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The Road to High Data Rates in Space: Terahertz vs. Optical Wireless Communication

Ali J. Alqaraghuli, *Student Member, IEEE*, Jose V. Siles, *Senior Member, IEEE* and
Josep M. Jornet, *Senior Member, IEEE*

***Abstract*—With the ultimate vision of ubiquitous egalitarian worldwide coverage, private companies are launching satellite constellations at unprecedented rates. The large projected traffic in orbital cross-link communication will demand more spectrum to suit more users and to satisfy higher data rates. In this paper, terahertz and optical wireless communication technologies are explored as the two projected high-data-rate cross-link communication technologies and are compared in terms of device technology capabilities and wireless propagation properties. A performance analysis including a link budget directly compares the two technologies for space communication in low Earth orbit constellations. More importantly, a roadmap is provided paving the way to push both ultra-broadband wireless technologies forward.**

***Index Terms*—Terahertz communications; Optical wireless communications; Space cross-link communications; Non-terrestrial Networks**

I. INTRODUCTION

THE race for higher data rates and more ubiquitous networks has been a primary driver for the evolution of wireless communication systems on Earth. For decades, the need to allocate an increasing number of services in an otherwise overcrowded spectrum has motivated the exploration of higher frequency bands. Congruently, with the rise of the private space industry and the accelerated launch of satellite constellations, a spectrum congestion problem in space is inevitable [1]. Prior to SpaceX Starlink and other emerging Lower Earth Orbit (LEO) constellations [2], multi-GHz satellites were mainly deployed in geostationary orbit (GEO) for direct communication, broadcasting, or weather sensing. Today, communication and sensing satellites compete for electromagnetic and physical real state in space, as can be observed in Fig. 1. Along with high-altitude platform systems (HAPS) such as balloons, drones, and even zeppelins, satellites are a key component of the increasingly-popular non-terrestrial networks (NTN) [3], [4].

Beyond faster satellite uplink and downlink communications, higher data rates will be a necessity for cross-link communication systems in space [6]. Carrying the aggregated traffic of a massive number of users distributed across the globe, including underserved areas (e.g., rural areas) and areas were ground-based access has been disrupted (e.g., after an earthquake or tsunami) requires an infrastructure potentially comparable to the Internet backhaul itself. Additionally, tapping into technologies with larger bandwidth will allow high data rate communication across satellites and rovers or robots on planetary science missions.

Common wireless technologies in the microwave and the lower millimeter-wave (mmWave) bands (<100 GHz) in space cannot meet the projected spectrum demands, steering the direction towards higher frequency bands. Since bandwidth has been the main driver for high data rates, optical communication in the infrared and visible spectrum has often been considered to be the future of high data rate wireless communication given its mature device technology, although limited by the comparably slower electronics data handling capability [7]. Recent optical cross-links demonstrations include the 1.2 Gbps in orbit link of NASA's ILLUMA-T mission as part of the Laser Communication Relay Demonstration (LCRD) initiative [8], or the much slower 3U CubeSat cross-link rates of 20 Mbps expected to be reached in NASA's CLICK demonstration [9].

Nevertheless, between mmWaves and optics sits the terahertz band (0.1-10 THz), a suitable candidate for high data rate communication in space. The spectrum between 100 GHz and 10 THz (only regulated up to 275 GHz) can satisfy the bandwidth needs for high data rates while offering balanced trade-offs when compared to optical communication technology. Amongst such trade-offs exist advantages such as the existence of robust electronics-based mixers that can handle temperature fluctuations, smaller scattering and propagation losses, and absence of significant interference sources [10]. Additionally, terahertz signals are more affected by atmospheric absorption, making satellite-to-satellite links highly secure and shielded against Earth-based jamming or interference since Earth-based jammers would be unable to penetrate the atmosphere [6]. In [11], terahertz links showed higher cross-link data rates over Ka-band links in LEO constellations, motivating a comparison to optical communication. Moreover, while the spectrum above 100 GHz is also of major interest to the remote sensing scientific community, there are currently no satellites operating between 0.650 THz and 2.49 THz, to the best of our knowledge, allowing exploration of communication at true terahertz frequencies.

In this paper, terahertz technology for space is presented as a solution to meet both demands for spectrum and desire for high data rates. In Sec. II, state-of-the-art terahertz sources and detectors are identified and compared to optical wireless communication devices for cross-link satellite communication

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A. J. Alqaraghuli and J. M. Jornet are with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, USA.

J. V. Siles is with the NASA Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, CA, USA.

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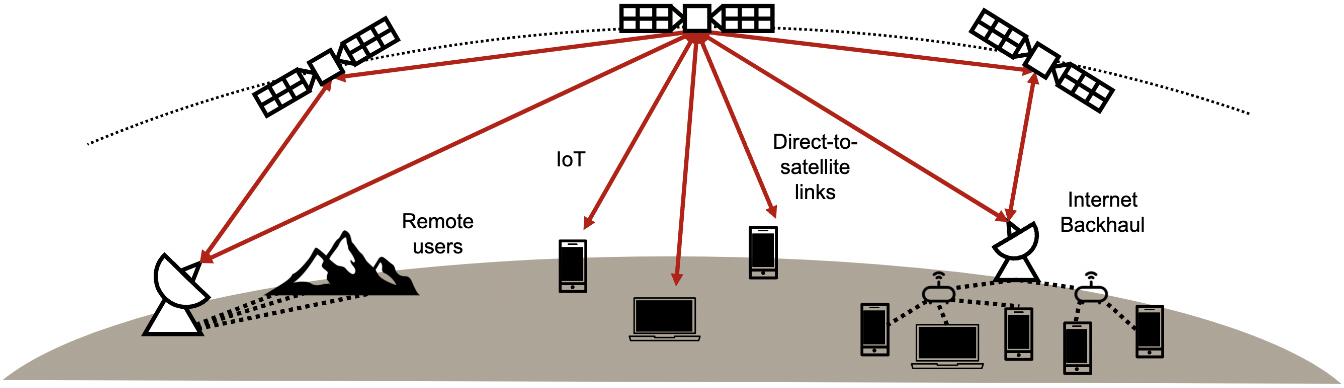

Fig. 1: The projected integration of satellites for space-based Internet and 6th Generation (6G) wireless communication, along with the integration of Internet of Things (IoT) devices, involving both users and gateways [5].

systems. Then, in Sec. III, terahertz and optics are compared in terms of propagation in space. A performance analysis between terahertz and optical wireless communication technologies is performed in Sec. IV to numerically demonstrate the trade-offs amongst the two technologies. Finally, in Sec. V, a detailed roadmap is established to identify the path going forward for both terahertz and optical wireless communication.

II. DEVICE OVERVIEW

A. *Device Requirements in Space*

A good reference for high-data-rate communication outlook for future spacecraft is NASA's Deep Space Optical Communication Initiative (DSOC) which calls for error-free communication data rates in space to be increased by 10 to 100 times over the current state of the art, without increasing mass, volume, or power [14]. This requirement becomes more rigorous for CubeSats which have significantly smaller structures and lower power budgets [15].

The state of the art for each technology for optical technology in space has been extensively explored in [16], and advancements in terahertz communication technology has been extensively described in [17]. This section highlights technologies drawing a fundamental comparison in system architecture.

B. *Terahertz Devices*

While many satellites have previously flown (and currently fly) terahertz devices for Earth and space active and passive sensing [18], such devices have not yet been used for space communication. Terahertz technologies are mostly classified as electronics, photonics, and hybrid combinations of the two.

*1) **Terahertz Transceivers**:*

*a) **Electronic Terahertz Technology**:* Compared to vacuum electronics being developed for terahertz applications, solid-state terahertz devices are more suitable for space due to compactness, reliability, and cost. Terahertz signals can be generated using Complementary-Metal-Oxide Semiconductor (CMOS) and Terahertz Monolithic Integrated Circuit (TMIC) Technologies. While CMOS is more widely available and can be manufactured at lower costs, TMIC uses III-V semiconductors allow higher cut-off frequencies [17]. TMIC technology branches into different devices such as Heterojunction Bipolar Transistors (HBT), High Electron-Mobility Transistors (HEMT), Heterostructure Barrier Varactors (HBV), and Schottky-Diodes. Such technologies also provide the means for amplifiers, multipliers, and mixers, which can be combined to assemble compact transmitters and receivers. Mixers are used to modulate message signals onto terahertz carriers.

*b) **Photonic Terahertz Technology**:* Terahertz signals can also be generated through photonic technologies, such as Uni-Travelling Carrier Photodiodes (UTC-PD) using high power RF photodiodes capable of generating signals between 100 GHz to a few THz through photo mixing chips and photoconductive antennas. Other photonic technologies include Quantum Cascade Lasers (QCL) and Resonant Tunneling Diodes (RTD) which can oscillate above 1 THz. RTDs currently do not generate strong enough signals (20–30 µW at 1 THz), and while QCLs do (1 mW at 4.96 THz), they are not well suited for space due to bulkiness and poor beam quality [6], [19]. Photonics can be combined with electronics to produce terahertz signals. Many testbeds and research laboratories use photonic/electronic combinatory circuits to produce terahertz signals, such as using a Schottky Diode tripler to multiply a UTC-PD source as oscillator [17].

*2) **Terahertz Antennas**:* An advantage for terahertz devices is the ease of coupling to conventional metallic antennas and versatility of antenna design. At terahertz frequencies, directional antennas with a gain of 40 dBi and above are only a few centimeters in size, and thus fit the compactness criteria. Antenna arrays can be utilized for beamforming and can be just as compact, although adding more complexity to the system in terms of control [20].

*3) **Terahertz Candidate Technology**:* For space communication in the terahertz range, devices must be compact, light-weight, power sparing, and temperature-stable. Such a requirement presents GaAs-based Schottky Diode technology as the most suitable technology. This technology has been demonstrated at frequencies ranging from 100 GHz to up to a few THz [12]. In fact, Schottky diode heterodyne devices have

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Technology	Schottky Diode TMIC	Schottky Diode TMIC	Master-Oscillator Power Amplifier	High Power Laser Diode
Central Frequency	0.24 THz	1 THz	193.4 THz	306 THz
Wavelength	1.24 mm	0.30 mm	1550 nm	980 nm
Size	10 cm x 18 cm x 3 cm	10cm x 20cm x 4 cm	10 cm × 10 cm × 3 cm	5 cm × 5 cm × 1 cm
Weight	130 g	150 g	250 g	100 g
Consumed Power	8 W	9 W	6.5 W	3.3 W
Transmit Power	200 mW	3 mW	200 mW	500 mW

TABLE I: Size, weight, and power comparison across terahertz [12] and optical [13] compact sources suited for CubeSats.

been used in mmWave and sub-millimeter wave instruments launched in scientific missions such as in NASA's Upper Atmosphere Research Satellite and the European Space Agency's Herschel Space Observatory.

C. *Optical Devices*

Optical devices generate signals in the frequency range of 180-1500 THz and are categorized based on wavelength: ultraviolet (200-390 nm), visible (390-750 nm), and infrared (750-1600 nm). While visible and ultraviolet technologies are being investigated, infrared has been the go-to technology for free-space optical communication. In addition to the optical cross-links mentioned in the introduction, NASA has demonstrated a communication link at 1550 nm from Lunar orbit to Earth and from GEO to ground stations on Earth through the Lunar Laser Communication Demonstration (LLCD) and the Laser Communication Relay Demonstration (LCRD) [8] programs, respectively. Although those demonstrations are for Earth to space communication, they had strengthened the overall interest in pursuing optical communication technology.

*1) **Optical Transceivers**:*

*a) **Optical Transmitters**:* To produce laser beams, diode lasers are simpler and more popular to transmit at a monochromatic wavelength, and provide significant size, power, and cost advantages in comparison to chemical lasers. They do not require high power for operation, but their main drawbacks are temperature sensitivity and overall low efficiency, although transmit power can be improved using multi-mode diodes at the cost of beam quality. Diode lasers can be used as optical pumps for solid-state lasers such as fiber lasers, which are more efficient and can be expected to be used for long-range deep space communication.

*b) **Optical Receivers**:* The most common photodetectors used are Positive-Intrinsic-Negative (PIN) photodiodes, Avalanche Photodiodes (APD), and phototransistors. APDs are fast and more sensitive with larger bandwidth, making them a potential option for cross-link optical detectors. Optical detectors in space require additional circuitry for temperature stability. Additionally, trade-offs between frequency response and size of photodiode make long-range high-datarate optical communication difficult and complex, requiring more precise focusing elements. Phase locked loops (PLLs) must be used for coherent detectors, adding complexity.

*c) **Optical Amplifiers**:* While fiber-optics initially used optoelectronic amplifiers requiring amplifying electronic signals and up-converting back to optics, laser and solid-state technologies have allowed purely optical amplifiers to exist and come in many forms. Erbium-doped fiber amplifiers (EDFAs), maturing around 1550 nm, are ideal for deep-space communication fiber-lasers. Semiconductor amplifiers use materials such as GaAs to pump the laser electronically, reducing cost but unable to match the EDFA performance. Non-linear fiber amplifiers such Raman or Brillouin amplifiers which can generate higher power output and maintain a lower noise figure but require higher pump power which may not be available in small spacecraft. Fiber amplifiers have higher gain than semiconductor amplifiers, and therefore can be expected for deep space cross-link communication.

*2) **Optical Antennas**:* Most lasers transmit Gaussian-shape directional beams, but require further densification of power through the use of lenses. This is the equivalent of antenna directivity gain in RF signals and can be modeled similarly. Cerium oxide doped glass, or synthetic silica are common lenses optical systems.

*3) **Optical Candidate Technology**:* The selection of a candidate technology for optical wireless systems directly relates to the operational wavelength. Most mature optical devices revolve around 1550 nm wavelength used in both NASA optical demonstrations in [8]. In [13], 980 nm devices are explored as an alternative. Non-coherent optical systems are simpler and cheaper since they do not require PLLs and, thus, desirable for CubeSats, but coherent systems are likely to be needed to meet the data-rates requirements.

Table I provides a comparison in terms of size, weight and power comparison of the terahertz and optical technologies suited for CubeSats as of today.

III. SIGNALS IN SPACE

A. *Terahertz vs. Optics Propagation*

For cross-link communication in space, terahertz and optical links are not hindered by molecular absorption nor atmospheric turbulence. It is worth noting that optical waves can pass through the atmosphere, while terahertz are absorbed. The absorption window is detailed in [11]. This makes optical signals superior for uplinks and downlinks, but favors terahertz as a more secure crosslink since signals cannot be jammed or eavesdropped by operators beneath the atmosphere. Another area that can give terahertz signals an advantage in space is beamwidth. Terahertz beams are not as wide as microwaves, nor as narrow as laser beams. This enables more relaxed pointing requirements compared to laser systems. This comparison can be better visualized in Fig. 2.

Spreading and scattering losses increase with frequency and, therefore, impact optical wireless systems more severely. In Earth orbits, there has been a noticeable increase in space debris floating at high speeds, posing potential damage from impact, but also increasing scattering. As the space environment changes with more crowding in LEO, signals will be more susceptible to fading and will need to be considered

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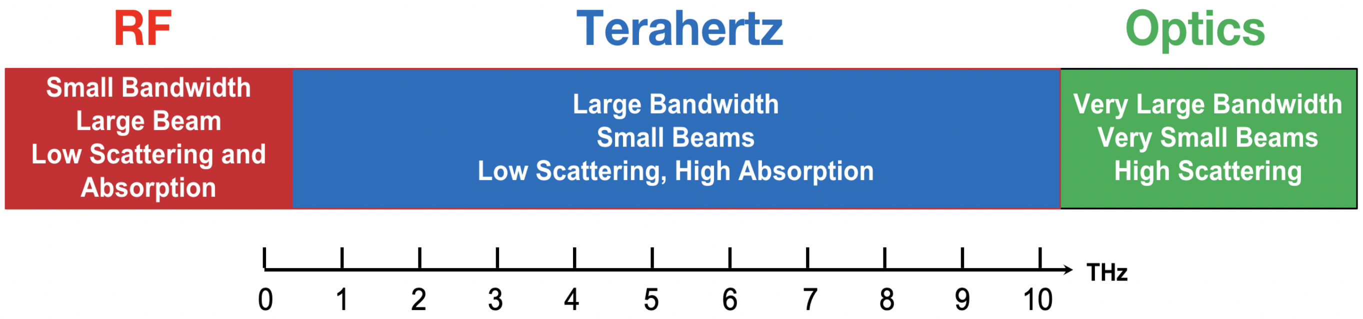

Fig. 2: A comparison of the fundamental propagation properties of RF, Terahertz, and and Optical signals.

in satellite system design, especially in the case of cross-link small-satellite constellations in LEO. To the best of our knowledge, there are currently no published fading models for terahertz or optical signals caused by space debris in any orbit.

B. *Terahertz vs. Optics Noise*

Thermal noise is present in terahertz and optical technology for both coherent and incoherent systems. Thermal noise is the main challenge for electronic devices in heterodyne terahertz systems such as mixers and amplifiers. Since this noise is increased with heat, heterodyne terahertz systems perform better upon cooling. **Cosmic noise** come mainly from distant star-formation regions in faraway galaxies for terahertz and from the sun in optics. The sun transmits most of its energy in the infrared, visible, and ultraviolet light spectrum [21]. **Dark noise** is present in photosensitive devices in their off state, where a small current flows through the detector even when no photons are being received. Such current directly correlates to the dark noise present in the devices. Dark current can be temperature-dependant and can exert **shot noise** from newly fluctuating particles. Shot noise is problematic in optical detectors with a low quantum efficiency as well as sensitive detectors. In electronics, shot noise is far less significant in heterodyne highlighted in the state of the art in comparison to direct detection systems. In heterodyne systems, **phase noise** become problematic with increased multiplications and require more stable local oscillators. In photonic-based terahertz systems, phase noise is reduced. Additional noise sources in semiconductor devices such as generation-recombination noise, burst noise, and flicker noise, all decrease with frequency and are temperature-independent. For coherent high-frequency systems, they are significantly small and in most cases they are negligible.

IV. PERFORMANCE IN SPACE

A. *Link Budget Analysis*

Traditionally, optics and microwave signals cannot be compared in the near field due to different diffraction effects. However, such effects dissipate in long-range communication, and approximations can be used. A link budget analysis based on the equivalent isotropic radiated power (EIRP) consideration, typical in microwave systems, can be used for optical link analysis beyond the first Fresnel zone when the distance between transmitter and receiver is 100 km or more [22]. In this case, to compare the terahertz and optical performance, two different central frequencies/wavelengths are chosen for each technology, as per Table I. For direct comparison, a coherent optical system is considered utilizing quadrature-amplitude modulation (QAM).

The bandwidth, which determines the achievable data-rate for a given modulation, is obtained from the minimal energy-per-bit over noise power density (Eb/N_0) and, correspondingly, signal to noise ratio (SNR) required to satisfy the target bit error rate (BER) with the listed modulation, taking into account the transmit power, propagation losses and noise. The antenna gain is used as a changing variable to demonstrate the necessary beamwidth to achieve Gigabit-per-second (Gbps) communication. The calculation framework is explained in [11].

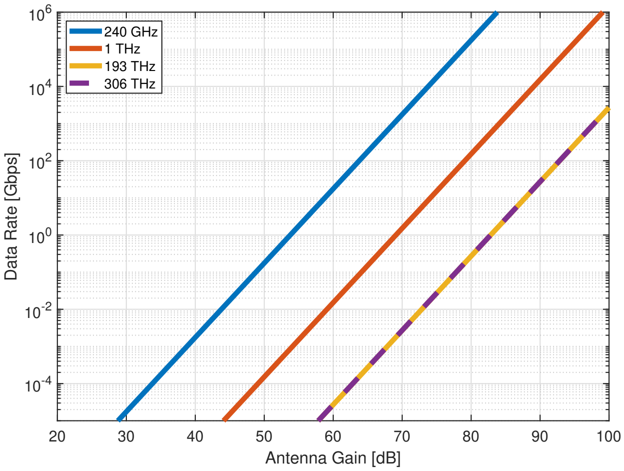

Fig. 3: Estimated data rates for cross-links between satellites in LEO orbit 100 km a part. The calculations utilize transmit power from Table I, noise figure of 8 dB, a bit error rate of 10^{-6} and 16-QAM modulation.

B. *Link Budget Findings*

*1) **Directivity Gain Requirement:*** In Fig. 3 and Fig. 4, the required gains and, correspondingly, antenna beamdwidth needed to close a reliable wireless cross-link between CubeSats in LEO is shown for the different technologies. While larger antenna gains (smaller beamwidths) are an effective

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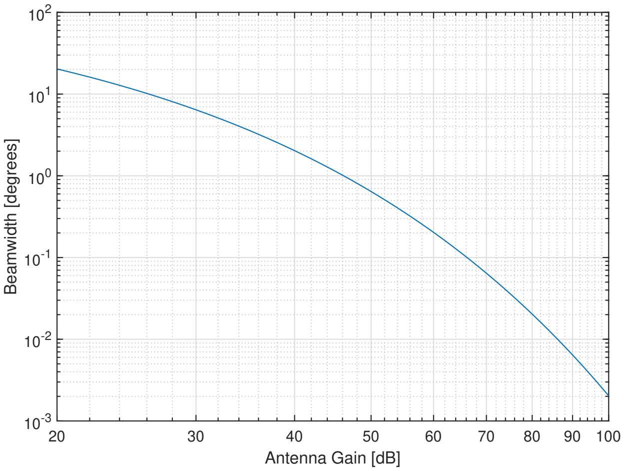

Fig. 4: Beamwidth as a function of antenna gain [23].

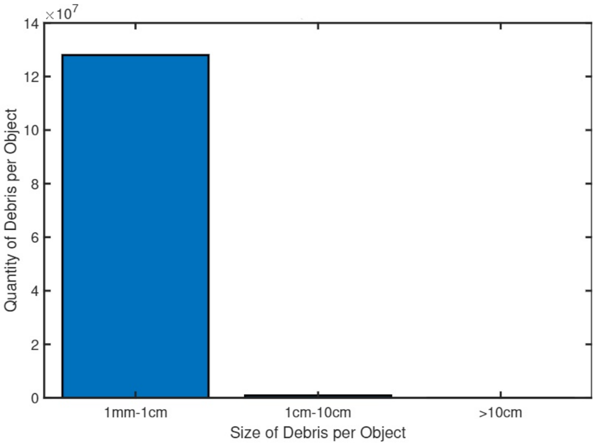

Fig. 5: A statistical model of space debris in orbit as of July 2022 per ESA.

path to increase the overall EIRP, having higher antenna gain makes requirements for tracking algorithms more rigorous. As terahertz device technology is maturing, increases in transmit power can compensate for lower gain antennas and ease pointing requirements. From Fig. 3, for LEO-LEO communication, to satisfy a 1 Gbps datarate, a gain of approximately 54 dBi is required for each antenna at 240 GHz, in comparison to 82 dBi at 193 THz. This translates into a reduction of the beamwidth from 0.41 degrees at 240 GHz to 0.016 degrees at 193 THz.

*2) **Neighbor Satellite Discovery**:* Larger beamwidth allows for quicker and more reliable detection amongst satellites in constellations. This can allow satellite constellations to have quicker discovery of neighboring satellites and be able to establish communication more quickly and more reliably. This also would eliminate the need for “beacon” signal sources that serve the sole purpose of detecting other satellites, reducing complexity, especially in CubeSats. Overall improvements in CubeSat tracking and communication are being studied [24].

*3) **Scattering/Interference**:* Figure 5 displays the estimated distribution of space debris per based on size. Of the larger tracked objects, the European Space Agency (ESA) estimated that 56% exist in LEO, while 3% exist in GEO. Space debris objects pose a great risk to terahertz and optical links. Smaller objects become more difficult to track and therefore cannot be maneuvered against ahead of time. Satellite constellations can benefit tremendously from having a larger beamwidth since it would reduce the likelihood of signal loss.

V. ROADMAP

A. *Path for Devices*

*1) **Materials**:* As mentioned in Sec. II, both technologies rely on III-V semiconductors. While current III-V semiconductor technology such as GaAs is already in use, Indium Phosphate would enhance performance but faces fabrication challenges. Beyond III-V materials, two-dimensional materials such as graphene are being explored for terahertz applications. While the very low power of graphene-based terahertz sources limits their applications in space, the very high speed tunability of graphene opens the door to large bandwidth modulators and beamforming array structures. Moreover, graphene can be combined with other two-dimensional materials for enhanced and diverse functionalities. Heterogeneous material combinations would benefit both terahertz and optical technologies.

*2) **Digitalization**:* Besides the front-ends, both technologies face a shared challenge: the digital problem. While both technologies enable the use of 10-100 GHz bandwidth, analog-digital interfaces are hindering such widely available bandwidth. While converters with higher sampling rates would be a solution, their power consumption and complexity impose a constrain, particularly for CubeSats. Alternatively, massive parallelization and multiplexing can be leveraged to divide large bandwidth into smaller channels to be processed by different analog/digital chains and then recombined into ultra-broadband signals.

*3) **Hybridization**:* Hybrid terahertz-optical communication systems can be deployed on spacecraft where a continuous high-data-rate stream is required. A **dual-band cognitive radio** could rapidly decide which band can maintain communication at high data rates based on environmental inputs such as cosmic noise and pointing difficulty [25]. Depending on the design, terahertz and optical radios can share elements and may benefit from a shared electronic architecture. For either shared or separate architectures, automatic data-rate control systems can be used for the dual-band radio to track SNR and adjust modulation schemes accordingly in real-time.

*4) **Reconfigurability**:* Hardware reconfigurability is highly desirable given the long life of each CubeSat in contrast to the rapidly changing market demands and regulations. This is especially the case for commercial satellites. Software-defined radios able to support massive bandwidths are at the center of several ongoing research efforts, for example focused on innovative FPGA-based **Radio Frequency Systems on Chip (RFSoC)**. In Fig. 6, different CubeSats are shown performing different functions. Such constellations can receive commands to change roles or make that decision autonomously.

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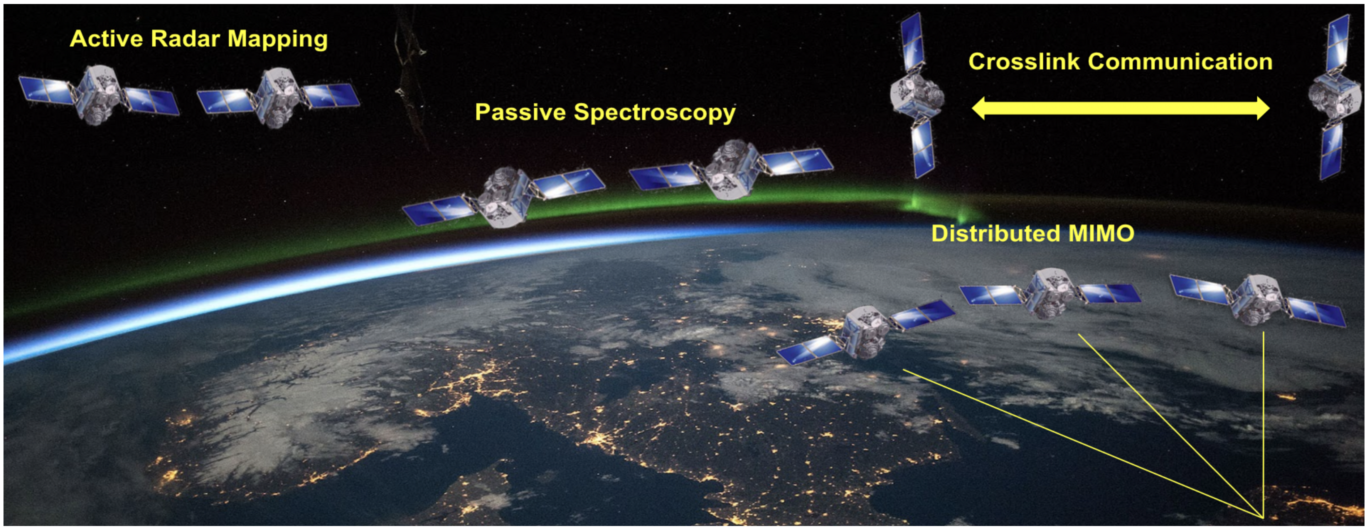

Fig. 6: Reconfigurable CubeSat constellation performing various functions pertaining to a joint communication and sensing architecture in space.

B. *Path for Antennas and Propagation*

*1) **High Gain Antennas**:* Compact terahertz antennas must be designed with minimal side lobes to ensure co-existence with sensing terahertz technology in space. Highly-accurate beams with minimal side lobes can be achieved through beamforming antenna arrays. The use of two-dimensional materials could provide such capabilities since it allows the design and fabrication of denser arrays with smaller antennas. On top of all these, dielectric lenses can be utilized for additional directivity gains. For optical systems, lasers enhanced with lenses are highly directive but require stricter pointing and tracking systems when compared to terahertz systems. Challenges such as beam divergence, beam clipping, and scattering are discussed in [26]. Pointing delay as a function of antenna steering must be studied for both terahertz and optical links in order to determine the most efficient constellation designs. A contact plan showing a potential connectivity distribution for optical links is proposed in [27].

*2) **Wavefront Engineering**:* Advances in electromagnetic wavefront control have opened the door to propagating signals with potential advantages that can be of use to satellite communications. While traditional Gaussian beams are used for both laser and directional-terahertz signal propagation, **Bessel, Airy**, and **Laguerre** beams are examples of potential methods of propagating signals with outcomes such as self-healing and bending [28]. While wavefront engineering has been explored for the desired frequencies [29], [30], wavefront engineering has yet to be extensively explored in the context of satellite communications.

*3) **Distributed Systems**:* With the achievement of high data rate and low latency, more sophisticated technologies such as distributed spacecraft arrays could revolutionize small satellite constellations. Uniting constellations to perform similar to how an array of satellites would in distributed interferometers, could be the key to high data rates for deep-space communication. The possibility of **distributed/cooperative multiple-input multiple-output** (MIMO) technology among distributed satellites would increase both capacity and coverage, allowing for longer range space communication links. Fig. 6 demonstrates how distributed MIMO technology can use multiple satellites to communicate with a ground station on Earth.

*4) **Channel Modeling**:* While some channel models have been established to predict propagation behavior at THz frequencies [31], more accurate propagation and channel models are needed to capture the impact of obstacles, ranging from other satellites to especially the space debris discussed in the previous section. A probabilistic situational awareness model is initiated in [32], and can be improved with addition of Raleigh/Rician fading models [33], [34]. Such fading models can be established by tracking space debris in orbits of interest and can be categorized based on wavelength. With the presence of such mechanical and electromagnetic debris sources, in addition to the rapidly increasing number of satellites in orbit, multi-path channel models are more likely to be considered [35].

C. *Path for Signals, Communications and Networks*

Based on the OSI model referenced in Fig. 7, the roadmap is laid as follows:

*1) **Physical Layer**:* As in any complex networking scenario, modulation and coding schemes, bandwidth, frequency band, and antenna resources most be jointly selected through a low-complexity physical and application-aware resource allocation problem. While there are modulation schemes that support high data rates such as phase-shift keying (PSK) or pulse-position modulation (PPM) utilizing orthogonal frequency-division multiplexing (OFDM), such schemes can still be limited by the available bandwidth [36]. To increase data rates without utilizing more spectral resources, more sophisticated methods of modulating signals can be implemented. **Orbital angular momentum (OAM)** has been a promising emerging method of modulating data without requiring more bandwidth, providing an additional degree freedom for equipping data onto a waveform. Such orthogonal helical polarization can

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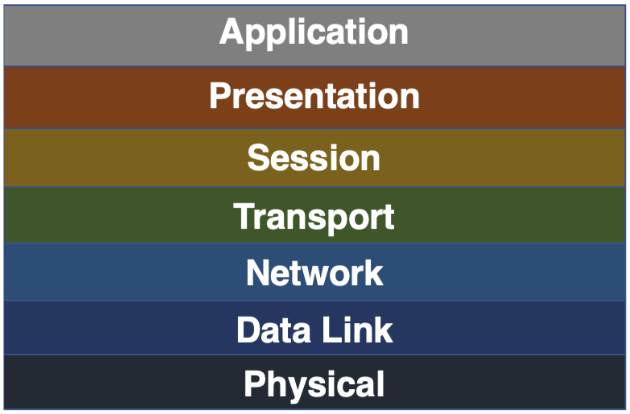

Fig. 7: A breakdown of the Open System Interconnection (OSI) model.

be leveraged to enhance data-rate, multiplexing, and security. OAM has been explored in the literature and was demonstrated above 100 km [37], showing it can be used in cross-link satellite communications. Furthermore, OAM's biggest obstacle is atmospheric turbulence, which is negligent in cross-link channels.

*2) **Data Link Layer**:* In both terahertz and optical systems; time, frequency, and phase synchronization must be designed and optimized for quick discovery, stable connectivity, and reduced errors. Such synchronization is more difficult at higher frequencies due to the highly directional beams amongst the mobile satellites in the dynamic space environment. To handle errors, repeat request strategies are unlikely to be used for deep space constellations due to long propagation time. Additionally, due to the same long propagation time, significantly long frames should be used to maximize the channel efficiency in high data rate space communications. Low-density parity check (LDPC) coding can be used for such long frames. Adaptive code rates can be implemented to compensate in the dynamic space environment.

*3) **Network & Transport Layer**:* While current high-frequency constellation rings relay on neighboring cross-link communication and uplink communication guidance, it is likely that an internet protocol (IP) friendly stack will be required for the Internet of Space Things constellations. Having IP-based networks would pave the way for space-based internet [38]. Having space-based internet would enhance interplanetary communication and take the internet to the solar system beyond Earth. However, due to the peculiarities of the satellite networks and the low computational resources, a cross-layer approach appears as the way to proceed. **Deep learning** can be utilized on a unit level and system level to be able to compute and choose the optimal destination for adaptive networks.

D. Path for Regulation and Coexistance

*1) **Joint Communications and Sensing**:* While the deployment of large number of satellites has been exciting in terms of increasing data rates in space and potentially providing space-based internet, the sensing community has raised concerns over the large sheets of metal that such constellations are forming against Earth-based detectors. Architectures for joint communication and sensing in space in terahertz devices can make satellites more reconfigurable serving as communication, radar, and spectroscopy terminals, as shown in Fig. 6. For situations where joint communication and sensing is not feasible, action must be taken to prevent telecommunication and private internet industries from disrupting the scientific community in space. Since commercial telecommunications companies are backed by large funds, while scientific mission do not generate revenue, deploying the proper regulations will be crucial to maintain scientific progress.

*2) **Spectrum Sharing**:* Another challenge between communication and sensing is spectrum. Currently, there are bands which are allocated for scientific use only at all times [39]. The federal communications commission (FCC) frequency allocation table demonstrates portions of the spectrum that are fixed for specific usage at all times. This poses a disadvantage for communication since the large contiguous bandwidths are often interrupted with small sensing bands, removing the ability to communicate at ultra-high rates [40]. One potential solution can be to use spectrum sharing regulations, where communication satellites are permitted to transmit data during windows where sensing detectors are inactive for given bands, and can coordinate a sharing strategy either based on a schedule or real-time demands of the sensing satellites. While the protection of scientific sensing satellites is of higher priority, spectrum sharing enables satellite to communicate at higher data rates. Spectrum sharing strategies are yet to be explored for space.

VI. CONCLUSIONS

In this paper, terahertz communication has been compared to free-space optical wireless communication as potential space communication technology in terms of devices and propagation and performed a link budget analysis to further demonstrate requirements for Gbps data-rates in space. Terahertz offered certain advantages that were explored, and with mature device technology, it is ready to be taken to the next level of deployment in space. Challenges were listed for both terahertz and optical wireless communication, in which many were identified as shared challenges laying a mutual roadmap. Ultimately, the question should not be which technology to move forward, but how to improve upon both technologies in order to synergistically advance the two of them and meet the requirements of an LEO mega-constellations for ultra-broadband Internet access equality.

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Ali Jamal Alqaraghuli [M'20] received his B.S. and M.S. degrees in Electrical Engineering form the University at Buffalo in 2018 and 2020, respectively. He gained industry experience through interning at Northrop Grumman Aerospace Systems and NASA Kennedy Space Center, and has lead the University at Buffalo Nanosatellite Laboratory as a communication systems lead engineer for RF and laser missions. He has recently served as an intern for the Submillimeter Wave Advance Technology group at the NASA Jet Propulsion Laboratory. His current research interests include high data rate space communications in addition to terahertz communication and sensing systems.

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Jose V Siles [M’03] received the Ph.D. degree received the Ph.D. degree in electrical engineering from the Technical University of Madrid, Madrid, Spain, in 2008. In September 2010, he joined the Submillimeter-Wave Advanced Technology Group at NASA’s Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, as a Fulbright Post-Doctoral Fellow. His research interests involve the design, development, and test of solid-state power-combined multiplied local oscillator sources and receivers for high-resolution multipixel heterodyne cameras at submillimeter-wave and terahertz frequencies for astrophysics, planetary science, and radar imaging applications.

Josep Miquel Jornet [M’13, SM’20] received the Ph.D. degree in Electrical and Computer Engineering (ECE) from the Georgia Institute of Technology in 2013. Between 2013 and 2019, he was with the Department of Electrical Engineering at University at Buffalo. Since August 2019, he is an Associate Professor in the Department of ECE at Northeastern University. His research interests are in Terahertz-band communications and Wireless Nano-bio-communication Networks. He has co-authored more than 160 peer-reviewed scientific publications, one book, and has been granted 4 US patents, and is serving as the lead PI on multiple grants from U.S. federal agencies.