# Non-Terrestrial Networks for Space Vehicles beyond 6G: Applications, Architecture, and Capacity Limits

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***Abstract*—Non-Terrestrial Networks (NTNs) are becoming increasingly popular in serving ground and airborne users on the way from 5G to 6G networks. In this work, we present and analyze *a novel attractive use case for satellite networks* – serving other satellites and space vehicles used for scientific and commercial missions. We start by presenting our visionary approach and its rationale from technical and commercial perspectives. We then discuss possible system architectures to implement such a service in existing and forthcoming NTNs. We finally present a simple first-order case study, illustrating performance gains with the proposed approach when using both existing Ku-band wireless links (18 GHz) and currently under development sub-terahertz links (220 GHz). Our preliminary findings confirm that, if implemented properly, such a vision may offer *up to an order of magnitude improvement* in capacity, contact time, and energy efficiency for next-generation scientific, military, and commercial satellites.**

## I. Introduction

From the first satellite beacons to modern global broadband constellations, satellite communications have continually redefined the boundaries of connectivity. Since the launch of the first commercial communications satellite, Intelsat-I, which operated in geostationary orbit (GEO) and offered no more than 50 MHz of bandwidth [1], the industry has followed a clear trajectory of advancement. Specifically, satellite communication systems have evolved in two major directions: (1) increased capacity through the adoption of higher carrier frequencies, enabling larger bandwidths, and (2) reduced latency through the deployment of satellites at Low-Earth Orbits (LEOs) between $400\,\text{km}$ and 2,000 km, significantly lowering latency from the $\sim 600\,\text{ms}$ at GEO to $\sim 8\,\text{ms}$.

Today, high-rate satellite communication among hundreds and even thousands of satellites deployed at LEO, potentially supported by High Altitude Platforms (HAPs) such as balloons, drones, and airships, has become a reality. Recently referred to as Non-Terrestrial Networks (NTNs) by standardization bodies like 3GPP [2], these systems, along with their seamless integration into terrestrial cellular communication infrastructure, are envisioned as a cornerstone of the sixth-generation (6G) of wireless systems beyond 2030. Moreover, with millimeter wave communications (mmWave, $\approx$30 GHz–100 GHz, including the Ka band [3]) already integrated into 5G terrestrial networks, there is growing interest in extending these capabilities to space-based networks through the exploration of sub-terahertz (sub-THz, 100 GHz–300 GHz [4]), and even THz (300 GHz–3 THz) frequency bands [5], [6]. Wireless communications using these new bands may theoretically provide much greater capacity [7], lower latency [8], and better spatial diversity [9], among other decisive advantages.

While the development of broadband NTNs is motivated by the significant benefits of providing space-based connectivity to ground users, there is also a growing user base of potential NTN clients located beyond Earth. In particular, a renewed interest in space exploration is fueling the growth of this user base, which mainly consists of scientific and small satellites (e.g. CubeSats), space telescopes, space tourism vehicles, and more. Furthermore, these users are becoming increasingly advanced, equipped with state-of-the-art imaging payloads capable of generating vast volumes of remote sensing data, including high-resolution images and videos. This surge in data generation creates a growing demand for robust space-based data services, which is hard to guarantee with the capabilities of current ground data systems (GDSs). Even the National Aeronautics and Space Administration (NASA)'s Deep Space Network (DSN), targeted at space users beyond the Moon's orbit, has projected congestion issues due to the rising number of service clients with escalating demands [10]. These challenges are exacerbated by reliance on ground infrastructure operating at frequencies below the Ku/Ka bands, making spectrum and antenna time congestion forecasts an imminent reality. For this reason, the possibility of utilizing advanced commercial NTNs leveraging new spectrum in the sub-THz band to provide connectivity to such space users emerges as a compelling option.

The use of satellites to relay data from space has been explored before. For instance, NASA has been operating the Tracking and Data Relay Satellite System (TDRSS) for over $\sim 30$ years. The relay system primarily consists of five large relay satellites in GEO orbit, offering up to Ku-band coverage with limited bandwidth [11]. Although many challenges remain, plans are underway to upgrade this system

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to support optical communications [12]. Similarly, the China National Space Administration (CNSA) has been operating a Chinese lunar relay communication satellite to support lunar far-side missions in the S- and Ku-bands [13]. Additionally, NASA has considered multiple relay architectures to support near-Earth and Deep Space exploration missions [14]–[17]. However, these works predominantly focus on dedicated relay constellations operating below 100 GHz and orbiting the target planet, rather than leveraging Earth-orbiting NTNs with beyond-100 GHz connectivity. While some prior works address airplane to LEO satellite coverage [18], only Palermo et al. [19] appear to have considered an Earth-orbiting relay system for space users, albeit operating at Ku-band and employing dedicated architectures rather than reusing emerging NTN systems.

Despite the intuitive advantages of serving space users through sub-THz NTN systems, to the best of the authors' knowledge, there is no comprehensive study to objectively characterize the impact of this solution over existing methods, thus giving the motivation for the present study.

In this regard, the main contributions of this work are:

- *Innovative system architecture*: We present a vision for using prospective sub-THz NTNs to serve users beyond the ground. We delve into the key prospective advantages, challenges, and implementation alternatives.
- *Comprehensive modeling methodology*: We present a constructive approach to accurately quantify the capacity available to space users when connected through (1) new network architectures involving NTNs, and (2) state-of-the-art sub-THz technology. Notably, these users present a novel use case that expands these novel network architectures' impact, usability, and client base.
- *Extensive numerical study*: We then utilize this approach for a comprehensive numerical study to assess the channel capacity offered by such novel LEO systems. We utilize current Ku-band ground data systems as a baseline to reveal a couple of orders of magnitude improvements in coverage probability, total data download capacity, and energy efficiency.

The rest of the paper is organized as follows. Sec. II provides an overview of the system architecture and applications of NTNs serving space vehicles, making a clear distinction between ground services, near-Earth connectivity, and Deep Space applications. Sec. III introduces the system model and architectures considered, the key propagation and routing assumptions in our analysis, and the metrics of interest analyzed. In Sec. IV, the simulation results of the developed models are presented, highlighting the main insights observed. The concluding remarks are drawn in Sec. V.

## II. Expanding NTN Horizons: Enabling Connectivity for Space Users

### A. Vision

NTNs are poised to revolutionize space communication, bridging the gap between Earth and beyond by enabling seamless, high-capacity connectivity for space vehicles—a vision that pushes the boundaries of what 6G and beyond can achieve. One of the key advantages is that the NTN infrastructure deployment and maintenance is already in place, minimizing the need for dedicated satellite relay deployments. Additionally, the traffic demand from these space vehicles is significantly lower compared to the high data demands of ground users, making the integration more manageable. This approach also offers massive cost savings for space payloads, as a standardized, mass-produced radio interface could be utilized instead of dedicated space communication subsystems. Furthermore, NTNs have the capability to provide continuous 24/7 coverage if required, ensuring uninterrupted communication. Finally, instead of developing an entirely new GDS, or relying on third-party GDS services, these users could simply employ a 'SIM-card'-like interface and a standardized radio payload to seamlessly relay their data through the NTNs, further simplifying operations.

### B. Applications and Artchitecture

Initially intended for users on the ground, the applications of NTNs have been expanding rapidly, with breakthroughs such as direct-to-device NTN connectivity recently demonstrating their potential [20], [21]. A schematic depicting the wide range of such applications is included in Fig. 1 However, amidst these and further advancements in cost-effective space accessibility, an often overlooked use case stands out: serving space users. These users include a diverse array of entities with increasing presence and number of instances such as research and/or academic small satellites, lunar south pole landers, Mars orbiters and rovers, scientific telescopes, orbiting stations with continued human presence, and even space tourism vehicles. Currently, these systems rely on complex, bulky communication payloads to handle data transmission, telemetry downloads, and command reception, significantly increasing their design and operational complexity.

In our vision, NTNs have the potential to transform connectivity for these space users by making it as seamless as connecting a smartphone to a base station. By integrating a standardized radio interface and a SIM card-equivalent system, the communication subsystems on these spacecraft could be dramatically simplified. This paradigm shift would reduce hardware demands and improve the scalability and download capacity of such missions, fostering innovation, largely expanding their scientific and/or service value, and reducing costs.

From a practical standpoint, this vision can be realized in several ways. One approach involves dynamically rotating NTN nodes to serve space users when they are over unpopulated areas or oceans, where ground service demand is minimal. However, this method could introduce extensive operational challenges. An alternative approach would be to equip next-generation NTN satellites with zenith-facing antennas, designed to naturally communicate with space users without disrupting service to ground users. These nodes could relay data seamlessly to the NTN backbone network with minimal

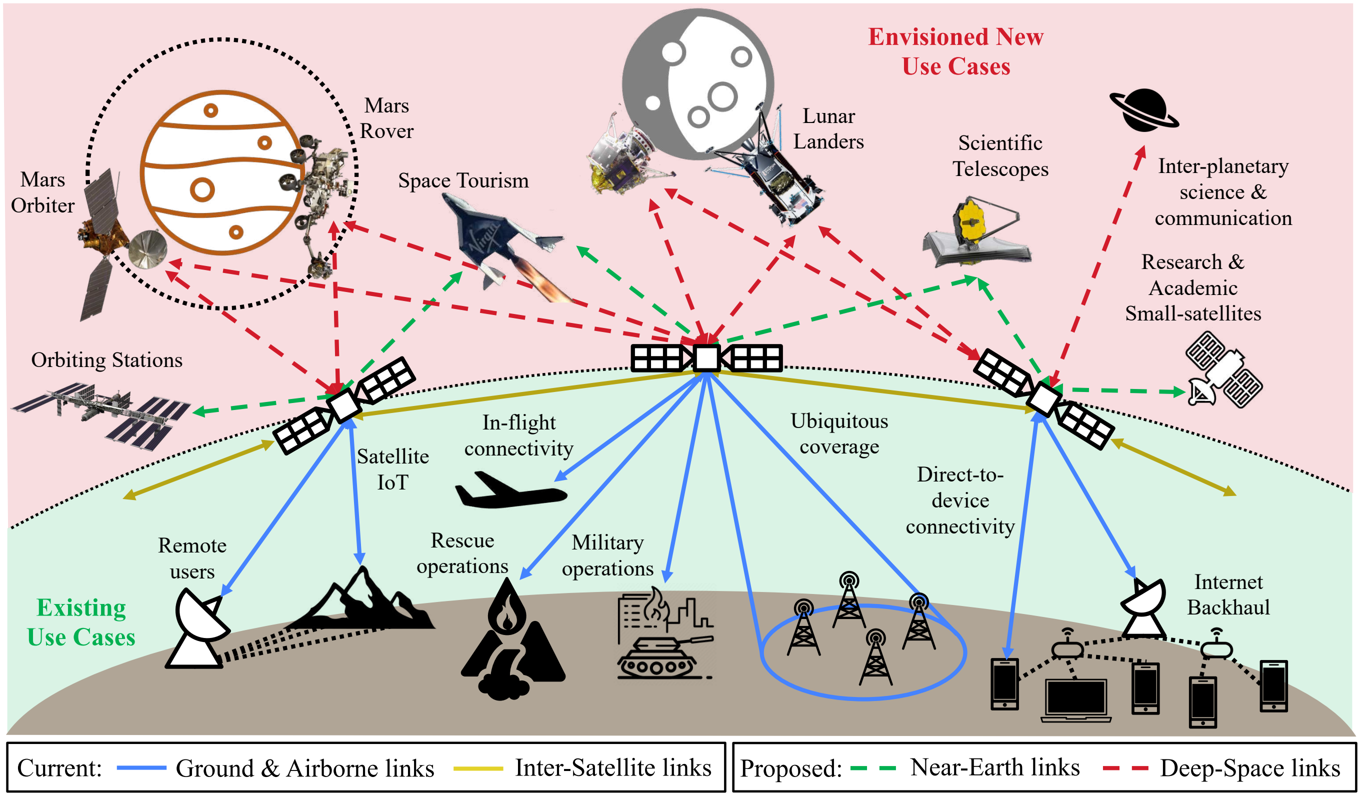



**Fig. 1.** Envisioned scope of 6G+ NTN connectivity to support *space users* (scientific telescopes and missions, space tourism, lunar landers, and Mars orbiters, etc.), alongside traditional *terrestrial and airborne users*.

operational disturbance, ensuring data delivery to stakeholders such as mission operations centers and scientific teams. These relay capabilities are ensured by the seamless integration of NTNs with ground communications infrastructure, as already provisioned by major standardization bodies such as 3GPP [2].

Given these advantages and the flexibility of implementation, this study seeks to objectively quantify the potential improvements offered by NTN connectivity to space users over traditional ground station architectures. By doing so, we aim to evaluate the transformative potential of this proposed space communication architecture.

## III. System Model

In this section, we introduce the main assumptions for our model, including the system architecture considered, the propagation and network models adopted, and relevant metrics of interest.

### A. Deployment Scenario Considered

The system model for this study comprises a LEO CubeSat orbiting at altitude $h_{\text{CS}} \in [400, 2000]$km above sea level, as depicted in Fig. 2, where $R_e$ indicates the Earth's radius. The CubeSat requires downlink connectivity to download the scientific data gathered, which includes measurements, images, and/or videos, as well as spacecraft telemetry. We aim to comprehend the downlink channel capacity, its variability over time, and the total amount of data that can be downloaded from the CubeSat when utilizing sub-THz NTN-assisted communications. We achieve this by analyzing three elemental architectures with varying levels of complexity, which serve as a reference for upcoming satellite mega-constellations currently being deployed or developed. These elemental architectures, illustrated in Fig. 2, are:

1) *Ground Station*: Serving the CubeSat from the ground is the nominal solution for most of the space users currently in orbit and serves as our baseline architecture.
2) *Single NTN relay*: Offering a direct one-to-one comparison with the baseline, this architecture captures the dynamics of relaying the data to a satellite located in a co-planar orbit with the user (CubeSat).
3) *Multiple NTN relays*: Expanding the previous architecture to $N_{\text{NTN}}$ relays allows us to generalize the results for this elemental NTN architecture.

The choice of a co-planar orbit for the NTN relays is based on the assumption that the entire constellation comprises multiple orbital planes arranged in a shell-like pattern around the Earth. A type of NTN constellation design with such a pattern is the Walker-Delta constellation, which is widely adopted for its extensive coverage of the globe's most densely populated areas [22]. Due to the high density of orbital planes in traditional Walker-Delta constellations, the CubeSat's orbit is expected to be nearly co-planar with the NTN relays for most of the time, even accounting for orbit

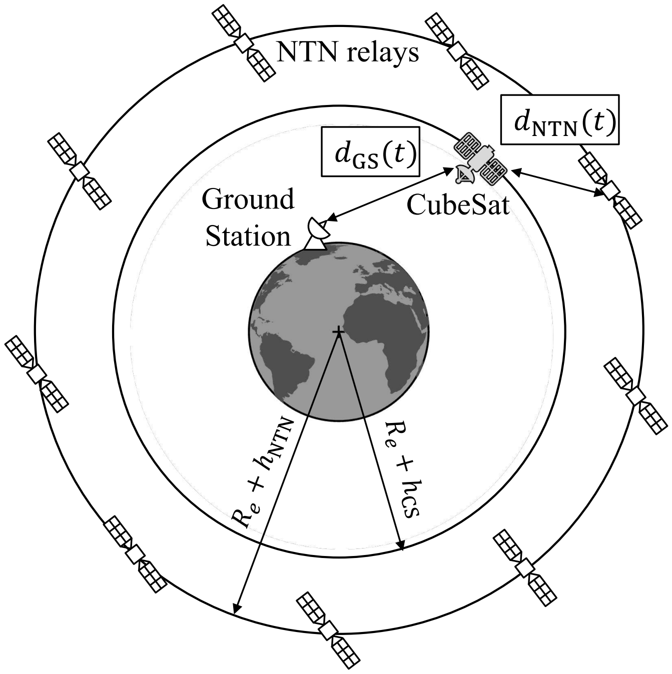



**Fig. 2.** Modeling space user connectivity through NTN-assisted downlink.

precession. Consequently, the simplified co-planar analysis provides representative insights into the system's dynamics. Additionally, the feeder links between the NTN and the ground are considered to be seamlessly integrated with the ground communications infrastructure, as indicated in Sec. II, and, thus, are omitted from our study.

### *B. Propagation and routing assumptions*

In our study, we model the signal propagation through the Friis transmission equation, in which the received power at either the ground station (GS) or an NTN relay, $P_{\text{Rx}}$ is calculated as:

$$P_{\text{Rx}} = \frac{P_{\text{Tx}} G_{\text{CS}} G_{\text{Rx}}}{L(f_c, d(t))}, \tag{1}$$

where $P_{\text{Tx}}$ and $G_{\text{CS}}$ are the CubeSat's transmitted power and antenna gain, respectively, $G_{\text{Rx}}$ is the receiver antenna gain, located either at the GS or onboard an NTN relay, and $L(f_c, d(t))$ is the channel path loss. $f_c$ is the carrier frequency utilized and $d(t)$ is the time-varying distance between the CubeSat and the downlink node (GS or NTN relay).

The transmission of data from the CubeSat to an NTN relay occurs entirely outside the atmosphere. For this reason, only spreading losses are accounted for in this case, $L(f_c, d(t)) \equiv L_{\text{spr}}(f_c, d(t))$, where:

$$L_{\text{spr}}(f_c, d(t)) = \left(\frac{4\pi d(t) f_c}{c}\right)^2. \tag{2}$$

On the other hand, when communicating with a ground station, the loss incurred due to the strong molecular absorption in the atmosphere needs to be accurately modeled. Specifically, in our study, we model this absorption loss, $L_{\text{abs}}(f_c, d(t))$, as:

$$L_{\text{abs}}(f_c, d(t)) = \exp\left[\int_0^{d(t)} \kappa(f_c, Q(r), p(r), T(r)) dr\right], \tag{3}$$

where $\kappa$ is the molecular absorption coefficient for the atmosphere, which depends on the composition $Q(r)$, the pressure $p(r)$, and the temperature $T(r)$ profiles. These parameters in turn change along the propagation path. These profiles, along with the dependence of $\kappa$ on them, are obtained from the ITU Recommendation ITU-R P.676-12 [23] as well as Recommendation ITU-R P.835 [24]. Thus, when communication from the CubeSat to the GS is considered, we model the total path loss as $L(f_c, d(t)) \equiv L_{\text{spr}}(f_c, d(t)) L_{\text{abs}}(f_c, d(t))$.

To analyze the capacity of relaying the CubeSat data to a multi-node NTN constellation, certain assumptions need to be made about the routing strategy used. In our study, we assume that CubeSat transmits to the closest NTN relay visible whenever possible.

### *C. Metrics of Interest*

The main emphasis of our study is to accurately examine the CubeSat's coverage improvement when a sub-THz NTN architecture is utilized. While technical limitations might limit the actual transferrable data rates (e.g. limited capabilities onboard the CubeSat), we aim at providing an upper bound on the overall performance of the system. Thus, the relevant metrics of interest for our study are:

*a)* ***Contact Probability,*** *$Q$:* Defined as the probability that the CubeSat is in line of sight (LoS) with an NTN relay or a GS, it is computed by dividing the total contact time, $T_{\text{c}}$, by the scenario repetition period, $T$, as:

$$Q = \frac{T_{\text{c}}}{T}. \tag{4}$$

The scenario repetition period considered for providing connectivity to LEO spacecraft with a GS is typically considered to be $T_{\text{GS}} = T_{\text{day}} = 24$h, since an entire day is enough to capture the scenario dynamics of spacecraft with an orbital period between 1.5h and 2.1h (corresponding to altitudes between 400km and 2000km). However, in the case of the co-planar NTN relays, the scenario repetition period can not be as trivially approximated since it largely depends on the difference in orbit altitudes. In that case, the scenario repetition period is approximated by [25]:

$$T_{\text{NTN}} = \frac{2\pi / N_{\text{NTN}}}{\sqrt{\mu}\left|(R_{\text{e}} + h_{\text{NTN}})^{-3/2} - (R_{\text{e}} + h_{\text{CS}})^{-3/2}\right|}. \tag{5}$$

*b)* ***Channel Capacity,*** *$C(t)$:* This time-varying metric is computed through the well-known formula derived by Shannon [26]:

$$C(t) = W \log_2(1 + \rho(t)) = W \log_2\left(1 + \frac{P_{\text{Rx}}(t)}{P_N}\right), \tag{6}$$

where $W$ is the channel bandwidth utilized, $\rho(t)$ is the instantaneous signal-to-noise ratio (SNR), $P_N = kT_{\text{sys}}W$ is the noise power at the receiver, and $k$ is Boltzman's constant. The instantaneous received power, $P_{\text{Rx}}(t)$, is given by (6), and mainly changed due to the variation in the distance $d(t)$ caused by the scenario's orbital dynamics. $T_{\text{sys}} = T_{\text{a}} + T_{\text{e}}$ is the system's noise temperature, modeled as the sum of the noise temperature captured by the antenna, $T_{\text{a}}$, and the equivalent noise temperature of the receiver, $T_{\text{e}}$, respectively. In turn, this receiver temperature is modeled through the noise factor of the receiver, $F$, as $T_{\text{e}} = (F-1)T_0$, where $T_0 = 290\text{K}$ is the reference noise temperature.

*c) **Download Capacity,*** $\Gamma$*:* We compute the average download capacity over 24h by averaging the channel capacity over the scenario repetition period and extending it to 24h:

$$\Gamma = \frac{T_{\text{day}}}{T} \int_0^T C(t)dt. \tag{7}$$

*d) **Energy Efficiency,*** $\eta$*:* Refers to the ratio of the useful data transmitted to the total energy consumed by the system. In our analysis, we assume a constant power output whenever the CubeSat is in LoS, e.g. using a constant amplitude modulation such as a phase modulation, thus:

$$\eta = \frac{1}{P_{\text{Tx}} T_{\text{c}}} \int_0^T C(t)dt. \tag{8}$$

This metric measures how effectively the CubeSat uses power to achieve reliable communication, which is critical for battery-powered or resource-constrained environments.

## IV. Numerical Results

The performance analysis of utilizing a sub-THz NTN architecture to download the CubeSat data through the evaluation procedure outlined above is presented in this section. In our study, we considered that the CubeSat is orbiting at a Sun-Synchronous Orbit (SSO) as this type of orbit is commonly targeted by scientific satellites due to the constant illumination conditions of the targeted surface area. For this reason, we use a GS located in Svalbard as a baseline, as its almost polar location provides the best coverage for SSOs. In addition, we consider the NTN relay nodes to be orbiting at an altitude of $h_{\text{NTN}} = 550\text{km}$. We utilize the MATLAB Satellite Communication Toolbox to set up and analyze the geometry of the scenarios. The simulation focuses on calculating two key quantities: the contact time, or visibility, $T_{\text{c}}$, and the distance to the CubeSat throughout its orbit when it is in LoS, $d(t)$.

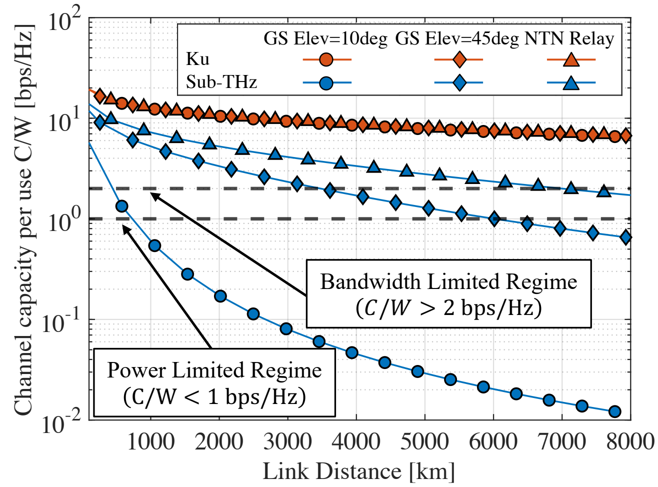
### A. Channel Capacity

Our numerical study focuses on two wireless communication bands. The first, serving as our baseline, is Ku-band, the common frequency range typically used for spacecraft data downlink, spanning frequencies between 12 and 18GHz. The second technology involves using the unlicensed sub-THz band to achieve ultra-broadband downlink communication, which is becoming increasingly important as demand for higher data rates and the number of deployed spacecraft continues to grow. The selected modeling parameters for both bands are detailed in Table I.

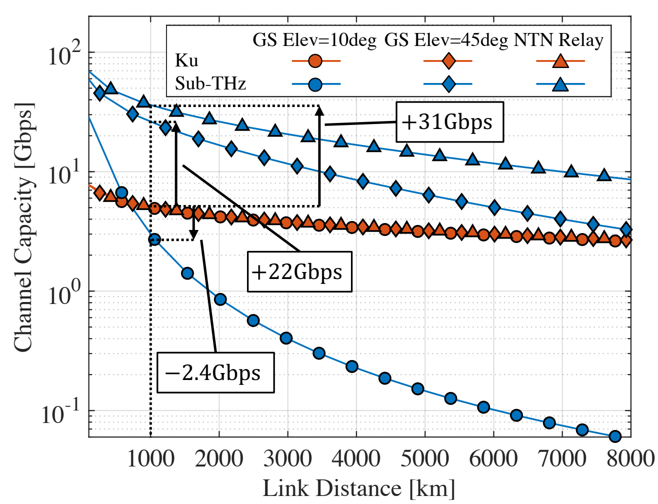
| Parameter | Ku-band (baseline) | sub-THz |
|---|---|---|
| $f_{\text{C}}$ | 18 GHz [27] | 220 GHz [28] |
| $W$ | 400 MHz [29] | 5 GHz [30] |
| $P_{\text{Tx}}$ | 40dBm (10W) [29] | 17dBm (50mW) [28] |
| $G_{\text{Tx}}$ (10cm diameter) | 23 dBi | 45 dBi |
| $G_{\text{Rx}}$ (60cm diameter) | 38 dBi | 60 dBi |
| $F$ | 3 dB [29] | 8 dB [28] |

**TABLE I.** Parameters utilized in the analysis for each frequency band.

The antenna gain values utilized are obtained by considering a 60% antenna efficiency. Fig. 3 depicts the performance of each radio technology as a function of link distance.




(a) Channel capacity per use




(b) Total channel capacity

**Fig. 3.** Communication link performance as a function of distance, highlighting power- and bandwidth-limited regimes.

Although state-of-the-art sub-THz technology is not yet flight-proven, the capacity per channel use depicted in Fig. 3(a) demonstrates that it is finally overcoming the power-limited regime (power- and bandwidth-limited regions are defined as in [31]). This indicates that the advantages of the large bandwidth available in the sub-THz band are now becoming accessible, thanks to recent advancements in sub-THz technology that address its historically limited output power capabilities.

It is worth emphasizing that Ku-band technology, which benefits from mature, flight-proven hardware, remains above sub-THz technology in terms of channel capacity per use. This highlights the primary limitation of bandwidth availability in the Ku-band — compared to the power constraints historically faced by sub-THz systems.

The total channel capacity, depicted in Fig. 3(b), reveals that even in the power-limited regime, the sub-THz band's large bandwidth results in significantly higher capacities in many scenarios. For example, at a link distance of 1000 km, typical for LEO satellite links, sub-THz technology achieves 22 Gbps and 31 Gbps more capacity than the Ku-band using a GS or an NTN relay, respectively. Notably, in scenarios where the GS operates at low elevation angles, the Ku-band is better suited to mitigate the substantial losses caused by the longer slant path through the atmosphere.

Noteworthy, compensating the lower output power of the sub-THz band with the larger available bandwidth can be regarded as more efficient communication, since less power is required per bit of information. This efficiency is explored further below.

### B. Time-dependent Results

Fig. 4 captures the impact of utilizing the NTN architecture, along with sub-THz radio technology. First, from Fig. 4(a) and Fig. 4(b), it is important to note that continuous coverage of the CubeSat is achieved with just 10 NTN relays in a coplanar orbit. This represents a substantial improvement over the short and intermittent contacts provided by a GS.

Another notable advantage is the reduction in link distance. While a single NTN relay can be further away compared to a GS by up to a factor of 2.9 for $h_{\mathrm{CS}} = 400\,\mathrm{km}$, introducing multiple NTN relays dramatically reduces the link distance to the CubeSat at its closest point. For instance, in the scenario with $h_{\mathrm{CS}} = 400\,\mathrm{km}$, a 90% reduction in link distance is observed when using multiple NTN relays. This reduction directly contributes to improved communication performance and lower latency.

The figures also highlight differences in contact time periodicity. Over a 24-hour simulation, the periodicity of GS and multiple relay scenarios is easily captured. However, the repetition period for a single relay is less clear. For $h_{\mathrm{CS}} = 400\,\mathrm{km}$, a single, long contact dominates, whereas at $h_{\mathrm{CS}} = 2000\,\mathrm{km}$ multiple shorter contacts occur within the same time frame. This variability underscores the importance of accurately capturing the denominator in (4), as a fixed 24-hour simulation period may not be adequate for all scenarios.

Notably, as the CubeSat's altitude increases, the link distance naturally grows. However, this effect is mitigated by the extended contact time in the GS scenario and the reduced variability in link distance with multiple NTN nodes. When the number of relays is further increased (e.g., 50 relays), the link distance stabilizes even further, as each relay spends less time at its closest approach.

Nonetheless, the results in Fig. 4(c) and Fig. 4(d) reveal that despite these longer and more stable contacts (21 min for $h_{\mathrm{CS}} = 2000\,\mathrm{km}$ compared to 8 min for $h_{\mathrm{CS}} = 400\,\mathrm{km}$), the resulting channel capacity is lower due to the increased link distances. This highlights the trade-off between contact time and link performance in such architectures. In other words, as long as the sub-THz link is in a power-limited regime, shorter distances will produce a larger capacity increase due to a quadratic dependence, as opposed to the linear dependence with increased contact time.

When comparing the sub-THz band to the Ku-band within the same NTN relay architecture, the figures illustrate a dramatic improvement, with peak channel capacities increasing almost by an order of magnitude. Furthermore, comparing the full NTN relay architecture to the Ku-band GS baseline demonstrates even more substantial capacity enhancements. Across all considered altitudes, peak channel capacities increase nearly 15 times for $h_{\mathrm{CS}} = 400\,\mathrm{km}$ and 7 times for$h_{\mathrm{CS}} = 2000\,\mathrm{km}$. These results underscore the transformative potential of integrating advanced NTN architectures and high-frequency bands to meet the growing data demands of space applications.

### C. Time-averaged Results

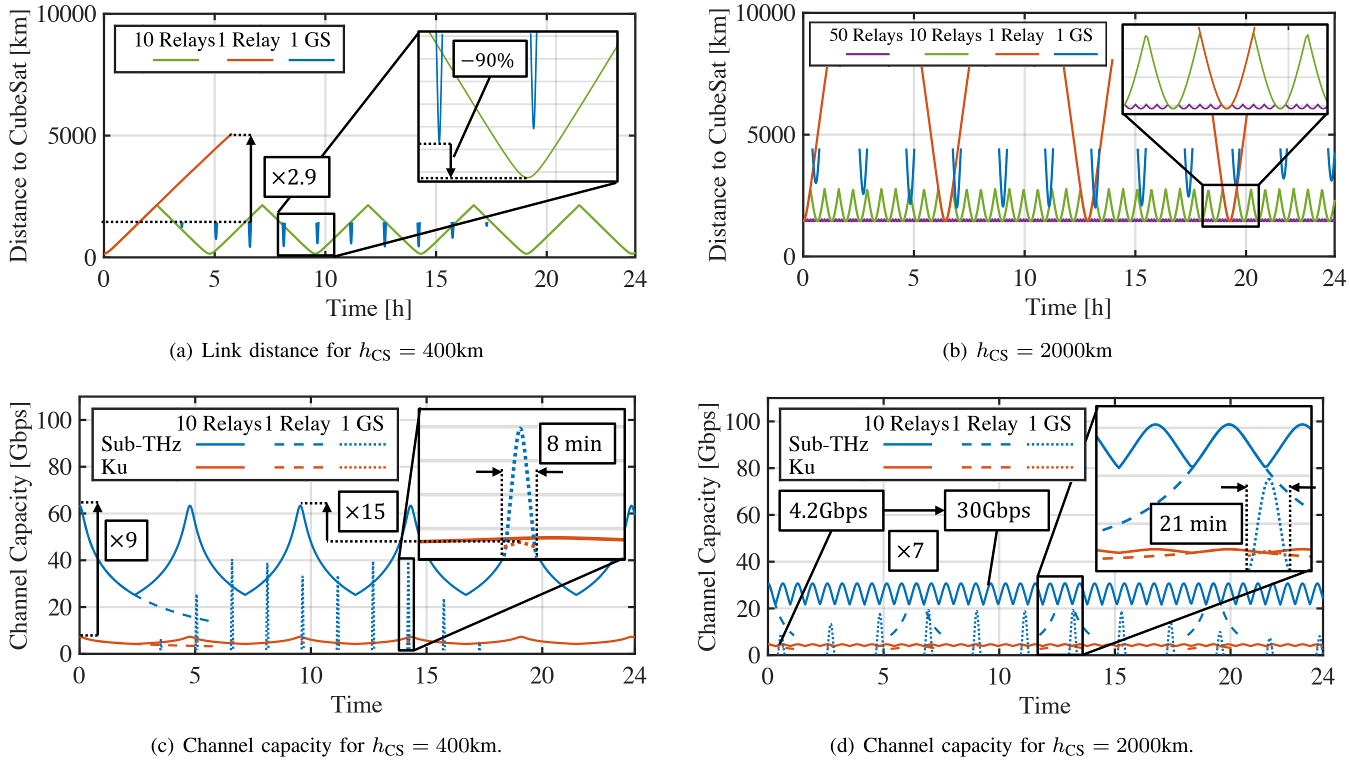
The results above are further explored through their integration over time, thus obtaining the main metrics of interest outlined in Sec. III-C. Fig. 5 illustrates the probability of maintaining LoS contact with the CubeSat as a function of its altitude, revealing key insights about different NTN relay architectures.

As discussed in Sec. III-C, considering only a 24-hour scenario repetition period ($T = T_{\mathrm{day}}$) for the single NTN relay architecture introduces variability in the contact probability curve. This is due to the changing number of contacts captured for different CubeSat altitudes within this limited time frame. By adjusting $T$ to match the NTN repetition period, $T_{\mathrm{NTN}}$, the curve stabilizes, exhibiting minimal variability across the range of CubeSat altitudes.

This corrected curve, when analyzed alongside the other two architectures, provides an important observation: the probability of contact with a CubeSat in LEO is largely unaffected by its altitude, regardless of the chosen architecture. Furthermore, the data highlight the efficiency of NTN relay systems. Even with a single NTN relay, the probability of contact triples compared to using a ground station. With just 10 NTN relays, the system achieves constant coverage at all altitudes, offering a robust solution for uninterrupted CubeSat communication.

In Fig. 6 we showcase the 24-hour average download capacity and energy efficiency across CubeSat altitudes, providing key insights into the performance of different architectures and radio technologies.

Focusing on Fig. 6(a), the improvements offered by the NTN architecture over a GS architecture are notable, particularly when utilizing sub-THz frequencies. For the Ku-band, even with 10 NTN relays, the improvements in download




(a) Link distance for $h_{\mathrm{CS}} = 400\mathrm{km}$

(b) $h_{\mathrm{CS}} = 2000\mathrm{km}$

(c) Channel capacity for $h_{\mathrm{CS}} = 400\mathrm{km}$.

(d) Channel capacity for $h_{\mathrm{CS}} = 2000\mathrm{km}$.

**Fig. 4.** Comparing link distance and channel capacity over time between a GS and multiple NTN relays..

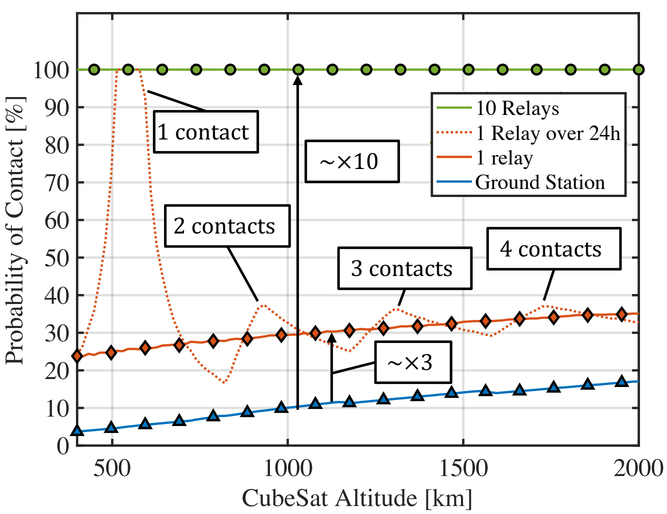



**Fig. 5.** Comparing the probability of contact with the CubeSat between a GS and multiple NTN relays.

capacity are modest, staying within the same order of magnitude as the GS architecture. In contrast, sub-THz performance exhibits a stark improvement. While the results for a single sub-THz relay remain comparable to the GS architecture, the introduction of 10 NTN relays yields an order-of-magnitude increase in performance.

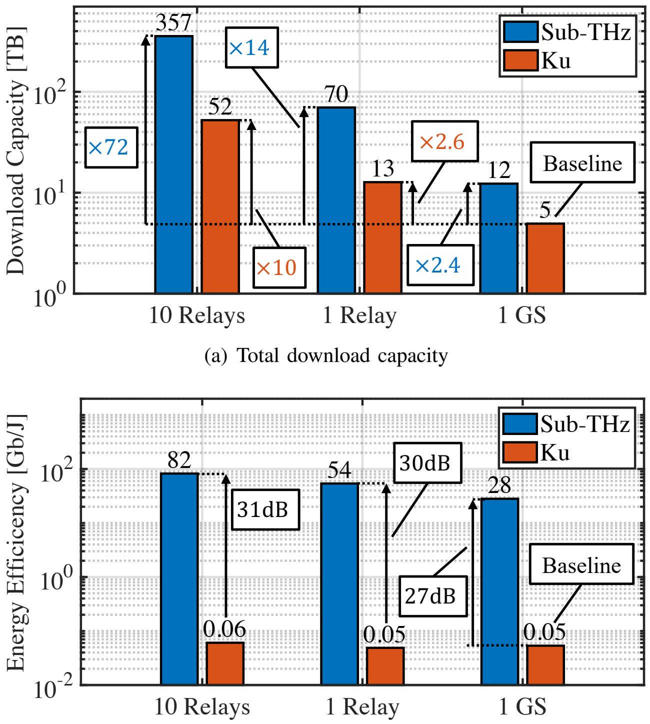
When comparing these results to the baseline, the enhancements are significant. Specifically, the download capacity improves by a factor of 70 when utilizing 10 sub-THz NTN relays and doubles when using a sub-THz GS.

From Fig. 6(b), we highlight the remarkable energy efficiency gains achieved by NTN relays. Across all architectures, the use of sub-THz frequencies provides an almost 30 dB improvement in energy efficiency compared to the Ku-band. Such efficiency gains are crucial for extending the on-board available power for CubeSats' payloads and optimizing the overall energy budget of space communication systems. Together, these figures emphasize the transformative potential of sub-THz NTN architectures in boosting data throughput and energy efficiency for next-generation space communication networks.

## V. Conclusions and Next Steps

In this work, we characterize the benefits of using a sub-THz NTN architecture to serve space users. Alongside a system architecture, key advantages, and prospective implementation alternatives, we present a numerical analysis and performance characterization, offering insights into the potential of NTNs for space-based connectivity.

Our results demonstrate that NTN architectures provide significantly more robust and reliable connectivity for space users compared to GS-based systems. Moreover, leveraging state-of-the-art sub-THz technology yields exceptional improvements in downlink performance, with nearly two orders of magnitude enhancement over current Ku-band GS systems.




(a) Total download capacity

(b) Link energy efficiency

**Fig. 6.** Download capacity and energy efficiency for sub-THz and Ku-bands across NTN relay configurations.

We believe these results offer a compelling case for future NTN service providers to extend their services to near-Earth users, creating new opportunities in the rapidly evolving domain of space exploration and commercialization. As a natural next step, this work will be expanded to include a similar analysis for users beyond LEO, such as those in Medium Earth Orbit (MEO), GEO, and cislunar space. This will help further refine the design and operational potential of NTNs for an even broader range of space applications.

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