Cell Breathing Scheme for Mega-Constellation Satellite Networks

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Abstract: Low earth orbit (LEO) mega-constellations can provide global low-latency high bandwidth coverage compared to the terrestrial network. The time-varying topology of satellite networks and the uneven traffic distribution lead to the mismatch between satellites and users, resulting in the waste of satellite resources and the degradation of user performance. Through negotiation with neighbors, the traditional terrestrial cell breathing continuously converges to the optimal cell size in the face of user tides, but this method is difficult to converge timely when facing rapid and extreme flow changes caused by the rapid movement of satellites. This paper presents a fast adaptive cell breathing scheme (FaB) through sub-block division and satellite cell initialization and adjustment. FaB divides the ground into sub-blocks according to the user density. When the satellite moves in the same sub-block, the step size of breathing is adjusted according to the cell size difference between the previous satellite and the current satellite. When the satellite switches between different sub-blocks, the initial value of the cell is determined according to the density of the new sub-block. In addition to negotiating with neighboring satellites, this scheme also introduces location information to directly adjust the parameters of cell breathing and decrease the time of cell breathing convergence. From the real constellation data-driven simulation, we conclude that FaB can quickly adjust the size of the cell with the location changing, and the utilization rate is increased by 2.66 times compared to the method with no cell breathing, and by 2.37 times compared to the method with cell breathing without location information.

Keywords: satellite networks; cell breathing; mega-constellation; block division

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0 Introduction

Large-scale low earth orbit (LEO) satellite constellations can provide global low-latency high bandwidth coverage compared to the terrestrial network. Several LEO mega-constellations, such as Starlink[1], OneWeb[2] and Kuiper[3] have been proposed recently. Whether satellites can be fully utilized is related to the long-term success of satellite companies[4]. The first wave of commercial constellations appeared in the 1980s and 1990s, with 15 commercial LEO constellations targeting broadband, short message service (SMS) and voice, but most companies failed around 2000. Even Orbcomm, Iridium and Globalstar, which successfully launched the first generation of satellites, went bankrupt due to far less than expected utilization[5]. Due to the dual limitations of business models and technical bottlenecks, commercial communication satellites could not compete with the terrestrial Internet, and have entered a stage of slow rise. In late 2014 and early 2015, the International Telecommunication Union (ITU) received six applications for mega-constellations for the first time, which also marked the emergence of the second wave of constellation booms. On 19 March, 2022, Starlink, the most densely launched of these constellations, has launched 2 335 satellites and has obtained service authorizations in 29 countries and regions. A

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new business model for communication satellites is being piloted. However, the utilization of satellite constellations is affected not only by the business model, but also by the constellation configuration and user distribution.

Considering the issues of satellite launch, orbit maintenance, and relative motion of the satellites and the Earth, many existing LEO mega-constellations have adopted a uniform constellation configuration to provide Internet services for users. However, the distribution of users on the ground is extremely uneven, about 86% of the population is concentrated on 5% of the ground[6]. Sparsely populated areas occupy most of the Earth's surface. Communication satellites will be in a low load or idle state when they are over these areas, and the utilization rate is low. In contrast, satellites over dense areas are congested due to insufficient capacity. This congestion drives the constellation to increase in size evenly, further exacerbating the waste of idle satellites in sparse areas. Idle satellites consume a lot of traffic irrelevant energy, but satellite energy is precious. Satellites are usually equipped with solar panels and rechargeable battery cells as their energy source and storage. During the eclipse phase where sunlight is blocked by the Earth, satellites face the problem of insufficient energy. On the sunny side, the angle of the solar panel and the light may be too small to ensure sufficient power[7]. Also, prolonged low-flow operations can also cause unnecessary wear and tear.

Unlike satellite networks, terrestrial networks are deployed on-demand, so there is no such serious waste. However, due to changes in user behavior over time, there will also be tidal changes in traffic, and the response strategy on the ground is cell breathing[8]. By adjusting the hardware or power, the coverage area of base stations (BSes) can be changed. The cell size in the area with dense users is reduced, and the size in the area with sparse users is enlarged so that users in dense areas can access BSes with lower loads and the throughput can be improved. The BSes with very low load in sparse areas are subactive to reduce energy consumption. The utilization of BSes can be improved by cell breathing.

Cell breathing is a viable option to increase utilization of satellite networks. The changes faced by the ground BSes are only the user tides, and BSes can adjust the state of the cell by learning the characteristics of user behaviors. But satellites also face reverse tides caused by satellite motion. The superposition of the two tides will cause the cell breathing to face the following problems:

(1) Dramatic change in satellite traffic. The scheme needs to converge in time to adapt the cell size to the traffic characteristics.

(2) Constantly change of neighbor relationship. As a joint optimization strategy, satellites lack stable neighbors for continuous negotiation to gradually optimize cell size.

(3) Continuous movement of coverage area. The continuous movement of the coverage area makes global coverage hard to guarantee.

For these characteristics, this paper presents FaB, a fast adaptive cell breathing scheme(FaB) for mega-constellation networks. FaB divides the Earth's surface into sub-blocks according to the density distribution of traffic. The density within the same sub-block is similar, and the density between sub-blocks is diversified. Then we present an initialization scheme for breathing through neighbor negotiation, which can adjust cell size without coverage holes. The adaptive scheme changes the step size according to the gap from the previous satellite inside a sub-block, and when switching between sub-blocks, the initial value of the cell is set according to the density of the new sub-block. Without coverage holes, FaB can quickly adapt to changes in traffic and reduce the impact of changes in neighboring satellites.

1 Related Work

Cell breathing performs load balancing and energy saving by modifying the coverage area of BSes or access points (APs), as shown in Fig.1. When users are evenly distributed, each cell has the same size. When congestion occurs in a cell, it can reduce the cell size, and neighbors increase the cell size for load balancing. When the entire user traffic is low,

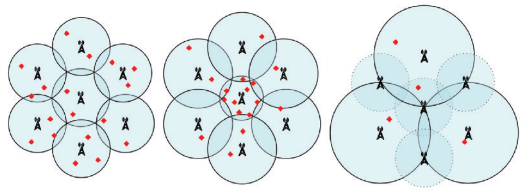


Fig.1 Cell breathing

some cells can be increased in size, and other cells can sleep to save energy. Cell breathing is also called cell zooming.

Common cell size adjustment techniques include:

(1) Physical adjustment[9]. The coverage can be adjusted by changing the height or elevation of the antenna.

(2) Adjust the pilot signal power[10]. The user selects the connected BS according to the strength of the pilot signal, and the modification of the strength of the pilot signal can affect the selection of the user's associated cell, changing the actual range of the cell.

(3) Relay technology. Relay nodes can be deployed inside a cell or between two cells. The former can help improve the performance of the cell edge, and the latter can balance the traffic of the two cells.

(4) Association strategy adjustment[11-12]. By coupling signal strength and other parameters, such as BS load, the user's associated cell selection can be changed, and the actual service area of the BS can be changed.

Cell breathing was first proposed and used in code division multiple access (CDMA) systems for throughput improvement of load balancing[7]. Das et. al. proposed two centralized coordination scheduling schemes to optimize the connection with the joint goals of throughput maximization and load balancing[13]. Du et. al. proposed a distributed scheme, which imitates the bubble oscillation algorithm in physics and takes the coverage area of each BS as a bubble, and the bubble constantly oscillates and tends to balance[9].

In wireless local area networks (WLANs) based on IEEE 802.11, the throughput can also be improved through cell breathing. Bejerano et al. set multiple levels of beacon signal transmission power for APs, and calculated it according to the user's location[10]. Bahl et al. found the best match of APs and terminals by building a bipartite graph with weights and building a linear programming model, and then adjusting the power of APs[14]. Wang et al. presented a variable polyhedron genetic algorithm (GA) for AP service spoofing and AP service vulnerability caused by the use of adjusted beacon power for cell breathing[15]. These solutions aim at small systems and require calculations down to the granularity of users, which are unaffordable for satellites.

Cell breathing is applied to reduce the energy consumption of BSes by putting some BSes to sleep state and supplementing the original coverage area of the sleeping BSes with neighbor BSes[16]. Exploiting greedy thoughts, two examples of BS sleep schemes are given with cell zooming[17]. Peng et al. proposed a way of dividing sub-blocks to ensure coverage and sleep at the same time[18], but the unfixed sub-block affiliation and neighbors of satellites made this scheme difficult to use.

Various schemes apply cell breathing technology to improve the performance of heterogeneous cellular networks (HetNets)[16]. Zhang et al. used it to perform load balancing under congestion and sleep energy saving under idle conditions in micro cells according to the overall traffic load[19]. Xu et al. applied game theory to optimize the cell zooming factor based on reducing area power consumption[20]. Mollahasani et al. proposed two heuristics to adapt the density of BSes to network parameters to improve throughput, energy efficiency, and spectrum effectiveness[21]. But there is a magnitude difference between the different types of cells in HetNets, which is not a necessary condition for satellite systems that are highly similar in the altitude.

Compared with the rapidly developing and widely used terrestrial cell breathing technology, the development of satellite constellation-related technologies is limited. As early as 1994, Jamalipour et al. found that the signal-to-noise ratio of different satellites was very different in non-uniform traffic scenarios, which affected the communication quality[22]. Qian et al. found the problem of unfairness between regions caused by uniform beam coverage patterns, and designed a dynamic beam adjustment and spectrum allocation scheme to make hot spots always closer to the beam center[23]. Zheng et al. used a seasonal autoregressive synthetic moving average model for satellite load forecasting, and then expanded or shrank satellite coverage based on load conditions[24]. These solutions are either for a single satellite, or only for small constellations or polar orbit constellations, and can no longer be adapted to the current mega-constellations.

2 System Model

2.1 Orbit model

The Walker constellation[25] is the most popular constellation at present. It contains many variants such as δ, σ, Ω. Among Rosette[26] constellations, the most widely used is the Walker-δ constellation (Walker constellation represents the Walker-δ constellation unless otherwise specified). A walker constellation can be represented by $N/P/F : h : i$, where h and i are the altitude and the inclination; N the total number of satellites; P the number of orbits; and F the relative phase difference between satellites of adjacent orbits passing through the equatorial plane.

For a satellite numbered m in the constellation, the right ascension of ascending node Ω_m and mean anomaly from perigee at epoch u_m can be calculated as

$$\begin{cases} \Omega_m = \dfrac{2\pi}{P}\left(P_m - 1\right) & P_m = 1,2,\cdots,P \\ u_m = \dfrac{2\pi}{s}\left(N_m - 1\right) + \dfrac{2\pi}{N} F\left(P_m - 1\right) & N_j = 1,2,\cdots,S-1 \end{cases} \tag{1}$$

where P_m is the orbit number, and N_m the number in orbit. That is, $P_m = m/s + 1$, $N_m = m - \left(P_m - 1\right)$. Several mega-constellations currently deployed consist of multiple shells, and each shell is a walker constellation. The parameters of the existing multiple constellations are shown in Table 1. Fig. 2 shows the orbit and satellite distribution of Kuiper.

Table 1 Constellation parameters

Constellation	Plane	Satellites per plane	Altitude/(°)	Inclination/(°)
Telesat	27/40	13/33	1 015/1 325	98.98/50.88
OneWeb	36/32/32	49/72/72	1 200	87.9/55/40
Kuiper	28/36/34	28/36/34	590/610/630	33/42/51.9
Starlink	72/72/6/4/36	22/22/58/43/20	540/550/560/560/570	53.2/53/97.6/97.6/70

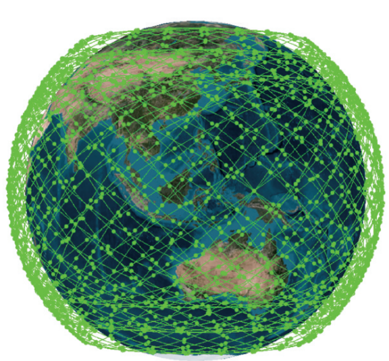


Fig.2 Multilayer walker constellation (Kuiper)

2.2 Coverage model

Terrestrial users can directly associate with a satellite through a smartphone or a small handheld device. They take satellites as access points to the Internet. There is overlapping coverage between satellites, as shown in Fig.3(a). Once the user enters

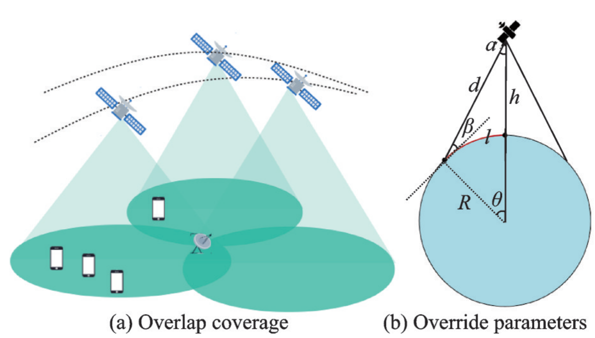


Fig.3 Communication scene and coverage model

this satellite network, it initials a scanning operation and associates with the satellite with the strongest received signal strength indicator (RSSI). The user can switch when a satellite with stronger RSSI appears, or when the communication strength is insufficient when the user is far away from the satellite.

As shown in Fig.3(b), the radius of the Earth is R. For the satellite with an altitude of h, the coverage angle of it is α, and the corresponding user elevation angle is β. At this point, the geocentric angle θ corresponding to the satellite and the user and satellite coverage radius l can be calculated according to the law of sine

$$\theta = \arcsin\left(\frac{R+h}{R}\sin\alpha\right) - \alpha \tag{2}$$

$$l = \theta R \tag{3}$$

The coverage of multiple beams of a satellite forms the coverage of the satellite. Satellites can adjust the coverage size through the change of beam pattern or the pilot power. For simplicity, we assume that the received power is only related to distance. When a more precise formula is required, calculations such as cloud attenuation and rain attenuation can be added. According to Ref.[14], the power p_{us} received by the user u from the satellite s is

$$p_{us} = \frac{\alpha p_s}{(D_{us})^{\alpha}} \tag{4}$$

where α is the attenuation factor, which is set to 2 in this paper; D_{us} the distance between user u and satellite s; and p_s the transmit power of the satellite.

We set the optimal user-perceived power as $\widehat{p_{us}}$, a circle with the same p_{us} within the satellite coverage is called an isopower line. When the satellite power is the highest, the area within the isopower line where the user's received power is $\widehat{p_{us}}$ is the coverage area of the satellite. Two satellites are considered as neighbor satellites if their coverage areas overlap.

For a transmit power p_s, the area within the isopower line with received power $\widehat{p_{us}}$ is the satellite's work scope. Users within the scope can perceive the satellite with power exceeding $\widehat{p_{us}}$. Users outside the line can perceive the satellite, but the satellite is not preferred due to the lower power, only without other choice the user can choose to associate this satellite.

In a mega-constellation, due to the large number of satellites, there is a serious overlapping coverage, and dozens or even hundreds of satellites are within a user's line of sight.

3 Cell Breathing for Satellites

3.1 Benefits

Constellation networks cannot be deployed on-demand like the ground networks due to its dynamic nature, and can only adopt a relatively uniform configuration. This configuration has different densities at different latitudes. Fig.4 shows the capacity distribution of Starlink at different latitudes. In addition, a constellation has almost the same distribution of capacity at different longitudes. However, the distribution of ground traffic is uneven and irregular.

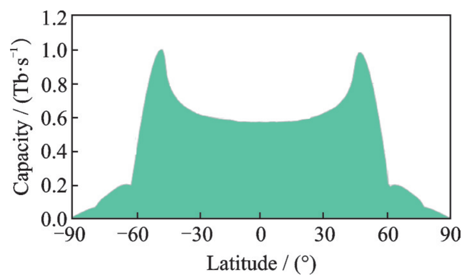


Fig.4 Satellite capacity distribution of Starlink

Cell breathing has a very broad application prospect in constellations. First, the reason for the continuous expansion of satellite constellations is the demand of users in high-density areas. A uniform constellation means that to meet the needs of users in the dense area, the number of satellites needs to be increased several times or even dozens of times of the capacity of the dense area. Cell breathing can disperse users in dense areas to satellites with lower neighbor loads, and improve satellite throughput without increasing the constellation scale.

Second, a single satellite can pass through all areas within the highest latitude due to its orbital laws and the Earth's rotation, which means that it spends most of its time over the ocean, and satellites are wasted a lot. Compared with the tidal changes in the behavior of ground users, satellites change faster and more dramatically due to space movement. Due to the relative shortage of satellite energy, some satellites can be put to sleep, and other satellites can fill the coverage gap by expanding the coverage area through cell breathing.

3.2 Challenges

First, dramatic change in satellite traffic. The orbital period of the satellite is

$$T=\sqrt{\frac{4\pi^2(R+h)^3}{GM}} \tag{5}$$

where R is the Earth's radius and h the orbital height. A low-orbit satellite can only serve a user for a few minutes.

Due to the rapid movement of satellites, satellites will quickly switch between areas with extremely different user densities, and the load on the satellite may experience trough-to-peak variations in a few minutes, and will experience such variations many times during an orbital period, as shown in Fig.5. Therefore, even in two close time slices, the optimization results may be extremely different. As a scheme that requires constant adaptation, cell breathing may not be able to adapt to rapid changes in satellite loads.

Second, constantly change of neighbor relationship. The neighbor changes of satellites come from three types of dynamics. (1) As the latitude increases, the distance between adjacent orbits gradually decreases, so the number of the satellite's neighbors gradually increases. (2) Satellites traveling north can overlap with satellites traveling south, but they travel in opposite directions, so they overlap and separate quickly. (3) The different orbital altitudes of the satellites of different shells make the satellites move at different speeds, so they also move relative to each other, causing the neighbors to change.

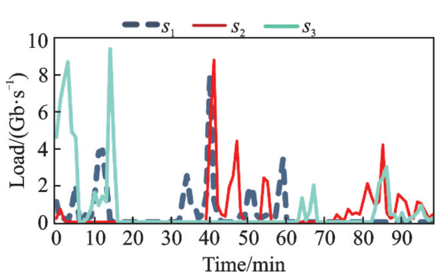


Fig.5 Satellite load change with time

Finally, continuous movement of coverage area. Multiple satellites work together to complete global coverage, but mobility causes the combination of satellites that can currently achieve global coverage may not be able to complete coverage at the next moment.

3.3 Objective

For satellite networks, the goal is to match satellite capacity more closely for user distribution. The capacity of a single satellite s is G_s, and its capacity is 0 when the satellite is in the sleep state. The capacity usage of satellite s is g_s. Then, for the mega-constellation, the goal of cell breathing is to maximize the utilization U.

$$U=\frac{\sum_{s=1}^{N} g_s}{\sum_{s=1}^{N} G_s} \tag{6}$$

That is, the objective is to make satellites sleep as much as possible, and improve the throughput by modifying the cell size to distribute users in dense areas to sparse areas.

4 Fast Adaptive Cell Breathing Scheme

FaB is the first scheme to apply cell breathing to satellite mega-constellations. It divides the ground into sub-blocks according to user distribution. For each sub-block, cell breathing includes three parts: Initialization, mobility adaptation and sub-block handover adaptation.

4.1 Sub-block division

There are extreme differences between different areas on the ground. In areas with sparse users, like oceans, satellites are wasted, while in areas with dense users, there is congestion. These types of areas are usually adjacent. For example, a desolate ocean is adjacent to a densely populated coastal metropolis. As a result, there may be extreme differences in satellite cells between adjacent areas, making it difficult to adapt quickly. Therefore, in this scheme, the ground is divided into sub-blocks according to the user distribution. Later we will introduce how to adjust the cell size quickly when switching sub-blocks.

Each location has a location level corresponding to user density. The location level is calculated based on the density of users within a circle with different radii centered on the location. The specific calculation method is as follows. For a certain location, we can calculate the work scope corresponding to different power levels of the satellite at the location, as well as the number of users within the work scope. When the users around the location are denser, the number of users in the work scope of the satellite under the smaller power level can reach the load threshold of the satellite. The power level is recorded when the location reaches the load threshold, and the location is rated based on this power. Finally, the areas are divided according to the location level.

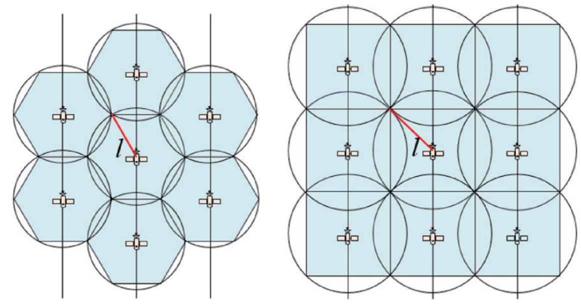
It is worth noted that this calculation does not consider the overlapping of satellites, and it does not reflect the interaction between satellites. In fact, not all users within the work scope are connected to the satellite, so this calculation is inaccurate and cannot be directly used for satellite power settings. However, this level can reflect the distribution of users under the satellite work scope over different locations. The adjacent areas with the same location level are divided into the same sub-block.

4.2 Satellite cell initialization

There are multiple levels of satellite power, and the power difference between each level is called the step size. During initialization, the satellite adjusts the power with a fixed step size, and then the user re-selects the access satellite according to the adjusted power. The adjustment continues until it converges to a stable value.

To ensure global coverage, each satellite has a minimum work scope, and when all satellites operate at the power corresponding to this scope, the maximum received power of all users should exceed $\widehat{p_{us}}$. Fig.6 shows the conditions that the minimum scope of a single-shell constellation needs to meet. For a constellation with P orbits and s satellites in each orbit, the scope radius l corresponding to Fig. 6 (a) should satisfies

$$\begin{cases} \sqrt{3}\, ls \geqslant 2\pi R \\ lP \geqslant 2\pi R \end{cases} \tag{6}$$



(a) Hexagonal coverage area (b) Rectangular coverage area

Fig.6 Minimum work scope

For satellite s, if the coverage of another active satellite s' can completely cover the minimum work scope of s, s is considered to be an alternative. This concept is used to determine whether the satellite can sleep.

The load threshold of the satellite is set to be Ψ_o. When the satellite load exceeds the threshold, the load is considered too heavy. In each loop of adjustment, the satellite negotiates with its neighbors based on the load. The negotiation process is as follows, for each satellite:

(1) If the satellite is idle, and it is an alternative, the sleep of the satellite will not cause coverage holes or user congestion. Therefore, the satellite adjusts the power to 0 and informs its neighbors and then goes to sleep.

(2) When the satellite load exceeds Ψ_o, if there is a neighbor satellite whose load does not exceed Ψ_o, reducing the work scope of the satellite can reduce the load without causing congestion of other satellites, so the satellite power is reduced by one level.

(3) When the satellite load is lower than Ψ_o, if the load of the satellite in the neighbor exceeds Ψ_o, the power of the satellite is increased by one level to increase the work scope and share the load of the neighbor.

The state will converge after multiple negotiations, and the overall throughput and the satellite state will tend to be stable.

4.3 Dynamic cell adjustment

Due to the change in time, the user activity in the area will change. This part of the change is similar to the change in the ground and is called the user tide. Since user tides change slowly and have periodicity and regularity, adaptive cell breathing is sufficient.

For satellites, the unique change is satellite reverse tide, that is, the infrastructure is also constantly changing. The changes consist of three parts: (1) The relationship between satellites and users is constantly changing; (2) the neighbors of the satellites are constantly changing; and (3) the affiliation between sub-block and satellites is constantly changing.

For the reverse tide, this section quickly adapts to the rapid load changes by adjusting the step size of the power change and the initial value of the power level enters a new block.

4.3.1 Move within a sub-block

When the satellite moves within a sub-block, the satellite will not have sudden traffic changes, but the distribution of users within the block is irregular, and the neighbors of the satellite continue to change. In order to cope with the untimely satellite convergence due to load changes and constant neighbor switching, the satellite uses the previous satellite state as the prediction information to assist the satellite to adjust the step size for rapid convergence.

The orbital period T of the existing LEO satellite constellations can be calculated according to Eq.(4). The rotation time of the Earth is T_e. For a constellation with s satellites in an orbit, the time difference between two adjacent satellites in the same orbit passing through the same latitude is T/s. During the period of time, the rotation angle of the Earth is $2\pi T/(T_e s)$, which is only 1° for Starlink. Therefore, the difference between the areas served by two adjacent satellites is small. Moreover, due to the uniform configuration of the constellation, the neighbor states are relatively similar when two adjacent satellites pass through the same latitude.

Therefore, the current state of the previous satellite can be used as the target state predicted by the current satellite, and the step size of the current satellite can be set according to the difference from the target.

In each time slice, the satellite records the power of the previous satellite at the current time, and compares the difference with the current satellite's power. The time to move from the current orbital position to the next orbital position is t, and the power difference is Δp, then the power change step size of the satellite is $\Delta p/t$.

The prediction here does not completely inherit the power of the previous satellite, but only adjusts the speed of the satellite power change according to the difference in power. That is, the prediction information can be regarded as the load difference between the two locations, and the satellite can continue to decide how to adjust based on neighbor information. This approach has both adaptive flexibility and predictive accuracy.

4.3.2 Move between sub-blocks

When a satellite switches between two sub-blocks, since the differences between blocks are often extreme, modifying cell adjustments step size may not be fast enough to adapt quickly to the change. The initial value is introduced here. When the satellite enters the designated sub-block, the cell size is directly set to the region-specific initial value.

However, there are differences in the distribution of users even in the same block, resulting in different satellite power levels over the block. Since the initial value of the area is used for power setting when the satellites newly enter the block, the initial value of the block is set as the average value of the power of the satellites at the edge of the block after initialization.

5 Performance Evaluation

5.1 Simulation settings

(1) Constellation

Since Starlink is currently the largest constellation deployed, the data of this constellation is used. We choose phase I (72×22, 550 km, 53°) that Starlink has basically deployed so far for verification. Set The maximum satellite-to-ground capacity of each satellite is set to 10 Gb/s.

(2) Traffic patterns

The terrestrial traffic refers to the population distribution of GPW v4[27]. The data provides estimates of the population count for 2020, with a 1°× 1° latitude and longitude block as the granularity, given the number of users predicted for each block. We use this data as the weight to generate users randomly. The requirement for each user is 100 Mb/s. Unless otherwise specified, 20 000 users with 2 000 Gb/s traffic requirements are randomly generated in the subsequent simulation.

(3) Parameter settings

The maximum power level of the satellite is set to 100, corresponding to the maximum power, and the step size in the initialization process is 10. The load threshold is set to be 80% of the satellite capacity. Due to the obvious bipolar distribution on the ground, only two location levels are set here. When the number of users in the coverage area of the satellite exceeds the load threshold, the area is set to level 1, otherwise, it is set to level 0. Fig.7 shows the distribution of levels in different regions within [−53°, 53°] latitude range.

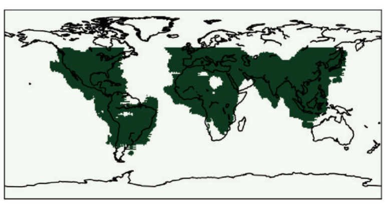


Fig.7 Location level distribution

(4) Comparisons

This paper compares FaB with three schemes. The BASE scheme does not use cell breathing. The INIT scheme runs the cell initialization algorithm according to the current traffic at every time slice. Since the user needs to be disconnected multiple times to achieve convergence at every time slice, it cannot be used in practice. The ADAPT scheme only adjusts once per time slice based on the current traffic and neighbor load without making predictions after initialization.

5.2 Performance improvement

From the perspective of the entire constellation, the primary focus is on the proportion of sleep satellites and the reduction of user congestion. Fig.8(a) shows the proportion of active satellites over time after initialization. Among them, INIT has the least number of active satellites because it converges to a stable cell size suitable for the current traffic in each time slice. The number of active satellites of FaB is only 1.3 times that of INIT. Since it is initialized to the specified initial value when switching between regions, some satellites that could have been adjusted to sleep are also used, resulting in a small amount of waste. Only 7.5% of the satellites in the ADAPT scheme are put to sleep. This is because the satellites in this scheme lack prior knowledge. As long as there are high-load neighbors, they will be active, but they cannot share the load with the neighbors even when they are active, causing waste.

From the standpoint of reducing blocking, as shown in Fig.8(b), INIT is still optimal. For BASE, an average of 42.5 Gb/s of traffic is blocked, and INIT reduces it to 6.7 Gb/s. The ADAPT scheme has an improvement close to INIT due to its conservative sleep strategy, and the blocking traffic is reduced to 16.7 Gb/s. FaB can reduce it to 35.2 Gb/s, limited by the lack of cooperation between blocks. In general, the utilization rate of BASE is 12.36%, that of INIT can reach 43.22%, and the utilization rate of FaB is 2.66 times that of BASE, which is 32.83%. The utilization rate of ADAPT is 13.83%, a little better than doing nothing because of limited sleep satellites.

Fig.9 shows the time-varying load and power of a satellite in the constellation under different strategies. From the load point of view, the satellite in FaB is not only fully loaded when passing through dense areas, but also shares loads of dense areas when they are around dense areas, thereby reducing congestion. In terms of power, the power of INIT shows extreme differences when it passes through different types of sub-blocks, but ADAPT cannot quickly adapt to such extreme differences so that a large number of satellites cannot sleep. Although FaB cannot be completely the same as INIT, it can achieve extreme differences in different sub-blocks

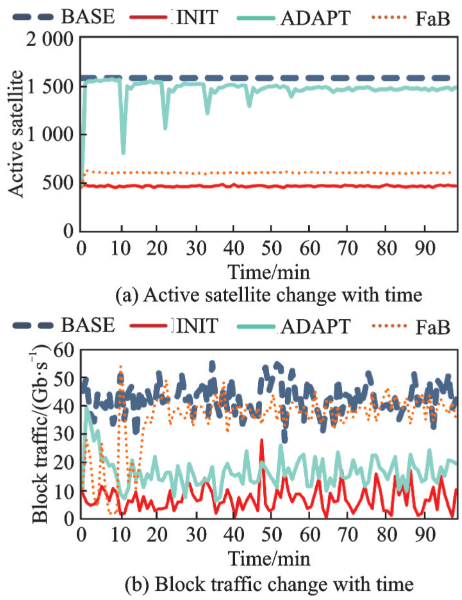


Fig.8 Constellation performance improvement

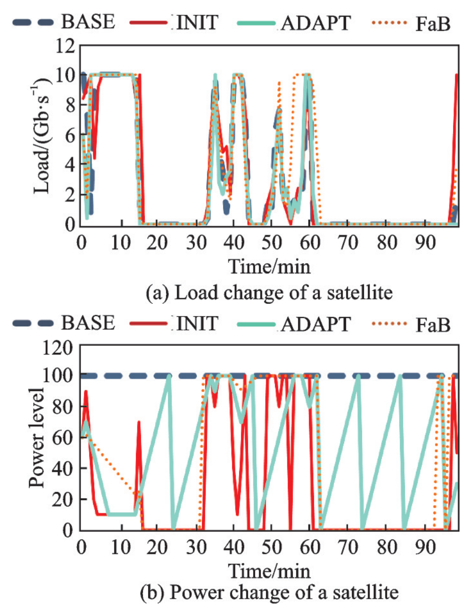


Fig.9 Single satellite change with time

through block division, and achieve the same trend adjustment as INIT through breathing. So it has better performance.

5.3 Effects of parameter changes on performance

Changes in traffic scale will affect the performance of FaB. As shown in Table 2, when the users are sparse, more satellites enter the sleep state due to low load. When users are denser, FaB only needs to add a small number of satellites to enter the active state, and the satellites above the area with location level 0 remain sleep. Even if a large number of users

Table 2 The impact of traffic scale

Traffic scale/ $(Gb \cdot s^{-1})$	Original block/%	Improved block%	Active satellite
4 000	12.72	11.96	509
3 000	7.94	6.74	478
2 000	1.96	0.22	451
1 000	0.02	0.02	426
500	0.02	0.02	424

are blocked, FaB will not blindly increase the number of active satellites, but will only increase the number of active satellites when needed over the area.

Using a different power adjustment step size at initialization will affect the eventual result. For satellites with power levels from 0 to 100, step sizes of 2, 5, 10, 20, and 30 are tested here. As shown in Table 3, when the step size is large, the granularity of adjustment is limited, which cannot further reduce user blocking and increase sleep satellites. When the step size is too small, the convergence time is too long. For example, when the step size is 2, it takes 100 min to converge, and the satellite can circle the Earth within this time.

Table 3 The impact of step size

Step size	Coverage time/ min	Block/ $(Gb \cdot s^{-1})$	Active satellite
30	8	11.2	453
20	10	15.6	452
10	20	4.8	451
5	40	4.8	449
2	100	5.6	449

6 Conclusions

This paper proposes a fast adaptive cell breathing scheme (FaB) that is suitable for mega-constellation networks. Compared with the traditional terrestrial schemes, FaB introduces location information to directly adjust the parameters of cell breathing so that it can cope with the extreme difference of user distribution and the high-speed change of satellite traffic. Simulation shows that this scheme can not only alleviate user congestion in dense areas, but also reduce satellite waste in sparse areas. Compared to the method with no cell breathing, the utilization rate is increased by 2.66 times. Compared to the method with cell breathing without location information, the utilization rate is increased by 2.37 times.

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面向巨型星座卫星网络的小区呼吸方案

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摘要:相较于地面网络,低轨巨型星座可以提供覆盖全球的低延迟高带宽互联网服务。卫星网络的时变拓扑和不均匀的用户分布导致了卫星与用户之间的不匹配,进而造成卫星资源的浪费和用户性能的下降。传统地面的小区呼吸在面对用户潮汐时,一般通过与邻居不断协商收敛到最优小区大小,然而这种方法在面对卫星快速移动引起的快速极端流量变化时难以及时收敛。本文提出了一种新的小区呼吸方案FaB,通过子块划分和卫星小区的自适应初始化和调整来应对这种变化。FaB根据用户密度将地面划分为子块。当卫星在同一个子块中移动时,根据前一卫星与当前卫星的小区大小差异调整呼吸的步长。当卫星在不同子块之间切换时,根据新子块的密度确定小区的初始值。除了与相邻卫星协商外,FaB还引入位置信息直接调整小区呼吸参数,从而减少了小区呼吸收敛时间。从真实星座数据驱动的仿真可以看出,FaB可以随着位置变化快速调整小区大小,相较于没有使用小区呼吸前,卫星的利用率提升至2.66倍;相较于地面没有使用位置信息的小区呼吸,FaB将利用率提高到2.37倍。

关键词:卫星网络;小区呼吸;巨型星座;区块划分