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Special Topic: Spectrum, Coverage, and Enabling Technologies for Intelligent 6G

Coverage enhancement for 6G satellite-terrestrial integrated networks: performance metrics, constellation configuration and resource allocation

Min SHENG[1], Di ZHOU[1*], Weigang BAI[1], Junyu LIU[1], Haoran LI[1], Yan SHI[1] & Jiandong LI[1,2]

[1]*State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an* 710071*, China;*
[2]*Department of Broadband Communication, Peng Cheng Laboratory, Shenzhen* 518055*, China*

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Abstract Since the base station-centric wireless coverage mode of 5G is difficult to support future stereoscopic global wireless coverage demands, the future infrastructure of 6G satellite-terrestrial integrated network (STIN) with mega constellations will extend from the terrestrial network to the integrated satellite-terrestrial architecture, so as to realize the improvement of wireless coverage capability through extending the spatial and temporal coverage. However, what are the specific quantitative indicators of wireless coverage? What is the basis for the effect of network configuration with mega constellations on coverage performance? How to form non-uniform coverage through intelligent resource scheduling to match non-uniformly distributed service requirements in the future 6G STIN? The aforementioned unknown fundamental problems have become a bottleneck restricting the further development of coverage expansion in the future 6G STIN. In this paper, we start with the evolution route of wireless coverage and the vision of 6G coverage and propose coverage performance evaluation metrics in 6G STINs from the perspective of signal coverage, capacity coverage, and service coverage. Furthermore, we investigate the relationship between coverage structure and coverage capability in 6G STINs with mega constellations and we find network structure characteristics suitable for 6G non-uniform service requirements, thus guiding constellation design in 6G STINs by analyzing and comparing the coverage performance of several typical mega constellations. Afterwards, we explore the application of artificial intelligence in resource collaboration to provide technology reference to enhance coverage capability for dynamic 6G service demands. Finally, we analyze possible technical challenges for improving service coverage performance in 6G STINs to provide researchers with new ideas.

Keywords 6G satellite-terrestrial integrated networks, on-demand wireless coverage, performance metrics, constellation configuration, intelligent resource scheduling

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1 Introduction

The fifth-generation (5G) mobile communication system enhancements are reaching maturity with the completion of Release 17 by the third-generation partnership project (3GPP). Emerging services such as billions of machine connections, ultra-telemedicine, and holographic communication, have put forward higher requirements for service performance such as delay, reliability, and rate [1–3]. However, the base station-centric wireless coverage mode of 5G is difficult to support future service demands. Therefore, the sixth-generation (6G) mobile communication system needs to provide more powerful wireless coverage capabilities to guarantee service continuity. In this section, we will introduce the evolution and development of wireless coverage and analyze the vision of 6G wireless coverage. Finally, the research works on wireless coverage, and the main contributions of this paper are introduced.

* Corresponding author (email: zhoudi@xidian.edu.cn)

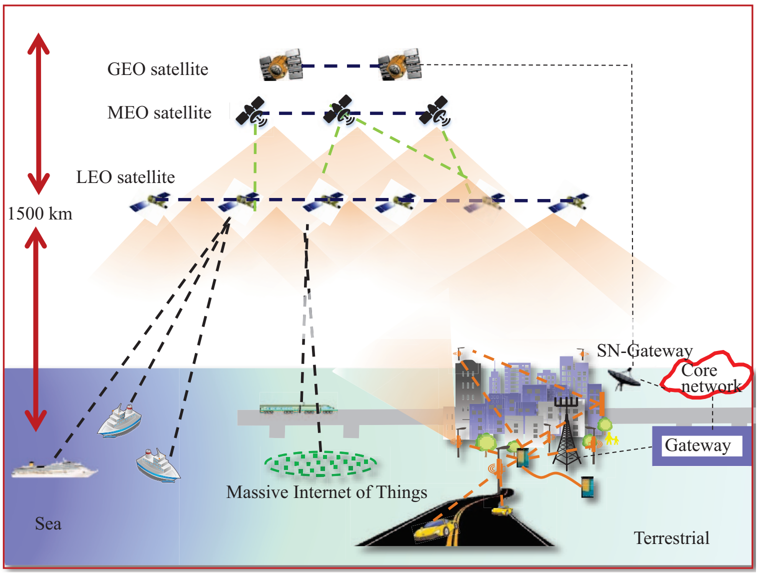

Figure 1 (Color online) The STIN scenario.

1.1 Evolution and development of wireless coverage

As one of the key problems in wireless communication, wireless coverage structure has been constantly updated and changed since 1G. Specifically, in the 1G era, the large coverage system structure was applied to increase the number of users covered by a single station. In the 2G and 3G eras, due to the digitization of the analog pattern and the widening of the communication frequency band, the coverage was reduced, and the small coverage system structure was officially opened. The goal of 2/3G is to achieve signal coverage for users in a cell. So far, the small coverage cellular system has been used all the time, and with the development of wireless communication systems, the coverage area of the cell was decreasing. Furthermore, based on the regular deployment of cells, 4G added irregular deployment of microcells to make up for capacity coverage holes and achieve capacity coverage in densely populated areas. 5G expects to achieve customized service coverage for vertical industries by building an ultra-dense heterogeneous cellular coverage structure. However, the state-of-the-art infrastructure for 5G is still limited to terrestrial communication systems and its coverage still does not include the ocean, desert, and remote areas, and 5G service capacity is insufficient to provide efficient guarantees in terms of capacity, latency, or reliability [4, 5]. Therefore, the primary condition for realizing the new requirements is that the communication system can provide global service coverage by improving service capability. It is foreseeable that in the future, the wireless communication system will integrate higher altitude equipment, the 6G network architecture will undergo radical changes to achieve global on-demand service coverage, and many key technologies will be transformed to better adapt to future industry requirements [6–10].

As the most favored network architecture, the satellite-terrestrial integrated network (STIN) has received extensive attention from academia to industry and is considered to have great potential in achieving global service coverage and meeting the above application requirements [11–14]. The STIN scenario is shown in Figure 1. Meanwhile, some progress has been made in the practical application of the satellite network (SN) to assist the terrestrial network (TN). For example, more and more organizations have started to carry out their projects on the SN aiming at achieving seamless global coverage and ubiquitous communication by constructing large-scale satellite constellations, such as the SpaceX [15], OneWeb [16], and Telesat [17]. Various constellations in orbit are shown in Table 1. Not only that, it has always been the research direction of the academic and industrial circles to use the SN to assist the TN to achieve more extensive coverage and higher quality communication. So far, from the perspective of coverage, the development of the SN-assisted TN can be divided into three stages as shown in Figure 2. (1) Signal coverage phase. The received signal strength is mainly considered at this stage. Furthermore, most satellite communication systems used geostationary earth orbit (GEO) satellites to achieve ground signal coverage, and due to the wide coverage characteristics of GEO satellites, three GEO satellites could achieve global signal coverage. A typical satellite communication system is Thuraya. (2) Capacity coverage

Table 1 Overview of typical constellations in orbit

Comp. / Cons. Name (Country)	# Sat.	Orb. Alt. (Km)	Orb. Type	Inter-satellite links (ISLs)	Services and project progress
GlobalStar (USA)	48 + 12	1414	Inclined	No	Voice, fax, data, short message, location
OneWeb (USA)	720 (47844)	1200	Polar	No	428 satellites have been launched
StarLink (USA)	42000	550–1325	Inclined	Yes	3108 satellites have been launched
Kuiper (USA)	3236	590–630	–	–	Global internet service
Iridium (USA)	66	677	Polar	Yes	Abandoning frequency applications in 2003
Iridium-II (USA)	66+9	780	Polar	Yes	–
LeoSat (USA)	108	1432	Polar	Yes	Launch the first experimental satellite in 2019
Hongyan (China)	324	1000	Polar	Yes	Launch the first experimental satellite
Galaxy Aerospace (China)	>1000	500–1200	–	No	Launch the first satellite
Skywalker (China)	36	900	Inclined	Yes	5 satellites have been launched
O3b-I (UK)	20	8062–8067	Equatorial	No	Provide broadband services for north-south latitude at 50
O3b-II (UK)	22	8062	Inclined + Equatorial	–	GEO and MEO integrated service system
Telesat (Canada)	117	1000	Polar + Inclined	–	Launch the experimental satellite

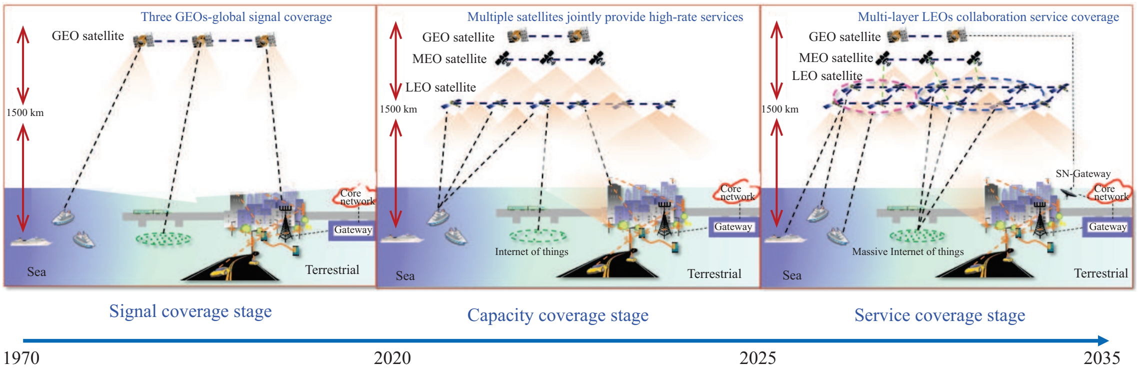

Figure 2 (Color online) Three development stages of the 6G STIN from the perspective of wireless coverage.

phase. At this stage, the accessible data transmission rate is mainly considered. Meanwhile, low earth orbit (LEO) and medium earth orbit (MEO) constellations are constructed, and each constellation has dozens or hundreds of satellites, enabling multiple satellites to cover an area at the same time to meet the high-rate demands of users. The typical satellite communication system is Iridium NEXT. (3) Service coverage phase. At this stage, whether the service capacity can meet the service demand is mainly considered. Recently, multi-layer large-scale satellite constellations are being built to provide strong access and carrying capacity to provide users with on-demand service coverage. StarLink is currently a fast-growing and representative constellation that has been striving to provide on-demand services. Different from the previous two stages, in the service coverage stage, the SN and the TN will be truly integrated into one system, i.e., STIN to jointly realize the on-demand service coverage requirements of the future 6G.

1.2 6G coverage vision

In the process of the development of communication systems, the human vision of communication demands has always been the source of power to stimulate the continuous updating of communication technologies and communication systems. After the commercialization of 5G, human has put forward a new vision for future wireless coverage, which can be summarized into four parts: (1) ubiquitous coverage; (2) no time-hole coverage; (3) high capacity and energy-efficient coverage; (4) on-demand service coverage. These four visions clarify the requirements for future 6G coverage from the perspectives of time, space, capacity, and service. Specifically, our vision for future 6G coverage is to achieve global on-demand service coverage and meet diversified service demands. Details are as follows.

- Ultra-high data density service. The future communication mode will be immersive, such as virtual reality, augmented reality, and holographic communication, which is not only a visual experience but also a comprehensive feeling such as touch and smell. Meanwhile, due to high requirements on connection rate and delay, its possible application environment and coverage are in relatively static buildings such as residences.
- Ultra-low power service. The service is mainly oriented to the Internet of things scenarios such as power, agriculture, meteorology, and earthquake monitoring composed of a large number of sensor devices. It has low requirements on connection rate and delay but has certain requirements on connection density and mobility.

• Ubiquitous mobile ultra-wideband service. Global emergency communication, global positioning, and navigation belong to this category and need to achieve global coverage including air, mountain, ocean, and desert. The connection rate and mobility are required.

• High mobility and low delay services. Emerging industries such as autonomous driving and the Internet of vehicles, which are currently developing, will develop rapidly under the higher performance provided by 6G, such as lower latency and higher mobility.

• Long-distance high-reliability service. With the help of high-reliability assurance and global wide area coverage, telemedicine, remote machine control, and remote industrial management are expected to be realized.

• Ultra-large scale machine service. The development of smart cities and the industrial Internet will bring a new look to human production and life and is also a beautiful vision for people. It requires higher connection density and higher reliability.

The global population distribution and service distribution lead to differentiated service demands, and the service performance requirements such as data rate, delay, and reliability are different. Therefore, it is necessary to design 6G STIN focusing on the differentiated and non-uniform characteristics of demand, to achieve efficient on-demand services capability.

1.3 6G service requirements driven technical challenges

While seeing that 6G STINs bring more promising applications in the future, we also clearly recognize that 6G STINs and 5G network architectures are very different. The 6G STIN is not a simple interconnection between heterogeneous networks, but a deep integration of systems, technologies, and applications. Therefore, to give full play to the service performance brought by the converged network, the 6G STIN needs to break through the technical challenges beyond the traditional single network. Details are as follows.

• Due to the gradual improvement of users' personalized demands and the non-uniform distribution of user demands to be caused by factors such as the economy and population density, on-demand service requires flexible transformation and dynamic reconfiguration of the coverage structure in 6G STINs. Therefore, how to fully consider the service coverage capabilities of various areas on the ground, and design the STIN configuration according to different service demands to meet the individual demands of users is an urgent problem to be solved.

• Due to the dual mobility of users as well as satellites, the resources available in 6G STINs are highly dynamic. Meanwhile, the differentiated service demands resulting from global population distribution, service distribution and the personalized demands of users require the resources, and the service performance requirements such as rate, delay, and reliability are different. Therefore, how to intelligently allocate on-board resources (OBR), realize efficient satellite-terrestrial coordinated resource scheduling, and improve service performance is also a problem worthy of attention.

• Due to the user's personalized, diversified, and differentiated service demands, the dynamic network environment, and other higher requirements for 6G, STIN as the future 6G network architecture must be able to quickly adapt to changes in the network environment, dynamically adjust network resources to maintain high-performance services, and meet on-demand service demands. Therefore, a high degree of autonomy will be the key for STIN to improve network performance, and artificial intelligence (AI) will be an important technology for 6G STINs to achieve global on-demand service coverage. Meanwhile, more and more researchers in the academic community have studied STIN from different perspectives, and some emerging technologies such as AI [18,19], edge computing [20,21], and reconfigurable intelligent surfaces [22,23] are widely used as an important means to improve the performance of STIN.

There have been state-of-the-art researches on coverage, which are shown in Table 2 [24–31]. Specifically, Sheng et al. [24] studied the service coverage performance of different mega-satellite constellations, including network access capacity, space segment capacity, and service coverage rate, but did not include the service coverage study of STIN. However, in [25], a theoretical framework for the average uplink capacity analysis was proposed to design the mega-constellation design for STIN to achieve global seamless connectivity. Further, Zhu et al. [26] investigated the STIN from the perspective of systematic design and proposed the new STIN design mode from the bottom up to achieve the on-demand service. While designing systems with higher network capacity, efficient resource management methods are also widely concerned in STIN. Fu et al. [27] improved the system throughput performance during the downlink transmission of STIN by introducing terrestrial relays and air relays. However, the traditional solution

Table 2 Summary of existing researches on coverage

Reference	Type	Attention	Contributions
[24]	Service coverage	The service coverage performance of different mega-satellite constellations.	The future direction of 6G wireless coverage expansion is revealed from the perspective of key factors affecting service coverage performance.
[25]	Capacity coverage	Mega-constellation design for STIN for global seamless connectivity.	Considering the capacity of terrestrial backhaul links, a mega satellite constellation is designed to enable global connectivity with a minimal number of satellites.
[26]	Service coverage	Investigate the STIN towards 6G from the perspective of systematic design.	The new STIN design mode from the bottom up to achieve the on-demand service is proposed.
[27]	Capacity coverage	Aim to guarantee the throughput fairness.	Two kinds of relays to improve the system throughput in the STIN are introduced.
[28]	Capacity coverage	Efficient and intelligent resource management.	An intelligent mission-resource two-sided matching framework is proposed to achieve efficient multi-dimensional resource management in the dynamic and complex STIN environment.
[29]	Service coverage	A comprehensive survey of the STIN toward 6G.	The typical applications of the STIN in expanding the capability of network coverage and ensuring service continuity are discussed.
[30]	Service coverage	STIN for maritime Internet of things.	STIN-supported maritime communication demands are investigated, including extending network coverage and providing maritime-specific services.
[31]	Service coverage	Architectures, key techniques, and experimental progresses of STIN.	The experiment realizes the remote immersive robot control service, showing the feasibility of STIN to support emerging industrial Internet applications.

optimization method adopted makes it impossible to expand the satellite scale in [27], which is difficult to apply to the future STIN. The difference is that Mi et al. [28] proposed an intelligent mission-resource two-side matching framework to achieve efficient multi-dimensional resource management in the dynamic and complex STIN environment. So far, the investigation on STIN is relatively scattered and hardly involves the investigation of the 6G service coverage of STIN. First, as the top priority of any system design, network architecture is always the primary object of investigation [29, 30]. Second, the future opportunities, challenges, and applications of STIN have also been well considered [29–32]. Meanwhile, the discussion on the enhanced coverage performance of STIN has also been reflected in [29–32], but there is still no detailed review of service coverage. Compared with the above-mentioned papers, this survey mainly focuses on the STIN enabled on-demand coverage in 6G and the main contributions are shown as follows. (1) We conduct an in-depth overview of the key technologies to enhance the on-demand coverage needs of users in 6G from the perspective of signal coverage, capacity coverage, and service coverage. (2) We comprehensively analyze the STIN driven global on-demand service coverage performance in 6G from three aspects: coverage performance evaluation, the impact of constellation configuration on coverage performance, and the improvement of coverage performance by intelligent resource scheduling. In constellation configuration, we concentrate on the design of constellation spatial configuration and inter-satellite topology connection to maximize the network capacity. In resource management, we investigate how to match multi-dimensional resources and various demands efficiently and maximize service capability. Constellation configuration improves the performance of a constellation from the perspective of network geometry and topological connection. While resource management is based on the constellation configuration, which further enhances the service capability of the 6G STIN by efficient scheduling of scattered satellite resources. In addition, we also provide researchers with learnable technology challenges and future research directions for service coverage enhancement in 6G.

The rest of this paper is organized as follows. Section 2 mainly introduces the coverage performance evaluation metrics in 6G STINs, including on-demand coverage definition and coverage performance evaluation indicators. Then, Section 3 introduces the influence of different satellite constellation configurations on the performance of service coverage in 6G STINs. Section 4 analyzes the key technologies for improving the performance of service coverage in 6G STINs from the perspective of resource scheduling. Finally, in Section 5, we analyze possible research challenges and directions for enhancing service coverage in 6G STINs. For convenience, the list of abbreviations used in this paper is given in Table 3.

Table 3 The list of abbreviations

Abbreviation	Description	Abbreviation	Description
4G	Fourth-generation	5G	Fifth-generation
6G	Sixth-generation	AI	Artificial intelligence
CPU	Central processing unit	DRL	Deep reinforcement learning
DSS	Delay-sensitive services	FPGA	Field-programmable gate array
IoRT	Internet of remote things	IoT	Internet of things
ISL	Inter-satellite link	GEO	Geostationary earth orbit
GPU	Graphic processing unit	LEO	Low earth orbit
MEO	Medium earth orbit	NFV	Network function virtualization
OBR	On-board resource	QoS	Quality of service
SDN	Software defined network	SN	Satellite network
STCDC	Satellite-terrestrial collaborative distributed computing	STIN	Satellite-terrestrial integrated network
TN	Terrestrial network	UE	User equipment

2 Coverage performance evaluation in 6G STINs

A vital goal for 6G STINs is to provide extensive coverage for remote areas such as polar regions and mountainous areas for seamless global service [2]. In this section, we investigate the coverage performance in 6G STINs and define a comprehensive measure of wireless coverage capability in 6G STINs from three perspectives: signal coverage, capacity coverage, and service coverage. The signal coverage reflects the probability of achievable communication from the perspective of signal strength provided by the 6G STIN, while the capacity coverage quantifies the maximum transmission rate provided by the 6G STIN. In addition, service coverage focuses on the user service demands, and comprehensively evaluates the transmission capability of the 6G STIN relative to the user service demands. The proposed three metrics can cover the evaluation of coverage in space, time, capacity, and service. The ubiquitous coverage and the no-time-hole coverage correspond to the seamless signal coverage. High capacity coverage corresponds to capacity coverage, and on-demand service coverage corresponds to service coverage, respectively.

2.1 Signal coverage

Signal coverage is the probability that the received signal strength per unit area exceeds a certain threshold. Signal coverage is a concise indicator to evaluate the coverage capability of 6G STIN. The value of signal coverage reflects the possibility of communication. The Iridium system and the Globalstar system can achieve 100% global signal coverage [33, 34].

Coverage performance is a fundamental performance indicator of SNs and has been widely investigated by scholars. Ref. [35] calculated the actual number of satellites to achieve coverage in different regions and evaluated the coverage capability of multiple constellations. Further, the authors of [36] proposed a coverage metric to measure the coverage level of a satellite constellation. The satellite constellation achieves global coverage by minimizing the overlapping coverage between satellites. Recently, stochastic geometry has attracted the attention of many scholars as a tool for the mathematical analysis of large-scale constellations. Okati et al. [37] leveraged stochastic geometry to derive an expression for the coverage probability under LEO networks. Further, Ref. [38] investigated the relationship between the height of a dense satellite constellation and the coverage, then evaluated the coverage capability under different scenarios at the optimal height. Soon after, authors in [39] analyzed the expressions for the coverage probability of the SN leveraging stochastic geometry and derived a tight lower bound for the coverage probability. These studies advance the evaluation of the constellation's signal coverage and establish the foundation for further service delivery through signal coverage.

We evaluate the signal coverage of OneWeb and Telesat in Figure 3 with the parameters in Table 4. It can be noticed that OneWeb distributes 720 satellites evenly across eighteen orbits in a single layer, and OneWeb's evenly single-layer constellation configuration can more easily achieve global signal coverage. Furthermore, all satellites of OneWeb are located in polar orbits, which can cover polar and mid and low-latitude regions. To sum up, OneWeb has an even distribution of signal coverage and can provide reliable signal connectivity possibilities for most areas, except for a few globally scattered coverage voids. Compared with the OneWeb constellation, since the Telesat constellation has fewer satellites and is a two-

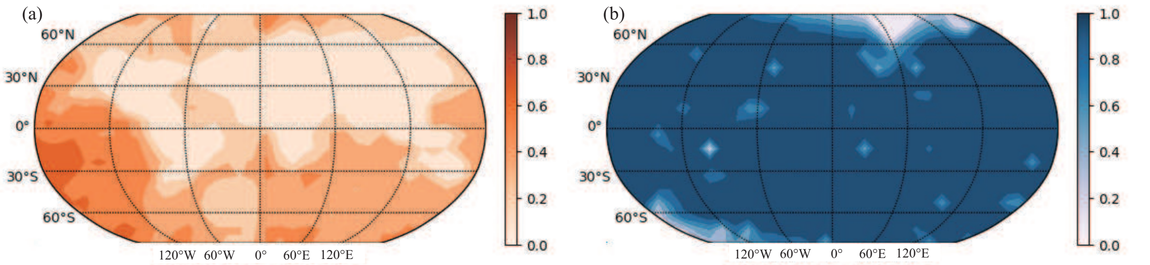

Figure 3 (Color online) The signal coverage of (a) OneWeb and (b) Telesat.

Table 4 The simulation parameters of OneWeb and Telesat

System	Orbital planes	#Plane	#Sat. /plane	#Sat.	Average data rate/sat. (Gbps)	Max. data rate/sat. (Gbps)	Average gateway antennas/sat.
OneWeb	1200 km (87.9°)	18	40	720	8.80	9.97	1
Telesat	1000 km (99.5°)	6	12	117	35.65	38.68	2
	1248 km (37.4°)	5	9				

layer constellation structure with a polar orbit and inclined orbit, the Telesat constellation has limited coverage of the polar regions, where there is a signal coverage plunge. It is worth noting that high signal coverage in an area is not guaranteed to provide adequate data rates due to the reduced data rates caused by the lower elevation angle [17]. Signal coverage only roughly describes signal strength from a single perspective, and coverage capability remains to be portrayed from others aspects.

2.2 Capacity coverage

The purpose of satellite signal coverage is to perform continuous transmission data transmission, which further leads to capacity coverage. Capacity coverage refers to the sum of data transmission rates carried per unit area. Capacity coverage portrays the transmission capability of a system in a certain area and further enriches the coverage capability evaluation.

Existing investigations about SN capacity coverage deduce capacity formulas and evaluate the impact of various parameters on capacity. The authors in [40] evaluated the impact of parameters, such as the number of access connections, and satellite altitude on the capacity of a two-tier network. Then, in their follow-up work [41], they deduced the closed-form approximate expression for the network capacity. In addition, Ref. [36] revealed the trends of coverage and capacity in different latitudes. Furthermore, the authors in [42] formulated the data collection and delivery problem of energy-constrained small SNs as an optimization problem and evaluate the network capacity performance. Recent research [43] evaluated the performance of satellite backhaul for remote Internet of things (IoT) and revealed the relationship between the capacity and the network scale. Focusing on large-scale SNs, Ref. [44] derived the upper limit of channel capacity with multiple single-antenna satellites. These studies aim to reveal the factors influencing the constellation capacity and thus improve capacity coverage.

To evaluate the capacity coverage of the constellation, we divide the ground into multiple regions. Then we assume that when a satellite is visible in n regions at the same time, the satellite in that region provides $1/n$ of the single-satellite data rate. Capacity coverage is the summation of the single-satellite rates for all satellites in each region. The global distribution of capacity coverage of OneWeb and Telesat is shown in Figure 4 according to the parameters in Table 4. It can be seen that compared to the Telesat constellation since OneWeb is a single-layer polar-orbiting constellation and has a higher number of satellites, it has a more uniform distribution capacity coverage and presents higher capacity coverage in high latitudes. Besides, since Telesat is a two-layer SN structure, i.e., a constellation configuration with a combination of polar and inclined orbits, Telesat's polar orbit satellites and inclined orbit satellites can jointly provide capacity coverage of the mid and low-latitude regions. Therefore, the Telesat constellation can provide higher capacity coverage for mid and low-latitude regions compared with OneWeb's only polar orbiting satellites. Consequently, the performance of capacity coverage is closely related to the configuration distribution of satellites.

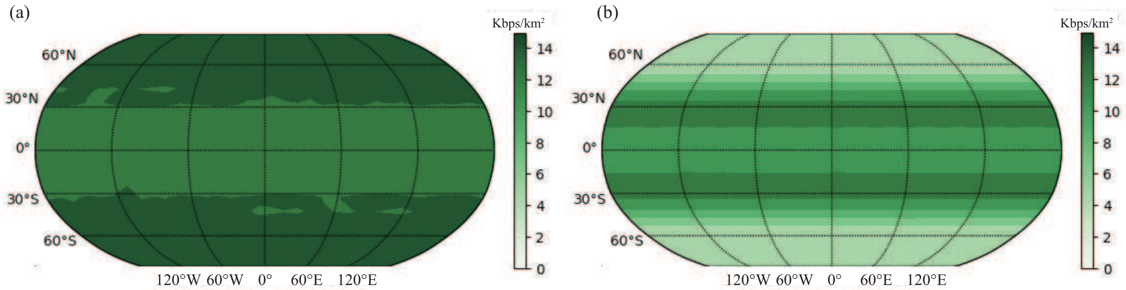

Figure 4 (Color online) The capacity coverage of (a) OneWeb and (b) Telesat.

2.3 Service coverage

The ultimate goal of the 6G STIN is to provide global services, which include not only densely populated areas with high data demand but also areas with low data demand such as oceans and deserts. Due to the non-uniform division of population[1)] and mobile data demand [45], the global business distribution is non-uniform as shown in Figure 5(a).

With the diverse types of services as well as the uneven distribution of global services in 6G STINs, ensuring on-demand service coverage for specific traffic demands is one of the pivotal indicators for system evaluation. Service coverage is the ratio of network service rate (throughput) to service demand per unit area [24].

Since the global service demand is differentiated, for example, a desert area may have a service demand of 1 Mbps while an urban area may have a service demand of 10 Mbps. Through the design of the satellite constellation configuration and the coordination of resources, the differentiated service demands of these two regions are met separately so that their service coverage can reach 100%. It is worth noting that the service coverage different from the traditional definition of traffic density. The service coverage is an intuitive evaluation indicator based on the service capacity under the service demand.

Figures 5(b) and (c) show the global service coverage performance of OneWeb and Telesat with the demand in Figure 5(a). We can find that the service coverage of both constellations is still low in areas of intense demand, although Telesat has designed low inclination orbits to serve low and medium latitudes additionally. Service coverage is an important metric to portray the capability of 6G STIN for on-demand services. Therefore, the design of constellation configuration and satellite-terrestrial integrated resource management scheme for 6G STINs will focus on demand distribution, with service coverage as an important evaluation indicator.

To sum up, with the continuous enhancement of service demand, users have higher and higher requirements for coverage capability, which promotes the development of wireless coverage from signal coverage and capacity coverage to service coverage. Up to now, although the satellite constellation has achieved good performance in terms of signal coverage and capacity coverage, due to the significant improvement in the individualization and differentiation of user demands, the service coverage performance of the areas with the same signal coverage and capacity coverage performance is significantly different. Therefore, improving the service coverage capacity is the key to realizing on-demand services, and the improvement of service coverage capacity will also promote further enhancement of signal coverage and capacity coverage.

3 The effect of constellation configuration on coverage

A satellite constellation consists of multiple satellites in a configuration, through an appropriate design and optimization, a stable spatial geometry configuration is formed between satellite orbits. In addition, a certain topological connection exists between satellites to provide the required data transmission services. The satellite constellation configuration directly affects the signal coverage and capacity coverage, which in turn affects service coverage. This section discusses the constellation configuration design from two aspects: constellation spatial configuration and inter-satellite topology connection configuration. It provides theoretical support for the design of the 6G STIN configurations to enhance wireless coverage capability.

1) https://sedac.ciesin.columbia.edu/data/collection/gpw-v4.

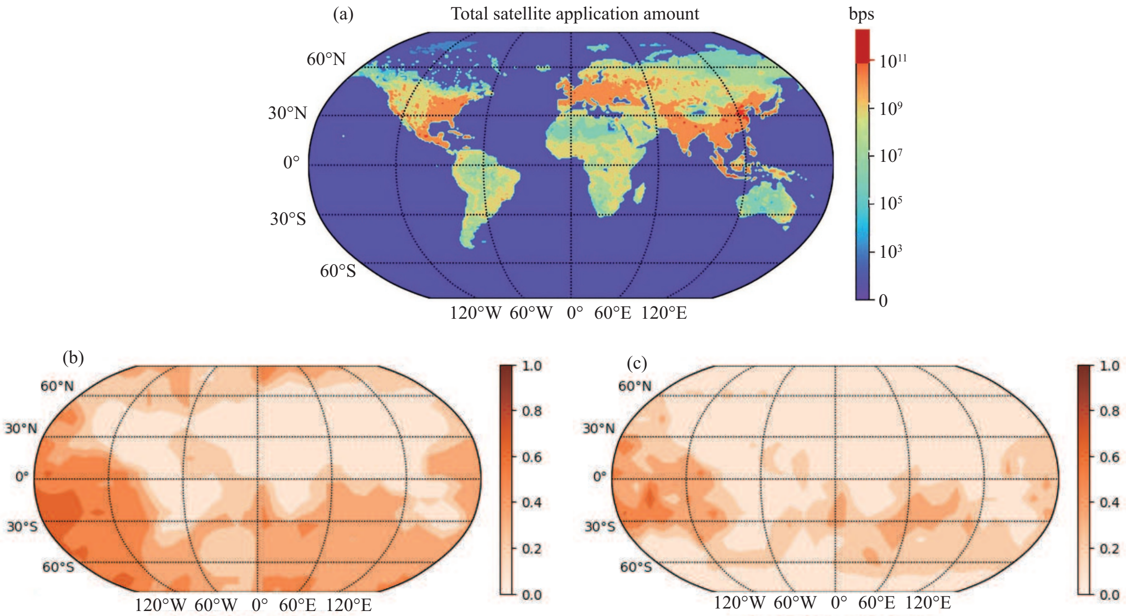

Figure 5 (Color online) (a) Satellite application amount. The service coverage of (b) OneWeb and (c) Telesat.

3.1 Constellation spatial configuration

In the process of satellite constellation design, the determination of satellite orbit parameters is an important part, which directly affects the network signal coverage and capacity coverage. Constellation spatial configurations can be divided into polar and inclined orbits and hybrid orbit configurations according to the orbit type. Initially, the concept of using polar orbit constellations to achieve global coverage was proposed [46], and currently, most commercial constellations follow inclined orbits or hybrid orbits.

3.1.1 *Constellation based on polar orbit*

The orbital inclination of polar-orbiting constellations allows all orbital planes to cross each other at the north and south poles so that the satellites of polar-orbiting constellations are dense at high latitudes and sparse at low latitudes. Polar-orbiting constellations have superior coverage of polar regions and high latitudes and are capable of global coverage [47]. Iridium and OneWeb are the typical polar orbit constellations.

The authors in [48] proposed a set of near-polar satellite constellations with continuous single and double coverage in circular orbits and present the optimal constellation set. For high latitudes and polar regions, Beste [49] and Rider [50] showed that polar orbital constellations with a uniform distribution of orbital planes in the $(0, \pi)$ range have the best coverage performance. Then, in [51], a polar-orbiting satellite constellation network was proposed to serve large-scale users, which can achieve low latency global coverage. Focusing on the coverage time, the design in [52] achieved a long coverage duration and obtains numerical solutions for near-polar orbit constellations. These efforts focus on the polar-orbiting constellation and optimize the polar-orbiting constellation parameters with the guarantee of coverage capability.

We evaluated the capacity coverage capability of the single-layer polar-orbiting constellation (with orbital parameters in Table 5) in Figure 6(a). It can be seen that the single-layer polar-orbiting constellation can provide capacity coverage globally, with a few enhancements in the polar regions. However, the services are mainly concentrated in low and mid-latitude regions with a more dense population. The polar-orbiting constellation configuration can result in the underutilization of satellite resources.

3.1.2 *Constellation based on inclined orbit*

Due to the superior coverage characteristics in densely populated areas, inclined orbits are becoming increasingly popular in commercial constellations [17]. Consequently, many investigations on inclined orbit constellations have been carried out. The authors of [53] obtained the optimal structure of the

Table 5 The simulation parameters of different types of constellations

Constellation type	Orbital planes	#Plane	#Sat./plane	#Sat.
Single-layer polar orbit constellation	1200 km (89°)	24	60	1440
Single-layer inclined orbit constellation	1200 km (50°)	24	60	1440
Two-layer inclined orbit constellation	1200 km (89°)	18	40	1449
	1200 km (50°)	27	27	
Three-layer inclined orbit constellation	1200 km (89°)	18	20	1449
	1200 km (50°)	27	27	
	1200 km (30°)	18	20	
Average satellite data rate	9.96 Gbps			

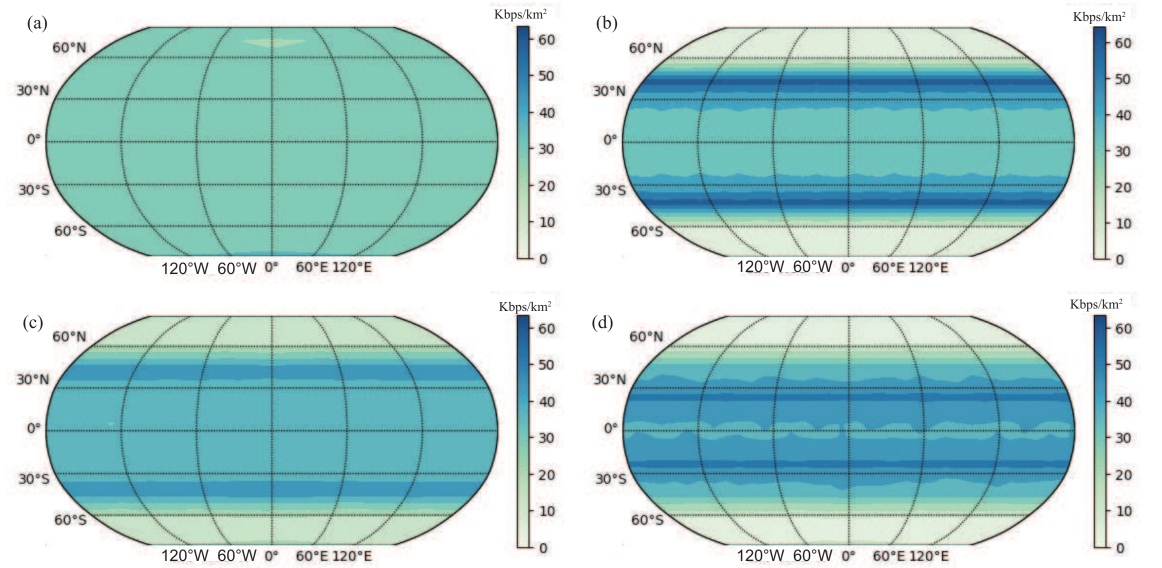

Figure 6 (Color online) (a) The capacity coverage of single-layer polar orbit constellation (with 1440 satellites). (b) The capacity coverage of (b) single-layer, (c) two-layer, and (d) three-layer inclined orbit constellations.

satellite constellation with continuous coverage of the mid-latitude band. Further, Ref. [54] proposed a distributed survival routing algorithm based on inclined orbit mega-constellation to enhance the network services. Okati et al. [55] derived the coverage probability and data rate of inclined LEO constellation with downlink and uplink resolution expressions under fading. They also provided guidance for the selection of constellation parameters such as the total number of satellites, altitude, and inclination. Ref. [56] effectively reduced the average hop count of user equipment (UE) in mega-constellation with inclined orbits by optimizing the constellation phase factor to provide better service capability.

These studies focus on inclined orbit constellations and investigate the factors affecting signal coverage and capacity coverage to guide the design of inclined orbit constellations. However, due to the inherent shortcomings of inclined orbit constellations with low signal coverage in polar regions, a seamless global service cannot be guaranteed.

3.1.3 *Constellation based on hybrid orbit*

Hybrid orbit constellation configurations become popular in the construction of commercial constellations in recent years, such as SpaceX and Telesat [57]. By achieving global coverage through polar-orbiting satellites and additional coverage at mid and low latitudes with inclined orbiting satellites, the hybrid orbiting constellation is competitive in enhancing coverage capability.

Hybrid orbit Constellations have attracted a great number of scholarly attention in recent years. A rose constellation combined with polar orbits is adopted to optimize the coverage in polar regions to achieve seamless coverage in [58]. Some scholars focus on the trade-off between coverage and cost in constellation design [59]. In addition, the selection of constellation parameters can be considered an optimization problem, and in [60], the authors leveraged the discrete-continuous variable sampling method to solve for the number of orbital planes and the number of satellites in a system. In [61], several hybrid LEO constellations were proposed and optimized using genetic algorithms to achieve uniform global coverage. Recently, the authors of [62] presented an optimal inclination search algorithm to calculate the orbital inclination to maximize the geometric coverage of single or multiple ground targets. Further, Ref. [57] analyzed commercial hybrid orbital satellite coverage capabilities that are currently being promoted. Further, considering the satellite deployment overhead, Ref. [63] proposed a demand-based optimization method for LEO satellite constellations to minimize the number of satellites and obtained the number of satellites deployed versus coverage.

The hybrid orbital constellation is competitive in guaranteeing 100% global signal coverage and on-demand services. The coverage performance of the constellation orbit configurations with different orbit types and different layers under an approximate number of satellites are shown in Figures 6(a)–(d). Table 5 shows the specific simulation parameters. As shown in Figures 6(c) and (d), the two-layer constellation provides the same capacity coverage in the latitude range of 0°–30°. The three-layer constellation is able to provide multiple layers of coverage for hotspot areas and thus has stronger capacity coverage in densely populated areas near 30° latitudes compared with the two-layer constellation. By adjusting the satellite inclination in more layers, the three-layer constellation makes it more flexible to provide on-demand services for users around the world. Since the majority of the service demands are concentrated in the middle and low latitudes, a multi-layer constellation with a mixture of polar and inclined orbits is a significant means to enhance the network coverage capability and achieve seamless global coverage.

3.2 Inter-satellite topology connection configuration

The network with inter-satellite topology constructed by inter-satellite links is a wireless network with a data transmission function between satellites. As a means to enhance the coverage capability of the constellation, it is essential to optimize the configuration parameters of the constellation. The research for SN topology is mainly divided into two aspects, i.e., intra-layer and inter-layer topology connections.

3.2.1 *Intra-layer topology connection configuration*

The intra-layer satellite topology consists of satellites connected at the same or similar altitudes with the same orbital period, and the neighboring satellites are visible at line-of-sight throughout the period with a high probability. Therefore, the connection relationship of intra-layer topology is relatively fixed.

Intra-layer topological connections are mainly based on rules and stable configurations, such as Mesh in Figure 7(a) [41, 64, 65]. Intra-layer topological connections are mainly divided into two categories, capacity-oriented [41,65,66], and mission-oriented topological connections [67]. Ref. [65] investigated the structural properties of the Walker constellation and found that this constellation could avoid the effect of the reverse seam on the heterodyne link, resulting in a 2D-Torus configuration. Figure 7(b) shows the connection relationship of 2D-Tours topology with 6×10 satellites, where 6 denotes 6 orbits and 10 denotes the number of satellites per orbit. Furthermore, it has been found that for a fixed number of satellites, the Walker constellation can provide the best coverage performance provided that the number of orbital planes is equal to the number of satellites in each orbital plane. Similarly, Ref. [66] found another 2D-Torus configuration in the 121/11/0 Walker constellation, which has stronger connectivity and coverage capability. Therefore, for the same constellation configuration, by changing the number of satellite orbits, the number of satellites per orbit, and other parameters that affect the network capacity, the capacity coverage capability can be effectively improved. In addition, the authors in [41] analyzed the capacity of a two-layer network based on intra-layer low-orbit interstellar connections based on Mesh and investigated the effect of the existence of the seam on the capacity. Then they derived the network parameter conditions for capacity enhancement to improve the capacity coverage of networks. Considering the user requirements, Ref. [67] proposed a long-term optimal capacity allocation algorithm to maximize the long-term utility and analyze the LEO intra-layer capacity.

A novel rectangular twisted torus topology was proposed in [68], and we refer to the topology of such twisted structures as the Mobius topology. Figure 7(c) shows the Mobius topology connection. The average hop counts of 2D-Torus and Mobius are 4.0678 and 3.6441 in the network of 6×10 satellites, respectively. The twisted connection characteristic of the Mobius topology attributes the network to stronger connectivity and higher capacity. It is a competitive direction to improve the network service capability by investigating the Mobius-based topology of the 6G STIN network.

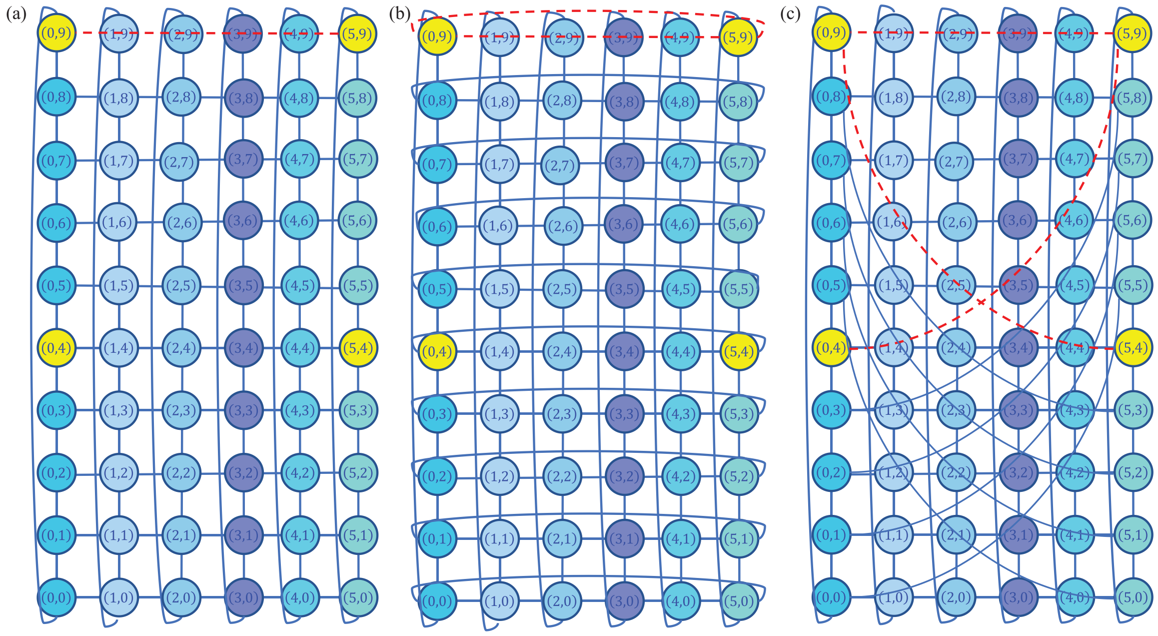

Figure 7 (Color online) (a) The Mesh topology (with 6 × 10 satellites); (b) the 2D-Tours topology (with 6 × 10 satellites); (c) the Mobius topology (with 6 × 10 satellites).

3.2.2 *Inter-layer topology connection configuration*

The inter-layer topology consists of satellites located in different altitude constellations, with large differences in the orbital periods of the satellites. The line of sight between two satellites can be blocked by the Earth, resulting in a highly dynamic topology and frequent connection switching [69].

Focusing on the dynamics of the network, a two-layer network model and topology based on LEO and GEO constellations is developed in [70]. Further, in [71], the authors proposed a high orbit-centric inter-layer link establishment strategy with high-orbit-centric for two-layer SNs. In [72], a two-stage synchronous switching strategy was proposed for inter-layer laser links, which divides the inter-layer links into two groups for alternate switching. This ensures network connectivity while reducing the constellation switching overhead, which helps to improve the service capability. The above research shows that, according to the dynamically changing network topology, timely adjustment of the inter-layer link establishment strategy can effectively guarantee network coverage performance.

The above inter-layer topology connection construction strategies enhance the network transmission capacity and reduce the overhead to further improve the coverage capability. However, there is not much research on the topology construction of mega-constellation. Moreover, the construction of constellation topology should be an optimization problem focusing on satellite position dynamics and traffic dynamics in the long term. Therefore, the investigation of link construction for long-term optimization of large-scale constellations is pivotal to improving the coverage capability for 6G STINs. At the same time, the future inter-satellite topology is developing towards a large-scale and multi-layer trend.

4 Intelligent resource scheduling enabled on-demand coverage

The resource scheduling maximizes the on-demand coverage capability by efficiently matching the uneven demands and OBR. Therefore, designing efficient resource scheduling algorithms is essential to improve the coverage performance of on-demand networks. This section investigates the coverage performance improvement from three perspectives: SN co-optimization, satellite-terrestrial co-optimization as well as satellite-terrestrial co-computation. It provides a comprehensive analysis of current resource management optimization techniques for SN and provides a reference for resource management to enhance on-demand coverage in 6G STINs.

4.1 SN resource scheduling enabled on-demand coverage

The SN delivers mission data to gateways or UE through efficient collaborative forwarding and scheduling among satellites. In this way, the SN realizes on-demand coverage of on-satellite resources. The SN optimization of coverage performance can be classified into single-layer optimization and multi-layer optimization according to the structure of the SN.

4.1.1 *Single-layer SN enabled on-demand coverage*

With the wide area coverage and limited cost of satellites, SN is attracting increasing attention. Single-layer low-orbit SN optimization is widely used for data backhaul and emergency mission response. Improving SN capability is an important way to improve service coverage [73–77]. These references overcame the dynamic transmission opportunities between satellites to improve the SN service capability. For the service coverage of emergency missions, authors in [78, 79], improved the emergency planning capability of future SN for emergent missions through equivalent decomposition and iterative neighborhood search methods, respectively. Further, in [80], for dynamic energy resource acquisition, AI technology significantly improved satellite-wide-area IoT service coverage capabilities.

These investigations have enhanced the coverage capability of single-layer SN through elaborate coordination of limited resources. However, single-layer SNs are not concerning the hierarchical structure between satellites. With the trend of the multi-layer evolution of SNs, it is urgent to enhance the on-demand coverage through multi-layer networks [67].

4.1.2 *Multi-layer SN enabled on-demand coverage*

Multi-layer network scheduling focuses on the resource status and mission demands status of each layer of the network to balance the load and optimize the on-demand coverage performance of the system. In [81], the quality of service (QoS) support multi-routing scheme was proposed to ensure the mission QoS requirements by using the time aggregation map to obtain the dynamic resources of the SN and various mission requirements. Focusing on the scheduling optimization problem of LEO and GEO, authors based on AI technique [82, 83] and two-stage optimization [84] for resource scheduling. Furthermore, in view of the traffic imbalance between layers in a multi-layer SN, the traffic probability of each layer of the network was estimated, and a load-aware routing strategy for the multi-layer SN was proposed to achieve low end-to-end delay and high throughput in [85]. The latest work [86] investigated the optimization of resource management among multi-domain satellites to improve resource utilization.

Multi-layering is a vital direction for the development of 6G STIN. Existing studies investigated the characteristics of multi-layer SNs, focusing on joint resource scheduling within and between layers to improve the throughput of the entire network and the on-demand coverage capability of 6G STIN. The current commercial satellite constellation shows the development trend of hierarchy and scale, and the large-scale multi-layer SN is an important part of the 6G STIN. The current multi-layer SN on-demand coverage optimization technology is relatively simple in satellite node modeling, and the joint optimization of storage, communication, energy, and computing resources for large-scale multi-layer SN will be the pivotal technology for 6G STINs.

4.2 STIN enabled on-demand coverage

STIN is the inevitable trend of network development, and 6G STINs impose higher requirements on coverage optimization. We present an in-depth discussion of service optimization, computation optimization, and gateway deployment optimization, to achieve on-demand and seamless on-demand coverage services for 6G STINs.

4.2.1 *Satellite-terrestrial collaboration enhances on-demand coverage*

6G STINs require efficient on-demand coverage optimization to support (1) areas where the TN is not deployed (2) traffic congestion areas (3) specific space or terrestrial missions, e.g., weather observation and post-disaster information gathering. With dynamic topology, non-uniform missions, limited on-board storage, and forwarding resources in 6G STINs, effective satellite-terrestrial collaboration is critical to improving network coverage capability.

First, Ref. [32] utilized satellites to provide backhaul. Specifically, the user association and resource allocation are jointly optimized to maximize UE access and thus enhance service coverage. In addition, the authors leveraged graph neural networks and reinforcement learning for link selection strategies in [87]. Then, considering the multi-dimensional resources in STIN, Ref. [88] investigated the space-terrestrial communication to achieve the high efficiency of data transmission. Some other scholars focused on achieving dynamic and stable connections between satellites, and ground users in highly dynamic STIN and proposed a two-layer matching optimization algorithm in [89].

To provide on-demand services to areas lacking TN coverage and areas of high demand, 6G STIN is moving toward collaborative satellite-terrestrial scheduling. Existing studies focused on maximizing the on-demand service of 6G STIN through collaborative management of satellite and terrestrial resources. These methods are all efficient joint satellite-terrestrial optimization with fixed gateways. The deployment of gateways, which has a great impact on the throughput, is indispensable to be considered for enhancing the on-demand coverage in 6G STIN.

4.2.2 *The impact of gateway deployment on on-demand coverage*

The gateway is a vital piece of equipment for 6G STINs since part of the service demand data from the satellite to the terminal user must pass through the satellite gateway. Therefore, gateway deployment affects the throughput of 6G STIN, which is critical to the on-demand coverage. The optimal gateway deployment is challenging and can be determined by a combination of factors such as gateway size, location, constellation parameters, user demand, link capacity, and gateway service capability.

First, the impact of constrained satellite link capacity on gateway deployment in the STIN was investigated in [90]. In addition, the authors in [91], aiming to guarantee reliability and minimize the latency, proposed a particle swarm optimization algorithm to obtain feasible deployment schemes while reducing the complexity. Further, building on the previous, Ref. [92] investigated the more challenging joint gateway and controller deployment problem and proposed lightweight annealing algorithms to obtain deployment schemes. Satellite links are affected by weather and terrain, and the link quality deteriorates under the cloud, rainfall, and extreme weather conditions. Further, in [12], the variable channel conditions under the influence of the atmospheric environment and the distribution of service data were considered, and the gateway deployment problem was modeled as a multi-objective optimization.

The 6G STIN has a large amount of data and requires to be unloaded through gateways. These existing studies noted that the deployment of gateways will directly affect the throughput of 6G STIN, and jointly optimized data transmission and gateway deployment for the complex and variable satellite-terrestrial channel. Table 6 [12, 32, 87–96] summarizes the literature on satellite-terrestrial collaboration to improve coverage capability. Throughput is enhanced by optimizing the deployment of gateways, which contributes to on-demand coverage. However, this joint optimization of satellite resources and gateway deployment in 6G STIN poses a severe test on network computing power.

4.3 Satellite-terrestrial intelligent collaborative computing enabled on-demand coverage

Through efficient resource control and dynamic allocation of network resources, adapting network resources to user demands and network environment is the key to achieving high-quality on-demand coverage. Therefore, the accuracy and timeliness of network resource management determine the performance of coverage capability, which raises new requirements for the computing capability of the network. At present, the on-board computing capability is available, as shown in Table 7, both the CPU-based satellites and the novel AI computing satellites have a significant increase in computing power. On-board computing will be the key technology to significantly improve the on-demand coverage capability of the 6G STIN. Specifically, first, on-board computing power makes it possible to directly process the collected data on satellites, which significantly reduces the high service response required by traditional ground-based computing. Therefore, some network control and sensing tasks can be settled at the edge of the satellite to complete the on-orbit processing, thus achieving effective integration of communication and computing, reducing the data transmission of satellite sensing and status data, and improving the timeliness of services by avoiding unnecessary data transmission with high communication time, which can remarkably improve the service capability of traffic demands with strict delay requirements. In addition, on-board computing avoids unnecessary data transmission, which reduces the pressure of network backhaul and the consumption of bandwidth resources. Through on-board computing, 6G STIN significantly reduces the redundant consumption of communication resources, which can provide services

Table 6 Summary of researches on satellite-terrestrial collaborative coverage capability optimization

Reference	Gateway optimization	Atmospheric conditions	Actual traffic distribution	Considered factor	Optimization object	Computing mode	AI-based
[32]				Limited link capacity	Data rate, accessed ground users	Centralized	
[87]				link selection	Number of served user	Centralized	✓
[88]				Caching, computing, communication joint management	Network energy efficiency	Centralized	
[89]		✓		Large-scale and dynamic connection	Revenues	Centralized	
[90]	✓			Limited link capacity, network reliability	Hop count	Centralized	
[91]	✓			Delay, network reliability	Delay	Centralized	
[92]	✓			Limited link capacity, network reliability, controller deployment	Delay	Centralized	
[93]	✓	✓		Limited hop, multi-object	Delay, traffic peak, load balance	Centralized	
[94]	✓	✓		Delay, power dissipation	Hop count	Centralized	
[12]	✓	✓	✓	Average access distance, number of gateway, revenues	Multi-object	Distributed	
[95]				Offloading location bandwidth	Offloading cost	Centralized	✓
[96]		✓		Link capacity rain attenuation	Offloaded mission power consumption	Centralized	✓

Table 7 Satellite computing power

Satellite type	Satellite	Computing unit	Computing power
Satellite with AI computing power	NASA	S-A1760 Venus	1.26 TOPS
	Ladybug series	FPGA	3 TOPS
	Chaohu	GRID-AICore	4 TOPS
	Stardetect Xingxi 02	FPGA+GPU	20 TOPS
Satellite with GPU computing power	Europ	CPU: SPARC	70 MIPS
	USA	CPU: RAD5500	100 MIPS

for more traffic demands. With the development of AI technology as well as high-performance computing chip technology, 6G STIN resource management is progressing toward AI-based satellite-terrestrial collaborative computing.

There has been extensive work applying AI techniques to STIN and obtaining coverage performance enhancement by improving the accuracy and timeliness of network resource management. In [80], the AI technique was leveraged to learn scheduling strategies to overcome the dynamic energy acquisition and release processes in space. Considering the topological dynamics of space networks as well as mission dynamics, recent studies [77, 83] adopted AI techniques to achieve efficient resource scheduling. The authors in [97] leveraged deep convolutional neural networks to achieve efficient data transfer optimization in space networks with uncertain structures. Since the computational capability is already available on the satellite, UE can offload the computational mission to the satellite for execution. In [95], the authors investigated the mission offloading problem in satellite-terrestrial edge computing networks and proposed a deep reinforcement learning (DRL)-based mission offloading method. Rapid mission response is achieved by adjusting the number of candidate locations to accelerate the learning process. Ref. [96] investigated the joint optimization of offloading path selection and resource allocation to offload computationally intensive and delay-sensitive services (DSSs). The authors use a DRL approach to make optimal decisions by considering the dynamic queues of IoRT devices, channel conditions, and the computational capacity of gateways.

Compared with traditional centralized learning, distributed AI can effectively exert the computing power of heterogeneous nodes in satellite and ground, and reduce the data transmission overhead. Therefore, distributed AI has great potential in applications such as satellite collaborative observation and satellite Internet of Things. Wei et al. [98] proposed a distributed AI computing architecture for SNs and leveraged a lightweight neural network model to speed up satellite data processing. In addition, in the problem of real-time multi-satellite cooperative observation, a distributed satellite scheduling algorithm based on multi-agent reinforcement learning was proposed in [99]. The satellites can make scheduling decisions independently, with very low communication requirements and real-time scheduling. Moreover, Ref. [100] proposed a relay selection strategy based on distributed Q-learning, which was used in satellite-terrestrial networks with large-scale IoT devices and multiple relays.

Traditional machine learning approaches aggregate all data in a single center for processing. A large amount of data is needed to train neural networks, which leads to high transmission costs and delays. In addition, data sharing may be prohibited due to privacy or data ownership issues. Federated learning is an innovative distributed learning method, which can be used to intelligently manage resource scheduling problems in STIN while ensuring security and user privacy. Fadlullah et al. [101] proposed a federated learning model for the nodes in STIN, without explicit data exchange with the cloud. The network overhead is low and data privacy is protected. Furthermore, Chen et al. [102] proposed a federated learning based computing network in satellite constellations and verified the advantages in communication overhead and delay. Moreover, Ref. [103] proposed a traffic offloading method based on federated reinforcement learning, which adapts to the heterogeneous structure and high dynamics of STIN, while ensuring user privacy.

In 6G STIN, on-board computing power will be available on satellites, which can significantly reduce the service response time required for traditional ground-based computing through on-board computing. Consequently, the existing studies shortened the service response time and improved on-demand coverage through on-board computing. Due to the highly dynamic characteristics of STIN, it is necessary for AI to improve the computational timeliness for optimization in 6G STIN to avoid the failure of optimization strategies. In addition, due to the large size of 6G STIN, the distributed AI control architecture and federated learning are expected to reduce the scale of optimization while ensuring data privacy.

5 Research challenges and directions

5.1 Flexible service coverage structure

The opening of the 6G era has raised the personalized demands of users to a new level. The 6G STIN must have the ability to provide on-demand services to meet personalized demands. Therefore, the 6G STIN should be able to dynamically adjust the service coverage structure according to user demands and have flexible reconfigurable service coverage capabilities. However, due to the influence of the economy, population density, and geographical location, users are unevenly distributed on the earth's surface and the satellite constellation usually has a uniform configuration, which makes some areas with high service demand unable to obtain high-quality services. To this end, mega satellite constellations are being constructed to assist 6G STIN. However, for multi-layer, heterogeneous and mega satellite constellations, the network configuration is complex and the coverage capability is influenced by many factors, such as the number of satellites per layer, the established way of the inter-layer links, and the number of inter-layer links. Therefore, in the design service coverage structure of the 6G STIN, how to intelligently and quickly determine the optimal coverage structure according to the various demands of users is the focus of future research.

5.2 On-demand coverage assisted by large-scale satellite-terrestrial collaborative computing

The mega satellite constellation system with numerous nodes, a wide range of services, and high service variability is prone to ineffective scheduling of DSS caused by long scheduling time. Therefore, the traditional terrestrial-dependent computing mode is not suitable for the demands of DSS such as high-speed connectivity and real-time monitoring. By leveraging satellite-terrestrial collaborative distributed computing (STCDC), we can simplify the information flow of the mega satellite constellation and improve mission responsiveness. The computing missions with complex constraints and objectives are distributed on the terrestrial and satellites with computing capabilities. Satellite-terrestrial collaborative computing can shorten the response time of services, which will effectively improve the service capability for emergent missions and DSS, and thus enhance the service coverage. In addition, data sharing may be prohibited in 6G STIN due to data privacy. Federated learning is a distributed learning method that guarantees user privacy. Moreover, unlike traditional machine learning methods, federated learning will be able to distribute training models, avoiding the transmission of large amounts of raw data, which alleviates expensive transmission costs and latency in SNs. Furthermore, due to the large scale of the 6G STIN, the on-board computing resources are limited, and satellite-terrestrial collaborative computing may involve two parts, inter-satellite cooperation and satellite-terrestrial cooperation. It is necessary to investigate how to make full use of distributed small computing resources and the structure of satellite-terrestrial cooperative computing to obtain better service coverage performance. The research of large-scale 6G STIN service coverage will be carried out in combination with STCDC and federated learning, etc.

5.3 High on-demand coverage based on multi-domain resource collaboration

With the expansion of 6G STIN operations, the 6G STIN covers a number of functional domains such as navigation systems, communication systems, and observation systems. The extension of services stimulates the scale growth of users and nodes in the space, which is challenging to enhance the coverage of multi-domain services in 6G STINs. Synergizing individual domains through cross-domain collaboration is a promising solution to enhance service coverage. Network function virtualization (NFV) and software defined network (SDN) are pivot tools for managing multi-domain network resources. High service coverage based on multi-domain resource collaboration can be investigated from the following perspectives. (1) Multi-domain collaboration to meet differentiated services: It is challenging for SNs with uniform coverage to deliver high-quality services to regions with high service demand, and the resource utilization efficiency of regions with low service demand is relatively low. This is due to the non-uniform distribution of users and the enhancement of users' personalized demands. Therefore, there is an urgent need to optimize the effective matching of OBR and QoS according to the differentiated service requirements, to achieve efficient utilization of resources in 6G STINs and further enhance service coverage in the case of limited capacity coverage. (2) Multi-domain collaboration to enhance service coverage: It is a promising research direction to combine multiple domains and multi-dimensional resources to enhance service coverage with limited capacity coverage. Multi-domain resource synergy enhances resource utilization and service coverage by constructing a cross-domain resource utilization mechanism. Building multi-domain collaboration requires technologies such as satellite resource mobility [104], SDN, NFV, and resource virtualization.

6 Conclusion

This survey has focused on the challenges faced by 6G STINs in improving the wireless coverage capability and summarized two key technologies of service coverage structure and intelligent resource scheduling in 6G STINs. Specifically, we started with the evolution route of wireless coverage, the 6G coverage vision, and the existing key technologies and surveys related to wireless coverage performance enhancement. Afterward, we introduced coverage performance evaluation in 6G STINs, which mainly includes the definition of on-demand wireless coverage and coverage performance evaluation indicators. Furthermore, we investigated the impact of satellite constellation configuration on coverage performance and we found network structure characteristics suitable for 6G non-uniform service requirements, thus guiding constellation design in 6G STINs. Besides, we studied the improvement of coverage performance through intelligent resource scheduling. Meanwhile, we have analyzed the advantages of exploiting satellite-terrestrial collaborative computing with AI in improving 6G service performance in the highly dynamic environment in 6G STINs. Finally, we analyzed some technical challenges for service coverage improvement in 6G STINs. We hope that this paper can provide researchers with work on wireless coverage that can be used for reference, and provide effective guidance for future research on 6G STINs to improve service coverage performance.

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