6G Service Coverage with Mega Satellite Constellations

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Abstract: The rapid development and continuous updating of the mega satellite constellation (MSC) have brought new visions for the future 6G coverage extension, where the global seamless signal coverage can realize ubiquitous services for user terminals. However, global traffic demands present non-uniform characteristics. Therefore, how to ensure the on-demand service coverage for the specific traffic demand, i.e., the ratio of traffic density to service requirement per unit area, is the core issue of 6G wireless coverage extension exploiting the MSC. To this regard, this paper first discusses the open challenges to reveal the future direction of 6G wireless coverage extension from the perspective of key factors affecting service coverage performance, i.e., the network access capacity, space segment capacity and their matching-relationship. Furthermore, we elaborate on the key factors affecting effective matchings of the aforementioned aspects, thereby improving service coverage capability.

Keywords: 6G; mega satellite constellations; on-demand service coverage; un-uniform traffic demands; resource management

I. INTRODUCTION

At present, the terrestrial mobile communication system is undergoing 5G innovation to provide users with higher-quality communication services. To allow the wireless communication networks to better serve and integrate or even subvert the production and life of all mankind and the world, people have begun to dream about the 6G era [1]. Different from the trade-offs on latency, energy, costs, hardware, throughput, and reliability in 5G, the 6G system is envisioned to jointly meet stringent network demands, such as capacity, coverage, efficiency, latency, reliability, in view of the foreseen economic, social, technological, and environmental context of the 2030s [2]. With 6G, applications such as augmented reality, holographic telepresence, eHealth, ubiquitous connectivity, and unmanned mobility will come into and change the human life [2]. To realize these expectations, many researchers have developed their 6G studies regarding advanced modulation schemes for data rate [3], space-air-ground-sea integrated network for connectivity [4–6], VHF [7] and unmanned aerial vehicle (UAV) communications [8] for system capacity, machine learning for realizing intelligence [9], etc. Notably, one of the key features and expectations in the 6G is to provide the full global coverage, i.e., 100% geographical coverage [10]. However, the limited and fixed terrestrial cellular infrastructures still restrict the wireless coverage seriously, which firstly hinders the worldwide 6G service provision. Thus, the 6G system needs to be complemented with non-terrestrial networks such as satellites to further develop the 6G coverage research [10].

With the continuous reduction of satellite launch costs and the gradual maturity of satellite mass production, the low Earth orbit (LEO) satellite mega-constellations, which can provide seamless coverage, high data rate and low latency, become a hot spot for technological and commercial development and an indispensable component for 6G wireless coverage extension from land to the sea to achieve global three-

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dimensional seamless coverage [3–6, 11]. Specifically, satellites will play an irreplaceable role in future 6G networks. First and foremost, satellite networks can provide global seamless coverage [12]. While providing relatively cheap 6G services for remote areas [13], satellites can also provide ubiquitous access and global service continuity guarantees [14]. Not only that, satellites also enhance the resilience of 6G communication systems[15]. Meanwhile, non-terrestrial satellites can also provide multiple backup routes for 6G wireless connections [16], thus enhancing the flexibility of wireless services. Furthermore, satellites can also be utilized for scenarios such as enhanced backhauling and global Internet of Things (IoT) broadcasting [4, 17]. Besides, due to the use of solar energy, satellite communications are greener and more environmentally friendly than traditional base stations. Therefore, this paper contributes to 6G coverage extension from the perspective of LEO mega satellite constellations [18].

After 20 years of development, the satellite communication network has entered a new era. According to the more than 30 constellation plans that have been released worldwide, the satellite communication network shows the following three remarkable features:

- The LEO satellite constellation has become a hot spot for current development [19]. Iridium, OneWeb, SpaceX, Amazon and other commercial companies have implemented or announced their ambitious plans for LEO mobile satellite constellations [12].
- The large-scale development trend of LEO satellite constellations is significant. The number of LEO satellite constellations has changed from small-scale constellations such as 48 (Global Star) and 60 (Iridium) to large-scale constellations such as 720 (OneWeb), 3236 (Kuiper), and more than 12,000 (Starlink). The most representative constellation is the Starlink constellation, which currently has 1,890 satellites in orbit.
- The service demands of users are becoming more and more diversified. Specifically, the service demands of users have expanded from traditional mobile communication services to broadband Internet services.

With the explosive growth of demand for 6G broadband services on the ground network, applications served by satellite communication networks will also show a growing trend in the future, e.g., broadband civil aviation applications and aviation and navigation monitoring applications. The traffic requirements of these typical applications are closely related to factors such as population density, economic development, etc., so they are characterized by non-uniform distribution. With the continuous expansion of constellation scale and the diversified development of application services in 6G, the traditional signal coverage which denotes the probability that the received signal strength reaches to a predefined receiving threshold, cannot be utilized to evaluate the service capability of satellite networks for non-uniform services and guide the network configuration design for the satellite networks. Therefore, a metric dedicated to the capability evaluation of 6G satellite networks is the key to the satellite network design.

In this paper, a new network performance metric, i.e., service coverage, is creatively proposed, which is defined as the ratio of traffic density to service requirement per unit area. Notably, the service coverage is a comprehensive metric covering signal coverage and capacity coverage, and related to traffic demands. More importantly, the proposed service coverage metric can describe the degree of matching relationships between satellite network service capabilities and application requirements, and can provide effective guidance for the configuration design and optimization of satellite communication networks. Specifically, the network configuration of satellites could affect such as the frequency and launch issues, which is a complex system engineering and not similar to the terrestrial networks to increase/reduce the base stations casually for capacity supplement. Our service coverage is based on the macro statistical distribution of services but not the sudden and fine-grained resource allocation to guide the configuration, scale, and key parameter design of the satellite constellation. As for the dynamic network requirements which have spatial and temporal but not completely random distribution rules, we can apply resource scheduling, such as network slicing and QoS guarantee, after matching the macro service distribution to ensure the performance of single services.

It is worth noting that the performance of network service coverage is closely related to the constellation structure, access capacity, space segment capacity, and the matching relationship among them. In this paper, we first provide an overview of the challenges enhancing service coverage, including the theoretical modeling of satellite access and space segment capacity, and the effective matchings among service demands, access capacity, and space segment capacity. Following that, we present a detailed analysis of key factors affecting the matchings mentioned above to support efficient service coverage exploiting mega satellite constellations towards 6G. Based on the analyzed factors, we further propose a traffic demand oriented network configuration strategy and conduct simulations to verify the efficiency of the proposed system design in terms of service coverage. Conclusions are drawn in the final section.

II. CHALLENGES AFFECTING SERVICE COVERAGE

The key factors that affect the service coverage include access capacity, space segment capacity, and the deployment of ground gateways. For the improvement of service coverage, this paper mainly explores two significant challenges that must be broken in the modeling and networking, that is, the theoretical modeling of satellite access and space segment capacity, and the effective matching among non-uniform service demands, access capacity, and space segment capacity.

2.1 Theoretical Modeling of Satellite Access and Space Segment Capacity

As the scale of the satellite constellation continues to expand, the theoretical relationship among the constellation scale, structure, frequency rules, and access and space segment capacity is blurred, which brings severe challenges to the design of space ultra-dense networking systems in the theoretical modeling of satellite access and space segment capacity.

- **Access Capacity**: Access capacity is defined as the traffic volume of services that a single satellite can successfully provide. The space-time evolution law of satellite-to-earth channel interference is a key guiding factor to characterize access capacity. The evolution law not only affects the boundary of the access capacity but also determines which system parameters (e.g., orbital altitude, beamwidth, reuse factor) could be adjusted to approach to the boundary. However, with the continuous expansion of the scale of the LEO satellite constellation and the complexity of the configuration, the aforementioned evolution law is difficult to be effectively described. Consequently, how to effectively characterize the aforementioned temporal and spatial evolution law so as to clarify the theoretical model of access capacity is one of the core challenges to improve service coverage.
- **Space Segment Capacity**: The space segment capacity is defined as the product of the number of traffic flows and the maximum achievable flow rate, which is related to the size of the space segment constellation, orbit, and the transmission capacity of the inter-satellite links (ISLs). The theoretical relationship among the space segment capacity, constellation scale, and constellation configurations is still fuzzy to support the constellation structure design effectively. To determine the capacity and efficiency of the space segment, two problems need to be addressed, that is, how to balance the efficiency of a single satellite as the expanding of constellation scale brings the capacity gain, and how to construct a reasonable constellation topology (i.e., inclination, the number of orbits, the number of satellites per orbit, ISL distance) according to the scale and configuration of the constellation.

2.2 Effective Matching Among Traffic Demands, Access Capacity, and Space Segment Capacity

To improve the network service coverage capability, two matching relationships should be emphasized in networking design. One is the matching between demand distribution and network access capacity, and the other is the matching between network access capacity and space segment capacity.

2.2.1 Matching of Non-uniform Traffic Demands and Network Access Capacity

Figure 1 gives an example of evaluating the traffic distribution of terrestrial mobile data traffic and aviation and navigation surveillance application. The application demand shows uneven distribution characteris-

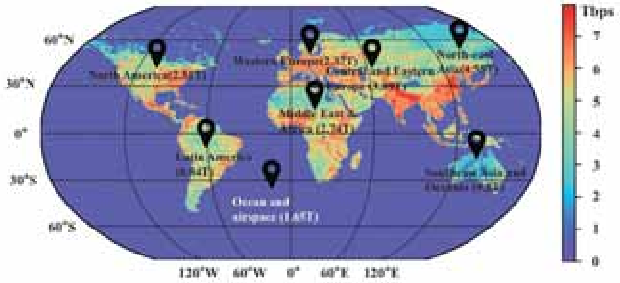


Figure 1. *The traffic distribution of terrestrial mobile data traffic and aviation and navigation surveillance application.*

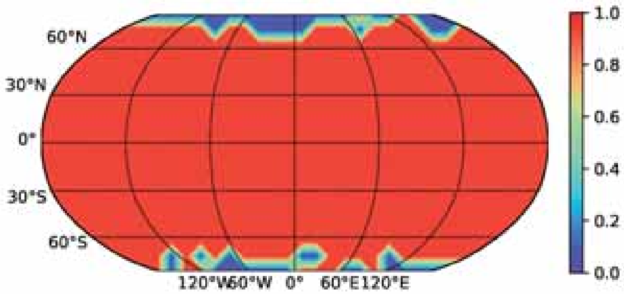


Figure 2. *The signal coverage of SpaceX constellation.*

Table 1. *Constellation scale and configuration parameters.*

Constellations	Orbital parameters	No. orbits	No. satellites per orbit(%)
OneWeb	$1200km(87.9°)$	18	40
Starlink (Parameters for the first declaration)	$1150km(53°)$	32	50
	$1110km(53.8°)$	32	50
	$1130km(74°)$	8	50
	$1275km(81°)$	5	75
	$1325km(70°)$	6	75
Telesat	$1000km(99.5°)$	6	12
	$1248km(37.4°)$	5	9

tics, and the high demand in densely-populated and economically-developed areas are obvious.

The signal coverage of the SpaceX constellation is shown in Figure 2. The signal coverage is defined as the possibility that receiving signal strength per unit area exceeds a certain threshold. As shown in Figure 2, the SpaceX constellation can realize a well-performed signal coverage except for the polar areas. It can be noted from Figures 1 and 2 that the SpaceX constellation has undifferentiated signal coverage between 60°N and 60°S. However, the traffic demand in these areas shows differentiated characteristics.

Furthermore, we could discuss the impact of the number of visible satellites (NVS) on constellation scale and configuration design. Figure 3 is the NVS distribution in terms of three constellations, including Telesat, OneWeb and Starlink. Table 1 shows their scales and configuration parameters [9]. The difference is obvious in terms of the NVS distribution of these three constellations. The NVS of Telesat constellation distribute symmetrically and the satellite number remains at about 1 in the areas from 60°S to 60°N. Entering the higher-latitude areas, NVS begins to increase and up to 18 at the polar areas. Though the scale of Telesat constellations is smaller than that of OneWeb constellations, the NVS of Telesat constellation in the areas from 60°S to 60°N is larger than OneWeb's. This is because Telesat constellation applies the double-layer configuration, and one of them is a constellation with a smaller inclination. Because of the scale expansion with smaller-inclined constellations, Starlink constellation has much more NVS than other constellations. More than 20 satellites can be visible in the areas from 60°S to 60°N.

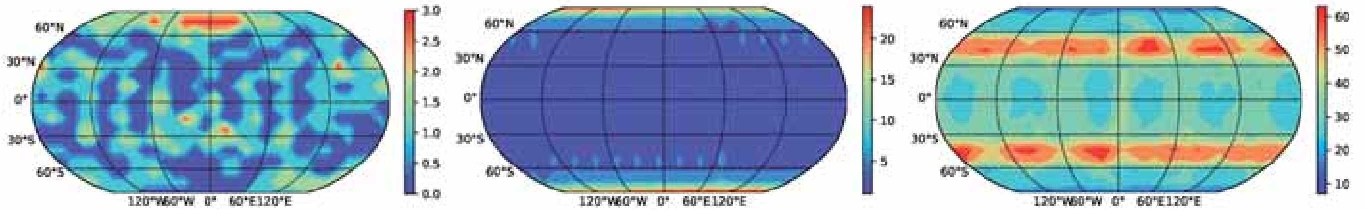
Based on the above analysis, constellation scale and configuration parameters make a great difference to NVS distribution. Then constellation access capability would be influenced. To satisfy the growing application demand and distribution characteristics, corresponding appropriate constellation scale and configuration should be designed, which will lay the foundation for improving the access capability of satellite networks.

2.2.2 Matching of Network Access Capacity and Space Segment Capacity

The space segment capacity is an important factor that affects the network service coverage performance. Although the scale of the constellation continues to expand, the relationship between the constellation scale and its space segment capacity is still unclear, and it is difficult to support the top-level design of the constellation.

As the scale of the constellation expands, it is difficult to obtain the space segment capacity of a larger-scale constellation due to the limitation of simulation software capabilities. Therefore, it is necessary to explore the internal relationship among the constellation scale, structure, and space segment capacity to reduce the waste of network resources or insufficient service capacity caused by unreasonable designs of constellation scale and capacity.

As the access points for data services are adjusted



(a) *Telesat.* (b) *OneWeb.* (c) *Starlink.*

Figure 3. *The number of distributions of visible satellite.*

from terrestrial networks to satellite networks, gateways play a pivotal role in both of the matchings since different deployment schemes of gateways will produce different service coverage. In detail, the reasons are two-fold:

- **The effect of gateway distribution on the service coverage:** Generally, the wireless gateway links work at Ka-band and are greatly influenced by weather conditions, such as rains, clouds and ionization scintillation [20]. Due to regional differences in weather conditions, the communication links between satellites and gateways at different geographical locations will suffer differentiated atmospheric attenuation, which further leads to different maximum error-free transmission rates of the links. In all, the actual amount of traffic demands that is accessed to the space network varies with the distribution of gateways. In other words, the distribution of the gateways affects the service coverage of satellite networks.
- **The effect of the number of gateways on the service coverage:** The number of gateways also has an influence on the service coverage. In general, the larger the number of deployed gateways, the more satellites that the gateways can connect; thus, the number of communication links that can be established between the gateways and the satellites also increases, which makes the access resources in the network more abundant, thereby increasing the service coverage.

Through the above analysis, it can be observed that the scale and configuration of the constellation have a significant influence on the distribution of visible satellites, which in turn affects the access capacity of the constellation. It is necessary to design the constellation scale and configurations matching the ever-increasing application requirements and distributions. Meanwhile, based on the matching of access capacity and service requirements, the relationship between access capacity and space segment capacity should also be carefully considered, where the space segment capacity contains the regenerative processing capability and bent pipe forwarding capability. As analyzed above, the space segment capacity is related to the constellation scale, configurations, and ISL rates, while the bent pipe forwarding capability is only related to the gateway link parameters and the deployment of ground stations.

III. KEY FACTORS ENABLING EFFECTIVE SERVICE COVERAGE

In this section, we elaborate on three key factors enabling effective service coverage from the perspective of the models and analyses for access capacity and space segment capacity, and the efficient gateway deployment strategy.

3.1 Modeling and Analysis for Access Capacity Exploiting Mega Satellite Constellations

To investigate the access capacity of a mega satellite constellation, we need to analyze the interference between systems and within the constellation to study its impact on the system access capacity. Notably, the unreasonable use of frequency resources will inevitably cause serious inter-system and intra-system interference, thus deteriorating the access capacity of the network [21].

As shown in Figure 4, interference in LEO satellite networks can be divided into four categories: the interference among different LEO satellite systems, the online interference between GEO and LEO satellite systems, the interference between a satellite and

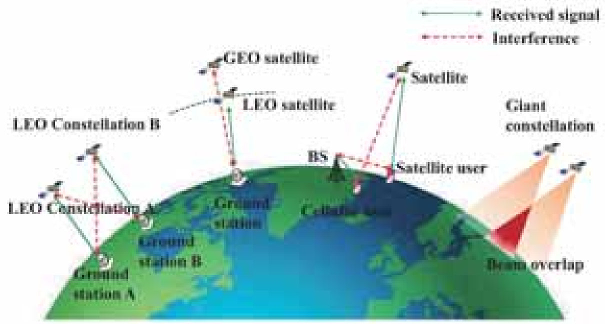


Figure 4. *LEO constellation interference.*

ground systems, and the interference within constellations. The same frequency band is likely used for communication between different LEO satellite systems and terrestrial-satellite systems, resulting in the same frequency interference between systems. When the positions of the two satellites and the ground station are on a straight line at the same time, collinear interference will occur [22]. With the large-scale and dense deployment of satellite constellation systems, frequency conflicts have intensified, and two or more adjacent satellites reuse the same frequency resources, resulting in serious intra-system interference.

Interference in the system is mainly due to the reuse of the same frequency resources by two or more adjacent satellites, which leads to resource conflicts. However, from the perspective of user service quality with high data rate requirements, beam overlap on the same frequency is necessary. If the interference cannot be dealt with, the access capacity and coverage will be greatly reduced. In addition, since the available spectrum resources allocated to a constellation are very limited, interference may become overwhelming, especially when the constellation scale becomes larger. Therefore, it is necessary to study the interference in the system.

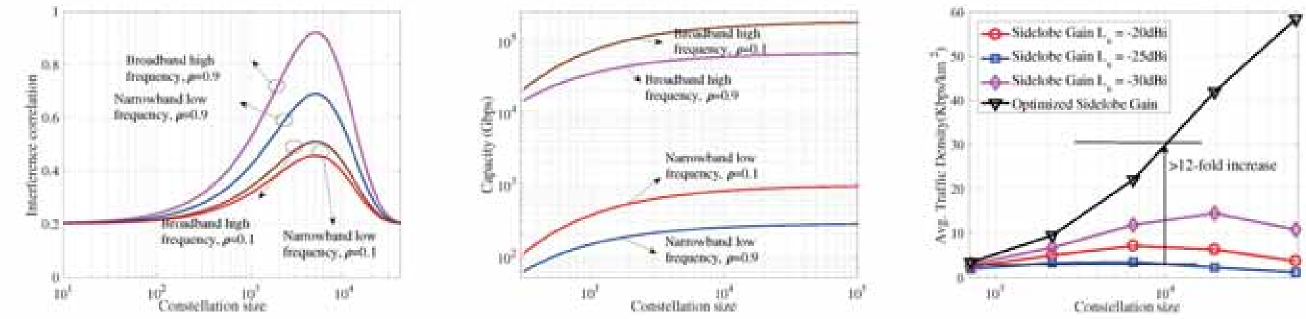
The interference within the constellation has complex characteristics. The orbital motion of satellites and the time dependence of the satellite-earth channel interference within the giant constellation system have a significant space-time evolution law, which determines the access capability boundary of the giant constellation system. This enables us to approximate the boundaries of system access capabilities by adjusting some system parameters, thus limiting the service capabilities of satellite constellation systems. Therefore, the interference correlation factor θ can be used to capture the influence of the interference correlation factor on the access capacity

$$\theta = \left\{\rho E\left[H^2\right]+(1-\rho)E\left[H^2\right]\right\}\times Ne^{-\kappa N}\times A, \quad (1)$$

$$C \backsim \frac{1}{\Xi\left(\theta\right)+e^{-\kappa N}}. \quad (2)$$

Here ρ represents the temporal correlation of the satellite-ground channel; H represents the channel gain of the satellite-ground channel; N represents the constellation size; κ and A stand for functions of other system parameters. Besides, C denotes the capacity of a satellite. Notably, C is inversely proportional to θ, which means that the larger the correlation factor θ is, the larger the capacity of a single satellite is.

Based on the satellite parameters of 16 beams and half beam angle of $0.44°$ for each satellite [12], the simulation is carried out under the conditions of broadband high frequency (frequency = $28GHz$, bandwidth = $45MHz$) and narrowband low frequency (frequency = $2GHz$, bandwidth = $50KHz$). We investigate the changes of the interference correlation coefficient, access capacity, and average traffic density with the increase of network size, i.e., the number of satellites. As shown in Figure 5a, when the constellation size is small, as the constellation size increases, the interfering satellite sets on different time slots are spatially correlated, increasing the interference correlation factor. When the scale of the constellation increases to a certain extent, the influence of rain attenuation on the interference is reduced, which will reduce the correlation of the interference. In addition, the increased interference correlation inevitably causes the link transmission interruption to be related to time, and the access capacity is reduced by the interference correlation, as shown in Figure 5b. Since the results show that interference correlation will reduce the capacity of satellite access networks, we intend to reduce interference and interference correlation through-beam optimization. It can be seen from Figure 5c that proper sidelobe gain can greatly alleviate the interference in the constellation so that the access capacity will not be reduced due to improper beam design, thereby significantly increasing the average service density.



(a) *Interference correlation coefficients varying with constellation size.*

(b) *Access capacity varying with constellation size.*

(c) *Traffic density varying with constellation size at different sidelobe gains.*

Figure 5. *Network performances vary with constellation size.*

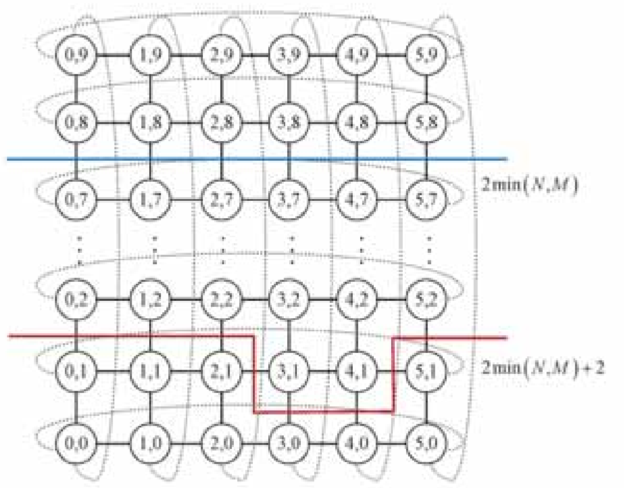


Figure 6. *The minimum cut set of the seamless two-dimensional grid graph.*

3.2 Modeling and Analysis for Space Segment Capacity

Analyzing the relationship between the space segment capacity and constellation parameters can guide the design of constellation space segment capacity to match the service coverage capability of the constellation. In this paper, we propose a theoretical model of space segment capacity and extend our previous research [23] to give an accurate expression of space segment capacity. This paper uses the symmetrical grid topology to model the satellite network. Then, we adopt $G_1 = (V, E_1)$ to represent the topological graph of the seamless satellite network.

The specific modeling is as follows. Assume that the number of orbits is N and the number of single-orbit satellites is M. Each satellite corresponds to a node in the proposed gridded graph. Each node has two adjacent nodes connected by the edge whose maximum transmission rate is B_l in the vertical and horizontal dimensions. The maximum flow minimum cut method is used to analyze the capacity of the seamless satellite network under saturated traffic. We first calculate the size of the minimum cut set, then calculate the capacity of a single node pair, and finally calculate the network capacity.

For a two-dimensional grid graph without reverse seam, when $N \to \infty$ and $M \to \infty$, the size of the minimum cut set is $\varepsilon_{\infty\infty}(n) \geq 4\sqrt{n}$ [24]. When N and M are finite, the following rules can be obtained according to the characteristics of the grid.

- When $n \in \left\{1, 2, \cdots, \left\lceil \frac{\min(N^2, M^2)}{4} \right\rceil \right\}$, the cutset is the same as $N \to \infty$ and $M \to \infty$, that is, $\varepsilon_{NM}(n) = \varepsilon_{\infty\infty}(n) \geq 4\sqrt{n}$.
- When $n \in \left\{ \left\lceil \frac{\min(N^2, M^2)}{4} \right\rceil + 1, \ldots, \left\lceil \frac{NM}{2} \right\rceil \right\}$ and the number of nodes to be cut is a multiple of $\min(N, M)$, the cut set cuts the network in the horizontal or vertical direction, and the size of the minimum cut set is $2\min(N, M)$, as shown by the blue line in Figure 6. Specifically, when $N < M$, the cut set cuts the network in the horizontal direction, and the size of the minimum cut set is $2N$. When $N > M$, the cut set cuts the network in the vertical direction, and the size of the minimum cut set is $2M$.
- When $n \in \left\{ \left\lceil \frac{\min(N^2, M^2)}{4} \right\rceil + 1, \ldots, \left\lceil \frac{NM}{2} \right\rceil \right\}$ and the number of nodes to be cut is not a multiple of N or M, the size of the minimum cut set

Table 2. *The simulated and theoretical values of the seamless network capacity.*

# Sat. (N, M)	60 (6, 10)	120 (8, 15)	180 (9, 20)	240 (10, 24)	300 (15, 20)
The theoretical value ($Gbps$)	4.72	6.357	7.16	7.9667	11.96
The simulated value ($Gbps$)	4.714	6.369	7.131	7.949	11.878

is $2\min(N, M) + 2$, as shown by the red line in Figure 6. Specifically, when $N < M$, the cut set cuts the network in the horizontal direction, and the size of the minimum cut set is $2N + 2$. When $N > M$, the cut set cuts the network in the vertical direction, and the size of the minimum cut set is $2M + 2$.

In summary, the size of the minimum cut set of the network denoted as ε_{NM} can be expressed as (3). The maximum traffic that can be transmitted between each pair of nodes is shown as follows

$$c_{\max} = \min \frac{\varepsilon_{NM}(n) B_l}{n(NM - n)}. \tag{4}$$

Based on the above analysis, for a seamless low-orbit satellite network with N orbits and M satellites, assuming that the maximum feasible transmission rate of each link in the network is B_l, the network capacity can be calculated as follow

$$C = \begin{cases} \frac{8(NM-1)B_l}{M} & N \leq M, M\, is\, even \\ \frac{8M(NM-1)B_l}{M^2-1} & N \leq M, M\, is\, odd \\ \frac{8(NM-1)B_l}{N} & N > M, N\, is\, even \\ \frac{8N(NM-1)B_l}{N^2-1} & N > M, N\, is\, odd \end{cases}. \tag{5}$$

Table.2 shows the simulated and theoretical values of the seamless network capacity. The maximum feasible transmission rate of each link B_l is set as $100Mbps$ in this scenario. It can be seen that the network capacity presents an upward trend with the increase of constellation scale, i.e., the number of satellites. Besides, it is noteworthy that the simulation value and the theoretical value of the network capacity are consistent, which verifies the correctness of the theoretical results in this section.

Algorithm 1. *NSGA-II based ground station placement optimization algorithm.*

Input: Constellation information, the set of terrestrial switch locations, feeder link rates, data demands and population distribution.

Output: A set of selected ground station collections with three objective functions.

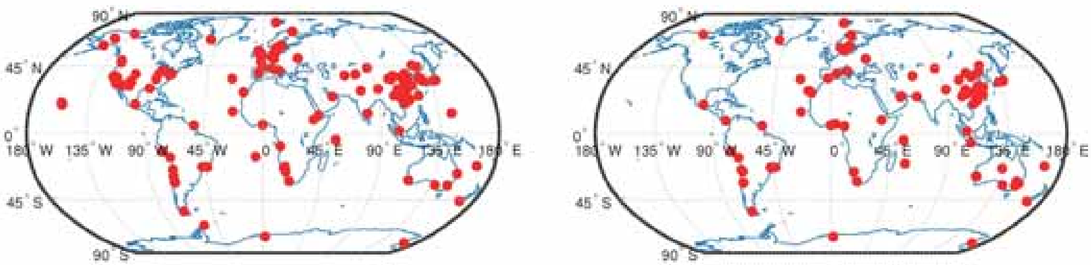
1: **Initialization:** Population size, mutation probabilities, the maximum number of iterations, and iteration index.
2: Create the first generation by randomly selecting collections from the set of terrestrial switch locations.
3: **for** each collection in the selected set **do**
4: Evaluate from three dimensions.
5: **end for**
6: Perform non-domination sorting process over the selected set.
7: **if** the number of iterations does not reach the maximum **then**
8: Select half of the collections as the parents.
9: Perform crossovers over parents and produce the offspring.
10: Apply mutation over parents and the offspring.
11: Combine the mutated parents and offspring to form a new generation, and **Go to** 3.
12: **end if**

3.3 Traffic-aware Gateway Deployment Strategy

There are mainly two factors that affect the deployment of gateways, namely the weather conditions and the distribution of traffic demands. Intuitively, a gateway with more stable weather conditions and greater corresponding traffic demands tends to be chosen. Notably, the network service coverage is related to not only the gateway distribution but also the number of deployed gateways. In this regard, to enhance the service coverage, we propose a traffic-aware gateway deployment strategy, in which the weather conditions and the traffic distribution are jointly considered to strike a balance between service coverage and the number of deployed gateways.

Recently, most gateway deployment problems are modeled as a typical optimization. The formulated problems generally have many integers, and thus heuristic algorithms are presented for solutions. Dif-

$$\varepsilon_{NM}=\begin{cases} \varepsilon_{\infty\infty}(n) \geq 4\sqrt{n} & n\in\left\{1,2,\cdots,\left\lceil\frac{\min\left(N^2,M^2\right)}{4}\right\rceil\right\} \\ 2\min(N,M)+2 & n\in\left\{x|x\in\left\{\left\lceil\frac{\min\left(N^2,M^2\right)}{4}\right\rceil+1,\ldots,\lceil\frac{NM}{2}\rceil\right\}\&\left(x \bmod \left(\min\left(N,M\right)\right)\right)\neq 0\right\} \\ 2\min(N,M) & n\in\left\{x|x\in\left\{\left\lceil\frac{\min\left(N^2,M^2\right)}{4}\right\rceil+1,\ldots,\lceil\frac{NM}{2}\rceil\right\}\&\left(x \bmod \left(\min\left(N,M\right)\right)\right)=0\right\} \end{cases}. \quad (3)$$



(a) *The 128 selected gateway locations of SpaceX constellation.* **(b)** *The 83 selected gateway locations of the proposed constellation.*

Figure 7. *Distribution of gateway locations of different constellations.*

ferently, we propose a scheme based on the genetic algorithm in this paper, as shown in Algorithm 1. Specifically, we first analyze the weather conditions for a given set of potential gateway locations to obtain the total propagation loss of the link. Then, calculate the signal-to-noise ratio of the link according to the propagation loss, path loss, and preset transceiver parameters, and use the Shannon formula to get the upper limit of the error-free transmission rate of each link. Next, according to the method in [25], the global communication traffic demand is modeled, and the grid traffic demand with the latitude and vertical resolution of 1° is obtained. Subsequently, the gateway placement problem is modeled as a multi-objective optimization problem to maximize service coverage and minimize the number of deployed gateways. Finally, we propose a non-dominated genetic algorithm to solve the gateway deployment problem.

IV. NETWORK CONFIGURATION STRATEGY AND PERFORMANCE EVALUATION

In this section, we first propose a traffic demand oriented system according to the analyzed factors affecting service coverage. Then, we conduct simulations to verify the efficiency of the proposed network configuration in terms of the network service coverage.

Table 3. *The orbital parameters of the proposed constellation.*

#Plane	#Sat./Plane	Inclination	Altitude (km)
20	21	84°	1345
24	25	68°	375
28	29	56°	370
29	30	53°	365
26	27	47°	445
30	30	55°	455

4.1 Traffic Demand Oriented System Design

According to the interference and beam management policies for access segment, network structure design for space segment, as well as the joint optimization of the deployment of gateways, we optimize the number of satellite layers, the number of orbital planes per layer, the number of satellites per orbit, the inclination, and the orbital altitude for a new constellation. The proposed constellation contains 6 satellite layers with a total number of 4304 satellites. The detailed orbital parameters are given in Table 3, and those parameters of SpaceX are shown in Table 4 for comparison [26].

Table 4. *The orbital parameters of SpaceX.*

#Plane	#Sat./Plane	Inclination	Altitude (km)
22	72	53°	550
32	50	53.8°	550
8	50	74°	1130
5	75	81°	1275
6	75	70°	1325

With the designed constellation, we perform the traffic-aware gateway deployment process. Since the deployment of the gateways is limited by location and political reasons, for example, we may not be allowed to deploy gateways in the U.S., the size of the initial gateway set in the proposed case is reduced to 128. By optimizing the deployment of the gateways for services, we select 83 gateways to achieve the optimal performance in the proposed constellation. It can be seen that compared with SpaceX that requires 128 gateways to achieve its optimal performance when the number of available gateways is 232, the proposed system needs a smaller number of gateways to achieve performance convergence and the optimal service coverage performance. The selected gateway locations of both constellations are given in Figures 7(a) and 7(b).

4.2 Performance Evaluation

In order to evaluate the performance of our constellation design, we mainly evaluated the service coverage of the network. The specific process for assessing service coverage is as follows:

- Obtain the visibility matrix for the satellite and ground grids. Then, calculate the average business rate for the ground grid.
- Divide the constellation network capacity by the constellation size to get the average service rate of a single satellite.
- According to the visibility relationship between satellites and the ground grid, the service rate of a single satellite is averaged to each visible grid to obtain the average service rate for each ground grid.
- Use $\min\left\{1, \frac{\text{Average Service Rate}}{\text{Average Traffic Rate}}\right\}$ to measure service coverage for each grid. The service coverage rate of the constellation is calculated by averaging the service coverage of all grids.

Table 5. *The beam resource allocation of the proposed constellation.*

Ave. access capacity per sat.(#beam)-scheme1	Ave. access capacity per sat.(#beam)-scheme2
$3.6Gbps(5)$	$3.6Gbps(5)$
$8.64Gbps(12)$	$12.96Gbps(18)$
$21.6Gbps(30)$	$25.2Gbps(35)$
$25.4Gbps(35)$	$28.8Gbps(40)$
$25.5Gbps(35)$	$28.8Gbps(40)$
$8.4Gbps(12)$	$21.6Gbps(30)$

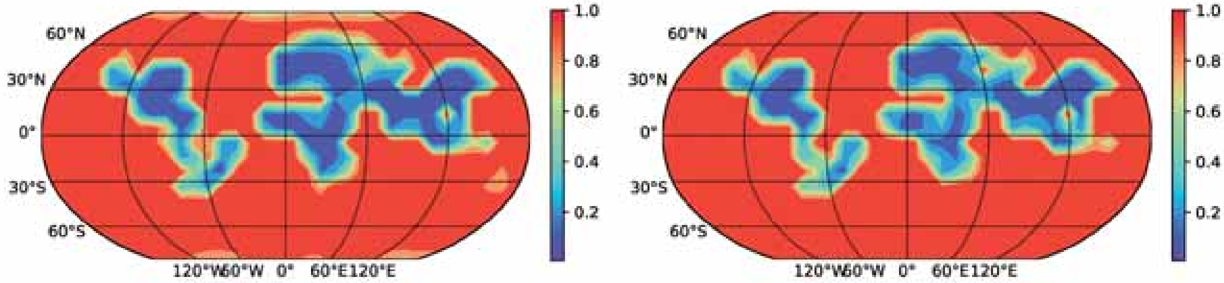
Table 6. *Performances of different constellations.*

Constellations	Access capacity	Space segment capacity	Average service coverage (%)
The proposed constellation	$72.41Tbps$	$30.58Tbps$	84.05
	$95.25Tbps$	$30.58Tbps$	85.17
SpaceX	$94.17Tbps$	$14.58Tbps$	81.8

Furthermore, we bring up two beam resource allocation schemes for each satellite on the 6 satellite layers, as shown in Table 5.

The resulted performance values of the two constellations are given in Table 6. It can be seen that for the proposed constellation scheme 1, we design less beam resources for each satellite, with a total access capacity of $72.41Tbps$. With the optimization of space segment, the satellite network capacity is also improved to $30.58Tbps$ compared with $14.58Tbps$ of the SpaceX. In this case, we achieve an average service coverage of 84.05%. Therefore, through the efficient on-demand matching of the access capacity and the non-uniform service requirements, the proposed constellation can maintain or even exceed the service coverage performance of the SpaceX constellation with the approximate constellation scale and fewer resources.

As for scheme 2, we increase the beam service capability of each satellite compared with the scheme 1, such that the access capacity is similar to that of the SpaceX constellation, and the space segment capacity remains at $30.58Tbps$. As a result, the average service coverage can be increased from 81.8% to 85.17% even with a smaller number of gateways compared with SpaceX, which indicates that when the access capacity of the proposed constellation is approximately equal to that of the SpaceX system, the service coverage of the proposed constellation is increased by 3.4% compared with SpaceX system. Notably, in this case,



(a) *SpaceX constellation.*

(b) *The proposed constellation.*

Figure 8. *Service coverage of different constellations.*

the effective constellation structure design makes up for the performance degradation caused by the inability to deploy gateways globally.

Furthermore, Figures 8a and 8b show the service coverage performance of the SpaceX constellation and the proposed constellation, respectively. It can be observed that the proposed constellation uses a smaller number of gateways but achieves better service coverage in densely populated areas at middle and low latitudes as well as areas with high service demands. Therefore, the proposed system design scheme has the following advantages. On the one hand, the proposed system design strategy can shrink down the access capacity to ensure the performance of the service coverage while avoiding the waste of access capacity resources. On the other hand, by jointly optimizing the structure of the constellation and gateway deployment strategy to improve the space segment capacity and the access capacity, the network service coverage performance can be further improved.

Notably, the design of our simulation scenarios and parameters is based on the orbits and related constellation parameters released in the FCC documents of SpaceX [26]. Meanwhile, the demand model is generated as a gridded map that determines the number of people covered by the beams of a satellite located in a particular orbital position, using the Gridded Population of the World v4 dataset, which estimates the population counts for the year 2020 [12]. Furthermore, our definition of measuring network performance, that is the service coverage, can effectively reflect the effectiveness of network services. It not only covers the signal coverage and capacity coverage determined by the system but also relates to the actual network service demands. More importantly, our results can give some meaningful guidance for satellite network design. For example, it is difficult to well serve areas with high service demands in low and middle latitudes. Through our design of differentiated beam capacity, we can effectively improve the service coverage of these hot areas.

V. CONCLUSION

Integrated satellite-terrestrial networks with mega satellite constellations have been proved to be the potential architecture for paving the way to future 6G wireless service coverage extension. In this paper, we firstly discuss three challenges for 6G wireless service coverage extension from satellite access networks and space segment networks perspectives. Furthermore, we investigate three key factors in view of their potential to be deployed in satellite access networks and space segment networks, including theoretical models of access capacity and space segment capacity, and gateway deployment techniques. In addition, we propose a system architecture to achieve efficient matching among traffic demands, access capacity, and space segment capacity to improve the service coverage. Simulation results verify the effectiveness of the proposed system architecture in adapting to non-uniform services and achieving an improvement in service coverage.

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