Performance Analysis of a Dual Terahertz/Ka Band Communication System for Satellite Mega-Constellations

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***Abstract*—With the rise of satellite mega-constellations, high-data-rate and low-latency space-based internet is set to transform the lives of users in remote locations with no access to the fiber-optic infrastructure. While current commercial constellations are relying on microwaves, they are legally and technologically limited to only a few gigahertz of bandwidth, paralyzing the potential for ultra high data rate performance. In this paper, a dual terahertz/Ka-band communication system is proposed and studied as a solution. A space-Earth propagation model based on the International Telecommunication Union most recent recommendations is presented, and a mega-constellation of 8,320 small satellites in low Earth orbit is designed to test the dual-band performance for the uplink, downlink, and crosslink. Extensive simulations are performed using an in-house-developed orbital simulation tool to calculate data rates for each terahertz and Ka band links based on signal-to-noise ratio estimates with dynamic decision making to constantly provide the highest data rate possible. For links between Earth and space, the results show similar performance for terahertz and Ka-band communications, while terahertz significantly outperforms in inter-satellite links. Simulation results show that terahertz communication can be a good candidate for space-Earth and inter-satellite links as both an enhancement to existing microwave technology and as a stand-alone technology with the identified challenges addressed.**

***Index Terms*—CubeSat mega-constellations; Terahertz communication; Ka-band communication; Space networks**

I. Introduction

The use of the electromagnetic spectrum in space has historically been motivated by scientific missions including Earth observations, space exploration, and relay satellites supporting such missions. Nonetheless, the recent commercialization of space has frenzied the push for higher data rates to serve newer applications enabled by space-based internet [1]. A space-based internet can greatly serve users living in remote areas where optical fiber networks are not cost-effective, and could provide lower latency in circumstances where terrestrial internet is prone to structural delays and sub-optimal interaction time between endpoints [2]. This has led multiple private companies to race towards establishing satellite mega-constellations to provide high-data-rate low-latency internet, such as with the SpaceX Starlink constellation [3].

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Currently, the most suitable technologies for communication between the satellite constellations and the users (whether directly or through gateways) lay within the microwave and millimeter-wave spectral bands, such as L (1-2 GHz), S (2-4 GHz), X (8-12 GHz), K (12-40 GHz), and V (40-75 GHz) bands.

Recently, the most popular band is the Ka portion (26-40 GHz) of the K band, which is located higher in the microwave spectrum and is able to provide larger regulated bandwidth, while sitting below the 60 GHz water vapor absorption line (see Fig 1). That being said, the limitations in bandwidth both through technology and the International Telecommunication Union (ITU) and US Federal Communications Commission (FCC) regulations limit such bands to only a few gigahertz of continuous bandwidth [4]. Although improvements can be made to the microwave technology to push for higher data-rates, the bottleneck of limited bandwidth will favor moving towards higher frequencies, where more bandwidth is available.

A candidate technology for future space communication has been the terahertz band (0.1-10 THz) [5]. This frequency band can offer large contiguous bandwidths in its regulated (under 275 GHz) and unregulated (above 275 GHz) portions. The use of the terahertz band has been studied in the literature for inter-satellite communications [6], but its feasibility for space-to-Earth links remains unclear. In particular, there have been claims that it could provide up to 1 Tbps in ideal conditions [7]. While terahertz links have been explored for inter-satellite links, and space-to-Earth links for specific scenarios, a quantitative analysis for an end-to-end terahertz communication link is missing. Similarly, an end-to-end comparison to the performance of terahertz signals to microwaves is missing. This motivates a closer look at the performance of terahertz in space communication in comparison to the Ka band, exploring the strengths and challenges of both technologies in terms of performance and feasibility.

In this paper, we investigate the performance of terahertz and Ka band signals for uplink (UL), downlink (DL), and crosslink (CL) and discuss the limitations including legally allocated bandwidth and technology capabilities, amongst other variables. In Sec. II, we describe the propagation model adopted in our study, identify relevant frequency bands and

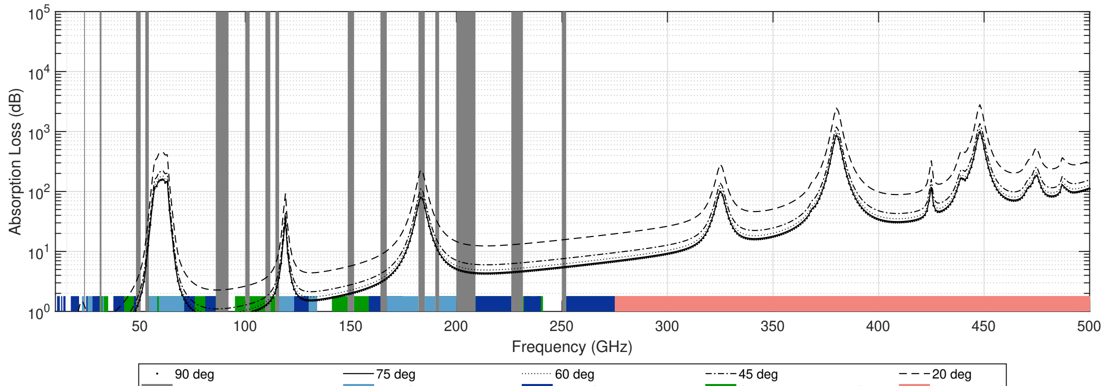

Fig. 1. Molecular absorption loss spectrum for a link between sea-level on Earth and a 500 km satellite in LEO. Different elevation angles are listed. The regulated and unregulated portions of the spectrum are shown per the US FCC most recent frequency allocations table [4].

calculate the attenuation due to spreading and absorption losses. Starting from these results, in Sec. III, we design a constellation in Lower Earth Orbit (LEO) employing satellites with a dual band THz and Ka communication system capable of transmitting and receiving signals in both bands. We define the performance metrics and simulate performance using an in-house built orbital estimation tool specialized for satellite constellation networks. Finally, in Sec. IV, we demonstrate simulation results and discuss performance, challenges, and opportunities, paving a roadmap for dual-band high data rate communication system in orbit.

II. Atmospheric Propagation Model

Besides the very high spreading losses resulting from the sub-millimeter wavelengths of terahertz waves [5], an additional challenge for terahertz on-Earth communication is molecular absorption, which is present at certain frequency bands within the terahertz spectrum as visualized in Fig. 1. Molecular absorption depends on the composition of the atmosphere (particularly the concentration of water vapor molecules), the temperature and the pressure. The total spreading and absorption losses based on the ground station height and the orbit of the satellite are given by

$$L_{spr}(f,d) = \left(\frac{4\pi d f}{c}\right)^2, \text{ and} \tag{1}$$

$$L_{abs}(f,d) = \exp\left(\int_0^d k_a\left(f, Q(r), p(r), T(r)\right) dr\right), \tag{2}$$

where f stands for frequency, d stands for the total slant path length and k_a is the molecular absorption coefficient for the atmosphere, which depends on the composition Q, the pressure p and the temperature T. These parameters on their turn change across altitude. In our analysis, we follow the Recommendation ITU-R P.676-12 [8] to compute k_a and utilize the altitude profiles for Q, p and T given by Recommendation ITU-R P.835 [9]. Unless otherwise stated, we consider the reference standard atmosphere model.

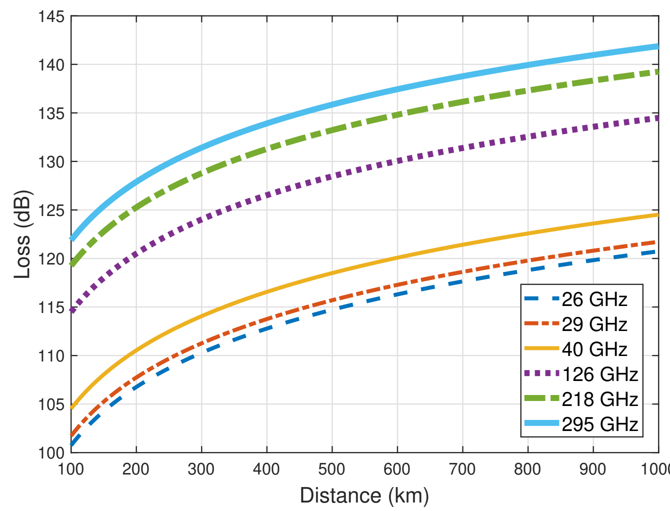

Fig. 2. Total absorption and spreading losses for Earth to space signals between a ground station at sea level and satellites in various altitudes at a 90°elevation angle.

In Fig. 2, we illustrate the propagation loss as a function of distance for three different frequencies in both Ka and terahertz available bands. We note that the absorption loss has no visible significance at the frequencies of our interest when compared to the high spreading losses. In fact, absorption loss for terahertz signals for UL and DL can be further reduced by placing ground stations in high-altitude locations, which can be of great benefit to remote mountainous regions in need of high data rates.

The propagation model plays a key role in the system design, as it determines both the constellation features, including altitudes, distance between satellites, frequencies of use, and duration of coverage (Sec. III-A), as well as the radio system specifications, including frequency, bandwidth, power and antenna gain (Sec. III-B). Based on the propagation model established in this section, we build a foundation for the requirements to support the design and deployment of satellite constellation operating a dual band terahertz/Ka band radio for the UL, DL, and CL.

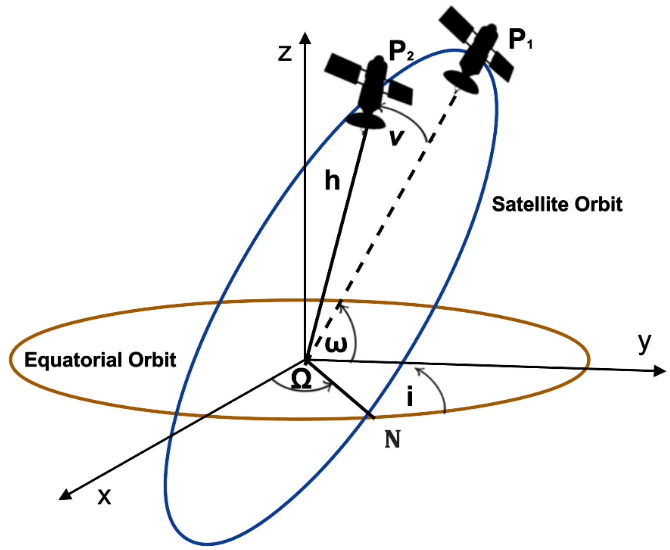

Fig. 3. Defining placement and positioning of satellite constellation in orbits using geocentric-based Keplerian elements

III. System Design

With the propagation model in mind, in this section we design our proposed satellite communication system for UL, DL, and CL, including constellation design, radio specifications, and communication and networking requirements.

A. Satellite Constellation Design

Using the geocentric equatorial model, we design a satellite constellation to determine the placement of satellites in orbit. The constellation design in this scenario is elementary and aims to achieve the goal of constant connectivity between satellites. There are multiple variables that determine the constellation orbit and the position of each satellite in space. The altitude of the constellation must be picked based on a trade-off between latency and coverage, where a lower altitude enhances latency but reduces the coverage angle. This trade-off is given by

$$\theta = \cos^{-1}\left(\frac{R_e}{R_e + h}\cos\phi\right) - \phi, \tag{3}$$

where θ is the coverage angle, h stands for altitude, ϕ is the elevation angle, and R_e is the circular radius of the Earth. We choose an altitude of 300 km as per the model in Fig. 1.

The position and shape of the orbit, which define the position of the satellite at all times, depends on the Keplerian elements, namely, eccentricity (e), semi-major axis (a), inclination (i), longitude of the ascending node (Ω), argument of periapsis (ω), and true anomaly (ν). For constant coverage and constant satellite velocity, the orbit chosen is circular and therefore has an eccentricity of $e = 0$, a semi-major axis equal to the radius, and a constant satellite velocity. Thus the three Euler angles that determine the orbit are the Ω, ω, and i as shown in Fig. 3. With the xyz coordinate system as a reference, each orbit establishes an intermediate frame of reference given by

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = A \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \tag{4}$$

where A is the rotational matrix defined as

$$A_x(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix}, A_z(\beta) = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{5}$$

Based on the rotational matrices along the x and z axes, we define the position of the satellite as a function of the three Euler angles

$$P = A_z^T(\Omega)\ A_x^T(i)\ A_z^T(\omega), \tag{6}$$

described as

$$P = \begin{pmatrix} \cos\Omega\cos\omega - \sin\omega\cos i\sin\omega & -\cos\Omega\sin\omega - \sin\Omega\cos i\cos\omega & \sin\Omega\sin i \\ \sin\Omega\cos\omega + \cos\omega\cos i\sin\omega & -\sin\Omega\sin\omega + \cos\Omega\cos i\cos\omega & -\cos\Omega\sin i \\ \sin i\sin\omega & \sin i\cos\omega & \cos i \end{pmatrix}. \tag{7}$$

With an inclination of 0°, a satellite would strictly orbit the equator, while for 90°, it would orbit the North and South poles. To provide more area coverage per satellite and capture the largest number of users possible, we design the constellation on the basis of having a 50° inclination angle. The inclination angle is fixed for all satellites and keeps them spatially synchronized. To establish multiple satellite planes for consistent latitude coverage, 16 orbital planes are used with values distributed uniformly between 0° and 320°, which is calculated through varying the longitude of the ascending node (Ω). Finally, in order to organize the satellites in each plane and maintain a consistent longitude coverage and a small separation distance crucial for terahertz CL, the satellites are randomly placed in their orbital planes while making sure no two satellites collide. The final position of the satellite is calculated by adding the argument of periapsis to the true anomaly. In the case of the circular orbit, where there is no uniquely determined argument of periapses, the argument of latitude is used as the angle u to describe the satellite's position in the orbit given by $u = \omega + \nu$.

B. Dual Band Radio Design

1) Central Frequencies and Bandwidth: The initial requirements for the design of the dual band radio are set by the FCC allocations for UL, DL, and CL for each band. The allocated frequencies are used to determine the central frequency and bandwidth consideration for each band based on legally and technologically available bandwidth per FCC allocations, and partially in the unregulated band for the terahertz links. While the bandwidth of terahertz signals far exceeds the Ka band, the performance of the Ka band has the advantage of higher SNR at the receiver due to lesser propagation losses, lower noise, and higher transmit power. The data rate estimation algorithm used by the dual band radio is explained in Sec. III-C1.

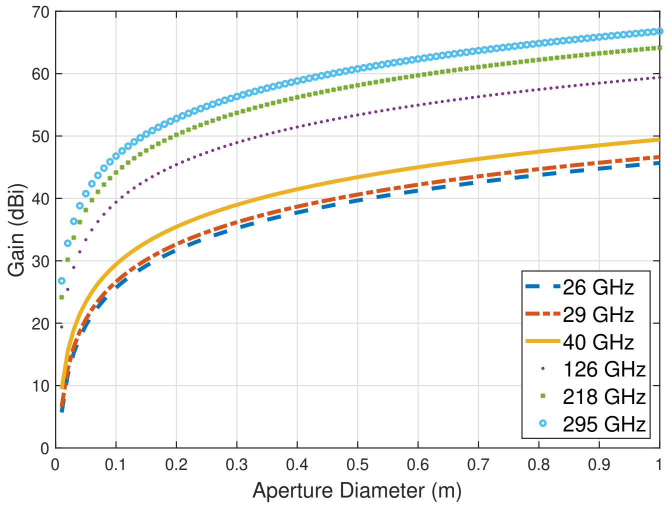

Fig. 4. Parabolic antenna gain with 50 percent efficiency.

Terahertz Band			
Link	Uplink	Downlink	Crosslink
Frequency (GHz)	217.5	295	295
Bandwidth (GHz)	17	40	40
Satellite Gain (dBi)	45	48	48
Terminal Gain (dBi)	69	72	-
Tx Power (mW)	200	200	200
Ka Band			
Link	Uplink	Downlink	Crosslink
Frequency (GHz)	28.75	40	26.375
Bandwidth (GHz)	2.5	5	2.25
Satellite Gain (dBi)	28	30	27
Terminal Gain (dBi)	52	54	-
Tx Power (mW)	5000	5000	5000

Fig. 5. Dual Band Radio design metrics to be inserted into simulation, based on propagation model, constellation design, regulations, and the current state of the art and commercially available electronic devices.

2) Antenna Gain: One advantage of using higher frequencies is being able to achieve higher gain for a smaller sized aperture due to the decrease in wavelength. This becomes a stronger advantage for higher frequency systems being deployed on small (CubeSats), as the size and weight requirements become significantly more rigorous [10]. The parabolic antenna relationship between aperture and antenna gain is given by

$$G = k\left(\frac{\pi D}{\lambda}\right)^2, \tag{8}$$

where k is antenna efficiency, and D is the aperture diameter. This is visualized in Fig. 4, which points to the larger opportunity for terahertz systems in CubeSats than large satellites, given the ability to have higher gain at smaller real-estate. However, as of the current state of the art, terahertz systems are bulkier and require more power, which hinders the smaller and lighter-weight passive antenna advantage.

3) Transmission Power: Traditionally, the lack of high-power terahertz signal sources and mixers has limited the transmission power of terahertz transmitters, further limiting the distance of communication between two nodes. However, in this decade, recent developments in terahertz electronics highlighted by compact Schottky-diode based sources have allowed transmission of up to 200 mW at 0.24 THz, 30 mW at 0.55 THz, and and up to 5 mW at 1 THz [11]. Still, today, terahertz radios in the lower range (0.1-0.3 THz) sit at an order of magnitude lower than Ka band commercial radios. On the receiver side, the performance of a communication system is mostly driven by the noise at the receiver. In our analysis, we utilize a noise figure of 7 dB to account for thermal noises including amplifier, mixer, and antenna temperature as described in [12]. The dual band radio design metrics are shown in Fig. 5.

C. Communication and Networking Design

1) Data Rate Estimation: In this early study, we consider that the dual-band radio determines the frequency, bandwidth and modulation to utilize based on a link budget analysis. For the lowest modulation order available at the receiver and a target bit error rate (BER), the minimum signal-to-noise ratio (SNR) at the receiver is calculated as

$$SNR = 10\log_{10}\left(\frac{E_b}{N_0}B_{eff}\right) + NF, \tag{9}$$

where E_b/N_0 is the ratio of the energy per bit to spectral noise density required to meet the BER constraint, B_{eff} is the modulation efficiency of the chosen modulation order, and NF is the noise figure of the receiver. The bandwidth of the receiver B plays a key role, as it both determines the achievable data-rate and the total system noise. The maximum noise power N that the system can tolerate is given by

$$N = P_{tx} + 2G - L - SNR, \tag{10}$$

where P_{tx} is the transmission power, G is the antenna gain and L are the total losses obtained by combining (1) and (2). Correspondingly, the maximum bandwidth B is given by

$$B = 10^{(N/10)}/KT, \tag{11}$$

where K is the Boltzmann constant and T stands for the system temperature. If this bandwidth is larger than the allocation by the FCC, the legal maximum is adopted. Also in that case, the process is repeated for higher order modulations. Finally, the data rate is obtained as

$$R = B \cdot B_{eff}. \tag{12}$$

The radio then chooses the band with the higher data rate and begins transmission.

2) Routing: The routing protocol used is simple in nature, setting a lower bound on the propagation delay and a upper bound on the CL data rates. The routing protocol is designed to ensure that each relaying hop is the shortest possible distance in the direction of the destination. That being said, the performance of the CL and propagation delay not only depend on the routing protocol but also the constellation design, mainly number of satellites in the constellation. The routing algorithm makes the following considerations: *1)* Satellites not only know their relative location, but also all the coordinates of all other satellites in the constellation; *2)* There are no objects in space blocking inter-satellite links; and, *3)* the transmitter and receiver are synchronized and ready for communication. We discuss the associated challenges that need to be addressed to support this scheme in Sec. IV-C.

IV. Performance Analysis

A. Simulation Platform

To numerically investigate the performance of the proposed system, we have developed an orbital simulation tool in-house for satellite and space communication networks. In our platform, based on the locality of the satellites at a particular transmission time (modeled as Poisson Process), a source and a target satellite are identified based on having the shortest distance to their respective Earth stations and that the Earth stations are within the area of coverage of the satellite. From there, we initiate the routing protocol described in Sec. III-C to find the inter-satellite distances, and the total route distance. Finally, we utilize the path-loss model presented in Sec. II and radio specifications and link-budget described Sec. III-A to calculate the data rates achieved by a Ka-band-only system, a terahertz-only system, and a hybrid solution. The simulation time duration is set to 4 hours in order to ensure all satellites complete at least one full rotation around the Earth. The source and destination ground stations are picked at random from a list of 11 cities (namely, Custer County-South Dakota, Fresno-California, Raleigh-North Carolina, Omaha-Nebraska, Albuquerque-New Mexico, Moscow-Russia, Izmir-Turkey, Nairobi-Kenya, Esfahan-Iran, Yeravan-Armenia and Tibet-China). The elevation of these cities are taken into account during the path-loss calculation. We ran multiple simulations of 500 frames each as well as a long simulation of 6,000 frames. All the simulations yielded similar results, which are presented in the following section.

B. Numerical Results

1) Ka Band: In Fig. 6, we illustrate the normalized histogram of the achieved data-rates for UL, DL, and CL for a Ka-band-only system. The Ka band system suffers less spreading loss and no absorption loss and thus can be seen as a more reliable solution, however during best case conditions the Ka band system is limited in bandwidth and thus the performance is capped at a limit regardless of channel conditions, satellite distance, and traffic load in the UL and DL. On the other hand, due to the distances between satellites during routing, and the lower antenna gains achieved by the antenna utilized in the satellite system, the cross-link data-rates are slightly better to what is achieved in the DL and UL.

2) Terahertz Band: In Fig. 7, we illustrate the results achieved by utilizing a terahertz-only solution for UL, DL, and CL. The THz-Band can achieve higher data-rates even when utilizing a 200 mW transceiver when compared to the 5 W transceiver utilized in the Ka band system, thanks to the higher antenna gain achievable for a fixed footprint. With that being said, the higher data-rates have low probability of occurrence mostly due to the high spreading and absorption losses encountered over the long transmission distances. However, there are multiple realizations in which a combination of high altitude of the ground station and close location of the satellites lead to very high rates of almost 10 Gbps for both the UL and DL. On the other hand, the CL data rates are almost 10 times better than what the Ka band can offer due to the available bandwidth, and the high antenna gains utilized in the satellite system. With that being said, a hybrid solution only makes sense for UL and DL transmission in order to ensure a more reliable system that can boost in performance when some conditions are met such as location of ground station, and channel conditions.

3) Hybrid Solution: In Fig. 8, we illustrate the results achieved by utilizing a hybrid solution for the UL, and DL transmissions. A hybrid solution is not necessary for CL, since a terahertz-only system can achieve almost 10 times higher data-rates in inter-satellite communication. The hybrid solutions can provide much higher data rates when applicable since the bandwidth is no longer a limiting factor, but is also more reliable than the terahertz solution during conditions that out of our control such as the location the user ground station. Finally, we also present the propagation delay encountered during transmission utilizing our routing protocol. For nearby ground stations we can expect propagation delays in the lower end ranging from (0,40] ms. For long distance transmissions, the propagation delay can potentially go up 80 ms depending on the location of the satellites, and the available route utilized.

C. Discussion, Challenges, and Opportunities

The simulation scenario assumes an ideal-case basis for different elements of the communication systems. To bring the state of the art closer to this ideal scenario, some of the challenges are defined as follows:

1) Hardware: The lack of compact and efficient terahertz sources and amplifiers remains the main challenge. Advances in terahertz electronics highlighted by compact designs are desired for space application. Similarly, it is known that a terahertz antenna can provide higher gain for a small aperture, but the fabrication of terahertz antennas is not trivial. Especially in the case of parabolic reflectors, micron-scale precision is required to insure low scattering of antenna. Dual terahertz and Ka band antennas can also be explored in the case of using a dual band radio design for future satellites.

2) Coverage and Pointing: The use of the terahertz band will force the use of narrower beams, which could make full coverage more difficult with traditional antennas. Antenna arrays can solve this problem but will require high precision and fast scanning. A thorough analysis of the pointing-induced

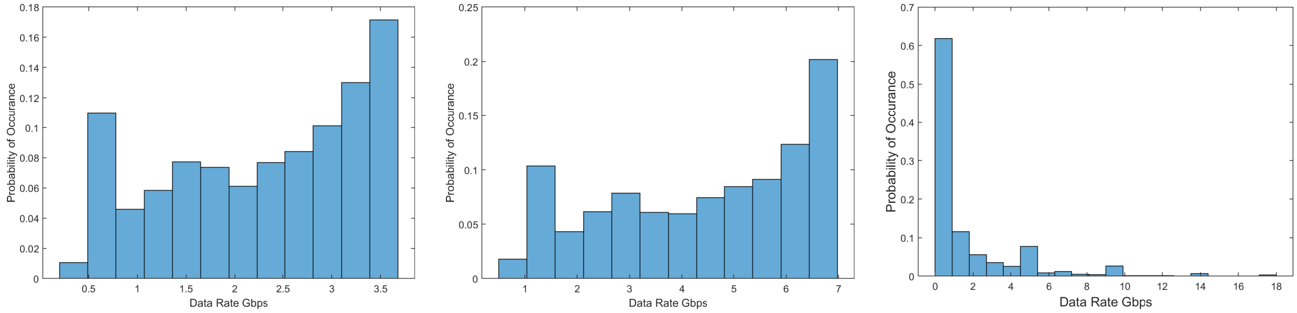

Fig. 6. Ka band performance: UL (left), DL (center), CL (right).

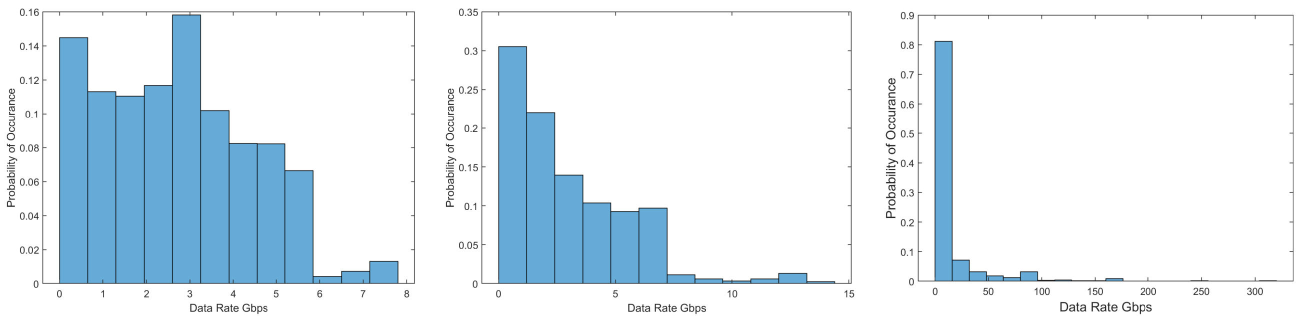

Fig. 7. Terahertz band performance: UL (left), DL (center), CL (right).

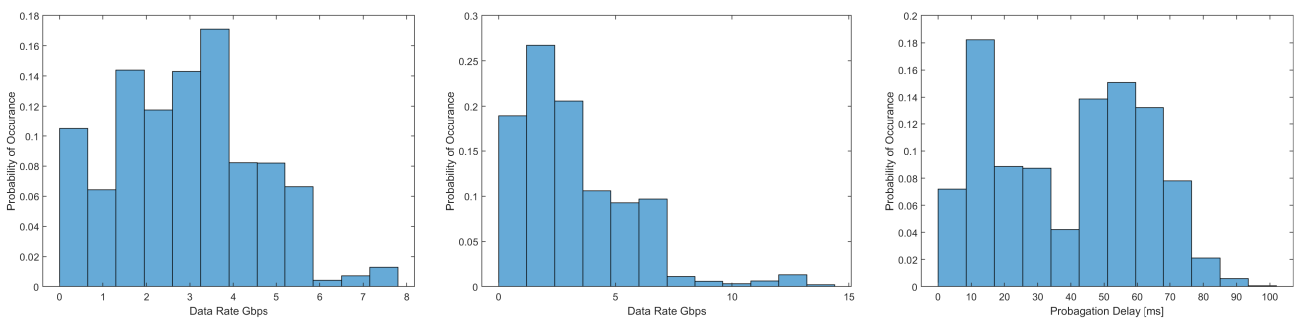

Fig. 8. Hybrid system performance: uplink (left) and downlink (center). Propagation delay (right).

errors must be completed to deeply understand overall feasibility of terahertz signals in small satellites

3) Networking: Routing algorithms have not been developed for terahertz satellite constellations, and this area remains unexplored. The use of deep learning in routing can be useful to cognitive satellite constellations especially in the terahertz band. As this paper uses a preliminary routing algorithm, routing algorithms for both a stand-alone terahertz constellation and for a dual-band constellation would be of importance.

4) Joint Communications and Sensing: An important element of using a terahertz radio in a space vehicle is that it can be reconfigured to perform science duties as well as communications. With a large number of terahertz detectors in LEO, the signal processing algorithms in the radio can be reconfigured to be able to scan and map the atmosphere for scientific purposes during times where the satellite is not actively engaged in communication. The dual-use of a terahertz radio would further enhance the efficiency of infrastructure and spectrum in space.

V. Conclusions

In this paper, we have designed and simulated the performance of a dual terahertz/Ka-band communication system for UL, DL and CL. The proposed systems captures the state of the art in terahertz/Ka-band hardware technologies, leverages sophisticated atmospheric propagation models, takes into account actual FCC spectrum allocations for satellite communication networks, and implements the principles of orbital dynamics for the design of a tailored constellation. Utilizing an in-house-built platform, we have demonstrated that the terahertz band can provide comparable performance to the Ka-band in UL/DL, with a lower transmission power but much higher antenna gain for the same footprint. Moreover, in the case of CL, the terahertz band provides a 10x improvement consistently. Finally, we briefly describe the key bottlenecks that need to be overcome to advance the technology readiness level of terahertz space communications.

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