SPOT BEAM JUDGEMENT ALGORITHM IN LEO SATELLITE BASED ON OPNET

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Abstract: Low earth orbit (LEO) satellite constellation networks have a predominance of global coverage with low propagation delays. A new spot beam judgement algorithm is presented in LEO satellite constellation. At first, judgement of central spot beam is considered. Then the judgement of outlying spot beam is achieved by two algorithms. One is 2-D space judgement algorithm and the other is 3-D space judgement algorithm. Based on these algorithms, an Iridium model implemented on OPNET with dynamic topology nodes and network layer protocols is presented and simulation results are obtained. The simulation results show that the satellite serving time has obviously increased through the method of longest visible time criterion and the equal beam width model is validated.

Key words: satellite communication; spot beam; judgement; constellation; longest visible time

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INTRODUCTION

Due to superior performances of low earth orbit (LEO) satellites, such as global coverage, low transmission loss, small end-to-end delay and user mobility, it has become a hot topic in the global personal wireless communication. In the terrestrial wireless communication, it can improve the system capacity by the way of frequency reuse[1], while in the satellite communication, it will implement the frequency reuse by the way of multiple spot beam. The methods of multiple spot beam adopted for frequency reuse has been the concept of satellite cellular coverage. One coverage area of the spot beam is considered as one "cell"[2].

Currently there are two typical spot-beam models with equal beam width and equal spot-area. The antenna angle of equal beam width model (half-power beam width) is equal, while the geocentric angle of equal spot-area model is equal. The antenna structure and parameters of equal beam width model are completely equal, as it is beneficial to the simplification of satellite antenna. The equal spot-area model has two potential values: (1) The antenna angle of the spot beam which takes substellar point as the center is larger than others, in addition, the antenna gain is smaller. However, the antenna angle of view of the spot beams which are far away from the substellar point is smaller and the antenna gain is larger. It compensates the increase in path loss which is caused by larger propagation path in some extent. (2) The equal spot-area model is beneficial to the even coverage of system capacity for terrestrial service area. For the mobile cells which move with the movement of constellation, the equal spot-area model is a better choice[2-5].

1 GEOMETRICAL RELATIONSHIP OF SATELLITE ORBIT

LEO satellite constellation can be classified into two groups based on the shape of orbits: elliptical or circular[6]. When a circular orbit is in use, the earth is located at the orbit center. The inclination angle and the altitude of the satellite from the earth center are constant during the mo-

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tion. The speed of the satellite is fixed during the rotation. Iridium constellation[7] is a classical example of circular orbits. Iridium satellites are distributed among six evenly spaced, near-polar orbits with 86.4° inclination and 780 km above the earth. Sixty-six satellites provide the overlapping global coverage, including polar regions[8-9].

Suppose that satellites are particles and the earth is a perfect ball, the orbits of the LEO satellites are conic (circular or elliptical) sections. Based on Kepler's three laws of planetary motion and the orbital theory, the satellite orbit equations in orbital plane coordinate system can be obtained in Eq. 1. In this paper, we need to know where the satellite is from an observation point on the earth surface, so a transformation from the orbit plane coordinates (x_0, y_0, z_0) to the rectangular coordinates (x_r, y_r, z_r) is given in Eq. (2)

$$\begin{cases} r_0 = a(1-e^2)/(1+e\cos\varphi_0) \\ x_0 = r_0\cos\varphi_0 \\ y_0 = r_0\sin\varphi_0 \end{cases} \tag{1}$$

$$\begin{bmatrix} x_r(t) \\ y_r(t) \\ z_r(t) \end{bmatrix} = \begin{bmatrix} \cos(\Omega_e T_e) & \sin(\Omega_e T) & 0 \\ -\sin(\Omega_e T) & \cos(\Omega_e T_e) & 0 \\ 0 & 0 & 1 \end{bmatrix} \times$$

$$\begin{bmatrix} A & B & \sin\Omega_R \sin i \\ C & D & -\cos\Omega_R \sin i \\ \sin\omega_n \sin i & \sin i\cos\omega_n & \cos i \end{bmatrix} \begin{bmatrix} x_o(t) \\ y_o(t) \\ z_o(t) \end{bmatrix} \tag{2}$$

where

$$A = \cos\Omega_R\cos\omega_n - \sin\Omega_R\sin\omega_n\cos i$$
$$B = -\cos\Omega_R\sin\omega_n - \sin\Omega_R\cos\omega_n\cos i$$
$$C = \sin\Omega_R\cos\omega_n - \cos\Omega_R\sin\omega_n\cos i$$
$$D = -\sin\Omega_R\cos\omega_n - \sin\Omega_R\cos\omega_n\cos i$$

Here are some orbital elements: Inclination i, right ascension of the ascending node Ω_R, eccentricity e, argument of perigee ω_n, $\Omega_e T_e = a_{g0} + 0.250\,684\,47t$ is the universal time (UT), the standard time for most scientific and engineering purposes. r_0 is the radius of the orbit in polar coordinate, Φ_0 is measured from axis x_0 and is called the true anomaly.

2 SPOT BEAM MODELING

2.1 Judgement of central spot beam

It shows the coverage of LEO satellite in Fig. 1, $R_E = 6\,378$ km is the radius of earth, h the height of the satellite, ε the minimal elevation, θ the included angle between the substellar point and edge point of the central spot beam. If it is the equal beam width model, β_2 is one half of β_1, and if it is the equal spot-area model, θ_2 is one half of θ_1.

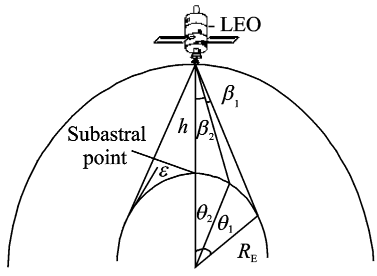

Fig. 1 Substellar point and spot beam

The coordinate of the satellite is (S_x, S_y, S_z), the coordinate of the user is (U_x, U_y, U_z), the satellite, the substellar point, and the center of the earth whose coordinate is (0, 0, 0) are in the same straight. The coordinate of substellar point (S'_x, S'_y, S'_z) is obtained as

$$m = \frac{h}{\sqrt{S_x^2 + S_y^2 + S_z^2}}$$

$$\begin{cases} S'_x = S_x(1-m) \\ S'_y = S_y(1-m) \\ S'_z = S_z(1-m) \end{cases} \tag{3}$$

Then the radius of central spot beam r and the distance between the user and substellar point d can be calculated. According to r and d, the position relation of user and central spot beam is determinate. The algorithm is as follows:

(1) Calculate the coordinates of the user and satellite.

(2) Calculate the coordinate of the substellar point.

If $d > r$, the user is not in the central spot beam, else the user is in the central spot beam.

The distance between the user and substellar point is $d = \sqrt{(U_x - S'_x)^2 + (U_y - S'_y)^2 + (U_z - S'_z)^2}$.

If it is the equal beam width model, the radius of central spot beam r can be obtained as

$$s = \frac{\sqrt{(2R\sin\varepsilon)^2 + 4(h^2 + 2hR_E)} - 2R_E\sin\varepsilon}{2} \tag{4}$$

where s is the maximum distance between the satellite and the user.

If the spot beam has two layers, according to the sine theorem, it can be obtained as

$$\frac{\sin(\theta_1+\theta_2)}{s}=\frac{\sin(90^\circ+\varepsilon)}{R_E+h}$$

$$r=\frac{1}{3}R_E(\theta_1+\theta_2) \tag{5}$$

If the spot beam has three layers

$$r=\frac{1}{5}R_E\cdot(\theta_1+\theta_2)$$

If the spot beam has n layers

$$r=\frac{1}{2n-1}R_E\cdot(\theta_1+\theta_2+\cdots+\theta_n)$$

If it is equal spot-area model, β_2 is one half of β_1, the relationship among r, ε, β_2 and β_1 is given by (supposed the spot beam has two layers)

$$\begin{cases}\dfrac{\sin(\beta_1+\beta_2)}{R_E}=\dfrac{\sin(90^\circ+\varepsilon)}{R_E+h}\\ \beta_2=\dfrac{1}{2}\beta_1\\ \dfrac{\sin\beta_1}{R_E}=\dfrac{\sin\rho}{R+h}\\ \theta_2=\pi-\rho-\beta_2\\ r=R_E\theta_2\end{cases} \tag{6}$$

2.2 Judgement of outlying spot beam

The number of spot beams usually is one in the first layer (central spot beam), six in the second layer, twelve in the third layer, eighteen in the forth layer…and $6(n-1)-6$ in the nth layer.

(1) Geometrical judgement of 2-D space

The sketch map of satellite coverage is shown in Fig. 2. Supposing that O is substellar point, $\boldsymbol{V}_1$ is the vector of the satellite's motion direction, and $\boldsymbol{V}_2$ is the vector which points from the substellar point to the user.

$$\boldsymbol{V}_2=\{(U_x-S'_x),(U_y-S'_y),(U_z-S'_z)\} \tag{7}$$

The included angle between vector $\boldsymbol{V}_1$ and vector $\boldsymbol{V}_2$ is given by

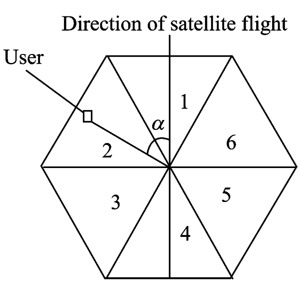

Fig. 2 Subastral beam coverage

$$\cos\alpha=\frac{\boldsymbol{V}_1\times\boldsymbol{V}_2}{\|\boldsymbol{V}_1\|\times\|\boldsymbol{V}_2\|} \tag{8}$$

The angle range of α is $(0^\circ, 180^\circ)$. If the beam has two layers, according to Fig. 2, it only can judge the user in spot beam 1 or spot beam 4, in spot beam 2 or 6, and in spot beam 3 or 5. The algorithm is given as

$$\begin{cases}\text{If } 0^\circ\leqslant\alpha\leqslant30^\circ \text{ users are in beam 1}\\ \text{Else if } 30^\circ\leqslant\alpha\leqslant90^\circ \text{ users are in beam 2 or 6}\\ \text{Else if } 90^\circ\leqslant\alpha\leqslant150^\circ \text{ users are in beam 3 or 5}\\ \text{Else if } 150^\circ\leqslant\alpha\leqslant180^\circ \text{ users are in beam 4}\end{cases}$$

If the spot beam has three layers, as shown in Fig. 3, the character c represents the third layer, the character a in the center represents the central spot beam, and the character d the forth layer.

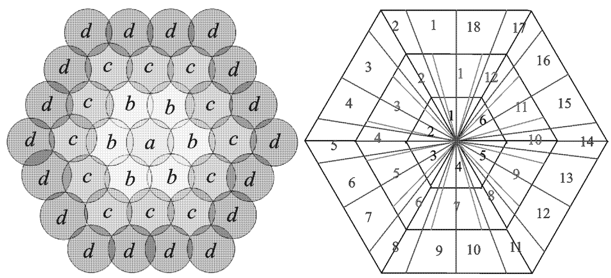

Fig. 3 Four-layer beam

In Fig. 4 it is obvious that $A_1B_1=B_1C_1=C_1A_1$, $B_1E_1=E_1D_1=E_1D_1=F_1C_1$, so it deduces that $\angle E_1A_1D_1=\angle F_1A_1D_1=14.037\,5^\circ$ and $\angle B_1A_1E_1=\angle C_1A_1F_1=15.962\,5^\circ$. The judgement algorithm of range of beam spot is presented as

$$\begin{cases}\text{If } 0^\circ\leqslant\alpha\leqslant14.037\,5^\circ \text{ users are in beam 1}\\ \text{Else if } 14.037\,5^\circ\leqslant\alpha\leqslant45.962\,5^\circ \text{ users are in beam 2 or 12}\\ \text{Else if } 45.962\,5^\circ\leqslant\alpha\leqslant74.037\,5^\circ \text{ users are in beam 3 or 11}\\ \text{Else if } 74.037\,5^\circ\leqslant\alpha\leqslant105.962\,5^\circ \text{ users are in beam 4 or 10}\\ \text{Else if } 105.962\,5^\circ\leqslant\alpha\leqslant134.037\,5^\circ \text{ users are in beam 5 or 9}\\ \text{Else if } 134.037\,5^\circ\leqslant\alpha\leqslant165.962\,5^\circ \text{ users are in beam 6 or 8}\\ \text{Else if } 165.962\,5^\circ\leqslant\alpha\leqslant180^\circ \text{ users are in beam 7}\end{cases}$$

If the spot beam has four layers, the character d represents the forth layer. In Fig. 4 it is obvious that $A_2B_2=B_2C_2=C_2A_2$ and $E_2D_2=D_2F_2=2B_2E_2=2F_2C_2$, so it deduces that $\angle E_2A_2D_2=$

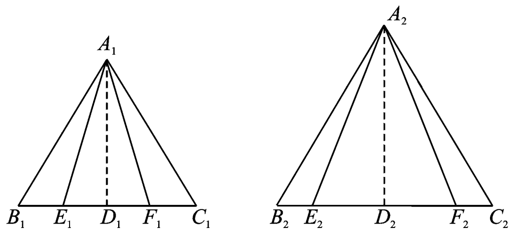

Fig. 4 Relation graph of spot beam judgement

$\angle F_2A_2D_2 = 18.437\ 8°$and $\angle B_2A_2E_2 = \angle C_2A_2F_2 = 11.562\ 2°$, the judgement algorithm of range of beam spot is given as

If $0° \leqslant \alpha \leqslant 18.437\ 8°$ users are in beam 1 or 18
Else if $18.4378° \leqslant \alpha \leqslant 41.562\ 2°$ users are in beam 2 or 17
Else if $41.562\ 2° \leqslant \alpha \leqslant 60°$ users are in beam 3 or 16
Else if $60° \leqslant \alpha \leqslant 78.437\ 8°$ users are in beam 4 or 15
Else if $78.437\ 8° \leqslant \alpha \leqslant 101.562\ 2°$ users are in beam 5 or 14
Else if $101.562\ 2° \leqslant \alpha \leqslant 120°$ users are in beam 6 or 13
Else if $120° \leqslant \alpha \leqslant 138.437\ 8°$ users are in beam 7 or 12
Else if $138.437\ 8° \leqslant \alpha \leqslant 161.562\ 2°$ users are in beam 8 or 11
Else if $161.562\ 2° \leqslant \alpha \leqslant 180°$ users are in beam 9 or 10

(2) Geometrical judgement of 3-D space

It cannot judge whether the user in the beam 2 or 6 in the 2-D space. In the 2-D space, the beam 2 or 6 represents that the user in the left or right of the satellite's motion vector. In the 3-D space, the beam 2 or 6 represents that the user is above or below the orbital plane of satellite.

Supposing that the celestial sphere is divided into two parts by orbital plane of the satellite, it can determine whether the user is above or below the orbital plane with the method of left-hand rule. Flung up the left hand and crook the fingers, the direction of the thumb pointed represents that the user is above the orbital plane, while the opposite direction is below the orbital plane.

In Fig. 5, B and A represent that the user is above or below the orbital plane respectively. Supposing that C is the reference point, O is the geo-centre. It is obvious that the angle of BOC is obtuse while the angle of AOC is acute. According to the angle it can deduce the position of user in space. Supposing that the longitude and latitude of user is (λ_u, φ_u), the longitude and latitude of reference point is $(\lambda_u = \Omega_i + 90°, \varepsilon - 90°)$, therefore the included angle between the user and reference point is given as

$$\delta = \arccos(\sin\phi_i \sin\phi_u + \cos\phi_u \cos(\lambda_i - \lambda_u)) \quad (9)$$

The algorithm is given as

If $0° \leqslant \delta \leqslant 90\ °$ users are below the orbital plane (beam 2 or beam 3)
Else if $90° \leqslant \alpha \leqslant 180\ °$ users are above the orbital plane (beam 6 or beam 5)

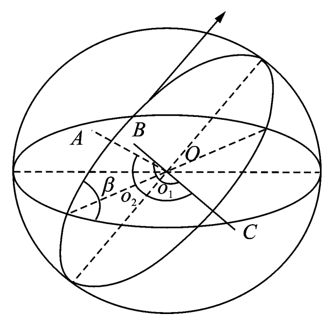

Fig. 5 Spatial geometrical relationship between location of user, reference point and geo-centre

3 SIMULATION RESULT ANALYSIS

In this paper, an Iridium constellation system model is built based on OPNET platform combining with MATLAB which is good at matrix operation. The world map is placed as the simulation background. Iridium orbital files are imported into OPNET model generated by STK software with orbital parameters. The nodes in the system are user terminals, Iridium satellite constellation and the earth stations. In the OPNET simulation, it should judge which spot beam the user is in and whether the user is above or below the orbital plane. The flow chart is shown in Figs. 6,7.

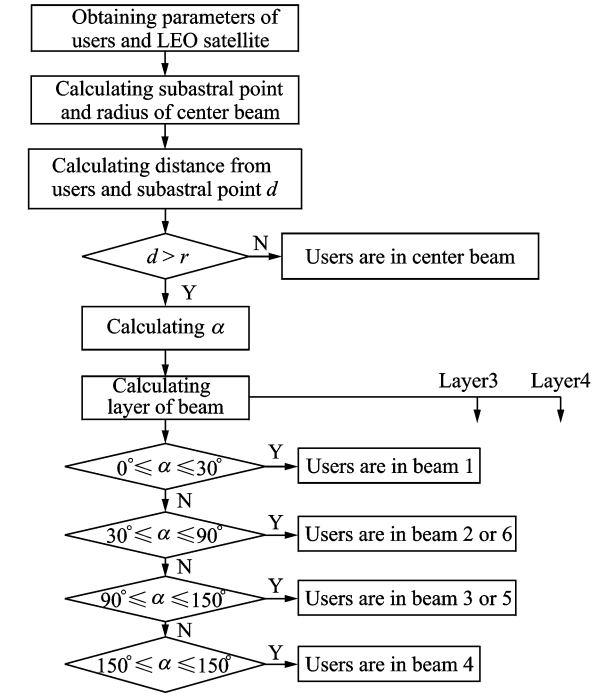

Fig. 6 Spot beam judgement of 2-D space process in system

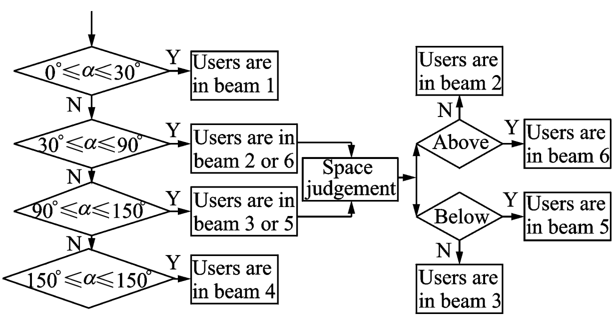

Fig. 7 Spot beam judgement of 3-D space process in system

The simulation time is set as 48 h, and the users are located in the southeast whose latitude and longitude are about 31°N, 121°E. The orbital parameters of Iridium 8 are shown in Table1.

Table 1 Parameters of Iridium 8

Satellite		Iridium 8	
Catalog number	24 792	Orbital period/min	100.4
Epoch time	7 077.527 687 54	Semimajor axis a/km	7 156
Inclination i/(°)	82.297 0	Apogee altitude/km	793
RA of Node Ω_e/(°)	53.406 8	Perigee altitude/km	776
Eccentricity e	0.001 176 6	Apogee latitude/(°(+N/−S))	−29.1
Arg of Perigee ω/(°)	150.590 0	Perigee latitude/(°(+N/−S))	29.1
Mean anomaly M/(°)	0	Mean motion n/(rev · day^{-1})	14.342 172

The selection of the next servicing satellite is based on some rules. In the paper, the minimum distance (MD) selection and the longest visible time selection are used. According to this criterion, the user will be served by the closest satellite or the longest serving satellite. For the user, no matter which satellite comes to access, the access criterions are the same. In the paper, the layers of beams are set as 2, 3, 4 and the beam shape is shown in Fig. 3.

The cumulative distribution of the satellite serving time is illustrated in Fig. 8. We observe that 50% of the satellite serving time of the longest visible time selection is more than 350 s, while 50% of the satellite serving time of MD is only more than 200 s. The average satellite serving time of the longest visible time selection is about 410 s, while the latter is 250 s. Therefore, there is a good agreement with the characteristics of Iridium constellation, and the hypothesis is accepted. The satellite serving time has obviously increased through the method of the longest visible time criterion.

Fig. 8 Cumulative distribution of satellite serving time

In the following, the equal beam width model of 2, 3 and 4 layers is adopted, respectively. In the same simulation condition, the average cell serving time curves of 2, 3 and 4 layers are shown in Figs. 9,10,11, respectively. While the instantaneous cell serving time curves are shown in Figs. 12,13 and 14. From Figs. 9,10,11, it can be seen that the average cell serving time of 2, 3 and 4 layer models is about 55, 75 and 120 s. The instantaneous cell serving time vary from 0 s up to 600 s.

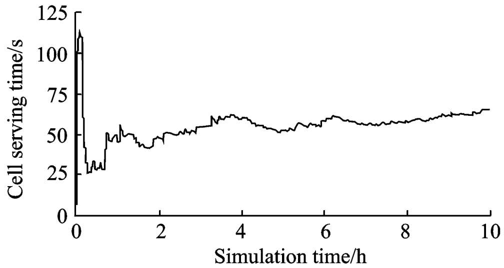

Fig. 9 Average cell serving time curves of 2-layer beam

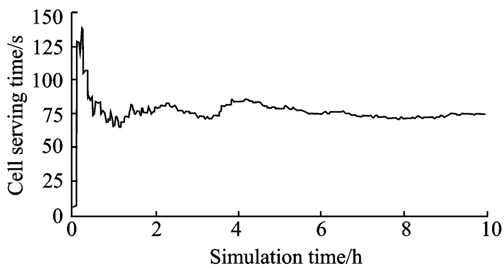

Fig. 10 Average cell serving time curves of 3-layer beam

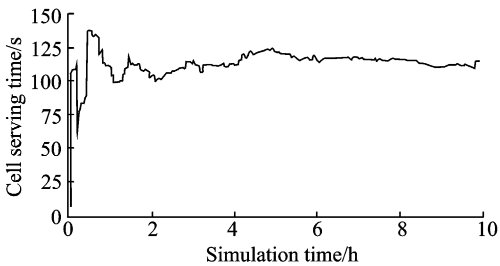

Fig. 11 Average cell serving time curves of 4-layer beam

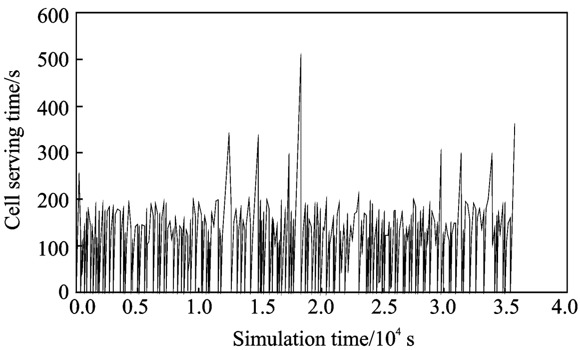

Fig. 12 Instantaneous cell serving time of 2-layer beam

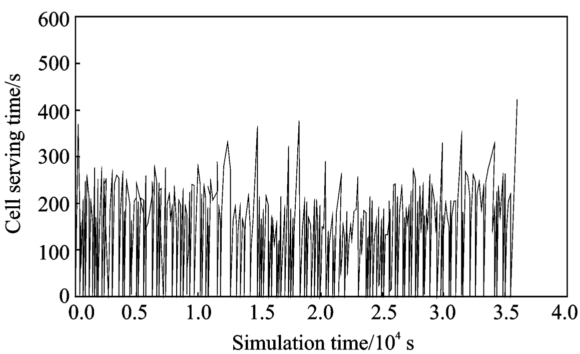

Fig. 13 Instantaneous cell serving time of 3-layer beam

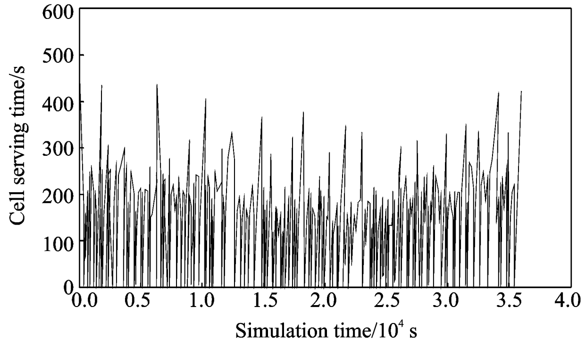

Fig. 14 Instantaneous cell serving time of 4-layer beam

4 CONCLUSION

In actual system, the handovers between different satellites or different beams vary with the pilot signal intensity. However, in the system simulation, it is impossible to determine the spot beam which the user is in through the method of pilot signal. Usually it will determine the spot beam which the user is in through the method of coverage in the simulation. In the paper, it presents a new spot beam judgement algorithm in LEO satellite constellation, and an Iridium model implemented on OPNET with dynamic topology nodes and network layer protocols is presented and simulation results are obtained.

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基于OPNET的低轨卫星的点波束确定算法

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摘要：低轨道卫星通信网络具有低时延的全球覆盖优势。文中提出了一种新的低轨卫星的波束判断方法。该方法首先需要确定用户是否在中心波束，如果不在中心波束，通过两个步骤确定用户所在的边缘波束：第一步采用二维波束算法；第二步采用三维波束算法。基于这些算法，在OPNET平台上实现了具有动态节点和网络协议的铱星通信仿真系统，并获得仿真结果。结果显示，最长可视时间准则明显增加了卫星服务的时间，并且验证了波束宽度模型的应用。

关键词：卫星通信；波束；判断法则；星座；最长可视时间

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