A Bibliometric Analysis of Satellite Networking Routing Protocols (Postprint)

Authors: Li Qiangqiang, Yao Xiujuan, Zhang Cen

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Abstract

Due to the dynamic nature of satellite network topology, traditional network routing protocols are no longer applicable to satellite networks. Using bibliometric methods, the current research status of space satellite network routing both domestically and internationally is analyzed, summarized and categorized into virtual node-based routing protocols and virtual topology-based routing protocols, and an improved method for the SGRP routing protocol is proposed.

Full Text

Preamble

Research on Satellite Network Routing Protocols Based on Bibliometrics

LI Qiang-qiang[1,2], YAO Xiu-juan[1], ZHANG Cen[2,3]
(1. National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. National Science Library, Chinese Academy of Sciences, Beijing 100190, China)

Abstract: Due to the dynamic topology of satellite networks, traditional Internet routing protocols are no longer applicable to satellite networks. This paper employs bibliometric methods to analyze the current state of space satellite network routing research both domestically and internationally, categorizing routing protocols into virtual node-based and virtual topology-based approaches. Additionally, an improved method for the SGRP routing protocol is proposed.

Keywords: satellite network; routing protocols; satellite constellation; bibliometrics

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According to the satellite database published by the Union of Concerned Scientists on June 30, 2016, there were 1,419 satellites orbiting Earth, with the United States accounting for nearly half of this total while China possessed only 181 satellites. This indicates a substantial gap between China and developed countries in terms of both the scale and practical application effectiveness of space information networks. Consequently, China urgently needs to prioritize the establishment of space information networks. As stipulated in China' s 13th Five-Year Plan outline, the "Space-Ground Integrated Information Network" is listed among the hundred major projects to be implemented within the next five years, with satellite networking serving as the critical foundation for realizing this vision.

This paper aims to analyze domestic and international research on satellite network routing through bibliometric methods, providing both theoretical significance and practical value for space networking routing protocol research. Although several scholars have previously conducted review studies—for instance, Lu Yong and Zhao Youjian' s "Satellite Network Routing Technology," which traces the development of satellite network routing technology and elaborates on key mechanisms and characteristics from a classification perspective, ultimately proposing development trends based on application requirements; and Dai Guoliang and Zhao Shanghong' s "Overview of Satellite Network Routing Technology," which surveys various routing algorithms from the perspective of satellite constellation networking architectures (single-layer, dual-layer, and multi-layer satellite network routing) with corresponding analysis and comparisons—few have utilized bibliometric methods. This paper distinguishes itself by employing bibliometric analysis to examine satellite network routing technology, thereby more clearly revealing relevant research content and facilitating subsequent analysis.

2. Data Sources and Research Methods

For domestic literature, CNKI was used as the data source, with "satellite" AND "routing" as search terms, "subject" as the search field, and "information technology" as the domain, yielding 711 documents. For international literature, Web of Science served as the data source, using "satellite" AND "routing" as search terms, which returned 2,178 documents. The co-word analysis method was employed, clustering keywords by statistically counting their co-occurrence frequencies in pairs across the literature. This approach reflects the relationships between terms and reveals structural changes in the corresponding disciplines and topics.

2.1.1 Keyword Frequency Analysis

To summarize domain development while minimizing interference from low-frequency terms, this study extracted 30 high-frequency keywords (frequency 8) from the 711 domestic documents.

Domestic Literature Top 30 Keywords (Frequency 8)

Using Sati software, keywords were paired to form a 30×30 similarity matrix, which was then visualized using the social network analysis software Ucinet. In the resulting keyword association map, node size represents keyword centrality—larger nodes indicate higher centrality. Notably, "satellite network," "routing protocol,""satellite communication,"and "inter-satellite link"appear as prominent nodes, representing key research hotspots to some extent. Through clustering, strongly correlated keywords form a complex, interconnected research network.

Domestic High-Frequency Keyword Similarity Matrix (Partial)

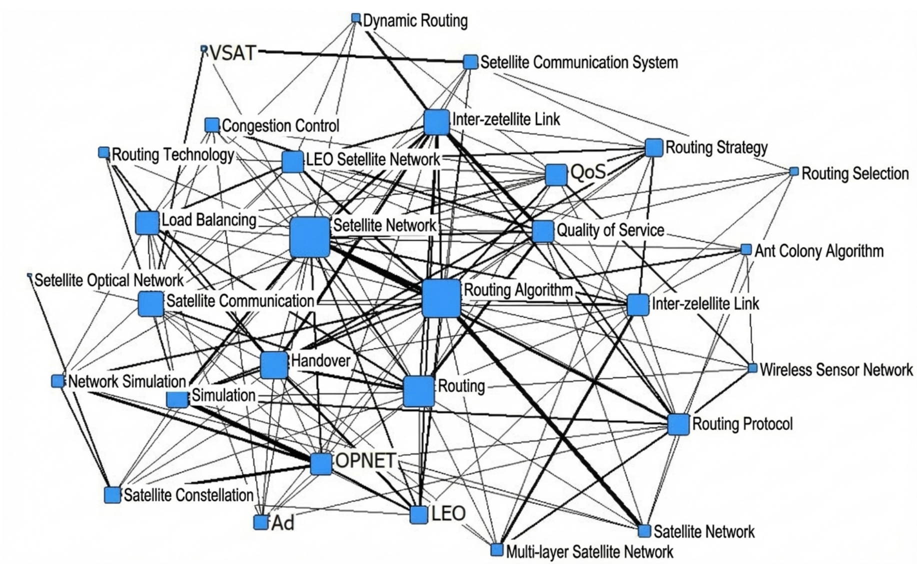

Figure 1: Figure 1

Domestic "Satellite" & "Routing" Keyword Cluster Analysis

2.1.2 Keyword Cluster Analysis

Cluster analysis of the similarity matrix using SPSS software, as shown in Figure 2

, reveals two primary research directions. The first focuses on satellite networks, represented by keywords such as satellite constellation, wireless sensor networks,

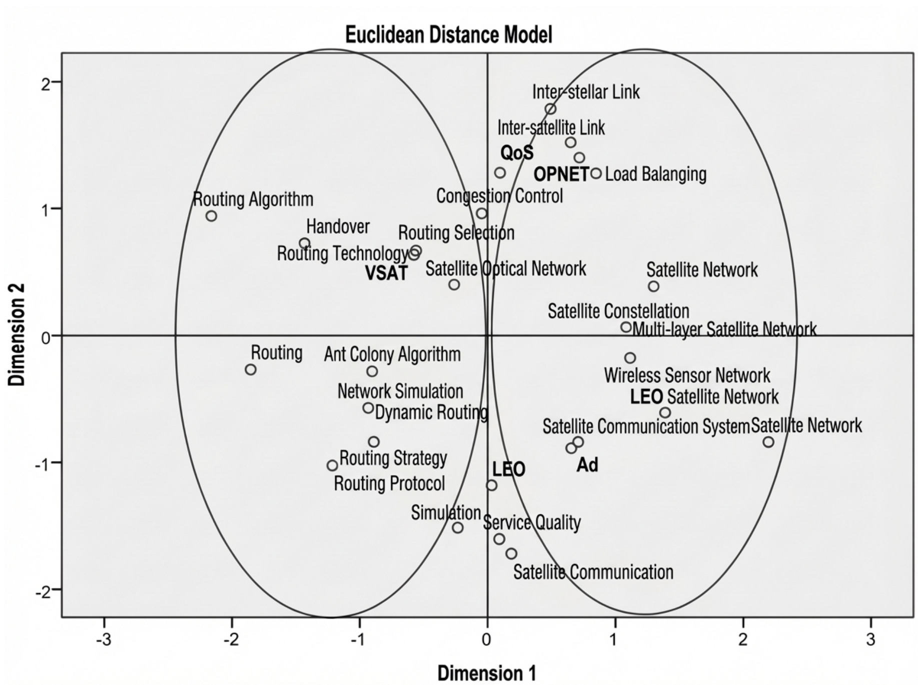

Figure 2: Figure 2

and satellite communication. The second concentrates on routing technology, represented by dynamic routing, routing protocols, and network simulation.

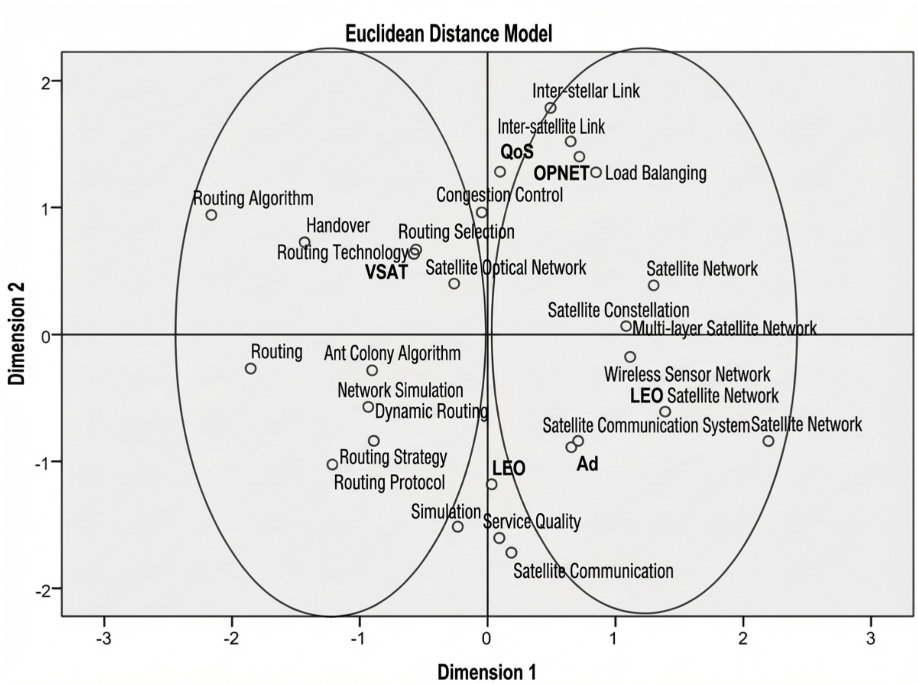

Figure 3: Figure 2

Multidimensional Scaling Analysis of Domestic High-Frequency Keywords

2.2.1 Keyword Analysis

For international literature, 49 keywords with frequencies exceeding 8 were selected. Analysis shows that beyond the search terms "satellite" and "routing," topics such as "migration," "satellite network," and "QoS" have also received considerable attention.

International Literature Top 51 Keywords (Frequency 8)

[FIGURE:3] International "Satellite" & "Routing" Literature Keyword Cluster Analysis

2.2.2 Keyword Cluster Analysis

Based on SPSS cluster analysis, international research keywords can be categorized into four major groups, as illustrated in Figure 4

. The first category addresses routing and QoS technologies in satellite networks, represented by keywords such as Route, adaptive routing, and QoS. The second

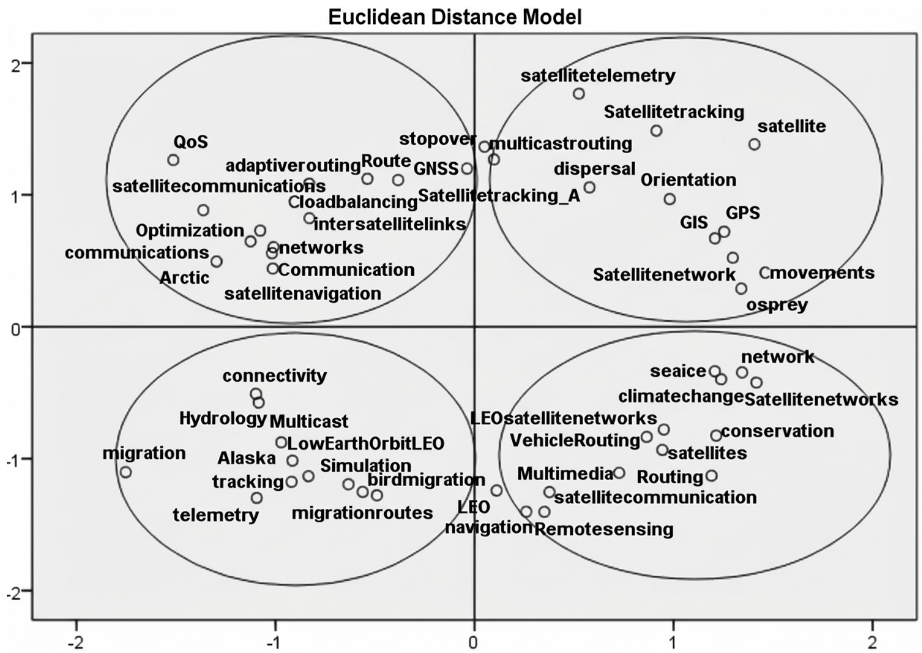

Figure 4: Figure 4

category focuses on satellite network constellations and routing technologies, represented by satellite networks and routing. The third category concerns mobile satellite communication tracking and simulation technologies, represented by migration, tracking, and movement. The fourth category centers on technologies such as GIS and GPS.

Multidimensional Scaling Analysis of International High-Frequency Keywords

2.3 Research Content Analysis

Based on the above analysis, current research hotspots fall into two main categories. The first category involves routing protocol research based on satellite networks, specifically focusing on inter-satellite link routing protocols. The second category addresses satellite communication research based on mobile satellites, concentrating on satellite-ground link communication. Since satellite-ground link communication is relatively mature while space satellite network research remains in its infancy, this paper focuses specifically on routing protocol research based on satellite networks.

3. Satellite Network Routing Technology

Routing technology represents both a critical challenge and key focus in satellite networking. To discover paths from source to destination satellites that meet

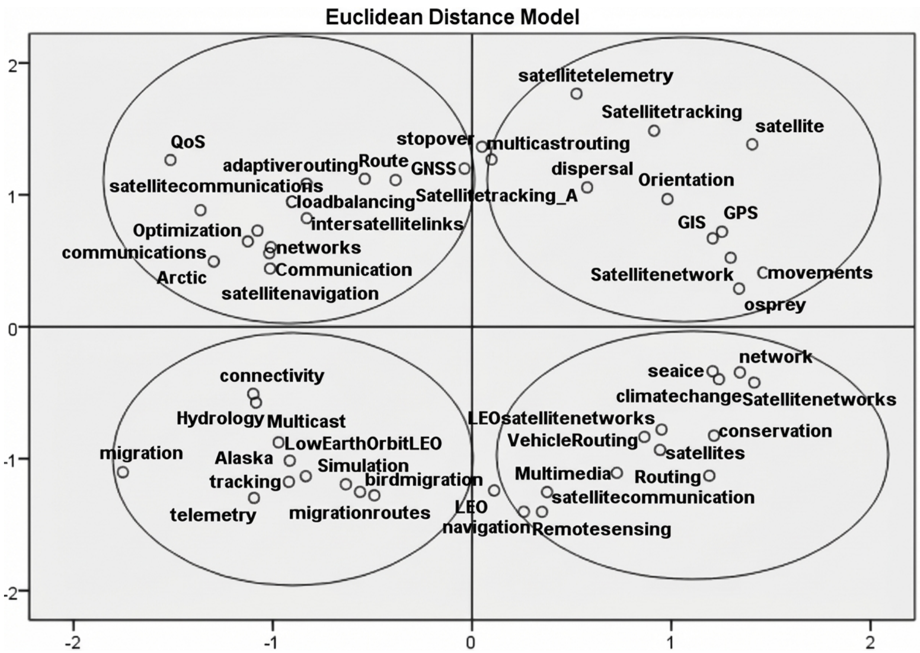

Figure 5: Figure 4

specific requirements, the fundamental issue of time-varying satellite network topology must first be resolved. Network routing strategies aimed at pathfinding in time-varying topologies form the foundation of satellite network routing algorithms. Consequently, satellite networking routing algorithms are divided into virtual node-based routing algorithms and virtual topology-based routing algorithms.

3.1 Virtual Node-Based Routing Strategy

Hashimoto Y proposed a routing framework based on coverage area division, considered the prototype of virtual node routing. This framework employs IP hierarchical addressing and Mobile IP concepts, dividing Earth’ s surface into square regions of 160 km side length called supercells, each further subdivided into nine sub-cells. Fixed logical addresses are assigned to these regions, and routing tables to all other regions are computed. During system operation, logical addresses are allocated to satellite nodes based on proximity principles. As satellites acquire logical addresses, they simultaneously obtain routing table information. This algorithm requires joint operation of on-orbit satellites, ground gateways, and ground terminals to complete the routing process. The mechanism’ s advantages include leveraging the symmetry and periodicity of network topology to avoid dynamic routing calculations, thereby offering high adaptability. However, constructing ground gateway stations globally is extremely challenging.

Henderson proposed DGRA (Distributed Geographic Routing Algorithm), which introduced the concept of distributed routing. Unlike previous approaches, DGRA forwards satellite packets in two stages: when the distance to the exit satellite exceeds a threshold, nodes forward packets based on global routing information; when packets approach the exit satellite, forwarding relies on local routing information.

Although virtual node routing is simple to implement with low protocol overhead, it is only effective for regularly structured satellite constellations and suffers from poor scalability and robustness. Nearly all virtual node-based routing methods use polar-orbiting LEO constellations as models due to their regular topology and simple calculations. Extending virtual node routing methods to inclined-orbit satellite constellations requires substantial modifications, increasing computational complexity and protocol overhead. Multi-layer satellite constellations, which feature overlapping coverage, prevent ground logical regions from binding uniquely to constellation satellites, making virtual node routing methods unsuitable.

3.2 Virtual Topology-Based Routing Strategy

Virtual topology-based routing represents a relatively widespread approach in satellite routing algorithms. The concept was initially proposed by Werner et al., who subsequently conducted extensive in-depth investigations and extensions. The core idea exploits the periodic nature of satellite orbits and the predictable characteristics of constellation structures. Within a satellite operation period T, time is discretized into n time slices [t ,t], [t ,t], ···, [t ,t]. Within any time slice [t ,t], the satellite topology can be virtualized as a connection graph G . When n is sufficiently large (i.e., time slices are sufficiently small), the satellite topology connection graph G can be considered static. After obtaining the static topology connection graph G , the classic Dijkstra SPF (Shortest Path First) algorithm is applied to compute connection paths between every node pair. Notably, these operations are completed during the initial satellite system design phase, with routing calculation results for each time slice stored in satellite equipment. During on-orbit operation, satellites simply identify the current time slice and retrieve the corresponding routing table to obtain routing information.

Building upon Werner’ s research, Chen Chao et al. proposed a packet routing strategy for LEO/MEO dual-layer satellite networks, extending virtual topology strategy to dual-layer networks for the first time. The paper defines a snapshot as any moment when all LEO/MEO group member relationships remain identical. Within each snapshot, the affiliation between LEO and MEO satellites is constant, allowing the network topology to be considered unchanged. Consequently, the continuously varying topology of LEO/MEO dual-layer satellite networks is solidified into a series of discrete snapshots. Within each topology snapshot, the SPF algorithm is used to find the shortest path for every OD (Origin-Destination) node pair. Since topology snapshots can be precomputed, shortest paths between each OD pair are calculated in advance by ground gateways and uploaded to satellite nodes. While this virtual topology grouping strategy solves the topology solidification problem for multi-layer satellite networks, it suffers from excessive snapshots within a system period, resulting in frequent snapshot switching and high protocol overhead. Similar approaches include MLSR (Multi-Layered Satellite Routing). MLSR is applicable to three-layer satellite networks composed of LEO/MEO/GEO satellites and was the first protocol to apply virtual topology-based routing to three-layer networks. It similarly groups lower-layer satellites based on the footprints of higher-layer satellites, performs hierarchical network topology collection, and computes routing tables for lower-layer satellites when group member relationships change. However, MLSR lacks a rapid response mechanism for congestion due to its reliance on periodic routing table calculations.

Following MLSR, Chen et al. proposed SGRP (Satellite Grouping and Routing Protocol). SGRP inherits MLSR' s grouping concept for application in LEO/MEO dual-layer satellite constellations, fully leveraging the cooperative relationship between LEO and MEO layers with MEO satellites serving as managers for the LEO layer. SGRP' s primary objective is to transmit data packets along the shortest delay path while transferring routing table computation tasks from LEO satellites to MEO satellites. Like MLSR, SGRP divides LEO satellites into groups, where LEO satellites within the same MEO satellite' s footprint area are grouped together. Group relationships change when LEO satellites enter or leave a MEO satellite' s footprint area. In SGRP, changes in LEO grouping relationships are treated as network topology changes, with each change generating a new snapshot. Within each snapshot, the satellite network topology is considered static. Each MEO satellite acts as the group leader for LEO satellites within its footprint, responsible for collecting and exchanging LEO layer link delay information and computing routing tables for LEO satellites. LEO satellites receive routing tables from MEO satellites and forward packets accordingly.

SGRP' s greatest advantage lies in delegating routing computation tasks to more capable MEO satellites, balancing resource consumption between LEO and MEO satellites and extending system lifetime. SGRP also physically separates signaling from data traffic, ensuring that link congestion cannot affect the response time of delay reporting and routing computation.

3.3 Improvements to SGRP

Based on the above analysis, although SGRP addresses MLSR' s inefficient congestion handling, refines the LEO layer satellite grouping routing mechanism, and reduces the routing computation burden on LEO layer satellites, several issues remain:

1. It negates the role of ground gateways in routing computation by assigning all routing computation and management tasks to MEO satellites, increasing MEO satellite burden and reducing overall system lifetime, robustness, and survivability.
2. It binds LEO grouping changes to LEO logical position changes, increasing the number of snapshots within a system period and resulting in excessive protocol overhead and system burden.
3. Frequent LEO satellite entry/exit from MEO satellite footprint areas generates too many snapshots within a system period, hindering routing algorithm application.

Based on this analysis, this paper proposes a new satellite grouping routing protocol called NSGRP (New Satellite Grouping and Routing Protocol). This protocol improves the virtual topology routing strategy by significantly reducing the number of snapshots within a system period through snapshot merging methods that eliminate overly short snapshots. It also integrates both virtual node and virtual topology routing strategies for application in LEO/MEO/GEO three-layer satellite networks.

Two common approaches exist for reducing snapshots within a system period: redefining topology snapshots or merging existing snapshots. Under the LEO/MEO virtual topology grouping strategy framework, where snapshot division is based on LEO grouping changes, redefining topology snapshots is difficult to implement. Therefore, the second approach is adopted—reducing snapshot quantity through snapshot merging.

Assuming the switching moments derived from snapshot division methods are [t ,···t ,···,t], at moment t , LEO satellite L undergoes group switching and is simultaneously covered by MEO satellites M and M . Starting from the first snapshot division moment t , if this division moment falls within satellite L ' s free time period, then L can switch at moment t , thereby merging one snapshot. This process continues iteratively, merging all possible snapshots to obtain a new switching schedule. The snapshot merging principle is illustrated in Figure 5 [FIGURE:5].

[FIGURE:5] Snapshot Merging Principle Diagram

4. Conclusion

Space satellite networking is a critical component for realizing the "Space-Ground Integrated Information Network," with networking routing strategy being one of its key technologies. This paper analyzed virtual node-based and virtual topology-based routing strategies, examined their main characteristics and existing problems, and proposed improvements to SGRP that reduce snapshots and enhance protocol performance.

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Author Biographies:

LI Qiang-qiang (born 1991), male, from Lianyungang, Jiangsu, is a master' s student at the National Space Science Center, Chinese Academy of Sciences. His research focuses on satellite network routing protocols.

YAO Xiu-juan (born 1977), female, is a master’ s supervisor at the National Space Science Center, Chinese Academy of Sciences.

ZHANG Cen (born 1991), female, is a master’ s student at the National Science Library, Chinese Academy of Sciences.