IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 15, 2021, accepted December 26, 2021, date of publication December 28, 2021, date of current version January 7, 2022.

Digital Object Identifier 10.1109/ACCESS.2021.3139073

A Model of Addressing Abnormal Users in IP/LEO Satellite Communication System Based on Geographical Information Subnet

MENG SUN[1], **(Graduate Student Member, IEEE), LIANG LIU**[2], **AND TAO ZHANG**[1]
[1]Department of Electronic and Information Engineering, Beihang University, Beijing 100191, China
[2]Institute of Telecommunication and Navigation Satellite, CAST, Beijing 100094, China

Corresponding author: Tao Zhang (zhtao73@163.com)

This work was supported by the National Key Research and Development Program of China under Grant 2020YFB1806801 and Grant 2019YFB1803100.

ABSTRACT The geographic information-based subnet partitioning scheme provides the basis for satellite-ground integrated addressing. Meanwhile, this scheme will inevitably cause addressing abnormal users (AAUs), i.e., the satellite which has address convergence relationship with users' co-subnet and the satellite which users actual access to may be different. This problem will decrease the network communication efficiency. With the aim of quantifying the statistical variation pattern of AAUs to reduce the impact, this paper constructs a statistical model of AAUs under the general closed geographic partition shape. Further, considering the orbit characteristics and the uniform rotation of Earth, this paper derives an analytic formula for the average addressing abnormal user rate (AAUR) under circle and polygon geographic partition. Meanwhile, by simulating a specific LEO satellite constellation, this paper obtains the temporal average of AAUR in spherical trapezoidal partition during one orbital period, which is sufficiently approximated to the result of analytic formula, verifying the validity of this model. The model shows that the average of the AAUR decreases gradually as the ratio of satellite coverage area to geographic partition area increases. When the ratio is greater than 1.6, the average AAUR is less than 5%. The research work in this thesis quantifies the relationship between the average of the AAUR and satellite to earth communication range, geographic subnet range, geographic subnet shape, which can provide a reference for the matching design of geographic partitioning under any constellation configuration.

INDEX TERMS Addressing scheme, IP/LEO network, mobility management, subnet division.

I. INTRODUCTION

With the continuous development of communication technology and the growing demand for communication worldwide, LEO satellite constellations, as communication systems capable of providing global coverage, have become a central issue today. Among the many LEO satellite constellation systems, Iridium II [1] has completed its network construction, Oneweb [2] has hundreds of operational satellites in orbit, Starlink [3] has launched thousands of satellites, and the Kuiper system [4] and Lightspeed system [5] are under construction. In order to provide global long-distance end-to-end communication services and avoid the limitation of ground station construction, the LEO satellite communication system adopts a multi-hop forwarding mode combining inter-satellite link and satellite-ground link, which makes the whole system constitute an IP switching network, thus realizing the interconnection of nodes in the whole network.

Considering that the LEO satellite constellation network has the characteristic of fast traversal switching between satellites and ground users, for purpose of guaranteeing the effectiveness and reliability of the LEO satellite communication system with inter-satellite links, it is necessary to solve the problem of integrated IP addressing including satellite nodes and ground end users.

As the most widely used networking protocol worldwide, the IP protocol is the cornerstone of applying Internet to the world. The core idea is the unified data-independent packet switching method. By querying the routing table including all destination nodes in the whole network, we can obtain

The associate editor coordinating the review of this manuscript and approving it for publication was Hayder Al-Hraishawi.

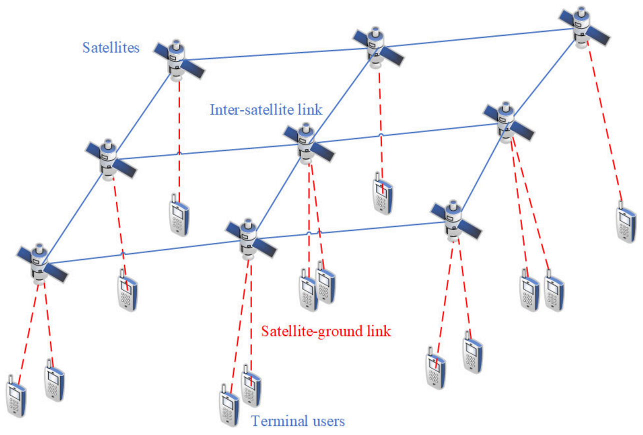


FIGURE 1. End-to-end packet communication network based on LEO satellite constellation.

next-hop forwarding addresses, and forward packets to the destination nodes hop by hop. Considering the large scale of nodes within the whole network, in order to reduce the table lookup overhead, the IP protocol adopts a subnet mask-based address aggregation mechanism, which divides all node addresses of the whole network into several hierarchical networks. On this basis, the higher-level routing table only needs to record the subnet mask of the next level, so that it can be retrieved level by level during route lookup. Thus, the address aggregation mechanism makes the IP protocol well scalable. However, the fast-relative velocity of LEO satellites to the Earth's surface causes rapid traversal switching of star-ground connections in LEO satellite networks, creating a serious obstacle to the popularization of IP protocols to LEO satellite constellations. Specifically, the speed of the LEO satellites relative to the Earth is close to the first cosmic velocity, at the same time, considering the limited ground coverage of the satellites, it is preliminarily estimated that after about 10 minutes [6], all satellite-ground links will have switched. Therefore, it is difficult to establish a continuous and stable access between users and satellites to meet the address aggregation condition, resulting in unacceptable routing table lookup overhead and signaling interaction overhead for satellite-ground switching.

To build address convergence relationships in the frequent switching scenarios of LEO satellite constellations, Tsunoda *et al.* proposed an idea of subnetting based on geographic information [7]. The key point is to divide the earth's surface into several geographic zones that are separated from each other. Each geographic zone corresponds to a subnet, so that the users located in that geographic zone are the subnet users. On this basis, different network segments are assigned to different subnets, and IP addresses belonging to that network segment are assigned to users within that subnet, independent of the satellite to which users are connected. In addition, when the subsatellite point is located within a geographic zone, the address of the satellite to ground port is set as the first address of the geographic zone's corresponding subnet, thus building the address convergence relationship between the satellite node and the geographic partition subnet. Based on this, patent [8] proposes a method for constructing a geographically partitioned subnet under a specific Walker constellation configuration, including geographic area shape, IP address segmentation, etc. However, this method is difficult to avoid the problem of addressing abnormalities. This is because satellites are always in motion relative to the Earth's surface and it is difficult to establish a stable coverage relationship with geographic partitions. As shown in Fig.2, the blue square indicates the geographically partitioned subnet, and the red circle indicates the satellite coverage. The user U1 located in the shaded area cannot directly establish a connection with the satellite Sat that has the address convergence relationship with the subnet, and this user U1 is the addressing abnormal user.

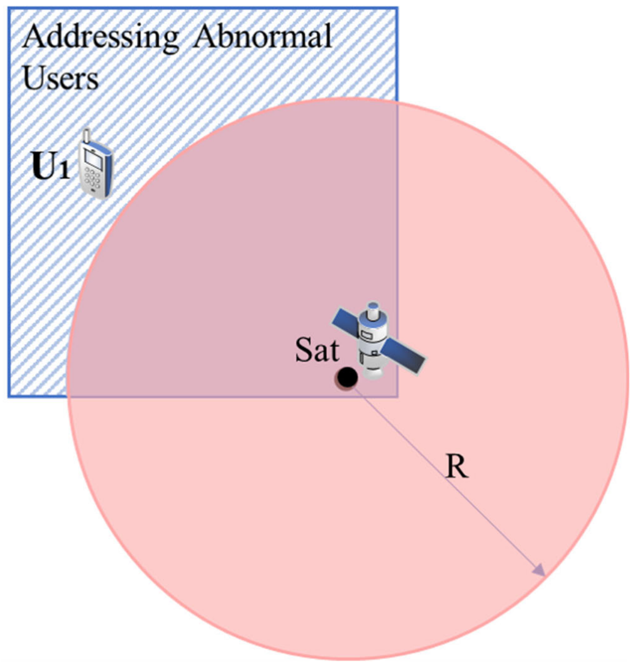


FIGURE 2. Diagram of addressing abnormal users.

A mobile management scheme based on satellite mobile mode is proposed in [9]. The database located in the ground server is used to maintain the data accessibility relationship between ground nodes and satellites, and the information of ground users with unreachable data (some of them are addressing abnormal users) is stored in the central server for inquiry and forwarding. Because the mobility management scheme needs to use ground servers to store a large number of node data, it is too dependent on ground facilities, and the independence of satellite network is poor. Research [10] proposed a virtual connection point scheme based on geographical location. The scheme makes full use of the geographic location information of endpoints to determine the virtual connection points of ground users. The service scope of the virtual connection point is a geographical area, and the satellite bounding to the virtual connection point can provide available and stable communication services in this geographical area at any time. The implementation is simpler when the satellite communication service area covers the entire virtual connection point service range. Otherwise, binding updates occur frequently. However, the influence of satellite communication service range on binding update cost is not analyzed in [10]. Research [11] proposed a user-centered switching scheme for ultra-dense low orbit satellite network. The basic idea is to use the storage capacity of satellites to improve the communication quality of users. By caching the user's downlink data in multiple satellites simultaneously, the ground user can seamlessly switch and always access the satellite with the best link quality. The mobility management architecture based on location and identity separation and convergent switching mechanism of satellite network are proposed in [12] and [13]. According to the distribution of the ground gateway, the coverage area of the satellite constellation can be divided into several areas. Each gateway implements localized location management for terminals in its own area and realizes global location management through synchronization between all gateways, avoiding sub-optimal routing and improving efficiency. Considering the regularity of passive motion caused by satellite mobility, the convergent switching mechanism performs pre-switching for users under the same satellite.

The literature above does not discuss the number of users outside the boundary of satellite coverage (called addressing abnormal users) in geographic information addressing schemes in depth. If we can reduce the number of such users when designing the geographic subnet division scheme, we can reduce the subsequent stress on mobile management. To reduce the impact of abnormal users in the geographic information addressing scheme, a statistical model of the number of addressing abnormal users including the geographical partition parameters (mainly considering the shape and size of the geographic subnet) is constructed, and a scenario simulation is carried out to verify the correctness of the model in this paper.

In view of the advantages of multi-beam antenna technology, such as seamless coverage, high gain and large capacity, multi-beam antenna is usually used in LEO satellite mobile communication system to expand the number of users. On the one hand, users always want to access the satellite with a short distance, which has a relatively light signal attenuation and can obtain a relatively large SNR. On the other hand, when users access satellites belonging to the same subnet, they can easily obtain IP address aggregation and facilitate message transmission. Combined with the above analysis, with the high-speed motion of the satellite, there will be frequent user and beam switching, as well as user and satellite switching. In this paper, based on the studies of literature [14] and [18], the coverage area of satellite to earth is modeled as a circle, and the switching between different satellites of ground users is focused on.

For the addressing anomaly problem, Xiao *et al.* proposed a time-ratio model for addressing abnormal users [14], [15].

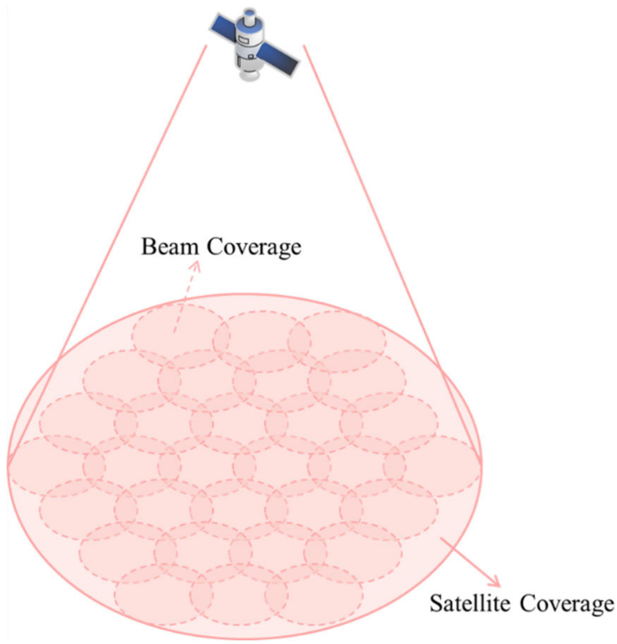


FIGURE 3. Diagram of beam coverage and satellite coverage.

The model shows that the geographic partitioning scheme affects the number of addressing abnormal users through the time ratio of logical coverage to full coverage. The number of addressing abnormal users and local routing cost decrease when the full coverage to logical coverage time ratio increases as the geographic subnet range becomes smaller. The number of addressing abnormal users decreases at a slower rate as the ground subnet range becomes smaller, with a more significant increase in mobility management cost and on-star routing table entries. However, the time-ratio model only considers the case when the subsatellite point trajectory completely crosses the geographic subnetwork and does not consider the case when the satellite briefly accesses the subnetwork at the edge of the geographic partition subnet. So that it cannot completely describe all the relative position relationships between the satellite coverage area and the geographic subnetwork area. Moreover, when simplifying the model, the paper does not consider the diversity of geographic area shapes, thus limiting the applicability of the model in real scenarios.

In this paper, we propose a model of the average rate of addressing abnormal users caused by geographic information-based subnetwork addressing in LEO satellite constellations, model the effect of satellite coverage and geographic subnetwork range on the average addressing abnormal user rate, and verify the applicability of the model under a polygonal geographic subnetwork partitioning scheme. It has been shown that since the ratio of the period of rotation of LEO satellites around the Earth to the period of rotation of the Earth is irrational, the subsatellite points can be considered to be uniformly distributed on the ground [14]. As a result, in the spatial dimension, the mean of probability distribution of addressing abnormal user rate is computed when the subsatellite points are at different locations within the geographic subnetwork. Considering the effect of the Earth's rotation, the trajectory of the subsatellite point is different each time it crosses the subnet, resulting difference in the addressing anomaly region. On this basis, in the temporal dimension, the addressing abnormal user rate of a near-polar orbit constellation varying with time is simulated and average calculated in this paper. The temporal simulation result is very similar to the spatial theoretical deduction. Thus, the validity of the theoretical model is verified.

For geographically partitioned subnet schemes, it is first necessary to design the shape of the partition. Considering factors such as government control, it is usually necessary to delineate the boundary of the subnetwork according to administrative boundaries of countries and regions. Related information shows that the Iridium system uses a country- and region-wide partitioning approach when subnetting [16].

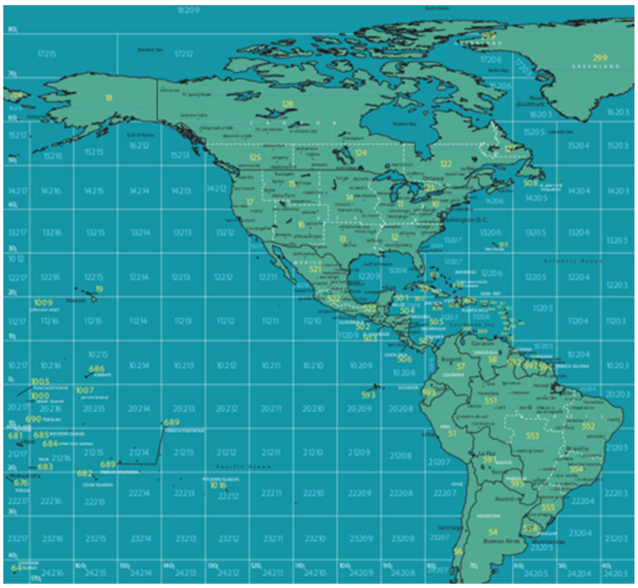


FIGURE 4. Iridium system subnetting.

For simplicity, an outer joined polygon as close as possible to the administrative area is used in this paper for the approximation of the geographical partition. On this basis, the design of subnet size needs to be matched, regarding the difference in accessible range of single satellite in different constellations. In this paper, the ratio of satellite coverage to geographic subnet area is used for analysis and evaluation. Further, for the geographic partitioning scheme with arbitrary positive polygons, a low-complexity equivalent solution for addressing anomalous user rates under this scheme is given.

The specific algorithm steps are as follows. First, considering that a positive polygon with infinite number of sides approximates a circle, a model of the average rate of the addressing abnormal users under a circular geographic partition is given. After that, the difference of average addressing abnormal user rates between positive polygon subnets with different number of edges and the circular subnet is calculated numerically, then the difference is fitted using second-order Fourier formula to obtain six sets of fitting parameters. Finally, with the number of positive polygon sides as the independent variable, the six sets of parameters are fitted and calculated, then the correction formula for the average addressing anomaly user rate of a positive polygon geographic subnet compared to a circular subnet is obtained. At the same time, this paper also carries out the simulation analysis on the temporal traversal of addressing anomaly user rate in specific constellation, and the temporal simulation results are sufficiently close to the results of spatial traversal, verifying the effectiveness of the algorithm proposed in this paper.

The content of the follow-up article is as follows. Chapter II describes the geographic subnet partitioning scheme under the LEO satellite constellation and the addressing anomalies introduced by this scheme. Chapter III gives the analysis and optimization of the addressing anomaly problem, including the preconditions and basic assumptions of the model for the average addressing abnormal user rate, the calculation, simplification and analysis of the results of the model. Chapter IV provides a simulation analysis of the applicability of the model; Chapter V concludes this thesis.

The abbreviations are defined as following Table.1.

TABLE 1. Abbreviations and the expansions.

Abbreviation	Expansion
AAU	Addressing Abnormal User
AAUR	Addressing Abnormal User Rate

II. DESCRIPTION OF THE ADDRESSING ABNORMAL USER IN THE LEO SATELLITE CONSTELLATION NETWORK

A. LEO SATELLITE CONSTELLATION SYSTEM

For LEO satellite constellations, this paper focuses on the high-speed switching between LEO satellite networks and ground users. Consider a LEO satellite constellation based on the Walker Constellation [17], which satisfies that each orbital plane has the same inclination, the difference of the right ascension of ascending node between adjacent orbits is same, and the satellites in each orbital plane are uniformly distributed. In the LEO satellite constellation, the satellite's rotation speed around the Earth is sufficiently close to the first cosmic speed (7.9km/s). In addition, due to the influence of the Earth's rotation, which causes high-speed traversal switching between the satellite and the ground user, the connection between a single satellite and a single user can last only about ten minutes [6]. As shown in Fig.5, the blue quadrilateral indicates the geographic subnet area and the red circle indicates the satellite coverage area. Terrestrial user User1 establishes a satellite-ground connection with satellite Sat1 at moment t1. As the satellite moves, the subsatellite point of Sat1 moves out of the user's co-subnet and the subsatellite point of Sat2 moves into the subnet.

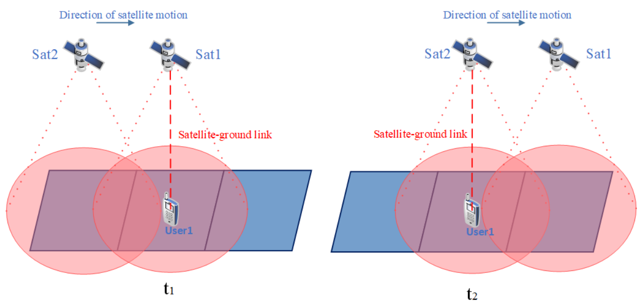


FIGURE 5. Satellite-ground connection switching diagram.

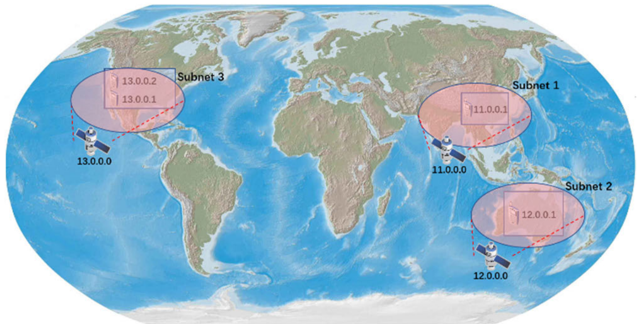


FIGURE 6. Subnet address segmentation diagram for geographic partitioning.

Then, at moment t2, the satellite-ground connection of terrestrial user User1 switches to the connection with satellite Sat2.

B. GEOGRAPHIC INFORMATION-BASED SUBNET PARTITIONING SCHEME

For the mobility management in LEO satellite communication systems and the problem of satellite-ground integrated addressing, Tsunoda *et al.* proposed a geographic information-based subnet partitioning scheme [7]. The key of the scheme is to decouple node addressing from node mobility using geographic information. First, the earth's surface is divided into different geographic location area based on geographic location information, and each geographic location area corresponds to a subnet. The IP addresses of nodes are only related to the geographic location area in which they are located. When the subsatellite point is in a geographic region, the on-satellite router's ground port is assigned the first address of the subnet of that region. The satellite is responsible for the communication of user nodes in the subnet until the satellite moves out of the subnet and the next satellite enters the subnet, then the routing port setting of the next satellite is updated. If a satellite needs to send message to an end-user node, it can route the message to the satellite that meets the address aggregation relationship with the subnet including the terminal node. Routing to users across the network can be achieved by keeping only the routing table entries of each subnet segment on the satellite router. Based on the above design, on one hand, the number of geographic regions determines the number of subnets. Greater number of geographic regions results in larger on-star routing table size and hence adds the table lookup overhead. On the other hand, the smaller the number of geographic partitions, the larger the range of individual partitions, the more frequently handoff of ground nodes between subnets, which results in a larger mobility management overhead.

C. ADDRESSING ABNORMAL USERS

Based on the above geographically partitioned addressing method, the routing lookup overhead no longer increases with the number of terminals, and the signaling interaction overhead caused by the frequent switching between satellites and ground users is effectively reduced, which is conducive to the expansion of terminals and services in the LEO satellite constellation network. However, this method suffers from AAUs, as described below.

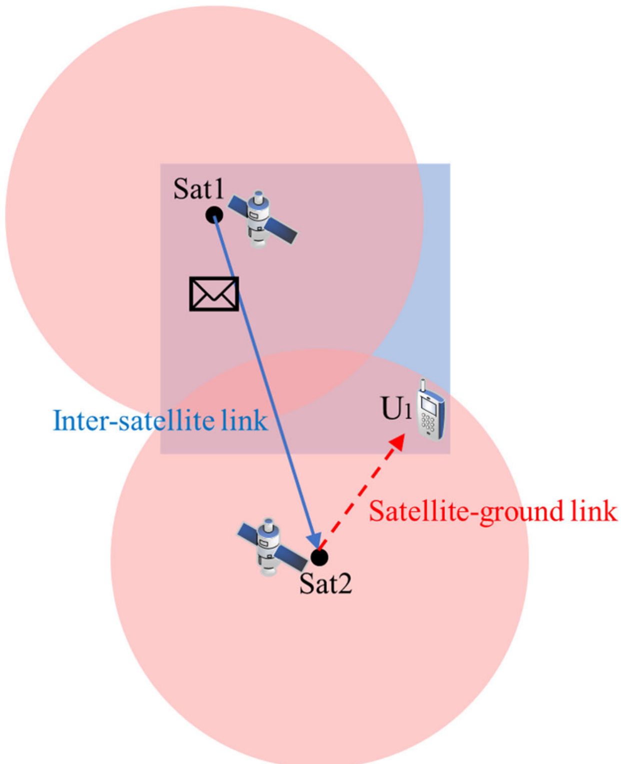


FIGURE 7. AAU multi-hop forwarding.

Under the geographically partitioned addressing scheme, the terminal establishes address aggregation relationships with satellites belonging to the same geographical partition subnet to ensure route reachability towards that terminal node. However, addressing anomalies inevitably occur when the actual accessible satellite of the terminal is not in the geographical partition in which the terminal is located. As shown in the Fig.7, the subnet where terminal U1 is located satisfies the address aggregation relationship with satellite Sat1, but at this time terminal U1 is actually connected to satellite Sat2, then the data packets sent to terminal U1 by any source node will first be routed to satellite Sat1, and then by satellite Sat1, forwarded to satellite Sat2 and then forwarded to terminal U1.

The addressing anomaly introduces additional forwarding delay on the one hand and takes up additional inter-satellite link bandwidth on the other hand, thus affecting the transmission performance of the LEO satellite constellation network.

Definition 1: An addressing abnormal user is a user in a geographic subnet area that cannot be covered by the communication range of a satellite Sat that satisfies the address aggregation relationship with that geographic subnet at a certain time t.

It has been shown in research [18] that in a satellite-ground communication scenario, the satellite's actual accessible range on the Earth's surface can be modeled as a circle with the sub-satellite point as the center. The communication capability of the satellite determines the radius R of this circle. The red circle represents the accessible range of the satellite, the blue square indicates the geographical subnet area, and the user located in the blue shaded area is the AAU. Fig.8 respectively illustrates the satellite Sat just accessing the subnet, fully covering the subnet, and about to leave the subnet. It can be seen that the satellite-ground coverage relationship changes as the subsatellite point changes in the subnet area, and at the same time, the uncovering area by the satellite and the AAU also change.

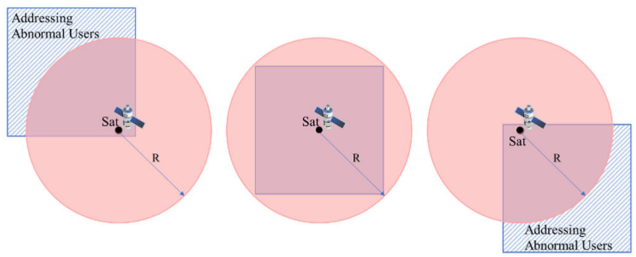


FIGURE 8. Different coverage relationships between satellites and subnets.

III. ANALYSIS AND OPTIMIZATION OF ADDRESSING ANOMALY PROBLEM

As mentioned above, in the geographic information partitioned subnet scheme, end users that cannot be covered by satellites that satisfy the address aggregation relationship with the subnet are AAUs. These users have an impact on the routing and mobility management of LEO satellite communication systems, deteriorating IP addressing performance and leading to increased packet loss in the network. Therefore, how to reduce the number of AAUs in the system is a key issue for the design of geographic information partitioning scheme.

For simplicity, this paper uses convex polygons to construct geographic partitions, and then assigns corresponding subnet addresses to each geographic partition. The subsequent work in this paper is based on the following assumptions. Considering the near-polar Walker Constellation [17], all satellites have an approximate circular coverage of the ground. The scope of the geo-partitioned subnet does not exceed the satellite coverage, i.e. the longest diagonal of the geo-partitioned subnet does not exceed the diameter of the satellite coverage. Then, for a certain geographic subnet area, there always exists a certain location in the area that the satellite achieves complete coverage of the subnet area when the subsatellite point is at that location. Finally, assuming a uniform distribution of terrestrial users in a certain geographic subnet area, i.e., the user density θ is constant.

A. ANALYSIS OF THE STATISTICAL MODEL FOR THE NUMBER OF ADDRESSING ABNORMAL USERS

Suppose a certain geographic subnetting scheme divides the earth's surface into N geographic subnet regions according to the rule $\varphi(x, y)$, and the i-th (i = 1, 2, ..., N) subnet is represented by the following point set (1)

$$W_i = \{(x, y) \mid \varphi(x, y)\} \tag{1}$$

where (x, y) denotes the position coordinates of each point in the subnet W_i. Let the area of subnet i be S_i and let L_i be the maximum value of the distance between any two points in subnet W_i. The density function of user terminals in this region is $\theta_i(x, y)$, and in general, the density of user terminals varies with different coordinates of points.

Let the satellite Sat_j's subsatellite point $M(X, Y) \in W_i$ at moment t. If satellite Sat_j is connected to the subnet W_i, use the point set (2)

$$Sat_j = \left\{(x, y) \mid (x - X)^2 + (y - Y)^2 \le R_j^2\right\} \tag{2}$$

to indicate the coverage area of the satellite, where R_j is the communication radius of the satellite Sat_j, according to above assumptions, $2R_j \ge L_i$.

Definition 2: The uncovering range U_i is the range in a geographic subnet W_i that is not covered by the satellite Sat_j responsible for the communication of this subnet, then the uncovering range U_i can be represented by the difference set of the above two point sets (1) and (2).

$$U_i(x, y) = \left\{W_i - Sat_j \mid (x, y) \in W_i\right\} \tag{3}$$

Then the number of AAUs UN_i in the subnet W_i at moment t is defined as (4)

$$UN_i = \iint_{U_i(x,y)} \theta_i(x, y) d(x, y) \tag{4}$$

According to the assumption that the density of user terminals in the subnet is constant, then we get (5)

$$UN_i = \theta \iint_{U_i(x,y)} d(x, y) \tag{5}$$

Equation (5) expresses the number of AAUs as the product of the user density constant θ and the uncovering area. The uncovering area is related to the subnet division scheme and the location of the subsatellite point $M(X, Y)$. For the entire satellite constellation, the number of AAUs at moment t is as (6)

$$\text{Num} = \sum_{i}^{N} UN_i \tag{6}$$

Due to the dynamic nature of satellites, when a satellite accesses to a subnet, the uncovering area in that subnet varies with the location of the subsatellite point. To calculate the uncovering area, it is necessary to study the motion pattern of the subsatellite point. According to the literature [14], with the periodic rotation of the satellite around the Earth and the rotation of the Earth, the subsatellite point $M(X, Y)$ is uniformly distributed on the Earth's surface for both time and space, i.e., for a region, the probability that the subsatellite point is located at any point in the region at moment t, is the same. Then the mean of probability distribution of the AAU for a certain division scheme is as (7)

$$\mathrm{E}\,(Num) = \sum_{i}^{N} E(UN_i) \tag{7}$$

For a geographical subnet W_i with area S_i, the probability density function of the uniform distribution of a subsatellite point in the subnet W_i is as (8)

$$\mathrm{f}\,(X, Y) = \frac{1}{S_i} \tag{8}$$

The uncovering area $\mathrm{U}_i\,(x, y)$ is a function of the subsatellite point's position (X, Y), and as the assumption in (9)

$$\mathrm{U}_i\,(x, y) = g\,(X, Y) \tag{9}$$

Let the probability density function of the uncovering area U_i be $\mathrm{h}\,(U_i)$, and according to page 41 to 42 in [19], there is the formula (10) as follows

$$\begin{aligned}\mathrm{E}\,(U_i) &= \int U_i \times \mathrm{h}\,(U_i)\, dU_i \\ &= \int g\,(X, Y) \times \mathrm{f}\,(X, Y)\, d\,(X, Y)\end{aligned} \tag{10}$$

Calculate the average of (5), we have

$$\mathrm{E}\,(UN_i) = \mathrm{E}(\theta \iint_{U_i(x,y)} d\,(x, y)) = \theta \times \mathrm{E}\,(U_i) \tag{11}$$

Considering (10) (11) and (7) together, there are

$$\begin{aligned}\mathrm{E}\,(Num) &= \theta \times \sum_{i}^{N} \mathrm{E}\,(U_i) \\ &= \theta \times \sum_{i}^{N} \int g\,(X, Y) \times \mathrm{f}\,(X, Y)\, d\,(X, Y)\end{aligned} \tag{12}$$

Equation (12) expresses the mean of probability distribution of the AAUs as a function of several variables. These variables are the user density constant θ, the relationship function between the uncovering area and the location of the subsatellite point $g\,(X, Y)$, the probability density function $\mathrm{f}\,(X, Y)$ for the uniform distribution of the subsatellite point in the subnet, and the subsatellite point location (X, Y). Among them, only the relationship function $g\,(X, Y)$ between the uncovering area and the location of the subsatellite point is unknown, then only the relationship function $g\,(X, Y)$ need to be studied.

B. MODEL OF THE AVERAGE RATE OF ADDRESSING ABNORMAL USERS IN CIRCULAR GEOGRAPHIC SUBNET

The above study has simplified the problem of AAUs to the study of the function between the uncovering area and the location of the subsatellite point. For the division of geographic subnets, theoretically, under the premise of achieving global coverage and no overlap between two subnets, geographic subnets can be any shape, such as convex polygons, concave polygons, irregular boundary polygons, etc. For the convenience of engineering implementation, geographic subnets are generally designed as convex polygons with regular boundaries. Considered in terms of limits, any convex equilateral N-sided polygon tends to be circular as N tends to infinity. We firstly normalize the size of different geographic subnets by using the ratio of the satellite coverage to the geographical subnet scope. Secondly, based on the formula of average AAUR in circular geographic subnet, a model of average AAUR in different polygonal geographic subnet regions is given by adding a correction function with polygon side number N as independent variable. Thus, this model does not require that all geographic subnets have the same shape.

In this paper, we firstly consider the circular geographic subnet and derive the theoretical formula for the relationship function between the uncovering area and the location of subsatellite points. For a circular geographic subnet region, when the subsatellite point moves into the geographic subnet region, the position of the subsatellite point can be expressed as the distance between the subsatellite point and the circle center of the circular subnet. For different points in a circular geographic subnet, when they have the same distance from the circle center of the geographic subnet, they form a circular boundary. When the subsatellite points are at different positions in this circular boundary, the uncovering areas are the same.

As shown in Fig.9,

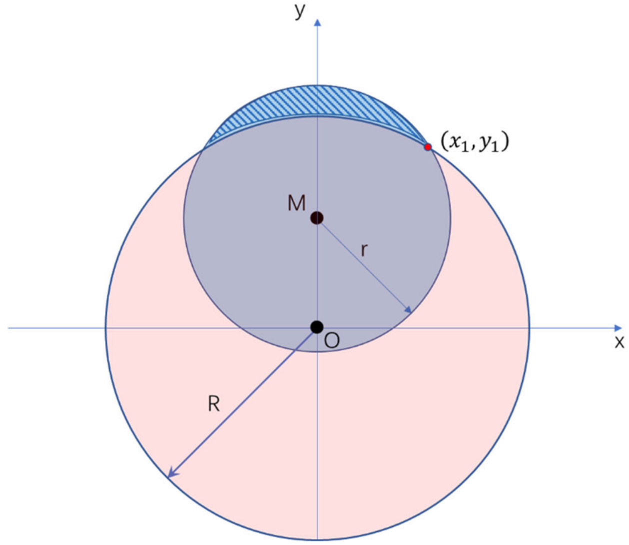


FIGURE 9. Coverage relationship between satellite communication range and circular geographic subnetwork (a).

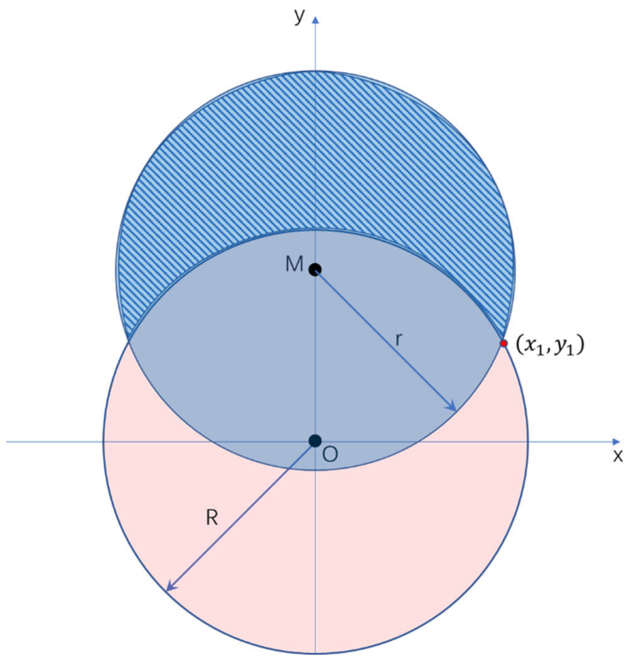


FIGURE 10. Coverage relationship between satellite communication range and circular geographic subnetwork (b).

Establish a rectangular coordinate system with the center O of the circle of the satellite coverage area (red) as the coordinate origin, and let the radius of the satellite accessible range be R. The equation of the satellite coverage area is (13)

$$x^2 + y^2 \leq R^2 \tag{13}$$

Let the radius of the circular geographic subnet (blue) be r and the coordinates of the geographic subnet circle center M be $(0, b)$, then the equation of the geographic subnet region is (14)

$$x^2 + (y - b)^2 \leq r^2 \tag{14}$$

According to the hypothesis, the parameters satisfy the relationship in (15)

$$\begin{cases} r \leq R < 2r \\ R - r \leq b \leq r \end{cases} \tag{15}$$

When b $< R - r$, the satellite achieves full coverage of the geographic subnet and there is no uncovering area. When $2r \leq R$, as long as the subsatellite point is in the geographic subnet, full coverage is achieved and there is no uncovering area. The two circular formulas (13) (14) are combined to find the intersection point of the two circles, where the abscissa of the right intersection point is (16)

$$x_1 = \frac{\sqrt{\left[(R+b)^2 - r^2\right]\left[r^2 - (R-b)^2\right]}}{2b} \tag{16}$$

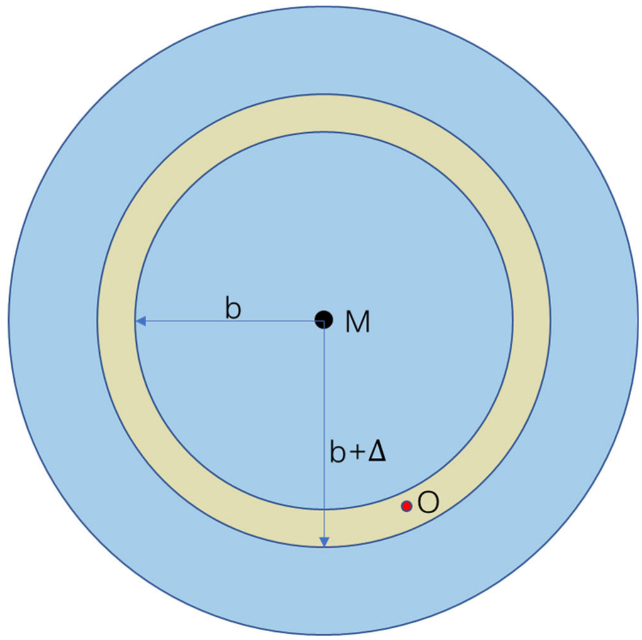


FIGURE 11. Circular geographic subnet.

When b $\leq \sqrt{R^2 - r^2}$, the uncovering area (shaded area) in the circular subnet region is (17)

$$\mathrm{U}_1(b) = 2 \times \int_0^{x_1} \left[\sqrt{r^2 - x^2} + b - \sqrt{R^2 - x^2}\right] dx \tag{17}$$

When b $> \sqrt{R^2 - r^2}$, as in Fig.10.

At this situation the uncovering area in the circular geographic subnet region is (18)

$$\mathrm{U}_2(b) = \pi \times r^2 - 2 \times \int_0^{x_1} \left[\sqrt{R^2 - x^2} - b + \sqrt{r^2 - x^2}\right] dx \tag{18}$$

According to the idea of limit, it can be considered that the circular geographic subnet is composed of an infinite number of concentric rings whose width tends to be close to zero. When the subsatellite point is located at different points in the same ring, the uncovering area in the circular geographic subnet is the same. It is only needed to calculate the uncovering area when the subsatellite point is located at a point in the ring, then calculate the proportion of the area of this ring to the area of the circular geographic subnet, and multiply the two together, finally sum over all the products to obtain the probability mean of the uncovering area for this subnet. As shown in Fig.11.

According to the idea of limit, let the width of the annulus $\Delta \to 0$, the inner radius of the annulus is b and the outer radius of the annulus is b $+ \Delta$, then the area of the annulus is (19)

$$\pi\,(\mathrm{b} + \Delta)^2 - \pi b^2 \tag{19}$$

Then the probability function of the distance b between the subsatellite point and the circle center of the subnet is (20)

$$f(b) = \lim_{\Delta\to 0} \frac{\pi (b+\Delta)^2 - \pi b^2}{\pi r^2} = \lim_{\Delta\to 0} \frac{2b\Delta + \Delta^2}{r^2} \quad (20)$$

For the above equations, we have the relationship as (21)

$$\begin{cases} b = \alpha r \\ 2R = \beta * 2r \end{cases} \quad (21)$$

and according to (15), there is (22)

$$\begin{cases} 1 \le \beta < 2 \\ \beta - 1 \le \alpha \le 1 \end{cases} \quad (22)$$

According to the formula of indefinite integral, when $a^2 > x^2$, there is (23)

$$\int \sqrt{a^2 - x^2} dx = \frac{1}{2} x \sqrt{a^2 - x^2} + \frac{a^2}{2} arcsin \frac{x}{a} + C \quad (23)$$

In where C is a constant term. Since in the integral of area, there are $R^2 > x^2$ and $r^2 > x^2$

Then, simplifying (17) and (18), we get (24) and (25)

$$U_1(\alpha, \beta) = \frac{r^2}{2}\sqrt{\left[(\beta+\alpha)^2 - 1\right]\left[1 - (\beta-\alpha)^2\right]} + r^2 arcsin \frac{\sqrt{\left[(\beta+\alpha)^2 - 1\right]\left[1 - (\beta-\alpha)^2\right]}}{2\alpha} - \beta^2 r^2 arcsin \frac{\sqrt{\left[(\beta+\alpha)^2 - 1\right]\left[1 - (\beta-\alpha)^2\right]}}{2\alpha\beta} \quad (24)$$

$$U_2(\alpha, \beta) = \pi r^2 + \frac{r^2}{2}\sqrt{\left[(\beta+\alpha)^2 - 1\right]\left[1 - (\beta-\alpha)^2\right]} - r^2 arcsin \frac{\sqrt{\left[(\beta+\alpha)^2 - 1\right]\left[1 - (\beta-\alpha)^2\right]}}{2\alpha} - \beta^2 r^2 arcsin \frac{\sqrt{\left[(\beta+\alpha)^2 - 1\right]\left[1 - (\beta-\alpha)^2\right]}}{2\alpha\beta} \quad (25)$$

Let

$$\Delta = \frac{r}{n} \quad (26)$$

In (26), as n tends to infinity, Δ tends to zero.

Then according to (20) and (26), we have (27)

$$f(\alpha) = \lim_{n\to\infty} \frac{2\alpha n + 1}{n^2} \quad (27)$$

Definition 3: The uncovering rate is the uncovering area as a percentage of the subnet area, as shown in (28)

$$W(\alpha, \beta) = \begin{cases} \frac{U_1(\alpha, \beta)}{\pi r^2} \times 100\%, & \beta - 1 \le \alpha \le \sqrt{\beta^2 - 1} \\ \frac{U_2(\alpha, \beta)}{\pi r^2} \times 100\%, & \sqrt{\beta^2 - 1} < \alpha \le 1 \end{cases} \quad (28)$$

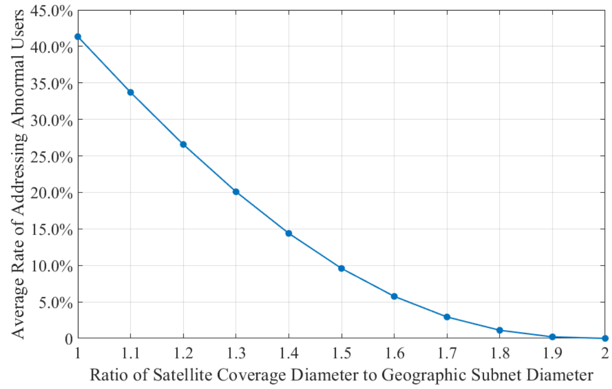


FIGURE 12. Average AAUR curve for circular geographic subnets.

Finally, this paper obtains the equation of the average uncovering rate of circular geographic subnet as (29)

$$E_W(\beta) = \int_{\beta-1}^{1} W(\alpha, \beta) \times f(\alpha) d\alpha \quad (29)$$

In (29), β denotes the ratio of the satellite coverage diameter to the diameter of the circular geographic subnet, α denotes the position of the subsatellite point (i.e., the ratio of the distance between the subsatellite point and the geographic subnet circle center to the geographic subnet radius), W denotes the uncovering rate, i.e., the uncovering area as a percentage of the subnet area, see (28), and $f(\alpha)$ denotes the probability when the subsatellite point position takes the value α, see (27).

As in (29), after integrating with respect to α, the only unknown in the equation is β. It can be seen that when the geographic subnet is circular, the average uncovering rate E_W is only related to the ratio β of the satellite coverage radius to the geographic subnet radius.

For the relationship between the uncovering rate and the abnormal user rate, there is the following derivation.

$$\begin{aligned} & uncovering\ rate \\ &= \frac{uncovering\ area}{subnet\ area} \\ &= \frac{user\ density\ constant \times uncovering\ area}{user\ density\ constant \times subnet\ area} \\ &= \frac{number\ of\ abnormal\ users}{total\ number\ of\ users\ in\ the\ subnet} \\ &= abnormal\ user\ rate \end{aligned}$$

By computing the probability mean for the above equation, it can be concluded that the model for the average AAUR is the same as the model for the average uncovering rate.

According to (22), there is $1 \le \beta < 2$. Bringing $1 \le \beta < 2$ into (29), the result is shown in Fig.12.

The abscissa in the above figure is β, which is the ratio of the satellite coverage diameter to the geographic subnet diameter, and the ordinate is the average rate of AAUs in the circular geographic subnet. As can be seen from the

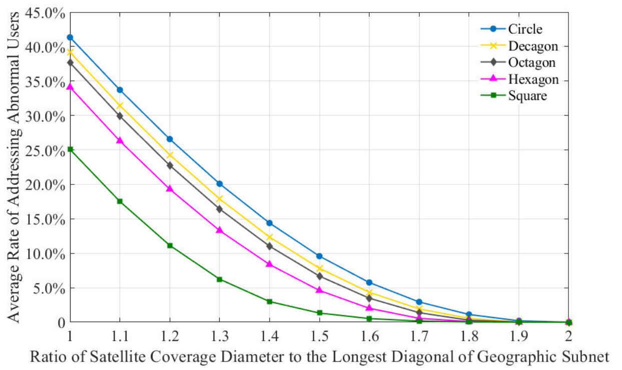


FIGURE 13. Average rates of the AAU in equilateral N-sided polygon and circular geographic subnet.

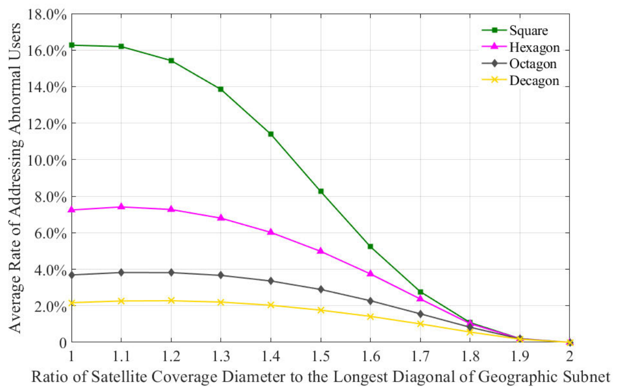


FIGURE 14. Difference curves of average anomalous user rate between circular and polygonal geographic subnetworks.

Fig.12, the average rate of AAUs becomes smaller and the average rate of AAUs decreases more slowly as the ratio β of satellite coverage diameter to geographic subnet diameter gradually increases. Further, when $\beta = 1$, the average AAUR is 41.3%, which is the same conclusion as in the paper [14]. Moreover, when $\beta = 2$, the average AAUR is 0, i.e., no AAU appears when the diameter of the designed geographic subnetwork is less than or equal to half of the satellite coverage diameter.

C. CORRECTIONG FUNCTION FOR THE AVERAGE ADDRESSING ABNORMAL USER RATE OF POLYGONAL GEOGRAPHIC SUBNETS

The foregoing describes the core of the statistical model of AAUs as a function of the average uncovering rate with respect to the location of subsatellite points. And the theoretical formula is derived, where the average AAUR of the circular geographic subnet is only related to the ratio of the satellite coverage diameter to the geographic subnet diameter. Considering that in engineering applications, for the feasibility and convenience, geographic subnets are usually regular convex polygons. Therefore, this section proposes a correction function for (29) so that (29) is applicable to the circularly-interconnected equilateral N-sided polygon geographic subnetwork region after the correction.

TABLE 2. Parameters for the second-order Fourier fitting of the difference curves in Fig.14.

N	R-square	A0	A1	B1	A2	B2	W
10	0.9996	0.01231	-0.01101	-0.00392	-0.00151	-0.00039	3.142
8	0.9996	0.02132	-0.00657	-0.01812	0.002085	-0.00097	3.736
6	0.9999	0.04054	-0.009	-0.03598	0.004162	0.000422	3.896
4	0.9997	0.07941	-0.07578	0.01832	0.008223	0.009565	2.944

1) NUMERICALLY CALCULATION

Let the longest diagonal of the equilateral N-sided polygon be the same as the diameter of the circular geographic subnet. Firstly, the average rates of the AAU in the square, hexagonal, octagonal and decagonal geographic subnet are simulated numerically, and the results are plotted as Fig.13.

Considering that this paper normalizes the size of different geographic subnets by using the ratio of the satellite coverage to the geographical subnet scope. When this ratio is the same, the more sides there are, the more area there is, and the more uncovering area there is with the same satellite coverage area. In addition, the more sides there are in the regular polygon, the closer it is to the circle, so the curve of the regular decagon is closer to the circle curve in Fig.13.

2) CALCULATE DIFFERENCE

Respectively subtract the average abnormal user rate in the equilateral N-sided polygon geographic subnet from the average abnormal user rate in the circular geographic subnet, and the difference is plotted as Fig.14.

It can be seen that the trends of these difference curves are roughly similar to the trend of the trigonometric curve.

3) FOURIER FITTING

A second-order Fourier fitting is performed on the four curves in Fig.14, and the second-order Fourier equation is as follows.

$$DE(\beta) = A0 + A1\cos(\beta W) + B1\sin(\beta W) + A2\cos(2\beta W) + B2\sin(2\beta W)$$

For different number of sides N, the imitative effect (R-square) and fitting parameters are different, as shown in the following Table.2.

4) FITTING THE PARAMETERS IN TABLE 2

Further, the six coefficients in Table 2 were fitted with the independent variable N to obtain the following (30) to (35).

$$A0(N) = 0.2909 * e^{-0.3254N} - 3.273 * 10^{-16} * e^{2.647N} \tag{30}$$

$$A1(N) = 0.0009696 * N^3 - 0.02491 * N^2 + 0.208 * N - 0.571 \tag{31}$$

$$B1(N) = 14.6 * e^{-1.104N} - 1.289 * e^{-0.5243N} \tag{32}$$

$$A2(N) = -0.001283 * \sin(N - \pi)$$

$$+0.0002659 * (N-10)^2 - 0.0001415 \quad (33)$$

$$B2(N) = -0.0001024 * N^3 + 0.002766 * N^2 - 0.02438 * N + 0.06938 \quad (34)$$

$$W(N) = 0.01777 * N^3 - 0.4682 * N^2 + 3.82 * N - 5.988 \quad (35)$$

The imitative effect (R-square) are as Table.3.

TABLE 3. R-square of the fitting to the six sets of parameters in Table 2.

	R-square
A0(N)	0.9996
A1(N)	0.9985
A2(N)	0.9806
B1(N)	0.9901
B2(N)	0.9995
W(N)	0.9975

5) CORRECTION FORMULA

For the circle-interconnected equilateral N-sided polygon geographic subnetwork, the correction formula for the average AAUR is as (36)

$$C(N,\beta) = A0(N) + A1(N) * \cos(\beta * W(N)) + B1(N) * \sin(\beta * W(N)) + A2(N) * \cos(2\beta * W(N)) + B2(N) * \sin(2\beta * W(N)) \quad (36)$$

The statistical model of the average AAUR in the circle-internal equilateral N-sided polygon subnet is as (37)

$$E_W(\beta) = \int_{\beta-1}^{1} W(\alpha,\beta) \times f(\alpha)\, d\alpha - C(N,\beta) \quad (37)$$

6) VERIFY THE CORRECTNESS OF (37)

Let N = 12 and bring it into (30) to (35) to obtain the formula for the correction function of the equilateral dodecagon.

$$C(12,\beta) = -0.014551 + 0.0134288 * \cos(\beta * 3.13776) - 0.002361 * \sin(\beta * 3.13776) + 2.3368 * 10^{-4} * \cos(2\beta * 3.13776) - 0.0018232 * \sin(2\beta * 3.13776) \quad (38)$$

Then the formula for the average AAUR in the circle-interconnected equilateral dodecagon subnet is (39).

$$E_W(\beta) = \int_{\beta-1}^{1} W(\alpha,\beta) \times f(\alpha)\, d\alpha - C(12,\beta) \quad (39)$$

First, numerical calculation of the average AAUR in the equilateral dodecagon subnet is performed directly using Matlab. After that, make $1 \le \beta < 2$, and bring β into (39) to calculate $E_W(\beta)$, the two sets of results are compared to make the following graph.

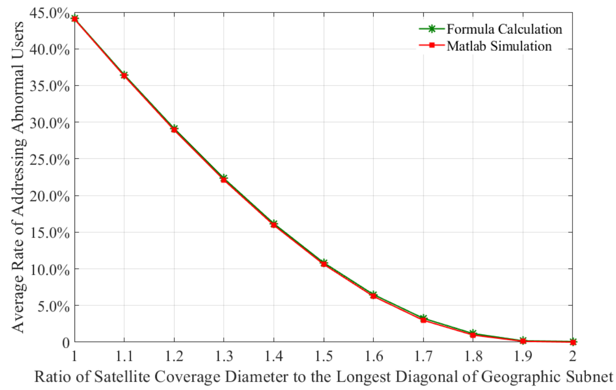


FIGURE 15. Numerical and theoretical calculation curves of the average AAUR in the equilateral dodecagon subnet.

As can be seen from the Fig.15, the difference between the two sets of results is very small, proving that (37) is also applicable for the equilateral dodecagon.

D. SUMMARY OF CHAPTER III

This chapter firstly proposes a statistical model of the average AAUR in the LEO satellite constellation system. The key to the model is the average uncovering area rate in the geographic subnet as a function of the subsatellite point's position. The model shows that the average AAUR in a LEO satellite constellation system is related to the density distribution of end users over different regions of the Earth, the shape and size of the geographically partitioned subnet, and the size of the satellite's coverage. Secondly, a model of the average AAUR in the circular geographically partitioned subnetwork is derived under the assumption that the density of end users is the same constant in different regions of the Earth. The model shows that for a circular geographically partitioned subnet, the average AAUR will be exclusively determined by the ratio β of the satellite coverage diameter to the diameter of that subnet. Finally, the above average AAUR model is further extended to an equilateral N-sided-polygon geographically partitioned subnet by calculating the corresponding correction function. The results show that the average rate of the AAU is determined by the ratio β of the satellite coverage diameter to the longest diagonal of the subnet, and the number of sides, N, for an equilateral N-sided-polygon geographically partitioned subnet.

IV. LEO SATELLITE SYSTEM SCENARIO SIMULATION ANALYSIS

This chapter gives the scenario simulation analysis of the average AAUR in the LEO satellite system. By counting the number of users who are not covered by satellites that satisfy the address convergence relationship with the subnet (i.e., AAUs) during one orbital period, the abnormal user rate is given for different ratio of satellite coverage diameter to the longest diagonal of the subnet and compared with the previous theoretical derivation results. The specific simulation parameters and simulation results are as follows.

A. SIMULATION PARAMETERS

1) LEO SATELLITE CONSTELLATION PARAMETERS

The near-polar orbit satellite constellation is adopted, with an orbital inclination of 87 degrees, 12 satellites in each orbit, a total of 6 orbits, and a 15-degree difference between the adjacent orbits' right ascension of ascending node.

2) GEOGRAPHIC SUBNETTING

The Earth's surface is divided into 72 geographic subnet areas and the geographic subnets are numbered. Each geographic subnet area spans 30 degrees of longitude and latitude. The specific division scheme and geographic subnet numbering are shown in Fig.16.

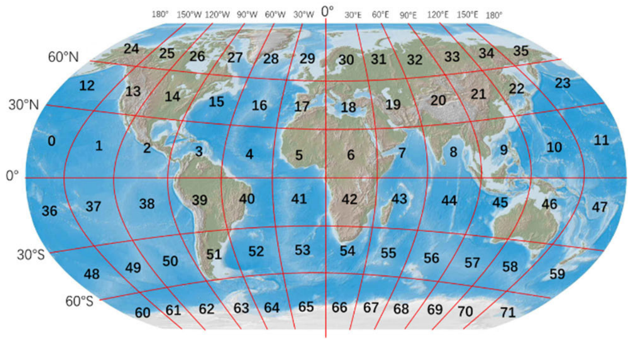


FIGURE 16. Diagram of geographic subnet partitioning in the simulation scenario.

This simulation counts the data of cells 0 to 11. For cells 0 to 11, the shape is a spherical isosceles trapezoid, that can be approximated as a two-dimensional square, i.e., $N = 4$. Based on the previous assumptions, 60,000 terrestrial users are uniformly distributed in cells 0 to 11, with 5,000 terrestrial users in each cell.

3) OTHER SIMULATION PARAMETERS

In the scenario simulation, the ratio β is defined as the value of the diameter of the satellite coverage divided by the longest diagonal of the geographic subnetwork. Combined with the orbit altitude range (700km to 1500 km) of the LEO satellite constellation [20], the value of this ratio β in this simulation ranges from 1.06 to 1.73. The simulation gives the average AAUR corresponding to 21 different ratios in this range. We counted the probability average of the ratio of the AAUs to the total users for cells 0 to 11. The specific statistical method is as follows. For simulation scenarios with different ratios, the orbital period, T, is calculated. Let the unit length of the simulation time be T/600. Finally, calculate the average of AAURs after 600 units of simulation time.

B. ANALYSIS OF SCENARIO SIMULATION RESULTS

1) SIMULATION ANALYSIS OF ADDRESSING ABNORMAL USER RATES OVER TIME

Fig.17 shows the scatter plot of the AAUR varying with simulation time for three different randomly-selected satellite coverage to geographic subnetwork range ratios. In order

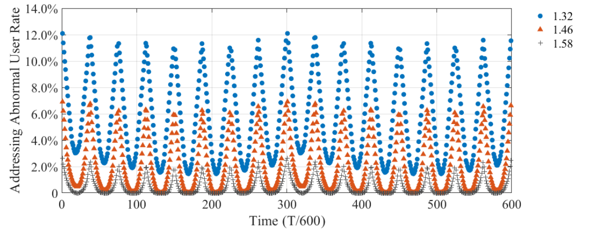


FIGURE 17. Variation of AAUR with time for different ratios β.

to investigate the variation law of the AAUR with time for different ratios β and whether the law is affected by the ratio β, the ratios in the Fig.17 are randomly selected as 1.32, 1.46 and 1.58, respectively. For simulation scenarios with different ratios, let the orbital period be T. The horizontal coordinate in the above figure is the time t in T/600, and the vertical coordinate is the AAUR at a certain moment. Fig.17 illustrates that, during the scenario simulation, the AAUR for different ratios β show periodic changes as time progresses. The mean squared errors are 0.0309($\beta = 1.32$), 0.0198($\beta = 1.46$), 0.0062($\beta = 1.58$). And we can see that the larger the beta, the more stable the data, i.e., the closer the number of abnormal users is at different times.

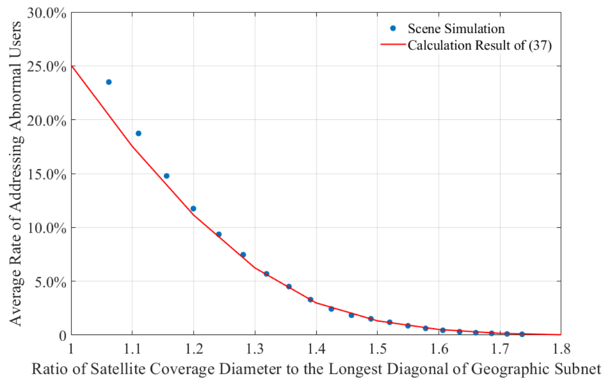


FIGURE 18. Simulation and theoretical calculation results of the average abnormal user rate in subnet partitioned according to Fig.16.

2) COMPARATIVE ANALYSIS OF SCENARIO SIMULATION RESULTS AND THEORETICAL CALCULATION RESULTS

The abscissa in the Fig.18 is β, which is the ratio of the satellite coverage diameter to the longest diagonal of the geographic subnet, and the ordinate is the average rate of AAU. Considering the subnetting scheme in the scenario simulation, there is an edge number $N = 4$. The red curve is the theoretical calculation result of $E_W(\beta)$ obtained by bringing $N = 4$ into (37), and the blue dotted trace is the scenario simulation result.

As can be seen from the Fig.18, the average abnormal user rate in the LEO satellite constellation decreases as the ratio of satellite coverage to geographic subnetwork range increases, and the result of the scenario simulation are similar to the result of the equation derived theoretically in this study (as shown in (37)). In addition, when the ratio of satellite coverage to geographic subnetwork range is greater than 1.5, its corresponding average AAUR will be close to 0, i.e., the number of AAUs in the system is very small at this time.

Considering the geographic information-based subnetting scheme needs to ensure each geographic subnet always has a satellite access, the number of geographic subnets is determined by the number of satellites in the constellation. Therefore, for a certain LEO satellite constellation, when the satellite's coverage range to the ground is certain, we can obtain different numbers of subnets by adjusting the number of satellites in the constellation, and then adjust the size of the subnet range, so as to obtain different ratios of satellite coverage to geographical subnet range. For the quadrilateral subnet, when the ratio is greater than 1.5, the AAUs have little impact on the LEO satellite constellation system with the geographic information subnet partitioning scheme.

We mainly consider the management overhead caused by the dynamic switch between ground users and satellite ports to earth. The simulation scenario is described in section A. In the satellite-fixed subnet solution, the ground ports of each satellite are assigned different subnet start addresses. When ground users switch to different satellites, IP addresses belonging to the satellite-fixed subnet address segment are assigned to the ground users, and all users must be informed of the switchover. In the geographic information subnet scheme, when a satellite moves out or into a different geographic subnet, the satellite's ground port switches to the first address of the geographic subnet, and the user's IP address remains unchanged, and the switch only needs to be notified to all other satellites.

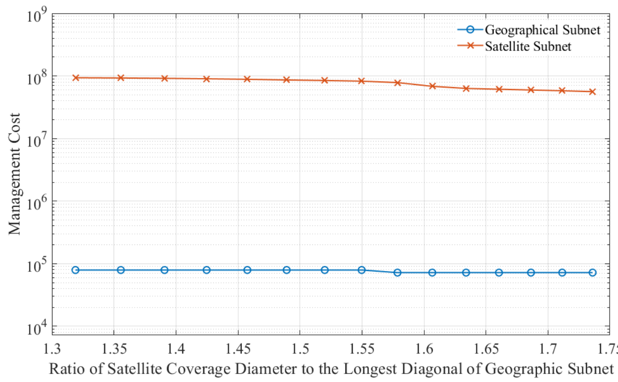


FIGURE 19. The mobility management cost in different subnet partitioning scheme.

As can be seen from Fig.19, the mobility management cost of the geographic subnet scheme is about five orders of magnitude less than that of the satellite-fixed subnet scheme, and the ratio of satellite coverage to geographic subnet scope has little influence on the mobility management cost. The simulation results in literature [7] also show that when the satellite coverage is constant, the size of different geographical subnet regions (that is, the different ratio of satellite coverage to geographic subnet range) has little influence on the mobility management overhead.

V. CONCLUSION

This thesis first introduces the IP/LEO addressing scheme based on geographic information and the problems of the scheme. Inevitably, there will be AAUs when adopting this scheme. After giving the definition of AAUs, a statistical model of AAUs based on the geographic information subnetwork partitioning scheme is derived. The model describes the relationship between the average AAUR and the ratio of satellite coverage to geographic subnetwork range. The average AAUR decreases as the ratio of satellite coverage to geographic subnetwork range increases, and the rate of decrease reduces as the ratio increases. For the constellation design, according to the relationship between satellite coverage, geographic subnetwork range, and average AAUR, quantified in this paper, we can adjust the number of satellites in the constellation, so as to obtain different satellite coverage to geographic subnetwork range ratios, and thus achieve a smaller AAUR and ultimately meet the specific performance requirements.

For a N-sided equilateral polygon geographic subnet, the average AAUR is determined by the number of sides N of the geographic subnet, and the ratio of the satellite coverage diameter to the longest diagonal of the geographic subnet. When this ratio is greater than 1.6, the average AAUR drops to about 5%. Further, for the quadrilateral geographic subnet, the average AAUR decreases from 25.1% to 0 when the ratio of the satellite coverage diameter to the longest diagonal of the geographic subnet increases from 1 to 2. The scenario simulation results show that the average AAUR decreases with the increase of the ratio of the satellite coverage area to the geographic subnet area in the near-polar LEO satellite constellation and that the mobility management cost of the geographic subnet scheme is about five orders of magnitude less than that of the satellite-fixed subnet scheme, and the ratio of satellite coverage to geographic subnet scope has little influence on the mobility management cost. The scenario simulation results are similar to the results of the theoretical derivation, which verifies the correctness of the theoretical derivation.

REFERENCES

[1] P. Noschese, S. Porfili, and S. Di Girolamo, "ADS-B via iridium NEXT satellites," in *Proc. Tyrrhenian Int. Workshop Digit. Commun. Enhanced Surveill. Aircr. Vehicles*, 2011, pp. 213–218.

[2] O. B. Osoro and E. J. Oughton, "A techno-economic framework for satellite networks applied to low Earth orbit constellations: Assessing starlink, OneWeb and kuiper," *IEEE Access*, vol. 9, pp. 141611–141625, 2021, doi: 10.1109/ACCESS.2021.3119634.

[3] A. Sayin, M. Cherniakov, and M. Antoniou, "Passive radar using starlink transmissions: A theoretical study," in *Proc. 20th Int. Radar Symp. (IRS)*, Jun. 2019, pp. 1–7, doi: 10.23919/IRS.2019.8768105.

[4] J. Sedin, L. Feltrin, and X. Lin, "Throughput and capacity evaluation of 5G new radio non-terrestrial networks with LEO satellites," in *Proc. GLOBECOM IEEE Global Commun. Conf.*, Dec. 2020, pp. 1–6, doi: 10.1109/GLOBECOM42002.2020.9347998.

[5] N. Pachler, I. del Portillo, E. F. Crawley, and B. G. Cameron, "An updated comparison of four low Earth orbit satellite constellation systems to provide global broadband," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Jun. 2021, pp. 1–7, doi: 10.1109/ICCWorkshops50388.2021.9473799.

[6] Y. Wu, G. Hu, F. Jin, and J. Zu, "A satellite handover strategy based on the potential game in LEO satellite networks," *IEEE Access*, vol. 7, pp. 133641–133652, 2019, doi: 10.1109/ACCESS.2019.2941217.

[7] H. Tsunoda, K. Ohta, N. Kato, and Y. Nemoto, "Supporting IP/LEO satellite networks by handover-independent IP mobility management," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 2, pp. 300–307, Feb. 2004, doi: 10.1109/JSAC.2003.819977.

[8] T. Zhang and L. Liang, "IP addressing method and device for polar-orbit low orbit satellite network," China Patent CN 106 533 536 A, Mar. 22, 2017.

[9] A. Tuysuz and F. Alagoz, "Satellite mobility pattern based handover management algorithm in LEO satellites," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2006, pp. 1867–1872, doi: 10.1109/ICC.2006.254992.

[10] Z. Zhang, B. Zhao, W. Yu, and C. Wu, "Supporting location/identity separation in mobility-enhanced satellite networks by virtual attachment point," *Pervas. Mobile Comput.*, vol. 42, pp. 1–14, Dec. 2017, doi: 10.1016/j.pmcj.2017.09.001.

[11] J. Li, K. Xue, J. Liu, and Y. Zhang, "A user-centric handover scheme for ultra-dense LEO satellite networks," *IEEE Wireless Commun. Lett.*, vol. 9, no. 11, pp. 1904–1908, Nov. 2020, doi: 10.1109/LWC.2020.3007818.

[12] W. Dai, H. Li, Q. Wu, and X. Wang, "Flexible and aggregated mobility management in integrated satellite-terrestrial networks," in *Proc. Int. Wireless Commun. Mobile Comput. (IWCMC)*, Jun. 2020, pp. 982–987, doi: 10.1109/IWCMC48107.2020.9148088.

[13] W. Han, B. Wang, Z. Feng, B. Zhao, W. Yu, and Z. Tang, "GRIMM: A locator/identifier split-based mobility management architecture for LEO satellite network," in *Proc. 6th Int. Conf. Instrum. Meas., Comput., Commun. Control (IMCCC)*, Jul. 2016, pp. 605–608, doi: 10.1109/IMCCC.2016.62.

[14] Y. L. Xiao, T. Zhang, and L. Liu, "Addressing subnet division based on geographical information for satellite-ground integrated network," *IEEE Access*, vol. 6, pp. 75824–75833, 2018, doi: 10.1109/ACCESS.2018.2882594.

[15] Y. Xiao, T. Zhang, and M. Sun, "Geographical addressing strategy for space-ground integrated network," *Int. J. Satell. Commun. Netw.*, vol. 39, no. 2, pp. 178–192, Mar. 2021, doi: 10.1002/sat.1373.

[16] *UM_Iridium-Global-Paging-Service_Codes-and-Coverage-Maps_DEC01, America*. Accessed: Mar. 2020. [Online]. Available: http://www.e-sat.fr/wp-content/uploads/2020/03/UM_Iridium-Global-Paging-Service_Codes-and-Coverage-Maps_DEC01.pdf

[17] Y. Luo and P. Shu, "Optimization design of Walker constellation for multi-target rapid revisit," in *Proc. 8th Int. Conf. Instrum. Meas., Comput., Commun. Control (IMCCC)*, Jul. 2018, pp. 483–486, doi: 10.1109/IMCCC.2018.00107.

[18] T. N. Kaifas, D. G. Babas, G. Toso, and J. N. Sahalos, "Multibeam antennas for global satellite coverage: Theory and design," *IET Microw., Antennas Propag.*, vol. 10, no. 14, pp. 1475–1484, Nov. 2016, doi: 10.1049/iet-map.2015.0811.

[19] M. S. Ross, *Introduction to Probability Models*, 10th ed. Beijing, China: Posts & Telecom Press Co., LTD, 2011, pp. 41–42.

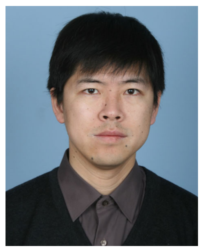
[20] A. D. P. Hands, K. A. Ryden, N. P. Meredith, S. A. Glauert, and R. B. Horne, "Radiation effects on satellites during extreme space weather events," *Space Weather*, vol. 16, no. 9, pp. 1216–1226, Sep. 2018, doi: 10.1029/2018SW001913.

MENG SUN (Graduate Student Member, IEEE) was born in 1997. She received the B.S. degree in electrical engineering from Beihang University, Beijing, China, in 2019, where she is currently pursuing the master's degree in electronics and information engineering.

Her research interests include satellite network systems and satellite routing algorithm.

LIANG LIU was born in 1986. He received the B.S.E.E. degree from Beihang University, Beijing, China, in 2009, and the Ph.D. degree from BUAA, in 2017.

His research interests include network coding, mobile communication, and satellite communication.



TAO ZHANG was born in 1973. He received the B.S.E.E. degree from the Huazhong University of Science and Technology, Wuhan, China, in 1995, and the Ph.D. degree from Beihang University, Beijing, China, in 2006.

He is currently a Professor with the School of Electronics and Information Engineering, Beihang University. His research interests include QoS routing, mobile communication, and satellite network communication.