Research on the Model of Formulating SOTM Satellite-switching Strategy Based on Probabilistic Visibility and Breadth-first Search

Yiyi Li*, Weimin Jia¹, Wei Jin¹ and Fenggan Zhang²
¹Nuclear Engineering College, Rocket Force University of Engineering, Xi’an, Shanxi, 710025, China
²Combat Support College, Rocket Force University of Engineering, Xi’an, Shanxi, 710025, China
*Corresponding author’s e-mail: 907554635@qq.com

Abstract. In order to let the Satcom-on-the-move (SOTM) users know the communication status of the current driving road in advance and avoid the blindness of the information transmission, a model of formulating SOTM satellite-switching strategy based on probabilistic visibility and breadth-first search is established. Firstly, through adapting JANUS visibility algorithm, a probabilistic visibility model based on terrain description error and interpolation algorithm is proposed to quantitatively represent the communication status of each road point on the whole road. Then, the breadth-first search algorithm is used to obtain the satellite-switching strategy on the condition of different satellite-switching time, and the appropriate satellite-switching strategy is selected for the user according to their requirements. Finally, the validity and practicability of the model are verified by an example.

1. Introduction
SOTM refers to the satellite communication system in motion. The satellite communication ground station is installed on mobile carriers such as vehicles, ships, airplanes, etc., and the antenna beam is directed to the target satellite during the movement of the carrier, continuously transmitting multimedia information such as voice, images and data. It has the characteristics of wide coverage area, long communication distance, large channel capacity, fast network deployment, high maneuverability and flexibility. Thus, it has become a hotspot in the research and application of satellite mobile communication[1][2]. The working frequency band of SOTM is Ku or above Ku, which belongs to the line of sight propagation. Therefore, SOTM is often blocked by bridges, mountains, tall buildings, etc. during the movement, causing communication interruption[3]. However, if the user does not know that the current communication has been interrupted and continues to transmit information, it will cause information loss or network communication congestion. Therefore, the shadow problem of the satellite communication link is a crucial issue[4]. For the SOTM users, it is urgent to know the communication status of the current driving road in advance to ensure reliable transmission of information[5].

At present, the focus of research on the shadow problem of the satellite communication link at home and abroad is how to detect the shadow in real time and reliably, and the rapid recapture problem after the shadow is removed. For example, the link budget method is used in the [4], which applies satellite beacon signals as criteria for judging shadows. However, this method cannot predict
the communication status of the current driving section. Thus for the SOTM users, there is a big blindness in transmitting information. In addition, the communication state may be different when SOTM is aimed at different communication satellites at different orbital positions. Therefore, if there is only one road between the departure point and the destination, user can formulate a satellite-switching strategy in advance according to the communication status of all road points when aimed at different satellites, that is, which satellite is to be targeted on which section, and at which point it is necessary to switch satellites. As a result, the communication status of the entire road is optimal.

Therefore, this paper establishes a model of formulating SOTM satellite-switching strategy based on probabilistic visibility and breadth-first search. Firstly, this paper establishes a probabilistic visibility model based on terrain description error and interpolation algorithm to calculate the probability of terrain occlusion between SOTM and satellites. Then an index system is established, and the breadth-first search algorithm is used to obtain the satellite-switching strategy on conditions of different satellite-switching time, and the appropriate satellite-switching strategy is selected for the user according to their requirements. Finally, the model is applied to an instance.

2. The probabilistic visibility model based on terrain description error and interpolation algorithm

In traditional visibility algorithms, the visibility result between SOTM and satellites is described as a "0 or 1" model. This "0 or 1" model will greatly influence the judgment of SOTM users if its result is incorrect. In order to solve this problem, a probabilistic visibility model based on terrain description error and interpolation algorithm is established. The visibility result is represented by a probability range from 0 to 1, and the communication quality is measured by the magnitude of the visibility probability. In this model, the JANUS visibility algorithm is used, and the uncertainty of the elevation data and the uncertainty caused by the interpolation algorithm are considered comprehensively. The uncertainty of the elevation data is indicated mainly through the DEM terrain description error, and the interpolation algorithm studied in this model is the bilinear interpolation algorithm.

2.1. Visibility algorithm

The visibility between SOTM and satellites studied in this paper is a point-to-point visibility problem. To judge the point-to-point visibility is to judge whether you can see another point from one point. Taking the vehicle-mounted SOTM as an example, assuming that SOTM is the viewpoint V, the satellite is the target point T, and the connecting line of the viewpoint V and the target point T is called the line of sight (LOS). When any point on the LOS is above the terrain, V and T can be seen through. Otherwise, it is not visible. The visibility model between SOTM and satellite is shown in Figure 1, where part (a) shows SOTM without terrain shadow and part (b) shows SOTM with terrain shadow. In JANUS visibility algorithm, the checkpoint is calculated by the equal step size on the projected line of the LOS on the xoy plane[6].

![Figure 1. Visibility model between SOTM and satellite](image)

2.2. DEM terrain description error

Under the assumption that the sampling error of the DEM elevation is zero, Tang Guoan defines the difference between the simulation ground and the actual ground as the DEM terrain description error (Et)[7]. As shown in the figure 2, point A and point B are the DEM ground elevation sampling points,
and the connection between $A$ and $B$ is the DEM simulation ground. Assuming that the elevation sampling error of $A$ and $B$ is zero, the terrain description errors of three points $C$, $D$, and $E$ are respectively $E_{tC}$, $E_{tD}$ and $E_{tE}$.

![Figure 2. Schematic diagram of terrain description error](image)

In order to calculate $E_t$, the difference between the elevation of the midpoint of the grid and the average elevation of the four corners of the grid is defined as the terrain description error of the grid. As shown in the figure 3, in the DEM cell grid $abcd$, point $O''$ is the grid center point, and points $A$, $B$, $C$, $D$, and $O$ are ground points, whose elevation sampling errors are zero. $H_A$, $H_B$, $H_C$, $H_D$ and $H_O$ are the elevations at points $A$, $B$, $C$, $D$ and $O$, respectively, and point $O'$ is the average point of points $A$, $B$, $C$ and $D$. Thus, the terrain description error $E_t$ of the grid is equal to the elevation difference between the point $O$ and the point $O'$. The calculation formula is as follows:

$$E_t = H_O - H_{O'} = H_O - \left( \frac{H_A + H_B + H_C + H_D}{4} \right)$$

(1)

![Figure 3. DEM elevation sampling grid element](image)

2.3. Bilinear interpolation method

The mathematical model of bilinear interpolation is as follows[8]:

$$H = a_0 + a_1x + a_2y + a_3xy$$

(2)

Where $x, y$ is the value in the plane coordinate system, $H$ is the elevation, and $a_0, a_1, a_2, a_3$ are undetermined coefficients. As shown in the figure 4(a), the point $P$ is a point in the grid $ABCD$ randomly, and its elevation is $H_P$. Then $H_P$ can be calculated as follows:

$$H_P = \frac{d_3 - d_4}{d_3} \left( \frac{d_2}{d_1} H_A + \frac{d_1 - d_2}{d_1} H_B \right) + \frac{d_4}{d_3} \left( \frac{d_1 - d_2}{d_1} H_C + \frac{d_1}{d_1} H_D \right)$$

(3)
2.4. Model establishment

The point $P$ is a certain checkpoint. Its elevations on the terrain and on the LOS are $H_P$ and $H_{PLOS}$, respectively. The position of the point $P$ in the grid is shown in the figure 4(b). The model establishment mainly concludes the following steps.

Step one: Calculate the elevation $H_P$ of the checkpoint $P$ through formula (3).

Step two: Calculate the terrain description error $E_t P$ of the checkpoint $P$. Firstly, $E_t A$, $E_t B$, $E_t C$, and $E_t D$, the terrain description errors of the four grid sampling points $A$, $B$, $C$, and $D$, are calculated. The calculation formula is as follows:

$$
\begin{align*}
E_t A &= H_A - \left( H_{A_i} + H_{A_j} + H_B + H_C \right) / 4 \\
E_t B &= H_B - \left( H_A + H_{A_i} + H_{B_i} + H_D \right) / 4 \\
E_t C &= H_C - \left( H_{C_i} + H_{A_i} + H_B + H_{D_i} \right) / 4 \\
E_t D &= H_D - \left( H_{C_i} + H_B + H_{C_j} + H_{D_j} \right) / 4
\end{align*}
$$

Then the idea of bilinear interpolation method is applied to calculate the terrain description error $E_t P$ of checkpoint $P$, and the calculation formula is as follows:

$$
E_t P = \frac{d_3 - d_2}{d_3} \left( \frac{d_2}{d_1} E_t A_1 + \frac{d_1 - d_2}{d_1} E_t A_2 \right) + \frac{d_1}{d_3} \left( \frac{d_2}{d_1} E_t C_1 + \frac{d_1 - d_2}{d_1} E_t C_2 \right)
$$

Step three: Calculate the elevation range of the checkpoint $P \left[ H_{PMIN}, H_{PMAX} \right]$, and the calculation formula is as follows:

$$
\begin{align*}
H_{PMIN} &= H_p \cdot E_t P \\
H_{PMAX} &= H_p + E_t P
\end{align*}
$$

Step four: Calculate the visibility probability $Percent_P$ of the checkpoint $P$. The cross-sectional view is as shown in the figure 5.
3. The model of formulating SOTM satellite-switching strategy

The SOTM satellite-switching strategy uses the breadth-first search algorithm to obtain the satellite-switching strategy with different satellite-switching time. Breadth-first search algorithm is a commonly used graph search algorithm, which is a searching process in a hierarchical progressive search mode [9] [10]. Firstly, the index system of the model is constructed. Then the model hypothesis of the model is given. Finally, the detailed steps of the solution are given.

3.1. Construction of index system

The indexes related to the model of formulating SOTM satellite-switching strategy include communication status, satellite-switching time, and cost of switching satellite. This section mainly analyzes these three indexes, communication status, satellite-switching time, and the cost of switching satellite.

3.1.1. Communication status. The communication status is an important indicator reflecting the quality of satellite communication, and it also decides whether SOTM users can transmit information effectively and reliably. We use the probabilistic visibility model proposed in section 2 to calculate the visibility probability of all points on the driving road. And the communication status can be directly reflected by the visibility probability.

3.1.2. Satellite-switching time. The communication satellites used by SOTM are all geosynchronous orbit satellites. The terrain covered by the LOS between SOTM and satellites will change with the change of the satellite orbital positions. Therefore, SOTM in the same position may have different communication status when aiming at different satellites. Due to the cumbersome operation of switching satellites during the actual use of SOTM, this process takes a lot of time. Therefore, switching satellites too frequently does not conform to the actual project, and it is necessary to limit satellite-switching time.

3.1.3. The cost of switching satellite. Satellites have different azimuths and elevations when aiming at different satellites. The antenna servos of the satellites function to adjust the azimuth and elevation of the antennas when switching satellites. Thus, the cost of switching satellite is defined as the antenna
change value of the azimuth and elevation angle. Besides, when SOTM locates at a satellite-switching position, the cost of switching satellite depends on the longitude difference between the two satellites before and after the switch. Therefore, the cost of switching satellite can be presented by the absolute value of the longitude difference between the two satellites before and after the switch.

3.2. Model hypothesis
We make the following assumptions:
(a) Assume that the analysis object in the model is the vehicle-mounted SOTM.
(b) The driving road is fixed and there is only one, and the communication state is analyzed every 90m along the longitude or latitude direction on the road.
(c) Assume that the vehicle-mounted SOTM moves at a constant speed of 60km/h. Besides, if the vehicle-mounted SOTM does not get connection with a satellite for more than 5 or 6 seconds, we regard the situation as losing satellite, and the communication is interrupted.

3.3. Model establishment and solution
Detailed steps are as follows:

3.3.1. Determine the optimization objective and influencing factors. The goal of the model is to optimize the communication status of the entire road, which can be represented by the average value of the visibility probability of all road sampling points. Since the model is based on the premise that there is only one driving road, the influencing factors are satellite-switching time and the cost of switching satellite.

3.3.2. Calculate the visibility probability of all road sampling points. Firstly, the driving road is uniformly sampled to obtain the latitude and longitude of each road point. Next, the parameters of common communication satellite over China are obtained. Finally, the JANUS visibility algorithm and the probabilistic visibility model proposed in section 2 are comprehensively utilized to calculate the visibility probability of all road points, when aiming at 22 common communication satellites over China, and the visibility probability data is saved as a file.

3.3.3. Pre-processing of visibility probability data. In the model hypothesis, the speed of the vehicle-mounted SOTM is 60km/h, and if the vehicle-mounted SOTM does not get connection with a satellite for more than 5 or 6 seconds, it is regarded as communication interruption. This means that if the vehicle moves within the shadow area for more than 100m on the road, it is regarded as communication interruption. Besides, because we take a point every 90m along the longitude or latitude direction on the road, the following pre-processing can be performed on the visibility probability data:

Assume that A, B, and C are three consecutive points on the road. The visibility of the three road points are $P_A$, $P_B$, and $P_C$, respectively. If $P_A < 0.8$, $P_C < 0.8$, $P_B > 0.9$, then $P_b = (P_A + P_C) / 2$; if $P_A > 0.9$, $P_B < 0.9$, then $P_b = (P_A + P_C) / 2$. In the section where the tunnel appears, the visibility probability is set to zero.

3.3.4. Formulate the satellite-switching strategy. In the actual use of SOTM, the operation of switching satellites is cumbersome. Switching satellites too frequently does not conform to the actual project. Therefore, satellite-switching time is limited to 4 times (including 4 times). Next, the breadth-first search algorithm is utilized to search for the best satellite-switching strategy when satellite-switching time is 0, 1, 2, 3, and 4 respectively, so that the communication status of the whole road is optimal. The detailed steps are described as follows.

Step one: Create a container that stores all satellite information, and associate the satellite name, longitude and number, which is called a satellite container. Then, create a container that stores all the sampling road point sequences and their visibility probability to each satellite, which is called the
attribute container. Next, create a container of the current satellite sequence of all road points, which is called the satellite sequence container.

Step two: Set the satellite-switching time as $m$, and create a container to store the positions of the satellite-switching road points, which is called the satellite-switching point container. Then, select $m$ satellite-switching points randomly, requiring that the distance between two satellite-switching points should be greater than 1 km, so that the whole road is divided into $m+1$ segments.

Step three: Read the attribute container, firstly traverse the visibility probability of the first segment and find the maximum average value $\bar{P}_{\text{max},1}$. Then use the breadth-first search method to push forward, and the maximum average values of the remaining segments $\bar{P}_{\text{max},2}, \ldots, \bar{P}_{\text{max},m+1}$ can be obtained similarly. Besides, the adjacent two segments cannot be aligned with the same satellite. If one segment has the same maximum average visibility probability value when aligned with different satellites, we should calculate and compare their cost of switching satellite and take the less one. We use $\bar{P}_{\text{max}}$ to present the maximum average visibility probability of the entire road, which can be calculated as follows:

$$\bar{P}_{\text{max}} = \left( \frac{\bar{P}_{\text{max},1} + \bar{P}_{\text{max},2} + \cdots + \bar{P}_{\text{max},m+1}}{m+1} \right)$$

Then we store the satellite numbers corresponding to all road sampling points in the satellite sequence container, and store the positions of all satellite-switching points in the satellite-switching point container.

Step four: Cycle through step four to step five to continually update $\bar{P}_{\text{max}}$ and the value in the satellite sequence container and the satellite-switching point container until the positions of all satellite-switching are traversed.

Step five: Find the satellite name in the satellite container corresponding to the satellite number that is stored in the satellite sequence container, and finally output $\bar{P}_{\text{max}}$, the position of the satellite-switching point and the aligned satellite name of all segments.

3.3.5. Users choose the satellite-switching strategy according to their needs. In the satellite-switching strategy with different satellite-switching time, the highest visibility probability will increase with the number of satellite-switching time. However, the greater the number of satellite-switching time is, the more time it takes to switch satellite. So the users can choose the satellite-switching strategy according to their needs. For users who have higher requirements for communication status and are proficient in satellite-switching operations, it is recommended to choose the satellite-switching strategy with high satellite-switching time and high visibility probability. For users who are unskilled in satellite-switching operations, it is recommended to choose the satellite-switching strategy with less satellite-switching time. For users who want to take into account both operating time and communication status, it is recommended to choose the satellite-switching strategy in which satellite-switching time and communication status are both centered.

4. APPLICATION

We select a road in Lantian County, Xi'an City, Shaanxi Province, and set the starting point and the ending point as is shown in the figure 6. And there are 642 sampling points on the road.
Figure 6. The instance diagram of the model of formulating SOTM satellite-switching strategy
calculate the visibility probability of all sampling points when aimed at different satellites. The
used elevation data is DEM data with 30m precision. The calculation results are shown in the table 1.

Table 1. Visibility probability results of some road sampling points

| Satellite name | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | ... | Point 641 | Point 642 |
|----------------|--------|--------|--------|--------|--------|-----|----------|----------|
| International-704 | 98.88% | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| PA-10 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| APshtar-2R | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Asia-2 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Zhongxing-20 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Telcom-1 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| SINOSAT-1 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Zhongxing-6B | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Thaicom-1A | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Asia-4 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| Zhongxing-6A | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| APshtar-5 | 1    | 1    | 1    | 1    | 1   | ... | 1    | 1   |
| PA-8 | 59.91% | 78.14% | 1    | 1    | 1   | ... | 91.90% | 84.92% |
| PA-2 | 57.43% | 73.57% | 1    | 1    | 1   | ... | 85.38% | 78.79% |

Based on the visibility probability results in table 1, satellite-switching strategies with different
satellite-switching time are shown in the table 2. The number on the arrow presents the number of the
satellite-switching point.

Table 2. Satellite-switching strategies with different satellite-switching time

| Strategy number | Satellite-switching time | Average visibility probability | Satellite-switching strategy |
|-----------------|--------------------------|--------------------------------|------------------------------|
| ONE             | 0                        | 98.13%                         | SINOSAT-1                    |
| TWO             | 1                        | 98.36%                         | SINOSAT-1 → APshtar-5        |
| THREE           | 2                        | 98.38%                         | SINOSAT-1 → Zhongxing-6B → APshtar-5 |
| FOUR            | 3                        | 98.45%                         | SINOSAT-1 → APshtar-5 → SINOSAT-1 → APshtar-5 |
| FIVE            | 4                        | 98.48%                         | SINOSAT-1 → APshtar-5 → SINOSAT-1 → APshtar-5 |

Finally, the SOTM users choose the satellite-switching strategy according to their needs. For users
who are willing to spend more time to get better communication status, it is recommended to choose
the strategy FOUR or FIVE. For users who are unskilled in satellite-switching operation, it is
recommended to choose strategy ONE. For users who want to take into account both operating time and communication status, it is recommended to choose strategy TWO or THREE.

5. CONCLUSION
This paper proposes a model of formulating SOTM satellite-switching strategy based on probabilistic visibility and breadth-first search. Firstly, through the JANUS visibility algorithm, a probabilistic visibility model based on terrain description error and interpolation algorithm is proposed to calculate the communication probability value of each segment on the communication road. Then the breadth-first search algorithm is used to get the satellite-switching strategy with different satellite-switching time, and the appropriate star-changing strategy is selected for the SOTM users according to their needs. Finally, the model is applied to an instance, which shows that the model can make the SOTM users avoid the blindness of transmitting information, and has good practicability and effectiveness.

References
[1] Louis J Ippolito Jr. 2012 Satellite Communication Systems Engineering. Beijing: National Defence Industry Press, Beijing.
[2] Yang Xinhua, Liu Yang, Lei Diwei. 2018 Link Budget and Case Study of On-the-Move Satellite Communications System. Communication Technology, 51(01): 24-9.
[3] Ding Ling. 2016 Research on the Line Guarantee Method of the Satellite Relay System on Motion https://www.ixueshu.com/document/3ef9bc45e21db2f7ec8b4f308072b7f5.html.
[4] Wang Dong. 2017 Research on Satellite Link Budget Issues. http://xueshu.baidu.com/usercenter/paper/show.
[5] Liu Shan, Jia Weimin, Wu Shiqi, et al. 2016 Analysis of the SOTM Shadow Based on Geographic Location Information. In: National Safety Geophysics Series. Anshan. pp. 252-6.
[6] Zhang Feilian. 2015 Research on Quantitative Calculation Method of Landscape Visibility. http://cdmd.cnki.com.cn/Article/CDMD-10590-1015408486.htm.
[7] Tang Guoan, Gong Jianya, Chen Zhengjiang, et al. 2001 Variable-scale network based on bilinear interpolation and variable-scale pooling. Journal of Surveying and Mapping, 30: 361-5.
[8] Zhao Wei, Zhong Huicai, Xing Yu, Cui Shiyian. 2019 A Scale Variable Network Based on Bilinear Interpolation and Pooling. Electronic Design Engineering, 27(01): 19-24.
[9] Zhang Chen, Wang Minggen, Li Yuhao, et al. 2018 Research on general solution of alcohol problem based on graph theory and breadth-first search algorithm. Digital Technology & Applications, 36:38-40.
[10] Xu Qize, Han Wenting, Chen Junshi, An Hong. (2019) Optimization of Breadth-first Search Algorithm Based on Many-core Platform. Computer Science, 46(01):314-9.