On the Use of Mega Constellation Services in Space

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***Abstract*—Mega-constellations are being deployed to offer innovative services to Earth's users. Our work shows how they can provide seamless connectivity to LEO spacecrafts, too, and transform them into highly responsive space network nodes, thus enabling a myriad of innovative applications. For realizing the new mega-constellation services in space paradigm, in this paper we present a complete design of the LEO space terminal, suitable to any hosting platform, even CubeSats and SmallSats. By focusing on existing mega-constellations, like OneWeb and Starlink, we derive the service performance for four terminal configurations under realistic scenarios and show that Tbit/day-scale capacity is the common case for space users, by constant data dripping. Finally, we compare this new paradigm with existing services like Ground Station Networks and Data Relay Systems. All the results show that the new approach can be potentially disruptive for the space ecosystem, by transforming each satellite into a 24/7 available node characterized by high throughput, low latency, and low cost.**

***Index Terms*—Space Terminal, Space-to-Space, Inter-Satellite Links, Mega Constellations, Low-Earth Orbit**

I. Introduction

A. The Need for Connectivity

In the NewSpace ecosystem [1], there are thousands of LEO satellites being launched for a multitude of applications like Earth Observation (remote sensing, weather monitoring, fleet monitoring), Communication, Positioning and Navigation, Technology Demonstration, Space Exploration, etc. [2], all of which face the same challenges: discontinuous and time-limited links with the ground - a major limitation for satellite-based data services. Traditional Earth-to-spacecraft communication, and vice versa, can only occur during short windows when a satellite is above the horizon of a ground station. If you miss that window, you have to wait several minutes or hours before the satellite is accessible again. Among the primary consequences of this data latency are the need to store and delay the delivery of the observational data and to perform a number of tasks onboard, where limited computational power is available.

Existing solutions are Ground Station Networks (GSN) and data relay systems using geostationary (GEO) and mid-Earth orbit (MEO) satellites. However, flexible, high throughput, low latency, and low cost 24/7 communications cannot be easily achieved by GSN, due to their limited installed capacity, tangled scheduling, and hand-over requirements, as well as complex logistics. Given the rapid pace at which new LEO payloads are being deployed and its expected growth in the coming decades [3], not even data relay systems and highly autonomous ground station networks for near-real time high-throughput connectivity may be enough to provide the necessary coverage, capacity, and latency.

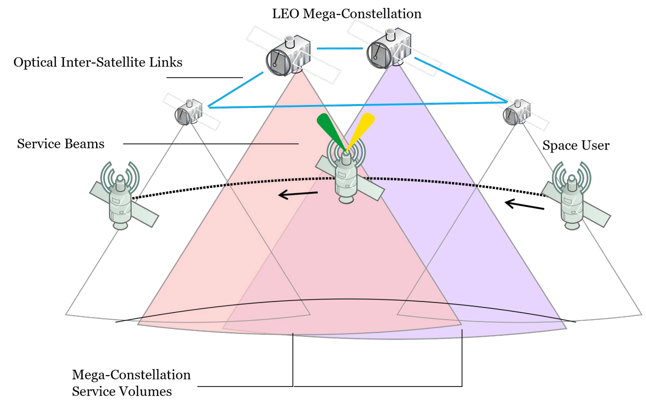


Fig. 1: Mega-Constellation Services in Space Paradigm

B. The Mega-Constellation Service in Space Paradigm

Mega-constellations are the next step of space-based connectivity for terrestrial users, offering unrivaled coverage through hundreds to thousands of Low-Earth Orbit (LEO) satellites for low-latency broadband and Internet-of-Things applications. Given their massive coverage and capacity, an idea was born: "Can currently deployed mega-constellations be used to provide LEO spacecraft with broadband low-latency services? If so, how? Is there a business case for it?" "What can mega-constellations and their internet services do for satellites?".

To investigate this novel concept, a project was funded by ESA's Open Space Innovation Platform [4]. In the newly developed **Mega-Constellation Services in Space (MCSS) paradigm**, described by Fig.1, LEO mega-constellations can allow LEO *space users* (user satellites or spacecrafts operating in LEO) to communicate 24/7 at high rates (up to hundreds of Mbps) and low latency (<50 ms). This also enables many new and complex missions such as active debris removal, in-orbit servicing, space robotics, tandem and formation flying, characterized by exceptionally hard requirements that often require ground-in-the-loop architectures, and are then severely limited by ground access frequency and contact duration.

High-performance spacecraft connectivity from mega-constellations can potentially render satellites as highly responsive as Extreme-Mobile Edge Computers, alleviating the need for on-board autonomy and freeing limited resources for other tasks. Moreover, it has disruptive effects on platform design and performance in all mission phases (mission analysis and satellite design, assembly integration validation and pre-launch activities, launch and early operation phase, special and end of life operations, etc.). Risk, one of the main mission and cost drivers, can also be reduced due to increased connectivity.

C. Paper Contributions

In [5], we presented a first set of results characterising the communication link between the mega-constellations and the LEO satellites in terms of availability, access duration, Doppler, and path losses as a function of user orbital parameters, identifying optimal user orbits to make use of mega-constellation connectivity. Building upon these results, in this new paper we present the design of a custom multi-system, multi-orbit, software-defined space user terminal (SUT) architecture within the constraints of common-off-the-shelf software-defined radios (SDRs), antennas, power amplifiers, and modems, to provide implementers and users with the flexibility to tune the terminal to their applications and service providers.

Assessing the performance of the four proposed design configurations (low-end, common case, high-end (36 MHz), and high-end (125 MHz)), this custom terminal is shown to provide users with Tbit-scale daily data volumes using low-power (10 W), passive wide-beam patch antennas (8 dBi gain), data dripping at constant data rates (20 Mbps), and high link margins (3 dB) within a 10x10x10 cm footprint and a 1.5 kg maximum mass for the common case - especially suitable for small satellites and smaller platforms.

Using this antenna, terminal can simultaneously communicate with multiple satellites in visibility, with two-to-four parallel channels being optimal for common users, shifting the typical approach of inter-satellite links towards a point-to-multipoint paradigm and simplifying acquisition, tracking, and pointing.

Through the new paradigm, spacecrafts can access mega-constellations' enormous resources (Tbit/s throughputs) and global coverage at a lower cost than traditional ground station networks or MEO/GEO data relay systems (two to fifty times cheaper, that is, a few hundred to a few thousand dollars per month for a daily net capacity from hundreds of Gbit up to almost ten Tbit). Ultimately, the proposed solution is extremely flexible, being suitable for any platform and mission, and its impacts on the hosting platform are incommensurate with the tremendous coverage and capacity it unlocks.

D. Scenario

In a realistic scenario, we consider OneWeb [6] and Starlink [7] Phase 1 mega-constellations (Table I), which are in an advanced deployment stage. These non-geostationary orbit (NGSO) constellations employ highly directive antennas that aim at serving terrestrial user terminals, located within their coverage, and use strong side-lobe suppression techniques, limiting connectivity to space users within service volumes, mostly LEO regime. Starlink and OneWeb share the same frequency bands and possess similar terminal configurations, which means future terminals may be able to freely switch between both networks - akin to how a cellphone selects a mobile operator. Thus, we also assess the potential service that could be offered by an unified OneWeb + Starlink constellation.

Mega-Constellation	Altitude [km]	Inclination [deg]	Planes	Satellites/Plane	Total
OneWeb	1200	87.9	12	49	588
OneWeb	1200	55.0	8	16	128
Starlink	540	53.2	72	22	1584
Starlink	550	53	72	22	1584
Starlink	560	97.6	6	58	348
Starlink	560	97.6	4	43	172
Starlink	570	70.0	36	20	720

TABLE I: Mega-Constellation Configuration

It is important to note that active LEO payloads are overwhelmingly located in polar and near-circular orbits at mid-inclinations, with 500-to-550 and 750-to-800 km altitudes, and 45-to-60 and 80-to-90 degree inclinations, reflecting current Earth Observation and communications use cases [2]. Remarkably, this is unlikely to change in the near future as the key driver of payload orbits are application needs. Spacecrafts may be placed in a sun-synchronous orbit for shadowing, imaging, or energy constraints; communication satellites may be inserted into polar or mid-inclination orbits to obtain the desired coverage; satellite altitude trades-off sensor coverage, satellite size, weight, and power, atmospheric drag, communication link budget, fuel storage and satellite lifetime. As a consequence, the applied methodology (Section II) is uniquely suitable to assess the performance that such LEO payloads could expect from MCSS.

Because data relay constellations [8]–[13] are often proposed as a solution by industry and academia alike, we also address the potential services provided by existing RF data relay systems in MEO and GEO, such as SES's MEO O3b mPOWER and GEO High Throughput systems (HTS) [14], [15]. We not only compare their performance against MCSS, but also look at how MEO systems can complement MCSS in an integrated LEO and MEO solution that may be eventually offered by Ku-band satellite operators, as has recently happened for GEO and MEO systems [16].

E. Paper Organization

This paper is organized as follows: an extended discussion on the methodology and key assumptions employed throughout the paper is present in Section II, from which we derive novel results presented in Section III - including a full characterisation of MCSS in terms of bit rate, daily capacity, and number of users. Then, Section IV defines the unit-level space user terminal architecture, discussing its key aspects and impacts on the hosting (spacecraft) platform. Building upon this discussion, Section V showcases how truly global multi-orbit constellations can provide In-Spaceflight Connectivity solutions to a vast amount of space users, thereby making satellites connected at a scale far beyond data relay systems and ground station networks.

Finally, Section VII summarises key results, showing that indeed LEO mega-constellations can provide service to lower

LEO users with a greater quality of service than existing systems, and presents commercial and technical aspects still to be explored in future before the MCSS can become operational.

II. Methodology

A. Coverage Analysis

To obtain the results presented in this paper, we applied a similar methodology to that presented in [5], that is, starting from FCC filings of Earth Stations (terminals, gateways) and Space Stations (satellites) of each selected satellite operator [17], [18]. we created realistic scenarios around potential space user orbits and terminals that are compatible with operational satellite constellations. By using information provided by the satellite operators themselves, we ensure that the data is robust and faithful to the deployed constellations and their coverage volumes.

Then, to characterise mega-constellation links, an analysis technique had to be selected. Analytical techniques where coverage is computed considering exact (location-based) or randomly distributed (stochastic) user and satellite positions [19]–[22], are extremely useful to derive initial metrics at reduced complexity since they eliminate the need for precise orbit propagation. However, such a level of abstraction makes it impossible to distinguish and compare the performance of mega-constellations with similar orbital configurations, but different technologies and capabilities. In these instances, numerical analysis is the only solution.

Such a solution has been employed throughout literature to analyse mega-constellation performance [23], [24] and relies on the step-wise propagation of the LEO user and constellation satellite positions, trading-off computational complexity, which scales with the number of LEO users, for numerical accuracy [25]. Thus, we have implemented our own numerical simulator in Python that starting from a set of initial state vectors of positions and velocities, user and constellation satellite positions are iteratively propagated using a SGP4 model [26] over a time window of interest.

From their positions, the simulator computes the relative position, range, Doppler offset, and visibility angles between user and constellation satellites, and evaluates whether the visibility angles satisfy constellation and user constraints (as per FCC filings). That is, whether the constellation satellite is in line-of-sight of the user at an elevation equal to or greater than the minimum elevation angle of the user's Zenith-pointing antenna, like a ground station (and vice-versa) [27]. Whenever this condition is satisfied, a possible access is available. At this point, the simulator applies user policies (i.e., which satellite to select (random or closest), Doppler offset/rate constraints, ...).

Considering that the mega-constellation service volumes encompass hundreds to thousands of kilometers above Earth, that signal characteristics depend on the relative dynamics of the platforms hosting the radio payloads, and taking into account that computational complexity scales with the number of satellites, step size, and simulation horizon, we employ a Monte Carlo [28] strategy with 1000 LEO users uniformly distributed across the main payload planes, and to improve accuracy near constellation shells, where geometric constraints are strongest, we add 100 users at an altitude below and within 100 km of each constellation's maximum altitude ([470 570] km, [1100 1200] km).

This approach was also selected so we could perform the link and capacity analysis in the future using stochastical simulations because these analyses involve many statistical effects associated to the communication channel (i.e., fading), resource demand, satellite selection, and network utilisation that inherently depend on the SUT distribution and behaviour (not assessed in this paper). For reproducibility, a sample dataset of the coverage results is available in [29].

B. Terminal Design & Assessment

Using coverage results, the simulator applies user traffic models and channel model and physical layer parameters (i.e., modulation and coding, radio-frequency front-end bandwidth, antenna beamwidth and steering capabilities, service channel bandwidth, Doppler offsets). Next, it computes link accesses while evaluating relevant policies and metrics. The resulting data is then binned according to user orbital parameters and plotted for visualization.

From this data, we produced a high-level flight terminal reference design to satisfy user needs under the constraints imposed by space-based connectivity, such as limited power and size and fast orbital dynamics. This flight terminal design was iterated over several design cycles in parallel with a numerical evaluation of its expected performance using our coverage simulator and compared with existing flight terminals.

To determine how many channels to use, we consider a simplified power allocation problem; given identical channel gains, noise powers, and channel bandwidths, what is the optimum number of channels assuming power is equally split between channels? This reduction in bandwidth and power for every added channel implies a trade-off between bandwidth, complexity, power, MODCOD choice and diminishing returns from spreading the power across channels.

After settling on a design, we assessed its capabilities and performance and its impacts on the satellite hosting platform. Finally, we evaluated our MCSS paradigm against its competitors, focusing on their performance and service fares, to confirm its feasibility and market competitiveness.

C. Major Assumptions

Mega-constellations rely on high-angle communications with highly directional beams and strong side-lobe suppression to provide high throughput services using nadir-pointing transmission cones, which limits coverage to LEO SUTs; serving satellite beams are aligned with SUTs within their steering range; SUTs can freely roam between different providers; there are no collisions in service channels; and there is seamless handover (i.e., no packet loss, negligible switching times).

For the space terminal, we consider an additive white Gaussian noise line-of-sight channel with no fading, multi-path effects, and sun-noise; 3-dB design margin for interference and carrier, timing, phase, frame synchronisation impairments; 1-dB of implementation losses; 1-dB of insertion losses at the transmitter and at the receiver; 0.25 dB of polarisation losses (circular polarisation); and 0.1 dB of pointing losses. Additionally, the ITU-R P.618 [30] propagation model is considered for Space-to-Earth links targeting 99.9% availability. Then, to account for link failures due to fading, multi-path, unavailable resources, Sun-noise, and other phenomena, we discard 20% of the coverage time, which translates into a 20% capacity penalty. A 20% protocol overhead is also considered. As a baseline for the analysis, we consider DVB-S2X waveforms and their quasi-error free performance [31] at a 20% roll-off and Constant Code and Modulation (CCM). Digital pre-distortion or an appropriate back-off is supposed to be used.

D. Competing Systems

Looking at MCSS competitors, that is, commercial data relay systems and ground station networks, in terms of performance and cost, we focus on commercial radiofrequency (RF) data relays that are already deployed and employ terminals comparable to our Concept. Optical (laser-based) communication and data relay systems such as the European Data Relay System [8] have been heavily invested in, especially by Europe, which sees them as a key technology for future satellite communications [32]. However, even if laser terminals offer capacities beyond the Gbps rate, they come with a completely different set of trade-offs, being more costly to build (and therefore to procure) and much more complex to operate with respect to the RF inter-satellite link proposed in this study, which can operate continuously and to a higher degree of autonomy, while benefiting of less accurate temperature control, less sensitivity to environmental factors, less need for calibration, easier and faster acquisition, tracking, and pointing in particular with wide-beam antennae.

Moreover, current MEO and LEO commercial laser data relay constellations are still in early development such as WarpSpace's WarpHub InterSat [13] and Kepler's Aether Optical High-Data Rate Service [12], the latter with a limited coverage once their first orbital plane is fully deployed; while GEO optical relays are limited to institutional customers [33]–[35]. Nevertheless, these solutions might be limited only to high-end missions that can afford the premium service cost and demanding optical terminal hosting requirements and operational constraints. Also considering the limited scalability of the different systems deployed and in development due to the reduced number of simultaneous users each of the relay network node is able to simultaneously serve, these systems have not been considered in our analysis.

There are many challenges that make an accurate comparison between MCSS and its competitors difficult; accurate estimates of device and service costs are rarely public as they are subject to commercial agreements; flight terminals are often spacecraft, system, and mission-specific because of their cost and impacts on the hosting platform (i.e., size, weight, power, duty cycle); ground station network locations and pricing are a function of communication system capabilities, satellite orbits, and backhaul costs; among others.

Given that our goal is not to identify the best solution for a specific mission from a set of vendor proposals, but to obtain generalisable results in a fair comparison that can be readily applied by designers in a wide spectrum of space applications, we consider a sun-synchronous SUT at a 500-km altitude as baseline, which not only experiences some of the highest path losses, but also best represents active payloads and the common case of constant connectivity with mega-constellations. Using this baseline, we assess the performance of the proposed Concept configurations (low-end, common case, high-end) across different systems, deriving capacity and throughput bounds.

Standardising the terminal implies similar costs and hosting requirements, eliminating the variability between flight terminals of different systems, thus simplifying the analysis, and allowing us to make reasonable assessments. This fits well with our multi-system multi-orbit paradigm, and enables us to explore the quality-of-service provided by MEO and GEO systems to space users – a potential solution to increase capacity and coverage probability and a first step towards providing services to users above 1200 km, which have not yet been studied as far as mega-constellations and active payloads are overwhelmingly located below this altitude. Similarly, because the Concept is frequency-agnostic, we can also assess the performance of the proposed configurations when employed for Space-to-Earth links in X-band. However, the greatest drawback of this approach is that it does not consider proprietary implementation (constellation)-specific constraints that should be taken account when building a production device that must be operated within these systems.

To compare MCSS using OneWeb and Starlink services against data relay systems, we look at SES' O3b mPOWER and GEO Ku-band platforms. We consider a 10.5-degree half-cone for GEO beams, similar to NASA'S Tracking and Data Relay Satellite System [34], and a 26-degree half-cone for O3b mPOWER due to its lower altitude and target coverage from 45N to 45S.

Mega-constellations' Phase 1 minimum G/T, maximum EIRP, and minimum elevation angles specified in FCC filings [17], [18] are used. In this case, G/T is 8.7 dB/K, 20 dB/K, and 20 dB/K, for OneWeb and SES' MEO O3b mPOWER and SES' GEO HTS, such as SES-15 [36], [37].

Instead, to compare MCSS to GSaaS, we estimate the performance of the proposed Concept configurations in X-band, where attenuation and rain losses are lower, imposing roughly identical hosting requirements on the spacecraft for space-to-space and Space-to-Earth communications – antenna size, because it increases with the wavelength, will be larger in this case. In this case, we assume attitude-pointing or electronic beam-steering to accurately track a Svalbard-like station subject to a 99.9% availability constraint including environmental effects, a 10-degree minimum elevation angle, and a 500-km altitude user - a trade-off between coverage and terminal performance - , the resulting propagation loss is 178.3 dB at 8.2 GHz - free space propagation losses (175.29 dB), rain losses (0.89 dB), gaseous attenuation (0.28 dB), cloud and fog attenuation (0.45 dB), and tropospheric scintillations (1.04 dB), polarisation losses (0.25 dB), and pointing losses (0.1 dB). At this elevation angle, sky temperature is 78.4K. Assuming a 1-dB receiver noise figure and a 3.7m reflector

Configuration	High-end (125 MHz)	High-end (36 MHz)	Common-case	Low-end
Output Power [dBm]	+39	+39	+40	+34
Antenna Gain [dBi]	+20	+20	+8	+3
EIRP [dBm]	+58	+58	+47	+36
BW [MHz]	125	36	20.3	10.96
MODCOD	8APSK 5/9-L	64APSK 11/15	QPSK 11/20	M-BPSK 1/5
Net Uplink Rate [Mbps]	171.58	85.68	18.41	1.82
Net Daily Capacity [Tbit]	9.320	4.650	1.000	0.099

TABLE II: Proposed Space User Terminal Configurations

(48-dBi), the ground station G/T is 25.1 dB/K, comparable to KSATLite [38] and AWS Ground Station [39] offerings.

Lastly, to evaluate MCSS in terms of number of concurrent users, we consider that user-to-gateway channel access is done by frequency division: satellites allocate frequency slot resources to users until resources are exhausted in a single-carrier frequency division multiple access scheme, as per OneWeb's FCC filings. To mitigate interference and avoid frequency collisions between users due to high channel dynamics (Doppler), appropriate guard bands are used (twice the maximum Doppler offset between a satellite and a user). Also, given the novelty of MCSS and the lack of SUT distribution and demand data, we employ a probabilistic model, assuming SUTs are uniformly distributed in space and every SUT requests uniformly distributed bandwidth resources but acknowledge that realistic distributions will produce uneven traffic loads (i.e., polar orbits are more common than equatorial orbits for LEO users).

III. Space User Terminal Design

In this section, we present the key results of the paper for various space user terminal configurations, estimating their performance as a function of user orbital parameters and demonstrating how easily MCSS can be adapted to user requirements. Furthermore, we show that it is possible to simultaneously connect space users to multiple constellation satellites, which has wide-ranging implications for the space user terminal architecture, later defined in this section. Finally, we explore how the MCSS can offer low-latency broadband to space users, making satellites effectively connected at a scale far beyond data relay systems and ground station networks.

a) Proposed Terminal Configurations: Table II proposes four exemplary configurations using DVB-S2X [31] CCM modulations and codings (MODCODs) that are referenced throughout the work:

- A high-end beam-steering terminal using modems of increasing complexity, with 125 MHz or 36 MHz of bandwidth (BW);
- A common-case solution based on common-off-the-shelf SDRs, 8-dBi wide-beam antennas, and 10 W amplifiers at saturation;
- A low-end configuration using hemispherical antennas with less than 2.5 W of power;

b) Uplink Capacity (SUT to Mega-Constellation): Considering a 500-km altitude SUT in polar orbit and a 25-degree minimum elevation angle, Figure 2 shows the achievable uplink (payload and telemetry links) capacities as a function of bandwidth and Effective Isotropic Radiated Power (EIRP). From left to right, capacities are computed for different bandwidth ranges: [0.1, 125] MHz, [0.1, 10] MHz, and [0.1, 1] MHz, respectively.

The high-end configuration provides 9.32 and 4.65 Tbit/day capacities with 125 MHz and 36 MHz of bandwidth, respectively, while the common-case solution offers 1 Tbit/day within a 20.3 MHz bandwidth; and the low-end configuration can yield up to 100 Gbit/day with fewer than 2.5W, showcasing the terminal's applicability to low-end, low-power applications, too. This demonstrates that Tbit-scale capacity through low-power antennas is the common case for MCSS, by constant data dripping, a consequence of short distances to the serving satellites and high coverage probability.

c) Downlink Capacity (Mega-Constellation to Space User): In the downlink, that is, the telecommand link, rates higher than 10 Mbps are unnecessary and a rate of 1-to-10 Mbps results in a daily capacity of 100-to-500 Gbit with a -21.7 dB/K receiver G/T.

d) User Orbits and Daily Capacity: Figure 3 shows the daily capacity of common case configurations using Constant Code and Modulation (CCM) as function of SUT orbital parameters (with low eccentricities). At 500-to-550 km, capacity is independent of inclination, while between 550-to-800 km, only users close to critical inclinations can cross the Tbit threshold.

Nevertheless, since the average elevation angle is 5-to-10-degrees greater than the minimum elevation angle, capacity can be increased by applying adaptive code and modulation and selecting more efficient MODCODs when the user is close to the serving satellites, particularly for SUTs at higher altitudes. Doppler rate can be as high as 22 kHz/s at the zenith and below 1 kHz/s when the satellite below 80-degrees elevation.

e) Effects of Multiple Channels on System Performance: Figure 4 shows the average number of visible satellites for three different minimum elevation angles (25, 40, and 55 degrees). SUTs below 750 km have many channels available, especially at critical inclinations. On average, there are 2-to-4 visible satellites at 25-degrees and 1-to-4 visible satellites at 40-degrees. At 55-degrees, there are fewer than two satellites visible on average there is also a reduction of coverage (not shown) due to geometric constraints. For the common case, two-to-four channels is optimal and there is a there is a 10-to-60% capacity gain.

f) Multi-point Paradigm: Processing is cheap; adding parallelised tracks is simpler and more power efficient than complex beamforming multi-beam antennas. It also adds robustness due to diversity; flexibility in resource allocation, as smaller resources slots are easier to assign across multiple

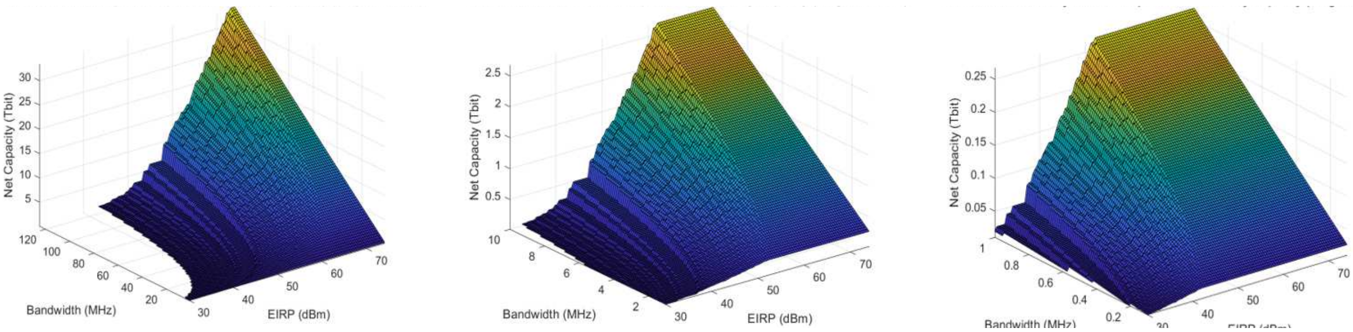


Fig. 2: Net Daily Uplink Capacities for a Space User (Polar Orbit, 500 km Altitude)

beams and satellites; and a high degree of configurability, enabling multi-satellite multi-orbit multi-constellation communication and shifting inter-satellite links from a point-to-point towards a point-to-multipoint paradigm.

This paradigm has wide-ranging implications when combined with wide-beam passive antennas: acquisition, tracking, and pointing is simplified because a fixed beam can illuminate several satellites at once while the Signal-to-Noise Ratio is above the threshold for tracking and carrier recovery loops at all elevation angles; there is no need for dedicated tracking beams and complex power-hungry beam-formers; the antenna pointing error can be almost neglected; handover complexity is reduced since satellites are always in visibility; and finally, it is easier to perform opportunistic transmissions if the terminal can always track satellites. Nevertheless, this approach has the drawback of needing Very Low Signal-to-Noise Ratio (VLSNR) MODCODs.

g) Maximum Number of Simultaneous Space Users: An upper bound for the maximum number of concurrent space users supported by mega-constellations can be written as:

$$N_{Users} = \lfloor \frac{BW_{Satellite} - N_{Users/Satellite} \times BW_{Guard\ Band}}{BW_{User}} \rfloor \times \frac{1}{k} \times N_{Satellites} \times N_{Beams/Satellite} \times N_{Polarisations/Beam} \quad (1)$$

Where $BW_{Satellite}$= 500 MHz is the Ku-band uplink bandwidth, the main constraint for space users; $BW_{Guard\ Band}$ = 1.1 MHz is the guard band; $N_{Satellites}$ is the number of satellites in the constellation; $N_{Beams/Satellite}$ is the number of beams per satellite; $N_{Polarisations/Beam}$ is the number of polarisations per beam, and k is the frequency re-use factor.

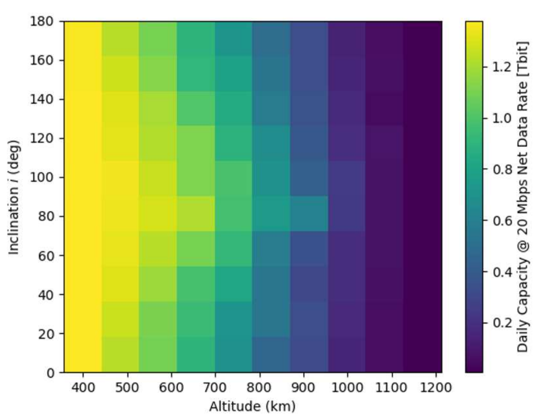


Fig. 3: Common Case Daily Uplink Capacity as a Function of SUT Orbital Parameters (Single CCM DVB-S2X Channel)

Focusing on the maximum number of concurrent SUTs supported by OneWeb, because of its high number of beams (16) and low frequency re-use factor (k = 2), and its size (716 satellites), it can support 450 thousand low-end SUTs, 250 thousand common case SUTs, and 34-to-148 thousand high-end SUTs. However, looking only at the channel access is not enough, one must also consider the satellite capacity - a crucial constraint for space users.

Literature [23], [24] suggests that ground users consume 20-to-30% of network resources on average, but satellites may experience full utilisation during congested periods. Mega-constellations were designed for terrestrial users, aiming at fulfilling ground capacity and coverage requirements, and space users are a new application for which they were not dimensioned. Hence, they cannot expect to access most of a constellation's capacity, especially considering the time-variant traffic demand and traffic matrices and the need to reserve capacity to deal with potential congestion.

Consequently, we investigate how space terminal configuration, available satellite capacity and channel access constraints impact the number of users. Figure 5 shows that for low available capacity ($< 30\%$), the number of users scale quasi-linearly with the capacity, but as the available capacity grows, channel access becomes the bottleneck except for the high-end configuration (36 MHz), which is limited by satellite capacity. The low-end configuration, where guard-bands correspond to 10% of the user bandwidth, is the first to saturate, followed by the common case and high-end (125 MHz) configurations.

It is our belief that 90% of mega-constellation capacity will be exclusively reserved to ground users and thus one can expect 155372, 42244, 11456, and 4296 SUTs in the low-end, common case, high-end (36 MHz, 125 MHz) configurations, which can serve beyond the current entire mission population.

IV. Terminal Architecture

Figure 6 illustrates the proposed multi-system, multi-orbit, multi-satellite SUT architecture. Its communication system is composed of four blocks: a constellation scheduler, an antenna subsystem; a Ku-band radio-frequency front-end, composed of an upconverter, a downconverter, a high-power amplifier, and a low-noise amplifier, and a multi-channel software-defined

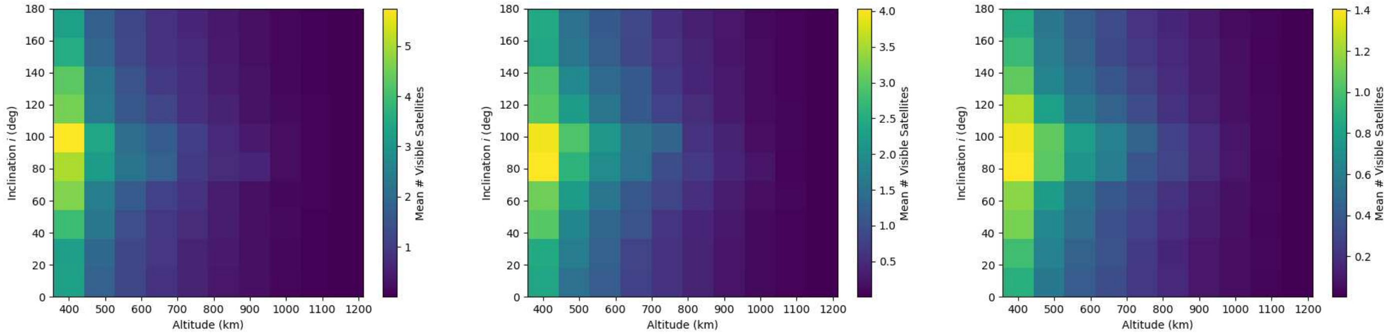


Fig. 4: Average Number of Visible Satellites as a Function of the SUT Minimum Elevation Angle.

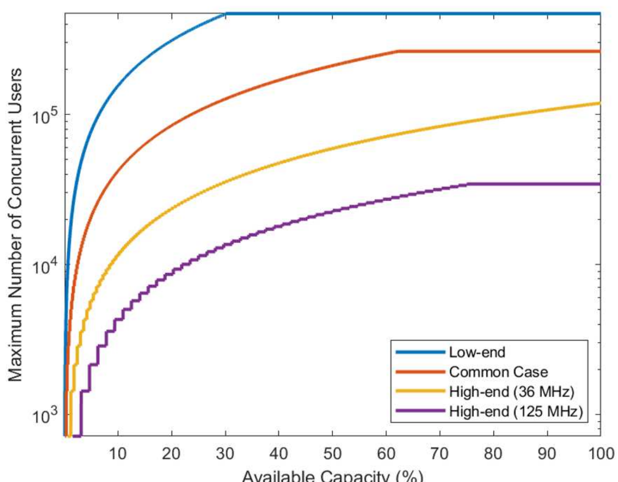


Fig. 5: Max. Concurrent SUTs Supported By OneWeb

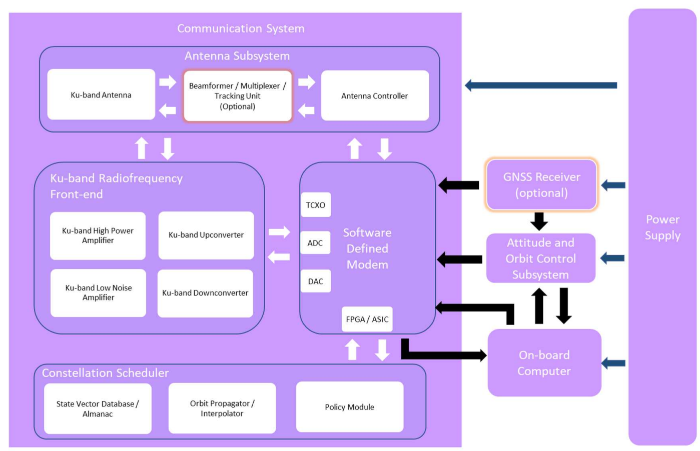


Fig. 6: Space User Terminal Architecture

modem, which interfaces with spacecraft subsystems such as the (optional) on-board Global Navigation Satellite System receiver, Attitude and Orbit Control Subsystem (AOCS), and On-Board Computer.

a) Modem: The modem has four units: a temperature-compensated crystal oscillator for clock generation, digital-to-analogue and analogue-to-digital converters to translate information between domains, and a Field Programmable Gate Array or Application Specific Integrated Circuit, which implements the digital front-end, DVB-S2X modulators and demodulators, and baseband and signal processing.

The modem is frequency-agile, supports two-to-four simultaneous channels in transmission and reception, and allows power to be dynamically controlled through the baseband signal. It interfaces with and is controlled by the on-board computer, the orchestrator of S/C activities that is also responsible for receiving and transmitting packets from/to the applications running at higher layers. From the AOCS interface, the modem receives S/C position, navigation, and timing, velocity and attitude data and antenna mounting matrices.

b) Constellation Scheduler: At the Constellation Scheduler, the State Vector Database stores each constellation's state vectors that are provided to the internal Orbit Propagator for on-demand propagation. By combining this information with the hosting platform's own orbital information, the terminal can better perform signal acquisition, synchronisation, and beam-steering, as it is aware of all visible satellites, their positions, and velocities. The final unit is the policy module, which determines which satellites the modem should communicate with and when to switch satellites.

c) Antenna: The antenna subsystem is composed of a controller, a beamformer or multiplexer (if present), and a Ku-band antenna, which determines SUT coverage and quality of service. High-throughput services (>100 Mbps) need multiple high-gain (> 20-dBi) antenna beams that must be steered, formed, or switched as the SUT moves across the sky, plus a wide low-gain tracking beam for initial acquisition and tracking, complicating the design. Instead, the common case demands far simpler antennas: circular polarisation, 8-dBi uplink gain (14.0-14.5 GHz), 3-dBi downlink gain (10.7-12.7 GHz), a 10 W uplink power rating, and a 25-to-40-degree minimum elevation angle. Then, if one aims at being frequency agile across the entire band, the fractional bandwidth should be at least 3.5% and 17% in uplink and downlink, respectively. To keep losses low and avoid complex impedance matching networks, the reflection coefficient and axial ratio should be lower than -10-dB and 6-dB, respectively.

Given that a 40-degree minimum elevation angle equals a 100-degree half-power beamwidth, a wide-beam patch (array) can fulfil requirements at a fraction of the cost, footprint ($\approx$ 10 cm), weight ($\approx$ 100-500 grams), and power of beam-steering solutions. Assuming a solid-state amplifier with 33% efficiency and low-power modems (10-15W power consumption) are used, one can expect a maximum input power of 45W. Modems typically have a <0.5U form factor and weigh up to 800g, which means that the terminal can fit a 1U form factor within a maximum 1.5 kg mass [40], [41].

d) Comparison Against Space-to-Earth Transceivers: Compared to state-of-the-art X/Ku/Ka-band transmitters for Space-to-Earth links, whose size, weight, and power range from 1.5-to-4.5 kg, 17x8x10-to-24x23x8 cm, and 45-to-95W [42], [43], the proposed terminal is lighter and smaller, allowing it to be retrofitted to existing CubeSat, nanosat, microsat, and smallsat platforms.

Performance-wise, these transceivers may provide the same capacity through ground station networks at 500-to-1000 Mbit/s data rates over 34-to-17 minutes per day using high-gain antennas, but data latencies remain an issue due to visibility constraints. However, if high-gain antennas were used for the space terminal, its data rates could be increased while still within the power budget of existing transceivers. Smaller (< 1U) and lower power (< 20 W) terminals for Space-to-Earth communications are commonly deployed in CubeSat and smallsat platforms, but at 100-to-200 Mbit/s rates, they require 90-to-120 minutes of contacts per day to reach the same capacity. And, if up to 100 Gbit of capacity is desired, the space terminal can provide it at reduced power. These trade-offs are highlighted in Table III.

e) Impacts of Terminal Configuration: Unlike high-rate transmitters, which have a typical 5-to-8% duty cycle, the space terminal can represent a constant power consumption (100% duty cycle), with many consequences for the electrical power subsystem (EPS). A subsystem that is always on is a concern when power is generated by photovoltaic cells because when they are not in sunlight, they do not generate power. During these periods, auxiliary generators, or, typically, battery banks must provide the required power, and the higher the power, the larger batteries and generators must be.

Larger batteries mean larger solar arrays; the greater the energy that must be stored in a fixed, orbit-dependent, amount of time, the more powerful should be the generator. Considering that battery capacity and solar panel requirements drive spacecraft cost, weight, and size, and that because of sporadic coverage and low utilisation, traditional payload downlinks are scheduled when other power-hungry spacecraft systems are offline, clearly the space terminal requires changes to how the EPS is dimensioned and operated. Alternatively, mission designs could consider off-duty cycles during eclipses as part of their data budgets and operational constraints when integrating the space terminal to avoid altering the EPS, or use a high-gain beam-forming antenna, transmitting for a shorter duration at a higher EIRP to increase spectral efficiency, but paying in peak power, weight, size, and complexity.

A powerful EPS composed of large batteries and deployable solar panels is a challenge for CubeSats and NanoSats, which are usually 1, 3, 6, 12, 16, and 24U sized and weigh 1-to-4 kg to 10-to-20 kg. For these platforms, where size is the real concern, the space terminal already represents 5-to-33% of their volume and mass and such an EPS can be prohibitive. Likewise, the S/C thermal design becomes more complex; it must keep all subsystems within their specified temperature ranges throughout their lifetime, and an always-on terminal is, from a thermal perspective, a heater to be managed and carefully installed. Bigger solar arrays also require robust deployment mechanisms, growing spacecraft weight and size, increasing the cost of attitude pointing and station keeping.

From the AOCS perspective, the space terminal does not demand the accurate tracking required by payload downlinks, only an attitude constraint: the antenna should point to the zenith, assuming the antenna is mounted in the -Z face in the local orbital Radial-Traverse-Normal frame of the platform.

Table IV synthesises the hosting impacts of each configuration. As we can see, **by balancing capacity and power requirements, the space terminal is suitable for any platform.**

V. Comparison with Data-Relay Networks and Ground Stations

1) Data Relay Systems:

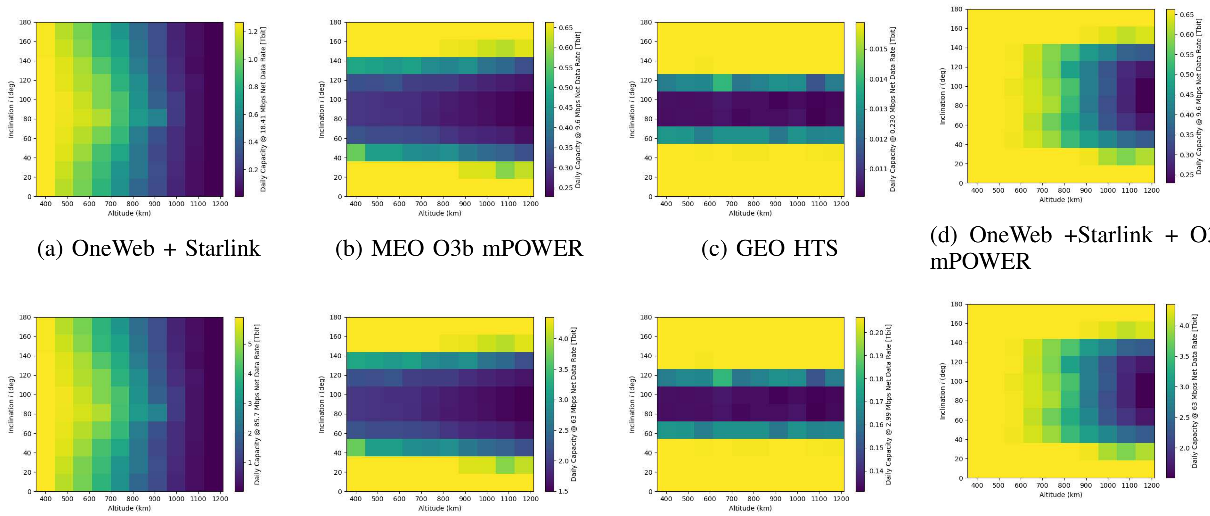
a) Key System Metrics: For the considered data relay systems, the maximum path losses range from 206.3 dB for GEO HTS systems to 189.8 dB for MEO O3b mPOWER, instead of 176.7 dB for OneWeb and Starlink LEO Mega-Constellations. Latencies range from 50 ms with OneWeb and Starlink to 150 ms for MEO O3b to 600 ms for GEO HTS platforms.

	Space Terminal	High-rate Transmitter	Low-rate Transmitter
Bandwidth	20 MHz	200-337.5 MHz	< 54 MHz
Net Data Rate	20 Mbps	500-1000 Mbps	< 200 Mbps
Daily Capacity	1 Tbit	1-10 Tbit	100-600 Gbit
Coverage (% orbit)	>90	<50 (Network) <10 (Station)	<50 (Network) <10 (Station)
Latency	<50 ms	20-90 min	20-90 min
Antenna	Passive	Active/Passive	Passive
Antenna Gain	Low (8-dBi)	High (> 16-dBi)	High (>16 dBi)
Pointing	Zenith	Ground Tracking	Ground Tracking
Duty Cycle (%)	100	5-10	5-10
Input Power	< 45W	45-100W	< 25W
Weight	< 1.5 kg	2-5 kg	< 1 kg
Form Factor	1U	2-4U	< 1U
Simplicity	High	Low	Medium
Battery Supply	High	Medium	Low
Power	Medium	High	Low

TABLE III: Terminal Comparison for the Common Case. Typical values for antenna, orbit, and GSN have been listed. A 50-min net daily contact with a polar station has been assumed.

	Low End	Common Case	High End
Bandwidth	10 MHz	20 MHz	125 MHz
Net Data Rate	1.8 Mbps	20 Mbps	171.5 Mbps
Daily Capacity (100% Duty Cycle)	100 Gbit	1 Tbit	9.3 Tbit
Antenna	Passive	Passive	Active
Antenna Gain	Low (3-dBi)	Low (8-dBi)	High (20-dBi)
# Beams	1	1	≥ 3
Input Power	<25 W	<45 W	45-100W
Weight	< 1 kg	< 1.5 kg	> 2 kg
Form Factor	< 1U	1U	> 2U
Handover	Digital	Digital	Hybrid (Beam-steering + Digital)
Complexity	Lowest	Low	High

TABLE IV: Potential Space Terminal Configurations



(a) OneWeb + Starlink (b) MEO O3b mPOWER (c) GEO HTS (d) OneWeb +Starlink + O3b mPOWER

(e) OneWeb + Starlink (f) MEO O3b mPOWER (g) GEO HTS (h) OneWeb + Starlink + O3b mPOWER

Fig. 7: Concept Daily Uplink Capacity as a Function of SUT Orbital Paraemters, Terminal Configuration, and Service Provider (Top: Common-case, Bottom: High-end). LEO Mega-Constellations vs. MEO O3b mPOWER vs. GEO HTS vs. LEO+MEO.

b) Optimal User Orbital Elements: GEO and MEO capacity is maximum for low-inclination SUTs ($<$ 30 degrees) and minimum for polar SUTs, visible only over the latitudes these systems were designed for. These figures are likely to increase when O3b mPOWER adds its proposed orbital plane at 70-degree inclination to better cover high latitude users.

Mega-constellations capacity quickly diminishes as SUT altitude increases, becoming negligible within 50 km of the highest shells because of steering range and minimum elevation angle constraints. Its capacity is maximum at 350 km, falling to 40-to-50% in the 800-to-850 km range, and depends on inclination: polar SUTs have the most capacity, followed by mid-inclination SUTs, and equatorial SUTs. Thus, there is an optimal SUT orbital range that varies across systems and a key difference in connectivity: for most users, mega-constellations space-based connectivity is intermittent, characterised by short accesses interspersed with short losses of contact, while data relay connectivity is described by long, continuous, accesses followed by long disconnections (i.e., polar users may be continuously out of visibility for up to 50% of their orbit, resulting in 30-to-60 min data latencies).

c) System Capacity, Terminal Configuration, and User Orbits: Figure 7 shows the daily capacity of the common case and high-end (36 MHz) configurations using CCM as a function of SUT orbital parameters and system. Low-end and high-end (125 MHz) configurations are not represented because they cannot close the link with the GEO platform; path losses are just too high. For mega-constellation common-case SUTs at 500-to-550 km, capacity is independent of inclination, while at 550-to-800 km altitudes, only users close to critical inclinations can cross the Tbit threshold. These same trends are present for high-end (36 MHz) SUTs, but all SUTs below 900-km in altitude can access Tbit capacity, up to 4-to-5 Tbit for SUTs below 600-km.

O3b mPOWER high-end (36 MHz) SUTs suffer a 26.5% reduction in net data rate but have a 1.5-to-4.5 Tbit capacity while common case SUTs have a 250-to-650 Gbit capacity. Instead, GEO platforms, due to higher path losses can only provide 230 kbps to 2.99 Mbps data rates to common case and high-end SUTs, respectively, so a capacity of 6.3-to-82 Gbit.

For completeness, in the downlink, the SUT can access net data rates of 1-to-10 Mbps, 0.18-to-13.15, and 0.08-to-0.31 Mbps and a capacity of 100-to-500 Gbit, 5.17-to-355 Gbit, and 2.44-to-8.77 Gbit, with EIRPs of 55-to-74 dBm, 70-to-90 dBm, and 86-to-90 dBm, for OneWeb+Starlink, O3b mPOWER, and SES GEO platforms respectively. Because there may be tens to hundreds of users sharing a beam, SUTs will experience even lower rates for GEO – only a few kbps.

d) Multi-system Performance: Combining multiple layer systems can enhance coverage and capacity. For example, using OneWeb and Starlink LEO Mega-Constellations plus MEO O3b mPOWER offers uniform capacity across all inclinations: 250-to-650 Gbit and 1.5-to-4 Tbit for the common case and high-end configurations, respectively. Without adaptive coding, data rates are limited by mPOWER's higher path losses, resulting in 26.5-to-50% lower data rates and reduced capacity at low altitudes, but increased for high altitudes. Still, high altitude polar SUTs remain with only 40-to-50% of coverage because of mega-constellations' steering range limitations and O3b's latitude constraints.

2) Ground Station Networks: Performance depends on ground station location (i.e., number of passes per day, pass duration, rain losses) and not all locations are visible over the same day, so we focus on how net daily capacity is affected by contact time, regardless of how the network guarantees it (i.e., which passes are booked at what locations).

a) Capacity: Large (3.7 m) ground station antennas can close the link throughout the EIRP and bandwidth range, providing 2.82-to-10.44 times higher data rates than space-

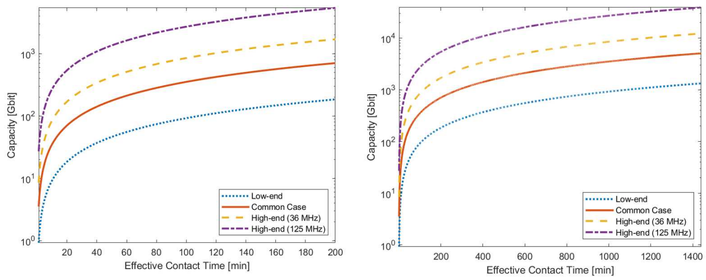


Fig. 8: Daily Net Capacity as a Function of GSN Contact Time for Various Concept Configurations

Feature	Concept	RF (LEO)	RF (MEO, GEO)	Optical (MEO, GEO)	GSaaS
Capacity	High	Low	Medium	High	High
Coverage	High	High	Medium	Medium	Low
Data Latency	Low	Low	Medium	Medium	High
Packet Latency	Low	Low	Medium High	Medium	Medium High
# Concurrent Users	High	Low	Low	Low	Medium
Terminal Complexity, Cost	Medium	Low	Low Medium	High	Medium
Hosting, Operational Requirements	Low	Low	Low Medium	High	Medium
Service Fee	Low	Low	Medium	High	Medium High

TABLE V: High-level Summary of Concept, Data Relay System and GSaaS Key Performance Indices

based services (19.22-to-564 Mbps over 1.84-to-200 Mbps) because of a 16.4 dB higher G/T (25.1 dB/K against 8.7 dB/K). Computing the capacity of the terminal configurations according to contact time (Figure 8), the low-end configuration needs 109 minutes of contact to provide 100 Gbit of capacity and the Tbit threshold is crossed with 284, 118, and 37 minutes of contact in the common case, high-end (36 MHz), and high-end (125 MHz) configurations, respectively. Over 50 minutes of contact per day is usually more than a single ground station can offer, but within the capabilities of a network.

b) Data Latency: NASA demonstrated recently how AWS GSaaS network can reduce LEO data latencies from 1.5-to-3 hours to under 25 minutes [44]. Recent works have also proposed ground station networks to bring latency down to 21 minutes for EO satellites [45] and to provide global coverage [46], [47] to LEO satellites. As networks grow, latency and capacity will be improved. Still, below-minute latencies will likely remain exclusive to space-based connectivity.

3) Service Fares: OneWeb and Starlink compete for the same low-latency broadband market and will likely have similar pricing strategies for high-throughput services, that is, US$100.00/month for a 50-to-250 Mbps downlink and 10-to-20 Mbps uplink, and US$500.00/month for a 150-to-500 Mbps downlink and 20-to-40 Mbps uplink [48], without data caps. In uplink, this corresponds to a price range of US$5.00-to-25.00/Mbps/month for NGSO broadband services, assuming space and ground users are subject to similar pricing.

High-throughput systems pricing depend on the provided services. Long-term leases on HTS capacity have a price range of US$100.00-to-500.00/Mbps/month [49]–[51] for commercial MEO and GEO systems, if not lower, as Eutelsat's Konnect [52] is estimated to cost US$40.00-to-60.00/Mbps/month. Since users pay for rates, strategies where traffic is optimised to minimise throughput are rewarded.

Ground Stations as a Service (GSaaS) capabilities and service fares vary across providers, rarely being public because they are tailored to customers' requirements and crucial to market competitiveness. Prices can wildly fluctuate between pricing models (i.e., per-minute, per-pass, subscription-based, volume-based commitments) and when committing to a number of minutes or passes. Per-pass pricing is also linked to locations, spacecraft orbits, and mission requirements.

Nevertheless, AWS Ground Station [39] publicly lists their service fares: a reserved per-minute pricing of US$3,00/min (<54 MHz) and US$10,00/min ([54, 500] MHz) for X-band. Consequently, we use this pricing model and modulate cost according to capacity and contact duration requirements independently of ground station locations and satellite orbits.

4) Comparison Summary: Table V and Table VI summarise the different competing services on a reference operational scenario for a 500-km altitude polar SUT.

The potential of MCSS is evident by solely comparing the uplink and downlink net data rates achieved with respect to other space-based services, with full coverage over the user orbit, and thus a given daily capacity can be met with less contact time (or spread over the orbit at lower data rates) at very competitive costs (about one order of magnitude less than that of MEO and GEO-based services), with the advantage of having an almost near real-time latency. In this case, LEO mega-constellations are the cheapest solution for any capacity. If instead we consider highest data relay fares, space-based connectivity would cost five times more, but mega-constellations would remain the cheapest provider to users requiring over 10 Gbit/day – a proof of financial viability.

To achieve a similar capacity solely relying on space-to-earth links with GSaaS services, estimated monthly costs explode with further disadvantages in terms of overall data latency and unavailability of broadband earth-to-space links. The maximum data transfer volume attainable in this case is 48.32 Tbit/day, which would imply a 432.000 USD/month service (equivalent to 10 USD/min, 1440 min/day, 30 days/month), a high-end transmitter and a challenging (if not unrealistic) 100% ground network coverage.

VI. Final Discussion

Mega-constellation connectivity is available to space users located within constellations' service volumes, which for Starlink and OneWeb, means that most LEO users below 1200 km can be served. These users represent the majority of addressable user base and thus the Mega Constellation Service in Space paradigm is not only viable now, but will remain so in the near future as the key driver of payload orbit design are application needs.

Our results show that Tbit-scale capacity using low-power passive patch antennas is the common case for the Concept terminal, by constant data dripping, because the sheer coverage provided by mega-constellations is the enabler of high-capacity applications, and the use of multiple parallel channels shift inter-satellite links towards a Point-to-Multipoint Paradigm that simplifies acquisition, tracking, and pointing because a fixed beam can illuminate several satellites at once.

After analysing the main competitors to MCSS using three comparable (in terms of costs and hosting requirements) user equipment configurations across the different systems, we observe that while MEO systems are able to provide net data rates just below those of LEO mega-constellations across the different terminal configurations, GEO data relays are affected both by higher signal latencies and path losses, reducing performance significantly with the same user equipment power and antenna gain. However, the difference in capacity is more pronounced, with a four-fold and ten-fold increase over the evaluated MEO and GEO systems, respectively.

Based on these assessments, it can be concluded that the quality of service that LEO mega-constellations could provide to LEO users is at least one order of magnitude better, both in data latency and volume capacity, to that offered by established radiofrequency data relay systems on similar user equipment capabilities. However, data relays can augment MCSS by providing multi-orbit connectivity and bridging potential coverage gaps for certain user orbits while offering diversity. Instead, GSaaS can offer comparable net capacities if provided enough contact time, requiring more than one contact per revolution on average, determining the data latency, which could be challenging for some orbits and/or ground networks.

By estimating operating costs, we conclude that MCSS offers the best cost-benefit trade-off for any capacity, even if volumes below 100 Gbit/day do not exhibit any scalability, maintaining monthly fees comparable to that of GSaaS for lower data volumes, with MEO and GEO costing about two-fold and five-fold for the same daily capacity. When increasing volumes, costs increase quickly for GSaaS and data relay systems, being up to twelve-to-fifty times higher than mega-constellations. Assessing the value that the Concept brings to space missions, we estimated an upper bound for the maximum number of concurrent space users supported by mega-constellations in the thousands to hundreds of thousands.

VII. Conclusions and Future Research

The main contribution of this paper are:

- The validation of the Mega-Constellation Service in Space paradigm as an effective solution to transform LEO space users into highly responsive nodes of a space internet, with high throughput, low latency and low cost.
- The design of four different Space User Terminal configurations, from low-end to common-case to high-end, characterized by increasing complexity and different values of key parameters like output power, antenna gain, bandwidth, and DVB-S2X MODCOM.
- The computation of the achievable daily capacity for the different terminals, for a space user in polar orbit, 500 km altitude and for generic LEO space users with altitudes from 350 to 1200 km and different altitudes. As an example, results show that the common case terminal onboard the LEO satellite at 500 km altitude, can achieve 1 Tbit/day uplink capacity at a constant bit rate (20 Mbps) with 10 W of transmitted power over a 20 MHz band with passive wide-beam patch antenna with 8 dBi gain.
- The definition and the discussion of the space user terminal architecture in terms of modem, antenna, scheduler and the comparison against space-to-Earth transceivers. Results show that by balancing capacity and power, the terminal is suitable for any platform, included small satellites and smaller platforms.
- The comparison against existing services like MEO/GEO Data Relay Systems and Ground Station Networks, showing the advantages provided by the mega-constellation approach.

Provider	OneWeb + Starlink	SES MEO	SES GEO	GSaaS
Gross Payload/Telemetry Rate [Mbps]	[9.2, 312.5]	[8.2, 200]	[2.3, 29.9]	[36.53, 833.33]
Net Payload/Telemetry Rate [Mbps]	[1.82, 172.5]	[0.82, 108.8]	[0.23, 2.99]	[19.22, 564.33]
Net Payload/Telemetry Capacity [Tbit]	[0.1, 9.3]	[0.022, 3.0]	[0.0063, 0.082]	[0.046, 10.83]
Net Telecommand Rate [Mbps]	[1, 10]	[0.18, 13.15]	[0.08, 0.31]	N/A
Net Telecommand Capacity [Gbit]	[100, 500]	[5.17, 355.54]	[2.44, 8.77]	N/A
Cost [USD/Month]	[46, 1562] (min) [230, 7812](max)	[820, 20000] (min) [4100, 100000] (max)	[230, 2990] (min) [1150, 14950] (max)	[63, 92150]
Latency	< 50 ms	< 150 ms	< 600 ms	[20, 90] min

TABLE VI: Numerical Summary of Concept, Data Relay System and GSaaS Key Performance Indices

Put together, these results prove that this innovative paradigm can be extremely disruptive for the space ecosystem, creating a truly low cost, low-latency high-throughput 24/7 Internet-like space network, where mega-constellations provide In-Space Connectivity services to user satellites - just as internet service providers on Earth.

Still, for MCSS to become operational, there are several commercial (service) and technical aspects that must be investigated, such as licensing, addressing and (dynamic aware) routing, location and mobility management, while considering constellation-specific waveforms, signal structures, channel allocation, and interference mitigation mechanisms. Using MEO constellations to service users in the 1200-to-8000 km altitude range and GSaaS to complement MCSS are left as promising areas to be explored in future work.

VIII. Acknowledgments

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