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SURVEY

Resource Allocation on Low-Earth Orbit Edge Infrastructure: Taxonomy, Survey, and Research Challenges

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ABSTRACT Low Earth Orbit (LEO) Edge Computing integrates space technology with Edge Computing to enhance connectivity and reduce latency, addressing critical limitations of terrestrial infrastructures. By leveraging LEO satellites, this paradigm enables global, low-latency data processing for applications such as remote sensing, Earth observation, and worldwide communications. However, it also presents challenges in resource allocation, thermal management, and space debris mitigation. This paper provides a comprehensive taxonomy and in-depth survey on resource allocation strategies in LEO Edge environments, identifying key challenges and future research directions.

INDEX TERMS Edge computing, LEO edge, low-earth orbit satellites, resource allocation, satellite constellation.

I. INTRODUCTION

Cloud computing has revolutionized how we store, process, and access data, bringing significant advantages in scalability, efficiency, and reduced operational costs [1]. However, as digitalization advances, new demands emerge that challenge the centralized model of cloud computing, particularly about latency in data transmission and the need for real-time processing [2]. The advent of Edge Computing emerged as a response to these limitations, proposing a decentralized processing architecture where data analysis occurs closer to the source, that is, at the edge of the network [1].

By distributing processing, Edge Computing directly confronts the problem of data centralization, which can lead to significant delays and security vulnerabilities. Still, even with the advances provided by Edge Computing, some barriers still need to be addressed when we depend exclusively on terrestrial infrastructures [3]. Remote or densely urbanized areas require more geographic coverage and connection quality. Furthermore, even the lowest latencies may be unacceptable for emerging technologies such as autonomous vehicles, which require virtually instantaneous and highly reliable communication. These challenges reinforce the search for innovative solutions that can complement and expand the capabilities of Edge Computing [1].

LEO Edge Computing emerges as a promising solution that seeks to overcome the latency constraints of conventional (terrestrial) computing models, offering global coverage and reducing data transmission time based on (i) low-latency communication based on satellites that are sufficiently close to the Earth (where most of the data is generated), (ii) a mesh network of interconnected satellites that can provide global coverage, and (iii) the ability to process data on the satellite itself (i.e., edge capabilities) that can reduce the amount of data that needs to be transmitted to the ground.

Despite the promising use cases of LEO Edge Computing, its inerently different characteristics compared to terrestrial computing models raise concerns about potential challenges and limitations of deploying and operating such systems. As such, review studies are needed to provide a comprehensive understanding of the state-of-the-art research in this area

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TABLE 1. Summary of LEO satellite infrastructure surveys.

Reference	Focus Area	Description
Ammar et al. [4], Kim et al. [5]	General Resource Allocation	Surveys concentrating on specific facets of resource allocation in LEO networks.
Li et al. [6]	Offloading Mechanisms	Explores offloading mechanisms within LEO satellite systems.
Farrea et al. [7]	6G Integration	Focuses on the integration of LEO satellites with 6G technologies.
Zhu et al. [8], Centenaro et al. [9]	Internet of Things (IoT)	Investigates the role of LEO satellites in IoT applications.
Boucetta e tal. [10]	Artificial Intelligence (AI)	Analyzes applications and challenges of AI within LEO satellite networks.
Wang et al. [11]	Comprehensive Resource Allocation	Attempts to encompass resource allocation dynamics more broadly across LEO infrastructures.

and facilitate the identification of research gaps and future research directions.

A. RELATED SURVEYS AND OUR CONTRIBUTION

The existing set of research on LEO satellite infrastructures is characterized by a multitude of surveys, yet many of these predominantly concentrate on highly specific facets of resource allocation [4], [5]. These surveys often delve deeply into niche topics such as offloading mechanisms [6] or are narrowly tailored to specific applications like 6G integration [7], the IoT [8], [9], or AI [10]. While these focused studies are invaluable for addressing targeted challenges within LEO satellite networks, they do not comprehensively encompass the entirety of resource allocation dynamics across these infrastructures [11]. Table 1 summarizes the related surveys.

While Table 1 summarizes previous studies on resource allocation in LEO Edge Computing, these works primarily focus on isolated aspects such as offloading mechanisms, 6G integration, and IoT applications. However, there is a lack of comprehensive research addressing holistic resource allocation strategies that encompass dynamic resource management, energy efficiency, and security concerns. Existing studies often examine static allocation methods, failing to explore adaptive models that respond to real-time fluctuations in workload demands. Furthermore, current approaches do not adequately consider the trade-offs between computational load distribution and power constraints in satellite networks. Future research should bridge this gap by proposing integrated allocation frameworks that dynamically adjust to varying network conditions, improving both efficiency and resilience.

As a result, there remains a noticeable gap in the literature when it comes to synthesizing broader insights that could potentially inform holistic approaches to resource management in LEO infrastructure.

Therefore, there exists a pressing necessity within the research community for a comprehensive survey that can more inclusively cover all conceivable aspects of resource allocation in LEO satellite networks. Our proposal extend beyond mere enumeration of available resources and delve into categorizing which resources are viable for allocation under varying operational conditions. Furthermore, it should explore the gamut of resource allocation and management strategies, evaluating their efficacy and applicability within the dynamic context of LEO satellite constellations. Equally critical is the incorporation of robust performance metrics that gauge the efficiency and reliability of these allocation strategies, alongside considerations of security frameworks that safeguard sensitive data transmissions and network integrity. By consolidating these diverse elements into a unified survey, researchers and practitioners alike can gain a comprehensive understanding of the complexities inherent to resource allocation in LEO satellite infrastructures, thereby fostering more informed decision-making and advancing the field as a whole.

```
LEO Edge Resource Allocation
 ├─ Resource Types
 ├─ Allocation Strategies
 ├─ Resource Management Models
 ├─ Performance Metrics
 ├─ Optimization Techniques
 ├─ Resource Allocation Policies
 └─ Security and Privacy Considerations
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FIGURE 1. Main topics of resource allocation on low-earth orbit edge Infrastructure.

B. LIMITATIONS

While this paper provides a structured taxonomy and survey on resource allocation in LEO Edge Computing, several limitations should be acknowledged.

- Lack of Empirical Validation – The study primarily focuses on existing literature and theoretical frameworks without empirical validation through simulations or real-world experiments. Future research should incorporate experimental analyses to validate the proposed concepts and frameworks.
- Economic and Business Feasibility – The discussion on resource allocation strategies primarily considers computational and network efficiency but does not delve deeply into the economic or business feasibility of large-scale LEO Edge Computing deployments. Economic sustainability and cost-benefit analyses should be explored to ensure practical implementation.

- Interoperability Challenges – The scope of this paper is limited to resource allocation challenges in LEO Edge Computing, without extensively addressing interoperability issues between terrestrial and non-terrestrial networks. Future work should investigate seamless integration strategies between LEO satellites and ground-based infrastructure to enhance connectivity and service continuity.

C. ARTICLE ORGANIZATION

The rest of the article is organized as follows: Section II presents a background on LEO edge infrastructure, focusing on the layered architecture between different types of satellites with the intention of localizing LEO in this context, as well as presenting some application areas and resources; Section III presents and discusses a resource allocation taxonomy in LEO Edge, and describes in detail some works that fit into the proposed classifications; Section IV presents some future directions that can be explored in future research; and our final considerations are presented in Section V.

II. BACKGROUND

A. ARCHITECTURE

The architecture of LEO Edge Computing integrates satellite networks with terrestrial Edge Computing infrastructure [12]. Figure 2 shows a diagram of a network architecture that integrates Edge Computing with satellite communication, specifically using satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO). On the left side is a Cloud Data Center, which represents traditional data centers where computing and storage resources are hosted. These data centers are connected to a set of terrestrial infrastructures called Ground-Based Edge Computing, where computing is carried out closer to the data source or end-user to reduce latency and increase processing speed. However, there are locations that even the terrestrial edge environment cannot reach with the necessary quality of service. Thus, in the middle of the diagram, we locate a Satellite Network Gateway, a terrestrial access point for the satellite network. It acts as a connection point between terrestrial networks and satellite constellations [13]. On the right side, we see three types of satellite constellations:

- LEO satellites operate at altitudes of approximately 160 to 2,000 kilometers above the Earth, which allows them to have higher speeds and lower latency times in data transfer, making them ideal for communications and Earth observation applications. However, due to their proximity to Earth, they have a shorter lifespan due to atmospheric drag, generally around 5 to 7 years.
- MEO satellites, located between 2,000 and 35,786 kilometers, are commonly used for satellite navigation (such as the GPS system). They have a longer lifespan and moderate speeds, with a data transfer rate that balances capacity and range.
- GEO satellites remain at a fixed altitude of approximately 35,786 kilometers above the equator, allowing them to cover vast geographic areas and maintain a static position relative to the Earth's surface. This is ideal for communications satellites, but the high altitude increases latency in transmissions. GEOs generally have the most extended lifespan, reaching 15 years or more, due to less exposure to atmospheric drag and low-altitude radiation.

The dotted blue arrows represent communications between different network elements. This includes communication between data centers and Edge Computing, network gateways, satellite constellations, and between satellites in the same or in different orbits. Lastly, there are Ground-Based Applications in the lower right corner, indicating the ground-based applications that use this integrated network and that benefit from this network architecture by receiving data and services quickly and efficiently. This architecture is designed to optimize the delivery of data and services to end users in diverse applications, taking advantage of the proximity of LEO satellites and the broad coverage of GEO and MEO satellites [14].

This architecture allows offloading applications through LEO satellites from terrestrial service cores to terrestrial applications [5]. Offloading data from the terrestrial edge to the LEO edge starts with collecting and analyzing data at specific terrestrial locations, where locally processing and storing data becomes impractical due to capacity constraints or infrastructure limitations. Instead of relying on distant terrestrial data centers, which could introduce prohibitive latencies, the data payload is transferred to satellites in low Earth orbit [15]. These satellites, equipped with advanced processing capabilities, function as Edge Computing points, processing data closest to its origin. Once data is processed at the LEO edge, it can be directed back to specific terrestrial applications to provide real-time insights or enable critical functionality that requires low latency. This approach is very useful in remote regions or areas where internet infrastructure is inadequate or non-existent, as it allows for the delivery of high-performance internet and computing services, significantly overcoming traditional connectivity and processing barriers [16]. Thus, offloading to the LEO edge alleviates the load on terrestrial edge infrastructures and democratizes access to advanced computing services, extending the reach of the internet and low-latency dependent applications to previously inaccessible locations.

B. APPLICATION AREAS

The advent of LEO satellites marks a significant evolution of data communications, heralding an era where latency—a critical measure of the time it takes for data to travel from its source to its destination—has been dramatically reduced. This development stands in stark contrast to the limitations inherent in traditional GEO satellites and terrestrial communication networks, particularly in terms of the

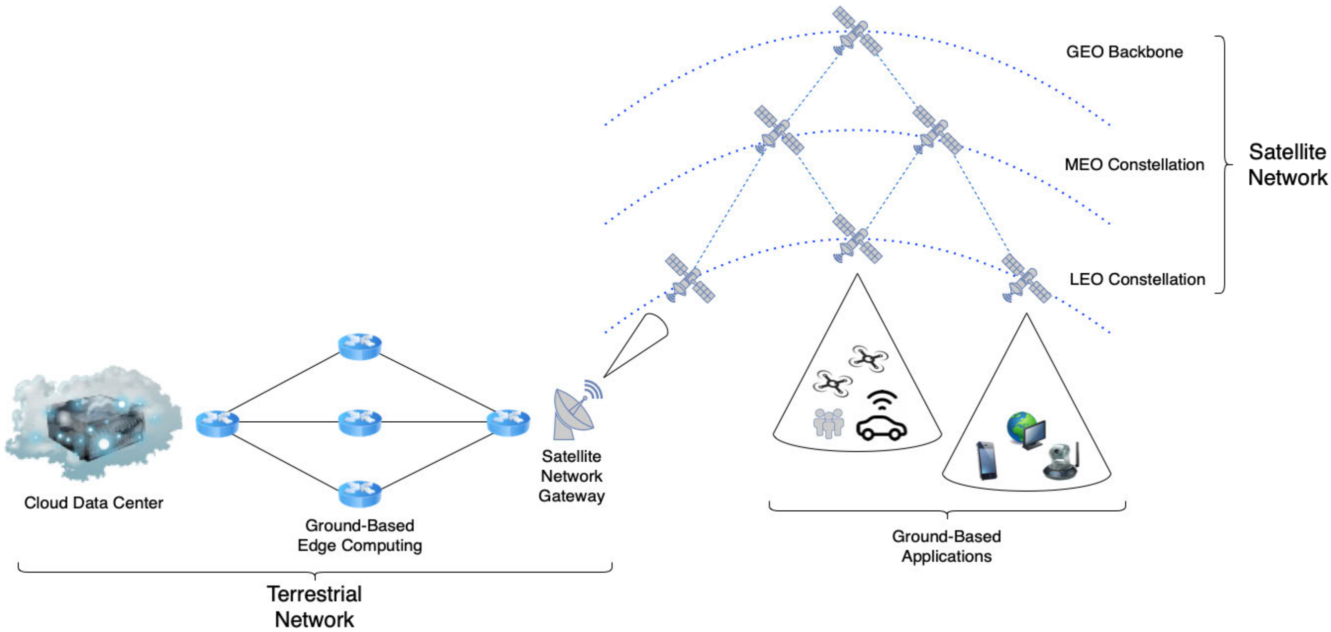

FIGURE 2. Satellite-terrestrial integrated edge computing networks.

latency they introduce. The implications of this advancement are wide-reaching, providing a critical infrastructure layer that promises to be transformative, especially for remote and underdeveloped regions where existing communication infrastructures are sparse or entirely absent [17].

The IoT domain stands to benefit immensely from the incorporation of LEO edge capabilities [18]. The proliferation of IoT devices—estimated to reach into the billions—demands an infrastructure that can support massive data flows while minimizing latency. By processing data closer to its source, LEO edge technology not only reduces network congestion but also enhances the efficiency of real-time data-driven decisions. This is particularly crucial for sectors reliant on instantaneous data processing, such as autonomous vehicle navigation systems and critical infrastructure monitoring. The local processing of data, prior to its transmission to centralized processing facilities or cloud storage, represents a leap forward in operational efficiency and responsiveness for these technologically advanced systems.

The entertainment industry, especially of online gaming and live streaming, is poised for a transformative experience courtesy of the reduced latency offered by LEO Edge technology [19]. The essence of online gaming and live streaming experiences hinges on low latency to ensure seamless, immersive interactions. The proximity of LEO edge servers significantly diminishes delays, thereby elevating the quality of service for users across the globe [20]. This enhancement not only benefits the end-user experience but also opens up new vistas for content creators and the entertainment industry at large, promising a new era of digital engagement and interactive experiences.

Furthermore, the application of LEO edge infrastructure extends into the domain of Earth observation [21]. Satellites equipped with state-of-the-art sensors play a pivotal role in monitoring global environmental conditions, weather patterns, and the progression of phenomena such as deforestation. The capability for on-edge data processing enables a distributed, rapid analysis paradigm, which is essential for a swift response to environmental crises, natural disasters, or the multifaceted challenges posed by accelerated climate change. By facilitating a more agile and informed response mechanism, LEO technology contributes significantly to the efforts aimed at sustainable Earth resource management, disaster mitigation, and the broader climate action agenda [22].

In such locales, the deployment of LEO satellites can facilitate near-real-time data communications, enabling connectivity levels previously deemed unattainable. This is not just a theoretical improvement but a practical solution that addresses a long-standing barrier to digital inclusivity. Moreover, the agility of LEO satellite networks in establishing connectivity makes them invaluable in scenarios marked by urgency and a critical need for communication, such as areas affected by natural disasters or conflict zones. Therefore, the deployment of LEO technology can be swiftly executed, providing a vital communications lifeline that supports both rescue and recovery operations, thereby underscoring the importance of LEO edge technology as a cornerstone for disaster response and management strategies [23].

In the defense and security sectors, the strategic advantages conferred by LEO edge technology cannot be overstated [24]. The real-time processing and communication of surveillance data directly from space to ground units empowers military and security operations with enhanced situational awareness

TABLE 2. Summary of works on LEO satellite applications.

Reference	Domain	Description
Wang et al. [17]	Digital Inclusivity	Highlights the role of LEO satellites in reducing latency and providing connectivity to remote and underserved regions.
Juan et al. [23]	Disaster Response	Discusses the importance of LEO technology in providing rapid communication solutions in areas affected by natural disasters or conflicts.
Jin et al. [18]	Internet of Things (IoT)	Explores the potential of LEO edge technology to support massive data flows from IoT devices while reducing latency and enhancing real-time data processing.
Lv et al. [21]	Earth Observation	Examines the use of LEO satellites for environmental monitoring, rapid analysis, and response to environmental crises.
Leyva-Mayorga et al. [22]	Climate Action	Highlights the application of LEO technology in supporting sustainable resource management and climate change response.
Ray et al. [24]	Defense and Security	Explores the strategic advantages of LEO edge technology in enhancing situational awareness and coordination for military operations.
Oh et al. [25]	Defense Strategy	Details the use of LEO technology for real-time threat detection and tactical decision-making.
Lin et al. [19]	Entertainment	Describes the impact of reduced latency from LEO edge technology on online gaming and live streaming experiences.
Zhang et al. [20]	Digital Engagement	Discusses the potential for improved user experience and new opportunities for content creators in the entertainment industry.

and coordination capabilities. This translates into faster threat detection, improved operational coordination, and the capacity to make swift, informed decisions in the face of dynamic threats and scenarios, thereby redefining the tactical landscape of modern defense strategies [25]. Table 2 summarizes the application areas.

C. RESOURCES

LEO satellites rely on specialized computational resources to tackle the challenges posed by the space environment and to ensure efficient operation and accurate data collection. Unlike other types of satellites that orbit at greater distances, LEO satellites are positioned at altitudes between 160 and 2,000 kilometers above the Earth's surface. At this range, they experience less communication delay, enabling near real-time data transmission, but they also require high processing capabilities to handle the speed of information exchange. This proximity to Earth allows these satellites, especially those operating in constellations, to communicate with each other and provide global connectivity to both remote and urban areas, frequently being used to deliver high-speed internet and environmental monitoring. However, for this to be feasible, the onboard computational systems must be robust, energy-efficient, and equipped with protection mechanisms against radiation effects.

In terrestrial edge computing, microservers and small computing devices function as edge nodes by bringing processing power closer to users and reducing the reliance on centralized cloud infrastructure. Similarly, satellites in low Earth orbit serve as edge computing nodes, processing data at the network periphery rather than relying solely on ground stations. This paradigm enables real-time data analytics, reduces transmission latency, and enhances overall network efficiency. The study of Starlink, Kuiper, and OneWeb satellite systems is essential in this context, as these constellations exemplify how distributed computing resources can be efficiently deployed in space. By analyzing their architectures, communication protocols, and resource management strategies, we can derive valuable insights into the development of optimized LEO edge computing frameworks that align with emerging technological demands.

The Starlink,[1] Kuiper,[2] and OneWeb[3] satellite constellations represent distinct approaches to providing global internet connectivity from low Earth orbit (LEO), as we can seen in Table 3. Each system is tailored to serve specific connectivity needs and leverages unique technological assets, such as propulsion methods, communication bands, and inter-satellite communication capabilities, which together inform the computational capabilities and potential of each network.

Starting with Starlink, SpaceX's approach focuses on rapid data transfer rates and robust inter-satellite communications, with an operational altitude of around 550 kilometers. By orbiting at this relatively low altitude, Starlink satellites can reduce latency, which is crucial for applications requiring real-time connectivity. Starlink satellites utilize Ka and Ku frequency bands, offering up to 20 Gbps of data transfer per satellite, which highlights its capability to support high-bandwidth applications like video streaming and data-intensive communications. This high throughput aligns with SpaceX's ambitious goal of providing internet access with minimal delay even in remote locations. Starlink also implements advanced inter-satellite communication via laser links, enabling direct communication between satellites without relying on ground stations. This network design allows data to travel across continents without touching Earth, which not only increases speed but also improves coverage efficiency, a critical advantage for users in geographically isolated areas.

The Amazon Kuiper project, still under development, aims to provide competitive connectivity capabilities but

[1] https://www.starlink.com

[2] https://amazon.jobs/pt/teams/project-kuiper

[3] https://oneweb.net

TABLE 3. Comparison among Starlink, Kuiper, and OneWeb satellites.

Feature	Starlink	Kuiper (Amazon)	OneWeb
Orbit (Altitude)	550 km (LEO)	590 km, 610 km, 630 km (LEO)	1,200 km (LEO)
Frequency Band	Ka, Ku	Ka, Ku	Ku, Ka
Data Capacity	Up to 20 Gbps per satellite	Not specified (uses Prometheus chip for high capacity)	Not specified (high bandwidth for global connectivity)
Inter-satellite Communication	Yes (laser)	Not specified	Yes (laser)
Control Station	Controlled by SpaceX	Controlled by Amazon	Controlled by OneWeb
Propulsion	Krypton ion	Hall thrusters	Not specified
Launches	SpaceX (Falcon 9)	ULA (Vulcan) and Blue Origin (New Glenn)	Arianespace (Soyuz), ISRO (GSLV)
Main Purpose	High-speed internet for global users	High-speed internet for remote communities and rural areas	Global connectivity in remote areas and for enterprise clients

focuses on reaching underserved communities and rural areas. Kuiper's planned orbital layers range from 590 to 630 kilometers, slightly higher than Starlink but still within the LEO range to maintain lower latency than traditional geostationary satellites. Kuiper uses Ka and Ku bands and integrates Amazon's proprietary Prometheus chip to optimize data handling across its network. Although Amazon has not specified Kuiper's precise data transfer rate, the Prometheus chip's design is intended to handle substantial data volumes efficiently, suggesting that Kuiper will be capable of supporting data-intensive applications similar to Starlink. The chip allows the satellite to manage high data throughput efficiently, enhancing computational resources for data routing and communication without extensive reliance on ground-based processing. However, unlike Starlink, there is limited information on whether Kuiper will incorporate inter-satellite communication, which could potentially place greater demand on its ground stations for data relay.

OneWeb, while sharing similar goals of bridging the digital divide, employs a slightly different architecture in terms of orbital altitude and data management strategy. OneWeb satellites orbit at 1,200 kilometers, nearly double the altitude of Starlink and Kuiper, which reduces the number of satellites required to cover the globe. This higher altitude can increase latency slightly compared to Starlink, yet it offers more comprehensive coverage per satellite, which is beneficial in terms of reducing the constellation's operational complexity and cost. Like the others, OneWeb operates in Ka and Ku frequency bands, which are commonly chosen for satellite internet due to their balance of bandwidth and atmospheric penetration capabilities. While exact data capacity figures are not disclosed, OneWeb's design emphasizes connectivity for remote regions and enterprise clients, suggesting a robust handling of data, albeit potentially with less throughput per satellite than Starlink due to the increased altitude. Additionally, OneWeb has inter-satellite laser communication, similar to Starlink, enabling direct satellite-to-satellite data routing. This capability allows OneWeb to efficiently deliver data across large distances without needing intermediate ground relays, a feature that reduces latency for long-distance connections.

In terms of computational resources, each constellation's design decisions around altitude, frequency bands, and data management reflect trade-offs between latency, throughput, and operational complexity. Starlink's low-altitude, high-data approach places high demands on its computational infrastructure, with advanced inter-satellite laser links requiring precise real-time data handling and routing. Kuiper's emphasis on the Prometheus chip suggests a focus on efficient data handling at potentially lower per-satellite throughput, making it suitable for Amazon's targeted regions. OneWeb's higher altitude increases coverage per satellite and reduces the constellation's complexity, though it may come at the cost of slightly higher latency and potentially lower data throughput per satellite compared to Starlink's high-speed infrastructure.

Overall, these satellite networks reflect innovative uses of computational resources to tackle the challenge of global internet access. While Starlink leads with a high-bandwidth, low-latency model suitable for a broad range of users, Kuiper and OneWeb prioritize regional connectivity with efficient data handling and operational simplicity, each meeting different connectivity needs. Together, these constellations exemplify how computational resources, communication protocols, and network architectures can be tailored to deliver diverse and effective connectivity solutions from space.

In terms of processing, LEO satellites are typically designed to be fault-tolerant and withstand the harsh space environment. Cosmic radiation and charged particles from the sun can cause errors in processing and even damage electronic circuits, a phenomenon known as "Single Event Upset" (SEU), which can lead to instruction errors and even reboots. To mitigate these effects, LEO satellites use radiation-hardened processors [26], often employing technologies that duplicate or triplicate critical circuits to ensure data integrity. Another common technique is the use of "watchdogs," circuits that monitor system functionality and restart components in case of failure. However, these additional protections tend to increase costs and power consumption, which is an issue in an environment with limited energy resources. LEO satellites generally depend on solar panels to generate power and on batteries to remain operational during periods when they are in Earth's shadow. Thus, energy efficiency in computational systems becomes a crucial factor, leading to the use of low-power processors and energy management

TABLE 4. Summary of computational resources in LEO satellites.

Aspect	Characteristics	Limitations
Processing Units	Fault-tolerant, radiation-hardened processors; duplication/triplication of critical circuits	Increased cost and power consumption; less powerful due to size and weight constraints
Radiation Protection Mechanisms	Use of watchdog circuits; radiation-resistant designs	Adds complexity and weight; higher energy consumption
Energy Efficiency	Low-power processors; energy management strategies; reliance on solar panels and batteries	Limited energy resources; need to shut down non-essential components when not in use
Storage and Memory	Use of flash storage for radiation resistance and low power consumption	Limited total storage; frequent data transmission to Earth required
Communication Systems	High-frequency transmitters and receivers; algorithms for data compression and error correction	Requires significant computational capabilities; data integrity challenges
Computational Capabilities	Specialized algorithms for orbit control and attitude adjustment	Limited compared to terrestrial systems; not suitable for complex onboard processing tasks
Ground Processing Dependency	Offloading intensive processing tasks to ground-based systems	Relies on frequent data transmission; potential delays in data analysis

strategies that turn off non-essential components when not in use [27].

The computational capabilities of these satellites are limited compared to terrestrial systems [28]. Due to size and weight constraints, LEO satellites use more compact and often less powerful processors. Although there are satellites with advanced processors, computational power is usually balanced with the need to keep weight low to reduce launch costs. Furthermore, storage and memory systems face significant limitations, with flash storage being widely used due to its radiation resistance and low power consumption. However, total available storage is limited, and collected data must be frequently sent to Earth to allow storage reuse for new information.

Communication between LEO satellites and ground stations is another area requiring considerable computational capabilities. Tracking, Telemetry, and Control (TT&C) [29] operations are vital to monitor satellite position and ensure it maintains the correct orbit. For that, satellites have navigation and control systems that use processors and specific algorithms for orbit correction and attitude adjustment, executed in response to data received from orientation sensors and gyroscopes. Also, data communication with Earth involves using high-frequency transmitters and receivers to send large volumes of data efficiently, which requires compression and error-correction algorithms to maximize data integrity.

Nevertheless, despite these capabilities, LEO satellites face significant limitations, especially in more complex operations that demand high computational power and extensive data storage [30]. For certain tasks, such as high-resolution image processing, many LEO satellites rely on ground-based processing, sending only raw or pre-processed data to Earth, where supercomputers can conduct full analyses. This division of processing is an effective strategy to overcome onboard system limitations, allowing the satellites to function as "eyes and ears" in space while more intensive processing takes place on the ground.

Finally, LEO satellites use computational resources that, although limited compared to terrestrial systems, are highly optimized for the space environment [31]. They feature radiation-resistant processors, specialized algorithms for orbit control and data compression, and failure-protection mechanisms. Their energy efficiency and strict resource management are essential for successful operation, given the limitations of onboard power and storage. These characteristics, though imposing certain restrictions, enable LEO satellites to fulfill their roles in communication, monitoring, and data collection, supporting applications ranging from global connectivity to environmental observation. Table 4 summarizes the LEO resources characteristics and limitations.

```
Resource Types
├─Computational Resources
│  ├─CPU
│  ├─GPU
│  ├─FPGA
│  └─Memory
├─Storage Resources
│  ├─Persistent Storage (SSD/HDD)
│  ├─In-Memory Storage
│  └─Cache
├─Network Resources
│  ├─Bandwidth
│  ├─Latency
│  └─Connectivity (uplink, downlink)
└─Power Resources
   ├─Battery Capacity
   ├─Solar Power Availability
   └─Power Management Systems
```

FIGURE 3. Resource types branch-cutting taxonomy.

III. TAXONOMY AND SURVEY

The taxonomy proposed in this work is based on the need to classify resource allocation in LEO edge in terms of resource types, allocation strategies, resource management models, performance metrics, optimization techniques, resource allocation policies, and security and privacy considerations.

A. RESOURCE TYPES

LEO edge infrastructures encompass a variety of resource types crucial for their effective functioning. These infrastructures rely on computational resources, including CPUs for processing tasks, GPUs for handling graphics-intensive operations, and FPGAs for customizable hardware acceleration, all supported by adequate memory to ensure smooth operation. Storage resources play a central role, with persistent storage options such as SSDs and HDDs providing long-term data retention, while in-memory storage facilitates rapid data access and cache systems enhance performance by temporarily storing frequently accessed data. Network resources are equally important, with bandwidth determining data transfer rates, latency affecting the speed of data processing and communication, and connectivity ensuring robust uplink and downlink capabilities. Power resources are vital for the sustainability of these infrastructures, with battery capacity providing backup during outages, solar power availability offering renewable energy solutions, and power management systems optimizing energy use to maintain efficiency and reliability. Figure 3 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

1) RELATED WORK

Regarding computational resources, research works such as Shi et al. [32] and Abbas et al. [33] explore the application of CPUs and GPUs in the context of Edge Computing, highlighting the need to optimize energy consumption and manage distributed workloads. In FPGAs, Xu et al. [34] discuss how these units can improve energy efficiency and performance in real-time data processing scenarios. Zhou et al. [35] investigate memory as a critical resource in distributed computing systems, emphasizing the importance of in-memory storage for operations requiring high access speeds. Data storage, in turn, is analyzed in detail by Zhao et al. [36], who examines the integration of persistent storage (SSD/HDD) with satellites, and by Qiu et al. [37], who discusses the role of cache and in-memory storage in reducing latency in satellite networks. As for network resources, works like those of Kim et al. [38] and Yu et al. [39] discuss the implications of latency and bandwidth in communications between satellites and ground stations. In contrast, Agbo et al. [40] detail the importance of uplink and downlink connectivity for the feasibility of time-sensitive edge applications. Energy resources have also been an important subject of analysis, and Li et al. [41] highlight the importance of battery capacity in LEO Edge Computing environments. In contrast, Li et al. [42] and Wang et al. [17] discuss how using solar energy and energy management systems is key to maximize efficiency and ensure the continuity of operations, especially in long-term missions.

2) DISCUSSION

Computational resources such as CPU, GPU, and FPGA show significant variations in performance and energy consumption, and the selection between these options depends on the application's specific needs, whether it be intensive data processing or optimization for low energy consumption. Additionally, FPGAs, in particular, are a promising solution for scenarios where efficient real-time data processing is required, a fundamental characteristic for satellites that process data locally before sending them back to Earth. Regarding storage resources, using cache and in-memory storage is essential to reducing latency in LEO satellite networks, where connectivity is limited and response times are critical. This approach reduces dependence on persistent storage, such as SSDs, which may have higher latency but remain essential for long-term data integrity. Regarding network resources, presented works emphasize the need to manage latency and bandwidth efficiently, with uplink and downlink connectivity essential to ensure real-time data synchronization between satellites and ground stations. Finally, energy management emerges as a central theme, as satellites operate in environments where energy is an extremely limited resource. Presented works emphasize that battery capacity and solar energy are the two main elements affecting the longevity of operations in Edge Computing. In this sense, discussed works suggest that optimizing energy management systems can offer more efficient solutions, allowing for a balance between computational performance and energy autonomy, which is essential for the viability of satellite networks.

```
Allocation Strategies
├─Static Allocation
│ └─Predefined resource allocation
│   └─Resource reservations
├─Dynamic Allocation
│ ├─On-demand resource allocation
│ ├─Elastic scaling (auto-scaling)
│ └─Load balancing
├─Predictive Allocation
│ ├─Machine learning-based
│ │ predictions
│ └─Historical data analysis
└─Priority-based Allocation
  ├─Quality of Service
  └─Service Level Agreements
```

FIGURE 4. Allocation strategies branch-cutting taxonomy.

B. ALLOCATION STRATEGIES

In designing LEO edge infrastructures, efficient resource management is fundamental, and various allocation strategies play a significant function in ensuring optimal performance and resource utilization. Static allocation involves predefined resource allocation and resource reservations, providing a fixed and predictable distribution of resources. In contrast, dynamic allocation adapts to real-time demands with on-demand resource allocation, elastic scaling (auto-scaling), and load balancing, which dynamically adjusts resource distribution based on current needs. Predictive allocation leverages machine learning-based predictions and historical data analysis to forecast future resource requirements, allowing for more informed and proactive resource management. Priority-based allocation ensures that resources are distributed according to Quality of Service (QoS) requirements and Service Level Agreements (SLAs), prioritizing critical tasks and services to maintain performance standards and contractual obligations. Figure 4 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

1) RELATED WORK

The variety of resource allocation strategies in Edge Computing has been a widely explored topic, especially in architectures based on LEO satellites. Studies focus on static, dynamic, predictive, and priority-based strategies, which make up the taxonomy discussed. Gao et al. [43] analyze static allocation in LEO infrastructures, highlighting the efficiency of pre-allocating resources for critical applications. Similarly, works like those of Kim et al. [44] explore resource reservation in edge environments, suggesting the reservation of bandwidth and computational capacity to avoid overloads. Dynamic allocation is also widely discussed in studies like that of Zhao et al. [16], which propose auto-scaling mechanisms for LEO infrastructures, where elasticity allows real-time adaptation to variable processing demands. Complementarily, Wang et al. [45] investigate load balancing in these systems, pointing to the need for efficient task distribution among edge nodes. Predictive strategies based on machine learning have attracted significant interest, with authors like Chan et al. [46] and Zhou et al. [47] using prediction models to allocate resources in advance, reducing latency and optimizing computational distribution. Other studies, such as those by Mi et al. [48], highlight the use of historical data analysis to predict traffic peaks in LEO networks. Finally, priority-based allocation, addressed by Tu et al. [49] explores the use of SLAs to ensure QoS in LEO Edge environments.

2) DISCUSSION

The findings of these studies reinforce the importance of different allocation strategies to optimize the performance and efficiency of LEO-based systems. Static allocation is effective for predictable load requirements, while dynamic allocation is essential for scenarios where workload floats unpredictably. However, a combination of predictive and dynamic allocation may be required to optimize scalability and resource use efficiency, and some works demonstrate machine learning models to predict demand accurately. Priority-based allocation stands out on LEO networks, especially when resources are scarce, and QoS is needed for specific applications. Therefore, the studies analyzed corroborate the need for a hybrid resource allocation approach, combining predictions with dynamic mechanisms and SLA-based reserves to maximize performance in different Edge Computing scenarios in the LEO context.

```
Resource Management Models
 └─Centralized Management
    └─Single control point
    └─Centralized decision-making
 └─Distributed Management
    └─Multiple control points
    └─Collaborative decision-making
 └─Hierarchical Management
    └─Multi-level control
    └─Top-down resource distribution
```

FIGURE 5. **Resource management models branch-cutting taxonomy.**

C. RESOURCE MANAGEMENT MODELS

In low-earth edge infrastructures, resource management models play an essential factor in optimizing performance and efficiency. Centralized management, with its single control point and centralized decision-making, ensures a streamlined and uniform approach to resource allocation. However, this can sometimes create bottlenecks and single points of failure. On the other hand, distributed management utilizes multiple control points and emphasizes collaborative decision-making, which can enhance resilience and flexibility but may lead to inconsistencies and coordination challenges. Hierarchical management strikes a balance between these approaches by implementing a multi-level control system with top-down resource distribution, allowing for both broad oversight and localized autonomy, thus optimizing resource allocation across different levels of the infrastructure. Figure 5 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

1) RELATED WORK

The management of resources in LEO Edge Computing environments has been widely investigated across different models, such as centralized, distributed, and hierarchical management. Several studies address the advantages and challenges of each model, considering the limitations and capabilities of the LEO satellite infrastructure. Works like Rodrigues et al. [50] explore centralized management, where a single control point centralizes resource allocation decisions in LEO networks. Sun et al. [51] discuss the implications of a single control entity in LEO networks, highlighting the potential for improved efficiency but emphasizing the risks of central point failures. The distributed model is also investigated by authors such as Guo et al. [52], who analyze how multiple control points can collaborate for distributed decision-making, reducing latency and increasing robustness. This distributed approach is reinforced by Wu et al. [53], who propose collaborative mechanisms between edge nodes to maximize efficient resource usage. On the other hand, hierarchical management has been studied by Jeon et al. [54], who explore a multi-level control model for LEO networks, suggesting a top-down resource distribution to ensure greater scalability. Additionally, the work of Li et al. [55] shows how a hierarchical structure can combine the advantages of centralization and distribution, promoting more efficient coordination between different control layers.

2) DISCUSSION

The findings in these studies point to different benefits and limitations in each resource management model in the context of LEO Edge Computing. Centralized management tends to be more efficient in environments with a predictable and homogeneous workload, allowing for better global resource optimization. However, this model is vulnerable to single points of failure, which can be problematic in dynamic and unpredictable environments. On the other hand, the distributed model offers greater flexibility and resilience by distributing responsibility across multiple nodes, reducing the risks associated with individual failures, especially in LEO networks where connectivity can be intermittent. Finally, hierarchical management balances the efficiency of a centralized approach with the robustness of a distributed system by introducing multiple levels of control. This hierarchical model appears particularly promising for large-scale LEO infrastructures, where coordination between different levels of nodes can optimize resource allocation and ensure QoS. Thus, these studies highlight the importance of choosing an appropriate resource management model depending on the specific characteristics of the application and the LEO environment.

D. PERFORMANCE METRICS

In the context of low-earth edge infrastructures, performance metrics are vital for evaluating and optimizing their effectiveness, with latency being a primary concern, encompassing both round-trip time and processing delay, which directly impact the speed of data exchange and response times; throughput is also essential, focusing on the data transfer rate and processing rate to ensure efficient handling of large volumes of information; reliability measures such as uptime and fault tolerance are fundamental to maintain continuous and dependable service; scalability is another key metric, with horizontal and vertical scaling strategies needed to accommodate growing demands; finally, energy efficiency, including power consumption and energy per computation, is increasingly important to minimize operational costs and environmental impact. Figure 6 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

```
Performance Metrics
 └─Latency
 │   └─Round-trip time
 │   └─Processing delay
 └─Throughput
 │   └─Data transfer rate
 │   └─Processing rate
 └─Reliability
 │   └─Uptime
 │   └─Fault tolerance
 └─Scalability
 │   └─Horizontal scaling
 │   └─Vertical scaling
 └─Energy Efficiency
     └─Power consumption
     └─Energy per computation
```

FIGURE 6. Performance metrics branch-cutting taxonomy.

1) RELATED WORK

The performance of LEO Edge Computing networks has been extensively investigated in terms of metrics such as latency, throughput, reliability, scalability, and energy efficiency. Several studies propose solutions to optimize these aspects in LEO infrastructures. Latency, one of the main concerns in Edge Computing systems, is extensively discussed by Kim et al. [44], who explore the reduction of round-trip time (RTT) in LEO networks, highlighting how the proximity of satellites to Earth can improve latency compared to higher-orbit satellites. Li et al. [56] analyze processing delays, proposing hybrid architectures between satellites and ground stations to minimize this effect. Throughput also receives significant attention, with Mahdi et al. [57] discussing the data transfer rate between satellites and edge nodes, and Ilchenko et al. [58] addressing the processing rate as a important point to optimize overall performance. Regarding reliability, studies such as those by Wang et al. [59] investigate fault tolerance in LEO networks, suggesting redundancy solutions to ensure adequate uptime. Scalability is also widely explored, with Herrería-Alonso et al. [60] analyzing horizontal and vertical scaling of resources in LEO Edge environments, while Farrea et al. [7] study the impact of increasing satellite density to support higher workloads. Finally, energy efficiency is another main subject, with Gupta et al. [61] discussing the energy consumption of LEO satellites, and Hussein et al. [62] exploring energy per computation as a fundamental metric to assess the sustainability of these architectures.

2) DISCUSSION

These studies reveal how different performance metrics can be optimized in LEO networks, depending on the specific needs and characteristics of the application. LEO architectures can significantly improve latency compared to traditional terrestrial networks, mainly when focusing on latency-sensitive applications, such as IoT real-time applications. However, it is necessary to balance latency with throughput, as research suggests that higher data transfer rates can be achieved at the cost of increased energy

```
Optimization Techniques
  Algorithmic Optimization
    Heuristic algorithms
    Metaheuristic algorithms
  Resource Virtualization
    Virtual Machines
    Containers
    Function-as-a-Service
  Data Localization
    Edge caching
    Data replication
  Load Forecasting
    Time series analysis
    Trend analysis
```

FIGURE 7. Optimization techniques branch-cutting taxonomy.

consumption and processing. On the other hand, reliability becomes important in LEO environments, where connectivity failures are common due to the rapid movement of satellites. Scalability, both horizontal and vertical, proves essential in handling the exponential growth of connected devices, requiring solutions that allow the addition of satellites or increased computational capacity without performance degradation. Lastly, energy efficiency is a limiting factor for the expansion of LEO networks, and studies highlight how energy consumption must be considered when designing these infrastructures, suggesting energy-efficient computing solutions to ensure sustainability. Thus, the studies reinforce the need for a balanced approach to optimize various performance metrics in LEO networks, ensuring that no metric is neglected to the detriment of another.

E. OPTIMIZATION TECHNIQUES

Optimization techniques in LEO edge infrastructures encompass several hierarchical strategies, starting with algorithmic optimization that employs both heuristic and metaheuristic algorithms to enhance computational efficiency and decision-making processes. Resource virtualization plays a necessary part through the use of virtual machines, containers, and functions-as-a-service, to ensure scalable and flexible deployment of services. Additionally, data localization strategies, including edge caching and data replication, are essential for minimizing latency and improving data access speeds by positioning data closer to the end-users. Furthermore, load forecasting techniques, such as time series and trend analysis, are utilized to predict and manage future demands, ensuring optimal resource allocation and maintaining service quality. Figure 7 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

1) RELATED WORK

Various optimization techniques have been proposed to maximize the performance of LEO Edge Computing networks, focusing on heuristic and metaheuristic algorithms, resource virtualization, data localization, and load forecasting. Studies like those by Yuan et al. [63] explore heuristic algorithms to optimize resource allocation in LEO networks, highlighting how these approaches can improve computational efficiency and bandwidth utilization. Similarly, Pachler et al. [64] use metaheuristic algorithms, such as genetic algorithms and particle swarm optimization (PSO), to improve load balancing and resource allocation, allowing for greater adaptability in dynamic LEO satellite networks. Regarding resource virtualization, Ferrus et al. [65] investigate the use of virtual machines in LEO edge architectures, suggesting that the flexibility provided by virtualization can help optimize resources. Zantou et al. [66] emphasize the role of containers as a lighter alternative to virtual machines, being particularly effective in low-latency and high-demand scenarios. Furthermore, Zhang et al. [67] introduce the concept of Function-as-a-Service (FaaS) for LEO networks, which allows specific functions to be executed on-demand, reducing idle resource consumption. Data localization is also a importat technique for optimization in LEO systems. Zhang et al. [20] discuss the use of edge caching to reduce latency in LEO networks, allowing the most accessed data to be stored locally. Works like those by Pfandzelter et al. [68] address data replication as a way to ensure information availability, even in cases of satellite failure or temporary disconnection. Load forecasting has also been explored by several authors. Kato et al. [69] use time series analysis to predict fluctuations in workload, allowing LEO systems to automatically adjust resources in advance. Trend analysis is a complementary approach explored by Bawa et al. [70], focusing on identifying usage patterns over time, which helps in more efficient resource allocation based on future usage predictions.

2) DISCUSSION

The findings of these studies reinforce the purpose of optimization techniques in the context of LEO Edge Computing. Heuristic and metaheuristic algorithms are particularly effective in scenarios where rapid adaptation to changing conditions is required, providing quick solutions to complex resource allocation problems. Resource virtualization emerges as a viable solution to increase the flexibility of LEO infrastructures, allowing computational resources to be allocated and released dynamically according to demand. Regarding data location, caching and replication techniques have proven singificant in reducing latency and improving data availability in distributed satellite networks. Load forecasting is another important technique, as it enables systems to proactively adjust their operations, optimizing resource usage and preventing overloads. These studies demonstrate that a combined approach to optimization techniques is necessary to address the complexity and dynamism of LEO Edge Computing networks.

```
Resource Allocation Policies
 ├─Fairness Policy
 │  ├─Equal resource distribution
 │  └─Proportional fairness
 ├─Efficiency Policy
 │  ├─Maximizing resource utilization
 │  └─Minimizing wastage
 └─Priority Policy
    ├─Priority queues
    └─Preemption policies
```

FIGURE 8. Resource allocation policies branch-cutting taxonomy.

F. RESOURCE ALLOCATION POLICIES

In the context of LEO edge infrastructures, resource allocation policies are fundamental to ensuring optimal performance and service quality. Fairness policies aim to achieve equal resource distribution among all users, ensuring proportional fairness to prevent any user from monopolizing resources. Efficiency policies focus on maximizing resource utilization, striving to minimize wastage to ensure that the infrastructure operates at its peak capacity. Priority policies play a key role in managing resource allocation by employing priority queues and preemption policies, allowing critical tasks to access resources promptly while managing the load effectively to maintain a balance between urgent and routine tasks. Figure 8 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

1) RELATED WORK

Several works investigate fairness, efficiency, and priority policies in the context of LEO systems. Regarding fairness, Tao et al. [71] analyze equitable resource distribution policies, highlighting that in LEO networks, where latency and connectivity can vary significantly, equal distribution ensures that all nodes receive a fair share of the available resources. Xu et al. [72] explore proportional fairness, where resources are allocated based on the demand of each node, ensuring a balance between equality and efficiency. In terms of efficiency, Liau et al. [73] propose policies to maximize resource utilization, showing that LEO satellite infrastructure can be optimized to use the maximum of its available computational and network resources. On the other hand, Wang et al. [74] investigate policies that minimize resource waste, suggesting techniques to ensure that computational power and bandwidth are not underutilized or inefficiently allocated. As for priority policies, Xiaoxue et al. [75] discuss the use of priority queues to give preference to more important tasks, while Ding et al. [76] explore preemption policies, where high-priority tasks can interrupt lower-priority ones to ensure that critical deadlines are met in dynamic edge environments.

2) DISCUSSION

These studies show that different resource allocation policies are essential to balance LEO systems' efficiency, fairness, and priority. Fairness policies are necessary when connectivity is inconsistent, and edge nodes have varying needs, ensuring that no node is excessively penalized due to connectivity limitations or demand. However, these policies must be balanced with efficiency. Studies highlight that maximizing resource utilization is significant in LEO networks, where resources are limited and expensive. In contrast, other studies emphasize minimizing waste, suggesting that idle or poorly allocated resources can harm the system's overall performance. Priority policies are vital in time-sensitive and critical applications, such as IoT and emergency communications, where specific tasks must be prioritized to ensure that latency and performance requirements are met. Therefore, the choice of resource allocation policies should consider the need for efficiency, fairness, and priority to optimize performance in different LEO Edge Computing scenarios.

```
Security and Privacy Considerations
 ├─Authentication and Authorization
 │  ├─User authentication
 │  └─Role-based access control
 ├─Data Encryption
 │  ├─In-transit encryption
 │  └─At-rest encryption
 ├─Anomaly Detection
 │  ├─Intrusion detection systems
 │  └─Behavior analysis
 └─Privacy Preservation
    ├─Data anonymization
    └─Differential privacy
```

FIGURE 9. Security and privacy considerations branch-cutting taxonomy.

G. SECURITY AND PRIVACY CONSIDERATIONS

When considering LEO edge infrastructures, it is vital to prioritize Security and Privacy Considerations, particularly focusing on robust Authentication and Authorization mechanisms, including User authentication and Role-based access control, to ensure only authorized users have access. Data Encryption plays a leading role, necessitating both in-transit encryption and at-rest encryption to protect data throughout its lifecycle. Anomaly Detection is essential, with the implementation of Intrusion detection systems and Behavior analysis to identify and mitigate potential threats promptly. Privacy Preservation methods such as Data anonymization and Differential privacy must be employed to safeguard user information and ensure compliance with privacy regulations, maintaining user trust and the integrity of the infrastructure. Figure 9 shows the proposed taxonomy branch, followed by a presentation of related work and a discussion.

1) RELATED WORK

Recent works explore aspects such as authentication, encryption, anomaly detection, and privacy preservation. In the field of authentication and authorization, studies such as those by Liu et al. [77] propose user authentication methods tailored for LEO networks, emphasizing the need for robust methods to prevent unauthorized access, especially in environments with variable latency. On the other hand, Hui Qi et al. [78] investigate the use of Role-Based Access Control (RBAC) adapted for LEO networks, ensuring that different levels of permission can be effectively managed in distributed systems. Regarding encryption, Khare et al. [79] discuss the implications of encryption in transit, focusing on protecting data transmitted between satellites and edge nodes against interception attacks. Additionally, Amdouni et al. [80] explore data encryption at rest, highlighting the need to protect information stored in dispersed and potentially vulnerable edge nodes. Anomaly detection is also widely explored. Studies such as those by Zhao et al. [81] propose intrusion detection systems tailored for LEO networks, where the dynamic behavior of satellites requires adaptive methods to identify emerging threats. Chundong et al. [82] investigate behavioral analysis to detect anomalous usage patterns that may indicate intrusion attempts or security compromises. Regarding privacy preservation, Petit et al. [83] discuss the use of data anonymization techniques in LEO systems, suggesting that anonymization is an effective approach to protect users' identities in distributed systems. Furthermore, Nguyen et al. [84] explore differential privacy as a technique to ensure that sensitive data are protected even in scenarios where large volumes of data are processed in a distributed manner.

2) DISCUSSION

These studies reveal the complexity of security and privacy challenges in LEO networks. Authentication and authorization are very important issues in protecting LEO systems from unauthorized access, mainly due to the large number of distributed nodes and the need for permission management at different levels. However, robust encryption solutions must complement these measures. Some studies emphasize the importance of encryption in transit and at rest, as communications between satellites and between satellites and edge nodes can be targets for interception attacks. In anomaly detection, studies highlight that intrusion detection systems and behavioral analysis are essential for identifying suspicious activities in a constantly moving and evolving environment, such as LEO networks. Finally, privacy preservation, primarily through data anonymization and differential privacy, is critical to ensure that user data remains protected, even in systems with large volumes of distributed data. These studies underline the need for a holistic approach to security and privacy, where multiple layers of protection are implemented to ensure the integrity and confidentiality of data in LEO systems.

H. SUMMARY

The taxonomy proposed for resource allocation for LEO Edge Computing focuses on categorizing resource allocation across several dimensions, including resource types, allocation strategies, management models, performance metrics, optimization techniques, resource policies, and security considerations. Key resource types include computational, storage, network, and power resources, each critical for LEO edge infrastructure performance. Allocation strategies vary from static to dynamic and predictive methods, enabling effective response to fluctuating demands.

Resource management models include centralized, distributed, and hierarchical frameworks, each with distinct advantages. Performance metrics such as latency, throughput, reliability, scalability, and energy efficiency are essential for optimizing system effectiveness. Optimization techniques, including algorithmic, resource virtualization, data localization, and load forecasting, are crucial in enhancing the adaptability and efficiency of these infrastructures.

The taxonomy also highlights resource allocation policies that emphasize fairness, efficiency, and priority, ensuring optimal performance while meeting specific service requirements. Security and privacy considerations involve robust authentication, encryption, anomaly detection, and privacy preservation, safeguarding the infrastructure and data. Together, these elements form a comprehensive taxonomy that addresses the complexities and requirements of resource allocation for LEO Edge environments, establishing a foundation for future innovations and optimizations in satellite-terrestrial integrated edge systems. Table 5 summarizes the proposed taxonomy.

IV. FUTURE RESEARCH DIRECTIONS

Satellite-Terrestrial Integrated Edge Computing involves the strategic placement of data processing capabilities in closer proximity to the data source, which could be either on satellites orbiting the earth or at terrestrial edge nodes strategically located to minimize distance from the data origin. Such a configuration is key to reduce the delay associated with the transmission and processing of data, thereby enhancing the efficiency and responsiveness of digital services [85].

The significance of this advancement extends beyond mere technical enhancement, as it achieves global coverage, particularly in the context of the Internet and computing services. LEO satellites emerge as a cornerstone in this endeavor, equipped with the capability to provide vital digital services to regions that are remote and historically underserved. This is a important step towards bridging the digital divide, ensuring that the benefits of the digital era are accessible across geographical and socio-economic barriers, thus fostering inclusivity in the digital landscape.

The architecture behind this innovative approach is designed with scalability in mind. The modularity of both satellite constellations and terrestrial Edge Computing nodes highlights this adaptability, creating systems that are efficient and flexible. This modular design allows for the infrastructure to expand in line with growing demand,

TABLE 5. Resource allocation of satellite-terrestrial edge computing.

Dimension	Category	Objective	Key References
Resource Types	Computational	CPU, GPU, and FPGA processing for efficiency and distributed loads	Shi et al. [59] Abbas et al. [1]
	Storage	SSD/HDD for persistence and cache for fast access	Zhao et al. [80] Qiu et al. [55]
	Network	Minimizing latency and optimizing bandwidth	Kim et al. [29] Yu et al. [73]
	Power	Efficiency in battery use and solar energy for sustainability	Li et al. [35] Wang et al. [64]
Allocation Strategies	Static Allocation	Fixed distribution for predictable tasks	Gao et al. [16] Kim et al. [30]
	Dynamic Allocation	Real-time adjustment with auto-scaling	Zhao et al. [78] Wang et al. [67]
	Predictive Allocation	ML-based prediction for proactive allocation	Chan et al. [8] Zhou et al. [82]
	Priority Allocation	QoS and SLAs for prioritizing critical tasks	Tu et al. [62] Mi et al. [46]
Resource Management Models	Centralized	Single control point for uniform allocation	Rodrigues et al. [57] Sun et al. [60]
	Distributed	Collaboration across multiple control points for resilience	Guo et al. [17] Wu et al. [69]
	Hierarchical	Multi-level control with centralized/localized balance	Jeon et al. [22] Li et al. [37]
Performance Metrics	Latency	Round-trip time and processing delay	Kim et al. [30] Li et al. [33]
	Reliability	Uptime and fault tolerance	Wang et al. [65] Herrería-Alonso et al. [19]
	Energy Efficiency	Reducing consumption and optimizing energy use	Gupta et al. [18] Hussein et al. [20]
Optimization Techniques	Metaheuristic Algorithms	Enhanced efficiency for complex resource allocation	Yuan et al. [74] Pachler et al. [49]
	Resource Virtualization	Flexibility with VMs, containers, and FaaS	Ferrus et al. [15] Zantou et al. [75]
	Data Localization	Latency reduction with caching and replication	Zhang et al. [77] Pfandzelter et al. [51]
	Load Forecasting	Proactive adjustment based on time series and trend analysis	Kato et al. [26] Bawa et al. [5]
Allocation Policies	Fairness	Equitable distribution to avoid resource monopolization	Tao et al. [61] Xu et al. [72]
	Efficiency	Maximizing resource usage with minimal waste	Liau et al. [38] Wang et al. [68]
	Priority	Critical task handling with preemption and priority queues	Xiaoxue et al. [70] Ding et al. [12]

ensuring that the network remains robust and can handle an increasing volume of data without sacrificing performance. Scalability is essential for the sustainability and evolution of digital services, enabling adaptation to the constantly changing landscape of digital needs and technological advancements.

A. CHALLENGES

Furthermore, the maintenance and repair of satellites in orbit present an intricate and costly challenge. Unlike terrestrial infrastructure, where upgrades and repairs can be conducted with relative ease, satellites operate in an extreme environment with limited intervention capabilities. The logistics of servicing satellites in space introduce financial and technical constraints that necessitate novel solutions, such as autonomous self-healing systems and extended mission lifespans through predictive maintenance. These challenges are further compounded by the limited computational power available on satellites and edge nodes. Although technological advancements have improved processing capabilities, they remain significantly constrained compared to terrestrial data centers. These constraints impose limitations on real-time data processing and advanced analytics, restricting the types of applications that can be efficiently deployed in space.

The strategic placement and migration of services within the LEO Edge Computing paradigm require a sophisticated orchestration of resources. Decision-making regarding data processing locations—whether on satellites, ground stations, or terrestrial edge nodes—depends on multiple interdependent factors, including latency sensitivity, computational intensity, and dynamic network conditions. Low-latency applications, such as real-time Earth observation and space-based IoT services, necessitate data processing at the nearest available node, often within the satellite

TABLE 6. Key challenges and advances in LEO edge computing.

Challenge	Key Issues	Description and Proposed Advances
Latency Variability	Dynamic Topology	Frequent changes in satellite position require adaptive routing and latency-aware processing strategies.
Computational Constraints	Limited Onboard Processing	Optimization of computational resources through AI-driven scheduling and edge-cloud collaboration.
Service Migration	Network Handover Complexity	Efficient task migration strategies to maintain service continuity despite frequent topology changes.
Space Sustainability	Debris and Collision Risks	Implementation of responsible deorbiting policies and active debris removal mechanisms.
Security	Cyber Threats and Interference	Development of robust encryption methods and secure communication protocols for resilient operations.
Scalability	Network Growth	Modular satellite architectures enabling incremental expansion of LEO constellations.
AI Integration	Autonomous Decision-Making	Incorporation of AI/ML for predictive analytics and adaptive network management.
International Collaboration	Governance and Standards	Establishment of global regulatory frameworks for interoperability and sustainable space operations.

TABLE 7. Emerging trends in LEO edge computing.

Trend	Key Focus	Description and Implications
AI-Driven Optimization	Predictive Analytics	Utilization of AI and ML for real-time resource allocation and performance enhancement.
Autonomous Resource Management	Self-Adaptive Systems	Dynamic workload balancing and task scheduling based on environmental conditions.
Cross-Layer Optimization	Integrated Efficiency	Coordination between network, computation, and energy management to improve service reliability.
Advanced Security Mechanisms	Cybersecurity	Development of AI-driven encryption, intrusion detection, and secure communication protocols.
Energy Efficiency	Power Optimization	Innovations in energy harvesting, adaptive workload distribution, and power-efficient hardware.
Regulatory Evolution	Governance	Formation of global policies to manage frequency allocation, interference, and sustainability.
Service Migration Strategies	Seamless Connectivity	AI-enhanced mobility management to optimize service continuity in dynamic LEO environments.
Sustainable Satellite Deployment	Space Sustainability	Implementation of eco-friendly deorbiting policies and modular satellite designs.

itself or a proximal edge server. Conversely, tasks requiring higher computational throughput may be delegated to ground stations, where more powerful resources can handle intensive workloads.

Service migration further complicates system operations. The high mobility of LEO satellites and fluctuating network conditions demand real-time service handover mechanisms that can seamlessly transfer computational tasks without service degradation. As satellites rapidly transition in and out of connectivity zones, advanced algorithms must ensure that task migration does not introduce excessive latency or data loss. The interplay between service placement and migration exemplifies the broader challenge of maintaining service continuity and performance optimization in a highly dynamic environment. The continued development of AI-driven orchestration strategies and predictive analytics is vital in mitigating these limitations and improving operational efficiency.

The rapid proliferation of LEO satellite constellations introduces pressing concerns regarding space sustainability. The accumulation of satellites in low orbit heightens the risks of space debris generation and potential collisions, necessitating proactive measures for debris mitigation, satellite deorbiting protocols, and sustainable space operations. The finite operational lifespan of LEO satellites underscores the necessity of responsible end-of-life management strategies, ensuring that decommissioned satellites do not contribute to the growing space debris problem.

Security is another critical challenge in LEO Edge Computing. The distributed nature of edge computing in space exposes systems to a broad spectrum of cyber threats, including signal jamming, spoofing, and unauthorized data interception. The development of robust security frameworks, leveraging encryption, secure communication protocols, and decentralized trust mechanisms, is imperative to safeguard sensitive data and ensure the integrity of LEO networks. In parallel, the governance of space-based edge computing necessitates unprecedented levels of international collaboration. The establishment of standardized regulatory frameworks and interoperability protocols among nations and private entities is crucial for fostering a sustainable and secure LEO ecosystem.

The advancement of LEO Edge Computing is contingent upon continuous innovation in network architectures, satellite miniaturization, and communication technologies. Future frameworks must dynamically allocate computational and storage resources in response to shifting operational demands, ensuring adaptability to the unpredictable nature of space environments. The convergence of miniaturization, enhanced onboard processing, and emerging communication technologies, such as optical beam networks, holds the potential to significantly augment the capabilities of LEO satellites, paving the way for the next generation of space-based edge computing. Table 6 summarizes research challenges.

B. TRENDS

Future research in LEO Edge Computing is poised to be driven by emerging technological trends that enhance performance, security, and sustainability. The increasing scale of satellite constellations demands intelligent and scalable resource management strategies. A major trend is the integration of AI and machine learning models to enable predictive analytics and real-time optimization. Autonomous resource allocation mechanisms, where satellites dynamically manage computational workloads based on real-time environmental and network conditions, are gaining traction. Furthermore, cross-layer optimization techniques are being explored to harmonize network, computation, and energy efficiency, ensuring seamless data transmission and robust service continuity.

Security and privacy in LEO networks remain a focal point, as these infrastructures are vulnerable to cyber threats, jamming, and signal interception. Future advancements will emphasize the development of sophisticated encryption methods, AI-driven intrusion detection systems, and resilient network architectures to enhance data integrity and communication reliability. In parallel, energy efficiency is a critical area of innovation. Research is trending toward novel energy-harvesting techniques, power-efficient hardware, and adaptive workload distribution mechanisms that optimize power consumption while maintaining computational performance.

Regulatory and governance frameworks are evolving to accommodate the rapid deployment of LEO satellites. Efforts are underway to establish global policies that ensure equitable access, manage frequency interference, and promote sustainable space operations. The collaboration between industry stakeholders, governments, and academia is becoming increasingly significant in shaping technological standards and governance models that will dictate the future of LEO Edge Computing.

As the field advances, several persistent challenges are being addressed through cutting-edge trends. Efficient resource allocation methods are being refined to balance processing power with energy constraints. Service migration strategies are leveraging AI-driven decision-making to handle satellite mobility while ensuring uninterrupted connectivity. Security solutions are evolving to counteract emerging cyber threats, integrating advanced cryptographic techniques and distributed trust mechanisms. Additionally, sustainable satellite deployment is being explored, incorporating eco-friendly deorbiting strategies and modular satellite architectures to minimize space debris. Table 7 summarizes research trends.

V. CONCLUDING REMARKS

The integration of Edge Computing within the LEO landscape opens a new frontier of possibilities and challenges, including addressing the multifaceted hurdles of variable latency, limited resources, sustainability, security, and international regulation. A key aspect of this evolution is the integration of AI/ML into satellite networks, marking a significant paradigm shift in space-based data processing and analysis. By leveraging these technologies, it is possible to process extensive datasets at the edge of space, reducing the necessity for data transmission back to Earth. This not only poses the possibility of enhancing data analysis efficiency but also empowers satellites with autonomous decision-making and real-time predictive analytics capabilities, significantly benefiting both space-bound and terrestrial missions through faster, more informed decision-making. The realization of LEO Edge Computing ultimately hinge on the establishment of global standards and security protocols to ensure system interoperability and safety. In this regard, international collaboration among space agencies, governments, industry stakeholders, and academic institutions is required. Particular technical challenges include the development of algorithms for seamless service migration and handover, as well as the energy-efficient resource allocation in the LEO environment.

The proposed taxonomy in this study organizes the complex landscape of resource allocation for Low Earth Orbit (LEO) Edge Computing, offering a structured framework to analyze and optimize resource allocation in satellite networks. This taxonomy addresses a pressing need within the research community to systematically classify the diverse elements involved in LEO-based edge computing, including computational resources, storage, network dynamics, power requirements, and security protocols. By creating precise categorizations, this taxonomy enables researchers and practitioners to navigate the multifaceted challenges of resource allocation for LEO Edge Computing with greater clarity and precision. Furthermore, it lays the foundation for future advancements by identifying critical areas for optimization and suggesting practical allocation strategies tailored to the unique constraints of LEO environments.

The findings within this taxonomy reveal significant insights that underscore the transformative potential of LEO Edge Computing in resource allocation. For instance, static and dynamic allocation strategies cater to predictable and fluctuating demand scenarios, enhancing the network's flexibility and scalability. Additionally, incorporating optimization techniques such as data caching and load forecasting demonstrates a sophisticated approach to handling resource constraints. The prioritization of security measures, including robust encryption and anomaly detection, ensures data integrity and resilience, which are essential for sustainable operation. These elements collectively position LEO Edge Computing as a viable solution to extend global connectivity, particularly for underserved regions, and effectively address latency-sensitive applications.

This work serves as a research tool and a strategic blueprint for future developments in LEO Edge Computing. By offering a comprehensive overview of resource management models, performance metrics, and allocation policies, this framework supports informed decision-making and facilitates the design of robust, scalable LEO networks. As the field progresses, this taxonomy will likely guide innovation and address the technical and operational challenges inherent to edge computing in space. This study thus contributes to a growing body of knowledge, fostering a collaborative environment where standardized approaches can drive forward the effective utilization of satellite-based edge computing systems.

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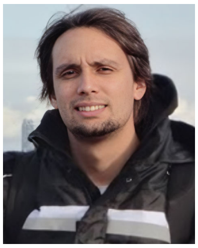

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