.218 s

Table 5

Patch antenna designs.

Number of elements	Antenna beamwidth [°]	Gain [dBi]	Dimensions [m]	Mass [kg]
2 × 2	114.6	4.47	0.312 × 0.312	0.29
3 × 3	57.3	9.88	0.469 × 0.469	0.66
4 × 4	38.2	13.05	0.625 × 0.625	1.17
5 × 5	28.6	15.29	0.781 × 0.781	1.83
6 × 6	22.9	17.03	0.937 × 0.937	2.63
7 × 7	19.1	18.46	1.094 × 1.094	3.58
8 × 8	16.4	19.66	1.250 × 1.250	4.67

to use the value of 2 W as the maximum user equipment output power. The UE is equipped with a basic monopole antenna with a gain of 2 dBi. The main noise source for the uplink is the system noise temperature of 290 K [52].

The uplink budget for one of the cases is presented in Table 3.

3.3.4. Quality of Service (QoS)

Communication channel throughput is limited not only by the Shannon Limit and other modulation parameters but also by the collision probability of data packages in the air. This blocking probability characterizes the QoS of a telecommunication network, which can be estimated using the Erlang B formula [61], originally developed for the determination of the maximum number of simultaneous users allowed in a telephone system to ensure a desired QoS.

For our messaging case, assuming that the satellite is in visibility at the moment, this approach can be used to estimate the probability that a LoRa packet, containing a message, will not collide with another LoRa packet, and it will be correctly received. In Table 4 the original parameters used as inputs for the Erlang B formula, and their analogues for the messaging case are presented. The calculation is conducted for the footprint with the center in the Beijing area, the antenna beamwidth of 40°, and the orbital height of 400 km. Channel bandwidth and spreading factor are considered to be equal to 125 kHz and 7, respectively.

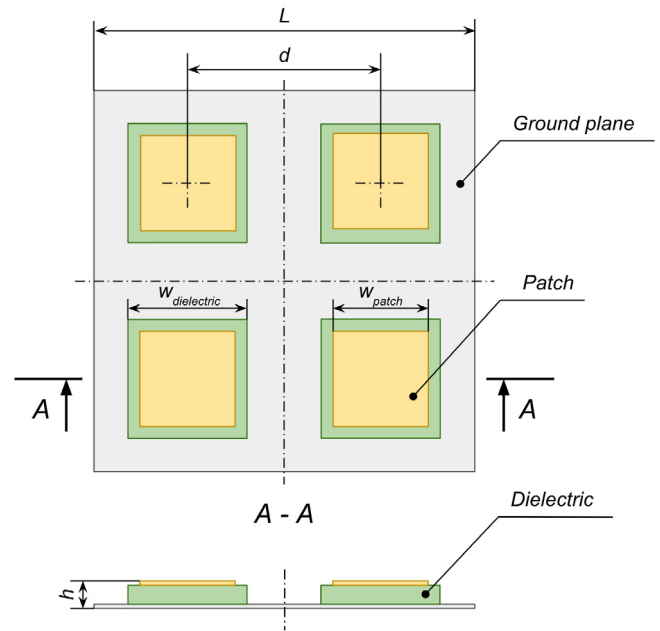


Fig. 13. 2 × 2 patch antenna array schematic view.

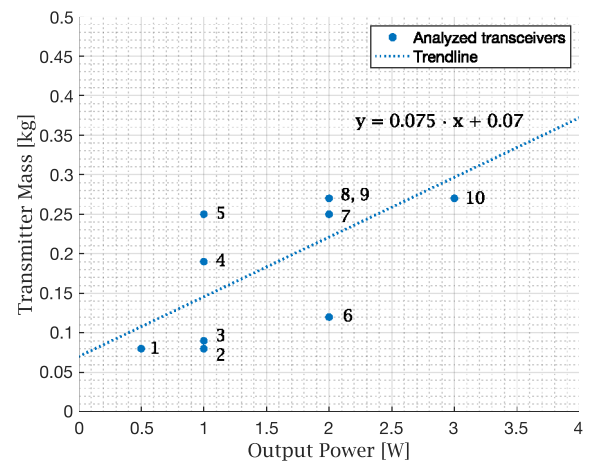


Fig. 14. Existing transmitter masses depending on an output power (see Table 6 for details).

In this case, there are 122 call-hours (Erlangs) in total, and according to the Erlang B Table [61], 126 channels ensure a blocking probability smaller than 5%. In total, we have 208 channels in the whole bandwidth, which means that there is almost a 40% margin for this footprint. In cases of larger footprints the number of users will grow, and a higher number of channels will be required to process all the incoming messages. For example, all 208 channels are needed to serve around 56 700 users with a blocking probability of 5%. This amount of users corresponds to the footprint formed by the antenna beamwidth of 57.5° from 400 km of orbital height. Larger footprints cannot be served with the same QoS, since for larger footprints, the blocking probability increases as well, and ultimately saturates the communication channels. However, this is the estimation for the footprint having the highest density of users, so in all other footprints the channels occupation will be lower.

In addition to instantly appearing messages, the ones that were sent earlier and were still waiting to be processed need additional throughput. In order to ensure better capacity, a dynamic full-duplex

Table 6

Existing transmitters (receivers) characteristics.

#	Transmitter (Receiver)	Frequency [MHz]	Output power [W]	Mass [kg]	Ref.
1	VHF uplink/UHF downlink full duplex transceiver (ISISPACE)	VHF/UHF	0.5	0.075	[62]
2	HiSPiCO (IQ Spacecom)	2100–2500	1.0	0.075	[63]
3	UHF-band transceiver (Endurosat)	400–403, 430–440	1.0	0.094	[64]
4	CubeSat S-band transceiver (NanoAvionics)	2200–2290, 2025–2110	1.0	0.191	[65]
5	NanoCom AX100 (GOMSpace)	VHF/UHF	1.0	0.245	[66]
6	S-band high data rate transmitter (ISIS)	2200–2290	2.0	0.120	[67]
7	S-band transmitter (Endurosat)	2200–2290	2.0	0.250	[68]
8	X-band transmitter (Endurosat)	7900–8400	2.0	0.270	[69]
9	X-band transmitter EWC27 (Syrlinks)	8000–8450	2.0	0.270	[70]
10	NanoCom XT8250 (GOMSpace)	8000–8500	3.0	0.270	[71]

Table 7

Morphological matrix.

Parameter	Values
Orbital height [km]	[400, 800, 1200, 1600, 2000, 2400, 2800]
Satellite transmitted peak power [W]	[1, 2, 3, 4, 5]
Transmitting antenna beamwidth [°] (see Table 5)	[16.4, 19.1, 22.9, 28.6, 38.2, 57.3, 114.6]
Channel bandwidth [kHz]	[125, 250, 500]
Spreading factor	[6, 7, 8, 9, 10, 11, 12]
UE transmitted peak power [W]	[1, 2]

system is considered for the tuning of available channels usage either for transmission or reception, depending on the existing demand.

4. Payload design assessment

In this section, a design approach is presented for a satellite telecommunications payload providing LoRa connectivity. Knowing the transmitted peak power, antenna beamwidth, channel bandwidth, spreading factor, and orbital height, the corresponding transceiver and patch antenna masses will be estimated for further payload architectures downselection.

4.1. Patch antenna array design

A patch antenna array is considered because it is compact, lightweight, and has an adequate performance-to-cost ratio. Also, a satellite platform is expected to have a CubeSat form factor due to the relatively low required transmitter output power. So, a light-weight and compact patch antenna is a suitable solution for a CubeSat. The patch antenna array consists of a ground plane, a dielectric, and microstrip patches. A schematic view of a patch antenna array with 4 microstrip patches is shown in Fig. 13.

Antenna parameters primarily depend on the signal frequency, the number of antenna elements, and the antenna dielectric constant. The total antenna dimension L can be estimated from signal wavelength (λ) and the number of elements in a row (N_{el}):

$$L \simeq N_{el} \cdot \frac{\lambda}{2}. \quad [\text{m}] \quad (10)$$

The resulting antenna beamwidth can be estimated as

$$\beta \simeq \frac{\lambda}{L}. \quad [\text{m}] \quad (11)$$

Patch antenna gain is determined from the directivity provided by an array (Eq. (1)). Assuming that the dielectric material is TMM3 [72] because of its low losses, the estimated antenna efficiency is 0.9 in our case.

The patch width w_{patch} is calculated using the dielectric constant ϵ_r of dielectric material ($\epsilon_r = 3.45$), and the wavelength:

$$w_{patch} = \lambda \cdot \sqrt{\frac{2}{\epsilon_r + 1}}. \quad [\text{m}] \quad (12)$$

To estimate the antenna array mass, the dielectric volume and density (ρ_{diel}) must be used. For TMM3 the density is 1780 kg/m³, and the dielectric height (h_{diel}) is 3.175 mm. Usually, the dielectric width is larger than the microstrip patch by $\sim 10\%$. For the total antenna mass estimation, we also have to account for the total number of patches $N_{patches}$. Thus, the estimated antenna array mass equals:

$$m_{AntAr} \simeq \rho_{diel} \cdot (w_{patch} \cdot 1.1)^2 \cdot h_{diel} \cdot N_{patches} \cdot [\text{m}^2] \quad (13)$$

Comparing the performance of 7 alternative antennas (Table 5), from 2×2 to 8×8 , it can be seen that the larger one provides the smaller antenna beamwidth, but its mass is also much higher. These antenna designs will be further used as alternatives for satellite telecommunications payload design in Section 5.

4.2. Transceiver design

Alongside with the antenna, another key element of the telecommunications payload is the LoRa transceiver itself. Its major functions are the conversion of radiowaves into an electric signal and back, modulation, demodulation, coding, and decoding of a signal. In order to establish the communications link, the transmitted signal power has to be larger than the required level determined by the link budget and the sensitivity. The higher the orbit, and the larger the antenna beamwidth, the higher the signal power has to be.

The transceiver mass is estimated based on existing ones. The gathered values of their masses depend on the corresponding output power, and a trendline for the mass estimation is derived. The signal frequency does not affect significantly the mass, and it can be excluded from the equations. The used equipment characteristics are listed in Table 6. The dependence of the mass on the output power with the trend line is shown in Fig. 14.

Knowing the required antenna beamwidth, and the transmitter output power and using the above equations, the telecommunications payload mass for each considered case can be estimated. These parameters will also have an impact on the satellite platform characteristics, which will be analyzed in Part II [39] of this study.

5. Payload architecture alternatives downselection

As it has been seen in previous sections, the antenna beamwidth and the transmitted peak power have a direct impact on the payload mass and cost, which are to be optimized. On the other hand, higher orbits and wider antenna beamwidths require larger transmitter signal power to meet the sensitivity level needed to establish the link budget.

At the payload level, there are four parameters: transmitting antenna beamwidth, peak power, channel bandwidth, and spreading factor, and one parameter from the UE side: the UE transmitted peak power, which can be traded to generate the payload architecture, providing the highest amount of transmitted LoRa packets from each considered orbital height with the lowest payload mass and cost. Table 7 summarizes the parameters and their values, and all their combinations resulted in 10 290 payload architecture alternatives, which are downselected based on the following priorities:

Table 8

Payload architectures after downselection (partial results).

#	Number of transmitted packets per second	Orbital height [km]	Tr. peak Power [W]	Antenna beam-width [°]	Channel BW [kHz]	Spreading Factor	UE Tr. peak power [W]	Payload mass [kg]
1	1602.6	400	1	28.6	125	6	1	1.97
6	1602.6	1600	2	16.4	125	6	2	4.89
7	938.2	400	1	38.2	125	7	1	1.32
17	938.2	2800	2	16.4	125	7	2	4.89
18	530.4	400	1	57.3	125	8	1	0.80
31	530.4	2800	2	22.9	125	8	2	2.85
33	296.1	400	2	114.6	125	9	2	0.51
46	296.1	2800	2	28.6	125	9	2	2.05
47	162.2	400	1	114.6	125	10	1	0.44
55	162.2	2800	1	28.6	125	10	1	1.97
58	89.7	800	2	114.6	125	11	2	0.51
64	89.7	2800	2	57.3	125	11	2	0.88
70	48.3	1600	2	114.6	125	12	2	0.51
73	48.3	2800	1	57.3	125	12	1	0.80

- firstly, the architectures not providing enough power to establish both the downlink and the uplink are eliminated;
- if the performance is the same, the architectures with narrower antenna beamwidths and higher transmitted peak power are removed as well, as so to cover more users with less powerful and lighter payloads;
- lower UE transmitted peak power is preferable, if the performance remains the same;
- lower SF ensures a larger amount of transmitted packets per unit of time, so in the case when the rest of the parameters are the same, the architectures with the lowest SF are preferable;
- wider channel bandwidths have some advantages as compared to narrower ones, including fewer losses for gaps between neighbor channels, easier pointing and tracking, while the increased noise impact can be partially mitigated by low-noise amplifiers;
- in case of conflicting priorities, lower transmitting power and wider antenna beamwidth are dominating above wider channel bandwidth.

Among all considered payload architecture alternatives, only around half of them (5474 architectures) are able to close both the uplink and the downlink. After applying the listed downselection priorities, the algorithm yielded 73 payload architectures for further trade-space analysis at the constellation level, making the simulation less computationally intensive. The partial set of downselected payload architectures is presented in Table 8, while the full set of them is shown in Appendix (Table A.1).

Analyzing the obtained results it can be seen that with the growth of SF , orbital height and antenna beamwidth are also growing. For example, all the cases with $SF = 6$ are located at the orbit not higher than 1600 km, and have antenna beamwidths not wider than 38.2° . Starting from $SF = 7$ payload architectures are located at all considered orbital heights from 400 to 2800 km. For the cases with $SF = 9$ it can be observed that the largest transmitting antenna beamwidth is 114.6° , corresponding to a 2×2 patch antenna. On average, higher spreading factors lead to larger antenna footprints, providing longer connectivity duration to users.

In all the selected cases satellite transmitted peak power does not exceed 2 W, because in order to consider payloads with higher values, the corresponding UE peak power has to increase as well, but it will go beyond the values allowed to mobile phones.

For the majority of payloads, channel bandwidth equals 125 kHz as it is the one requiring the lowest SNR level to demodulate the LoRa signal at the receiver side. However, in 6 cases a channel bandwidth of 250 kHz appeared, and these payloads have an increased SF .

Using the downselected payload architectures, constellations at various orbital heights and inclinations will be designed and compared in Part II [39] of this study to select the optimum designs in terms of satisfied demand and cost.

6. Discussion

In Part I of the presented study the theoretical feasibility of messages transmission via LoRa technology has been confirmed, assuming two technologies, that – to the authors' knowledge – have not been implemented yet. These technologies include UE with a chip for LoRa packet transmission and reception, as well as LoRa transceivers at frequencies outside of ISM with a higher output power. However, the LoRa chip output has already reached 2 W, as stated in the datasheet to G-NiceRF LoRa 126XF30 transceiver module [73]. It has been assessed that LoRa is able to provide sufficient throughput to provide unserved users, according to the developed demand map, with at least 1 message per user per day. This requirement is met even in the most densely populated regions of the world (i.e. the Beijing metropolitan area, followed by other Asian countries, including India, Pakistan, and African countries). The generated demand map represents the distribution of unserved population, but absolute numbers require further clarification as they deviate from GSMA and ITU reports, indicating the presence of the “usage gap” rather than the “coverage gap”.

Another simplification of the model lies in the estimation of the minimum required channel throughput, since characteristics of Medium Access Control as data packets transmission protocol, the probability of packets collisions, and packets losses are not taken into account.

Each country has its own regulations and policies regarding frequencies allocation and their use. According to ITU regulations [51] different regions have different frequencies allocated for the same service. Thus, the frequency selection has a direct impact on the whole constellation architecture, because the global communication system has to be able to handle all the selected operational frequencies. This can be achieved either by the selection of a bandwidth allocated for the same service in all regions or by designing a frequency agile payload.

Despite the fact that this study has considered the minimum LoRa $SF = 6$, to authors' knowledge there are no known implementations under $SF = 7$. Also, due to the Doppler Frequency Shift, feasible channel bandwidths are limited to 125, 250, and 500 kHz. As far as LoRa technology was originally developed for Internet of Things applications, the typical band on the ground is ISM, and the maximum operation duty cycle permitted is limited to 1% and the maximum signal power cannot exceed 1 W. Therefore, it is worth considering a frequency shift to other frequency bands to avoid these limitations.

Another crucial factor having a significant impact on the link margin is the noise level. It is especially high in cities with a high density of mobile devices, contributing to a large part of the total noise level. This noise level is steadily increasing, so the accepted value in the model for median business area man-made noise level may be underestimated.

Finally, the telecommunications system has been designed taking into account both the uplink and the downlink, because the maximum transmitted power is the limiting factor, which has to provide a decent margin to both uplink and downlink for establishing two-way communication.

7. Conclusions

In the presented study the framework for end-to-end constellation optimization and analysis is suggested, covering multiple elements such as users traffic, communication channel, telecommunication payload and satellite sizing, messages transfer simulation, constellation architecting and profitability estimation.

In Part I a demand map for the case of messaging service has been built based on the population density distribution not covered by terrestrial cell towers. Identified peaks are located in Asia and Africa with 2.2 billion potential users in total. Additionally, the study assessed the theoretical feasibility of messaging via LoRa technology and determined that a maximum channel capacity of 5.57 kbit/s could be achieved. This capacity would enable the transmission of at least one message per day to all potential customers, or even more, depending on the chosen constellation architecture.

After payload architectures downselection, 73 feasible payload alternatives have been selected, having from 2×2 to 8×8 patch antenna arrays and transceivers of 1–2 W transmitted peak power, enabling the transmission from 1602 to 48 LoRa data packets per second.

Analyzing LoRa channel parameters impact on the performance, it can be seen that orbital heights up to 3000 km or wide antenna beamwidth up to 90° can be achieved only with high SF, but channel capacity in these cases is quite low. For example, in the case of payload 70 from Table A.1, wider coverage of 114.6° antenna beamwidth from orbital height of 1600 km is provided, but at SF = 12 only 48.3 data packets per second can be transmitted. On the other hand, using SF = 6, 1602.6 data packets per second are already achievable, but the link can only be closed with narrow antenna footprints. For example, the first payload from Table A.1 is located at 400 km orbital height and has 28.6° antenna beamwidth.

This study has demonstrated that LoRa is a promising technology for messaging services via satellites. This technology is low-cost and does not require the acquisition of expensive equipment from users or satellites. Thanks to the low required signal power, even devices with the performance of regular smartphones can be used as user equipment to communicate with a CubeSat constellation. By integrating a LoRa module into smartphones “the usage gap” can be closed with this messaging service, potentially more affordable due to relatively low constellation cost.

In addition, this feasibility study of LoRa connectivity via satellites can assist in the design and optimization of other space systems that may benefit from LoRa technology. These are cases such as on-demand remote sensing [74], facilities remote control, and other applications that require low data rate exchange.

In Part II [39] of the study, the obtained payloads set is investigated as part of a satellite constellation, and the whole system is optimized in terms of satisfied demand level and the system’s economic performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This has been supported by the predoctoral program AGAUR-FI ajuts (2023 FI-1 00477) Joan Oró of the Secretariat of Universities and Research of the Department of Research and Universities of the Generalitat of Catalonia and the European Social Plus Fund.

This project was also sponsored in part by the project “GENESIS: GNSS Environmental and Societal Missions – Subproject UPC”, Grant PID2021-126436OB-C21, sponsored by MCIN/AEI/10.13039/501100011033/ and EU ERDF “A way to do Europe”.

This study would also not have been possible without the support of the Skolkovo Institute of Science and Technology, whose funding enabled the international collaboration through its Academic Mobility program.

During the preparation of this work the authors used ChatGPT [75] in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed, and take full responsibility for the content of the publication.

Appendix

See Table A.1.

Table A.1
Payload architectures after downselection.

#	Number of transmitted packets per second	Orbital height [km]	Tr. peak power [W]	Antenna beam-width [°]	Channel BW [kHz]	Spreading factor	UE Tr. peak power [W]	Payload mass [kg]
1	1602.6	400	1	28.6	125	6	1	1.97
2	1602.6	400	2	38.2	125	6	2	1.39
3	1602.6	800	1	19.1	125	6	1	3.73
4	1602.6	800	2	28.6	125	6	2	2.05
5	1602.6	1200	2	19.1	125	6	2	3.80
6	1602.6	1600	2	16.4	125	6	2	4.89
7	938.2	400	1	38.2	125	7	1	1.32
8	938.2	400	2	57.3	125	7	2	0.88
9	938.2	800	1	22.9	125	7	1	2.78
10	938.2	800	2	38.2	125	7	2	1.39
11	938.2	1200	1	19.1	125	7	1	3.73
12	938.2	1200	2	28.6	125	7	2	2.05
13	938.2	1600	1	16.4	125	7	1	4.82
14	938.2	1600	2	22.9	125	7	2	2.85
15	938.2	2000	2	19.1	125	7	2	3.80
16	938.2	2400	2	16.4	125	7	2	4.89
17	938.2	2800	2	16.4	125	7	2	4.89
18	530.4	400	1	57.3	125	8	1	0.80
20	530.4	800	1	28.6	125	8	1	1.97
21	530.4	800	1	38.2	125	8	2	1.32
22	530.4	1200	1	28.6	125	8	1	1.97
23	530.4	1200	2	38.2	125	8	2	1.39
24	530.4	1600	1	22.9	125	8	1	2.78
25	530.4	1600	2	28.6	125	8	2	2.05

(continued on next page)

Table A.1 (continued).

#	Number of transmitted packets per second	Orbital height [km]	Tr. peak power [W]	Antenna beam-width [°]	Channel BW [kHz]	Spreading factor	UE Tr. peak power [W]	Payload mass [kg]
26	530.4	2000	1	19.1	125	8	1	3.73
27	530.4	2000	2	28.6	125	8	2	2.05
28	530.4	2400	1	16.4	125	8	1	4.82
29	530.4	2400	2	22.9	125	8	2	2.85
30	530.4	2800	1	16.4	125	8	2	4.82
31	530.4	2800	2	22.9	125	8	2	2.85
32	296.1	400	1	57.3	250	9	1	0.80
33	296.1	400	2	114.6	125	9	2	0.51
34	296.1	800	1	38.2	125	9	1	1.32
35	296.1	800	2	57.3	125	9	2	0.88
36	296.1	1200	1	38.2	125	9	1	1.32
37	296.1	1200	2	57.3	125	9	2	0.88
38	296.1	1600	1	28.6	125	9	1	1.97
39	296.1	1600	2	38.2	125	9	2	1.39
40	296.1	2000	1	22.9	125	9	1	2.78
41	296.1	2000	1	28.6	125	9	2	1.97
42	296.1	2000	2	38.2	125	9	2	1.39
43	296.1	2400	1	22.9	125	9	1	2.78
44	296.1	2400	2	28.7	125	9	2	2.05
45	296.1	2800	1	19.1	125	9	1	3.73
46	296.1	2800	2	28.6	125	9	2	2.05
47	162.2	400	1	114.6	125	10	1	0.44
48	162.2	800	1	57.3	125	10	1	0.80
49	162.2	1200	1	38.2	250	10	1	1.32
50	162.2	1600	1	38.2	125	10	1	1.32
51	162.2	1600	2	57.3	125	10	2	0.88
52	162.2	2000	1	38.2	125	10	1	1.32
53	162.2	2400	1	28.6	125	10	1	1.97
54	162.2	2400	2	38.2	125	10	2	1.39
55	162.2	2800	1	28.6	125	10	1	1.97
56	162.2	2800	2	38.2	125	10	2	1.39
57	89.7	800	1	57.3	250	11	1	0.80
58	89.7	800	2	114.6	125	11	2	0.51
58	89.7	1200	1	57.3	125	11	1	0.80
59	89.7	1600	1	57.3	125	11	1	0.80
60	89.7	2000	2	57.3	125	11	2	0.88
61	89.7	2400	1	38.2	125	11	1	1.32
62	89.7	2400	2	57.3	125	11	2	0.88
63	89.7	2800	1	38.2	125	11	1	1.32
64	89.7	2800	2	57.3	125	11	2	0.88
65	48.3	400	1	114.6	250	12	1	0.44
66	48.3	800	1	114.6	125	12	1	0.44
67	48.3	1200	1	57.3	250	12	1	0.80
68	48.3	1200	2	114.6	125	12	2	0.51
69	48.3	1600	1	57.3	250	12	1	0.80
70	48.3	1600	2	114.6	125	12	2	0.51
71	48.3	2000	1	57.3	125	12	1	0.80
72	48.3	2400	1	57.3	125	12	1	0.80
73	48.3	2800	1	57.3	125	12	1	0.80

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Osipova, Ksenia; Camps, Adriano; Golkar, Alessandro; Ruiz-de-Azua, Joan A.; Fernandez, Lara ...

2024-10-01

Elsevier

<https://doi.org/10.1016/j.actaastro.2024.07.022>

Osipova K, Camps A, Golkar A, et al., (2024) Architecting CubeSat constellations for messaging service, Part I. Acta Astronautica, Volume 223, October 2024, pp. 525-539