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Routing Strategy of Integrated Satellite-Terrestrial Network Based on Hyperbolic Geometry

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ABSTRACT The integrated satellite-terrestrial network has the characteristics of large scale, complex, high dynamic and heterogeneousness. Adopting traditional routing methods in the integrated satellite-terrestrial network will cause problems of poor scalability and large routing overhead. Greedy forwarding strategy based on network mapping with hyperbolic geometry works well in large scale network. However, there is no study on applying the network mapping with hyperbolic geometry to complex networks beyond two dimensions, including the integrated satellite-terrestrial network. Based on the method of spherical polar projection, this paper proposes a hyperbolic coordinates mapping algorithm in three-dimensional geographic space suitable for the integrated satellite-terrestrial network. This algorithm gives nodes of heterogeneous layers in the integrated satellite-terrestrial network a unified expression based on four-dimensional hyperbolic coordinates, which helps to quickly identify and locate nodes without global information distribution and scheduling when routing. The routing strategy using greedy forwarding strategy based on this algorithm only costs low storage overhead, as it does not need routing tables. Simulations demonstrate that the performance of the algorithm is hardly affected by the exponential expansion of the network size, which means the property of scalability is excellent. Also, it is stable under heterogeneous network structure, and maintains a stable routing success rate for optimal path selection around 93% with a time complexity of O(n).

INDEX TERMS Integrated satellite-terrestrial network, hyperbolic geometry, network mapping, greedy forwarding.

I. INTRODUCTION

Since information has become increasingly diverse and complex after the third industrial revolution, the traditional terrestrial information facilities and transmission system cannot fully meet the need of the society and the military in information transmission and sharing. People called for taking advantage of spatial equipment to transmit and process information. The integrated satellite-terrestrial network has become the development trend of the future network. It is composed of three layers, as shown in Figure1, including the satellite network, the aerial network containing various flight detectors, and the terrestrial network. Among them, the satellite network consists of many LEO (Low Orbit

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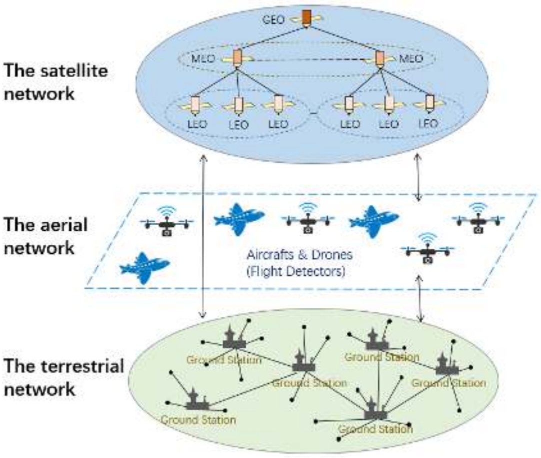

FIGURE 1. **Basic architecture of the integrated satellite-terrestrial network.**

Earth), MEO (Medium Earth Orbit), GEO (Geosynchronous Earth Orbit) satellites and other space nodes. Compared with the satellite nodes, the altitude of aerial nodes and terrestrial nodes under the stratosphere is very low. Therefore, they can be classified as near-surface nodes. On the whole, the integrated satellite-terrestrial network has the characteristics of large scale, complex, heterogeneousness and high dynamic. Adopting traditional routing methods in the integrated satellite-terrestrial network will cause problems of poor scalability and large routing overhead. Also, most of the existing routing strategies for the integrated satellite-terrestrial network rely on global information distribution and scheduling, which is not suitable for interactive information transmission among heterogeneous layers in this dynamic network environment. For example, Yang proposed inter-domain routing protocols [1]–[3] for integrated terrestrial- satellite networks to reduce routing update time and maintain network stability, but those methods still caused large routing storage overhead. The joint routing algorithm based on space-time graph [4] also had the same problem. Huang proposed a greedy-compound quadtree hierarchical routing model [5], using the composite quadtree model to represent the topology of the network, and greedy forwarding based on the model when routing, which helps to ensure the reliability of data transmission and the stability of the entire network, but this method need to know the global location and relationship of nodes necessarily with large overhead.

Greedy forwarding strategy based on network mapping causes low storage overhead in large scale network. Network mapping refers to using a coordinate system based on a certain geometric space to assign spatial coordinates to each node of the network through certain methods. After the network mapping is completed, the distance between any two nodes can be calculated based on their coordinates, so each node can forward the message greedily based on distance with only knowing the spatial coordinates of itself and its immediate neighbors. Greedy forwarding algorithm based on hyperbolic geometry means that the geometric space used for network mapping is the hyperbolic geometric space. Hyperbolic geometry [6] was proposed by Robacevsky. The curvature of the plane based on hyperbolic geometry is negative. Nowadays, the research of greedy forwarding algorithm based on hyperbolic geometry has been developed gradually. Krioukov proved that greedy forwarding was indeed effective in complex networks mapped in the hyperbolic geometric space [7]. Statistical inference techniques [8] were proposed to find the corresponding coordinates in the hyperbolic space of Internet nodes. With the help of hyperbolic coordinates, greedy forwarding in complex networks achieves efficiency and robustness [9]. So far, no research has applied the network mapping with hyperbolic geometry to complex networks beyond two dimensions, including the integrated satellite-terrestrial network in three-dimensional geographic space. The hyperbolic geometric space with the property of exponential expansion is appropriate for the integrated satellite-terrestrial network with the feature of large scale and complex. Therefore, it is a new and valuable research direction to combine the knowledge of hyperbolic geometry with the routing strategy of the integrated satellite-terrestrial network.

This paper proposes a hyperbolic coordinates mapping algorithm in three-dimensional geographic space suitable for the integrated satellite-terrestrial network, based on the method of spherical polar projection. This algorithm gives nodes of heterogeneous layers in the integrated satellite-terrestrial network a unified expression based on their geographical locations, which helps to quickly identify and locate the nodes in the network while routing. Also, it does not depend on global information distribution and scheduling. The dynamic change of network topology does not affect nodes to obtain current geographic coordinates of themselves and their direct neighbors through geographic location services such as GPS (Global Positioning System) and BDS (BeiDou Navigation Satellite System). This coordinates mapping algorithm is the most important prerequisite for realizing greedy forwarding based on hyperbolic geometry in the integrated satellite-terrestrial network. Finally, this paper generates the random wireless integrated satellite-terrestrial network topologies mapped to four-dimensional hyperbolic space and performs random greedy forwarding tests.

II. MAPPING ALGORITHM

Mathematically, the surface of an n-dimensional sphere is n-1 dimensional. That is, the surface of the four-dimensional hyperbolic hypersphere is a three-dimensional hypersphere called 3-sphere. This paper proposes a hyperbolic coordinates mapping algorithm in three-dimensional geographic space, by referring to the method of spherical polar projection to map the nodes of the integrated satellite-terrestrial network in the three-dimensional geographic space to 3-sphere, and then assigning hyperbolic coordinate components to the mapped nodes to identify the distance of the nodes from the four-dimensional spherical center. The details of algorithm are described below.

A. COORDINATES MAPPING PROCESS

1) USING SPHERICAL POLAR COORDINATES TO REPRESENT NODES

Initially, we use the center of the earth as the origin O to establish a spherical polar coordinate system in cosmic space. After this step, the coordinate expression form of any node in the integrated satellite-terrestrial network is $(\mathrm{r}, \theta, \varphi)$, $\mathrm{r} \in (0, \mathrm{R}]$, $\theta \in [0, \pi]$, $\varphi \in [0, 2\pi]$. R represents the maximum distance of a node in space from the center O of the earth. Taking a node A in space as an example, its coordinate can be expressed as $\mathrm{r_A}, \theta_\mathrm{A}, \varphi_\mathrm{A}$.

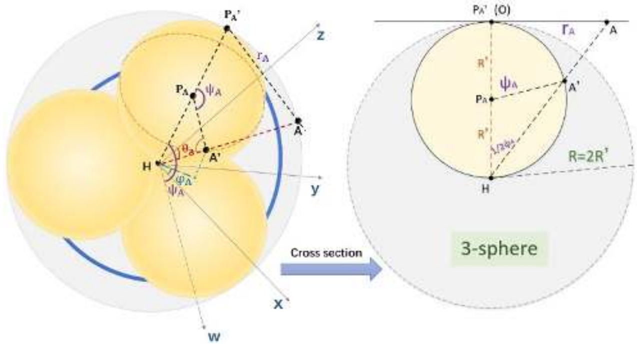

FIGURE 2. A′ is the mapping node of A in the 3-sphere.

2) MAPPING TO COORDINATES IN 3-SPHERE

The details that mapping node A to A′ in 3-sphere is illustrated as follows. It is known that the surface of the four-dimensional hyperbolic hypersphere space is a the 3-sphere, which can be abstractly represented by an uneven surface composed of many spheres. Figure 2 shows the three-dimensional projection of the four-dimensional hyperbolic hypersphere space compressed to only retain the 3-sphere. The outer gray dashed spherical range represents the 3-sphere. The spatial center of the four-dimensional hyperbolic hypersphere space after compression coincides with the spherical center of the 3-sphere, which is H. Each node in the network is separately assigned a spherical polar projection reference sphere. For example, for the node $\mathrm{A}(\mathrm{r_A}, \theta_\mathrm{A}, \varphi_\mathrm{A})$, the center of its corresponding spherical polar projection reference sphere is marked as $\mathrm{P_A}$. In the 3-sphere, all the spherical polar projection reference spheres are placed with H as the vertex, the same as $\mathrm{P_A}$. For $\mathrm{r} \in (0, \mathrm{R}]$, in order to ensure all the nodes in the network can be mapped completely, the radius of the sphere abstracted from the 3-sphere is set as R in this paper. The radius of the spherical polar projection reference spheres is R′, $\mathrm{R} = 2\mathrm{R}'$.

First, the mapping transformation is performed according to the radial distance $\mathrm{r_A}$ of the node A. $\mathrm{P'_A}$ is the center of the bottom of the spherical polar projection reference sphere $\mathrm{P_A}$. It is necessary to aligning $\mathrm{P'_A}$ to O, and use $\mathrm{P'_A}$ as the tangent point to make the tangent to the sphere $\mathrm{P_A}$ to ensure that $\mathrm{P'_A A} = \mathrm{OA} = \mathrm{r_A}$ when mapping. Then, we use H as the origin to construct a four-dimensional Cartesian coordinate system containing the x-axis, y-axis, z-axis, and w-axis. Those axes are perpendicular to each other. According to θ_A, φ_A and ψ_A, the specific coordinates of A′ in the 3-sphere can be determined. Among them, the mapping angular coordinate components ψ_A is calculated by (1).

$$\psi_A = 2arctan\frac{r_A}{R}, \quad \psi_A \in [0\ ,\ \frac{\pi}{2}) \tag{1}$$

In the direction where the w-axis rotates at the angle of ψ_A, the position of sphere $\mathrm{P_A}$ with the radius R′ in the 3-sphere is located. The mapping algorithm proposed in this paper does not change the angular position θ_A and φ_A of the node A in three-dimensional geographic space when mapping by means of spherical projection, so the angular orientation in xyz space of the mapping node A′ in 3-sphere under the four-dimensional coordinate system is still θ_A and φ_A. Up to the current step, $\mathrm{A}(\mathrm{r_A}, \theta_\mathrm{A}, \varphi_\mathrm{A})$ is successfully mapped to the 3-sphere as $\mathrm{A}'\ (\theta_\mathrm{A}, \varphi_\mathrm{A}, \psi_\mathrm{A})$.

Similarly, the other nodes in the network can be mapped one by one according to the above method. The nodes set $(\mathrm{r}, \theta, \varphi)$ with spherical polar coordinates in the integrated satellite-terrestrial network is mapped into the nodes set (θ, φ, ψ) in the 3-sphere.

3) ASSIGNING K TO OBTAIN FOUR-DIMENSIONAL HYPERBOLIC COORDINATES

The final step is to map the nodes from 3-sphere to four-dimensional hyperbolic hyperspace space to obtain the formal hyperbolic coordinates, by assigning the hyperbolic radius component k to the nodes mapped on the 3-sphere. k identifies the distance from nodes to the center of four-dimensional spherical, also affects the forwarding tendency when routing. The node closer to the center will be assigned smaller k, which means it has the higher forwarding tendency during routing.

Continue to take the node A as an example, the mapping result $\mathrm{A}'\ (\theta_\mathrm{A}, \varphi_\mathrm{A}, \psi_\mathrm{A})$ obtained above is currently only on the surface part of the entire four-dimensional hyperbolic hypersphere space that also known as 3-sphere. The hyperbolic radius component corresponding to the node A is expressed as $\mathrm{k_A}$. The node A′ completes the radial transformation relative to the center of the four-dimensional hyperbolic space according to $\mathrm{k_A}$. This process will not change the angular orientation of node. After that, the original node A in the three-dimensional geographic space is considered to successfully complete the mapping process and obtain the mapping expression $\mathrm{A}''(\theta_\mathrm{A}, \varphi_\mathrm{A}, \psi_\mathrm{A}, \mathrm{k_A})$ in the four-dimensional hyperbolic hypersphere space. Similarly, other nodes in the network also complete their mapping transformations according to their corresponding hyperbolic radius component values, and finally form a set of nodes with coordinates form $(\theta, \varphi, \psi, k)$ in four-dimensional hyperbolic hyperspace. The value of the hyperbolic radius component k should be adapted to the actual network. It only makes sense to discuss the value of k in a real scenario. Based on the results of following simulation experiments, this paper presents a preliminary method for determining the hyperbolic radius k.

The method of setting the value of k of the near-surface node is as follows. First, the nodes are arranged according to the communication radius r_c from high to low and divided into five levels. By defining the scale factor rank_n, $\text{rank}_n \in [0, 1]$, and then using it to multiply the number of nodes, the level division threshold Level_n can be calculated. The n is used to distinguish between levels, $n \in \{12, 3, 4, 5\}$. When $r_c \in (\text{Level}_{n-1}, \text{Level}_n]$, the level of the corresponding node is Level_n. The specific setting of the scale factor rank_n is shown in Figure 3, $\text{rank}_1 = 0.0625$, $\text{rank}_2 = 0.125$, $\text{rank}_3 = 0.25$, $\text{rank}_4 = 0.5$, $\text{rank}_5 = 1$.

FIGURE 3. **Ranking nodes according to the communication radius.**

Then, the hyperbolic radius component of each near-surface node can be calculated according to (2), where k_n represents the value corresponding to node Level_n, ε represents the increment range of the hyperbolic radius component, and $scale_{sur}$ is the total number of the near-surface nodes. When $(\varepsilon + \text{rank}_n \cdot scale_{sur})$ is uniformly distributed, its logarithm is subject to power law distribution, which theoretically meets the requirement that the distribution of hyperbolic radius values should obey the power law distribution. For example, when $scale_{sur} = 2000$, $\varepsilon = 30$, substituting the value of rank_n and keeping the calculation result with two decimal places, we can calculate the hyperbolic distances corresponding to the five levels of near-surface nodes as $k_1 = 7.28$, $k_2 = 8.13$, $k_3 = 9.05$, $k_4 = 10.01$, $k_5 = 10.99$.

$$k_n = log(\varepsilon + rank_n \cdot scale_{sur}) \tag{2}$$

For the satellite node, the values of k are set as follows. For LEO nodes, $k_{\text{LEO}} = 5.00$. For MEO nodes, $k_{\text{MEO}} = 4.90$. For GEO nodes, $k_{\text{GEO}} = 4.20$.

In summary, the implement of obtaining four-dimensional hyperbolic coordinates is shown in Algorithm 1.

Algorithm 1 Hyperbolic Coordinates Mapping

```
Input:
  SphericalPolarCoordinates3D: (r, $\theta$, $\varphi$).
  R: The maximum distance between the node and the center of the earth.
  nodeType : The types of node, as near-surface nodes or satellite nodes.
  surficialNodeNumber : The number of the near-surface nodes.
Output:
HyperbolicCoordinates4D: ($\theta$, $\varphi$, $\psi$, k)
$\psi \leftarrow 2arctan(r/R)$
if nodeType is the near-surface node do
    Rank near-surface nodes in descending order of communication radius
    Calculate the threshold $\text{Level}_n$ for dividing node rankings,
      $\text{Level}_n \leftarrow \text{rank}_n \cdot surficialNodeNumber$
    Calculate the hyperbolic radius $k_n$,
      $k_n \leftarrow log(\varepsilon + \text{rank}_n \cdot surficialNodeNumber)$
  if the ranking of a near-surface node is $\text{Level}_1$ do
      k $\leftarrow k_1$
  if the ranking of a near-surface node is $\text{Level}_2$ do
      k $\leftarrow k_2$
  if the ranking of a near-surface node is $\text{Level}_3$ do
      k $\leftarrow k_3$
  if the ranking of a near-surface node is $\text{Level}_4$ do
      k $\leftarrow k_4$
  if the ranking of a near-surface node is $\text{Level}_5$ do
      k $\leftarrow k_5$
else if nodeType is the satellite node do
  switch the type of a satellite node do
      case LEO
        k $\leftarrow k_{LEO}$;
      case MEO
        k $\leftarrow k_{MEO}$;
      case GEO
        k $\leftarrow k_{GEO}$;
  end switch
end if
End
```

B. CALCULATION METHOD OF THE HYPERBOLIC DISTANCE

The hyperbolic distance is the decision basis for the greedy forwarding strategy based on hyperbolic geometry in the integrated satellite-terrestrial network. According to the spherical cosine theorem, the angle between the two mapped nodes $(\theta_1, \varphi_1, \psi_1, k_1)$ and $(\theta_2, \varphi_2, \psi_2, k_2)$ can be calculated by (3). Then, the hyperbolic distance h of any two nodes in the four-dimensional hyperbolic space can be calculated by (4).

$$\rho = arccos cos\theta_1 cos\{\theta_2 + \sin\theta_1\, sin\theta_2[cos\varphi_1\, cos\varphi_2 + sin\varphi_1\, sin\varphi_2\, cos\,(\psi_2 - \psi_1)]\} \tag{3}$$

$$h = arccosh[cosh(k_1)\ cosh\,(k_2) - sinh(k_1)\ sinh(k_2)\ cos\rho] \tag{4}$$

III. RANDOM NETWORK TOPOLOGY GENERATOR

According to the mapping algorithm proposed in this paper, we generate a random wireless integrated satellite-terrestrial network topology that is mapped to four-dimensional hyperbolic space by C++, so that we can perform random greedy forwarding tests on it.

A. SETTING THE RANDOM NODES SET

When setting the random nodes set, the specific locations and the specific values of the communication ranges corresponding to the nodes in the generated network topology are set to be random. We only limit the number, category and other parameters of nodes. Nodes include satellite network nodes and near-surface nodes. The configuration of satellite network refers to the representative Akyildyz [11], whose coverage is global, as shown in Table1.

TABLE 1. **The configuration of the satellite network.**

Number of Satellites	Number of Tracks	Inclination of Track	Height of Track
LEO:72 MEO:18 GEO:3	LEO:12 MEO:6 GEO:1	LEO:90° MEO:90° GEO:3°	LEO:1375km MEO:16000km GEO:35786km

According to Table1, this paper can combine different numbers of near-surface nodes with the satellite network to generate random topologies of integrated satellite-terrestrial networks of different sizes.

However, in order to comply with the scale-free nature of the large-scale integrated satellite-terrestrial network, the overall degree distribution of nodes in the generation topology satisfies the power law distribution. In the wireless network, the degree of a node is the number of nodes within its communication range. By analyzing the relationship between the node's communication range area s and the degree k when the node's communication range increases per unit area, we can get the probability density function $P_s(s)$ that represents the distribution of the value of the communication area of the node, as shown in Equation 5, where ρ represents the number of nodes per unit area, and γ is the normalization factor so that the integral of the probability density function is 1. When the area distribution of nodes in the generated network topology satisfies (5), the scale-free distribution of node degrees in the network can be guaranteed. This article space is limited, so the specific derivation process will not be described in detail here. There is also a relationship between γ and the average degree $\overline{k}$ of the whole network as in (6) [12]. In this paper, $\overline{k}$ is approximately 4.92, and the corresponding value of γ is 2.255.

$$P_s(s) = \rho(\gamma - 1)(\rho \cdot \gamma \cdot s + 1 - \gamma)^{-\frac{2\gamma-1}{\gamma}} \tag{5}$$

$$\gamma = \frac{2\overline{k} - 1}{\overline{k} - 1} \tag{6}$$

The degree distribution of the random wireless integrated satellite-terrestrial network topology generated in this paper is shown in Figure 4, which conforms to the basic characteristics of the power law distribution.

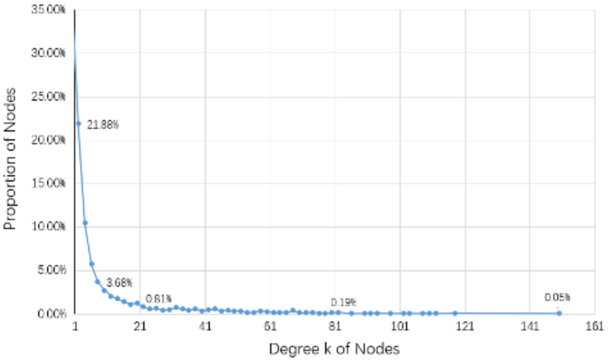

FIGURE 4. **The degree distribution of the generated network.**

B. ESTABLISHING CHANNELS BETWEEN NODES

When establishing channels between nodes in the random wireless integrated satellite-terrestrial network topology, it is necessary to judge whether a wireless communication link can exist between the two nodes.

If both nodes are in the atmosphere, the first judgment is whether the distance between the two nodes in the actual geographic space is less than the radius of their own communication area. If this condition is met, due to the reflection of the electromagnetic layer, the communication wave emitted by the source node will continue to be reflected until it reaches the destination node, so the effect of the curvature of the earth can be temporarily ignored. If the electromagnetic wave has been attenuated to 0 before reaching the destination node, these two nodes are also unreachable.

If the satellite node outside the atmosphere is involved, it is necessary to check whether the mathematical connection between the satellite node and the near-surface node is blocked by the earth, which can be judged by the mathematical theorem related to the plane equation as follows.

The Cartesian coordinate system is established with the center O of the earth sphere as the origin. Then, the Cartesian coordinates of the two nodes are $\mathrm{A}(\mathrm{x}_1, \mathrm{y}_1, \mathrm{z}_1)$, $\mathrm{B}(\mathrm{x}_2, \mathrm{y}_2, \mathrm{z}_2)$, and $\overrightarrow{\mathrm{AB}} = (\mathrm{x}_2 - \mathrm{x}_1, \mathrm{y}_2 - \mathrm{y}_1, \mathrm{z}_2 - \mathrm{z}_1)$. According to the mathematical theorem of point normal form equation of a plane, the plane equation of the plane passing through the origin $\mathrm{O}(0, 0, 0)$ with the normal vector $\overrightarrow{\mathrm{AB}}$ is described as (7), and the positional relationship between the two nodes and the plane can be judged by (8). As shown in Figure 5, when the calculation result l obtained from (8) is greater than 0, point A and B are on the same side of the plane defined by (7). At this time, the mathematical connection between the two nodes must not be blocked by the earth.

$$(x_2 - x_1)x + (y_2 - y_1)y + (z_2 - z_1)z = 0 \tag{7}$$

$$\begin{aligned} &\left[(x_2 - x_1)x_1 + (y_2 - y_1)y_1 + (z_2 - z_1)z_1\right] \\ &\quad * \left[(x_2 - x_1)x_2 + (y_2 - y_1)y_2 + (z_2 - z_1)z_2\right] = l \end{aligned} \tag{8}$$

However, if the result l calculated by (8) is less than 0, it means that the node A and node B are on the opposite side of the plane defined by (7). At this time, it is necessary to

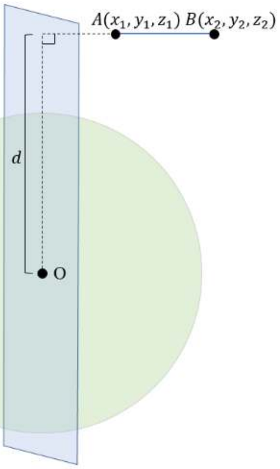

FIGURE 5. Two nodes are on the same side.

calculate the perpendicular distance d from the origin O to the connection between the node A and node B to further determine whether their mathematical connection is blocked by the earth. Based on the mathematical definition of vector product and vector modulus, d can be calculated by (9).

$$d = |\overrightarrow{\mathrm{AO}}| \cdot \sin\alpha = \frac{|\overrightarrow{\mathrm{AO}} \times \overrightarrow{\mathrm{AB}}|}{|\overrightarrow{\mathrm{AB}}|} = \frac{\sqrt{(z_1y_2 - y_1z_2)^2 + (x_1z_2 - z_1x_2)^2 + (y_1x_2 - x_1y_2)^2}}{\sqrt{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2}} \tag{9}$$

If the distance d is greater than the radius of the earth, as shown in Figure 6, it means that the mathematical connection between the two nodes is not blocked by the earth. Otherwise, the connection is blocked.

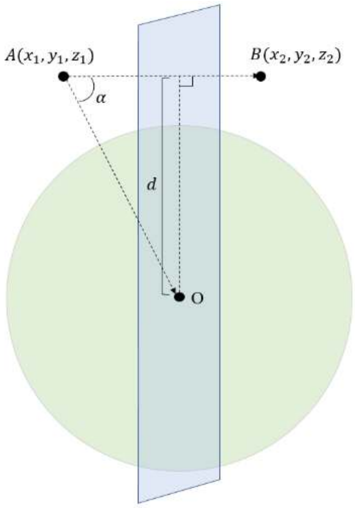

FIGURE 6. The perpendicular distance d.

C. IMPLEMENTATION OF HYPERBOLIC COORDINATE MAPPING

After generating the random positions of the nodes in the random wireless integrated satellite-terrestrial network topology, this paper uses the algorithm proposed above to assign the corresponding four-dimensional hyperbolic coordinates to the nodes. Through Algorithm 1, the three-dimensional spherical polar coordinates (r, θ, φ) of a input node are converted into four-dimensional hyperbolic coordinates (θ, φ, ψ, k). Related steps in details for hyperbolic coordinate mapping are described in the previous section.

IV. PERFORMANCE EVALUATION

A. THE IMPACT OF NETWORK EXPANSION ON ROUTING

In the generated connected subgraph of the random wireless integrated satellite-terrestrial network topology, two nodes are randomly selected as the source node and the destination node to start the greedy forwarding test. The origin greedy forwarding algorithm is adopted in the step of forwarding to observe the base case.

For observing the impact of network expansion on routing based on hyperbolic coordinates mapping algorithm proposed in this paper, this paper counts the results of 10,000 times random routing forwarding tests that are sequentially performed on random network topologies of different sizes. The results are shown in Figure 7, 8 and 9. When the number of network nodes increases exponentially, the number of routing hops required to reach the destination node is hardly affected by the exponential expansion of the network. Routing time also only varies linearly with a small amplitude, and the time complexity of routing is O(n). The routing success rate to achieve optimal path selection can gradually stabilize at around 93%.

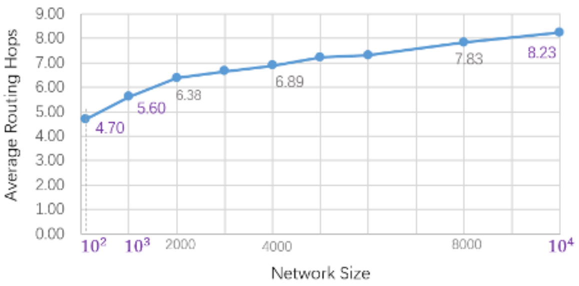

FIGURE 7. Relationship between average routing hops and network size.

B. THE IMPACT OF HETEROGENEOUS SATELITTE NETWORK STRUCTURE ON ROUTING

In the same way, this paper selects three classical network structures as input parameters to generate network topologies separately, and then conducts random greedy routing forwarding tests. In the 10,000 tests under different groups, the average results of each group are shown in Table 2 below. It can be observed that the greedy forwarding strategy based on hyperbolic coordinates mapping algorithm proposed in this paper is stable in the heterogeneous integrated satellite-terrestrial network structure, and it also can keep a good optimal path selection rate around 93%.

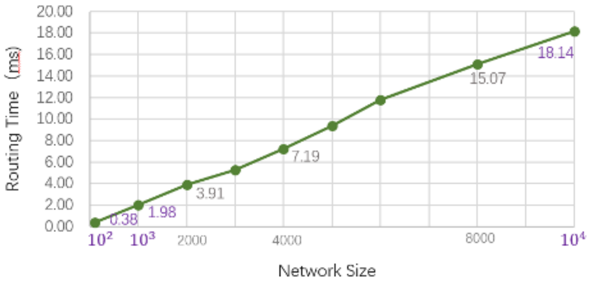

FIGURE 8. Relationship between average routing time and network size.

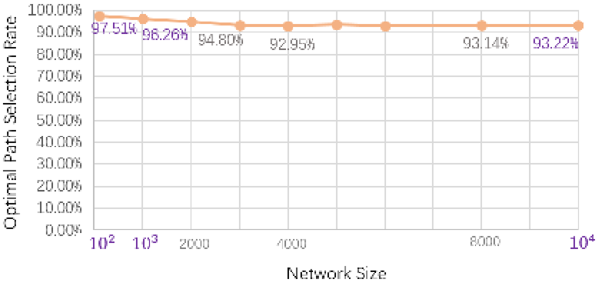

FIGURE 9. Relationship between optimal path selection rate and network size.

TABLE 2. The configuration of networks and routing results.

Designer (Country)	Werner (Germany)	Akyildyz (US)	Guke Huang (China)
Number of Satellite Nodes	LEO:66 MEO:15	LEO:72 MEO:18 GEO:3	LEO:48 MEO:12 GEO:3
Number of Tracks	LEO:6 MEO:3	LEO:12 MEO:6 GEO:1	LEO:8 MEO:3 GEO:0
Inclination of Track	LEO:86° MEO:54°	LEO:90° MEO:90° GEO:3°	LEO:52° MEO:55° GEO:0°
Height of Track (km)	LEO:784 MEO:6390	LEO:1375 MEO:16000 GEO:35786	LEO:1400 MEO:20000 GEO:35786
Number of Near-surface Nodes	10000	10000	10000
Average Route Hops	7.81	8.23	8.28
Average Routing Time	20.93ms	18.14ms	20.66ms
Optimal Path Selection Rate	93.21%	93.22%	93.45%

V. CONCLUSIONS AND FUTURE WORK

The integrated satellite-terrestrial network is the development trend of future networks. However, it has the characteristics of large scale, complex, high dynamic and heterogeneousness. Adopting traditional routing methods in the integrated satellite-terrestrial network caused many problems such as poor scalability and large routing overhead. This paper initially verifies that it is feasible and effective to apply the network mapping with hyperbolic geometry to the routing strategy of the integrated satellite-terrestrial network. This paper draws on the method of spherical polar projection to propose a hyperbolic coordinates mapping algorithm in three-dimensional geographic space, which suitable for the integrated satellite-terrestrial network. This algorithm implements the mapping of coordinates from three-dimensional geographic space to four-dimensional hyperbolic hypersphere space. With the help of hyperbolic coordinates, the routing strategy using greedy forwarding strategy based on this algorithm only causes low storage overhead for it does not need routing tables. This paper performed experiments that generate the random wireless integrated satellite-terrestrial network topologies mapped to four-dimensional hyperbolic space, and perform random greedy forwarding tests on them. The results show that the algorithm is hardly affected by the exponential expansion of the network size, which means the scalability is good. Also, it can be stable under heterogeneous network structure, and maintain a stable routing success rate for optimal path selection around 93% with time complexity of O(n).

Due to the complexity of research content and limited resources, the work of this article is still in the exploration stage. This paper initially verifies that it is feasible and effective to apply the relevant knowledge of hyperbolic geometry to the routing strategy of the integrated satellite-terrestrial network. In the future work, some specific forwarding requirements in specific applications scenarios of the integrated satellite-terrestrial network need to be considered in more detail. In terms of improving the routing success rate for achieving complete optimal path selection, further work is to keep optimizing the hyperbolic mapping algorithm in the three-dimensional space proposed in this paper. Hyperbolic coordinate components will affect the forwarding tendency, which can be used to help select nodes with better properties when forwarding, by studying a more adaptive hyperbolic coordinate component setting method that dynamically changes with forwarding requirements.

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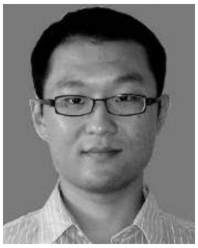

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