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Research article

The concept, technical architecture, applications and impacts of satellite internet: A systematic literature review

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ABSTRACT

To conduct a comprehensive review of international publications, this study focuses on discussing the development status and future trends of Satellite Internet. In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, all peer-reviewed publications in English from journals indexed with the SSCI and SCIE categories of the Web of Science are reviewed, with an emphasis on studies that focused only on the architecture, functions, technologies, and applications of Satellite Internet across the entire period. A total of 2085 records were identified, of which 69 met the inclusion criteria. Through a systematic literature review, the results show that three main research perspectives were summarised and a unified Satellite Internet definition and technical architecture were innovatively provided. Additionally, Satellite Internet application industries and scenarios were comprehensively sorted, and four types of potential impacts were categorised and discussed. This study provides an insightful analysis of recent trends in Satellite Internet research, which may provide guidance for planning and supporting the forthcoming wave of information infrastructure growth. Future research should broaden the scope of theoretical studies when assessing the strategic importance of Satellite Internet. Further quantitative research is needed to provide a more scientific and comprehensive perspective.

1. Introduction

Following wired and wireless communications, Satellite Internet is regarded as a major breakthrough in providing global seamless coverage in next-generation 6G oriented Space–Air–Ground Integrated Networks (SAGIN) [1,2]. With the accelerated evolution of the global technological revolution and industrial transformation, Satellite Internet will become the main battlefield for strategic technological competition among countries and a crucial domain for a country to obtain new advantages in global network competition owing to its fundamental nature, penetrative capability, and empowerment effect [3]. Therefore, countries around the world have accelerated the strategic deployment of Satellite Internet. For instance, the United States first opened an experimental spectrum for 6G, vigorously promoting research and practices in SAGIN. Europe leverages the strengths of various parties to collectively advance the research and development of Satellite Internet and has proposed that 6G services will achieve seamless global coverage [4]. In April 2020, China for the first time explicitly proposed incorporating Satellite Internet into the scope of the new infrastructure construction policy and spared no effort to support the development of a high speed, ubiquitous, integrated, and secure Satellite Internet industry. At the same time, Japan and South Korea are also actively formulating top-level designs and deploying strategies aimed at

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strengthening national Satellite Internet cooperation [5]. Consequently, conducting core theoretical and technological research on the Satellite Internet has already become a global consensus that can help a country take a leading position in international competition.

The current 5G system is still mainly used for urban coverage and is unable to fulfil the demand for ubiquitous connectivity in remote areas, such as oceans, space, mountains, forests, and deserts [6]. Compared to 5G, Satellite Internet can provide global seamless network coverage services, which not only fills the shortcomings of terrestrial networks but also meets the higher-quality communication requirements of digital industries such as virtual reality (VR), Vehicle-to-X (V2X), and the Internet of Things (IoT). Additionally, Satellite Internet can complement terrestrial networks, forming novel space-ground integrated networks (SGINs) [7]. With the continuous maturity of technologies, the application of Satellite Internet has had a significant impact on national cyberspace, culture, economy, and even political security. During the Russia–Ukraine conflict, the United States Starlink service system, which is a low earth orbit (LEO) satellite internet constellation developed by SpaceX to provide global broadband coverage, provided significant intelligence support to Ukraine, and the borderless global network and information space posed by this system presented disruptive challenges to the strategic, tactical, and operational forms of traditional warfare [8]. Satellite Internet plays an important role in the digital economy, driving the development of platform economies, electronic consumption, digital trade, and digital infrastructure. Therefore, effectively harnessing the role of Satellite Internet is critical to the evolution of global economic and geopolitical development.

From an academic perspective, the existing research has primarily focused on the development of Satellite Internet technology, standards, and the outlook of new technologies. Chen et al. [5] provide an overview of Satellite IoT, with an emphasis on revealing the characteristics of IoT services. It also shows the development trends of Satellite IoT in stimulating and encouraging further research in this broad area. However, the academic community has not yet reached a consensus on the connotations and characteristics of Satellite Internet. Second, most studies regard Satellite Internet as a single technical tool. Few studies have explained the fundamental theories and enabling mechanisms of Satellite Internet, and the research theories and perspectives applied are relatively fragmented, which is insufficient to achieve a global consensus on unified standards of Satellite Internet [9–11]. Furthermore, the continual extension of the Satellite Internet technology ecosystem led by one country can encompass data and information across many fields, such as global aviation, navigation, and finance [12,13]. As orbital and frequency band resources become increasingly scarce, they pose great challenges to the national network sovereignty and security of other countries [14]. At the same time, the diverse technological development paths of different countries not only hinder the application and diffusion of technology, but also undermine the existing communication ecosystem construction, resulting in substantial resource wastage and sunk costs [15]. These theoretical gaps and security challenges urgently require a more detailed review of the development and use of Satellite Internet. The academic community is increasingly focusing on the role of Satellite Internet in influencing the development of emerging economies. Shaengchart [16] used a quantitative approach to study the impact of the Starlink satellite project on Internet provider services in emerging economies. Therefore, more attention should be paid to the potential impacts of Satellite Internet.

To further consolidate the theoretical foundation and fill the gap in the research on building a unified theoretical framework for Satellite Internet, this study takes Satellite Internet as a unified research object and conducts a systematic literature review to reveal the key role played by Satellite Internet in the construction of the national strategic information infrastructure, aiming to provide theoretical guidance and references for research conducted by academia and industry. To guide our investigation, we propose the following research questions.

(1) What are the concepts and main characteristics of Satellite Internet?
(2) What are the core technologies and technical architecture of Satellite Internet?
(3) What are the application industries and scenarios of Satellite Internet?
(4) What are the potential impacts of Satellite Internet?

The following sections of this paper provide a comprehensive overview of the research process and findings, which is arranged as follows. Section 2 briefly introduces the materials and methods used in the literature search and review. We present our findings in Section 3, highlighting the recent advances in international Satellite Internet research in four key areas. The discussion in Section 4 explores the implications of these findings and their potential influence on the future strategic layout of Satellite Internet, as well as the limitations of this study. Finally, Section 5 presents the main conclusions and suggestions.

2. Methodology

2.1. Eligibility criteria and principal

To answer the specific research questions mentioned above, this study adopts a systematic literature review method and defines three basic principles to guide the implementation of systematic reviews, ensuring that the process of comprehensive evaluation of the literature is transparent and objective. The formulation of these principles not only helps to control and reduce the bias of researchers' literature selection and provides more reliable and accurate answers to research questions, but also maximises the scientific and rigorous nature of knowledge innovation and ensures that the collected papers are consistent with the research objectives [17]. The three basic principles are as follows: 1) Clear exclusion and inclusion criteria. This study established five exclusion criteria for papers: non-English, missing basic information, completely irrelevant, and irrelevant, while defining two inclusion criteria: relevant and closely relevant. Table 1 provides comprehensive information on the screening criteria and their explanation. 2) Objective assessment strategy. The selection of each paper and the collection of coding data were assessed by two assessors familiar with the basic knowledge of Satellite Internet. In cases of disagreement among the assessors, a final judgement was made through discussion. 3) Evidence-based data collection. For subjective judgement data (e.g. Satellite Internet concept), the original text of the paper was collected and used as supporting material.

2.2. Systematic literature review methods

A systematic literature review is considered an indispensable method for synthesising the results of research articles [18,19]. Compared with other traditional review methods, it utilises a predefined and explicit process to systematise research into an interpretative framework and then presents the findings to scholars and decision-makers in a relevant and easily understandable manner [20]. The systematic literature review method is commonly used to address phenomena that are not fully understood [21], therefore, it is better suited to achieve the objectives of this study. Furthermore, a systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Protocol 2020 guidelines. Although the PRISMA protocol was initially created in the healthcare sector, it has gained widespread recognition and adoption among researchers in various fields, extending its application to emerging topics, such as metaverses in medical emergencies [22] and security in chatbots [23].

This study followed the guidelines of the PRISMA methodology, which divides the review process into four phases: paper identification, paper screening and assessment, paper inclusion, and data processing and coding [24]. The paper identification stage is responsible for retrieving all papers from selected databases that may be relevant to the topic of Satellite Internet. The paper screening and assessment stage is responsible for filtering and retaining papers that contain complete information and directly related to the topic of Satellite Internet. The paper inclusion stage is responsible for incorporating and categorising papers that met the screening and evaluation criteria according to their relevance. The data processing and coding stage involve the preprocessing and coding of the data from the included papers (see Fig. 1).

2.3. Data selection process

This research aims to conceptualise the latest technological paradigm of Satellite Internet and systematically analyse its applications and potential impacts. To ensure the comprehensiveness and interdisciplinary nature of the included research, the Web of Science (WoS) database was chosen, which not only covers works published in 8700 journals, but also focuses on a wider range of disciplines, including hard sciences, technology, social sciences, art, and humanities [25]. Compared to Scopus, which is also a leading electronic database in different specific disciplines and has been widely adopted in prior academic research, WoS has a higher impact factor and stronger coverage rate in the research field [26]. Here, we refer to Singh et al.'s [27] approach for extracting data from journals indexed by SSCI and SCIE categories in the WoS database.

Specifically, in November 2023, we searched relevant articles with the topic of "Satellite Internet" in WoS databases, excluded articles not indexed by SSCI and SCIE, and collected 2085 papers in total. After deleting 113 duplicates, 1972 papers were preliminarily screened and 803 papers were obtained after excluding non-English (NCE), missing essential information (FIL), and non-academic articles (ENR-1) by reading article titles and other basic information. Next, we conducted a preliminary evaluation of the selected papers by reading the abstracts and keywords, and excluded 734 papers that are not related to Satellite Internet (ENR-2) and did not focus on Satellite Internet research (NR). After the papers were screened and assessed, we examined all eligible papers in detail and categorised them according to different inclusion criteria subcategories: relevant (R) and closely related (CR). Ultimately, 69 papers were collected, consisting of 31 closely related, 26 partially related, and 12 background support papers. Although the final sample size was relatively small, it fell within the recommended range for systematic review methods, exceeding the minimum sample size threshold of 40 articles [18].

Finally, we extracted, processed, and encoded the basic information of the collected sample articles, such as the title, authors, and journal, as well as key information such as concepts, core technologies, technical architecture, application industries, scenarios, and the impact of Satellite Internet, to explore and analyse the subsequent research questions. The results of the data coding were exported into an Excel spreadsheet and can be found in the supplementary material at the end of this paper.

Table 1
Exclusion and inclusion criteria for papers and their explanations.

Exclusion/ inclusion	Criteria	Criteria explanation
Exclusion	non-English(NCE)	Papers written in languages other than English, e.g. German, Spanish.
	Missing basic information(FIL)	The authors, affiliations, abstracts, and source journals information of the paper are incomplete
	Completely irrelevant (ENR)	(ENR-1). Non-academic papers: conference reviews, academic statements, special issue presentations, newspapers, etc. (ENR-2). Although keywords related to Satellite Internet appeared in the paper, the paper itself is not related to Satellite Internet: e.g., satellite night-time light data.
	irrelevant(NR)	Papers do not focus on Satellite Internet reviews, surveys, discussions, and problem solving: Satellite Internet is used only as a case study or appears only in the research background, future perspectives, or references of the paper
inclusion	relevant(R)	Satellite Internet as a supportive context for the challenges, issues or trends addressed by the study.
	closely related(CR)	The content of the paper is devoted throughout to Satellite Internet research.

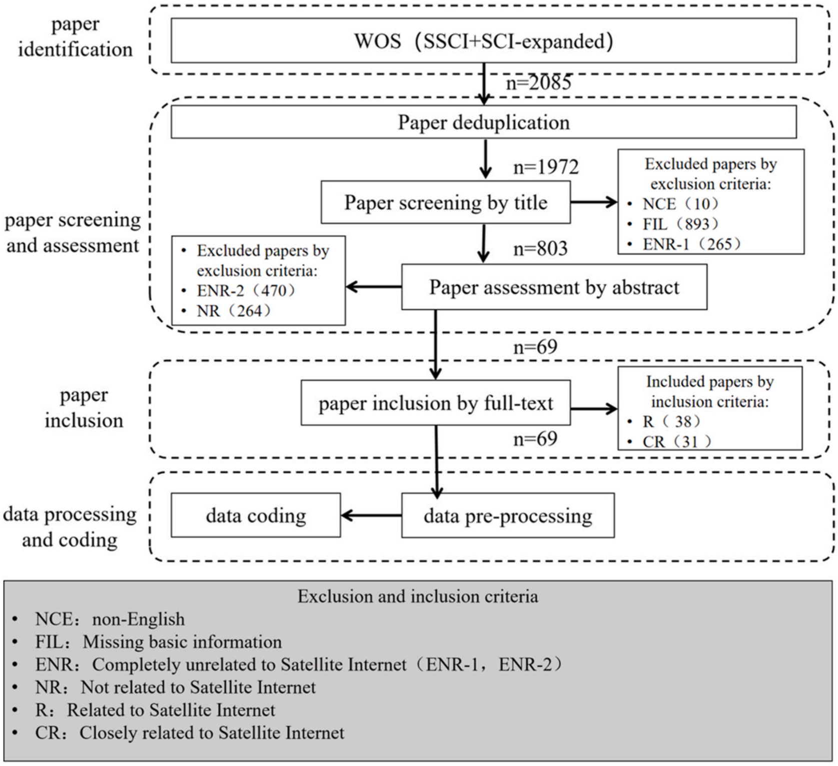

Fig. 1. Different stages of PRISMA

3. Analysis of results

3.1. Relevant concepts and main characteristics of satellite internet

Concepts are fundamental tools that serve as starting points for understanding the essential attributes of things. The ambiguity of this concept seriously erodes the basis of future research. Because Satellite Internet remains an emerging concept, to clarify its key elements, distinguish it from existing concepts, and delimit the scope of research, we reorganised the concepts and features related to Satellite Internet identified in the collected papers from the perspective of functionality. In doing so, a unified concept of Satellite Internet was provided to address the first research question.

Among the 69 collected papers, 38 attempted to provide an original or cited definition, whereas 31 did not present a clear definition. This inevitably raises concerns about the ambiguity of the concept of Satellite Internet. Additionally, owing to the dynamic nature of technological progress, scholars' definitions of Satellite Internet may be influenced by temporal and spatial changes. Therefore, in accordance with the evolution of relevant concepts, this study compiles a list of concepts and characteristics for Satellite Internet from the utility perspective and identifies three main research perspectives: network architecture ($n = 16$), connection objects ($n = 8$), and satellite type ($n = 14$). The following section provides a detailed analysis of each perspective.

3.1.1. Space nodes, space-based network and space–terrestrial integrated network from the perspective of network architecture

From the perspective of network architecture, Satellite Internet initially refers to space nodes supported by terrestrial networks [28], which only use satellites as transparent transmission channels and a globally distributed ground network to process and receive data. Typical representatives of such networks mainly include Inmarsat, Intelsat, and the wide band global satellite (WGS) communication system of the United States [29], which began networking in the 1960s, 1970s, and 1990s, respectively, with the initial purpose of providing continuous coverage communication services for military activities. Compared to the other two types of network architectures, space nodes supported by terrestrial networks require low-complexity space equipment, making the system easier to maintain and upgrade. However, as the core components of the network are still deployed on the ground, their ability to resist attacks is relatively poor.

Following technological advancements and optimisation, in addition to satellites, other space nodes, such as air vehicles, spacecraft, and various satellites in different orbits, have been incorporated into networks, collectively referred to as space-based networks [30]. The anti-attack capability of these networks has greatly improved, mainly because they can provide services through inter-satellite links (ISL), where signals can be demodulated and decoded on satellites and then directly transmitted to the destination through suitable inter-satellite routing without the need for terrestrial network participation. However, this has brought about the complexity of space equipment and an increase in construction and maintenance costs. Typical representatives of space-based network are the Iridium and Advanced Extreme High Frequency (AEHF) satellite systems of the United States [31], both of which achieve global communication through satellite-to-satellite relay communication.

The increase in the number of space nodes equipped with powerful communication links makes efficient space-terrestrial integrated communication possible [32]. In recent years, an increasing number of scholars have proposed the concept of space–terrestrial integrated networks (STINs) [33], which manifest as space networks responsible for global coverage, while terrestrial networks undertake most management and control functions. It can be seen that STINs combine the advantages of the two types of networks mentioned above, not only ensuring network security, but also serving as an extension of existing terrestrial networks, effectively reducing construction costs and making them more cost-effective. The characteristics of STINs are easy deployment, security and reliability, large-scale mobility, constant quality of service (QoS), broadcasting, and multicast. Furthermore, creating virtual isolation and logically parallel networks helps to further improve the continuity, universality, and extensibility of services, achieve a wide range of complex services and vertical applications, and narrow the digital divide. Some scholars have extended the concept of STINs to space–air–ground integrated networks (SAGIN) [7]. Both are envisioned to achieve global coverage for 6G and beyond, representing the latest paradigm of Satellite Internet [34].

3.1.2. *Internet of satellite and Satellite Internet of Things from the perspective of connection objects*

According to the different service objects, concepts related to Satellite Internet can be classified into two categories: user-oriented Internet of Satellites (IoS) and device-oriented Satellite Internet of Things (SIoT). The former refers to a system paradigm that creates multiple heterogeneous satellite networks based on autonomous satellite applications [35], which means that no satellite system architecture is predefined, but ad hoc inter-satellite networks are deployed based on specific tasks. Accordingly, SIoT refers to a broader internet connection with underserved or unserved remote IoT devices via satellite networks [36]. In recent research, SIoT has been characterised as a real-time network system capable of ensuring the freshness of various IoT devices in time-sensitive scenarios [37]. The biggest difference between the two is that IoS is mainly designed to provide on-demand services to users with characteristics such as low latency, high speed, adaptability, flexibility, extensibility, autonomy, and timely and accurate information [38]. Although SIoT can also utilise the vertical application of satellite slicing networks to provide customers with different levels of flexibility, its primary purpose is to connect terminal devices in sparsely populated and remote areas, which are renowned for their remote, low-power, all-weather service capabilities and strong resilience.

3.1.3. *GEO, LEO satellite internet and hybrid space network from the perspective of satellite types*

In general, satellites can be divided into three main types according to their orbital height: LEO, medium earth orbit (MEO), and geostationary Earth orbit (GEO) satellites [1]. Unfortunately, research on the MEO Satellite Internet is relatively scarce owing to several factors. On the one hand, MEO satellites have narrower coverage than GEO satellites and exhibit higher latency than LEO satellites. However, the cost of deploying and maintaining MEO satellite networks is high because they require more sophisticated technologies to maintain stable orbits. Consequently, existing studies predominantly focus on GEO or LEO scenarios alone, or integrate other kinds of satellites, particularly MEO satellites, into hybrid networks with LEO or GEO satellites [39]. Therefore, this article mainly introduces three types of Satellite Internet from the perspective of satellite types: GEO, LEO Satellite Internet, and hybrid space network.

Badavi [40] defines the network composed of satellites in a GEO Satellite Internet. GEO satellites possess abundant communication and computing resources, with one satellite covering almost the entire hemisphere and forming a regional communication system. GEO Satellite Internet has a large bandwidth, low latency, high speed, and seamless coverage. One of its typical representatives is the network composed of Chinasat 16, Chinasat 19, and Chinasat 26 High Throughput Satellites (HTS) [41], which can completely cover the entire territory of China and the key areas along "The Belt and Road Initiative" co-construction countries.

LEO Satellite Internet is the fastest growing and most concerning concept in recent academic research. This refers to a network composed of satellites with an orbit altitude of less than 2000 km [11]. LEO Satellite Internet requires relatively smaller satellites and lower networking costs. However, owing to the limited coverage of one or more LEO satellites, global coverage must be provided by establishing large satellite constellations, resulting in an increase in the number of satellites required for deployment [42]. Compared to GEO and MEO satellite systems, LEO satellite communication can utilise a low-orbit profile to connect massive numbers of ground users with low round-trip latency and provide high-speed data transformation services. Additionally, the manufacturing and launch costs of LEO satellites are relatively low, making them more likely to achieve global coverage. Typical representatives of giant global LEO Satellite Internet constellations include Oneweb of the United Kingdom, Telesat of Canada, and Starlink of the United States [43], all of which use hundreds of satellites and are designed to provide low-latency broadband services to global ground users. Starlink is successful and its commercial value continues to increase [44].

The rapid expansion of Satellite Internet users and the emergence of new applications pose challenges in delivering diverse services through GEO or LEO networks alone. The propagation latency from users to GEO satellites is excessively high for time-sensitive tasks, whereas LEO satellites face constraints owing to limited onboard resources, leading to increased waiting and processing delays. In this context, hybrid space networks play an important role in satisfying the diverse needs of users. A hybrid space network refers to a network system consisting of satellites in different orbits, including GEO, inclined geosynchronous orbit (IGSO), and MEO satellites. It provides enhanced navigation services through LEO and high-altitude platform stations (HAPS). This hybrid network paradigm can encourage cooperation among satellites, dynamically adjust user-scheduling strategies, and improve the efficiency of satellite resource utilisation [45]. A typical hybrid space network is the Beidou Navigation Satellite System of China [46], which is at the forefront of Satellite Internet research and has broad future development prospects.

3.1.4. The unified concept of satellite internet

This study summarises the related concepts and corresponding characteristics of Satellite Internet proposed in existing research from different perspectives, as shown in Fig. 2.

It can be seen that the intention and extension of Satellite Internet are still evolving, and neither industry nor academia has provided a unified and clear definition. However, at the functional level, different periods and perspectives of Satellite Internet have always been centred on five key features: global coverage, low latency, high speed, extensibility, and vertical application. This provides an approach for building a unified conceptual framework for Satellite Internet. First, global coverage, low latency, and high speed constitute the external characteristics of Satellite Internet. By providing seamless global coverage, human cyber–physical integration, high speed, and smooth network connections, Satellite Internet has broken through the physical constraints of ground space, expanded network coverage to the three-dimensional range of the entire Earth, and provided the foundation and guarantee for cross-space-time activities. Extensibility and vertical application constitute the intrinsic value of Satellite Internet, which not only provides a solid communication infrastructure with strong security and high damage resistance for the development of the national digital economy but also helps to achieve a digital society, business model innovation, and value creation by meeting the broad needs of various industries and connecting entities.

In summary, this study provides the following unified concept of Satellite Internet: Satellite Internet is a high-speed, diverse, solid, and full-coverage network based on satellite communications, which forms a large-scale network by launching a certain number of satellites and uses satellites as a medium to interconnect with ground equipment. It takes the enhancement of the effectiveness of traditional terrestrial networks (i.e. coverage, transmission rate, connection objects, etc.) as its starting point and aims to realise the ubiquitous communications vision (i.e. Space–Air–Ground-Sea Integrated Networks) of a new-generation network, which has important military, social, and economic value and provides a strong information infrastructure guarantee for national development.

3.2. Core technologies and technical architecture of satellite internet

Technical architecture is the foundation for the development of Satellite Internet, involving complex technical sorting and integration. However, the introduction of the core technologies and architecture of Satellite Internet in existing research is relatively scattered, and it is not yet known whether the focus of different research perspectives is the same. Therefore, in this section, we first extract the core technologies of Satellite Internet from all selected articles, then compare the differences in the core technologies from different perspectives, and finally sort out and summarise the unified technical architecture of Satellite Internet to answer question two.

3.2.1. Overall review of core technologies

Generally, there are 37 different technologies involved in the 69 collected papers. As shown in Fig. 3, the technologies with the highest frequency in all collected articles include fifth-generation mobile communications (5G), unmanned aerial vehicles (UAVs), satellite communication (SatCOM), Blockchain, ISL, edge computing, sixth-generation mobile communications (6G), and global navigation satellite system (GNSS) technologies. As cutting-edge technologies lead to a new round of global digital information infrastructure construction, these technologies can not only promote the development of Satellite Internet but also further coordinate with it to accelerate the construction of network ecosystems.

5G is recognised as one of the core enabling technologies for the next stage of Satellite Internet. The number of studies combining LEO satellites with ground network infrastructures to support ubiquitous Internet service coverage has been continuously increasing [47]. Existing 5G is trying to enhance the non-terrestrial network by improving the data transmission rate, bandwidth, and large-scale device connection [48], which can not only significantly improve the application of Satellite Internet in latency-sensitive scenarios, but also realise the connection between IoT devices and Satellite Internet. For example, Maraveas et al. [49] believe that the global deployment of advanced 5G technologies and LEO constellation broadband Internet will enhance the integration of IoT systems, thus optimising their applications in precision agriculture and smart greenhouses.

Multiple studies have suggested that UAVs will play a pivotal role in future Satellite Internet systems, particularly for on-demand coverage extension and prompt capacity enhancement. UAV can be deployed in the air as relay stations to provide better channels and wider coverage, thereby optimising the performance of mobile communication systems [50]. UAVs can provide temporary or mobile

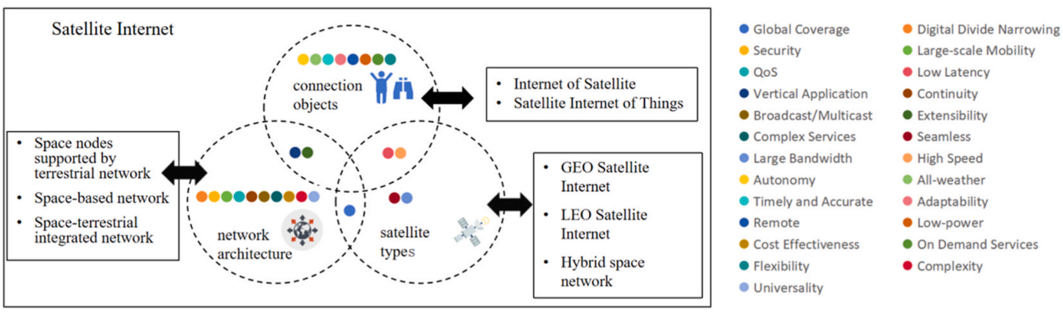

Fig. 2. Concepts and key features of Satellite Internet.

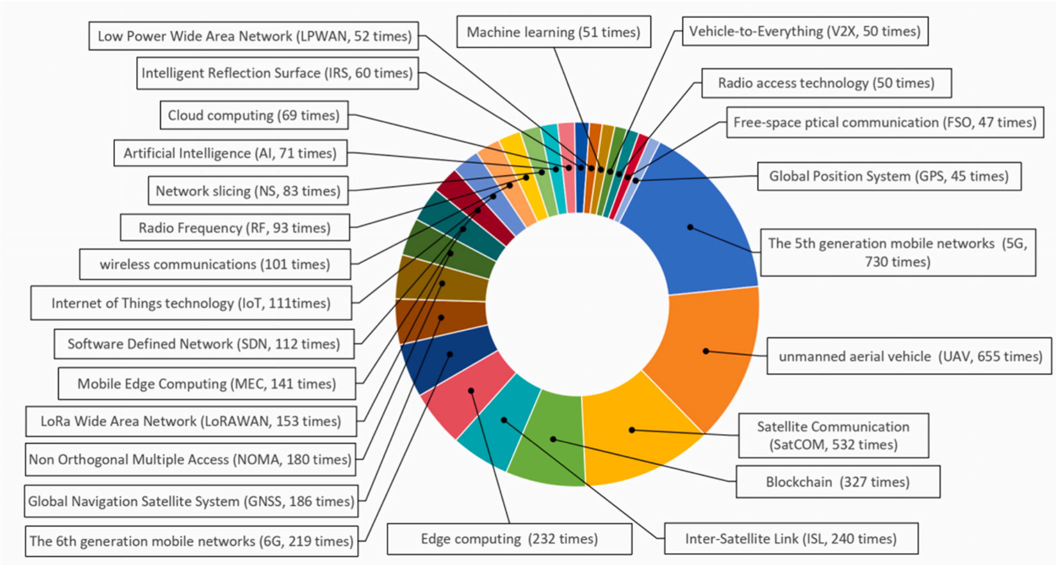

Fig. 3. Satellite Internet's technologies with the highest frequency in collected articles.

communication support in specific areas, particularly those with sparse populations or complex terrain. For instance, Fang et al. [51] proposed establishing a nearshore network by collaboratively utilising onshore terrestrial base stations (TBSs) and tethered UAVs to address the wide sparsity of maritime IoT and efficiently extend terrestrial services beyond the shoreline. Thus, many innovative applications can be created to promote the development of the digital economy.

3.2.2. *Classification of satellite internet technology systems*

This study further compares the similarities and differences in research on the core technologies of Satellite Internet from the perspectives of network architecture, connection objects, and satellite types. As shown in Fig. 4, there are 23 types of technologies proposed frequently by two or more perspectives, which is consistent with the most frequent technologies in all articles. In addition, four unique technologies have been emphasised by studies from a network architecture perspective: satellite-based augmentation system (SBAS), space-to-ground quantum network, modulation technique, and mobile communications. These technologies were proposed early and have been used to address issues such as information transmission between satellites and the ground, precise positioning and navigation, and flexible allocation of network resources. For example, satellite quantum key distribution technology enables secure network communication between multiple nodes, which requires effective scheduling of communication with terrestrial stations [52]. Research from the perspective of connection objects also mentioned four specific technologies: blockchain, network slicing (NS), intelligent reflection surfaces (IRS), and cloud computing. These new technical solutions are more inclined toward solving the problems of signal coverage and big data security. Typically, an IRS is a planar surface composed of numerous passive reconfigurable reflecting elements [53] that can enhance wireless signal propagation through intelligent control of reflections. In this manner, IRS is able to effectively address signal coverage obstacles in blind spots within large buildings or obstructed areas, thereby facilitating ubiquitous communication. Studies on satellite types involve three specific technologies: vehicle-to-everything (V2X), HTS, and visible light communication (VLC). These cutting-edge technologies focus on communication in high-speed mobile environments,

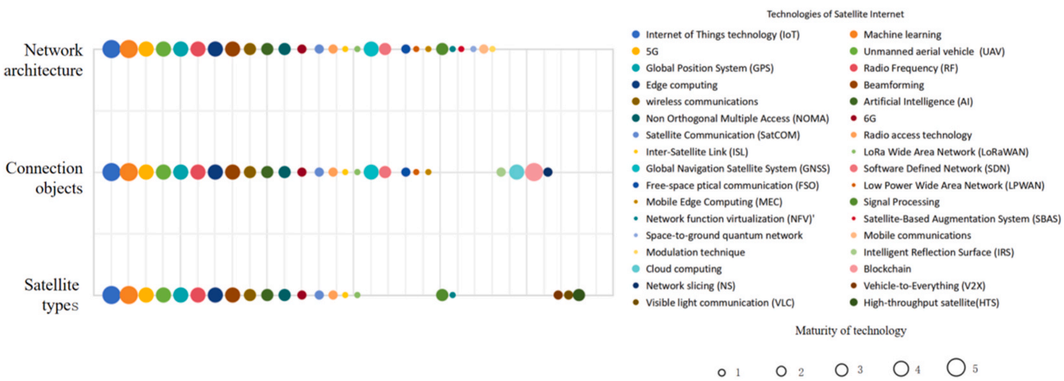

Fig. 4. Satellite Internet's technologies with the highest frequency in articles from different perspectives.

short-distance communication, and data transmission between satellites. For example, VLC is a new wireless communication method that utilises optical signals in the visible light band to transmit data and information. VLC has also been proven to have enormous potential for exchanging information between vehicles and infrastructure in intelligent transportation systems [54].

In summary, research from the perspective of network architecture emphasises finding more convenient and low-cost connection solutions to compensate for the insufficient coverage of terrestrial networks, whereas the perspective of connection objects focuses on developing solutions for ubiquitous communication and data security issues to meet the needs of a wide range of human cyber-–physical integration. Compared with the above two perspectives, the maturity of key technologies from the satellite-type perspective is relatively low (see Fig. 4), mainly emphasising the improvement of resource scheduling and network efficiency. In addition, the maturity of Satellite Internet technologies overlapping under different perspectives is generally high, providing researchers with a basis for realising efficient technology synergy and sharing.

3.2.3. *The unified technical architecture of satellite internet*

After obtaining the core technologies of Satellite Internet, using the text data mining software KH coder and by referring to the relevant literature, we further decompose the different technologies and build a unified Satellite Internet technical architecture. As shown in Fig. 5. Satellite Internet is divided into four technical layers: physical, link, network, and application. Next, we provide detailed explanations for each layer. (1) The physical layer is considered the cornerstone of Satellite Internet applications and services. Because the physical layer is primarily responsible for the connection, access, and signal transmission between physical devices[55], it must comply with specific parameters to maintain communication quality and system sustainability [2]. All physical components, including satellites, UAVs, HAPS, IoT devices, sensors, and other peripheral objects, should be placed. Furthermore, different frequency bands, including Ku, Ka, and Q/V, should be deployed optimally. Careful investigation must also be given to multicarrier modulation and antenna design, especially to provide a very low bit error rate and extremely high interruption mitigation solutions through propagation channel modelling. (2) The Link layer is crucial to achieve high-speed data transmission and large-scale user device access [56]. In this layer, various technical modules are used to reduce transmission power consumption and improve the security, stability, and scalability of bidirectional communication. It is worth noting that owing to the poor performance of the transmission control protocol (TCP) in error-prone environments of wireless channels, recent research on free-space optical (FSO) networks has begun to propose effective solutions. Given that FSO communication itself can provide high-speed data services over long distances without depleting radio frequency (RF) resources, it is considered to have broad application prospects in different network

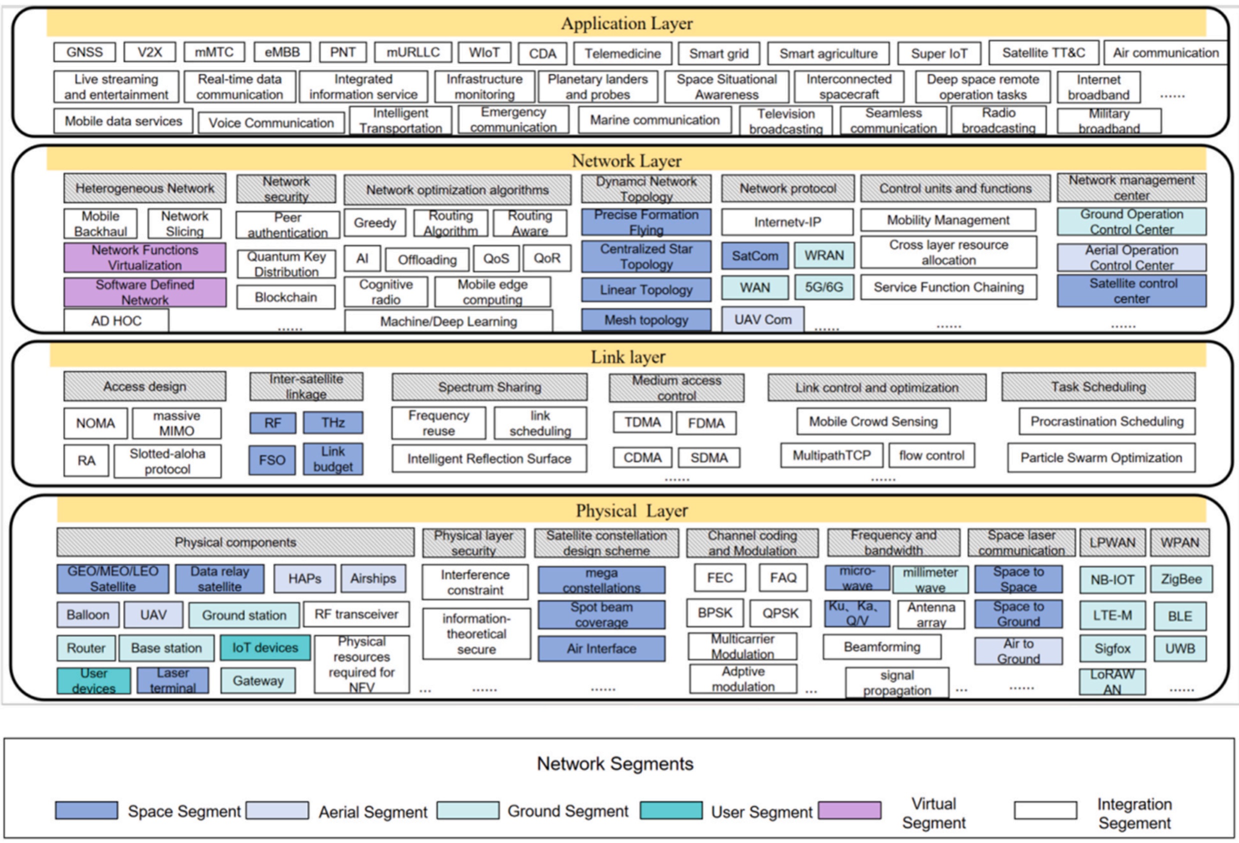

Fig. 5. Technical architecture of Satellite Internet.

scenarios, such as inter-satellite/deep-space links, ground station/vehicles, satellite/aerial links, and terrestrial links [57]. (3) The Network layer is the core component for realising network heterogeneity and dynamics. Since the success of Satellite Internet requires a hybrid approach with highly dynamic elements that are always under the same communication channel, technologies such as network function virtualisation (NFV), software-defined network (SDN) and NS can significantly improve the degree of freedom of network configuration, quantum key distribution (QKD) and Blockchain can ensure endogenous security of the network, cognitive radio, artificial intelligence (AI), and IRS can optimise network performance by realising network autonomous optimisation, maintenance and perception [58], and network management centres are mainly responsible for radio resource scheduling and network planning [59]. Technologies in the network layer help provide large-scale, personalised network services while further reducing network operating costs. (4) The Application layer provides solutions for Satellite Internet to adapt to different reality scenarios and is responsible for offering services to end users. For instance, V2X enables efficient and reliable communication between vehicles or between vehicles and infrastructure and provides users with services such as navigation, vehicle condition monitoring, and safety warnings [60]. With the continuous development of application technologies, more opportunities will be created for the development of Satellite Internet.

In terms of attribution, we categorise Satellite Internet technology into six network segments: space, aerial, ground, user, virtual, and integrated. The relationship between each segment is as follows: First, the space segment mainly contains satellite-to-satellite or satellite-to-ground communications, while the ground segment mainly covers ground-to-satellite, ground-to-ground, and satellite-to-user links, helping to establish communications between satellites and all terminals defined in the user segment. By contrast, the user segment includes user-to-ground and user-to-satellite links. The aerial segment is then carried by various aerial platforms, such as the high-altitude platform (HAP) of airships and low-altitude platform of drones, and has abundant spatial resources that enable flexible network deployment [61]. Aerial and space segments form a non-terrestrial network, which can further improve network performance and has great potential for future development [62]. Additionally, the virtual segment is the outcome of using NFV or other

Table 2
Satellite Internet's application scenarios in 20 industries.

Industries	Application scenario	Industries	Application scenario
Agriculture	Precision agriculture, remote sensing services for agricultural production and operation (such as crop identification, growth monitoring, yield estimation, crop pest and disease monitoring, and operation of agricultural machinery), etc.	Information technology services	Autonomous air–ground cooperative navigation, seamless in-vehicle navigation, GNSS performance enhancement in harsh environments, spatial data services, global real-time precise point positioning and ship automatic identification system (AIS), etc.
Information transmission service	Satellite calls, satellite link-enabled base stations, personal Internet access, networks for civil aircraft, network access for rural and remote areas, Internet of Everything, remote IoT, positioning of IoT devices in dense indoor environments, open data platforms (such as intelligent transportation systems and maritime transportation systems), etc.	Transportation and Logistics	Internet of Vehicles, detection of train's departure interval, Internet of Ships, intelligent trajectory prediction of vessels, cold-chain logistics, measurement of port congestion condition and monitoring of locks infrastructure, etc.
Finance	Asset monitoring, collection of enterprise's production and operation data, user portrait and risk control, etc.	Railway and highway engineering construction	Smart railways (such as natural disaster sensing, perimeter intrusion warning, infrastructure monitoring and remote decision-making) and road maintenance, etc.
Fishery	Ocean fishing, trajectory analysis of fishing vessels and discrimination of fishing grounds, maritime safety information broadcasting, etc.	Forestry	Natural resource capacity and field parameter assessment, longitudinal slope calculations for forest/logging roads, etc.
Disaster management	Forest monitoring, disaster early warning, post-disaster rescue, maritime distress alarm management and search and rescue command, etc.	Public administration	Urban air quality data governance ecosystems, urban data brains, and public safety, etc.
Mining	Remote mining, underground exploration and navigation, mine emergency response, etc.	Electricity	Smart grids, computing power for remote grids, etc.
Tourism	Cruise tourism, scenic area business process reengineering and intelligent operation and management, tourist location awareness, distress rescue, etc.	Manufacturing	Smart cars, self-driving car navigation, wearable devices, drones, smartphones, etc.
Medical and health services	Telemedicine, medical assistance at sea, remote consultation, remote care, patient activity monitoring and location awareness, etc.	Environmental protection	Wetland remote sensing monitoring, digital wildlife monitoring, multi-species assessment, pollutant dispersion prediction, etc.
Militarily	Enhancement of military communication quality and anti-strike capability, all-dimensional and all-weather three-dimensional reconnaissance and surveillance, improvement of positioning accuracy and anti-jamming capability of military navigation systems, monitoring of malicious events in wars, and assessment of post-war losses, etc.	Meteorological services	High-altitude meteorological detection, marine climate research, and accurate forecasting of catastrophic weather events, etc.
Energy	Oil and gas energy exploration and exploitation in remote areas, construction of offshore oil platforms, offshore oil field signal coverage, and emergency communications, etc.	Port and shipping facilities engineering	Smart Ships, smart Ports, weather forecasting, pollution control and oil platform monitoring, etc.

technologies to decouple services from the dedicated hardware. It can help space and aerial segments complete resource-intensive or power-consuming tasks and improve network sustainability, creating a new path to unleash the full potential of Satellite Internet [63]. Finally, the integration segment refers to the connection between the space, aerial, ground, and other network segments [64]. With its high throughput and adaptability, it can help Satellite Internet realise ubiquitous global connectivity [65].

Overall, the different network segments of Satellite Internet are distributed across the four technical layers (see Fig. 5). If a certain type of Satellite Internet is magnified, such as SIoT, it will be found that its technical architecture also has this feature. For example, one divides the SIoT into physical and nonphysical layers and summarises the technologies of the physical layer as modulation access, channel coding, resource allocation, millimetre wave, etc[66]. Sciddurlo et al.[67]designed a new IoT network over the LEO satellite system, which plans to utilise 24 LEO satellites equipped with protocol stacks that support the transmission of tens of bytes of information. It can be seen that the space segment of SIoT may also involve both physical, link and network layers. Thus, the development of Satellite Internet must consider cross-layer network design, resource allocation and data transmission, interoperability of heterogeneous devices, and other issues [68].

3.3. *Application industries and scenarios of satellite internet*

The development of Satellite Internet is driven by simultaneous technological progress and market demand, and its application value can only be brought into full play when integrated with industrial ecology. Therefore, it is necessary to systematically sort out Satellite Internet applications, which will not only help industry practitioners assess the development potential of Satellite Internet but also promote its innovation of Satellite Internet in the future. This section analyses the application demands and scenarios of Satellite Internet in different industries to answer Question 3.

Among the 69 collected papers, 55 mentioned specific application–industry issues. This study summarises 20 industries that have begun to explore Satellite Internet applications, including information transmission services ($n = 21$), transportation and logistics ($n = 17$), disaster management ($n = 13$), and public administration ($n = 9$). This is because Satellite Internet is integrated with emerging information technologies to form innovative services. However, the coverage of remote areas, seamless connectivity, and emergency communication demands of specific vertical industries are in line with the formulation of Satellite Internet. In terms of industry distribution, tertiary industries, such as software and information technology services, public administration, finance, and health, are still the main application industries of Satellite Internet, whereas applications in primary (e.g. agriculture and fishery) and secondary (e.g. mining and electricity) industries are also very promising. Table 2 shows the application scenarios of Satellite Internet in the 20 industries. Owing to the limited article length, we analysed six representative high-frequency application industries.

3.3.1. *Information transmission services*

In the context of traditional information transmission methods, efficient coverage of networks over long distances and large-scale connections in special areas are often limited by time and space. However, the seamless network coverage and widely sparse equipment connection of Satellite Internet create more possibilities for emerging communication methods, such as civil aircraft networks[69], maritime communications [51], network access in rural and remote areas [70], and worldwide remote sensing [71]. This emerging mode of information transfer significantly broadens the scope and target audience of network connectivity and promotes digital equity.

3.3.2. *Transportation and logistics*

Satellite Internet enables seamless interconnection between smart vehicles, roadside infrastructure, and pedestrians [72], facilitating the development of Internet of Vehicles to meet the evolving functional requirements of smart transportation and improve road safety, driving safety, and traffic efficiency. In addition, Satellite Internet provides valid solutions for logistics services, especially maritime transportation, such as Internet of Ships [73], intelligent trajectory prediction of vessels [13], and cold-chain logistics for ocean catches [74].

3.3.3. *Disaster management*

Disaster prevention and emergency management work require extremely high response speeds from government departments. However, the failure of infrastructure, such as large-scale communication, power systems, and transportation networks, after disasters often weakens the disaster preparedness, reduction, and relief capabilities of institutions and the resilience of disaster prevention and control systems. Through forest monitoring [75], post-disaster rescue [76], emergency imaging and monitoring in earthquake-stricken areas, maritime distress alarms, and other applications, Satellite Internet has provided a strong emergency communication guarantee system for government departments and has improved the quality and efficiency of disaster management services.

3.3.4. *Public administration*

Public administration aims to promote inclusive growth in the population, technology, economy, and society by integrating numerous complex urban infrastructure systems. In terms of universal connectivity and security, Satellite Internet has fully supported IoT services in remote and emerging urbanisation areas and improved government governance and public-service capabilities through smart cities [77], urban air governance, data governance [78], and other applications.

3.3.6. *Information technology services*

Satellite Internet can create more service scenarios and provide technical support for information technology services. On the one hand, Satellite Internet can provide enhanced positioning and navigation services, such as autonomous air–ground cooperative navigation [79], seamless in-vehicle navigation [80], and improved GNSS services in harsh environments [81]. On the other hand, Satellite Internet has promoted the utilisation of satellite big data, which is conducive to providing spatial data services such as large-scale in-orbit data sensing, machine learning of Earth resource data, Earth scene/event analysis [52], and other geographic remote sensing information services [82].

3.3.5. Agriculture

Accompanying the intelligent and sustainable transformation of traditional agriculture, Satellite Internet is enabling technological innovation in the accurate detection of crop health [83], intelligent analysis of soil quality [84], and yield prediction [85], providing farmers and researchers with all types of information to improve the efficiency of production and operational decision-making and make contributions to smart agriculture [86] and precision agriculture [87].

3.4. Potential impact of satellite internet

Understanding the potential impact of Satellite Internet can help policymakers evaluate its benefits and threats and promote its harmonious development of Satellite Internet. This review summarises the potential impacts of the Satellite Internet from four aspects: political (n = 4), economic (n = 22), technological (n = 21), and social (n = 11).

3.4.1. Political impact

The strategic value of Satellite Internet for national defence, space security, and warfare is growing with the militarisation of commercial Satellite Internet networks and satellite-data-based AI analysis. Integrating space development programs with national defence and security policies enables a country to leverage the dual-use nature of space programs to ensure national geopolitical security [88]. However, the impact of the infrastructure comprising space platforms and satellite systems on national security is severely underestimated. The malfunction and collapse of space infrastructure can lead to potentially fatal and highly destructive consequences [89]. In addition, the Starlink system played a pivotal role in providing communication channels to Ukraine, emerging as a key factor in shaping the trajectory of the war [8]. Scholars have explored the impact of commercial satellite imagery on empowering non-state actors in global politics and transparency [90].

3.4.2. Economic impact

Satellite Internet is poised to have a profound impact on productivity, distribution methods, market mechanisms, and economic organisational forms. It can enhance the quality of information transmission services and remote information processing capabilities to meet the demands of digital economic activities for next-generation network infrastructures. Using mobile vehicles as an example, advanced technologies can drive the development of digital services tailored to intelligent and autonomous solutions [91]. Furthermore, Satellite Internet facilitates effective collaboration among stakeholders along the value chain by reducing information asymmetry within and outside organisations [92] and helping enterprises access the knowledge required to develop innovative products and services [93,94]. Simultaneously, satellite data enable the creation of simulated environments, assisting in the accurate modelling of production processes [95,96], and thereby positively impacting firms' productivity and innovation performance [97]. In addition, some scholars have explored the potential impact of Satellite Internet on alleviating financing difficulties for enterprises[66,98], enhancing supply chain transparency [99], and changing the market competition structure [16].

3.4.3. Technical impact

The impact of Satellite Internet on technological advancement and technological innovation applications has received attention from researchers. Topics, such as technology clustering [100], technology applications in information asymmetry scenarios [101], and sources of technological innovation [102], have also been addressed. For example, breakthroughs in the next-generation satellite constellation communication systems may become a general-purpose technology to support the next K-wave economic growth globally and trigger a series of new technology clusters in society [71]. In addition, compared with traditional statistical data, satellite data have the advantages of large volume, multiple types, fast updates, and high timeliness [103], which can reflect surface information at multiple times, directions, and levels [104], and will become the main data source for future big data analysis [76].

3.4.4. Social impact

The direct impact of Satellite Internet on digital society and its indirect impact on social equity and sustainable development have received attention from researchers. Topics such as smart cities [105], geospatial monitoring and planning [106], environmental sustainability [107], and public-service accessibility [108] have also been addressed. It has also been pointed out that smart cities may have adverse impacts on the environment. Therefore, it is necessary to monitor smart cities in a timely manner using changes in multitemporal satellite data to maintain environmental sustainability. In addition, sustainable remote health services established by Satellite Internet can encourage more users to adopt remote medical technologies and improve healthcare services in rural areas [87]. Geographic information technology also plays a crucial role in achieving sustainable development goals [109].

4. Discussion

This review summarises the results of 69 relevant studies and highlights the future trajectory of national ICT infrastructure development. This underscores the importance of Satellite Internet development for countries to achieve a competitive edge and provides valuable insights into the global landscape of Satellite Internet development. While existing studies have not presented a unified perspective on the concept of Satellite Internet, this paper introduces three research perspectives on the topic: network architecture, connection objects, and satellite types within the context of technological advancement [20–22]. We aimed to examine the variations in the definition and attributes of Satellite Internet from diverse research perspectives to address the specific requirements of users at different intervals [25,27], rather than exhaustively enumerating all concepts related to Satellite Internet. Relatively few studies have investigated the characteristics of Satellite Internet. This study analyses the current state of global research and identifies five core characteristics that are common to Satellite Internet from different perspectives, which are divided into the external performance and internal value of Satellite Internet [1,11]. We have defined Satellite Internet comprehensively to align with the evolving requirements of contemporary research. This definition facilitates the establishment of a unified theoretical framework and presents a coherent research target for future studies.

The majority of existing research on Satellite Internet focuses on the technical and theoretical perspective. This study delves into the core technologies that form the backbone of Satellite Internet. It proposes a comprehensive technical architecture for Satellite Internet, categorising it into four distinct layers: physical, link, network, and application. This architecture encompasses six distinct network segments: space, aerial, ground, user, virtual, and integrated. This unified framework allows Satellite Internet to adapt to a wide range of environments. Furthermore, the distribution of these network segments across different layers presents a complex challenge for the development of Satellite Internet [9,41]. Therefore, it offers valuable insights for the Satellite Internet industry and businesses seeking to identify essential technologies and cybersecurity vulnerabilities. The fundamental technology behind Satellite Internet is propelling progress in the digital information infrastructure. It is imperative to foster inventive advancements in this domain by utilising a range of research methodologies and advocating the seamless integration and compatibility of Satellite Internet technology across different platforms and research domains.

This study comprehensively demonstrated the broad application prospects of Satellite Internet and prospectively explored and evaluated its application value. In fact, existing research has already explored potential application scenarios of Satellite Internet in 20 industries, and there is a high demand for Satellite Internet across different industries. For example, the tertiary industry has a high degree of digitisation and informatisation, and the integration of Satellite Internet with other technologies has resulted in diverse application scenarios and innovative business service models. Considering that primary and secondary industries possess abundant physical resources, Satellite Internet is continuously expanding its specific services tailored to the needs of vertical applications and is effectively compensating for the insufficient coverage of special scenes by 5G. In the foreseeable future, the convergence of space and Earth technologies is anticipated to drive the widespread adoption of Satellite Internet across various industries. This expansion will facilitate the creation of novel applications that contribute to advancements in emergency response, marine navigation, aviation, and other sectors. Furthermore, it will give rise to new applications, such as direct satellite connections, unmanned maritime and industrial operations, digital content delivery, and comprehensive intelligent monitoring. These innovative applications are poised to play a pivotal role in propelling the advancement of Satellite Internet technology.

This study also offers a comprehensive understanding of the potential impacts of Satellite Internet on politics, the economy, technology, and society. While most previous studies have focused on exploring or discussing one or two potential impacts of Satellite Internet within specific domains, this study proposes a more comprehensive approach by simultaneously evaluating both the positive and negative impacts to facilitate policymakers' adoption and utilisation of Satellite Internet. In our research, the positive impacts of Satellite Internet outweigh the negative ones, with the most frequently cited being its strategic value (e.g. military, national security, and new warfare applications) [110]. Social equity and sustainable development have emerged as critical issues in the provision of Satellite Internet services. Addressing how Satellite Internet can effectively contribute to bridging the digital divide, resolving disparities in industrial digitisation, and narrowing the urban–rural development gap should receive increased attention respectively[64, 83].

5. Conclusions, limitations and implications

In recent decades, the competition between countries for space-air-ground information has become increasingly fierce. With the development of new-generation information technologies, such as 5G, the IoT, big data, and AI, numerous promising applications and services are emerging. Because ubiquitous human-cyber-physical connections are becoming increasingly important, Satellite Internet has ushered in a new round of development opportunities. Therefore, it is necessary to understand the concept and development trend of Satellite Internet and identify its value and potential in various fields.

In this study, a systematic literature review on the research field of Satellite Internet was conducted, focusing on the concept and main characteristics, core technologies and technical architecture, application industries and scenarios, as well as potential impacts. Specifically, according to the PRISMA protocol, 69 eligible studies were considered for this study. First, we analysed concepts related to Satellite Internet from three perspectives: network architecture, connection objects, and satellite types; compared the similarities and differences of concepts and key features from different perspectives; and proposed a unified concept of Satellite Internet that can be highly generalised and conforms to the current research and development direction. Second, this study counts the overall high-frequency technologies of Satellite Internet, compares the technological differences under different perspectives, and designs a unified technical architecture of Satellite Internet. Finally, this study comprehensively sorted out the vertical application of Satellite Internet in 20 industries and summarised the multidimensional impact of Satellite Internet on politics, economy, technology, and society. In summary, this study presented a map that provides a more comprehensive understanding of the development status, application value, and impact of Satellite Internet.

This study has some limitations. First, this review only used the WoS as the sole source of the sample database, which may limit the scope and perspective of the study. Although WoS is an authoritative and representative database, it still cannot cover all research related to Satellite Internet topics. To further enhance the comprehensiveness of the literature review, future research should consider incorporating relevant studies from other databases such as Google Scholar, IEEE, Emerald, EBSCO, Scopus, and ScienceDirect, and include a wider range of journals, conference papers, and other materials. This will help to obtain more research opportunities on Satellite Internet, which is applicable to a wider range of backgrounds and diverse research.

Second, to ensure research quality, this review only includes articles published in SSCI- and SCIE-indexed journals, excluding studies published in other data sources, such as conference proceedings citation index-science (CPCI–S), which may introduce potential journal selection bias and result in marginal contributions from other valuable studies being ignored. Additionally, scholars tend to use various journal ranking methods to include the sample literature required for their review. Kossyva et al. [111] relied on the ABS Academic Journal Guide (2018) to include articles from three- and four-rated journals within their research scope. However, this approach resulted in articles from other journals that were not captured through the qualitative research. Therefore, future scholars should consider selecting a more appropriate journal ranking method to facilitate the inclusion of as many high-quality published articles related to Satellite Internet as possible, adjust the inclusion criterion of articles to fill the literature gap, update the search date to November 2023, capture the latest academic trends, and further deepen the exploration of topics such as Satellite Internet concepts, technical architecture, and applications. This provides an effective pathway for future researchers to obtain a more comprehensive understanding and results through in-depth qualitative research in Satellite Internet areas.

Thirdly, this paper followed the PRISMA 2020 guidelines to systematically review the Satellite Internet related research that met the inclusion criterion. It is worth mentioning that the eligible studies are mainly qualitative. Although this can provide rich application scenarios and practical examples, it limits the feasibility of conducting meta-analyses to determine the effectiveness of Satellite Internet adoption. Future researchers and scholars can consider using alternative methods such as bibliometric analysis, meta-analysis, and structured literature reviews to comprehensively analyse this topic. On this basis, to obtain more comprehensive statistical insights, future research could attempt to construct a systematic theoretical analysis framework based on clarifying the concept of Satellite Internet and employ various research methods to empirically test the strategic impact of Satellite Internet and offer policy recommendations with guiding significance.

This study has both theoretical and practical implications. From an academic perspective, as there is no existing systematic literature review on Satellite Internet, this study regards Satellite Internet as a whole for the first time, which can provide a solid conceptual basis for subsequent scholars to carry out relevant research. By reviewing the concepts, technical architecture, application industries, and scenarios, as well as the potential impacts of Satellite Internet, and discussing research opportunities in relevant frontier fields, it not only comprehensively outlines the overall research trends in the field but also provides inspiration for identifying areas to be further explored. From a managerial perspective, a structured research map can help professionals in different industries deepen their understanding of the concept, development experience, and application results of Satellite Internet. Enterprise managers can use this research map to provide information support for activities, such as strengthening the application of emerging enabling technologies and guiding digital transformation practices. Simultaneously, the results of this research can help policymakers in different countries and regions determine the key strategic deployment areas of next-generation Internet infrastructure and prioritise the development path of differentiated technologies in line with their national conditions. In addition, the research results can also help assess the benefits and risks brought by Satellite Internet and further guide the formulation of consistent incentive and defence policies.

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Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Yan Chen: Supervision, Project administration, Funding acquisition, Conceptualization. **Xin Ma:** Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Chaonan Wu:** Writing – review & editing, Writing – original draft, Validation, Data curation, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

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