A Survey on Satellite Computing: Connecting the Dots between Networks and Applications

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***Abstract*—Over the past decade, there has been a significant and rapid progression in satellite technology, mostly motivated by a wide deployment of *Low Earth Orbit* (LEO) mega-constellations and, more recently, emerging technologies like *Inter-Satellite (Laser) Links* (ISL) and multi-orbital constellations approaching maturity. This has rekindled interest towards the exploitation of satellite systems for a variety of tasks, including their use as computational servers similar to traditional Edge and Cloud infrastructures. Such paradigm, known as Satellite Computing, can serve any area on Earth in a holistic manner, enhancing applications anywhere and anytime in several distinct domains (e.g., environmental monitoring, emergency response and intelligent transportation). Despite being a highly active research area, Satellite Computing is still in early stages and, therefore, most research works are insular and target specific aspects and use cases. Moreover, the concept of Satellite Computing has not been standardized yet, thus its role in future network systems (e.g., beyond 5G/6G) remains unclear.**

This work aims to fill these gaps by providing a comprehensive survey of the state of the art. First, it discusses the network- and computing-related aspects that impact the realization of Satellite Computing in future systems. And second, it overviews specific use cases and applications enabled by Satellite Computing. Based on this two-fold analysis, a taxonomy of applications is derived from each application's requirements and key networking design choices. Finally, it provides an overview from an industrial perspective, while identifying open challenges in the Satellite Computing area in order to boost and steer possible pathways for future research.

***Index Terms*—Satellite Computing, Space-based Edge/Cloud, Beyond 5G/6G Non-Terrestrial Networks, Applications**

I. Introduction

In recent years, satellite communication has witnessed a resurgence thanks to advancements in satellite technology, in areas such as spectrum usage, active antenna design and Inter-Satellite Link (ISL) communication, as well as the emergence of new market players and business models. Traditional satellite communication leveraging Geo-Synchronous / Geo-stationary Orbit (GEO) satellites is quickly being augmented with large-scale Low Earth Orbit (LEO) constellations. As an example, established players (e.g. SpaceX and OneWeb) and newer ones (e.g. Project Kuiper by Amazon) are, respectively, expanding or deploying their LEO satellite constellations with the objective of providing global broadband Internet connectivity with higher capacity, reduced latency and higher data rates. Mobile operators are already announcing new offerings for satellite-based connectivity to address coverage gaps, enhance network reliability, and provide connectivity in remote or underserved areas without incurring on additional costs to deploy and maintain a terrestrial infrastructure in difficult-to-access areas. Standardization bodies and industrial associations are leveraging on such momentum to push the enhancement of the next-generation of mobile networks (i.e., beyond 5G/6G) with native support for Satellite Communications, as part of their efforts to integrate Terrestrial and Non-Terrestrial Networks (TN-NTNs), in order to provide seamless connectivity anywhere and anytime. Collectively, these efforts are driving advancements of satellite technologies in terms of capabilities and services, and paving the way for their democratization by reducing costs, simplifying access to wider population and organizations, and creating standards to ensure compatibility and interoperability.

From their initial purpose to overcome the limitation of terrestrial communication systems and enable long-distance communication (e.g., telephone calls, broadcast television and radio, and data transmission over large distances), advancements in satellite technology have been transforming these communication satellites into computing platforms. The evolution from simple communication relays to advanced computing hubs in orbit reflects a similar evolution to the one witnessed with terrestrial Cloud and Edge computing. Early satellites began incorporating basic data processing capabilities

TABLE I: Satellite Characteristics Overview

Platforms	Altitude Range	Orbit	Orbital Period	Beam Footprint Size	Horizon Time
GEO satellite	35786 Km	Geosynchronous orbit equal to Earth's rotational period	24 hours	1000 Km	24 hours
MEO satellite	7000 to 25000 Km	Circular orbit around Earth	12 hours	500 Km	1 to 2 hours
LEO satellite	300 to 1500 Km	Circular orbit around Earth	1.5 to 2 hours	100 Km	5 to 10 minutes

to handle the large volumes of data collected from sensors and instruments (e.g., performing preliminary data analysis and compression before transmitting the information back to Earth), thus overcoming the limited bandwidth between satellites and ground stations. Modern satellites are starting to be equipped with powerful onboard processing capabilities, allowing them to perform complex computations, data analysis, and even Artificial Intelligence (AI) tasks directly in space.

As satellite capabilities continue to evolve, a new usage model is also making its appearance: *Satellite Computing*. In other words, the use of satellites to run general (and potentially distributed) computation and storage tasks as opposed to simple communication [1]. Since satellite constellations and/or platforms are typically located across three different orbital planes (i.e., Low Earth Orbit, Medium Earth Orbit (MEO) and Geo-Synchronous / Geostationary Orbit), Satellite Computing will encounter specific challenges since each orbital plane presents a distinct set of characteristics (as summarized in Table I). Yet, it concurrently presents a diverse array of opportunities and benefits for applications in terms of e.g. resilience, reliability, scalability and energy efficiency. A limited approach for the Satellite Computing concept is already applied in areas such as Earth observation, where imagery needs to be pre-processed onboard of the satellite in order to limit the usage of downlink bandwidth [2]. However, an increasing number of industries is recognizing the potential benefits of Satellite Computing and considering its adoption to address operational needs. The most obvious use cases are related to operations in remote or underserved areas, including agricultural [3] and maritime [4] monitoring, as well as emergency response [5]. In addition, the integration of Satellite Computing with the Internet of Things (IoT) is raising interest in sectors, such as transportation and logistics [6]. As these new sectors are setting more demanding requirements (reduced network overhead and limited terrestrial infrastructure dependency, high energy efficiency and real-time processing) for future systems, Satellite Computing is expected to provide the necessary capability evolution to fully support them.

Satellite Computing is an entirely new concept compared to a simple combination of Edge/Cloud Computing and Satellite Communication. The network is mobile and non-homogeneous, space resources are constrained in many ways and a lot of issues like geographical restrictions, user authentication and resource balancing on a dynamic satellite network do not have state-of-the-art solutions. However, certain aspects of Satellite Computing can be mapped to either Edge Computing or Cloud Computing. On the one hand, the principles of Satellite Computing in the LEO and MEO mostly resemble those of the Edge Computing concept. Both LEO/MEO and Edge Computing act as a distributed and highly mobile computing paradigm that aim to bring computation resources and data storage closer to the location where they are needed, allowing to improve response times, optimize bandwidth and enhance data security and privacy. On the other hand, the principles of Satellite Computing in the GEO mostly suits the Cloud Computing concept. Both GEO and Cloud Computing approaches act as a centralized and static computing paradigm that aim at delivering on-demand access to a shared pool of computation resources and data storage, providing flexibility and scalability. An example of this dualistic nature is the potential of Satellite Computing to simultaneously offer Cloud and Internet-scale storage services, such as data lakes or Content Delivery Networks (CDNs) [7].

While Edge and Cloud Computing offer a possible reference framework for Satellite Computing, most research in the state of the art is largely insular and tied to specific business use cases. This hinders the identification of key requirements for Satellite Computing, as well as the establishment of generic computational and orchestration platforms.

TABLE II: Summary of relevant standardization / specification activities [8] [9] [10] [11] [12]

3GPP	**Description**
Release 16	**Study Items on Integration of Satellite Access in 5G** (e.g., study items on architectural aspects, including integration of Satellite Access in 5G, and solutions for NR to support NTNs)
Release 17	**Edge Enhancements** (e.g., 5G Core to support Edge computing); **Architecture aspects for using satellite access in 5G** (e.g., enhancements for RF and physical layer, protocols, radio resource management, and frequency bands, as well as TN-NTN roaming and timing-related issues); **NB-IoT and eMTC support for NTN** (e.g., IIoT and integrity for positioning, HARQ enhancements, RTT precompensation, etc.).
Release 18	**Architectural Enhancements** (e.g., satellite access, 5G system with satellite backhaul) **NTN enhancements** (e.g., mobility and service continuity between TN-NTN or across NTNs) **Spectrum and Radio Enhancements** (e.g., NR-based satellite access in bands above 10 GHz, investigating regulatory requirements); **Positioning and Localization** (e.g., NTN-verified user location)
Release 19 and beyond	**Architectural Enhancements** (e.g., satellite access over regenerative topologies); **Positioning and Localization** (e.g., positioning architecture evolution, high positioning accuracy and low-latency, side-link positioning, AI/ML-based positioning, NTN-based accurate localization)

ITU-R	**Description**
M.2460-0	Key Elements for Integration of Satellite Systems into Next Generation Access Technologies
M.2514-0	Vision, Requirements and Evaluation Guidelines for Satellite Radio Interface(s)

ITU-T	**Description**
FG NET-2030	**Architectural Enhancements** (i.e., integrated NTN-TN, LEO satellites as backbone network, networking slicing, access control and security, and transmissions modes); **Edge Enhancements** (i.e., Edge caching and computing)

GSMA	**Description**
GSMA Intelligence	**Architectural Enhancements** (i.e., Direct-to-Device, NTN as part of 3GPP, satellite backhaul)

TABLE III: Summary of NTN-related European (EU) Projects

Project	Description	Satellite Computing
5G-GOA[1]	5G enabled ground segment technologies over the air demonstrator	✗
5G-IS[2]	5G system infrastructure study	✗
5G-LEO[3]	OpenAirInterface™ extension for 5G satellite links	✗
5G-STARDUST[4]	Integrated 5G-non-terrestrial networks for intelligent multi-connectivity	✓
6G NTN[5]	6G Non-Terrestrial Networks for the full integration of NTN component into 6G	✓
6G Sentinel[6]	Six-G Enablers: Flexible Networks, THz Technology and Integration, Non-Terrestrial Networks, SidElink and Localization	✗
6G-SKY[7]	6G for Connected Sky	✗
6G TakeOff[8]	Holistic 3D Communication Networks for 6G	✗
ADROIT-6G[9]	Distributed Artificial Intelligence-Driven Open & Programmable Architecture for 6G Networks	✓
SUNRISE-6G[10]	Integrating a 6G-Non-Terrestrial Networks Testbed facility into a a pan-European 6G experimentation facility	✓
ETHER[11]	sElf-evolving terrestrial/non-Terrestrial Hybrid nEtwoRks	✓
FLECON-6G[12]	Flexible Open Architecture and AI-driven Enabling Technologies for a Novel 6G Connectivity Platform	✓
METASAT[13]	Modular Model-based Design and Testing for Applications in Satellites	✓
Edge SpAIce[14]	Unleashing AI potential to foster space accessibility and novel Earth Observation services creation	✓
SOPHOS[15]	Smart onboard processing for earth observation systems	✓
TRANTOR[16]	5G+ evoluTion to mutioRbitAl multi-baNd neTwORks	✗

A. Efforts in Standardization Bodies and Research Projects

Standardization plays a crucial role in defining reliable, interoperable, and compliant technology to be adopted in future systems (e.g., beyond 5G/6G), setting the pace for technological maturity and roll out in the market. Therefore, its analysis is paramount to understand the set of features already (or expected to be) available in satellites systems. Ongoing initiatives are mostly focused on feasibility studies and use cases analysis, spectrum and radio enhancements, positioning and localization, and architectural modernization, which shall shift in the next stage towards the interworking and convergence aspects of satellite systems. These efforts are expected to provide a solid base for the seamless integration of Satellite Computing capabilities, which is only expected to be systematically addressed in even later stages. A summary of the past, present, and future working items is presented in Table II.

Until then, the research community is already engaged in these future stages in a commitment to advance the state of the art in satellite technology, both in terms of communication and computing. As such, ongoing research projects are focused on evolving beyond 5G/6G systems to support Satellite-based NTNs and assessing their capability to provide increased robustness, resilience, low-latency, and high-capacity for communication in various use cases. Most of these projects define Satellite-based NTNs as networks to complement the terrestrial counterpart and/or to provide connectivity in areas without any terrestrial infrastructure. However, since their main objective focuses on the study of Satellite Communication aspects, most of ongoing or past projects seem to either disregard the support of onboard-satellite computing capabilities or name it a secondary objective. Nevertheless, many of the identified projects are still in their initial stages with limited results publicly available. It is expected that additional efforts and insights regarding Satellite Computing would appear in their later stages, with further development being pushed towards the standardization. A summary of the surveyed projects is presented in Table III, along with the identification of those that are targeting Satellite Computing aspects. Note that, it focuses exclusively on projects based in the European Union (EU), providing a representative overview within a reference funding framework.

B. Survey Scope and Contributions

This survey provides a compelling analysis of the state of the art that addresses the extension of satellite systems with computing capabilities (i.e., Satellite Computing concept), taking a greater focus on the networking and application aspects. Firstly, it discusses the network-related aspects, along with its implications for a convergent TN-NTN in beyond 5G/6G systems, that impact the realization of Satellite Computing. Secondly, it overviews specific use cases and applications enabled by Satellite Computing. To do so, it takes a functional perspective across the software stack, from network constraints to applications opportunities, with respect to the integration of Cloud and Edge computing capabilities and mechanisms within satellite networks. A six-fold analysis is carried out, covering the following aspects: *(i)* extending computing and storage to space; *(ii)* expanding beyond 5G/6G systems; *(iii)* architectural overview; *(iv)* future applications; *(v)* industrial application perspective and patent landscape; and *(vi)* lessons learnt and open challenges for future research.

[1]https://artes.esa.int/projects/5ggoa
[2]https://artes.esa.int/projects/5gis
[3]https://artes.esa.int/projects/5gleo
[4]https://www.5g-stardust.eu/
[5]https://www.6g-ntn.eu/
[6]https://www.iis.fraunhofer.de/en/ff/kom/mobile-kom/6g-sentinel.html
[7]https://6g-sky.net/
[8]https://www.6g-takeoff.de/
[9]https://adroit6g.eu/
[10]https://sunrise6g.eu/
[11]https://www.ether-project.eu/
[12]https://flecon6g.eu/
[13]https://metasat-project.eu/
[14]https://cordis.europa.eu/project/id/101135358
[15]https://sophoshorizon.eu/
[16]https://www.trantor-he.eu/

TABLE IV: Survey Structure and Overlap With the Existing Surveys and Tutorials (Partially Covered: σ, Covered: ✓)

	[1]	[13]	[14]	[15]	[16]	[17]	[18]	[19]
Sec. II: Satellite Computing: Extending Computations and Storage to Space								
A. Applicability Considerations	σ						σ	σ
B. Impact of Satellite Characteristics			σ		σ			
C. Edge and Cloud Perspective	σ				σ		σ	✓
D. Satellite Computing Rebranding in the Literature	σ						σ	
Sec. III: A Network Perspective								
A. Satellite and Terrestrial Networks Convergence		σ			σ	✓		
B. Satellite Computing over different Satellite Topologies								
C. Satellite Computing in 5G Ecosystems						✓		
Sec. IV: A Computing Perspective								
A. Satellite Configuration	σ							
B. Computation Frameworks	σ							✓
C. Resource Allocation	σ						σ	
D. Task Offloading	σ						σ	✓
D. Satellite Simulation				✓			σ	
Sec. V: Taxonomy of Satellite Computing Applications								
A. Taxonomy Overview								
B. Bent-Pipe Applications		σ	σ					
C. Edge and Cloud Applications		σ						
Sec. VI: Open Challenges and Pathways for Future Research	σ	σ	σ	✓	σ		σ	✓
Sec. VII: Industrial Application Perspective								
A. Evolution of Space Service								
B. Patent Landscape								

Such a survey, tackling the integration of both technologies, was still missing in the panorama of satellite systems research. Existing surveys and tutorials are mostly focused on the communication aspects (e.g., spectrum, radio, and networking) and the application of Artificial Intelligence (AI) / Machine Learning (ML) approaches. In [13], the authors review standardisation activities and technologies within 3GPP (departing from Release 15), presenting distinct options for the system architecture (covering different orbits, payload types, protocol architecture, and radio interfaces). In [17], a more tutorial-oriented approach is taken when describing the options for satellite integration in 5G Networks. Satellite Computing is also heavily researched in parallel. For example, in [14], recent technical advancements within the domain of satellite systems are collected, highlighting important research directions (including onboard processing capabilities and space-based data collection & processing). Similarly, in [16] and [19], the potential integration communication aspects for satellites into future communication networks are surveyed, including their expected evolution and new application scenarios that include Edge Computing and Space-based Cloud capabilities. In [15], a comprehensive summary of network simulators for satellite-terrestrial integrated networks is presented, which also includes solutions that consider the integration of Edge computing into future satellite systems. Up to our knowledge, the most comprehensive surveys on satellite computing are presented in [1] and [18], where the vision for satellite computing is presented. The former focuses on a summary of advancements on the satellite communication networks to enable Edge computing on satellites while introducing an open research platform for satellite computing on real satellites and some of its case studies / experiments deployed on it. The latter focuses on the advancements on orbital edge computing and potential technologies to overcome the identified challenges. Table IV provides a content comparison of this survey with the aforementioned works.

Building on our review of the state of the art and existing surveys, this survey identifies a key gap in the divide between networks and applications in the context of satellite computing. To bridge this gap, the main contributions of this survey paper can be summarized as follows, which also follow the outline of the remaining document:

- Reviews the applicability considerations for Satellite Computing, the characterization of its inherent infrastructure in terms of capabilities and constraints, and the evolution pathways of the Satellite Computing over the years (Section II).
- Analyses recognized strategies to integrate satellite networks within terrestrial systems (including beyond 5G/6G systems) and their implications to support Satellite Computing capabilities (Section III).
- Overviews the main components required to build a fully-functional Satellite Computing stack (Section IV).
- Derives a taxonomy of applications based on their requirements, and identifies the key network design choices that enable a satellite system to serve them. (Section V).
- Provides a comprehensive overview of the evolution of space services, the contributions of commercial technology to specific milestones, and the patent landscape in the industrial sector (Section VI).
- Outlines still open challenges in the Satellite Computing area, and define possible pathways for future research (Section VII).

C. Survey Structure

The structure of this survey is as follows: Section II delves into the considerations for applying Satellite Computing, detailing its infrastructure's capabilities and limitations, and tracing its development over time. Section III explores strategies for integrating satellite networks with terrestrial systems (including beyond 5G/6G networks) and examines their impact

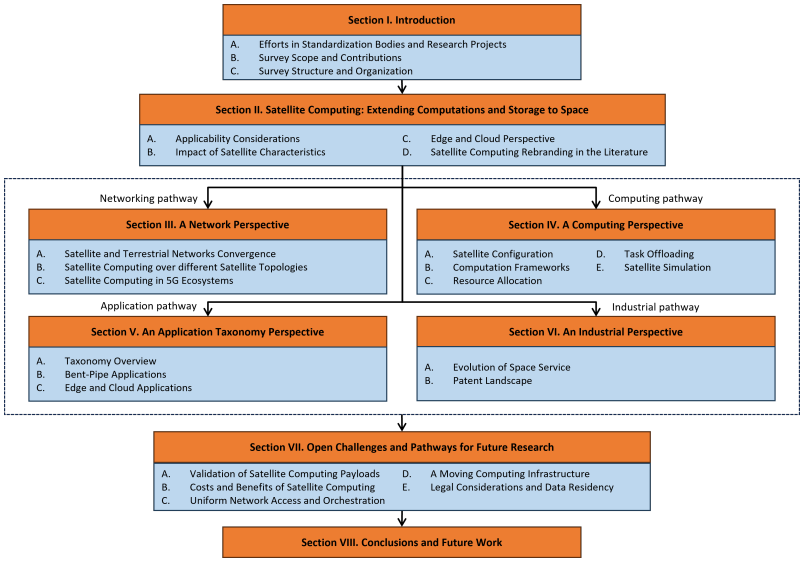

Fig. 1: Roadmap of the survey

on Satellite Computing capabilities. Section IV outlines the essential components needed to construct a complete Satellite Computing stack. Section V categorizes applications based on their requirements and highlight the critical network design decisions that enable satellite systems to support these applications. Section VI provides an extensive review of the evolution of space services, the role of commercial technology in achieving key milestones, and the patent landscape as indicator for adoption of Satellite Computing research work in commercial domain. Section VII identifies the ongoing challenges in the field of Satellite Computing and suggests potential directions for further research. Finally, Section VIII presents the conclusions drawn from this study and outlines potential future directions for research and development in Satellite Computing.

To help the readers navigate this survey, Fig. 1 outlines the organization of the survey, and Table V lists the acronyms that will be frequently used in the survey.

II. The Concept of Satellite Computing

The convergence of standardized space systems with Information and Operational Technology (IT/OT) enables novel opportunities for the use of satellite systems to ubiquitously provide computation and storage resources - the so-called *Satellite Computing*.

A. Applicability Considerations

A satellite system comprises nodes both in space (i.e., satellites) and on the ground (i.e. ground stations), thus Satellite Computing has the potential to provide computing capabilities across the entire ground-to-space continuum (as depicted in Fig. 2). Nevertheless, the core of a Satellite Computing infrastructure are the satellites equipped with onboard computing resources, especially with the advent of Direct-to-Device (D2D) capabilities where the ground stations are no longer required. By enabling Cloud and Edge Computing concepts to be seamlessly integrated across both the ground stations and satellites in different orbital layers, Satellite Computing is expected to empower organizations with the necessary infrastructure to operate assets in remote or underserved locations [20], expanding the connectivity opportunities with co-located computing resources that can enable not only rapid processing, analysis and storage of data close to the source but also scalable and centralized processing, storage and accessibility of data.

In general, Satellite Computing enables novel scenarios in many fields of industry, and two high-level classes of applications can benefit from such capabilities:

1) Standalone applications where data is either generated on the satellites themselves (e.g., in the case of Earth observation satellites producing raw imagery to be processed [2]), or provided by ground devices that have direct-to-satellite connectivity (e.g., in environmental monitoring [4] or asset management use cases [21]).
2) Applications that operate in the context of a mobile network (e.g., beyond 5G/6G), enabling e.g. edge and network orchestration use cases [22]. In this case, the satellite system needs to possess the necessary features to intercept and process traffic passing through (i.e. local breakout).

In broad terms, Satellite Computing allows for not only reducing latency and increase network efficiency but also improving availability when user devices or satellites are outside the coverage range of ground stations. In turn, ground stations also serve as complementary nodes that can be leveraged to support devices in the ground. This becomes necessary when the available bandwidth in satellite links is limited, requiring local pre-processing of data on the ground, as well as when satellites only provide limited or no computational capabilities and only serve as communication relays.

TABLE V: List of Acronyms

Acronym	Definition
AI	Artificial Intelligence
CDN	Content Delivery Network
COTS	Commercial Off-The-Shelf
CU	Central Unit
D2D	Direct-to-Device
DRL	Deep Reinforcement Learning
DtS	Direct-to-Satellite
DU	Distributed Unit
eMTC	enhanced Machine-Type Communication
GEO	Geo-Synchronous / Geostationary Orbit
gNB	gNodeB
HAP	High Altitude Platform
HARQ	Hybrid Automatic Repeat Request
IAB	Integrated Access and Backhaul
IIoT	Industrial IoT
IoRT	Internet of Remote Things
IoT	Internet of Things
IP	Internet Protocol
ISL	Inter-Satellite Link
IT	Information Technology
LEO	Low Earth Orbit
MAC	Medium Access Control
MEC	Multi-Access Edge Computing
MEO	Medium Earth Orbit
ML	Machine Learning
NB-IoT	Narrow Band-IoT
NGSO	Non-Geostationary Orbit
NG-RAN	Next Generation Radio Access Network
NPN	Non-Public Networks
NR	New Radio
NTN	Non-Terrestrial Network
OEC	Orbital Edge Computing
OT	Operational Technology
PNI-NPN	Public Network Integration with Non-Public Networks
PoP	Point of Presence
QKDs	Quantum Key Distribution
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RTT	Round-Trip Time
SCADA	Supervisory Control and Data Acquisition
SMEC	Satellite Multi-Access Edge Computing
TN	Terrestrial Network
UAV	Unmanned Aerial Vehicle
UE	User Equipment

B. Impact of Satellite Characteristics

A Satellite Computing infrastructure (as the one depicted in Fig. 2) is expected to be available on a wide range of satellite systems which might be directly interconnected or relying on ground-based gateways. However, there is no limitation in terms of the target satellites which might include satellites differing in *(i)* their communication capacity (high-throughput satellites and low-bitrate satellites); *(ii)* (multi-)orbital types (LEO, MEO, GEO); *(iii)* presence or absence of inter-satellite communication links; *(iv)* operational frequency bands; and *(v)* whether or not support Satellite Computing capabilities.

Due to the drastically different latency, mobility and payload characteristics of deployed satellites and the communication links between them, complex computational functions will likely need to be distributed across orbital layers [23]. This means that the support of computing capabilities onboard of satellites and ground stations will pave the way for hierarchical and stratified structures [24] that behave as a highly distributed computing system. Distinct computing clusters can

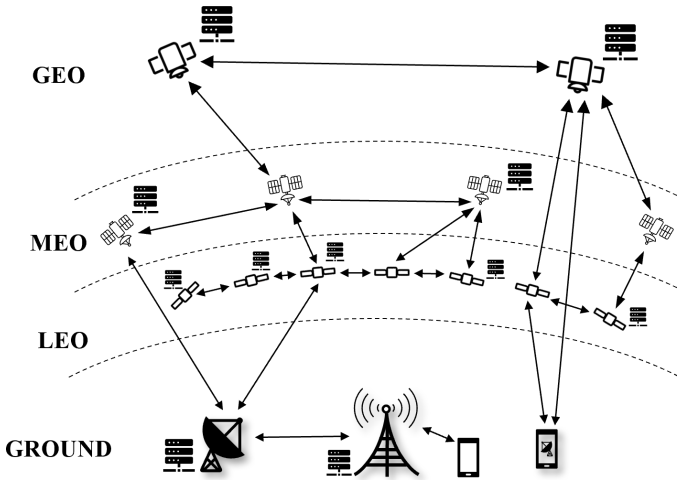

Fig. 2: Satellite Computing Infrastructure

be dynamically formed [25], while intelligently and cooperatively adapting running services according to the needs of applications. For example, controlling nodes (hosted in GEO satellites) are responsible for the deployment and scheduling of services in working nodes (hosted in LEO satellites) in the cluster [25].

A key implication of the above is that satellites are able to directly exchange information with one another not only within the same orbital layer but also across all orbital (e.g., multi-orbital constellations) layers [26]. On the one hand, satellite-to-ground and direct-to-device links primary enable communication between satellites and ground-stations or satellites and devices, respectively. While the former is already used to relay communication between satellites (same or different orbits), ISL links provide direct communication between satellites, thus enhancing coordination, distribution, and task scheduling within the satellite system as well as expediting the communication with ground stations. In addition, it is a meaningful building block to realize distributed computing scenarios within Satellite Computing environments, which lays the foundation for future use cases and research. With constellations such as Iridium and Starlink already (or planning to) making use of Radio Frequency (RF) [27] and laser [28] ISL respectively, such capabilities are expected to be a realistic assumption. In addition, ad-hoc strategies to coordinate resource sharing and allocation, either in ground or space, should be devised to steer performance and offloading for computation-intensive or storage tasks, as well as to improve energy efficiency and sustainability indicators [29]. Such heuristics may be significantly complex in the case of satellite constellations that exhibit high mobility (e.g., LEO-based constellations), where specific problems like the seamless handover of tasks may need to be addressed [30].

C. Edge and Cloud Perspective

The optimal approach for a Satellite Computing infrastructure is comparable to terrestrial Edge and Cloud infrastructures [31] [32], where each orbital layer offers distinct modes of operation, computational paradigms and availability

TABLE VI: Satellite Computing Comparison (derived and expanded from [33] [32] [34]

	LEO	MEO	GEO	Ground Stations
Paradigm	Edge-Native	Edge-Native	Cloud-Native	Cloud-Native
Architectural Model	Decentralized	Decentralized	Centralized	Centralized
Computing Model	Mostly Serverless	Mostly Serverless	Server-based or Serverless	Server-based or Serverless
Resources	Minimal to Medium	Minimal to Medium	Medium to High	High to Extreme
Operation	Mostly Stateless	Mostly Stateless	Stateless or Stateful	Stateless or Stateful
Usage	Proximity	Proximity	Scalable	Scalable
Availability	Mobile	Mobile	Fixed	Fixed
Maintainability	Low	Low	Low	High

features. Table VI presents a more complete characterization of the main features of a Satellite Computing infrastructures at its different orbital layers.

On the one hand, GEO satellites and ground stations are fixed in location, hence offering more permanent and stable connections, but more distant from the data sources, hence higher latency. Along with their sparse distribution in deeper segments of the network, GEO satellites and ground stations are considered to be mostly logically centralized. Furthermore, GEO satellites support in theory large payloads [35], while ground stations do not have payload limitations - for this reason, they can both be equipped with a considerable amount of powerful resources. Lastly, both are inherently cloud-native and server-based, making them more suitable to support stateful and scalable operations for applications with persistent data requirements.

On the other hand, Non-Geostationary Orbit (NGSO) (i.e., LEO and MEO) satellites are part of a moving constellation, thus their connections are extremely volatile. Along with their highly-distributed infrastructure closer to the network edges, LEO and MEO satellites are considered to follow a decentralized architectural model. Since, in theory, LEO and MEO satellites support smaller payloads, they are equipped with a limited amount of low-power and heterogeneous resources. Finally, LEO and MEO satellites are inherently edge-native and serverless, making them more suitable to support applications that require real-time data processing in the closest proximity to the data source.

Considering the properties above, GEO satellites and ground stations better reflect the properties of Cloud computing, while LEO and MEO satellites match those of Edge computing.

D. Satellite Computing Rebranding in the Literature

While applied Satellite Computing research is still in its early stages, the general topic of leveraging satellite communication and computation for accelerating Edge and Cloud applications has been dealt extensively, and many definitions have been created accordingly. These multiple definitions, as commonly found in the literature, are presented below in their order of appearance.

1) ***Internet of Remote Things (IoRT)****:* Satellite communication was initially identified as a feasible tool to enable connectivity to/from remote devices (e.g., sensors for environmental monitoring) which would otherwise require expensive terrestrial infrastructure to be deployed [36]. However, the possibility of offloading computations is not considered at this stage, and satellite topologies are therefore envisioned to follow a traditional bent-pipe model. Building upon this, the key enablers and challenges for the development of IoRT are surveyed in [37].

2) ***Orbital Edge Computing (OEC)****:* The idea of replacing the bent-pipe model with one where satellites are used as computational resources triggered a rebranding towards Orbital Edge Computing [38]. Still, the scope of this definition is limited to onboard computations (particularly for Earth observation) in order to reduce the reliance on downlink and uplink capabilities. Its scope is further elaborated and expanded to consider the offloading of computation (e.g., from low-power sensor hardware) to support general IoT [18]. In both cases, the discussion regarding inter-satellite distribution via ISL is secondary and mostly absent. Leveraging on the same concepts, the importance of AI-capable Edge satellite platforms started to be discussed for the evolution of IoT in a number of areas [39], including for mission-critical applications [40].

3) ***Satellite Multi-access Edge Computing (SMEC)****:* Departing from the assumption that computing capabilities were available onboard of the satellites, Satellite Multi-access Edge Computing appeared as a natural extension of the MEC concept used in the context of cellular networks [41]. Similar in principle to the OEC, SMEC is often preferred when dealing with the development of network technology, especially when discussing the importance of satellite-based Edge computing as a means to augment future beyond 5G/6G systems [42] [43] [44] [45] [46] [47].

4) ***Satellite Computing****:* The Satellite Computing concept is pushed to its furthest extent whenever considering satellites capable of supporting large-scale IoT [48] [49], Cloud [50] [51] and AI [52] infrastructures, in a distributed and seamless fashion [1]. This iteration of the Satellite Computing concept is arguably the most visionary, as it relies heavily on stable and high-bandwidth ISL, a technology that is just now reaching maturity.

The works discussing the IoRT and Satellite Computing concepts - published in 2015 and 2024 respectively - are separated by 9 years of technology development and by the meteoric rise of LEO satellite constellations. This rapid development is reflected in the terminology and increasing scope of the surveyed state of the art, where *(i)* IoRT envisions satellites as pure bent-pipe communication devices; *(ii)* OEC deems their use for specific edge computations possible; and *(iii)* SMEC and Satellite Computing consider a satellite Edge-supported Internet possible. With such rapid development, it is foreseeable that even the most visionary scenarios associated to Satellite Computing may come to fruition in the near future.

III. The Network Perspective

The satellite topology in place, its integration with ground devices, and the overall features of the satellite infrastructure are all critical aspects that define the foundations of the Satellite Computing. In the following are discussed the main network design choices associated with satellite communication systems and their impact on the realization of the Satellite Computing concepts. Due to its relevance to future beyond 5G/6G systems, this section also overviews several integration aspects with respect to today's 5G networking ecosystems.

A. Satellite and Terrestrial Networks Convergence

The wider realization of Satellite Computing is, in general, highly dependent on a tight integration and coordination between NTN and TN infrastructures. Despite the latter goal being already pursued by 5G and upcoming 6G systems [53], satellite networks and their terrestrial counterparts are still seen as two disjoint systems. Each progresses along its own path of evolution, with distinct stakeholders and operators. In particular to NTNs, each operator defines its own unique approach with respect to networking aspects, including deployment, topology management, and communication protocols.

All these aspects simultaneously play a fundamental role in both the opportunities they enable and the obstacles that must be overcome to fully realize the concept of Satellite Computing. Therefore, an interoperability layer will become increasingly relevant in the scope of Satellite Computing scenarios, facilitating seamless connectivity by enabling the communication and efficient data exchange across applications running in the computing payloads of different satellite systems. Additionally, this layer shall ensure the support of multi-orbit satellite integration, allowing a transparent harmonization of satellites in their different orbits. By bridging all these systems, the interoperability layer presents an opportunity to enhance the overall system security since it can implement unified security mechanisms. Additionally, it ensures robust and continuous coverage, availability, and coordination, on which a more resilient and effective satellite communication infrastructure that can adapt to varying operational conditions, can improve the services and application running on top of its computing infrastructure.

Up to our knowledge, satellite and terrestrial networks integration is currently relying on a thin and decoupled interoperability layer which relies on *(i)* IP-based communication systems, allowing them to communicate using standard Internet protocols; or *(ii)* IP-compatible protocols where border gateways are responsible for the protocol conversion and translation. Such interoperability layer also facilitates the communication between two distinctly operated satellite networks, which are commonly interconnected via nodes on the ground (i.e., terrestrial segment). A visual representation on possible integration models is depicted in Fig. 3, depending on network ownership and level of integration. In the first option (Option A), satellite networks and terrestrial networks are owned by different operators and, therefore, an interoperability layer that relies either on IP-based communication systems or IP-compatible protocols shall be in place. The

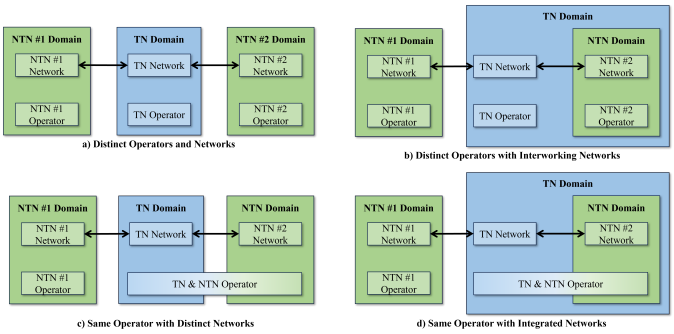

Fig. 3: TNs and NTNs Integration Models

former allows both domains to communicate using standard Internet protocols, while the latter uses border gateways that perform protocol conversion. In the second option (Option B), the terrestrial network leverages on the satellite network of a different operator, as an underlay, to provide connectivity to its devices. The third (Option C) and fourth (Option D) already set the terrestrial and the satellite networks under the same operator domain. In this case, both domains can be distinctly managed (but with a higher degree of trust) or fully converge as an interworking and integrated network. All options enable interconnection scenarios where ground stations around the world are potentially connected to distinct local terrestrial providers via e.g. autonomous systems interconnection.

A common aspect refers to the fact that the TN act as the logically centralized point for any Satellite-TN(-Satellite) communication and coordination. One of the main reasons is the fact that TNs are nowadays more mature than NTNs in terms of standardized deployment, which facilitates the instantiation of border gateways that implement interoperability and translation mechanisms. At the same time, such approach alone may not provide the necessary level of holism required to make full use of Satellite Computing, therefore a more robust and seamless interconnection, integration and/or convergence is required.

B. Satellite Computing over different Satellite Topologies

The selected topology by a given satellite system is a critical factor that defines how data traffic can be forwarded and routed within its networking segment [54]. There are four main topologies (depicted in Fig. 4) to consider [13]: *(i)* Bent-Pipe (Transparent) topology; *(ii)* Regenerative Topology; *(iii)* Inter-Satellite Link (ISL) topology; and *(iv)* Direct-to-Satellite (DtS) and Direct-to-Device (D2D). Each topology has its own unique characteristics and offers different trade-offs in terms of complexity, reliability, signal processing, and latency. These trade-offs will define the applicability, feasibility and performance to support Satellite Computing, which is also highly dependent on the target applications and their requirements.

1) ***Bent-Pipe (Transparent) Topology****:* In this topology, satellites act purely as repeaters without any control over the data they receive and/or transmit. Each satellite receives signals from a ground station, amplifies them, and retransmits them on a downlink frequency in a point-to-point or point-to-multipoint fashion towards ground stations [55]. Despite its

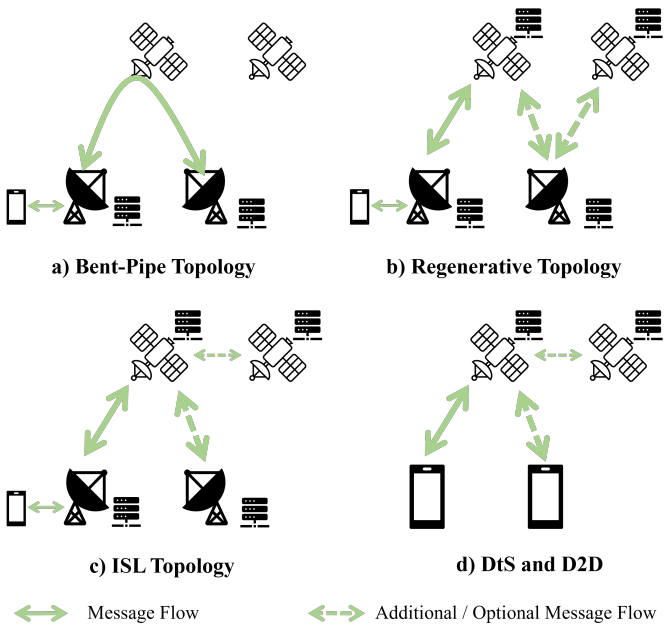

Fig. 4: Satellite Topologies Comparison for Satellite Computing

simple and reliable approach, signal processing takes place in the ground stations. Therefore, this topology lacks flexibility to support Satellite Computing capabilities onboard of the satellites. However, it can still play an active role in transporting data traffic to/from Edge and Clouds data center deployed in the ground, either in ground stations or within the terrestrial network. Since the transmission to the ground Edge/Clouds cannot be avoided, the bent-pipe topology causes additional service delays [56].

*2) **Regenerative Topology**:* In this topology, satellites already have onboard processing capabilities, terminating the protocols up to Layer 3 onboard the satellite [13]. Each satellite receives signals from a ground station, demodulates them to baseband, performs operations like routing or switching, and, finally, (re)modulates the signals to be transmitted on a downlink back to the ground. Despite making the satellites more complex and more subjected to errors, signal processing can take place directly on the satellite. Therefore, this topology not only allows for a more efficient use of the satellite capacity but also provides the required flexibility to support Satellite Computing capabilities onboard of the satellites. Data traffic can then be routed to the correspondent Satellite Edge/Cloud or, otherwise, be forwarded to a ground station as in the bent-pipe topology to be routed to a ground Edge/Cloud or its original destination. While it enables tasks to be offloaded and computed directly in the Satellite Edge/Cloud and, consequently, reducing the service latency [57], the transmission to the ground Edge/Clouds cannot be avoided if the Satellite Edge/Cloud (or virtual service) is provisioned by a different satellite. In particular cases, it might lead to even more additional delay due to the need of crossing the space segment twice.

*3) **Inter-Satellite Link Topology**:* In this topology, satellites support not only the same capabilities as in the regenerative topologies but also direct satellite-to-satellite communication, either within the same orbital layer or across different layers. Each satellite can send signals to neighbour satellites, if needed, without sending them to a ground station and back up to the space. Despite the increased complexity and the need for additional routing mechanisms, data traffic can achieve a more efficient and/or optimal path. In doing so, in case the Satellite Edge/Cloud (or virtual service) is provisioned by a different satellite (same or different orbits), a direct path can be established without any support from the ground infrastructure. Consequently, it reduces the service latency, the network overhead, and potentially be more sustainable as well as paves the way for a more efficient service orchestration and workload distribution [58].

*4) **Direct-to-Satellite and Direct-to-Device**:* In these topologies, satellites and devices can directly establish connectivity without any support of ground stations [59] [60], enabling scenarios where the communication between two devices is just mediated by a satellite node(s). Such capabilities can reduce costs and speed up the adoption of satellite services where ground stations or other terrestrial infrastructure are unavailable. Despite the benefits in terms of flexibility and coverage expansion, the lack of a ground infrastructure also reduces the opportunities for Satellite Computing deployments. In doing so, a Satellite Edge/Cloud might become the only available hop where to offload computations, but only in the scenario where a bent-pipe topology is not in place. It should also be considered that since topologies of this kind are often used to serve remote and inaccessible areas, ground devices will be battery-powered and therefore subject to tight power constraints [61].

TABLE VII: Comparative Analysis for the Placement of Satellite Computing Capabilities

	Bent-Pipe		**Regenerative**		**ISL**	
	Legacy	**D2D**	**Legacy**	**D2D**	**Legacy**	**D2D**
Satellite	Ineffective	Ineffective	Enhanced performance	Enhanced performance	Enhanced performance	Enhanced performance
Ground Station	Variable performance	Ineffective	Variable performance	Reduced Effect	Variable performance	Ineffective

Table VII provides a breakdown of placement location for satellite computing capabilities, summarizing their effectiveness according to the target satellite topologies.

C. Satellite Computing in 5G Ecosystems

As defined in 3GPP [62], NTNs are *"networks, or segment of networks, using an airborne or space-borne vehicle to embark a transmission equipment relay node or base station"*. Aligning to this vision, 6G is also expected to become a "network of networks" that connects multiple individual networks together (including mobile and NTN-based networks) to form a larger network, aggregating distinct types of resources and connecting them at different scales [63]. In simpler words, NTNs comprise the set of wireless communication systems that operate above the terrestrial surface, covering both the space segment and the air segment. In this respect, the integration of satellite networks, embodying any of the previously

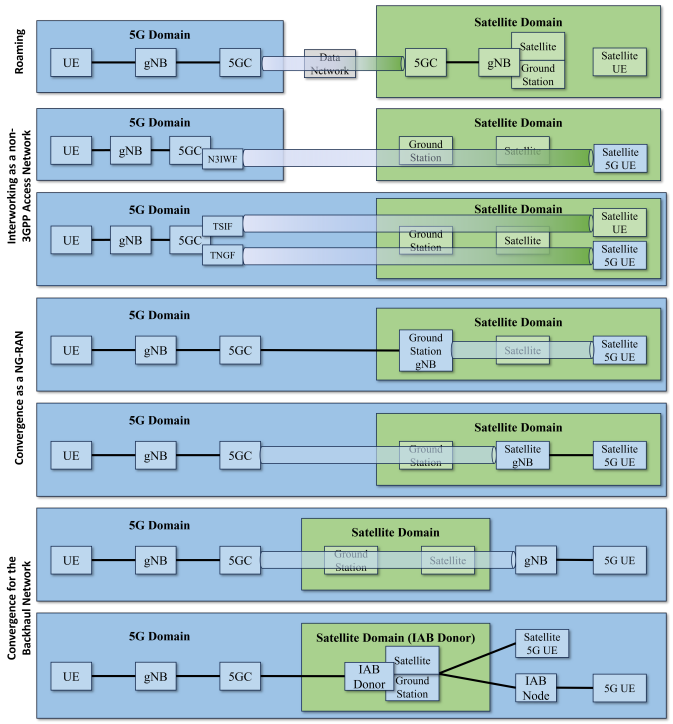

Fig. 5: Roaming, Interworking and Convergence of Satellite Networks within 5G Ecosystems

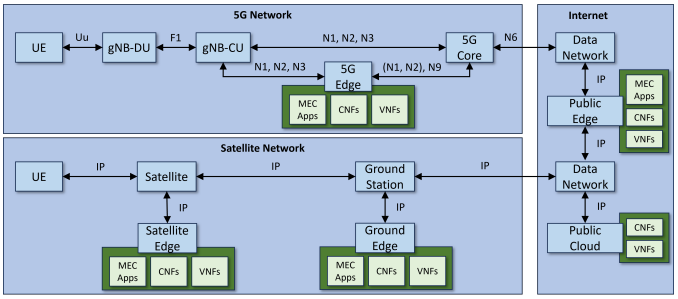

Fig. 6: Logical Overview of Edge Deployment Locations within the 5G Ecosystem

described topologies, also presents an opportunity to improve wireless technology for the next generation of mobile communications and it is currently one of the key enhancements for the upcoming 6G systems. From an architectural point of view, distinct options are available [17] [64] (as depicted in Fig. 5 and Fig. 6), each offering distinct levels of seamless integration, security, trustfulness, and performance:

1) ***Roaming****:* Roaming is a key feature in today's mobile networks, since it enables seamless connectivity between networks of distinct domains [65]. Its more predominant usage is manifested in cross-border scenarios, when a device travels outside the coverage area of its operator (i.e., home network) and must connect to available networks governed by another operator (i.e., visited network). Naturally, roaming can also be applied to interconnect 5G-enabled satellite networks with existing 5G terrestrial networks [66] [67], similarly to what happens already for the 5G Public Network Integration with Non-Public Networks (PNI-NPN) [68]. In such a deployment, the Satellite Computing resources available at the visited network can be exploited by home network devices.

2) ***Interworking as a non-3GPP Access Network****:* The interworking of satellite networks with terrestrial 5G systems can also explore already established mechanisms regarding untrusted or trusted non-3GPP access networks [69], significantly expediting the integration process and minimizing infrastructure development costs. Such approaches have already proven themselves as fundamental in the adoption of 5G NPNs for vertical domains that exploit heterogeneous access networks (e.g. WiFi) [70]. Despite providing a seamless interworking, these approaches still keep the satellite network decoupled and isolated from the 5G system, with convergence relying on gateways interconnecting both networking domains. Additional security mechanisms between the devices and non-3GPP functions are required [71], including the adaptation of access and authentication protocols for the non-3GPP access network and the establishment of secure tunnels for the control and data planes. While the integration as an untrusted non-3GPP Access Network limits the usage of the Satellite Computing resources up to the extent of a bent-pipe topology, if the integration follows its trusted counterpart and specific 5G functions are deployed onboard of the satellite resources, the usage of Satellite Computing follows the same assumption as the regenerative and ISL topologies.

3) ***Convergence as a NG-RAN****:* The satellite network can be envisioned as a NG-RAN where the base station capabilities are hosted in the satellites [72] [73] and/or ground stations [72] [74]. These approaches would offer a full convergence between the satellite networks and terrestrial 6G systems, thus requiring a conformity with radio resource management, connection and mobility management, security, and Quality of Service (QoS) procedures as defined by 3GPP. On the one hand, the convergence as a satellite NG-RAN allows the Satellite Computing to fully embody regenerative and ISL topologies. On the other hand, the convergence as a ground station NG-RAN limits the Satellite Computing capabilities to the extent of a bent-pipe topology [75]. Smaller variations of the previous approaches are also possible if a NG-RAN functional split is considered [72], where e.g. the Distributed Unit (DU) is hosted in the moving satellites, and the Central Unit (CU) is hosted in static nodes on the ground stations [76]. From the Satellite Computing perspective, such approach is the same as the ground station as NG-RAN.

4) ***Convergence for the Backhaul Network****:* Satellite networks also present interesting opportunities for the backhaul segment, with the potential of playing a pivotal role in bridging remote and underserved regions while enhancing overall robustness, resilience and scalability in a cost-effective manner. The Satellite-based backhaul network rises as an interesting opportunity to provide a backup path to offload [77] or to bridge remote networking sites over long distances, where a satellite backhaul could reduce the deployment costs whenever fiber is not available or is too cumbersome to lay [78]. Additionally, a Satellite-based Integrated Access and Backhaul (IAB) [79] [80] [81] can further enhance flexibility and scalability of the backhaul segment, not only as an appealing cost-affordable solution [82] to enable network operators to

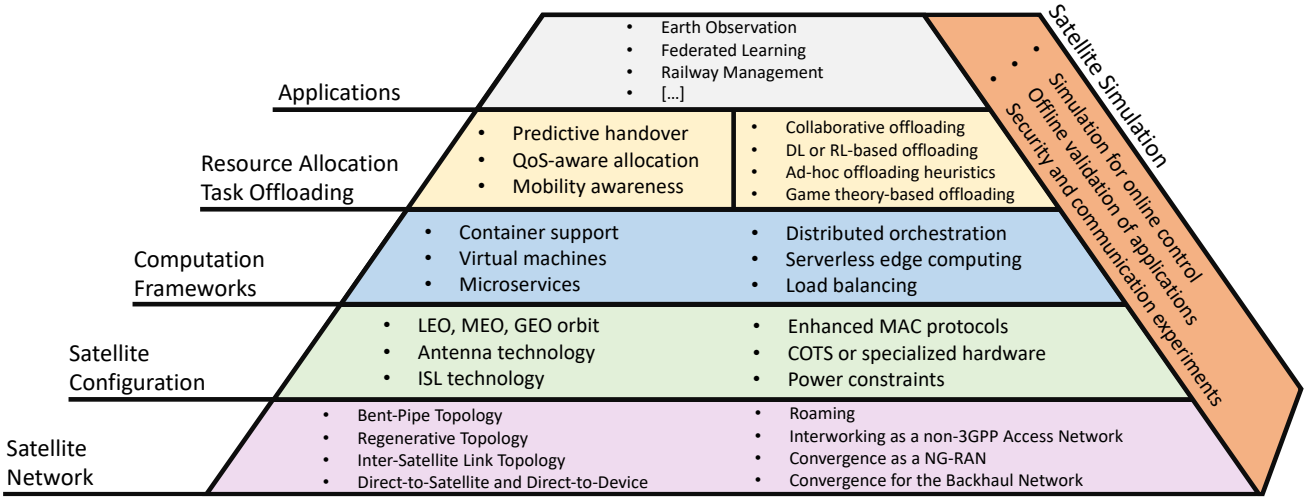

Fig. 7: The Layers of a Typical Satellite Computing Stack and a Summary of the Most Common Approaches and Variables Addressed by the State of the Art

cover wider areas [83], but also as a supplementary backhaul link to offload data traffic [84] [85]. The capability of the 5G operator to perform local breakout (or not) will define Satellite Computing capabilities, embodied in a similar way as the regenerative and ISL topologies (or those from bent-pipe topology).

IV. The Computing Perspective

Building a fully-functional Satellite Computing stack requires taking a series of design decisions ranging from the choice of satellite technology to the offloading of tasks. The main components of a Satellite Computing stack and the associated overarching choices are summarized in Fig. 7. The *Satellite Network* layer, at the base of the stack, is assumed to be designed following the considerations laid out in Section II and Section III. Therefore, this section focuses on the higher layers of the stack, exploring existing state of the art related to typical architectural and design considerations for such a system. Furthermore, an important feature of a Satellite Computing system not noted in Fig. 7 is *security*, since this survey focus primarily on functional and architectural aspects.

A. Satellite Configuration

As outlined in Section II, a key aspect behind the implementation of Satellite Computing is the choice of satellite hardware. Choosing a given constellation has a deep impact on the latency, bandwidth, and coverage of ground communication (due to differences like orbital planes, types of orbital, available services, and frequency bands), while onboard compute hardware needs to be able to cope with harsh radiation. In particular, LEO constellations are identified as the most suitable for IoRT purposes due to their latency characteristics and reduced exposure to radiation compared to more traditional MEO and GEO formations [86], introducing a set of implications in terms of constellation design and interference mitigation. Moreover, [87] [88] explores the possibility of using Commercial Off-The-Shelf (COTS) hardware for enabling Edge AI on satellites, while [89] discusses approaches for the validation of COTS hardware in a satellite setting. Closer to the software level, [59] (who employ the *Direct-to-Satellite IoT* definition) focuses on the need for novel Medium Access Control (MAC) protocols for direct satellite communication.

B. Computation Frameworks

Given a hardware platform, choosing a suitable computational framework is necessary to enable Satellite Computing applications, on which the main question is whether established Cloud and Edge technologies (e.g., microservices and container orchestration) are suitable for Satellite Computing applications. In this direction, [90] describes the Cloud-native operating system deployed on the BUPT-1 satellite, including virtualization of resources, as well as aspects regarding container support and their orchestration. However, such system is meant for control of a single satellite and not for distributed use cases. In turn, [91] proposes SatEC, a centralized microservices-based framework which enables deploying and managing Edge computing applications on satellite constellations. Similar conceptual architectures are proposed in [92] [93]. [94] proposes a LEO compute cloud orchestration system that hides the complexities introduced by satellite mobility and introduces a set of abstractions for application providers to specify the geographical region(s) where their application should be available. Other works tackle security and safety aspects, either by proposing a secure framework for edge task delegation [95]. The application of Multi-access Edge Computing (MEC) under LEO networks is also considered as a target computation framework [44] [45] [46] [47] [96], taking the diversity of user preferences, dynamic user association and computation offloading into account. Finally, *Serverless Edge Computing* paradigm is also highlighted as the one most fitting the dynamic nature of LEO constellations [34] [97] [98].

C. Resource Allocation

The next layer in the Satellite Computing stack comprises scheduling and allocation algorithms for tasks and resources, which take into account the peculiar characteristics of a Cloud-like Satellite Computing system. Note that, satellites in their different orbits or from distinct providers might possess heterogeneous resources, thus requiring proper resource allocation strategies to ensure efficient and effective task execution. For example, if a given satellite constellation supports inter-satellite links, collaborative resource allocation and sharing among distinct satellites can be optimized [99], aiming for a balance between latency, resource utilization, and energy consumption. The same rationale applies when considering multi-orbital constellations or satellite-to-ground Edge/Cloud scenarios. Therefore, existing and new solutions need to be, respectively, redesigned and devised in order to accommodate the unique constraints and challenges of satellite computing environments. Towards this direction, in [30], Kubernetes is augmented to take into account the orbital movement of LEO satellites. In doing so, it can trigger a predictive handover of deployed tasks and services to neighboring satellites and ensure a continuous coverage for ground users. Similarly, [100] and [101] propose a Quality of Service (QoS)-aware heuristic and DRL, respectively, for the placement of resources (e.g., microservices) on arbitrary satellite topologies, ensuring optimal coverage for ground users, while [102] [103] address the same problem with a deep learning-based scheme. In turn, a deep reinforcement learning task scheduling algorithm is applied within the context of Satellite MEC architectures with the goal of minimizing the average task processing time [104]. Other works consider the additional complexity of ground device mobility in *Internet of Vehicles* use cases [105] [106] [107] or of the satellite mobility itself [108] as well as the balance between latency requirements and energy consumption [109] [110] [111] [112]. Lastly, blockchain-based incentive approaches are used for implement a dynamic, safe and reliable task allocation mechanism for satellite edge computing [113].

D. Task Offloading

Task offloading allows to distribute computational tasks across satellites (within its different orbits) and ground stations, thereby reducing latency and improving real-time processing by bringing computation closer to the terminals as well as allowing terminals to offload complex tasks into more scalable and powerful resources. However, the intrinsic mobile infrastructure of non-geostationary orbit satellites (e.g., LEO and MEO) and, consequently, of its satellite computing infrastructure, along with an heterogeneous resources capacity among and across satellites in different orbital planes, places a new set of requirements over satellite computing. In the case of ground (edge) devices wishing to offload computations (e.g., AI/ML training and/or inference, data pre-processing / fusion, and data computations), choosing the target satellite needs to considered several properties (e.g., latency, available resources, connectivity window, and energy consumption). Otherwise, risking to not be advantageous. In addition, it might require to migrate computations across the moving satellites in order to maintain the overall performance of the satellite system but also running applications [99]. Therefore, specific policies must be further devised to dictate how, when and where edge computations should be executed. Many approaches have been proposed in this area of research, leveraging game theory [114] [115] [116] [46], deep learning [117] [103], (deep) reinforcement learning [118] [119] [120] [121] [122] [123], or specific heuristics [124] [125] [126] [127] [128] [129]. Nevertheless, the problem at hand is structured as an optimization process balancing the latency of a given edge task with the energy consumption of the ground device [130], as well as of the target satellite. A subset of works uses collaborative optimization schemes that can further improve the quality of offloading decisions [131] [132] [133] [134] and that consider adaptive mechanisms that take into consideration the the mobility and limited resources inherent in LEO satellites [135].

E. Satellite Simulation

The components of the Satellite Computing stack can be complemented by a satellite simulator, which replicates the mobility and connectivity conditions found in a real Satellite Computing environment. As simulation can be applied to any of the the Satellite Computing layers described so far, it can be seen as a vertical, cross-layer component in the stack. A simulation of this kind may have multiple purposes: *(i)* it allows to perform offline validation of applications before they are deployed to the Satellite Computing system; *(ii)* it can be integrated into an existing Satellite Computing orchestration system to augment its decisions, similarly to the approach pursued in [30]; *(iii)* it can be used for network and satellite technology evaluation to aid design decisions. The *COTE* simulator [136] and COSNO [137] are perfect examples of this, supporting both offline and online operational modes. Other simulators mostly focus on offline usage, such as *CELESTIAL* [138] and *HYPATIA* [139] focused on Satellite Computing Edge applications, or *Stargaze* [140] tailored for security experimentation.

V. An Application Taxonomy Perspective

Having defined the characteristics of an Satellite Computing stack, the applications of Satellite Computing (both operational and hypothetical) proposed in the state of the art are categorized according to a taxonomy.

A. Taxonomy Overview

The potential benefits of Satellite Computing have been investigated by the research community in a variety of fields [43] [39] [40]. These include, for example, *Industrial Automation*, where Satellite Computing could be used to bring edge capabilities to industrial sites not served well-enough by ground network infrastructure, or *Environmental Monitoring*, where Satellite Computing could enable edge pre-processing and aggregation of vast amounts of ground sensor data, as well as enable fusion with satellite imagery. Other areas of interest include *Disaster Response*, where Satellite Computing has the

potential to provide self-organizing communication infrastructures in the face of emergencies or *Intelligent Transportation*, where Satellite Computing could provide the necessary backbone for future vehicles and transportation networks [141] [142] [143] [20]. In some studies, the importance of quantum communication-enabled satellites for future secure applications has been underlined as well [144] [145]. Still, it should be noted that many applications still reside at a visionary stage and have not been implemented. One key exception to this is *Earth Observation*, or the use of onboard hardware to preprocess satellite-captured footage, where Satellite Computing has been leveraged for many years, though in a mostly non-distributed fashion.

In general, the applications can be categorized according to a *taxonomy* in order to simplify understanding of the Satellite Computing space as a whole. In particular, Satellite Computing applications can be placed in a bi-dimensional space, whose axes are the following:

- *Inter-Satellite Distribution*: distinguishes applications that require satellites to communicate with one another, thus achieving a distributed computation, from those that do not. The latter case is common for computations offloaded by ground edge devices, which often cannot be executed locally due to energy concerns despite being simple in nature. High distribution translates to a need for efficient and stable inter-satellite communication.
- *Downlink and Uplink Requirements*: determines an application's reliance on communication between ground devices and satellites. In practice, this is measured through the application's bandwidth (either for single ground devices, or aggregated at the satellite level) and latency requirements (e.g., for asynchronous applications vs. real-time ones). Used antenna and network technologies, as well as satellite ground coverage, are among the key factors along this axis.

In addition to the above, there is also a distinction of *Edge* and *Cloud* applications (i.e., satellites are used for actual computations) from *bent-pipe* ones (i.e., satellites are used as communication relays exclusively but no computing is performed). The proposed taxonomy is summarized in Fig. 8, which overall requirements are presented in Table VIII and Table X for *bent-pipe*, and *Edge* and *Cloud* applications, respectively. Table IX and Table XI provide insights of novel opportunities in the respective application scenarios based on introducing the new satellite computing paradigms.

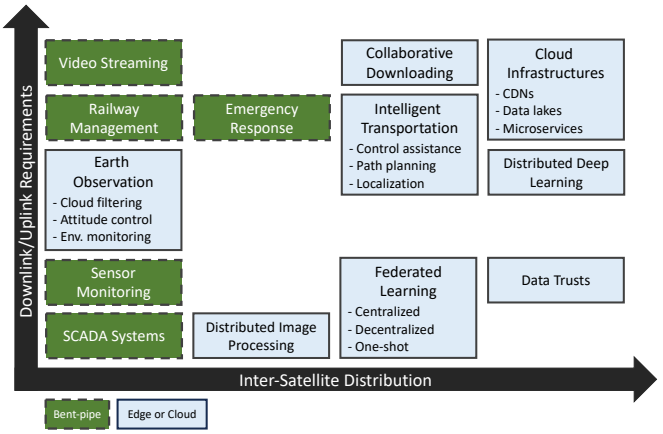

Fig. 8: A taxonomy of applications found in the literature that make use (or could benefit from) Satellite Computing. Dashed outlines are used for applications that are traditionally based on a bent-pipe communication model.

B. Bent-pipe Applications

Bent-pipe applications refer to the traditional paradigm of satellites as pure communication relays and, aside from some specific use cases, inter-satellite communication is also not required. Nonetheless, many of the surveyed applications can be augmented so as to offload computations to the satellite edge. Referring to Fig. 8, the following bent-pipe application categories were identified.

1) ***SCADA Systems****:* The use of satellites in the context of *Supervisory Control and Data Acquisition* (SCADA) applications is considered in [146]. The SCADA model encompasses a large variety of industrial applications, ranging from the management of oil and gas pipelines to the implementation of smart grid infrastructure [21]. Applications of this kind tend to have minimal bandwidth requirements, with ground devices sending or receiving few *Kbps*. Nonetheless, large fleets may still require significant satellite capacity.

2) ***Sensor Monitoring****:* Beyond the scope of SCADA applications, sensor monitoring represents another common bent-pipe satellite use case. In general, this consists of the collection of environmental sensor data from devices placed in isolated or harsh locations. For example, [4] evaluates the use of satellite-enabled IoT devices for marine monitoring, whereas [61] considers the more general problem of satellite communication for sensor monitoring. Similarly to SCADA applications, bandwidth is not a concern, as the data rate of ground devices is often constrained by the limits of battery power.

3) ***Railway Automation****:* At first glance, the railway automation use case may appear identical to SCADA systems. However, this is not the case due to the high mobility of trains and the tight latency constraints deriving from real-time operation. Several examples can be found in the literature, such as [147] where the evaluation of a satellite-augmented control system for the *East Midlands Trains* (EMT) operator in the UK is discussed, highlighting its effectiveness in areas with scarce connectivity. In this case, train video data is transmitted on top of ordinary sensor data, increasing bandwidth requirements. The *French National Railway Company* (SNCF) is also making use of satellite communication on certain routes [148]. Other studies focusing e.g. on the capacity of satellite systems to support railway critical service over Europe are also underway [149].

4) ***Emergency Response****:* In emergency response use cases, satellites are used to form a replacement network, following damage to the ground infrastructure due to disasters. For this reason, bandwidth and latency requirements tend to be demanding. Depending on the scale of the disaster, a certain amount of communication between satellites may be required

TABLE VIII: Summary of Bent-pipe Applications' Requirements

	SCADA Systems	Sensor Monitoring	Railway Automation	Emergency Response	Video Streaming
Bandwidth	Low but variable, depending on the amount of devices and type of monitored data.	Low to Medium, depending on the amount of devices and type of monitored data.	Low to Medium, depending on the amount of devices and type of monitored data.	High, for transmitting high-resolution images.	Medium to high (which can also be variable), depending on the quality of the video stream.
Packet Size	Small: monitoring data and command requests.	Small: monitoring data and command requests.	Small: monitoring data and command requests.	Large: high-quality imagery/video streams, other large meta-data.	Medium: video streams, often compressed for faster transmission.
Service Delivery	n:1 (many-to-one) where multiple devices and managed by the same entity.	n:1 (many-to-one) where multiple devices and managed by the same entity.	n:1 (many-to-one) where multiple devices and managed by the same entity.	n:1 (many-to-one) where a single server handles the data provided by several clients.	1:n (one-to-many) for live streaming or broadcast services.
Directionality	Bi-directional.	Unidirectional.	Bi-directional.	Unidirectional.	Unidirectional.
Number of Nodes / Clients	Large and fixed, depending on the amount and rate that their publish new sensing data.	Large and dynamic, depending on the amount and rate that their publish new sensing data.	High and fixed, comprising several types of devices along the rail track.	Low and fixed.	Dynamic, ranging from low for private streams up to high for public and widely distributed streams.
Networking	High availability, High reliability, Service Continuity, and Redundancy to ensure a correct operation at all times. Preferably real-time.	Delay sensitive, depending on the target domain.	High availability, High reliability, Service Continuity, and Redundancy to ensure a safe operation at all times. Preferably real-time.	High data-rates and reliable to support the large amounts of data being exchanged.	High reliability and high availability to ensure smooth and consistent experience, real-time to avoid poor QoE.

TABLE IX: Summary of Bent-pipe Applications' Novel Possibilities with Satellite Computing

Bent-Pipe Application	Enhancements enabled by Satellite Computing
SCADA Systems	Satellite Computing can potentially enable in-network user management, analyse monitoring data on the edge for unique devices (e.g., to predict when maintenance is required), and an overall bandwidth reductions by applying data pre-processing (e.g., compression of monitoring data). In addition, it can provide a more resilient system in case of disruption of the terrestrial infrastructure.
Sensor Monitoring	Satellite Computing enables in-network data pre-processing to offload tasks like data aggregation, data analytic, data filter, while being able to transparently perform down-sampling transparently and close to the source of data. It also opens new data storage possibilities for the sensing data, which might be consumed on-demand. The previous options might potentially reduce the required bandwidth in the downlink of satellite resources.
Railway Automation	Satellite Computing can be leveraged for tasks like data validation, adaptation of data models, and encryption to run as in-network functions. In addition, it can contribute to an increase of availability, reliability, service continuity, and redundancy in case of e.g. disruption of the ground communication infrastructure or in locations without terrestrial coverage. In such cases, it can keep latency low as the satellite Edge might be always one hop away from devices.
Emergency Response	Satellite Computing might contribute to more optimized deliver models by supporting a communication broker in the Space and one-hop away from all communication nodes, thus decreasing the bandwidth requirements by halving the use of the space to ground resources. Additionally, it can contribute to an increase of availability, reliability, service continuity, and redundancy in case of e.g. disruption of the ground communication infrastructure or in locations without terrestrial coverage, while keeping the latency low.
Video Streaming	Satellite Computing enables the optimization of the video for different devices, resolutions, and bandwidths. It has the potential to decrease the bandwidth requirements by leveraging on up-scaling algorithms, allowing lower resolution to be streamed by the endpoints and to run on the Satellite Edge, as well as by adaptation of the video stream to better fit to the location, devices, and the link requirements of the receiving nodes (including down-scaling). Finally it can contribute to the implementation of Space-based CDNs, as well as novel buffering, caching, packet recovering strategies to improve the QoE.

as well. As practical examples, [5] proposes an HAP-based system to compose temporary networks in the face of disasters, while [150] proposes a satellite-based backup communication system tailored for power infrastructure monitoring.

*5) **Video Streaming**:* Live video streaming is arguably one of the most demanding bent-pipe applications in terms of both bandwidth and latency requirements. In fact, streaming of YouTube videos (even at resolutions as low as 360p) over a GEO satellite link using traffic shaping might prove to be highly impractical in terms of performance [151]. The performance of real-time video delivery over the Starlink LEO constellation showed to be much more usable [152]. Alternatively, Quality of Experience (QoE)-aware streaming infrastructures leveraging modern 5G network features are also being proposed [153], showcasing satisfactory results.

C. Edge and Cloud Applications

Edge- and Cloud-based applications refer to both real and visionary applications that have been proposed in a Satellite Computing context. Unlike for bent-pipe use cases, distributed applications requiring inter-satellite communication are much more common. Once again, the categories are referred in Fig. 8.

TABLE X: Summary of Edge and Cloud Applications' Requirements

	Earth Observation	**Distributed Image Processing**	**Collaborative Downloading**	**Federated Learning**	**Intelligent Transportation**	**Data Trusts**	**Distributed Deep Learning**	**Cloud Infrastructures**
Bandwidth	High, for transmitting high-resolution images.	High (to Medium), for transmitting high-resolution (compressed)images.	High (to Medium), for transmitting high-resolution volumes of data.	High since it requires the exchange of model updates from multiple clients to a central server.	High (e.g. video streaming) to Low (e.g. sensor data) and variable, depending on the target application.	Low to High, depending on the amount type of data.	High since it requires a frequent exchange of model parameters and gradients between nodes during training.	High, as it needs to support the high volume of data transfer between the cloud and its clients.
Packet Size	Large due to the size of the data.	Large due to the size of the data.	Large due to the size of the data.	Large due to the transmission of model weights and gradients, which can be substantial for complex models.	Small to Medium, depending on the target application.	Small to Large, depending on the amount type of data.	Large due to the transmission of substantial amounts of data.	Small to Large, depending on the type of application and/or services running in the Cloud.
Service Delivery	n:1 (many-to-one) where a single server handles the data provided by several clients.	1:n (one-to-many) where one entity distributes image processing jobs across several neighbours.	1:n (one-to-many) where one entity distributes image processing jobs across several neighbours.	1:n (one-to-many) where several clients send the updates to a central server. n:1 (many-to-one) when the central server sends the updates to multiple clients.	1:n (one-to-many) on more centralized systems or n:m of fully decentralized systems.	1:n (one-to-many) on more centralized data trusts or n:m (many-to-many) of fully decentralized data trusts.	1:n where several clients send the updates to a central server. n:1 (many-to-one) when the central server sends the updates to multiple clients.	1:n (one-to-many), n:1 (many-to-one), and 1:1 (one-to-one), depending on the applications and/or service.
Directionality	Unidirectional.	Mostly unidirectional.	Mostly unidirectional.	Bi-directional.	Bi-directional.	Bi-directional.	Bi-directional.	Bi-directional.
Number of Nodes / Clients	Low and fixed.	Low and fixed.	Low and fixed.	Low to Medium, depending on the how much nodes are part of the learning process.	High and dynamic, comprising several types of devices that might appear and disappear.	Low and Fixed for the data trusts, and Medium and Variable to the clients.	Medium to Large.	Unlimited.
Networking	High data-rates and reliable to support the large amounts of data being exchanged.	High data-rates and reliable to support the large amounts of data being exchanged.	High data-rates and reliable to support the large amounts of data being exchanged.	High data-rates and reliable to support the large amounts of data being exchanged.	High availability, High reliability.	High data-rates and reliable to support the amounts of data being exchanged.	High data-rates and reliable to support the large amounts of data being exchanged.	High availability, High reliability, Service Continuity, and Redundancy to ensure a safe operation at all times.

*1) **Earth Observation**:* Capturing footage of the Earth is among the oldest uses for satellites, making this area among the most developed in Satellite Computing. Applications of this kind usually revolve around data enhancement and filtering, and therefore little inter-satellite communication is observed. Many works, for example, propose approaches for onboard image selection, in order to discard useless footage containing clouds, the ocean, or pointing at space. Many of these applications leverage modern AI methods [154] [155] [156] and some of them have been deployed to real satellites. This is the case for the random forest-based cloud detector on the EO-1 spacecraft [2] [157]. In a different direction, [158] proposes the use of Satellite Computing for onboard sensor fusion and image enhancement. Earth observation encompasses many more use cases, including deep learning-based approaches for detecting debris [159] or determining satellite attitude [160] based on image data. Finally, [161] [3] explore the use of Satellite Computing for onboard processing of useful indicators for agriculture and land monitoring.

TABLE XI: Summary of Edge and Cloud Applications' Novel Possibilities with Satellite Computing

Edge and Cloud Application	Enhancements enabled by Satellite Computing
Earth Observation	Satellite Computing allows images to be pre-processed still in the space (either on the earth observation satellite itself or any neighboring satellite with computing capabilities), thus avoiding the need to send images that are e.g. obstructed by clouds. In doing so, it contributes to a decrease on the downlink bandwidth requirements of satellite resources by allowing unviable images to be discarded still in the space.
Distributed Image Processing	This is a novel use case enabled by Satellite Computing. Refer to Section V.C.2.
Collaborative Downloading	This is a novel use case enabled by Satellite Computing. Refer to Section V.C.3.
Federated Learning	Satellite Computing might enable new update approaches whenever the central server runs in the satellite by leveraging on its nomadic characteristics. As the satellite moves around its orbit, the central server could receive and send model updates only within the geographically coverage of the satellite. By leveraging on groupcast communications and/or the intrinsic geographically load-balancing, it would be possible to reduce the bandwidth requirements. Moreover, Satellite Computing can support clients (especially those running in constraint devices) to offload part of the federated learning process to the Satellite Edges.
Intelligent Transportation	Satellite Computing enables in-network data pre-processing to offload tasks like data aggregation, data analytic, data filter, while being able to transparently perform down-sampling transparently and close to the source of data. It also opens new data storage possibilities for the sensing data, which might be consumed on-demand. The previous options might potentially reduce the required bandwidth in the downlink of satellite resources.
Data Trusts	Satellite Computing enhances data sharing within Data Trusts as distributed datalakes potentially make data available for secure sharing regardless of the consumer's geo-location. Apart from ensuring lower latency, a lightweight authentication protocol on board of datalake members also potentially provides user management, tackling privacy and security challenges often rising in data sharing of LEO satellites.
Distributed Deep Learning	Satellite Computing might enable new coordination approaches whenever the central server runs in the satellite by leveraging on its nomadic characteristics. As the satellite moves around its orbit, the central server could distribute the deep learning process only within the geographically coverage of the satellite. By leveraging this intrinsic geographically load-balancing, it would be possible to reduce the bandwidth requirements. Moreover, the satellites themselves can become possible locations to distribute the deep learning process, thus reducing the carbon footprint and electricity grid demand on the ground.
Cloud Infrastructures	Satellite Computing can contribute to an increase of availability, reliability, service continuity, and redundancy in case of e.g. disruption of the ground communication infrastructure or in locations without terrestrial coverage. In such cases, it can contribute to keep the latency low.

*2) **Distributed Image Processing**:* Distributing complex tasks among neighboring satellites can offer significant performance gains, as opposed to the insular processing typical of Earth observation applications. In order to enable this, a certain degree of inter-satellite communication is required. For example, the approach proposed in [162] uses distributed image compression in order to reduce the amount of data sent to ground stations. The basic assumption of this work is that neighbor satellites, especially in NGSO formations, collect partially-overlapping image data that can be easily stitched together. Therefore, it is advantageous to combine and compress such data at the source. While this use case refers to image data in particular, the same reasoning can be applied to a wide variety of data sources, as demonstrated for a generic MEC (i.e., terrestrial) use case [163].

*3) **Collaborative Downloading**:* Parallel to distributed image processing is the use of collaborative approaches for downlink management. The key difference between the two use cases is that, while in the former processed data may be kept at the satellite edge, in the latter the end purpose is always to optimize ground station communication, implying higher bandwidth requirements. Under this assumption, [164] proposes a deep reinforcement learning-based scheme for collaborative downloading, which takes into account the mobility of LEO satellites with respect to ground stations, allowing in turn the former to coordinate internally, route data and balance load. A similar scheme, based on iterative optimization, is proposed in [165].

*4) **Federated Learning**:* Use of modern AI technology to process satellite data or provide services is an enticing prospect and, among the possible approaches, federated learning is the most attractive. This allows to train models on the satellite edge based on local data in a loosely-coupled fashion, by leveraging inter-satellite communication. Bandwidth requirements are minimal, as only the model gradients are exchanged between satellites during training. In particular, [166] proposes an asynchronous federated learning scheme for LEO satellites, while [167] proposes to use HAPs to support training. Although both of these schemes rely on the use of centralized parameter servers, others propose the use of decentralized solutions [168] [169]. Even more extreme, [170] proposes a one-shot training scheme that requires a single communication round. Certain works tackle more specific use cases, such as Earth observation [171], or support of future 6G networks [22]

*5) **Intelligent Transportation**:* Supporting autonomous vehicles and, by extension, the transportation infrastructures of the future will require dealing with a wide range of problems. These include automatic control assistance, dynamic path planning, localization and many more - as their nature and the data they use (e.g., sensor or video data) is highly diverse, requirements for a supporting satellite infrastructure will also be diverse. [6] provides a general overview on how satellites can help implement an intelligent transportation infrastructure, in conjunction with future network technologies such as 6G. Alternatively, the use of HAPs as support infrastructure for transportation systems is also considered, focusing on the aspects of data caching and computation offloading [172].

*6) **Data Trusts**:* A concept that is gaining traction in the IoT space is that of *data trusts*, that is, blockchain-based marketplaces where data providers and consumers can securely share data of various kinds [173]. This idea is especially relevant for satellites, which can provide vast amounts of sensor and image data whose authenticity must be ensured at all times [174]. It follows that, in order to implement such a large-scale distributed system, stable and reliable ISL must be available. Various approaches to data trusts have been proposed: *(i)* a decentralized data trust system that can be used across LEO satellites and UAVs [175]; and *(ii)* a highly secure data trust for LEO satellites, leveraging homomorphic encryption [176].

*7) **Distributed Deep Learning**:* Compared to federated learning, traditional distributed deep learning has seen comparatively less development in the Satellite Computing context. This is mainly due to its higher bandwidth requirements, as well as the tighter and more centralized nature of its training computations. Efforts of this kind in the IoT space, such as the one proposed in [177], still require abundant computational resources (i.e., data center clusters) to coordinate distributed training of deep learning models in devices such as smartphones. Other applications borrow many elements from federated learning to enable a simplified form of distributed deep learning on satellites [58].

*8) **Cloud Infrastructures**:* Deploying full cloud infrastructures on satellites, supporting the global Internet, is arguably the final frontier for Satellite Computing, with extreme requirements in terms of bandwidth, latency as well as inter-satellite communication. [7] explores the overall concept of deploying *Points of Presence* (PoP) for CDNs on LEO satellites in a hierarchical fashion. Another similar study in [178] aimed more specifically at supporting 5G infrastructures. Other works tackle the more general problem of content caching, leveraging either single-layer approaches (e.g., content is cached uniformly on satellites) [179] [180] [181] [182] [183] or multi-layer ones (e.g., where ground stations and several LEO satellites layers implement a hierarchical cache) [184] [185] [186] [187] [188] [108]. [189] performs a case study about the behaviour of a distributed database deployed on a highly-mobile LEO satellite constellation. Many of the surveyed approaches in Section IV (under *Computation Frameworks*) can also be used to support applications of this kind.

VI. An Industrial Perspective

The evolution of space services has significantly transformed the industrial landscape, driving innovation and expanding the scope of commercial opportunities. In particular, the development and management of intellectual property portfolios have become crucial for companies seeking to protect their innovations and maintain competitive advantages in this rapidly evolving sector. The analysis of existing intellectual property portfolios provides a comprehensive overview of these trends, highlighting key milestones, emerging applications, and the strategic importance of intellectual property in fostering industrial growth and collaboration within the space industry, which main insights are presented in this section.

A. Evolution of Space Services

The involvement of private sector and an increased global connectivity demand are nowadays the primary drivers for advancements in satellite and space technology, shifting from its previous drivers mostly centered on scientific research and special service. This is strongly co-related with an experienced remarkable transformation of the civil satellite market over the last decades. Today, the market's ecosystem is subject to change and a continuous significant growth. Fig. 9 illustrates the key events over the last 30 years and how this also influences the transition from a proprietary, special service business to the establishment of general purpose services in the space sector.

In the 1990s, the launch of high-capacity geostationary satellites for telecommunication services and the deployment of LEO constellations provided the basis for satellite-based Internet and brings the satellite access layer for terrestrial systems closer to the terrestrial systems. This has been followed by attracting more interest from new application domains around 2000 ranging from availability of voice calls for broader user groups, remote sensing for agriculture use cases [190], disaster management and response systems [191], and the a general boom on earth observation use cases. The latter was driven by large governmental programs, providing crucial data for environmental monitoring, agriculture, and disaster management. In 2008, the "Cubesat" initiative [192] in research and education at universities started to teach students the design of satellites and spacecrafts but also make satellite and space technologies accessible to more researchers. Thus, the "Cubesat" concept as pico-satellite has been developed, where research groups started to build satellites which fitted in a cube of 10cm side length and a maximum mass of 1kg. This pico-satellite design concept allowed to launch the satellite as piggy-back to other missions. Hereby researcher and students have been enabled to build satellite with a low-entry barrier regarding design complexity, technology access, and build costs, but also were given a solution which allowed to not only build satellites but also launch research satellites at a very low-cost scale. This initiative has been followed by the fact that more and more interest in this topic has been achieved and many research groups started to look at the topic in multiple directions and for multiple completely new applications. In parallel, many new start-ups were founded in the space field due to this initiative. After 2010, the speed of evolution of the space ecosystem significantly increased, which finally led to the establishment of the term "new space". This covers the whole range from business-driven development of new missions by public agencies, technology advances like miniaturized satellites and high-speed inter-satellite communication [193], lower launch costs, as well as change in production technologies and processes from specialized, manufactory style of production of single spacecraft to an industry-alike space component and spacecraft mass production. In 2016, the development of the first real mega constellation was announced by Starlink, with its implementation starting in 2019 with the launches of the first batches of satellites. In 2020, the Starlink's mega constellation marked the first player in the

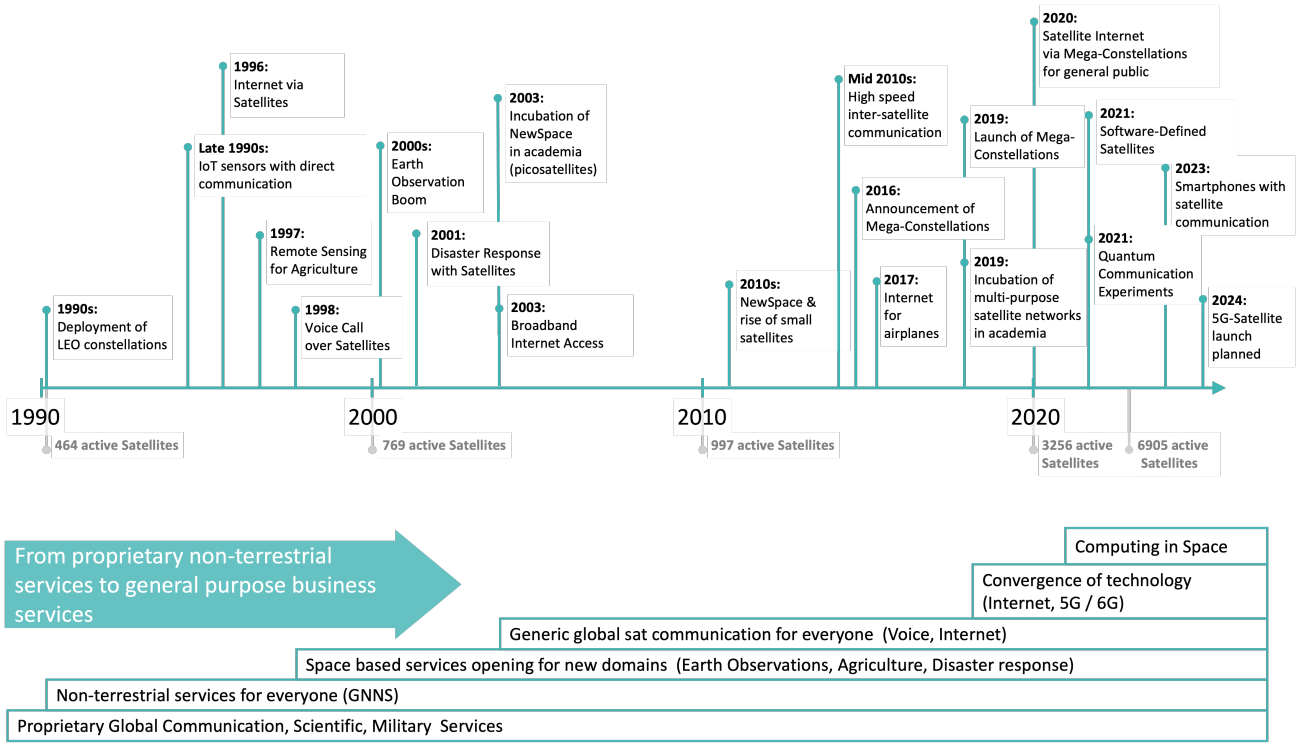

Fig. 9: The evolution of satellite technologies, services, and application milestones.

market to offer broadband satellite internet for everyone. This was one of the first services which directly made a general-purpose space service available to customers including the consumer market. Entering the 2020s, another trend evolved – the convergence of terrestrial and non-terrestrial technologies and services. Satellites started to make use of standardized and established technologies from terrestrial systems which leads to concepts like software-defined satellites, evaluation of quantum communication technologies [194], including space-based Quantum Key Distribution (QKD) concepts to secure the communication [195], the first smartphones with transceivers giving them direct access to satellite communication networks. NTNs are also getting significant traction in the standardization of mobile communication in the field of 5G, beyond 5G and 6G. All this goes together with the increased demand of multi-purpose computing resources in satellites driving the need to further research the field of satellite computing as a new form of edge computing with mobile computing nodes.

Summarizing these developments related to the space services, the whole ecosystems is currently changing and growing at a very high rate. The ecosystem is not anymore driven by public money but more and more driven by business applications, more and more new players both newly founded ones but also well-established ones from industry are entering the market. The offered services are transitioning from specialized, custom-built ones to general purpose services like high-speed internet for everyone. Even more, a trend towards the convergence of terrestrial and non-terrestrial services and be observed. Finally, the cost for space services is decreasing by orders of magnitude year over year and availability of space-based services continuously increases. For instance, the number of satellites in orbit increased by the factor of seven between 1990 and 2020 and doubled again from 2020 to 2023. As an example, SpaceX targets to provide a launch opportunity with 100 tons of payload every 6-8 hours, while scaling down the costs from 10 000 000 $ per kg to 100 $ per kg.

B. Patent Landscape

The topics of space flight and satellite operations are ongoing since the 1960s and traditionally the known big players in aerospace industry were active there. Since the last 10-20 years, non-aerospace industry players also entered the scene and changed the landscape significantly by introducing new paradigms (e.g., small satellites, satellite mega constellations) and new technology trends (e.g., IoT, IIoT, 6G). For better insight into these developments, we conducted an analysis on the count of active patents within the time frame spanning from 2015 to the first quarter of 2024, whose results are depicted in the figures and tables of this section. To do so, all companies with more than 5 active patent families related to NTN in 2024 were considered, along with the development of the number of active patent families over the last 10 years as presented in Fig. 10. In this analysis, active patent families were also clustered according to different industry sectors, namely aerospace, finance, government, industry, patent holders, research, and telecommunication. Aerospace and telecommunications represented the more traditional players, being active in this domain since decades. Industry contains all other industry sectors (e.g., automotive, IT) and patent holders are companies having invested in owning relevant patents and earning revenues from licensing. Note that, the numbers of 2024 in Fig. 10 are already over the 2023 numbers, despite

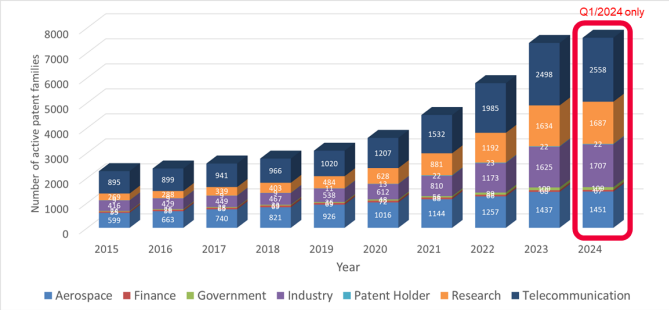

Fig. 10: Development of active intellectual property portfolios for NTN and 6G since 2015.

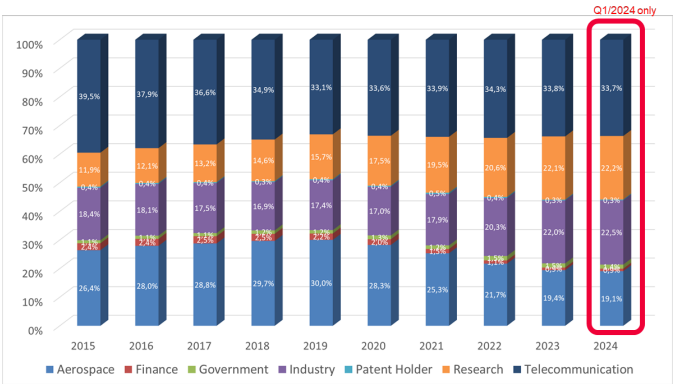

Fig. 11: Development of sectors' shares of patent families as share of total active portfolios since 2015.

TABLE XII: Number of active patent families 2015, 2013, and 2024 (*1st quarter) and their growth rate.

	2015	**2023**	**2024***	**Growth Rate [2015-2024]**
Aerospace	599	1437	1451	242%
Finance	55	68	67	122%
Government	24	109	109	454%
Industry	416	1625	1707	410%
Patent Holder	9	22	22	244%
Research	269	1634	1687	627%
Telecommunication	895	2498	2558	286%
Total	**2267**	**7393**	**7601**	**335%**

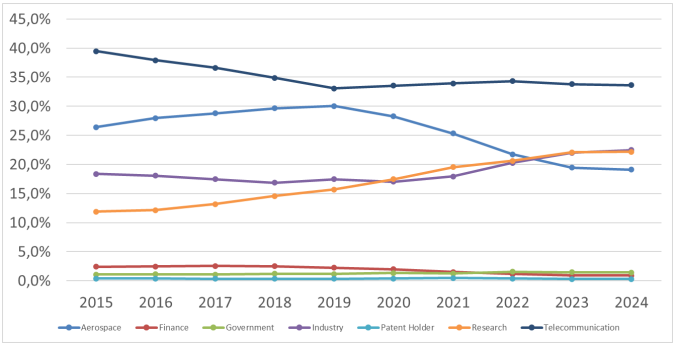

Fig. 12: Comparison of sectors' shares of patent families as share of total active portfolios since 2015.

only account for the first quarter of 2024. Therefore, a further significant increase can be expected in 2024 as well.

Since 2015, the number of active patent families increases to 335% in 2024. A slight increase is seen for the sectors aerospace with an increase to 242% and telecommunications with an increase to 286% compared to 2015 (see Table XII). Industry and research showed a very strong increase, respectively increasing 410% and 627% when compared to 2015.

The development of each sectors' share as part of the total active portfolio is shown in Fig. 11 and Fig. 12. Between 2015 and 2024, traditional sectors show a significant decrease in their share, aerospace dropped to 72.2% and telecommunication decreased to 85.2% compared to its 2015 share. The industry sector increased to 122.4% and research to 187%. Having a closer look into the numbers, it is revealed that the share of the telecommunication sector decreased from 2015 to 2019, following a rather steady sideward motion since 2019. The share of the aerospace sector showed small growth between 2015 and 2019 but then started to decrease below the 2015 value as of today. More interesting is the development of industry, starting the growth of its share in 2020.

Comparing now both the timelines - the one with the comparison of sectors' shares of patent families as share of total active portfolios since 2015 (see Fig. 12) with the evolution of satellite technologies, services, and application milestones (see Fig. 9), major milestones in 2019 and 2020, respectively the availability of mega constellations and the availability of satellite based Internet for everybody, have potentially triggering the increase of the industry interest.

A further analysis of the industry sector is given in Fig. 13 and Fig. 14 by segmenting the industry sector in automotive, consumer electronics, defense, energy, industry service providers, IT, manufacturing, multi-sector, technology suppliers, and others. In doing so, it is possible to verify how the total numbers of active patents increased for IT, consumer electronics, and manufacturing starting in 2020.

A further analysis of the development of the shares of numbers of active patent families of different industrial domains within the industry sector since 2015 is presented in Fig. 15, showing that the share of the IT domains have slightly shrunken, while consumer electronics and manufacturing significantly increased since 2020.

VII. Lessons Learnt, Open Challenges, and Pathways for Future Research

The deployment of complex AI pipelines on satellites [2] and the successful use of laser ISL [28] suggest that technology is approaching the required level of readiness to support most Satellite Computing applications. At the same time, the overview presented in the previous sections highlights a series of software-related challenges that still need to be addressed. In this section, we outline them and discuss potential directions for future research.

TABLE XIII: Comparison of sectors' shares of patent families as share of total active portfolios 2015 and 2024 (*1st quarter).

	2015	2024*	Change to [%]
Aerospace	26.4%	19.1%	72.2%
Finance	2.4%	0.9%	36.3%
Government	1.1%	1.4%	135.5%
Industry	18.4%	22.5%	122.4%
Patent Holder	0.4%	0.4%	72.9%
Research	11.9%	22.2%	187.0%
Telecommunication	39.5%	33.7%	85.2%

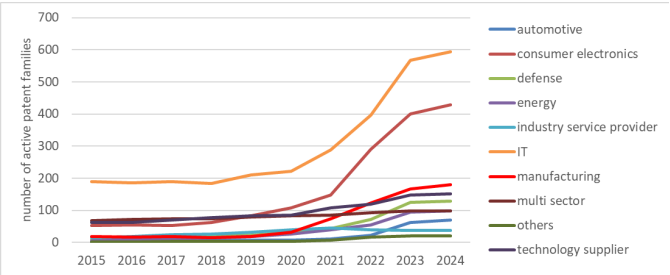

Fig. 13: Details of the development of number of active patent families inside the industry sector since 2015.

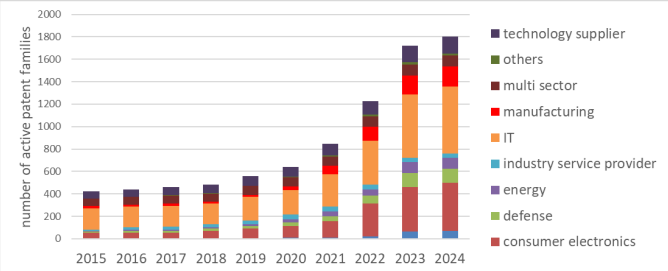

Fig. 14: Numbers of active patent families inside the industry sector since 2015.

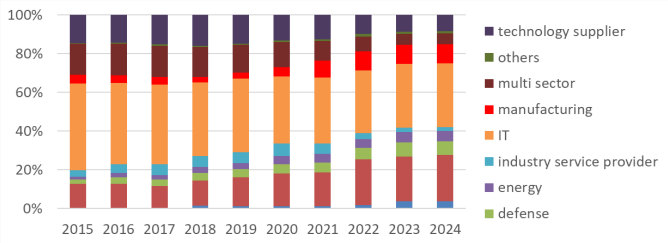

Fig. 15: Development of the shares of numbers of active patent families of different industrial domains within the industry sector since 2015.

A. Validation of Satellite Computing Payloads

With the exception of some Earth observation applications which have been battle-hardened by years of production use [2], most of the Satellite Computing use cases reviewed in Section V are still at a theoretical stage and have not been validated for use in a real satellite deployment. Devising effective validation strategies, representative of a real space environment, is therefore paramount for bridging this gap. These should consider not only the typical characteristics of a Satellite Computing deployment (e.g., satellite mobility, limited bandwidth and inter-satellite communication), but also other effects deriving from, for example, increased susceptibility to hardware faults due to radiation [89].

Challenge: Unlike terrestrial systems, Satellite Computing must operate reliably in unique and harsh conditions of the space environment while facing complex maintenance operations (if possible at all). Therefore, it is paramount to not only run testing campaigns validate satellite computing payloads and applications, but also create satellites systems that are flexible and capable of mutate and adapt to any foreseen and/or unforeseen situation.

Pathways for Future Research: *(i)* implementing software-defined and modular payloads in order to offer flexibility and enable their dynamic reconfiguration in order to adapt to changing requirements or maintenance operations; *(ii)* integrating onboard AI to not only support autonomous data analysis and decision-making but also to allow; *(iii)* investigating energy harvesting and management mechanisms to optimize the energy utilization and ensure a sustained operation; and *(iv)* providing a solid foundation for studies via e.g. simulations that could be expanded to offer a more comprehensive view of a typical Satellite Computing environment.

B. Costs and Benefits of Satellite Computing

There is little doubt that all of the Satellite Computing architectural blocks and applications (discussed in Sections IV and V respectively) could be deployed to a real environment with an adequate level of investment. However, a question that often remains unanswered is whether this *makes sense* or not from a costs and benefits perspective. In fact, Satellite Computing infrastructures will be in almost all cases more expensive, complex and harder to maintain than their ground counterparts. In specific cases, this investment is justified by the fact that Satellite Computing enables use cases that are otherwise simply impossible to realize (e.g., sensor monitoring in remote areas [4]). However, high-level quantitative analyses are needed in order to steer research into the areas where Satellite Computing could be most beneficial.

Challenge: Determining whether Satellite Computing infrastructures are economically justified compared to ground-based alternatives. This involves assessing the costs, complexity, and maintenance challenges associated with satellite computing as well as identifying its unique benefits that can be leveraged in specific use cases.

Pathways for Future Research: *(i)* conducting comparative studies between satellite and ground-based computing to identify specific use cases where Satellite Computing can offer unique and/or significant advantages; and *(ii)* reducing the costs associated with Satellite Computing by advancements in key enablers and economy of scale.

C. Uniform Network Access and Orchestration

As demonstrated in Section III, the integration of TN and NTN infrastructures can be achieved in a wide variety of ways. Although it is foreseeable that the underlying network's organization will be transparent to Satellite Computing applications, these will still be impacted by the Quality of Service (e.g., dictating which applications can or cannot be run on the NTN infrastructure) as well as by the functionality (e.g., with satellite nodes providing simple backhaul or full edge features) and domain separation of the network. Moreover, satellites can differ in terms of their computing and storage capabilities, which can significantly impact the types of applications they can support. As the integration of NTN infrastructures is a critical topic in standardization bodies (as outlined in Table II), we expect the mist surrounding the practical usage modes of Satellite Computing to clear out gradually in the coming years.

Challenge: The diversity in terms of computing, storage, and network capabilities among the Satellite Computing landscape creates a complex environment where resource allocation, management, orchestration, and coordination mechanisms are challenging to be executed uniformly. In addition, its inherently dynamic and decentralized nature is expected to limit the adoption of today's Edge/Cloud management and orchestration mechanisms.

Pathways for Future Research: *(i)* developing completely decentralized management and orchestration mechanisms to allow a direct coordination between neighboring satellites; *(ii)* implementing load-balancing and offloading strategies to ensure an efficient use of Satellite Computing resources while minimizing overloading and congestion situation; and *(iii)* defining maintain awareness of current standardization trends, especially if working in the areas of Satellite Computing orchestration.

D. A Moving Computing Infrastructure

As described in Section II, LEO and MEO satellites are constantly in motion, meaning an inherently moving Satellite Computing infrastructure. Therefore, in both these orbital layers, the dynamic nature of a moving infrastructure creates a complex environment with significant challenges, including continuous handovers and intermittent connectivity, variable latency, or even non-optimal resource allocation. These points are likely to disrupt seamless communication, leading to a highly failure-prone environment [196] and therefore impacting the QoE of applications with clear influence on e.g. latency and responsiveness. Overcoming these challenges are essential to fully unlock the potential of Satellite Computing at the LEO and MEO orbital layers, which shall be addressed together from the infrastructure and architectural point of view to optimally allocate resources, offload tasks, and migrate virtual components as well as from the adaptation of the application and devices to cope with higher levels of dynamism and, eventually, loss of connectivity during the handovers.

Challenge: The constantly changing positions of satellites creates a highly dynamic communication and computing topology which potentially lead to disruptions in the data transmissions and/or increased latency. If the former can be the result of variability in the communication links, which handover is not guaranteed to be seamless, the latter might be related to the fact that application components in the Satellite Computing are in constant movement. Overall, the impact on applications shall be mitigate, otherwise risking making Satellite Computing impractical, especially for applications that require real-time data processing, continuous connectivity, or deterministic behavior.

Pathways for Future Research: *(i)* investigate robust inter-satellite mesh networks that can dynamically adapt to topology changes and recover from failures while reducing their reliance on ground entities; *(ii)* using predictive mechanisms to preemptively mitigate potential disruptions and/or congestion in the communication links; and *(iii)* developing new routing algorithms that can dynamically adjust the routing paths based on the satellite locations and know orbits.

E. Legal Considerations and Data Residency

It is known that current legal frameworks lag behind the deployment of novel satellite infrastructures (e.g. when it comes to defining their responsibilities and boundaries in space [197]). This issue is expected to be greatly amplified under Satellite Computing, raising a number of questions. For example, to which nation's legal framework should a Satellite Computing application deployed on a LEO satellite comply? What kind of privacy guarantees should it supply, and where does ownership of data fall? And what about applications distributed on multiple satellites, potentially embracing multiple legal domains at the same time? Addressing these questions is paramount for achieving the adequate level of trust into Satellite Computing, compared to terrestrial Edge and Cloud deployments. A number of approaches could be considered for addressing issues of this kind, such as using sea law as a reference for molding future space legislation [198].

Challenge: Determining which legal framework an application deployed on the Satellite Computing of a LEO satellite should adhere to is complex, especially in scenarios where the applications are distributed across multiple legal domains. Whenever data needs to be processed within satellites that operate across international boundaries, data residency regulations (e.g., the General Data Protection Regulation in Europe) might enforce data to remain within the required jurisdiction. While regulatory and legal measures may address these issues in the future, interim solutions will need to be developed.

Pathways for Future Research: *(i)* developing strategies to ensure data remains within the designated geographic boundaries, otherwise protecting it to ensure it complies with existing data residency requirements; *(ii)* leveraging on techniques that allow to compute on encrypted data without deciphering it (e.g., homomorphic encryption), thus minimizing exposing the raw data handled within Satellite Computing scenarios; and *(iii)* investigating access control and routing mechanisms that can accommodate data residency requirements whenever it needs to be sent back to the ground.

VIII. Conclusions and Future Work

This paper presented a survey on the state of Satellite Computing, or the use of satellite hardware to run general-

purpose computational tasks and complement ground infrastructures. With novel satellite technology (e.g., LEO mega-constellations or laser ISL) being developed and deployed at a rapid pace, Satellite Computing has the potential to revolutionize the Cloud and Edge worlds, allowing to serve the most remote areas of Earth and enable, in turn, world-scale, holistic applications. However, while satellite technology is approaching the required readiness level, many challenges still lay on the road to Satellite Computing: these range from the definition of network standards dictating the integration of NTN infrastructures into TN ones, as well as of legal frameworks drawing the boundaries of satellite operation, all of the way to the validation of proposed Satellite Computing applications in realistic scenarios and the associated costs and benefits evaluation.

All the identified technological drivers enabled new industrial services and solutions and triggered an increasing involvement of different industry sectors, such as IT, consumer electronics, and manufacturing, in competition to the traditional aerospace and telecommunication industry. With mega constellations appearing in 2020, NTNs evolved from a small set of proprietary solutions to a broader used technology in industrial applications. A variety of vertical domains started to adopt NTNs to meet their communication requirements, including agriculture (by enabling real-time monitoring and management of crops even in remote locations); transportation (by providing global coverage and connectivity); environmental monitoring (by collecting real-time data from remote sensors); and global asset tracking (by improving logistics and supply chain management). With Satellite Computing these use cases are expected to be enhanced in several ways: *(i)* reduced latency; *(ii)* improved data security; *(iii)* real-time capabilities; *(iv)* enhanced scalability, reliability, and efficiency.

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REFERENCES

[1] S. Wang and Q. Li, "Satellite Computing: Vision and Challenges," *IEEE Internet of Things Journal*, 2023.

[2] K. L. Wagstaff, A. Altinok, S. A. Chien, U. Rebbapragada, S. R. Schaffer, D. R. Thompson, and D. Q. Tran, "Cloud Filtering and Novelty Detection using Onboard Machine Learning for the EO-1 Spacecraft," in *Proc. IJCAI Workshop AI in the Oceans and Space*, 2017.

[3] A. Agarwal, S. Gupta, S. Kumar, and D. Singh, "A Concept of Satellite-Based IoT for Downscaling the MODIS Data to Extract Land Surface Temperature," in *2018 9th International Symposium on Signal, Image, Video and Communications (ISIVC)*. IEEE, 2018, pp. 67–70.

[4] A. Fort, M. Mugnaini, G. Peruzzi, and A. Pozzebon, "Reliability Analysis of an IoT Satellite Facility for Remote Monitoring and Asset Tracking within Marine Environments," in *2022 IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea)*. IEEE, 2022, pp. 138–142.

[5] S. Aranti, M. Sanctis, S. Spinella, M. Monti, E. Cianca, A. Molinaro, A. Iera, and M. Ruggieri, "Hybrid System HAP-WiFi for Incident Area Networks," *Proc. of ICST Personal Satellite Services*, pp. 436–450, 2010.

[6] X. Deng, L. Wang, J. Gui, P. Jiang, X. Chen, F. Zeng, and S. Wan, "A Review of 6G Autonomous Intelligent Transportation Systems: Mechanisms, Applications and Challenges," *Journal of Systems Architecture*, p. 102929, 2023.

[7] T. Pfandzelter and D. Bermbach, "Edge (of the Earth) Replication: Optimizing Content Delivery in Large LEO Satellite Communication Networks," in *2021 IEEE/ACM 21st International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*. IEEE, 2021, pp. 565–575.

[8] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from Space: An Overview of 3GPP Non-Terrestrial Networks," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 147–153, 2021.

[9] G. Geraci, D. López-Pérez, M. Benzaghta, and S. Chatzinotas, "Integrating Terrestrial and Non-Terrestrial Networks: 3D Opportunities and Challenges," *IEEE Communications Magazine*, 2022.

[10] H. K. Dureppagari, C. Saha, H. S. Dhillon, and R. M. Buehrer, "NTN-based 6G Localization: Vision, Role of LEOs, and Open Problems," *arXiv preprint arXiv:2305.12259*, 2023.

[11] S. Euler, X. Fu, S. Hellsten, C. Kefeder, O. Liberg, E. Medeiros, E. Nordell, D. Singh, P. Synnergren, E. Trojer, and I. Xirouchakis, "Using 3GPP technology for Satellite Communication," *Ericsson Technology Review*, vol. 2023, no. 6, pp. 2–12, 2023.

[12] T. Darwish, G. K. Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, "LEO Satellites in 5G and Beyond Networks: A Review from a Standardization Perspective," *IEEE Access*, vol. 10, pp. 35 040–35 060, 2022.

[13] A. Guidotti, S. Cioni, G. Colavolpe, M. Conti, T. Foggi, A. Mengali, G. Montorsi, A. Piemontese, and A. Vanelli-Coralli, "Architectures, Standardisation, and Procedures for 5G Satellite Communications: A survey," *Computer Networks*, vol. 183, p. 107588, 2020.

[14] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff *et al.*, "Satellite communications in the new space era: A survey and future challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 70–109, 2020.

[15] W. Jiang, Y. Zhan, X. Xiao, and G. Sha, "Network Simulators for Satellite-Terrestrial Integrated Networks: A Survey," *IEEE Access*, 2023.

[16] H. Al-Hraishawi, H. Chougrani, S. Kisseleff, E. Lagunas, and S. Chatzinotas, "A Survey on Nongeostationary Satellite Systems: The Communication Perspective," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 1, pp. 101–132, 2023.

[17] M. Luglio, M. Quadrini, C. Roseti, and F. Zampognaro, "Modes and Models for Satellite Integration in 5G Networks," *IEEE Communications Magazine*, vol. 61, no. 4, pp. 50–56, 2023.

[18] C. Wu, Y. Li, M. Xu, C. Guo, Z. Yin, W. Gao, and C. Xi, "A Comprehensive Survey on Orbital Edge Computing: Systems, Applications, and Algorithms," *arXiv preprint arXiv:2306.00275*, 2023.

[19] X.-T. Li, S. Xu, Z.-P. Zhao, Z.-Y. Li, D.-A. Li, and J.-M. Zhao, "A Survey on Computing Offloading in Satellite-Terrestrial Integrated Edge Computing Networks," in *2023 15th International Conference on Communication Software and Networks (ICCSN)*, 2023, pp. 172–182.

[20] M. Sauer, H.-P. Huth, and F. Zeiger, "Space Based Hybrid Edge Cloud Architectures," in *72nd International Astronautical Congress*. International Astronautical Federation (IAF), 2021.

[21] K. Sohraby, D. Minoli, B. Occhiogrosso, and W. Wang, "A Review of Wireless and Satellite-Based M2M/IoT Services in Support of Smart Grids," *Mobile Networks and Applications*, vol. 23, pp. 881–895, 2018.

[22] M. Zhao, C. Chen, L. Liu, D. Lan, and S. Wan, "Orbital Collaborative Learning in 6G Space-Air-Ground Integrated Networks," *Neurocomputing*, vol. 497, pp. 94–109, 2022.

[23] Y. Lin, W. Feng, Y. Wang, Y. Chen, Y. Zhu, X. Zhang, and N. Ge, "Satellite-MEC Integration for 6G Internet of Things: Minimal Structures, Advances, and Prospects," *arXiv preprint arXiv:2308.14992*, 2023.

[24] P. Wang, J. Zhang, X. Zhang, Z. Yan, B. G. Evans, and W. Wang, "Convergence of Satellite and Terrestrial Networks: A Comprehensive Survey," *IEEE access*, vol. 8, pp. 5550–5588, 2019.

[25] H. Han, H. Wang, and S. Cao, "Space Edge Cloud Enabling Service Migration for On-Orbit Service," in *2020 12th International Conference on Communication Software and Networks (ICCSN)*, 2020, pp. 233–239.

[26] G. Wang, F. Yang, J. Song, and Z. Han, "Free Space Optical Communication for Inter-Satellite Link: Architecture, Potentials and Trends," *arXiv preprint arXiv:2310.17505*, 2023.

[27] C. Gomez, S. M. Darroudi, H. Naranjo, and J. Paradells, "On the Energy Performance of Iridium Satellite IoT Technology," *Sensors*, vol. 21, no. 21, 2021.

[28] A. U. Chaudhry and H. Yanikomeroglu, "Laser Intersatellite Links in a Starlink Constellation: A Classification and Analysis," *IEEE Vehicular Technology Magazine*, vol. 16, no. 2, pp. 48–56, 2021.

[29] X. Zhu and C. Jiang, "Integrated Satellite-Terrestrial Networks toward 6G: Architectures, Applications, and Challenges," *IEEE Internet of Things Journal*, vol. 9, no. 1, pp. 437–461, 2021.

[30] V. Bhosale, K. Bhardwaj, and A. Gavrilovska, "Toward Loosely Coupled Orchestration for the LEO Satellite Edge," in *3rd USENIX Workshop on Hot Topics in Edge Computing (HotEdge 20)*, 2020.

[31] H. Fang, Y. Jia, Y. Wang, Y. Zhao, Y. Gao, and X. Yang, "Matching Game Based Task Offloading and Resource Allocation Algorithm for Satellite Edge Computing Networks," in *2022 International Symposium on Networks, Computers and Communications (ISNCC)*. IEEE, 2022, pp. 1–5.

[32] S. Cao, Y. Zhao, J. Wei, S. Yang, H. Han, X. Sun, and L. Yan, "Space-based Cloud-Fog Computing Architecture and Its Applications," in *2019 IEEE World Congress on Services (SERVICES)*, vol. 2642. IEEE, 2019, pp. 166–171.

[33] J. Han, H. Wang, S. Wu, J. Wei, and L. Yan, "Task Scheduling of High Dynamic Edge Cluster in Satellite Edge Computing," in *2020 IEEE World Congress on Services (SERVICES)*. IEEE, 2020, pp. 287–293.

[34] T. Pfandzelter, J. Hasenburg, and D. Bermbach, "Towards a Computing Platform for the LEO Edge," in *Proceedings of the 4th International Workshop on Edge Systems, Analytics and Networking*, 2021, pp. 43–48.

[35] M. Höyhtyä, S. Boumard, A. Yastrebova, P. Järvensivu, M. Kiviranta, and A. Anttonen, "Sustainable Satellite Communications in the 6G Era: A European View for Multilayer Systems and Space Safety," *IEEE Access*, vol. 10, pp. 99 973–100 005, 2022.

[36] M. De Sanctis, E. Cianca, G. Araniti, I. Bisio, and R. Prasad, "Satellite Communications Supporting Internet of Remote Things," *IEEE Internet of Things Journal*, vol. 3, no. 1, pp. 113–123, 2015.

[37] M. Centenaro, C. E. Costa, F. Granelli, C. Sacchi, and L. Vangelista, "A Survey on Technologies, Standards and Open Challenges in Satellite IoT," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 3, pp. 1693–1720, 2021.

[38] B. Denby and B. Lucia, "Orbital Edge Computing: Machine Inference in Space," *IEEE Computer Architecture Letters*, vol. 18, no. 1, pp. 59–62, 2019.

[39] E. T. Michailidis, S. M. Potirakis, and A. G. Kanatas, "AI-inspired non-terrestrial networks for IIoT: Review on enabling technologies and applications," *IoT*, vol. 1, no. 1, p. 3, 2020.

[40] S. K. Routray, R. Tengshe, A. Javali, S. Sarkar, L. Sharma, and A. D. Ghosh, "Satellite Based IoT for Mission Critical Applications," in *2019 International Conference on Data Science and Communication (IconDSC)*. IEEE, 2019, pp. 1–6.

[41] R. Xie, Q. Tang, Q. Wang, X. Liu, F. R. Yu, and T. Huang, "Satellite-Terrestrial Integrated Edge Computing Networks: Architecture, Challenges, and Open Issues," *Ieee Network*, vol. 34, no. 3, pp. 224–231, 2020.

[42] E. Calvanese Strinati, S. Barbarossa, T. Choi, A. Pietrabissa, A. Giuseppi, E. De Santis, J. Vidal, Z. Becvar, T. Haustein, N. Cassiau, F. Costanzo, J. Kim, and I. Kim, "6G in the Sky: On-demand Intelligence at the Edge of 3D Networks (Invited Paper)," *ETRI Journal*, vol. 42, no. 5, pp. 643–657, 2020.

[43] Y. Lin, W. Feng, T. Zhou, Y. Wang, Y. Chen, N. Ge, and C.-X. Wang, "Integrating Satellites and Mobile Edge Computing for 6G Wide-Area Edge Intelligence: Minimal Structures and Systematic Thinking," *IEEE Network*, vol. 37, no. 2, pp. 14–21, 2023.

[44] J. Yang, J. He, Z. Yin, D. Han, N. Cheng, and R. Sun, "Mobile Edge Caching in LEO Satellite Network: A Graph Convolution Network-Based Approach," in *2023 IEEE 23rd International Conference on Communication Technology (ICCT)*. IEEE, 2023, pp. 1129–1134.

[45] J. Zhang, C. Hartmann, P. Sossalla, G. Nguyen, and F. H. Fitzek, "HORA: Joint Handover and Resource Allocation on 3D Networks for Industrial IoT," in *European Wireless 2023; 28th European Wireless Conference*. VDE, 2023, pp. 44–48.

[46] L. Liu, W. Mao, W. Li, J. Duan, G. Liu, and B. Guo, "Edge computing offloading strategy for space-air-ground integrated network based on game theory," *Computer Networks*, vol. 243, p. 110331, 2024.

[47] H. Zhang, H. Zhao, R. Liu, X. Gao, and S. Xu, "Dynamic User Association and Computation Offloading in Satellite Edge Computing Networks via Deep Reinforcement Learning," *IEEE Transactions on Green Communications and Networking*, 2024.

[48] J. Kua, S. W. Loke, C. Arora, N. Fernando, and C. Ranaweera, "Internet of Things in Space: A Review of Opportunities and Challenges from Satellite-Aided Computing to Digitally-Enhanced Space Living," *Sensors*, vol. 21, no. 23, p. 8117, 2021.

[49] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, "Satellite Communications in the New Space Era: A Survey and Future Challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 70–109, 2021.

[50] D. Bhattacherjee, S. Kassing, M. Licciardello, and A. Singla, "In-Orbit Computing: An Outlandish Thought Experiment?" in *Proceedings of the 19th ACM Workshop on Hot Topics in Networks*, 2020, pp. 197–204.

[51] D. Bermbach, A. Chandra, C. Krintz, A. Gokhale, A. Slominski, L. Thamsen, E. Cavalcante, T. Guo, I. Brandic, and R. Wolski, "On the Future of Cloud Engineering," in *2021 IEEE International conference on cloud engineering (IC2E)*. IEEE, 2021, pp. 264–275.

[52] V. Kothari, E. Liberis, and N. D. Lane, "The Final Frontier: Deep Learning in Space," in *Proceedings of the 21st international workshop on mobile computing systems and applications*, 2020, pp. 45–49.

[53] A. Guidotti, A. Vanelli-Coralli, V. Schena, N. Chuberre, M. El Jaafari, J. Puttonen, and S. Cioni, "The Path to 5G-Advanced and 6G Non-Terrestrial Network Systems," in *2022 11th Advanced Satellite Multimedia Systems Conference and the 17th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, 2022, pp. 1–8.

[54] M. M. Azari, S. Solanki, S. Chatzinotas, O. Kodheli, H. Sallouha, A. Colpaert, J. F. M. Montoya, S. Pollin, A. Haqiqatnejad, A. Mostaani *et al.*, "Evolution of Non-Terrestrial Networks from 5G to 6G: A Survey," *IEEE communications surveys & tutorials*, 2022.

[55] "A Practical Introductory Guide on Using Satellite Technology for Communications," Intelsat, Tech. Rep., 10 2020.

[56] T. Kim, J. Kwak, and J. P. Choi, "Satellite Edge Computing Architecture and Network Slice Scheduling for IoT Support," *IEEE Internet of Things Journal*, vol. 9, no. 16, pp. 14 938–14 951, 2022.

[57] C. Suzhi, W. Junyong, H. Hao, Z. Yi, Y. Shuling, Y. Lei, W. Shaojun, and G. Yongsheng, "Space Edge Cloud Enabling Network Slicing for 5G Satellite Network," in *2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC)*, 2019, pp. 787–792.

[58] J. Wei, J. Han, and S. Cao, "Satellite IoT Edge Intelligent Computing: A Research on Architecture," *Electronics*, vol. 8, no. 11, p. 1247, 2019.

[59] J. A. Fraire, S. Céspedes, and N. Accettura, "Direct-To-Satellite IoT - A Survey of the State of the Art and Future Research Perspectives," in *International Conference on Ad-Hoc Networks and Wireless*. Springer, 2019, pp. 241–258.

[60] K. L. Jones and A. L. Allison, "The Great Convergence and the Future of Satellite-Enabled Direct-to-Device," 9 2023.

[61] C. A. Hofmann and A. Knopp, "Direct Access to GEO Satellites: An Internet of Remote Things Technology," in *2019 IEEE 2nd 5G World Forum (5GWF)*. IEEE, 2019, pp. 578–583.

[62] 3GPP, "Study on New Radio (NR) to support non-terrestrial networks," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.811, 10 2020, version 15.4.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3234

[63] M. A. Uusitalo, P. Rugeland, M. R. Boldi, E. C. Strinati, P. Demestichas, M. Ericson, G. P. Fettweis, M. C. Filippou, A. Gati, M.-H. Hamon, M. Hoffmann, M. Latva-Aho, A. Pärssinen, B. Richerzhagen, H. Schotten, T. Svensson, G. Wikström, H. Wymeersch, V. Ziegler, and Y. Zou, "6G Vision, Value, Use Cases and Technologies From European 6G Flagship Project Hexa-X," *IEEE Access*, vol. 9, pp. 160 004–160 020, 2021.

[64] C. Guimarães, J. Quevedo, F. Zeiger, and M. Sauer, "Bridging Terrestrial and Satellite Networks: Exploring the Possibilities for 6G TN-NTN Convergence," in *IAF Space Communications and Navigation Symposium*. Milan, Italy: International Astronautical Federation (IAF), October 2024, pp. 536–546. [Online]. Available: https://doi.org/10.52202/078363-0055

[65] R. Keller, D. Castellanos, A. Sander, A. Robison, and A. Abtin, "Roaming in the 5G System: The 5GS Roaming Architecture," *Ericsson Technology Review*, vol. 2021, no. 6, pp. 2–11, 2021.

[66] H. Wang, W. Qi, X. Xia, C. Mei, Y. Xing, and Y. Liu, "Research on Roaming Architecture in Future Integrated Satellite-Terrestrial Network," in *2023 International Wireless Communications and Mobile Computing (IWCMC)*. IEEE, 2023, pp. 1292–1296.

[67] Y. Tao, H. Du, J. Xu, L. Su, and B. Cui, "On-Demand Anonymous Access and Roaming Authentication Protocols for 6G Satellite–Ground Integrated Networks," *Sensors*, vol. 23, no. 11, p. 5075, 2023.

[68] M. Corici, P. Chakraborty, T. Magedanz, A. S. Gomes, L. Cordeiro, and K. Mahmood, "5G Non-Public-Networks (NPN) Roaming Architecture," in *2021 12th International Conference on Network of the Future (NoF)*. IEEE, 2021, pp. 1–5.

[69] M. Luglio, M. Quadrini, C. Roseti, D. Verde, and F. Zampognaro, "Performance Evaluation of Untrusted non-3GPP Access to a 5G Core Network via Satellite," in *2022 International Symposium on Networks, Computers and Communications (ISNCC)*, 2022, pp. 1–6.

[70] J. Prados-Garzon, P. Ameigeiras, J. Ordonez-Lucena, P. Muñoz, O. Adamuz-Hinojosa, and D. Camps-Mur, "5G Non-Public Networks: Standardization, Architectures and Challenges," *IEEE Access*, vol. 9, pp. 153 893–153 908, 2021.

[71] C. Roseti, "Integration of a non-3GPP Satellite Interface in a 5G Multiple Access Configuration," in *2021 4th International Symposium on Advanced Electrical and Communication Technologies (ISAECT)*. IEEE, 2021, pp. 01–06.

[72] A. Sattarzadeh, Y. Liu, A. Mohamed, R. Song, P. Xiao, Z. Song, H. Zhang, R. Tafazolli, and C. Niu, "Satellite-based Non-Terrestrial Networks in 5G: Insights and Challenges," *IEEE Access*, vol. 10, pp. 11 274–11 283, 2021.

[73] B. T. Jou, O. Vidal, J. Cahill, F. Arnal, J.-M. Houssin, M. Boutin, and D. K. Chau, "Architecture Options for Satellite Integration into 5G Networks," in *2018 European Conference on Networks and Communications (EuCNC)*, 2018, pp. 398–9.

[74] V. Tikhvinskiy and V. Koval, "Prospects of 5G Satellite Networks Development," in *Moving Broadband Mobile Communications Forward*, A. Haidine, Ed. Rijeka: IntechOpen, 2020, ch. 5.

[75] A. Gaber, M. A. ElBahaay, A. Maher Mohamed, M. M. Zaki, A. Samir Abdo, and N. AbdelBaki, "5G and Satellite Network Convergence: Survey for Opportunities, Challenges and Enabler Technologies," in *2020 2nd Novel Intelligent and Leading Emerging Sciences Conference (NILES)*, 2020, pp. 366–373.

[76] M. Rihan, T. Due, M. Vakilifard, D. Wubben, and A. Dekorsy, "RAN Functional Split Options for Integrated Terrestrial and Non-Terrestrial 6G Networks," *arXiv preprint arXiv:2310.17317*, 2023.

[77] X. Artiga, J. Nunez-Martinez, A. Perez-Neira, G. J. L. Vela, J. M. F. Garcia, and G. Ziaragkas, "Terrestrial-Satellite Integration in Dynamic 5G Backhaul networks," in *2016 8th Advanced Satellite Multimedia Systems Conference and the 14th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, 2016, pp. 1–6.

[78] Y. Turk and E. Zeydan, "Satellite Backhauling for Next Generation Cellular Networks: Challenges and Opportunities," *IEEE Communications Magazine*, vol. 57, no. 12, pp. 52–57, 2019.

[79] Y. Zhang, M. A. Kishk, and M.-S. Alouini, "A Survey on Integrated Access and Backhaul Networks," *Frontiers in Communications and Networks*, vol. 2, p. 647284, 2021.

[80] M. Quadrini and C. Roseti, "Architectures for Non-Terrestrial RAN: Integrated Satellite Access and Backhaul," in *2023 International Symposium on Networks, Computers and Communications (ISNCC)*, 2023, pp. 1–6.

[81] Z. Abdullah, S. Kisseleff, E. Lagunas, V. N. Ha, F. Zeppenfeldt, and S. Chatzinotas, "Integrated Access and Backhaul via Satellites," in *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2023, pp. 1–6.

[82] B. Tezergil and E. Onur, "Wireless Backhaul in 5G and Beyond: Issues, Challenges and Opportunities," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 4, pp. 2579–2632, 2022.

[83] X. Artiga, A. Perez-Neira, J. Baranda, E. Lagunas, S. Chatzinotas, R. Zetik, P. Gorski, K. Ntougias, D. Perez, and G. Ziaragkas, "Shared Access Satellite-Terrestrial Reconfigurable Backhaul Network Enabled by Smart Antennas at mmWave Band," *IEEE Network*, vol. 32, no. 5, pp. 46–53, 2018.

[84] B. Di, H. Zhang, L. Song, Y. Li, and G. Y. Li, "Data Offloading in Ultra-Dense LEO-Based Integrated Terrestrial-Satellite Networks," in *2018 IEEE Global Communications Conference (GLOBECOM)*, 2018, pp. 1–6.

[85] R. Deng, B. Di, S. Chen, S. Sun, and L. Song, "Ultra-Dense LEO Satellite Offloading for Terrestrial Networks: How Much to Pay the Satellite Operator?" *IEEE Transactions on Wireless Communications*, vol. 19, no. 10, pp. 6240–6254, 2020.

[86] Z. Qu, G. Zhang, H. Cao, and J. Xie, "LEO Satellite Constellation for Internet of Things," *IEEE access*, vol. 5, pp. 18 391–18 401, 2017.

[87] G. Furano, G. Meoni, A. Dunne, D. Moloney, V. Ferlet-Cavrois, A. Tavoularis, J. Byrne, L. Buckley, M. Psarakis, K.-O. Voss *et al.*, "Towards the Use of Artificial Intelligence on the Edge in Space Systems: Challenges and Opportunities," *IEEE Aerospace and Electronic Systems Magazine*, vol. 35, no. 12, pp. 44–56, 2020.

[88] R. Ronen and B. Ben-Moshe, "SATLLA2.0: An Open Platform for Picosatellites," *IEEE Aerospace and Electronic Systems Magazine*, pp. 1–10, 2023.

[89] J. Budroweit and H. Patscheider, "Risk Assessment for the Use of COTS Devices in Space Systems under Consideration of Radiation Effects," *Electronics*, vol. 10, no. 9, p. 1008, 2021.

[90] C. Wang, Y. Zhang, Q. Li, A. Zhou, and S. Wang, "Satellite Computing: A Case Study of Cloud-Native Satellites," in *2023 IEEE International Conference on Edge Computing and Communications (EDGE)*. IEEE, 2023, pp. 262–270.

[91] L. Yan, S. Cao, Y. Gong, H. Han, J. Wei, Y. Zhao, and S. Yang, "SatEC: A 5G Satellite Edge Computing Framework Based on Microservice Architecture," *Sensors*, vol. 19, no. 4, 2019.

[92] C. Li, Y. Zhang, R. Xie, X. Hao, and T. Huang, "Integrating Edge Computing into Low Earth Orbit Satellite Networks: Architecture and Prototype," *Ieee Access*, vol. 9, pp. 39 126–39 137, 2021.

[93] Y. Huang, X. Zhang, and Z. Xu, "SatEdge: Platform of Edge Cloud at Satellite and Scheduling Mechanism for Microservice Modules," *IEEE Access*, 2023.

[94] V. Bhosale, A. Gavrilovska, and K. Bhardwaj, "Krios: Scheduling Abstractions and Mechanisms for Enabling a LEO Compute Cloud," in *Proceedings of the 2024 ACM Symposium on Cloud Computing*, 2024, pp. 322–340.

[95] Q. Kong, X. Qu, S. Zhang, F. Yin, R. Lu, and B. Chen, "A Secure Satellite-Edge Computing Framework for Collaborative Line Outage Identification in Smart Grid," *IEEE Transactions on Services Computing*, pp. 1–14, 2023.

[96] L. Zhong, Y. Li, M.-F. Ge, M. Feng, and S. Mao, "Joint Task Offloading and Resource Allocation for LEO Satellite-Based Mobile Edge Computing Systems With Heterogeneous Task Demands," *IEEE Transactions on Vehicular Technology*, 2025.

[97] T. Pfandzelter and D. Bermbach, "Komet: A Serverless Platform for Low-Earth Orbit Edge Services," in *Proceedings of the 2024 ACM Symposium on Cloud Computing*, 2024, pp. 866–882.

[98] T. Pusztai, C. Marcelino, and S. Nastic, "HyperDrive: Scheduling Serverless Functions in the Edge-Cloud-Space 3D Continuum," in *2024 IEEE/ACM Symposium on Edge Computing (SEC)*. IEEE, 2024, pp. 265–278.

[99] P. Peng, T. Xu, X. Chen, C. C. Zarakovitis, and C. Wu, "Blocked Job Offloading Based Computing Resources Sharing in LEO Satellite Networks," *IEEE Internet of Things Journal*, 2024.

[100] T. Pfandzelter and D. Bermbach, "QoS-Aware Resource Placement for LEO Satellite Edge Computing," in *2022 IEEE 6th International Conference on Fog and Edge Computing (ICFEC)*. IEEE, 2022, pp. 66–72.

[101] Q. Tang, R. Xie, Z. Fang, T. Huang, T. Chen, R. Zhang, and F. R. Yu, "Joint service deployment and task scheduling for satellite edge computing: A two-timescale hierarchical approach," *IEEE Journal on Selected Areas in Communications*, 2024.

[102] C. Qiu, H. Yao, F. R. Yu, F. Xu, and C. Zhao, "Deep Q-Learning Aided Networking, Caching, and Computing Resources Allocation in Software-Defined Satellite-Terrestrial Networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 6, pp. 5871–5883, 2019.

[103] M. Li, M. Li, K. Wang, F. R. Yu, Z. Wang, and P. Si, "Task Offloading and Resource Management for IIoT with Satellite-Terrestrial Integrated Computing Power Network Based on D3QN," *IEEE Internet of Things Journal*, 2025.

[104] S. Pang, J. Zheng, M. Wang, S. Qiao, X. He, and C. Gao, "Minimize Average Tasks Processing Time in Satellite Mobile Edge Computing Systems via a Deep Reinforcement Learning Method," *Journal of Cloud Computing*, vol. 12, no. 1, pp. 1–29, 2023.

[105] K. Lin, C. Li, P. Pace, and G. Fortino, "Multi-Level Cluster-based Satellite-Terrestrial Integrated Communication in Internet of Vehicles," *Computer Communications*, vol. 149, pp. 44–50, 2020.

[106] G. Cui, Y. Long, L. Xu, and W. Wang, "Joint Offloading and Resource Allocation for Satellite Assisted Vehicle-to-Vehicle Communication," *IEEE Systems Journal*, vol. 15, no. 3, pp. 3958–3969, 2020.

[107] C. Li, B. Shang, J. Feng, and S. Chen, "LEO Satellite-Assisted Vehicular Edge Computing," in *2023 3rd International Conference on Intelligent Communications and Computing (ICC)*. IEEE, 2023, pp. 157–162.

[108] J. Zhou, Q. Yang, L. Zhao, H. Dai, and F. Xiao, "Mobility-Aware Computation Offloading in Satellite Edge Computing Networks," *IEEE Transactions on Mobile Computing*, 2024.

[109] R. Zhang and B. Zhao, "Task Offloading and Resource Allocation for Cloud-Edge Collaboration in Low Earth Orbit Satellite Networks," in *2023 IEEE 23rd International Conference on Communication Technology (ICCT)*. IEEE, 2023, pp. 764–769.

[110] Q. Wang, X. Chen, and Q. Qi, "Energy-Efficient Design of Satellite-Terrestrial Computing in 6G Wireless Networks," *IEEE Transactions on Communications*, 2023.

[111] S. Xi, B. Shang, H. Zhang, J. Ma, and P. Fan, "Energy Optimization in Multi-Satellite-Enabled Edge Computing Systems," *IEEE Internet of Things Journal*, 2024.

[112] L. Cheng, G. Feng, Y. Sun, S. Qin, F. Wang, and T. Q. Quek, "Energy-constrained Satellite Edge Computing for Satellite-Terrestrial Integrated Networks," *IEEE Transactions on Vehicular Technology*, 2024.

[113] Z. Zhang, B. Guo, and C. Li, "For mega-constellations: Edge computing and safety management based on blockchain technology," *China Communications*, vol. 21, no. 2, pp. 59–73, 2024.

[114] Y. Wang, J. Yang, X. Guo, and Z. Qu, "A Game-Theoretic Approach to Computation Offloading in Satellite Edge Computing," *IEEE Access*, vol. 8, pp. 12 510–12 520, 2019.

[115] M. Tong, X. Wang, S. Li, and L. Peng, "Joint Offloading Decision and Resource Allocation in Mobile Edge Computing-Enabled Satellite-Terrestrial Network," *Symmetry*, vol. 14, no. 3, p. 564, 2022.

[116] Y. Gao, Z. Ji, K. Zhao, T. de Cola, and W. Li, "Game-Based Computation Offloading and Power Allocation for LEO Constellation Networks in Distributed and Dynamic Environment," *IEEE Internet of Things Journal*, 2023.

[117] Z. Ji, S. Wu, and C. Jiang, "Cooperative Multi-Agent Deep Reinforcement Learning for Computation Offloading in Digital Twin Satellite Edge Networks," *IEEE Journal on Selected Areas in Communications*, 2023.

[118] S. Zhang, A. Liu, C. Han, X. Liang, X. Xu, and G. Wang, "Multi-agent Reinforcement Learning-Based Orbital Edge Offloading in SAGIN Supporting Internet of Remote Things," *IEEE Internet of Things Journal*, 2023.

[119] J. Zou, Z. Yuan, P. Xin, Z. Xiao, J. Sun, S. Zhuang, Z. Guo, J. Fu, and Y. Liu, "Privacy-Friendly Task Offloading for Smart Grid in 6G Satellite–Terrestrial Edge Computing Networks," *Electronics*, vol. 12, no. 16, p. 3484, 2023.

[120] H. Wu, X. Yang, and Z. Bu, "Task Offloading With Service Migration for Satellite Edge Computing: A Deep Reinforcement Learning Approach," *IEEE Access*, vol. 12, pp. 25 844–25 856, 2024.

[121] X. Yang, H. Fang, Y. Gao, X. Wang, K. Wang, and Z. Liu, "Computation Offloading and Resource Allocation Based on P-DQN in LEO Satellite Edge Networks," *Sensors*, vol. 23, no. 24, p. 9885, 2023.

[122] L. Wang, J. Li, M. Dai, and H. Zhang, "Energy Efficient Multi-Task Offloading in Satellite-Assisted Vehicular Edge Computing Networks: An Improved Soft-Actor-Critic Approach," *IEEE Transactions on Vehicular Technology*, 2024.

[123] T. Lyu, Y. Xu, F. Liu, H. Xu, and Z. Han, "Task Offloading and Resource Allocation for Satellite-Terrestrial Integrated Networks," *IEEE Internet of Things Journal*, 2024.

[124] M. M. Gost, I. Leyva-Mayorga, A. Pérez-Neira, M. Á. Vázquez, B. Soret, and M. Moretti, "Edge Computing and Communication for Energy-Efficient Earth Surveillance with LEO Satellites," in *2022 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2022, pp. 556–561.

[125] Y. Zhang, C. Chen, L. Liu, D. Lan, H. Jiang, and S. Wan, "Aerial Edge Computing on Orbit: A Task Offloading and Allocation Scheme," *IEEE Transactions on Network Science and Engineering*, vol. 10, no. 1, pp. 275–285, 2022.

[126] Q. Tang, Z. Fei, B. Li, and Z. Han, "Computation Offloading in LEO Satellite Networks with Hybrid Cloud and Edge Computing," *IEEE Internet of Things Journal*, vol. 8, no. 11, pp. 9164–9176, 2021.

[127] J. Zhang, X. Zhang, P. Wang, L. Liu, and Y. Wang, "Double-Edge Intelligent Integrated Satellite Terrestrial Networks," *China Communications*, vol. 17, no. 9, pp. 128–146, 2020.

[128] Z. Zhang, W. Zhang, and F.-H. Tseng, "Satellite Mobile Edge Computing: Improving QoS of High-Speed Satellite-Terrestrial Networks Using Edge Computing Techniques," *IEEE network*, vol. 33, no. 1, pp. 70–76, 2019.

[129] Y. Wang, J. Zhang, X. Zhang, P. Wang, and L. Liu, "A Computation Offloading Strategy in Satellite Terrestrial Networks with Double Edge Computing," in *2018 IEEE international conference on communication systems (ICCS)*. IEEE, 2018, pp. 450–455.

[130] R. Zhang, Y. Feng, Y. Yang, and X. Li, "Task Offloading with Data-Dependent Constraints in Satellite Edge Computing Networks: A Multi-Objective Approach," *Aerospace*, vol. 10, no. 9, p. 804, 2023.

[131] P. Cassará, A. Gotta, M. Marchese, and F. Patrone, "Orbital Edge Offloading on Mega-LEO Satellite Constellations for Equal Access to Computing," *IEEE Communications Magazine*, vol. 60, no. 4, pp. 32–36, 2022.

[132] T. Leng, X. Li, D. Hu, G. Cui, and W. Wang, "Collaborative Computing and Resource Allocation for LEO Satellite-Assisted Internet of Things," *Wireless Communications and Mobile Computing*, vol. 2021, pp. 1–12, 2021.

[133] Z. Liu, Y. Jiang, and J. Rong, "Resource Allocation Strategy for Satellite Edge Computing Based on Task Dependency," *Applied Sciences*, vol. 13, no. 18, 2023.

[134] M. Liao, X. Li, and W. Luo, "Computing Offloading Based on Path Planning in Satellite Terrestrial Integrated Network," in *2024 5th International Symposium on Computer Engineering and Intelligent Communications (ISCEIC)*. IEEE, 2024, pp. 521–526.

[135] J. Zhou, Y. Zhao, L. Zhao, H. Cai, and F. Xiao, "Adaptive Task Offloading with Spatiotemporal Load Awareness in Satellite Edge Computing," *IEEE Transactions on Network Science and Engineering*, 2024.

[136] B. Denby and B. Lucia, "Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System," in *Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems*, 2020, pp. 939–954.

[137] Y. Breiting, E. Boriskova, C. Guimarães, A. Netti, M. Sauer, H.-P. Huth, and F. Zeiger, "A Non-Terrestrial Edge Infrastructure Testbed for Early Validation of Industrial Applications," in *2024 IEEE 29th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD) (CAMAD 2024)*, Athens, Greece, Oct. 2024.

[138] T. Pfandzelter and D. Bermbach, "Celestial: Virtual Software System Testbeds for the LEO Edge," in *Proceedings of the 23rd ACM/IFIP International Middleware Conference*, 2022, pp. 69–81.

[139] S. Kassing, D. Bhattacherjee, A. B. Águas, J. E. Saethre, and A. Singla, "Exploring the Internet from Space with Hypatia," in *Proceedings of the ACM Internet Measurement conference*, 2020, pp. 214–229.

[140] P. T. J. Kon, D. Barradas, and A. Chen, "Stargaze: A LEO Constellation Emulator for Security Experimentation," in *Proceedings of the 4th Workshop on CPS & IoT Security and Privacy*, 2022, pp. 47–53.

[141] L. Da Xu, W. He, and S. Li, "Internet of Things in Industries: A Survey," *IEEE Transactions on industrial informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.

[142] C. Kaufmann, H.-P. Huth, F. Zeiger, and M. Schmidt, "Performance Evaluation of Internet over Geostationary Satellite for Industrial Applications," in *70th International Astronautical Congress*. International Astronautical Federation (IAF), 2019.

[143] H.-P. Huth, F. Arslan, M. Sauer, and F. Zeiger, "Satellite Communication for Industrial IoT," in *72nd International Astronautical Congress*. International Astronautical Federation (IAF), 2021.

[144] A. Kumar, D. A. de Jesus Pacheco, K. Kaushik, and J. J. Rodrigues, "Futuristic View of the Internet of Quantum Drones: Review, Challenges and Research Agenda," *Vehicular Communications*, vol. 36, p. 100487, 2022.

[145] N. Ahmadi, S. Schwertfeger, P. Werner, L. Wiese, J. Lester, E. Da Ros, J. Krause, S. Ritter, M. Abasifard, C. Cholsuk *et al.*, "QUICK - Design of a Satellite-Based Quantum Light Source for Quantum Communication and Extended Physical Theory Tests in Space," *arXiv preprint arXiv:2301.11177*, 2023.

[146] R. J. Fang, M. Eroz, and N. Becker, "Data Collection and SCADA over GEO-MSS Satellites Using Spread SCMA," in *2009 International Workshop on Satellite and Space Communications*. IEEE, 2009, pp. 441–445.

[147] M. Kruijff, M. Dumville, M. Hutchinson, and A. Ginati, "Intelligent Railways via Integrated Satellite Services (IRISS)," IAC-11-B5. 2.7, Tech. Rep., 2011.

[148] S. Banerjee, M. Hempel, and H. Sharif, "A Survey of Wireless Communication Technologies & Their Performance for High Speed Railways," 2016.

[149] C. Iacurto, T. Catuogno, A. Brizzi, L. Pandolfi, A. Miglietta, C.-H. Rokitansky, K. Eschbacher, V. Pellegrini, and N. Toptsidis, "Capacity Study for a 5G Satellite System to Support Railway FRMCS Critical Service over Europe," in *2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring)*. IEEE, 2022, pp. 1–5.

[150] X. Xiao, Z. Fu, G. Liu, and C. Deng, "A Backup Data Network for Power System Automations Based on Satellite Communication," in

2010 International Conference on Power System Technology. IEEE, 2010, pp. 1–5.

[151] J. Liu, D. Lerner, J. Chung, U. Paul, A. Gupta, and E. Belding, "Watching Stars in Pixels: The Interplay of Traffic Shaping and YouTube Streaming QoE over GEO Satellite Networks," *arXiv preprint arXiv:2309.00686*, 2023.

[152] H. Zhao, H. Fang, F. Wang, and J. Liu, "Realtime Multimedia Services over Starlink: A Reality Check," in *Proceedings of the 33rd Workshop on Network and Operating System Support for Digital Audio and Video*, 2023, pp. 43–49.

[153] C. Ge, N. Wang, I. Selinis, J. Cahill, M. Kavanagh, K. Liolis, C. Politis, J. Nunes, B. Evans, Y. Rahulan *et al.*, "QoE-Assured Live Streaming via Satellite Backhaul in 5G Networks," *IEEE Transactions on Broadcasting*, vol. 65, no. 2, pp. 381–391, 2019.

[154] A. Maskey and M. Cho, "CubeSatNet: Ultralight Convolutional Neural Network Designed for On-orbit Binary Image Classification on a 1U CubeSat," *Engineering Applications of Artificial Intelligence*, vol. 96, p. 103952, 2020.

[155] G. Giuffrida, L. Diana, F. de Gioia, G. Benelli, G. Meoni, M. Donati, and L. Fanucci, "CloudScout: A Deep Neural Network for On-board Cloud Detection on Hyperspectral Images," *Remote Sensing*, vol. 12, no. 14, p. 2205, 2020.

[156] G. Giuffrida, L. Fanucci, G. Meoni, M. Batič, L. Buckley, A. Dunne, C. van Dijk, M. Esposito, J. Hefele, N. Vercruyssen *et al.*, "The Φ-Sat-1 Mission: The First On-board Deep Neural Network Demonstrator for Satellite Earth Observation," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 60, pp. 1–14, 2021.

[157] D. R. Thompson, A. Altinok, B. Bornstein, S. A. Chien, J. Doubleday, J. Bellardo, and K. L. Wagstaff, "Onboard Machine Learning Classification of Images by a Cubesat in Earth Orbit," *AI Matters*, vol. 1, no. 4, pp. 38–40, 2015.

[158] Z. Zhang, Z. Qu, S. Liu, D. Li, J. Cao, and G. Xie, "Expandable On-board Real-Time Edge Computing Architecture for Luojia3 Intelligent Remote Sensing Satellite," *Remote Sensing*, vol. 14, no. 15, p. 3596, 2022.

[159] B. Guthrie, M. Kim, H. Urrutxua, and J. Hare, "Image-Based Attitude Determination of Co-orbiting Satellites Using Deep Learning Technologies," *Aerospace Science and Technology*, vol. 120, p. 107232, 2022.

[160] Y. Iwasaki, Y. Kikuya, K. Sasaki, T. Ozawa, Y. Shintani, Y. Masuda, K. Watanabe, H. Mamiya, H. Ando, T. Nakashima *et al.*, "Development and Initial On-orbit Performance of Multi-functional Attitude Sensor Using Image Recognition," in *33rd Annual AIAA/USU Conference on Small Satellites*, 2019.

[161] A. Agarwal, S. Gupta, S. Kumar, and D. Singh, "An Efficient Use of IoT for Satellite Data in Land Cover Monitoring to Estimate LST and ET," in *2016 11th International Conference on Industrial and Information Systems (ICIIS)*. IEEE, 2016, pp. 905–909.

[162] I. Leyva-Mayorga, M. Martinez-Gost, M. Moretti, A. Peŕez-Neira, M. Á. Vázquez, P. Popovski, and B. Soret, "Satellite Edge Computing for Real-Time and Very-High Resolution Earth Observation," *IEEE Transactions on Communications*, 2023.

[163] J.-B. Wang, J. Zhang, C. Ding, H. Zhang, M. Lin, and J. Wang, "Joint Optimization of Transmission Bandwidth Allocation and Data Compression for Mobile-Edge Computing Systems," *IEEE Communications Letters*, vol. 24, no. 10, pp. 2245–2249, 2020.

[164] H. Choi and S. Pack, "Cooperative Downloading for LEO Satellite Networks: A DRL-Based Approach," *Sensors*, vol. 22, no. 18, p. 6853, 2022.

[165] X. Jia, T. Lv, F. He, and H. Huang, "Collaborative Data Downloading by using Inter-Satellite Links in LEO Satellite Networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1523–1532, 2017.

[166] N. Razmi, B. Matthiesen, A. Dekorsy, and P. Popovski, "On-board Federated Learning for Satellite Clusters with Inter-Satellite Links," *arXiv preprint arXiv:2307.08346*, 2023.

[167] M. Elmahallawy and T. Luo, "FedHAP: Fast Federated Learning for LEO Constellations Using Collaborative HAPs," in *2022 14th International Conference on Wireless Communications and Signal Processing (WCSP)*. IEEE, 2022, pp. 888–893.

[168] C. Wu, Y. Zhu, and F. Wang, "DSFL: Decentralized Satellite Federated Learning for Energy-Aware LEO Constellation Computing," in *2022 IEEE International Conference on Satellite Computing (Satellite)*. IEEE, 2022, pp. 25–30.

[169] M. R. Jabbarpour, B. Javadi, P. H. Leong, R. N. Calheiros, D. Boland, and C. Butler, "On-Board Federated Learning in Orbital Edge Computing," in *2023 IEEE 29th International Conference on Parallel and Distributed Systems (ICPADS)*. IEEE, 2023, pp. 1045–1052.

[170] M. Elmahallawy and T. Luo, "One-Shot Federated Learning for LEO Constellations that Reduces Convergence Time from Days to 90 Minutes," *arXiv preprint arXiv:2305.12316*, 2023.

[171] J. So, K. Hsieh, B. Arzani, S. Noghabi, S. Avestimehr, and R. Chandra, "Fedspace: An Efficient Federated Learning Framework at Satellites and Ground Stations," *arXiv preprint arXiv:2202.01267*, 2022.

[172] Q. Ren, O. Abbasi, G. K. Kurt, H. Yanikomeroglu, and J. Chen, "Caching and Computation Offloading in High Altitude Platform Station (HAPS) Assisted Intelligent Transportation Systems," *IEEE Transactions on Wireless Communications*, vol. 21, no. 11, pp. 9010–9024, 2022.

[173] X. Lin, J. Li, J. Wu, H. Liang, and W. Yang, "Making Knowledge Tradable in Edge-AI Enabled IoT: A Consortium Blockchain-Based Efficient and Incentive Approach," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 12, pp. 6367–6378, 2019.

[174] S. Crosby and K. Brenning, "On Trusting Third-party Satellite Data," 2022.

[175] S. R. Pokhrel, "Blockchain Brings Trust to Collaborative Drones and LEO Satellites: An Intelligent Decentralized Learning in the Space," *IEEE sensors journal*, vol. 21, no. 22, pp. 25 331–25 339, 2021.

[176] R. Wang, S. Zhang, B. Yang, Z. Yang, P. Zhang, and D. Wu, "Enabling Data Sharing through Data Trusts in LEO Satellite Internet," *IEEE Wireless Communications*, 2023.

[177] H. Jiang, J. Starkman, Y.-J. Lee, H. Chen, X. Qian, and M.-C. Huang, "Distributed Deep Learning Optimized System over the Cloud and Smart Phone Devices," *IEEE Transactions on Mobile Computing*, vol. 20, no. 1, pp. 147–161, 2019.

[178] M. Luglio, S. P. Romano, C. Roseti, and F. Zampognaro, "Service Delivery Models for Converged Satellite-Terrestrial 5G Network Deployment: A Satellite-Assisted CDN Use-Case," *IEEE Network*, vol. 33, no. 1, pp. 142–150, 2019.

[179] S. Liu, X. Hu, Y. Wang, G. Cui, and W. Wang, "Distributed Caching Based on Matching Game in LEO Satellite Constellation Networks," *IEEE Communications Letters*, vol. 22, no. 2, pp. 300–303, 2017.

[180] Y. Li, Q. Zhang, P. Yuan, and Z. Yang, "A Back-Tracing Partition Based On-path Caching Distribution Strategy over Integrated LEO Satellite and Terrestrial Networks," in *2018 10th International Conference on Wireless Communications and Signal Processing (WCSP)*. IEEE, 2018, pp. 1–6.

[181] S. Xi, B. Shang, H. Zhang, J. Ma, and P. Fan, "Multi-Satellite-Enabled Edge Computing: An Offloading and Computation Integration Approach," in *2023 3rd International Conference on Intelligent Communications and Computing (ICC)*. IEEE, 2023, pp. 151–156.

[182] B. Abdellatif, M. M. Shibl, T. Khattab, J. Tadrous, T. ElFouly, and N. Zorba, "Caching Through the Skies: The Case of LEO Satellites Connected Edges for 6G and Beyond," *arXiv preprint arXiv:2303.12895*, 2023.

[183] M. Wu, S. Dai, H. Hu, and Z. Wang, "Collaborative Edge Caching in LEO Satellites Networks: A MAPPO Based Approach," in *2024 IEEE International Conference on Multimedia and Expo (ICME)*. IEEE, 2024, pp. 1–6.

[184] H. Wu, J. Li, H. Lu, and P. Hong, "A Two-Layer Caching Model for Content Delivery Services in Satellite-Terrestrial Networks," in *2016 IEEE global communications conference (GLOBECOM)*. IEEE, 2016, pp. 1–6.

[185] E. Wang, H. Li, and S. Zhang, "Load Balancing Based on Cache Resource Allocation in Satellite Networks," *IEEE Access*, vol. 7, pp. 56 864–56 879, 2019.

[186] X. Zhu, C. Jiang, L. Kuang, and Z. Zhao, "Cooperative Multilayer Edge Caching in Integrated Satellite-Terrestrial Networks," *IEEE Transactions on Wireless Communications*, vol. 21, no. 5, pp. 2924–2937, 2021.

[187] B. Wang, C. Guo, and D. Huang, "Multi-Layer Resource Computing Offloading Based on Power Price Difference," in *2023 IEEE 23rd International Conference on Communication Technology (ICCT)*. IEEE, 2023, pp. 714–719.

[188] S. S. Shinde, D. Naseh, and D. Tarchi, "In-Space Computation Offloading for Multi-layer LEO Constellations," in *European Wireless 2023; 28th European Wireless Conference*. VDE, 2023, pp. 82–89.

[189] M. Sauer, A. Netti, E. Boriskova, and F. Zeiger, "Satellite-Based Data Lakes: A Technical Case Study Based on Existing Cloud Technologies," in *IAF Symposium on Integrated Applications*. Milan, Italy: International Astronautical Federation (IAF), October 2024, pp. 42–51. [Online]. Available: https://doi.org/10.52202/078366-0005

[190] R. Buick, "Precision agriculture: an integration of information technologies with farming," in *Proceedings of the New Zealand Plant Protection Conference*, vol. 50, 1997, pp. 176–184.
[191] R. T. Eguchi, C. K. Huyck, B. J. Adams, B. Mansouri, B. Houshmand, and M. Shinozuka, "Resilient disaster response: using remote sensing technologies for post-earthquake damage detection," *Earthquake Engineering to Extreme Events (MCEER), Research Progress and Accomplishments*, vol. 2003, p. 2003, 2001.
[192] A. Toorian, K. Diaz, and S. Lee, "The CubeSat Approach to Space Access," in *2008 IEEE aerospace conference*. IEEE, 2008, pp. 1–14.
[193] H. Arora and R. Goyal, "A review on inter-satellite link in inter-satellite optical wireless communication," *Journal of Optical Communications*, vol. 38, no. 1, pp. 63–67, 2017.
[194] J. S. Sidhu, S. K. Joshi, M. Gündoğan, T. Brougham, D. Lowndes, L. Mazzarella, M. Krutzik, S. Mohapatra, D. Dequal, G. Vallone *et al.*, "Advances in space quantum communications," *IET Quantum Communication*, vol. 2, no. 4, pp. 182–217, 2021.
[195] Y.-A. Chen, Q. Zhang, T.-Y. Chen, W.-Q. Cai, S.-K. Liao, J. Zhang, K. Chen, J. Yin, J.-G. Ren, Z. Chen *et al.*, "An integrated space-to-ground quantum communication network over 4,600 kilometres," *Nature*, vol. 589, no. 7841, pp. 214–219, 2021.
[196] T. Pfandzelter and D. Bermbach, "Edge Computing in Low-Earth Orbit–What Could Possibly Go Wrong?" in *Proceedings of the 1st ACM Workshop on LEO Networking and Communication*, 2023, pp. 19–24.
[197] K. Bhatia, "Starlinked! An Analysis of SpaceX's Small Satellite Mega-Constellation Under the Fourth Amendment," *Information & Communications Technology Law*, vol. 32, no. 1, pp. 1–22, 2023.
[198] L. Hallet, "Rise of Mega Constellations: A Case to Adapt Space Law Through the Law of the Sea," in *Legal Aspects Around Satellite Constellations: Volume 2*. Springer, 2021, pp. 179–211.

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