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# Addressing Subnet Division Based on Geographical Information for Satellite-Ground Integrated Network

**YUNLU XIAO** [1], **TAO ZHANG** [1], **AND LIANG LIU** [2]
[1]Department of Electronic and Information Engineering, Beihang University, Beijing 100191, China
[2]Institute of Telecommunication Satellite, CAST, Beijing 100094, China

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

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**ABSTRACT** To tackle the address aggregation problem for the low earth orbit (LEO) satellite communication system, a global geographical Internet Protocol subnet division model for space–ground integrated network addressing scheme is proposed in this paper. A 2-D spherical coordinate system based on spherical distance is applied to describe the LEO satellite track and the location information of geographical subnet zone. A mathematical framework for abnormal addressing users is constructed under the system. The size and division of geographical zone influence the expectation of abnormal user number through the ratio of logically covered and fully covered time. When the terrestrial regions are divided into small cells, the number of abnormal users reduces, as well as the partial routing cost. The simulation results confirm that the ratio of logically covered and fully covered time increase and the number of abnormal users decreases when the size of ground cells declines. The origin regions could be divided into smaller ground cells in order to reduce abnormal addressing users, balancing the cost on partial routing mechanism, mobility management, and satellite routing table items. This paper presented a solution and direction of addressing scheme and mobility management design for the space-terrestrial hybrid network.

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

## I. INTRODUCTION

The Low Earth Orbit (LEO) satellite network presents a promising solution for the developing wide-range global communications. Current LEO system, represented by Iridium II, OneWeb and Starlink, is designed to provide service directly to the ground end users [1]. To complete an end-to-end data transportation, the data flow would transit inside the terrestrial network, between satellite and ground nodes through satellite-ground links, and within the satellite network [2]. Figure 1. presents the basic structure of the integrated network. To provide IP connectivity to end users on earth, the integration of LEO satellite systems into Internet protocol (IP) networks as IP/LEO system should be examined in detail. The IP addressing problem, i.e. how to assign IP addresses to global end users, should be considered for the satellite network connecting to ground IP network.

The data transportation system for the terrestrial network is relatively matured during the development of the Internet [3].

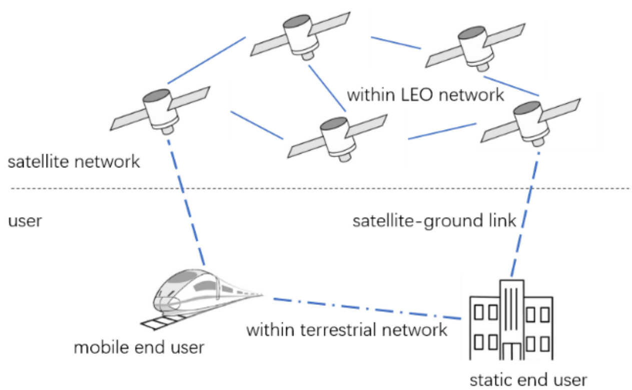


**FIGURE 1.** Basic structure of satellite-terrestrial integrate network.

The independent routing algorithm for LEO satellite network is studied in several works [4]. However, the satellite-based routing strategy aims at solving the data transportation inside space network instead of the integration of the space-ground network. The IP mechanism for ground user network could not provide a suitable solution for IP/LEO satellite network. Address aggregation should be applied in IP address assignment in order to reduce the items in router storage [5]. The existed IP addressing method is based on 'subnet + host' module. Every end users (host) is assigned to IP subnets, and each subnet binds to the designed router port through subnet head address [6]. In terrestrial mobile networks, the router ports are usually not subjected to motion, and therefore easy to maintain a relatively fixed connection with the corresponding subnet [7]. However, in LEO satellite networks the routers are placed on the satellites. The high-dynamic movement of satellite nodes makes it challenging for router ports to maintain a stable connection to the ground user subnets [8]. Moreover, the LEO network is designed to have wide coverage. Therefore, a large number of end users, especially the mobile users would suffer frequently handovers and IP updates due to the high mobility of connected satellite nodes, which would create challenges for the binding of subnet and router port required in present IP addressing strategy.

In [9] an idea of subnet division based on geographical information is provided. The surface of the earth is divided into several geographical areas, each area relates to a subnet. The users inside the area are assigned to the subnet. The IP addresses of ground users only associate to location information of their area and are therefore independent of the satellite movement. When a satellite covers an area, the on-satellite router port would be assigned to the head address of the relative subnet. The destination node of a transmission could be traced through its subnet address stored in the router. The satellite router could communicate to the whole network relying on the IP headers of subnets. In this scheme, the number of geographical areas decides the number of subnets, thereby affects the amount of routing table storage. Meanwhile, the size of the subnet area determines the handover frequency, thus produce an effect on mobility management cost. In [9] and [10] the relationship between mobility management cost and the size of ground cells are discussed. However, a practical scheme of global IP subnet division is not canvassed.

Moreover, the IP addressing scheme based on geographical information would surface the problem of abnormal addressing, resulting in partial routing cost for the satellite network. The covered area of the satellite would change continually because of the earth rotation and satellite mobility. Hence, it is possible that the communication range of a satellite that is assigned for a subnet head address could not fully cover the subnet area. The users that belong to the subnet while outside the coverage are defined as abnormal addressing users. These users would have to send the data to their connected satellites first and communicate with the assigned satellite through partial routing mechanism on the satellite network, which would cost extra bandwidth resources [11]. Therefore, to present a low-cost IP/LEO addressing scheme, the relation between abnormal addressing cost and the IP subnet division scheme (the size or distribution of subnet area) requires a systematic description.

In this paper, a mathematical framework for abnormal addressing users is constructed, and a global geographical IP subnet division model for space-ground integrity network is proposed. A two-dimensional spherical coordinate system based on spherical distance is applied to describe the LEO satellite track and the location information of geographical IP areas. It could be concluded that the size and division of subnets influence the expectation of abnormal user number through the ratio of logical cover and fully cover time. When the terrestrial IP regions are divided into small cells, the number of abnormal users reduces, the same as the partial routing cost. However, the decrease rate of abnormal users declines during the subdivision of IP areas, while the mobility management cost and satellite routing table items suffer a relatively rapid rise. The model proposed in this paper could help determine the suitable ground subnet cell distribution for lower cost in partial routing mechanism, mobility management, and satellite routing table items. When the geographical IP subnet division is completed, IP addresses could be distributed to the end users and covered satellites of each shunet area. The satellite could communicate with the ground users under IP network. The IP addresses would only change when users or satellites move to another subnet.

The rest of this paper is organized as follows. The satellite-to-terrestrial communication scenario and the handover conditions of geographical IP addressing are introduced in section 2. The case of abnormal IP addressing is explained. A general model for the distribution of abnormal addressing users is discussed and simplified in section 3. In section 4, a geographical IP subnet division scheme for IP/LEO network is introduced. A two-dimensional spherical coordinate system based on spherical distance is applied to describe the location information of geographical subnets. The model solution for the distribution of abnormal addressing users based on time ratio evaluation is discussed in section 5. Based on the geographical information of IP subnets and satellite ground tracks, the influence of logical coverage time and fully covered time on the expectation of abnormal addressing users is illustrated. Simulation results in terms of partial routing cost and satellite routing table items are shown in section 6. Conclusion and outlook are in section 7.

## II. SATELLITE-GROUND INTEGRATED SYSTEM MODEL

### A. LEO TO TERRESTRIAL COMMUNICATIONS SCENARIO

The LEO communication network covers the global surface with a large number of satellite nodes. The LEO satellites can communicate with ground end users directly and emerge with the ground Internet system. In order to build up connections between satellites and ground users, up and down satellite-ground links are formed and the information is delivered by the links through identification, handover, and data transmission processes. The process of satellite-to-ground communication is illustrated in Figure 2.

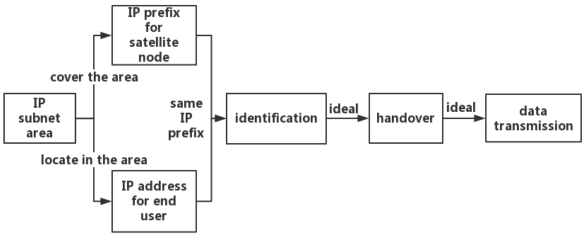


**FIGURE 2.** Process of satellite-to-ground communication.

In the IP/LEO network, the identification of satellite and ground nodes relies on IP framework [12]. The satellite identifies the source and destination nodes for the data packet through its IP address and therefore obtains the on-satellite transmission path by routing algorism. If the data packet's IP header could not be recognized by the satellite, the information could not be transmitted on the satellite network. Therefore, the link between satellite and ground user requires identification through IP address. the users would communicate with the satellite routing port that has the same subnet prefix as themselves.

When a ground user comes within the communication range of a satellite with the same IP prefix, the user would switch to the satellite-ground link of the satellite to build up a connection. Data flows could be transmitted between the satellite and the user when the handover is completed. In this paper, the handover procedure is assumed to be ideal. Satellites and end users could set up communication links and transmit information without delay and loss once the handover condition is fulfilled. Furthermore, the satellite-to-terrestrial communication channel is considered an ideal channel with infinite bandwidth resources. The signal would not suffer from channel attenuation during data transmission. Therefore, the quality of information transport in the satellite-ground link only depends on the identification of the IP address in this paper.

### B. THE GEOGRAPHICAL ZONE AND THE HANDOVER CONDITION

Considering the massive number of ground users and their high-velocity relative motion against the satellite, frequent handover would occur in a short time if the IP addresses of users are connected to the linking satellite. Therefore, in order to reduce the frequency of handover and binding update, IP addresses should be independent of the relative position between ground users and satellite and associated to only geographical location information, as [9] points out. The earth surface is divided into ground subnet cells under certain rules. The users inside one cell shared the same IP prefix. When a satellite covers the cell region, the satellite would be assigned the IP header of this region until it leaves the region. Therefore, the IP handover would only occur in two scenarios: 1) The ground users move to another region, hence change the IP address associated with the geographical information of the new cell. 2) The satellite interfaces with a different cell due to the motion of satellite or earth rotation, assigned to a different IP prefix in order to communicate with a new group of users.

The binding system for satellites and subnets should guarantee the data transmission on both satellite and ground user network. Therefore, at any moment, the IP address of each satellite should be unique for the validity of satellite-based routing strategy, which indicated that each terrestrial subnet would bind to only one satellite. Each ground region should also be assigned to a satellite anytime to maintain data up-link transmission and reduce handover occasions. Based on the above requirements, the handover conditions for a satellite to its IP subnet in this paper could be listed as follows: 1) A satellite is linked with a certain subnet region and assigned the IP header when the satellite's communication range covers half of the region. The data packages from and to the users in this region would be transported through the covered satellite. 2) Each ground subnet would connect to the first satellite that meets the handover condition, and switch to other satellite nodes only when the present node no longer fulfill the condition.

### C. ABNORMAL ADDRESSING USER

Defining the scenario when the satellite satisfies the handover condition and is assigned the IP header of subnet region $D$ as satellite 'logically covers' $D$. Figure 3. presents the logically covered scenario.

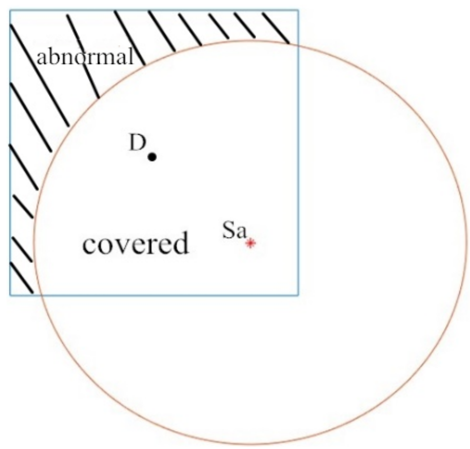


**FIGURE 3.** Logical coverage for an IP subnet area.

The communication coverage of the satellite would shift continuously over time due to the self-rotation of the earth and the movement of satellites. Therefore, the communication range of the satellite might not fully cover the whole subnet region during logical coverage, resulting in edge users which are outside the range of physical connection with the logically covered satellite, as the shadow area in Figure 3. presents. In this paper, they are defined as abnormal addressing user.

Data packets from the abnormal addressing users could not be transferred directly to the satellite routing port that would identify the IP addresses. If the abnormal users would not transmit information until they could directly link to the logically covered satellite, the network would suffer relatively severe end-to-end latency. If the abnormal users communicated with the actually connected satellite instead, the on-satellite route would not be able to recognize the IP packet without certain coping strategy due to the discrepancy of IP headers between data packets and routing port. The satellite network could not process the packets from abnormal users with routing algorism, and the information might be discarded during transmission.

To ensure the data transformation of abnormal addressing users, partial routing strategy is required. The abnormal users would communicate with the connected satellite first, the IP packages then transport between the physically connected satellite and the logically covered satellite on satellite network under certain routing strategy. An idea of partial routing strategy is illustrated in Figure 4.

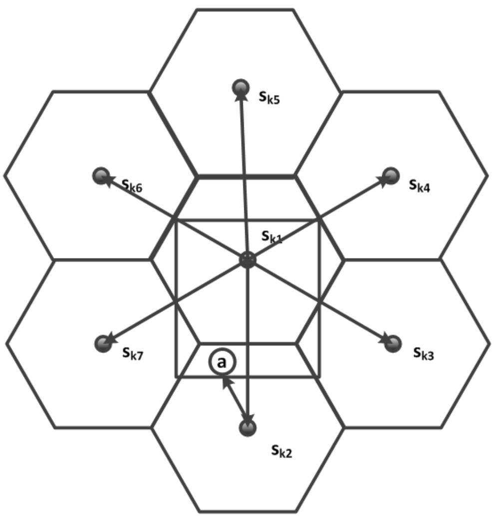


**FIGURE 4.** Partial routing strategy at the last hop.

The abnormal addressing user $a$ is logically covered by satellite $S_{k1}$ but physically connected with $S_{k2}$. According to the structure of LEO constellation, it is highly possible that $S_{k2}$ is a neighbor node for $S_{k1}$. Therefore, $S_{k1}$ could trigger a flooding and send the copies of the message for $a$ to all neighbors $S_{k2}$-$S_{k7}$. In the end, $S_{k2}$ would pass the message to $a$, while other nodes would discard the packet. On the other hand, $a$ would send the data flow to $S_{k2}$ first when a business start. $S_{k2}$ would flood the data packet to its neighbors for $S_{k1}$ to receive and identify the IP prefix, and transmit the packet on satellite network based on routing algorism after that.

Partial routing mechanism could provide a solution for the communication service from abnormal addressing users, but this mechanism would cost network resources. Take the partial routing idea proposed above as an example, data flooding would occur at a relatively high possibility at the last hop of data packet transmission, resulting in the cost of bandwidth resources in multiple links. The price of sending a packet would multiply, and the cost would increase when the number of abnormal addressing users grows for more communication services from the abnormal users requiring more partial routing mechanism. Therefore, the distribution of abnormal addressing users should be analyzed at top priority when designing the subnet division scheme for LEO/IP network.

## III. THE DISTRIBUTION OF ABNORMAL ADDRESSING USERS

### A. TOTAL NUMBER OF ABNORMAL ADDRESSING USERS

For a geographical subnet cell, the distribution of abnormal addressing users is determined by the communication coverage of satellites. The number of abnormal users would change over time due to the movement of satellites. For a certain moment $t$, the area of uncovered region $S_{ab}$ could be determined by the location of ground subnet cells and the satellites. The number of abnormal addressing users could be presented by

$$Num_i(t) = \iint_{S_{ad}(t)} \lambda_i(s)ds \tag{1}$$

$\lambda_i$ stands for the density distribution of satellite users of area $D_i$

The number of abnormal addressing users of the global network is the sum of abnormal users in each cell.

$$Num(t) = \sum Num_i(t) \tag{2}$$

The expectation of abnormal addressing users could be described by

$$E[Num] = \lim_{T\to\infty} \frac{1}{T} \cdot \int_0^T Num\,(t)\,dt \tag{3}$$

### B. SIMPLIFICATION AND ASSUMPTIONS

In order to discuss the abnormal user number in detail, the simplification for the general model is required. According to [13], all coverage areas of polar orbit satellite in the network could be assumed to be circular with radius $R_s$, as Figure 5. presents.

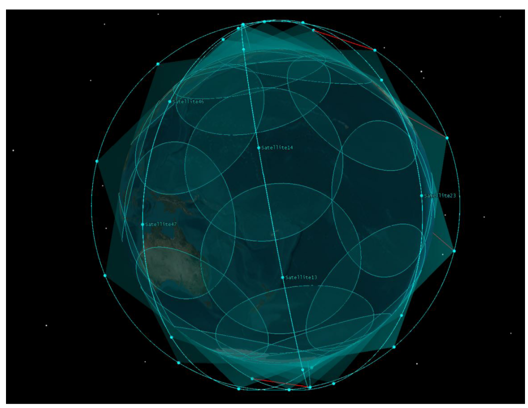

**FIGURE 5.** Global coverage for polar orbit LEO satellite.

The ratio between the period of LEO satellite movement and the earth rotation rate is usually an irrational number [14].

Hence, the projection of the satellite could be assumed to be a uniform ergodic distribution on the surface of the earth. For each subnet area, the analysis of abnormal addressing users could be the same, the discussion for one area could represent the global situation.

The topology structure of the LEO satellite constellation could influence the trajectory of satellite coverage on earth and therefore affect the change in abnormal user distribution over time. In this paper, the LEO network is considered as polar orbit satellites system, one of the typical constellation structures for LEO satellite network[15]. The projection of the polar orbit satellite moving track on the ground surface could be considered coinciding with the longitude.

For the ground condition, in this paper earth is considered as an ideal sphere with radius $R_e$. The users are assumed to be distributed evenly in one IP subnet region with the total number $N_i$, which means in one region the density $\lambda_i$ is a constant. The number of abnormal addressing users in $D_i$ could be presented by

$$Num_i(t) = N_i \cdot \frac{S_{ad}(t)}{S_{D_i}} \tag{4}$$

When the terrestrial addressing region distribution scheme is settled, the shape and location of ground cells would not change over time. Therefore, $N_i$ and the cell area $S_{D_i}$ would not change. The abnormal addressing users' number could be described by the size of uncover area.

## IV. GLOBAL GEOGRAPHICAL IP SUBNET DIVISION MODEL CONSTRUCTION

### A. TWO-DIMENSIONAL SPHERICAL COORDINATE SYSTEM

In this paper, a two-dimensional spherical coordinate system based on spherical distance is applied to describe the sub-satellite track and the location information of geographical subnet area. Take 0° parallel as $X$ axis and the 0° meridian as $Y$. Their intersection is the coordinate origin. For a point $(x, y)$, $x$ is the spherical distance to the 0° meridian and $y$ is to 0° parallel. Under this system, the minimum spherical distance between two points $(p_1, p_2)$ could be described by

$$\|p_1 p_2\|_2 = \sqrt{(x_{p_1} - x_{p_2})^2 + (y_{p_1} - y_{p_2})^2} \tag{5}$$

The distance coordinates could switch into spherical coordinates presented by longitude and latitude. The longitude $\phi$ and latitude $\theta$ could be presented as

$$\begin{cases} \phi = \dfrac{x}{\cos\frac{y}{R_e} \cdot R_e} & x \in [-\pi R_e, \pi R_e] \\ \theta = \dfrac{y}{R_e} & y = [-\dfrac{\pi}{2} R_e, \dfrac{\pi}{2} R_e] \end{cases} \tag{6}$$

### B. INITIAL IP SUBNET REGION DISTRIBUTION

The earth sphere could be covered by spherical isosceles trapezoids. In this paper, the ground subnet region is designed as isosceles trapezoid presented by center $(x_c, y_c)$, high $h$, lower base $a$ and upper base $b$, as Figure 6. presents.

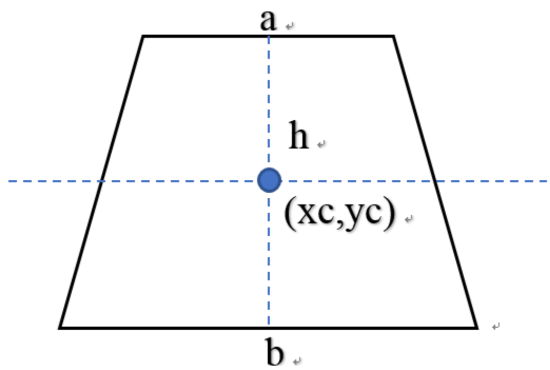


**FIGURE 6. IP addressing region.**

If the area of ground subnet exceeds the satellite coverage area, the satellite could not fully cover the region at any moment and the abnormal addressing users would always exist, which would lead to significant partial routing cost. Therefore, in this paper, an initial IP region distribution is presented. The area of an initial subnet is close to the inscribed square of the satellite coverage circle to guarantee full coverage. The high could be presented by

$$h = \sqrt{2}R_s \tag{7}$$

The number of initial subnets in one circle could be described by

$$k = ceil(\cos\frac{y_c - \frac{1}{2}h}{R_e} \cdot \frac{R_e}{\sqrt{2}R_s}) \tag{8}$$

*ceil* stands for rounding up to an integer.

The two bases could be described by

$$a = \cos\frac{y_c - \frac{1}{2}h}{R_e} \cdot \frac{R_e}{k} \tag{9}$$

$$b = \cos\frac{y_c + \frac{1}{2}h}{R_e} \cdot \frac{R_e}{k} \tag{10}$$

Therefore, the initial region distribution could be determined considering the satellite coverage area. The location information of regions could be obtained under the two-dimensional spherical coordinate system.

In this paper, the satellite logical covers the region when the area center reaches the satellite's communication range. The handover condition could satisfy the feasible condition and easy to practice. At the moment of handover, the average number of abnormal addressing users is half the total users' number in the area $N/2$.

## V. TIME RATIO MODEL CONSTRUCTION AND SOLUTION

### A. THE EXPECTATION MODEL OF ABNORMAL ADDRESSING USERS

During the logical coverage, the number of abnormal users would change from $N/2$ and reach 0 when the satellite fully covers the area. When the satellite moves far away from the area, the abnormal users would reappear and reach the maximum $N/2$ until the area is taken over by another satellite. According to (4), the number of abnormal addressing users could be presented by the uncovered area. Since the satellite moves at a steady speed, the area change of uncovered region could be matching by the polynomial. Thus, the curve between $N/2$ and 0 could be described as

$$Num = a(t-b)^k \tag{11}$$

Noting the logical cover time duration as $T_z$ and the fully cover duration as $T_q$, the moment when the satellite fully covers the area is $\frac{1}{2}(T_z - T_q)$. Put in $(0, \frac{1}{2}N)$, $(\frac{1}{2}(T_z - T_q), 0)$ to (11), the two unknows could be achieved.

$$a = \frac{N}{2(-b)^k}, \quad b = \frac{1}{2}(T_z - T_q) \tag{12}$$

The expectation of abnormal addressed users could be described by

$$\begin{aligned} E[Num] &= \frac{1}{T_z} \cdot 2 \int_0^{(T_z - T_q)/2} a(t-b)^k dt \\ &= \frac{N}{2(k+1)}(1 - \frac{T_q}{T_z}) \end{aligned} \tag{13}$$

Figure 7. illustrated the change of abnormal user number with different fully cover and logical cover time ratio. It could be noticed that the number of abnormal users is controlled by the time ratio. The higher time ratio indicates fewer abnormal user and lowers partial routing cost. Therefore, the analysis could focus on the model of the time ratio.

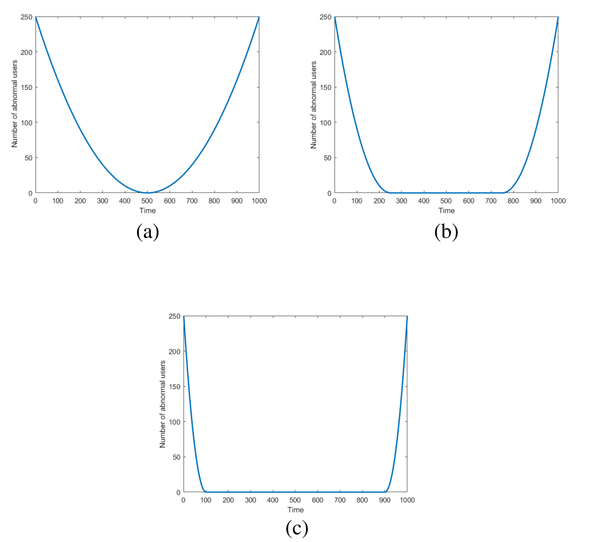


**FIGURE 7. Change of abnormal users over time. (a) $T_q = 0$. (b) $T_q = 0.5T_z$. (c) $T_q = 0.8T_z$.**

### *B. TIME RATIO MODEL BASED SOLUTION*

#### 1) SUB-SATELLITE TRACK

The sub-satellite ground point movement is the combination of satellite motion and rotation of the earth. For polar orbit LEO satellite, the satellite nodes move along the longitude with a constant velocity. Usually, the speed would be much larger than the maximum linear velocity of earth rotation (approximately 464m/s) [13]. Therefore, it is reasonable to presume that the earth rotation has little influence on the instantaneous speed of sub-satellite point. In this paper, it is assumed that the sub-satellite point moves at a constant speed along the longitude line.

For a sub-satellite point $(x_s, y_s)$, the tracks on the surface of the earth is the longitude line.

$$\phi = \frac{x_s}{\cos \frac{y_s}{R_e} \cdot R_e} \tag{14}$$

Associate with (6), the sub-satellite track could be presented by

$$Sa(x,y) = \frac{x_s}{\cos \frac{y_s}{R_e}} \cdot \cos \frac{y}{R_e} - x = 0 \tag{15}$$

#### 2) GROUND SUBNET CELLS

The isosceles trapezoid area could be equivalent to an equal-area rectangular presented in Figure 8. The width of the rectangular is the high of the trapezoid and the length is the mean of up and low bases of the trapezoid. Similarly, the division of the trapezoidal area into small cells could be equivalent to the division of rectangular.

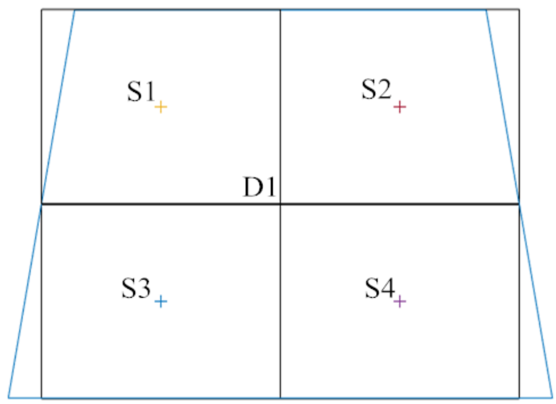


**FIGURE 8. The division of initial isosceles trapezoid area.**

Divided the rectangle area into $n^2$ pieces small areas, noted $n$ as the division factor. The length $a_n$ and the width $b_n$ of rectangular ground cells could be described by

$$a_n = \frac{(a+b)}{2n}, \quad b_n = \frac{h}{n} \tag{16}$$

The number of users in each small area is $N/n^2$ due to the even distribution of users in the origin area. For each small area, the expectation of abnormal addressing users could be presented by

$$E_i = \frac{N/n^2}{2(k+1)}(1 - (\frac{T_q}{T_z})_n) \tag{17}$$

The number of abnormal addressing users of the origin area is the sum of each small area.

Considering the earth as a uniform sphere, it could be seen that in one origin subnet area, the time ratio depends on the area of sub-region, while the location has relatively little influence on coverage ratio. Furthermore, the sub-satellite ground points could be considered uniformed distributed within the origin area. Thus, it could be noted that each small area has the same distribution of abnormal addressing users, thus the expectation of abnormal users of an area depends on the division factor $n$.

$$E[Num] = \sum_{i=1}^{n^2} E_i = \frac{N}{2(k+1)}(1-(\frac{T_q}{T_z})_n) \tag{18}$$

### 3) TIME RATIO

The handover for a satellite and ground cell $D_i$ is presented in figure 9. The sub-satellite point moves on the track $Sa(t)$. The rectangle area could be described by its length $a$, width $b$ and the center $D_i(x_c, y_c)$.

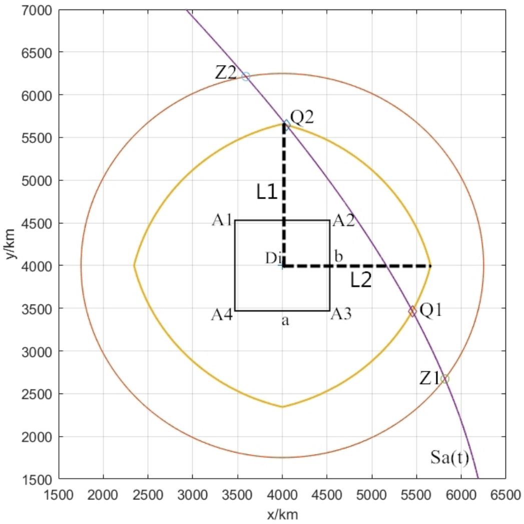


**FIGURE 9.** Handover for a satellite and ground cell.

The satellite coverage area could be present by a circle with radius $R_s$. When the center of an earth area goes inside the coverage, the area is logically covered by the satellite. Therefore, for logical coverage, the sub-satellite point should be in the circle

$$(x-x_c)^2 + (y-y_c)^2 = {R_s}^2 \tag{19}$$

Associate with the sub-satellite point track (15), solve the simultaneous equations could present two intersections $Z_1$, $Z_2$ . Considering the sub-satellite point moves with a constant velocity of $v_s$, the logical covered time could be described by

$$T_z(x_s, y_s) = \frac{|Z_1Z_2|}{v_s} \tag{20}$$

Length of track between $|Z_1Z_2|$ could be presented by

$$|Z_1Z_2| = \int_{Z_1Z_2} Sa(x,y)ds \tag{21}$$

When the satellite covers the whole area, the four vertexes, $A_1(x_c-a/2, y_c+b/2)$, $A_2(x_c+a/2, y_c+b/2)$, $A_3(x_c+a/2, y_c-b/2)$, $A_4(x_c-a/2, y_c-b/2)$ of the area should be within the satellite communication circle. For full coverage, the sub-satellite point should be in the area surrounded by four arcs, which could be presented by

$$\begin{cases} (x-x_{A1})^2 + (y-y_{A1})^2 = {R_s}^2 & x \in (x_c, x_c+L_2) \\ & y \in (y_c-L_1, y_c) \\ (x-x_{A2})^2 + (y-y_{A2})^2 = {R_s}^2 & x \in (x_c, x_c+L_2) \\ & y \in (y_c-L_1, y_c) \\ (x-x_{A3})^2 + (y-y_{A3})^2 = {R_s}^2 & x \in (x_c-L_2, x_c) \\ & y \in (y_c, y_c+L_1) \\ (x-x_{A4})^2 + (y-y_{A4})^2 = {R_s}^2 & x \in (x_c, x_c+L_2) \\ & y \in (y_c, y_c+L_1) \end{cases}$$

$$L_1 = \sqrt{{R_s}^2 - (\frac{1}{2}a)^2} - \frac{1}{2}b, \quad L_2 = \sqrt{{R_s}^2 - (\frac{1}{2}b)^2} - \frac{1}{2}a \tag{22}$$

Associate with the sub-satellite point track (15), the simultaneous equations could present two intersections $Q_1$, $Q_2$ . The fully covered time could be described by

$$T_q(x_s, y_s) = \frac{|Q_1Q_2|}{v_s} \tag{23}$$

$$|Q_1Q_2| = \int_{Q_1Q_2} Sa(x,y)ds \tag{24}$$

The time ratio could be presented as the ratio of arc lengths

$$\frac{T_q}{T_z}(x_s, y_s) = \frac{|Q_1Q_2|}{|Z_1Z_2|} \tag{25}$$

The time ratio of one area could be described by the average

$$\frac{T_q}{T_z} = \frac{1}{2\pi R_s}\int_C \frac{T_q}{T_z}(x_s, y_s)\, dx_s dy_s \tag{26}$$

$$C = (x_s-x_c)^2 + (y_s-y_c)^2 = {R_s}^2 \tag{27}$$

Associate with (18), the expectation of abnormal addressing users could be obtained.

With division factor $n$ increases, the area of one geographical zone decreases, which would make the satellite easier to fully cover the area. Figure 10. illustrates that the full coverage area expands when $n$ increases, while the logical coverage area remains the same. The length of the fully covered curve would increase as well. This might indicate that the full coverage time $T_q$ also increase, leading to the incline of time ratio $T_q/T_z$ and eventually the decline of abnormal addressing users, as well as the decrease of partial routing cost.

## VI. SIMULATION

In the simulation, the IP subnet division model proposed in this paper is applied to an LEO polar orbit satellite network. The communication coverage radius of a satellite is

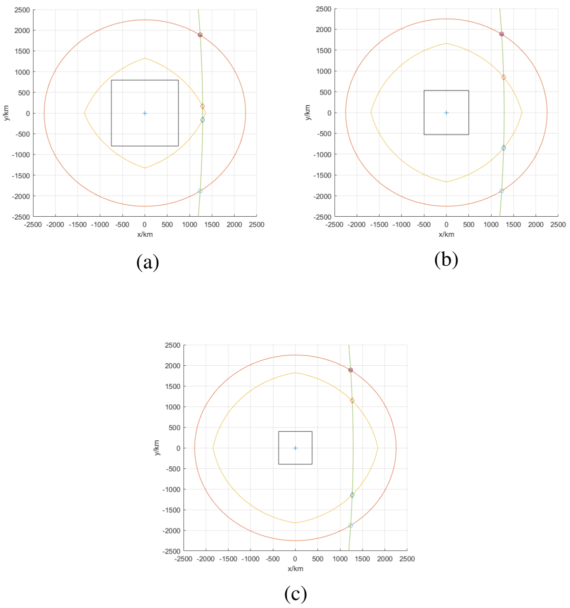


**FIGURE 10.** **Coverage with different division factor. (a) $n = 2$. (b) $n = 3$. (c) $n = 4$.**

set to $2250km$ as an example [16]. Associating with earth radius $R_e = 6400km$, the origin IP addressing geographical zone distribution could be obtained according to (7)-(10). Figure 11 shows the distribution under this certain $R_s$. The low attitude circle has 13 spherical rectangles with centers at the equator. The mid-latitude circle has 13 spherical isosceles trapezoids and the high latitude circle has 10. The upper base of the high latitude circle area reaches the polar circles. The two polar regions are considered as independent round area. In this paper, the polar regions are not discussed or divided into smaller ground cells, since there are few users in them that the impact on partial routing cost could be ignored. The surface could be divided into 5 circles of spherical rectangles

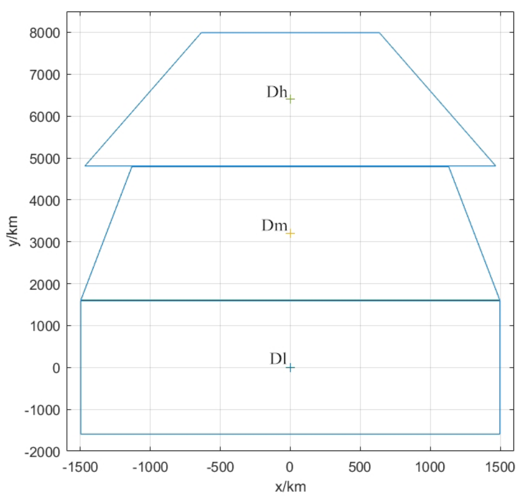


**FIGURE 11.** **The distribution of initial addressing region.**

and trapezoids, and two round polar regions. Except for the polar region, each origin region could be divided into $n^2$ ground cells according to the method discussed in the previous chapter.

For a sphere, the change of $X$ coordinates, i.e., the change of longitude would not affect the area of the ground cell and sub-satellite tracks that intersect the area. That means the time ratio would not change significantly when the subnet cell moves alongside the longitude. Figure 12. confirms the analysis. Therefore, for each latitude circle, the condition of one region could represent the entire circle.

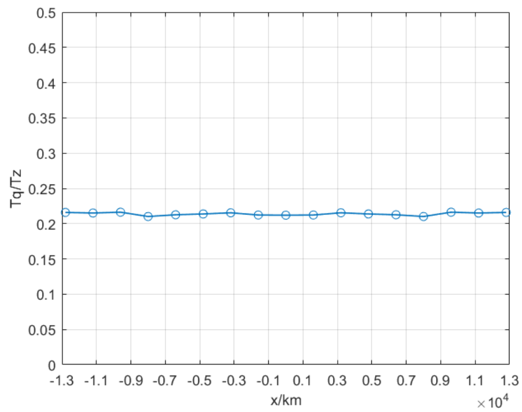


**FIGURE 12.** **Time ratio v x coordinates.**

Dividing the initial region at three latitude circles into small ground cells, the time ratio of cells with different y coordinates are compared. Figure 13. illustrates that inside each area, the difference of time ratio among ground cells is insignificant. The change of y coordinates has little influence on the division of one origin area. Therefore, it could be concluded that the time ratio of ground cells within one origin region is independent with the location, only determined by division factor $n$. Among regions in different latitude circles, noteworthy differences of time ratio appear when the division factor is identical. That is because the shape of regions and the curvature of sub-satellite point tracks are variant at different latitude level. Therefore, the three latitude circles should be analyzed in separation.

For three latitude different circles, the relation between division factor $n$ and the time ratio is presented in Figure 14.

It could be seen that the tendency of time ratio change is similar in three levels of latitude. When $n = 1$, the origin regions directly connect to satellites as addressing subnet units. The time ratio tends to 0 for the satellite could only fully cover the area when the sub-point reaches the region center. When factor $n$ increase, the size of each ground cell declines, which make it easier for the satellite to fully cover the cell. Thus, the time ratio increases. The ratio would reach the limit 1 when $n \to \infty$ and the ground cells turn into independent user nodes.

Associate with (17), setting the number of total users in the origin subnet region $N = 500$, the change of abnormal

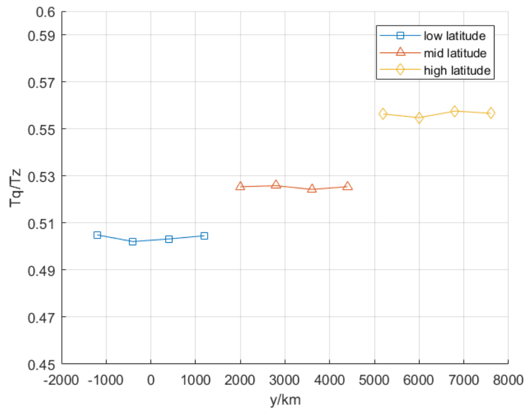


**FIGURE 13.** Time ratio v y coordinates when n=4.

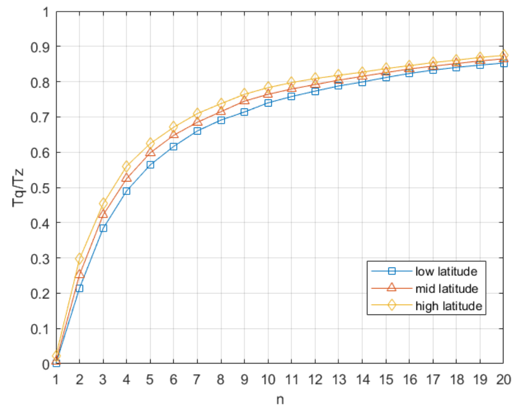


**FIGURE 14.** Time ratio v division factor.

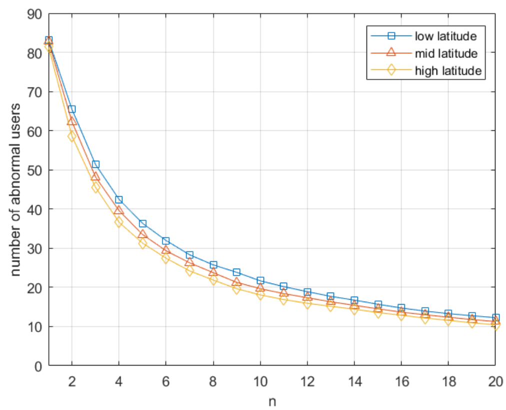


**FIGURE 15.** The change of abnormal addressing users with the increase of *n*.

addressing users with the increase of factor $n$ is illustrated in Figure 15.

It could be seen that when $n$ increase, the area of ground subnet area is divided into smaller cells and the number of abnormal users declines in all three circles, as the theoretical model suggests. When $n \rightarrow \infty$, the ground cells would become dots with zero area and the abnormal addressing number would then reach zero, which is consisted of the mobile IP scenario. Each ground user has its own IP address, and the address changes when the user subjects into motion. Thus, for a region with a given total users number, the required number of abnormal addressing users could be obtained at a certain factor $n$. The partial routing cost could be controlled at a given level since the cost is depended on the number of abnormal users. The initial regions could be divided into smaller ground cells in order to reduce abnormal addressing users, balancing the cost on partial routing mechanism, mobility management, and satellite routing table items.

The result also indicates that the rate of decline of abnormal addressing users tends to dwindle when factor $n$ increases. In this simulation, it could be seen that after $n = 6$, the increase of $n$ would not result in a significant decline of abnormal addressing users. Thus, the partial routing cost would not have remarkable optimization. Compared with the mobility management cost discussion shown in [9], it could be illustrated that when cell length reaches small value, which corresponds to the increase of $n$ in this paper, the mobility management cost would suffer a notable rise. The handover-independent method would lose the advantages in mobile management.

Figure 16. shows the variety of abnormal addressing users number and routing table items for one subnet when $n$ changes. It could be seen that the decline rate of abnormal users reduces, while the routing table items increasing notably which would increase the storage prize on satellite. When factor $n$ increase, the number of subnets would increase, leading to more IP headers in the network. The routing table items on the satellite would increase in order to recognize the user IP. The number of routing table items could be presented by the number of cells $n^2$. Therefore, cells that too small would have negative influences on routing table size that might outrank the advantage in partial routing cost reduction.

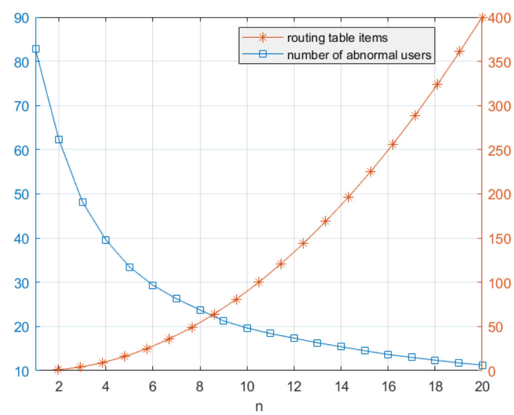


**FIGURE 16.** The variety of abnormal addressing users number and routing table items.

In practical use, the division of geographical IP zones should consider the trade-off among partial routing cost, mobile management cost and routing table size. For the districts that contain a large number of users, the China district for example, the partial routing cost caused by abnormal addressing users could be the dominant portion in the network communication prize. Thus, these districts could have large division factors and more subnets in order to reduce the abnormal addressing users to an acceptable level. For the districts that have relatively fewer users such as in the ocean, smaller factor $n$ could be applied in order to reduce the satellite routing table storage pressure and mobile management cost.

## VII. CONCLUSION AND OUTLOOK

A global geographical IP subnet division model for IP/LEO network addressing scheme is proposed in this paper. A time ratio mathematical model is constructed to measure the abnormal addressing users of geographical subnet regions. The number of abnormal addressing users in each IP subnet cell could be controlled by the division factor according to the mathematical model. Therefore, the partial routing cost could be reduced to a certain level. The simulation results confirm that the ratio of fully cover and logical cover time increases and the abnormal users decrease when the size of ground cells declines.

The work presented a solution and direction of IP addressing scheme and mobility management design for the space-terrestrial hybrid network. However, the detailed relation between partial routing cost and abnormal addressing users requires further discussion. Optimization of partial routing strategy could show the possibility to control routing cost while abnormal addressing users increasing. Thus, the design of geographical zones for IP/LEO network might be able to pay more attention to on-satellite routing table items and mobility management cost reduction. The weight of all three prices should be considered thoroughly in the architecture of the addressing scheme for IP/LEO hybrid network.

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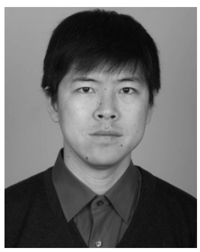
**YUNLU XIAO** was born in 1994. She rececived the B.S. degree in electrical engineering from Beihang University, Beijing, China, in 2017, where she is currently pursuing the master's degree in electronics and information engineering.

Her research interest includes mobile communication and satellite network system.



**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 the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2006.

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

**LIANG LIU** was born in 1986. He received the B.S.E.E. and Ph.D. degrees from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2009 and 2017, respectively.

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