Exploring Internet of Space Things (IoST) and Space-based Internet of Things (S-IoT): A Global Connectivity Revolution

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***Abstract*—The Internet of Things (IoT) has evolved into a multifaceted ecosystem, extending its reach into domains such as healthcare, space technology, and more. To overcome the constraints of terrestrial networks and unlock the full potential of IoT, two revolutionary paradigms have emerged: the Internet of Space Things (IoST) and Space-based Internet of Things (S-IoT). These innovations are redefining global connectivity. This concise review paper synthesizes key insights from multiple articles introducing IoST and S-IoT. It covers the principles, technologies (including Software-Defined Networking and Network Function Virtualization), and architectures that underpin these transformative concepts. Challenges related to network and protocol, routing, and resource allocation that the current IoT Framework will impose are discussed, emphasizing the need for innovative solutions. The review underscores the global connectivity potential of IoST and S-IoT, showcasing their applications in remote sensing, cellular backhauling, mission-critical communications, and more. It further discusses the pivotal role of space-based communication in mitigating the limitations of terrestrial networks. It discusses how IoST and S-IoT leverage advancements in nanosatellite design and advanced communication technologies for seamless global networking. By consolidating insights from various sources, this review offers a concise yet comprehensive view of the IoST and S-IoT in providing solutions for global connectivity.**

I. Introduction

THE rise of IoT in space is driven by challenges faced by terrestrial networks, particularly cellular networks, in offering seamless coverage to remote regions such as vast oceans, deserts, and polar areas where IoT applications demand reliable connectivity. [1] Satellite communication, with its capability for consistent connectivity, addresses these challenges effectively. [2] Before the widespread integration of IoT in space, satellite communication was mainly employed for point-to-point data transmission between ground stations and spacecraft. While effective for certain applications, this approach had limitations in supporting large-scale IoT device deployment. The advent of IoT has brought about a revolution in space communication, enabling the interconnection of a diverse network of devices, each with unique data and communication requirements. This transformation is pivotal in overcoming the limitations of traditional satellite communication and expanding the possibilities for connectivity in remote and challenging environments [3]. Over the last decade, the space industry has experienced a technological revolution, marked by advancements like CubeSat technology, reusable rockets, and the rapid evolution of microprocessors. Although traditional challenges such as satellite positioning difficulties and high manufacturing costs persist, the introduction of NB 5G-IoT satellite communications is poised to be a game-changer. This technology is anticipated to enable widespread adoption of 5G, with projections indicating that satellite IoT connectivity revenues will grow much, up to 14 times faster than traditional satellite revenues. The shift towards 5G-IoT facilitates near-real-time data transmission, providing better-quality communications globally without the need for specialized hardware [4]. Supported by organizations like the 3GPP and the European Space Agency, 5G-IoT in low-Earth orbit is gaining momentum, paving the way for a more accessible, scalable, and cost-effective IoT adoption in space [5]. This development positions NTN S-IoT as a significant technological advancement in the space industry, facilitating a highly connected future.

Before diving into the contents of this paper, it is imperitive to lay out some of the differences between IoST and S-IoT. The Internet of Space Things (IoST) and the Spatial Internet of Things (S-IoT) represent cutting-edge paradigms in the evolving landscape of connected technologies. IoST involves the integration of interconnected devices and sensors in space, enabling advanced data collection and communication among satellites and spacecraft and system deployed for extra terrestrial space exploration. On the other hand, S-IoT extends this connectivity to terrestrial applications, facilitating real-time insights from space via satellite constellations such as CubeSats to revolutionize various industries. These technologies hold immense potential in sectors like agriculture, energy, healthcare, and manufacturing, optimizing processes, enhancing monitoring capabilities, and improving overall efficiency. As IoST and S-IoT continue to evolve, their transformative impact is expected to shape the future of both space-based and terrestrial connectivity, ushering in a new era of interconnected systems and data-driven insights [6] [7].

A. Market Overview

The Satellite IoT market Size is expected to grow from US \$1.23 billion in 2022 to US \$5.86 billion by 2030; it is estimated to grow at a CAGR of 21.5% from 2022 to 2030. S-IoT is positioned to revolutionize multiple sectors by providing real-time data insights from space. In agriculture, S-IoT has the potential to enhance crop yields and minimize environmental impact. Within the energy industry, it facilitates monitoring and management of energy consumption. S-IoT's significant impact extends to healthcare, enabling remote patient monitoring, real-time tracking of organ

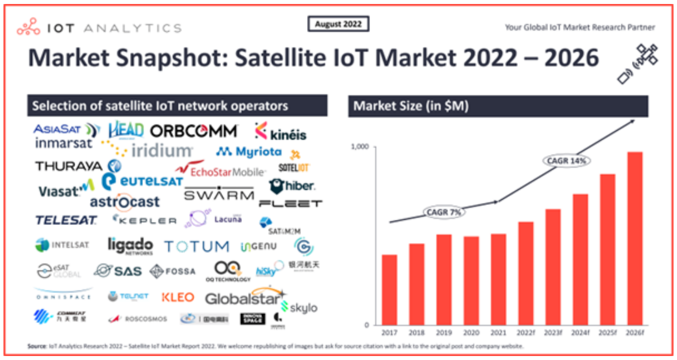


Fig. 1: Satellite IoT Market Overview [8]

deliveries, personalized treatment plans, and other medical supply logistics. In manufacturing, it can enhance production schedules, optimize resource utilization, and improve quality control. Beyond these key sectors, S-IoT has the capacity to overhaul supply chain management, adventure sports, and geospatial personal tracking. As S-IoT technology progresses, its transformative influence is anticipated to broaden further, shaping the trajectory of diverse industries, and enhancing the global quality of life.

B. Possibilities: Unveiling what was once Unattainable

S-IoT is now feasible due to advancements in small satellites (like Cubesats) technology, offering reduced costs, quicker development cycles, and increased agility. These improvements, along with progress in embedded and wireless systems, have addressed previous challenges, making space-based IoT more achievable and affordable [6]. The availability and accessibility of high-quality components and hardware has significantly increased in recent years and the lower costs of constructing and operating launch facilities has facilitated more CubeSat missions, over 150 in 2017 [9]. The computing hardware used in these satellites can be entirely build from Commercial Off-the-Shelf (COTS) components [10]. This has led to the decrease of costs in the deployment and operation when compared to traditional space programs. Much like the prevalent white-box switching hardware seen in wired SDN/NFV networks, CubeSats, with their utilization of COTS hardware, modest onboard processing capabilities, and cost-effectiveness, align seamlessly as an ideal choice for the network's data forwarding element, referred to as the data plane.

II. State-of-the-Art

The full potential of the Internet of Things (IoT) can only be achieved by integrating it with a ubiquitous connectivity platform that operates in even the most remote areas. CubeSats are one of the platforms to mitigate global connectivity at a low cost. Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are used to further enhance IoST over CubeSat, enabling precise control over the system hardware, optimizing network resource utilization, and simplifying network management [14]. The IoST architecture adheres to a layered structure to ensure control and data plane separation. It comprises the Infrastructure Layer, responsible

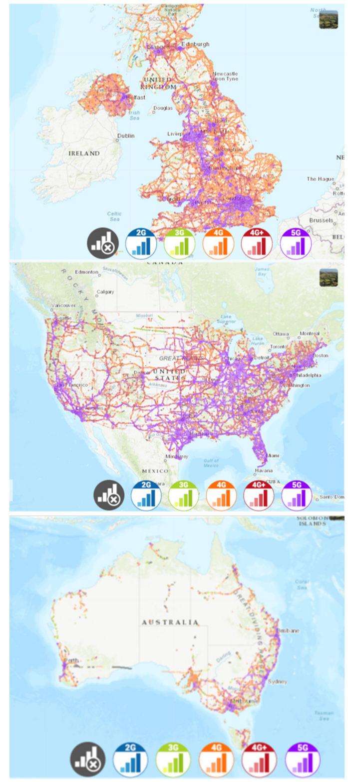


Fig. 2: From top to bottom: a) Heatmap of Vodafone network in United Kingdom [11]; b) Heatmap of AT&T network in United States [12]; c) Heatmap of Telstra network in Australia [13]. The Network heatmap coverage illustrates the coverage limitation of the existing terrestrial network. The connectivity heat map images of USA and Australia demonstrate the disparities in coverage across different regions. In the USA, the coverage is concentrated in urban areas, while rural areas have significantly lower coverage. In Australia, the coverage is even more sparse, with large areas having no connectivity at all.

for the physical hardware, including sensing devices, switches, gateways, servers, and CubeSats, along with hardware virtualization solutions; the Control and Management Layer (CML), analogous to the SDN and NFV control plane and management and orchestration entity, responsible for network orchestration, operations, and management; and the Policy Layer, enabling external entities to interact with the IoST system by providing tenants with a means to push their network policies and monitor network status [15].

A. Physical System

As shown in Figure 4, the Infrastructure Layer forms the underlying physical fabric of the cubesat based IoST system. It consists of the sensing devices, switches, gateways, and servers that form the Access Network(direct, indirect and near-earth) and IoST Hub (Ground stations and then backend software architecture), in addition to the CubeSats and Resource virtualization (of IoST Hub's , cubesat's and sensors's computing hardware and radio).

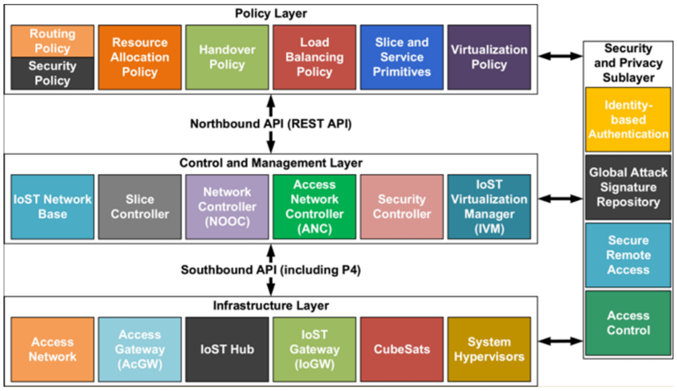


Fig. 3: IoST System Architecture

Control Management Layer(CML) is responsible for network control, management, and performance optimization. The CML interfaces with the Policy Layer that guides its functioning, and the system elements that come under the purview of the CML. It consist of entities such as IoST Network Base (Maintaining and managing ISLs, GSLs, CubeSats IDs, Orbital plane info, Sensing devices, access links, IoST Hub, Network slice), IoST Virtual Manager (Virtulisation of IoST hardware resources), Slice Controller (do network slicing characterised by tenancy, SLA, radio and computer resources), Network Orchestration and Operations Controller (NOOC) works in close cooperation with the IVM, and Slice Controller, ensuring elasticity and optimal resource utilization (manages PHY, MAC, Network Layer functions),Security Controller.

The Policy Layer in the IoST architecture is an external component that interfaces through the Network Base Interface (NBI). Each tenant possesses a unique Policy Layer responsible for managing IoST infrastructure utilization. It receives a simplified network state overview from the IoST Network Base, using this information to issue policy directives to the Control and Management Layer (CML) via the NBI. The CML incorporates these instructions into its network control strategies, such as directing the network to avoid specific routes or restricting locations and resource consumption for Network Functions (NFs).

B. Satellites

IoST is seeing an increase in the use of CubeSats for tasks like Earth observation, communication relays, and space research due to their cost-effectiveness and shorter development cycles. Thanks to their affordability and ease of deployment, CubeSats, have emerged as a key component of contemporary space initiatives. They can weigh as little as 1.33 kg per unit and are usually measured in multiples of 10×10×10 cm. CubeSats are used for a variety of purposes, ranging from commercial uses like imaging and telecommunication to scientific research like Earth observation and space weather monitoring. Commercial launch services have made it possible to launch CubeSats into orbit more frequently and for a much lower cost than in the past. Advancements in miniaturization has made it possible for sensors and communication systems to be compact which has enabled these tiny satellites to carry

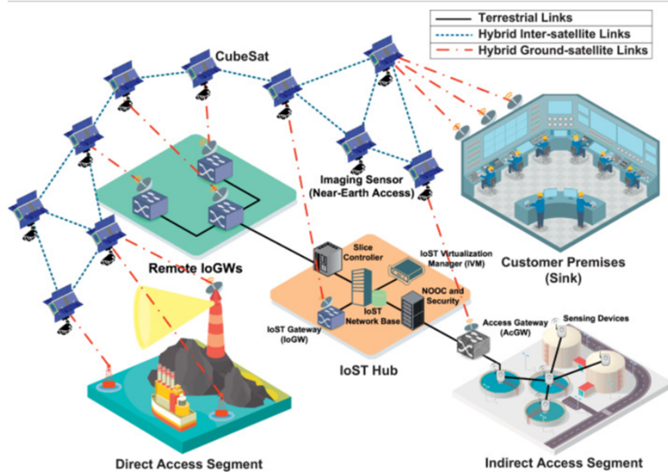


Fig. 4: IoST Physical System.

Fig. 5: Preliminary design of our next-generation 3U CubeSat

out tasks that were previously limited to much larger and more expensive satellites. Although CubeSats provide benefits in terms of cost, development timing, and latency, they also face specific challenges such as optimal physical-link layer resource allocation, long delays, and temporal variation in network topology, connectivity robustness, synchronization of IoST Hubs, handovers, hardware virtualization, and automated device provisioning. These challenges require novel solutions like vCSI, stateful segment routing, optimal IoST hub geo-locations, new network routing and convergence protocols, GSL outage forecasting, the need for a new virtualization system, and Access Network Controller, respectively. Cubesats can be considered as a class of LEO satellites and differs from GEO satellites in various aspects. Some of these differences are as follows:

- Due to their lower orbital altitude, typically below 2000 kilometers, LEO satellites experience shorter propagation delays compared to GEO satellites. This translates to a round-trip time (RTT) of less than 100 milliseconds for LEO satellites, whereas GEO satellites exhibit RTTs exceeding 600 milliseconds.
- Satellite IoT terminals are engineered to be compact, durable, and power-efficient. Leveraging the shorter propagation distance inherent in LEO satellite constellations, signal loss is minimized, enabling the realization of

optimal terminal designs.

- Communication through geostationary (GEO) satellites faces limitations in areas with challenging terrains due to the fixed position of both the terminals and the satellite. If a physical obstruction, such as a tree or cliff, blocks the line of sight (LOS) between a terminal and the satellite, communication is disrupted until the obstruction is removed. In contrast, LEO satellites, due to their constant movement, maintain connectivity even in the presence of nearby obstacles.
- Geostationary (GEO) satellites' fixed position relative to the ground makes them susceptible to intentional jamming by adversaries.
- Tracking signals from a GEO satellite is facilitated by its broad beam coverage. However, once essential parameters are obtained, employing deception jamming or coherent jamming can markedly increase the level of interference.

C. Role of SDN and NFV

Software-defined networking (SDN) revolutionizes network management by decoupling the control plane(how to route data) from the data plane (how to forward data), granting network administrators greater flexibility and control through software-based configuration, automated device discovery, and programmable network behaviour [16]. This leads to increased scalability, programmability, efficiency, and security, making SDN a compelling solution for modern networking challenges. The adoption of an SDN and NFV-based framework for satellite networks is driven by the need to overcome the limitations of traditional vendor-specific implementations that hinder network evolution and adaptability. Under the current approach, manual configuration dominates, and the introduction of new technologies is a slow and expensive process [15]. It is crucial to recognize that satellite networks are not merely infrastructure but a means to deliver transport services to a diverse range of applications, from remote sensor fields to near-Earth object monitoring. To effectively support these applications, the transport network must be tightly integrated with the applications it serves, a feat that is impossible with traditional network architectures. SDN adoption for satellite networks is further justified by advancements in satellite infrastructure design. CubeSats, utilizing Commercial Off-The-Shelf (COTS) components, play a key role in extending the whitebox concept from terrestrial to satellite networks, leading to substantial infrastructure cost savings. Despite this, the lack of standardized communication specifications often results in mission-specific implementations of the Communications Subsystem within CubeSat networks. SDN becomes crucial for the scalability of the IoST as it addresses CubeSats' resource limitations. By transferring the processing burden to ground-based server-grade hardware, SDN ensures scalability, overcoming constraints and facilitating the integration of CubeSat networks into the broader framework of network virtualization within IoST. Moreover SDN enables three key feature, dynamic scalable network configuration, CubeSats-as-a-Serivce(CaaS), & traffic management based on security provisioning.

SDN facilitates the virtualization of networking resources and their management by a centralized entity known as the Orchestrator. In the future, there will be a significant increase in the number of cubeSats and other IoST-based satellites deployed in low-Earth orbit (LEO). This will pose a number of challenges, including centralized management, virtual network function (VNF) deployment, and orchestration. The framework employs multiple levels of SDN controllers, including a level-1 SDN controller on ground stations responsible for providing information about communicating satellites to level-2 SDN controllers. A centralized orchestrator collects global information from the level-2 controller and makes decisions to optimize the overall satellite network, as well as to deploy Virtual Network Functions (VNFs) within the network. The details are given below:

1) Level-2 Ground Station SDN controller: The SDN controllers, positioned on ground stations, engage in communication with multiple satellites within their range. The gathered information from these satellites is then relayed to the Level-2 SDN controller.

2) Level-1 SDN controller: Residing at Level-2, the SDN controller consolidates information pertaining to satellite positioning, communication status, and network topology, forming a comprehensive centralized view. It then issues directives to the Level-1 SDN controllers, who relay instructions to the satellites, enabling VNF deployments and optimizing the global satellite network

3) Level-3 Orchestration layer: The centralized orchestrator serves as the overarching entity, overseeing the global state of the satellite network. It makes informed decisions to ensure seamless network operation, delivering high-quality service, exceptional user experience, low latency, and unwavering availability to users worldwide. To achieve this, it issues instructions to the Level-1 SDN controller, which in turn relays them to the local ground station-based controllers for prompt execution.

With the help of network function virtualization (NFV), services can be scaled more easily in response to changing demand. With IoST, where the network environment can change quickly, this is especially helpful. Using NFV, network components such as firewalls, load balancers, and intrusion detection systems can be implemented as virtualized services. This makes it possible to quickly adjust to shifting requirements without needing to send more hardware into orbit. It also significantly lowers costs by reducing reliance on specialized hardware, which is a critical benefit for space missions with limited funding. NFV makes it possible for network functions to be updated and deployed quickly, which is crucial for Internet of Things applications that need to react quickly to changing circumstances or mission requirements.

III. Performance Evaluation

This section discusses some of the performance metrics associated with an IoST system such as the various links between the different infrastructure components, hop metrics and the end-to-end operation. For evaluating the performance, various factors such as data rates, carrier frequencies, link

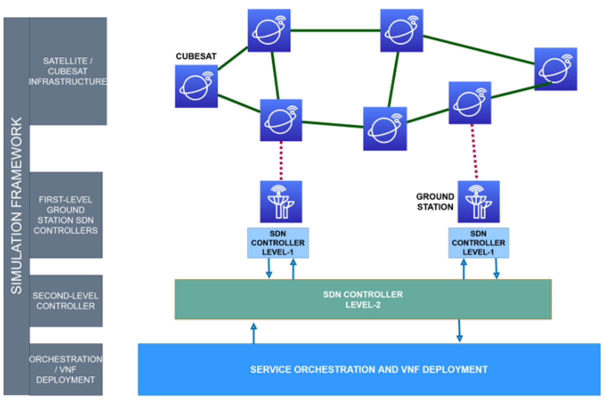


Fig. 6: Proposed SDN-based CubeSat Emulation Framework

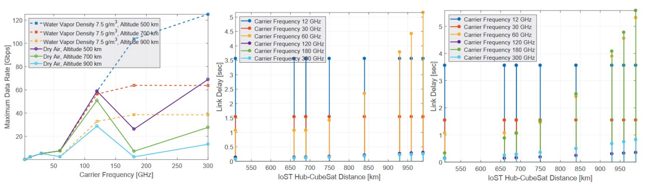
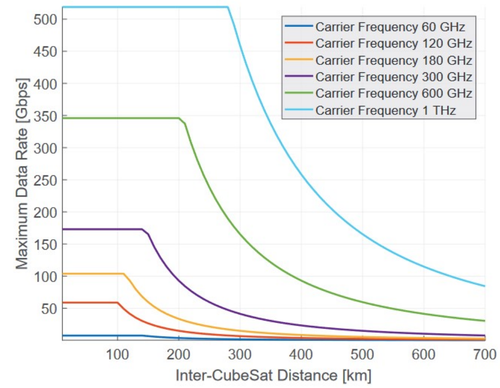
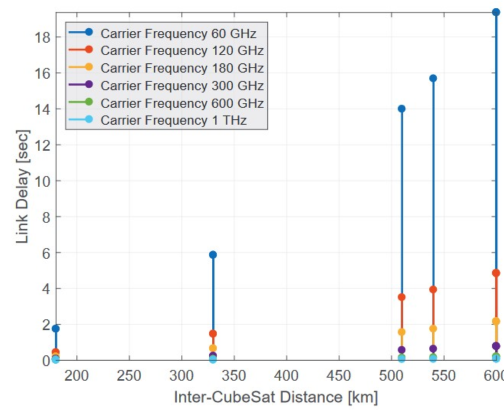


Fig. 7: Performance Analysis. From left to right: (a) Maximum achievable data rate; (b) Link delay (500 km orbit, dry air); (c) Link delay (500 km orbit, moist air)



(a) Maximum achievable data rate.



(b) Link delay.

Fig. 8: Inter-CubeSat Link (ISL) Analysis

durations and access durations are considered in understanding how these affect the performance of various metrics. The IoST system that was used for this analysis was implemented using Systems Toolkit (STK), Open vSwitch (OVS) virtual switch, and the OpenDaylight (ODL) controller operated in the in-band mode [17].

A. *IoST Hub-CubeSat Links (GSL)*

Figure 7a shows the maximum data rate vs. carrier frequency plot at different altitudes and atmospheric conditions. Regardless of atmospheric conditions, higher carrier frequencies generally lead to increased maximum data rates, while orbital altitude increase tends to decrease these rates due to larger channel bandwidths and higher path loss, respectively. At 60 and 180 GHz, a GSL faces increased attenuation, leading to lower data rates due to heightened molecular absorption by oxygen at 60 GHz and water vapor at 180 GHz.

Figure 7b-c shows the IoST Hub-CubeSat link's average delay variation with distance. This average includes propagation and transmission delays for a 1 GB data transfer over the GSL. The delay decreases with higher carrier frequencies, except for 60 GHz in dry air and 180 GHz in moist air, which remain outliers. Transmission delay nature depends on the data rate a carrier supports. Given the data rate challenges at 60 and 180 GHz due to molecular absorption, the link delay performance for these carriers is worse than others over long distances.

B. *Inter-CubeSat Links (ISL)*

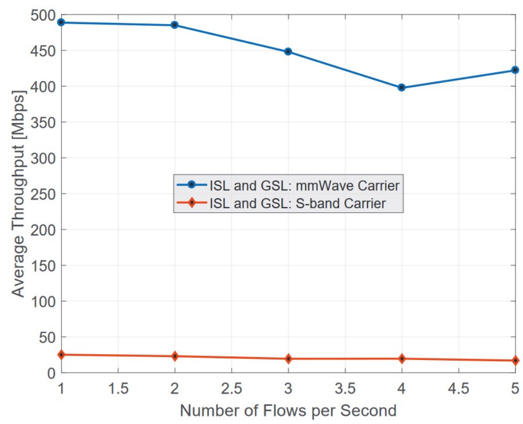
Deployed in the exosphere at altitudes of 500 km and above, the Inter-CubeSat Links (ISL) experiences negligible atmospheric attenuation. Figure 8a illustrates that in the absence of molecular absorption, the data rate rises with higher carrier frequencies without anomalies. Additionally, the data rate decreases with distance due to increased path loss.

In contrast to the GSL scenario, Figure 8b aligns with expectations: higher carrier frequencies lead to increased data rates, reducing average link latency. Meanwhile, greater link separations result in higher latencies due to growing propagation delays and decreasing data rates.

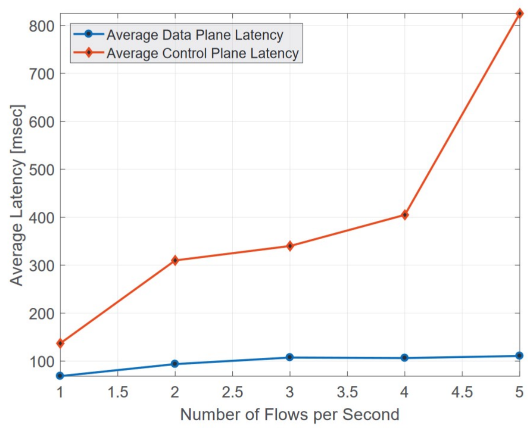
C. *End-to-end Operation*

End-to-end performance was tested by analyzing the data transfer between Atlanta and Lisbon where the GSL and ISL uses a 60 GHz carrier in a moist air environment. Other consideration was that the source and destination CubeSats are one hop away from each other. As seen from Figure 9a, as the number of active flows increase, more bandwidth is occupied more which in turn reduces the throughput. At 5 seconds, the throughput increases but this can be considered as an outlier due to the randomized nature of the source and destination. In addition, the mmWave link has a higher throughout when compared with the S-band.

Figure 9b compares the average latency of the data plane and control plane against different flow rates. As the flow increases, it can be seen that the latency also increases.



(a) End-to-end Throughput



(b) Link delay

Fig. 9: End-to-end Performance

Particularly in the control plane, a sharp rise in the latency is seen at 4 flows/sec. This is because the increase in traffic in the GSL and ISL has a significant impact on the SDN controller operated in the in-band mode.

IV. Conclusion

In conclusion, this survey paper has delved into the intricate landscape of the Internet of Space Things (IoST), exploring its state-of-the-art advancements, the role of CubeSats in IoST, the integration of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) in IoST, and the simulated performance analysis of various metrics like ISL (Inter-Satellite Links), GSL (Ground-Space Links), and next hop metrics. Through an in-depth examination, it's evident that IoST stands at the forefront of technological innovation, bridging the realms of space and connectivity to usher in a new era of possibilities.Central to the IoST landscape are Cubesats, which have emerged as transformative tools in democratizing access to space. Their compact size, cost-effectiveness, and versatility have revolutionized space missions, playing an integral role in IoST deployments. The evolution of satellites for IoST has been pivotal in expanding the horizons of connectivity, enabling seamless ubiquitous communication and data transfer.

Moreover, the comprehensive performance analysis conducted on key metrics like ISL, GSL, and next hop metrics has provided invaluable insights into the reliability, latency, and throughput of IoST networks. These metrics serve as fundamental benchmarks for enhancing the overall performance and reliability of IoST systems, ensuring robust connectivity and data transmission capabilities. As the realm of IoST continues to evolve, it is imperative to address emerging challenges and further refine existing technologies to meet the growing demands of a connected world. The findings and observations presented in this survey paper serve as a foundational understanding of IoST, laying the groundwork for future research, development, and innovation in this evolving field.

References

[1] N. Islam, M. M. Rashid, F. Pasandideh, B. Ray, S. Moore, and R. Kadel, "A review of applications and communication technologies for internet of things (iot) and unmanned aerial vehicle (uav) based sustainable smart farming," *Sustainability*, vol. 13, no. 4, 2021. [Online]. Available: https://www.mdpi.com/2071-1050/13/4/1821

[2] I. F. Akyildiz and A. Kak, "The internet of space things/cubesats: A ubiquitous cyber-physical system for the connected world," *Computer Networks*, vol. 150, pp. 134–149, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1389128618314191

[3] A. A. Shah, "A software-defined networking based simulation framework for internet of space things," in *2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring)*, 2023, pp. 1–4.

[4] N. Gupta, S. Sharma, P. K. Juneja, and U. Garg, "Sdnfv 5g-iot: A framework for the next generation 5g enabled iot," in *2020 International Conference on Advances in Computing, Communication Materials (ICACCM)*, 2020, pp. 289–294.

[5] F. Granelli, C. Sacchi, M. Centenaro, and C. Costa, *The Internet-of-Things, the Internet of Remote Things, and the Path Towards the Internet of Space Things*. Cham: Springer International Publishing, 2023, pp. 271–288. [Online]. Available: https://doi.org/10.1007/978-3-031-30762-1_12

[6] A. Kak and I. F. Akyildiz, "Designing large-scale constellations for the internet of space things with cubesats," *IEEE Internet of Things Journal*, vol. 8, no. 3, pp. 1749–1768, 2021.

[7] I. Priyadarshini, B. Bhola, R. Kumar, and C. So-In, "A novel cloud architecture for internet of space things (iost)," *IEEE Access*, vol. 10, pp. 15 118–15 134, 2022.

[8] E. Pasqua. (2022) Satellite iot connectivity: Three key developments to drive the market size beyond $1 billion. [Online]. Available: https://iot-analytics.com/satellite-iot-connectivity/

[9] M. Swartwout. (2016) Cubesats and mission success. [Online]. Available: https://nepp.nasa.gov/docs/etw/2016/14TUE/20160614-0900-Swartwout-etw2016.pdf

[10] C. Nagarajan, R. G. D'souza, S. Karumuri, and K. Kinger, "Design of a cubesat computer architecture using cots hardware for terrestrial thermal imaging," in *2014 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology*, 2014, pp. 67–76.

[11] NPERF. (2023) Vodafone mobile 3g / 4g / 5g coverage map, united kingdom. [Online]. Available: https://www.nperf.com/en/map/GB/-/164526.Vodafone-Mobile/signal/

[12] ——. (2023) At&t mobility 3g / 4g / 5g coverage map, united states. [Online]. Available: https://www.nperf.com/en/map/US/-/2420.ATT-Mobility/signal/

[13] ——. (2023) Telstra 3g / 4g / 5g coverage map, australia. [Online]. Available: https://www.nperf.com/en/map/AU/-/2445.Telstra/signal/

[14] N. Bizanis and F. A. Kuipers, "Sdn and virtualization solutions for the internet of things: A survey," *IEEE Access*, vol. 4, pp. 5591–5606, 2016.

[15] I. F. Akyildiz and A. Kak, "The internet of space things/cubesats," *IEEE Network*, vol. 33, no. 5, pp. 212–218, 2019.

[16] Q. Yan, F. R. Yu, Q. Gong, and J. Li, "Software-defined networking (sdn) and distributed denial of service (ddos) attacks in cloud computing environments: A survey, some research issues, and challenges," *IEEE Communications Surveys Tutorials*, vol. 18, no. 1, pp. 602–622, 2016.

[17] A. Kak, E. Guven, U. E. Ergin, and I. F. Akyildiz, "Performance evaluation of sdn-based internet of space things," in *2018 IEEE Globecom Workshops (GC Wkshps)*, 2018, pp. 1–6.