Assignment Report

TERM: **Spring, 2023-2024**

Module: **EE3626 Mobile Communications**

CLASS: 34092102

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5, June 2024

Overview of Routing Algorithms in LEO Satellite Constellation Networks

1 Introduction

Satellite communication utilizes satellites as relays for radio communication between ground-based stations. Compared to terrestrial communication, satellite communication offers advantages such as long-distance communication, extensive coverage, and independence from geographical constraints. These characteristics make it a crucial mode of communication, playing a vital role in global connectivity. Communication satellites can be classified based on their orbital altitude into geostationary orbit (GEO) satellites, medium Earth orbit (MEO) satellites, and low Earth orbit (LEO) satellites.

Early communication satellites primarily operated in GEO, where a single satellite could cover one-third of the Earth's surface, and three satellites could achieve global coverage. Despite its many advantages, GEO faces serious drawbacks, including limited orbital and frequency resources, long signal propagation delays, and high propagation losses [1]. Therefore, since the 1990s, there has been a growing focus on developing satellite communication systems using LEO orbits. The late 20th century saw the rise of the first generation of LEO constellation networks, exemplified by projects such as Iridium and Globalstar. Today, large-scale satellite constellations include the United States' GPS, Russia's GLONASS, Europe's Galileo, and China's Compass.

In terrestrial communication networks, classic routing algorithms include Dijkstra's algorithm and the Bellman-Ford algorithm. Common routing strategies encompass fixed routing, flooding, random routing, and adaptive routing [2]. Due to the low altitude of LEO satellites, they have short orbital periods and rapidly changing network topologies, making traditional terrestrial network routing unsuitable for the highly dynamic nature of LEO satellite networks. To adapt the dynamic changes in network topology and ensure the quality of LEO satellite communications, various routing technologies have been proposed.

This paper provides an overview of routing algorithms in LEO satellite constellation networks, classifying them into traditional routing algorithms based on graph theory and routing algorithms based on artificial intelligence.

2 Low Earth Orbit Satellite Constellation

Satellite constellations, or SCs, are groups of artificial satellites that work together to provide nearly continuous global coverage. These satellites are typically placed at similar altitudes, orbital eccentricities, and inclinations to ensure that most of the Earth's surface can receive signals. SCs can be located in Medium Earth Orbit (MEO) or Low Earth Orbit (LEO). Compared to MEO SCs, LEO SCs have more advantages.

The advantages of LEO SCs include:

Low latency: The orbital height of LEO satellites is generally around 1000 km, which is one-eighth of MEO (8000 km). Therefore, the latency can be reduced from over 200 ms to tens of milliseconds, which can be comparable to ground networks [3].

Broadband communication: To meet the growing demand for broadband services, emerging LEO satellite constellation networks widely use Ku, Ka, and higher frequency bands. Satellites use high communication frequencies, phased array multi-beam antennas, frequency reuse, and other technologies to significantly increase communication bandwidth, with a single satellite capacity of tens of Gbps and a network capacity of Tbps [4].

Lower path losses and power requirement: High communication frequencies and low orbital heights can achieve miniaturization of ground terminal antennas, saving power and reducing path losses [3].

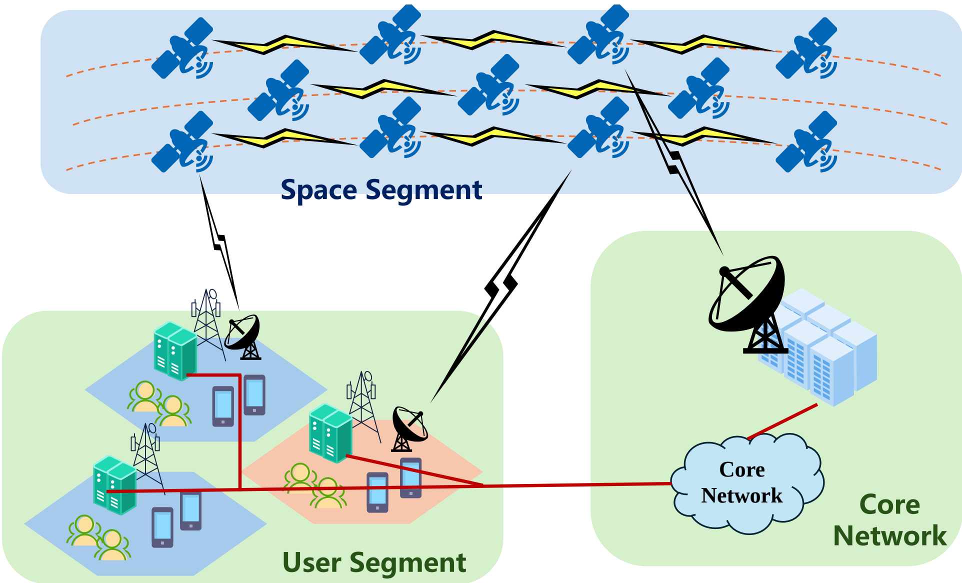

Figure 1: Architecture of a LEO Satellite Constellation Network

Figure 1 shows the architecture of a LEO satellite constellation network. The network consists of multiple satellites in LEO, each covering a specific area on the Earth's surface. The satellites communicate with each other and with ground stations to provide global coverage and support various communication services.

3 Routing Algorithms

Different scholars have classified LEO satellite constellation routing technologies from different perspectives. Reference [5] divides routing into connection-oriented and connection-less routing according to whether a connection is needed before data transmission between satellites.

Reference [6] introduces LEO routing technologies from two perspectives: business-centric and topology-centric.

This paper classifies LEO satellite constellation routing technologies into two categories: traditional routing algorithms based on graph theory and routing algorithms based on artificial intelligence, as shown in figure 2.

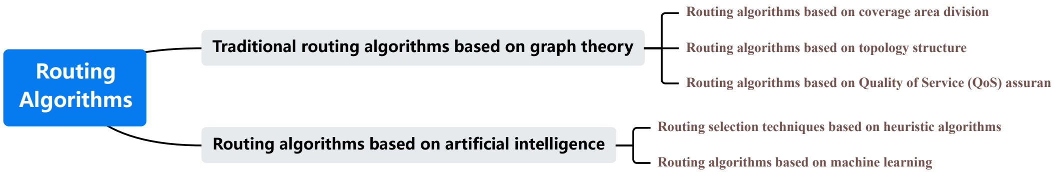

Figure 2: Classification of LEO Satellite Constellation Routing Algorithms

3.1 Traditional routing algorithms based on graph theory

3.1.1 Routing algorithms based on coverage area division

In Low Earth Orbit (LEO) satellite networks, the rapid movement of satellites causes continuous changes in their coverage areas. This dynamic characteristic necessitates frequent handovers to new satellites for ongoing communications. Each handover requires updating the connection path to ensure uninterrupted communication, leading to the so-called rerouting problem. The Footprint Handover Rerouting Protocol (FHRP) [7] is divided into two phases: Route Augmentation and Footprint Rerouting. It aims to maintain the optimality of the initial path without needing to re-execute the routing algorithm after each satellite handover. FHRP uses the footprints of the initial path as a reference for rerouting, ensuring that the new path after handover remains optimal.

Simulation studies have shown that FHRP significantly reduces the call blocking probability during handovers, especially for handover calls. Additionally, FHRP consistently demonstrates excellent performance across various traffic patterns.

3.1.2 Routing algorithms based on topology structure

LEO satellite network nodes move periodically, causing continuous changes in topology but also having predictability. Researchers classify LEO satellite routing into static and dynamic algorithms based on topology. Static routing algorithms do not consider changes in network topology and partition the satellite network in time and space. Dynamic routing algorithms continuously calculate and update routing tables in real-time to adapt to network topology and load changes.

Contact Graph Routing (CGR) algorithm [8] is a typical static routing algorithm that partitions the LEO satellite network in the time-space domain to mask the dynamic characteristics of the network topology. The workflow of CGR algorithm is shown in figure 3.

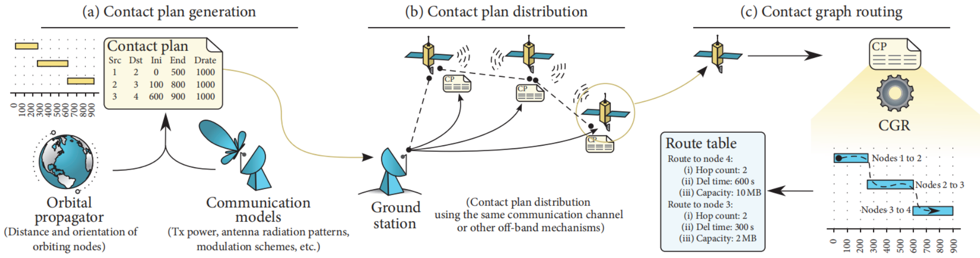

Figure 3: Contact plan generation, distribution, and utilization by CGR [8]

Dynamic routing algorithms obtain real-time status information of the satellite network and continuously optimize the routing algorithm, proposing routing algorithms based on the dynamic and predictable nature of satellite topology. Reference [9] designed a congestion prediction-based QoS-aware routing algorithm that adapts to both real-time and non-real-time traffic, effectively improving the efficiency of the satellite network and enhancing user QoS satisfaction.

3.1.3 Routing algorithms based on Quality of Service (QoS) assurance

Satellite networks are characterized by intermittent connectivity, large-scale delays, and time varying topology. These features seriously affect the transmission of mission data with traffic or latency requirements.

The existing relay-based Contact Graph Routing (CGR) method [8] cannot ensure the transmission of large volumes of data. To reduce transmission time, reference [10] proposed an algorithm based on the Storage Time Aggregated Graph (STAG) to solve the maximum flow problem in time-varying networks. The STAG algorithm establishes a network and task model, defines traffic constraints, and calculates task routing priorities, ultimately identifying multiple paths that maximize flow to complete mission data transmission within acceptable latency. This process includes describing network resources in time and space dimensions, modeling the start and end of tasks, and ensuring that task traffic does not exceed network capacity and node storage limitations under multiple constraints.

The STAG algorithm effectively matches scarce network resources, ensures task QoS, and improves task completion rates and resource utilization. The core of this routing technology lies in its ability to adapt to the dynamic changes of the network and provide an efficient solution for multi-task transmission. Figure 4 shows an example of the STAG algorithm.

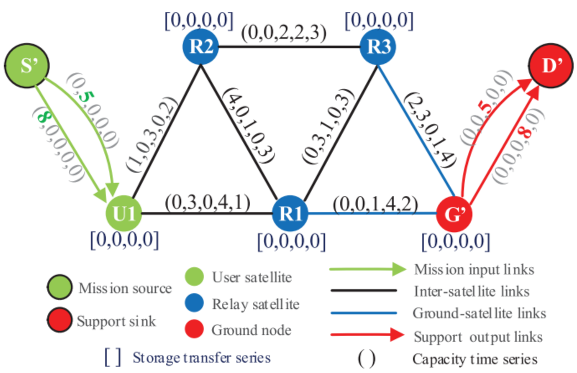

Figure 4: STAG algorithm model [10]

3.2 Routing algorithms based on artificial intelligence

The routing strategy of satellite constellations can be generally regarded as a multi-objective optimization problem. As the scale of satellite networks increases, the computational complexity also rises, making the search for routing space more challenging. When more factors are taken into account, such as optimizing for both QoS requirements and the time-varying conditions of satellite network links and interference, the difficulty of routing increases further.

Traditional routing design schemes are typically based on manually modeling network traffic characteristics, and routing strategies are designed accordingly. However, the current network traffic exhibits complex spatiotemporal distribution fluctuations, making manual modeling extremely difficult [11].

3.2.1 Routing selection techniques based on heuristic algorithms

Heuristic algorithms are a class of algorithms built on intuition or experience, designed to provide approximate optimal solutions to optimization problems within an acceptable computational complexity (both time and space complexity). Common heuristic algorithms include simulated annealing, colony optimization and genetic algorithms. Compared to traditional schemes, heuristic algorithms offer new approaches to solving NP-hard problems such as network routing.

To minimize the average data transmission delay from satellites to ground stations, while satisfying orbital determination requirements, reference [12] proposed a Heuristic Based on Maximum Weight Matching (HMWM) algorithm to solve the routing design problem. This algorithm assigns weights to each potential link, prioritizing those that benefit data flow while considering the ranging requirements. Compared to the Integer Linear Programming (ILP) method, this algorithm has lower computational complexity, thereby reducing the average network delay. Figure 5 shows an example of the HMWM algorithm, where $f^{td} = 6, f^{sm} = 4, L^{\min} = 2, \alpha = 2, \beta = 300, \eta = 0.5, Q = 50$.

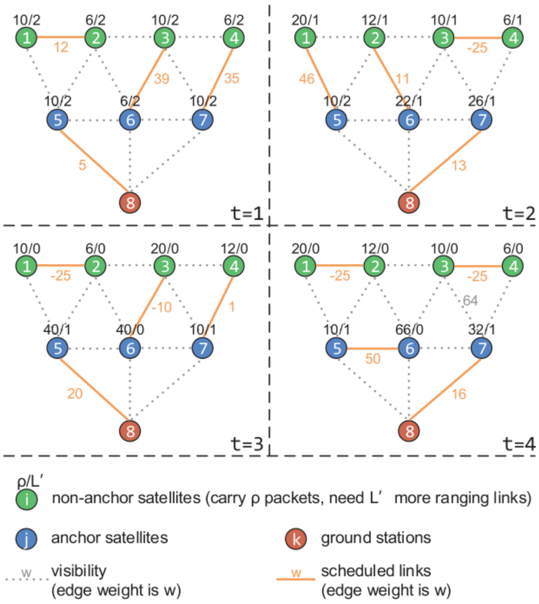

Figure 5: An example of the HMWM algorithm [12]

To improve load balancing and meet the QoS requirements of LEO satellite networks, reference [13] proposed an optimized routing algorithm based on ant colony optimization. By matching the initial pheromone concentration to the traffic demands of the satellite network, this algorithm reduces the pheromone accumulation on high-demand paths, avoiding network congestion caused by traffic aggregation, and thus converging to the optimal solution more quickly. By comprehensively considering multiple QoS optimization factors such as end-to-end delay, delay jitter, and remaining bandwidth, this algorithm can find the path with the minimum cost under delay and load balancing constraints for each service request.

3.2.2 Routing algorithms based on machine learning

Unlike heuristic algorithms, machine learning is a data-driven approach primarily aimed at training models through data to perform tasks such as prediction, classification, or others. Machine learning includes supervised learning, unsupervised learning, and reinforcement learning. Deep learning is a branch of machine learning, uses multilayer neural networks to learn and represent data. A typical deep learning algorithm is the Convolutional Neural Network (CNN) model.

To solve the issue of traffic load imbalance in LEO satellite networks, reference [14] proposed a Load Balancing Routing Algorithm Based on Q-routing in Low-Earth-Orbit Satellite Network (LBQR), as shown in figure 6. The algorithm reduces the risk of network congestion and achieves load balancing by introducing randomness and load evaluation. Q-routing incorporates randomness in action selection and uses remaining buffer space as a load evaluation metric when updating Q-values. Additionally, gradient calculation is included in the dynamic adjustment of the learning rate to adapt to environmental changes and improve algorithm performance.

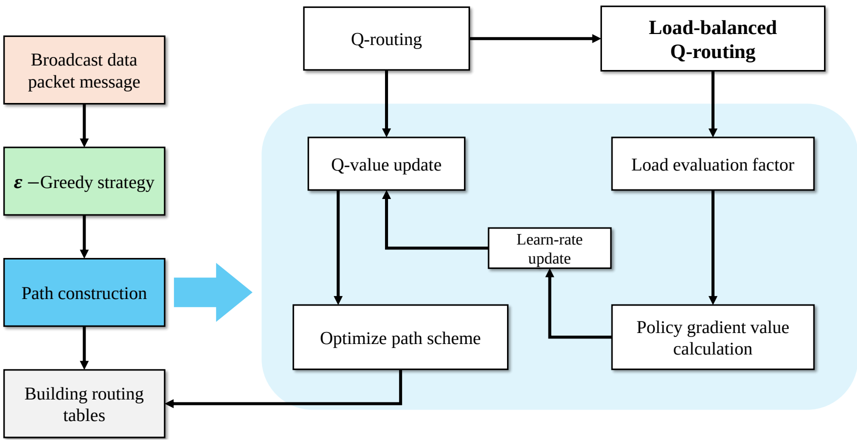

Figure 6: LBQR algorithm framework

To achieve efficient and secure forwarding of satellite network nodes, reference [15] designed an adaptive routing algorithm for Satellite Internet of Things (S-IoT) based on improved double Q-learning. The entire S-IoT is viewed as a reinforcement learning environment, with satellite nodes and ground nodes acting as agents, each maintaining two Q-tables for forwarding and evaluation. This algorithm provides more efficient and secure routing and forwarding in highly dynamic environments.

To solve the routing computation challenges in highly mobile satellite networks, reference [16] proposed a graph-based routing (GR) algorithm based on Graph Neural Networks and deep reinforcement learning, as shown in figure 7. The algorithm uses the DQN framework and Graph

Neural Networks to capture network topology changes and optimize routing selection. GR considers constraints like topology, bandwidth, and delay, performing representation learning through Graph Neural Networks. Simulation results show that GR significantly improves throughput, reduces packet loss, and ensures low latency.

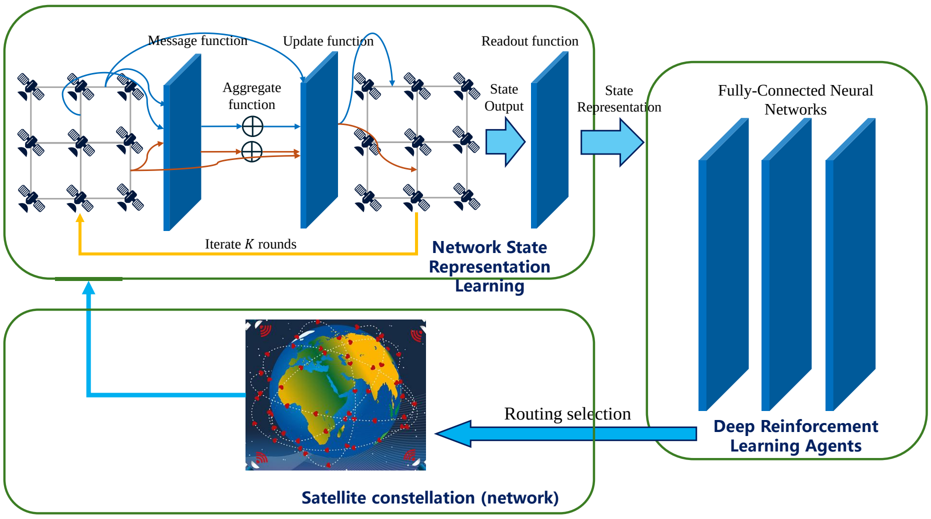

Figure 7: GR routing algorithm architecture

4 Critical Analysis of Technology

Table 1: Typical routing algorithms in LEO satellite constellation networks

Routing Algorithm		**Typical representative**
Based on graph theory	Coverage area division	FHRP
	Topology structure	CGR
	QoS assuran	STAG
Based on Artifical intelligence	Heuristic algorithms	HMWM
	Machine learning	LBQR
		GR

Table 1 summarizes the typical routing algorithms in LEO satellite constellation networks. In this section, cost and performance analyses will be conducted for each typical algorithm.

4.1 FHRP algorithm

Cost analysis:

• The new optimal route is calculated based on the coverage characteristics of the satellites after handover, avoiding complex algorithms and resulting in lower overhead.

• It is a handover control protocol that requires the participation of end-users, resulting in high complexity in the design of the end-user protocol.

Performance analysis:

Updating routes at fixed intervals can cause significant performance fluctuations.

4.2 CGR algorithm

Cost analysis:

• Regarding computational overhead, the CGR algorithm requires pre-calculation and distribution of a global contact plan, which includes the calculation of orbital propagation and communication models, resulting in significant overhead when the number of nodes is large. Additionally, CGR dynamically calculates the optimal path for each incoming data packet using Dijkstra's algorithm, requiring nodes to have high processing capabilities.

• When the network size is very large, satellites need to store a large number of routing tables, resulting in substantial storage overhead.

Performance analysis:

CGR offers high flexibility, allowing dynamic adjustment of routes to respond to changes in network topology and traffic conditions.

4.3 STAG algorithm

Cost analysis:

• The main steps of the algorithm include finding the augmented path and calculating the maximum flow and the residual network, resulting in a generally high computational complexity.

• The STAG model requires storing time-series data, leading to substantial storage overhead when there are many nodes and time intervals.

Performance analysis:

The QSMR algorithm significantly reduces the average task completion time, with task completion rates 5% to 10% higher than existing methods, and improves the utilization of link and node cache resources. This algorithm performs excellently in terms of task completion time, task completion rate, and resource utilization.

4.4 Based on HMWM algorithm

1. Cost analysis:

The time complexity of the Heuristic Algorithm based on Maximum Weight Matching (HMWM) is $O(T \cdot E \cdot N^2)$, where T is the number of time slots, E is the number of edges in the graph, and N is the number of nodes. The heuristic approach reduces this time complexity, making the algorithm's overhead manageable in practical applications.

2. Performance analysis:

• The algorithm performs excellently in optimizing data transmission delays. By using the maximum weight matching algorithm, it selects the highest-weight links for data transmission in each time slot, thereby reducing data waiting time and transmission delays.

• The maximum weight matching algorithm optimizes link selection, enhancing link utilization and ensuring that the network's link resources are fully utilized.

4.5 LBQR algorithm

Cost analysis:

The algorithm embeds a reinforcement learning module in the nodes and combines the ε-greedy strategy with policy gradient calculation, enabling real-time dynamic adjustment and adaptation to network loads. Although this introduces additional computational overhead, it effectively monitors and evaluates remaining cache to avoid network congestion, resulting in overall low overhead.

Performance analysis:

The LBQR algorithm demonstrates superior performance in terms of low latency, high throughput, and low transmission overhead ratio under different CBR rates. By dynamically adjusting the learning rate and incorporating load-aware heuristic information, it effectively improves the quality of routing strategies, load balancing capability, and network reliability, resulting in overall good performance.

4.6 GR algorithm

Cost analysis:

The algorithm incurs large computational overhead during the training phase, requiring substantial resources for message passing in the graph neural network and parameter optimization in deep reinforcement learning. However, in the practical application phase, the already trained model requires fewer computational resources for routing decisions, resulting in low overhead during real-time decision-making.

Performance analysis:

The GR algorithm performs excellently in terms of performance, significantly improving satellite network throughput and reducing packet loss while maintaining low latency.

4.7 Overall evaluation

After analyzing the cost and performance of some routing algorithms in LEO satellite constellation networks, it can be found that each algorithm has its advantages and disadvantages.

Traditional routing algorithms based on graph theory have high flexibility and adaptability, but they also have high computational complexity and storage overhead. Routing algorithms based on artificial intelligence have lower computational complexity and storage overhead, but the early training requires a large amount of data and have high training costs.

In the future, with the increasing scale of LEO satellite networks and the complexity of network topology, routing algorithms based on artificial intelligence will be more suitable for LEO satellite constellations. These algorithms can adapt to the dynamic changes in network topology and traffic conditions, optimize routing strategies, and improve network performance. However, artificial intelligence algorithms require a large amount of data for training. Therefore, future research should focus on reducing these issues in LEO satellite constellation networks.

5 Conclusions

This paper comprehensively reviews the research progress of routing algorithms for LEO satellite constellation networks by discussing both traditional and AI-based algorithms. It highlights that AI algorithms exhibit better adaptability and performance in future LEO satellite networks. These innovative studies not only provide important guidance for the development direction of future routing algorithms but also offer new insights for the advancement of LEO satellite networks. Looking ahead, as LEO satellite network technology continues to mature and its application domains expand, satellite constellation networks will employ more optimized algorithms and support a wider range of diversified and complex services. It is hoped that the summary provided in this paper will serve as a valuable reference for future researchers.

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[4] Chen Quan, Yang Lei, Guo Jianming, et al. Low-earth orbit mega-constellation network: networking technology and research status [J]. Journal of Communications, 2012,43(05):177-189.

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Overview of Routing Algorithms in LEO Satellite Constellation Networks

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Background

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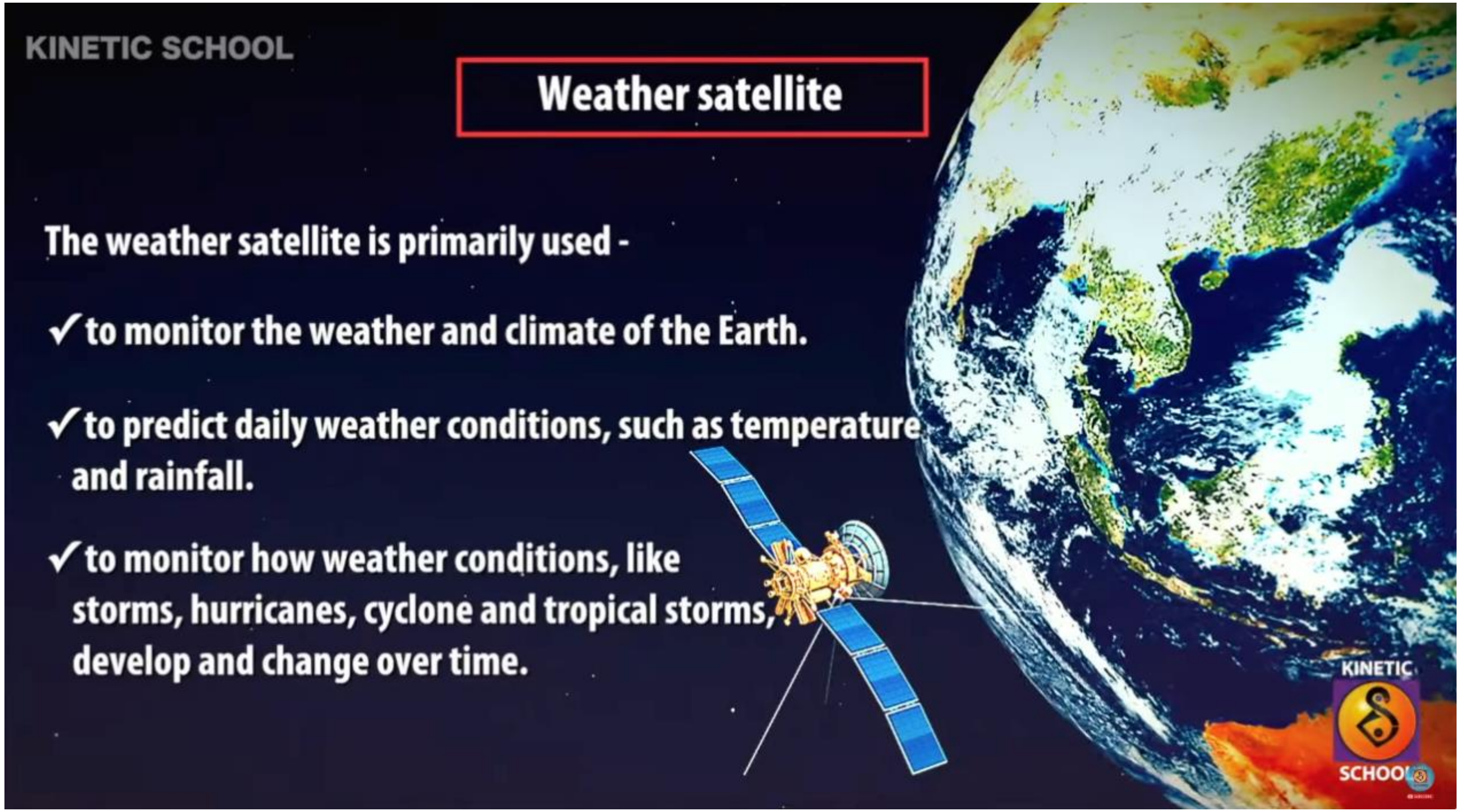

❑ What can satellites do?

- Earth observation satellites can monitor weather, disaster, agriculture...

Figrues are obtained from https://www.youtube.com/watch?v=n70zjMvm8L0

Background

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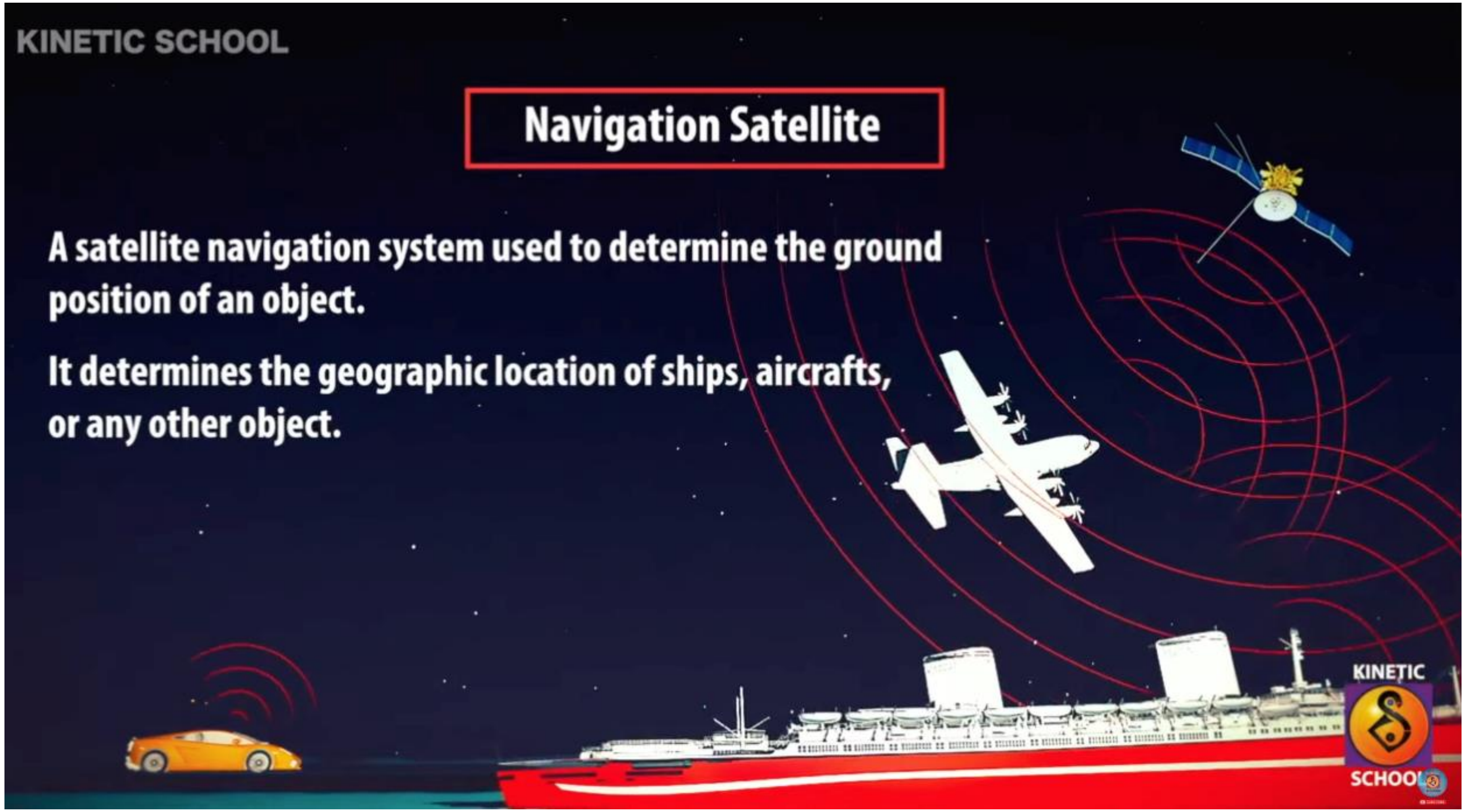

❑ What can satellites do?

- Navigation satellite can determine the ground position

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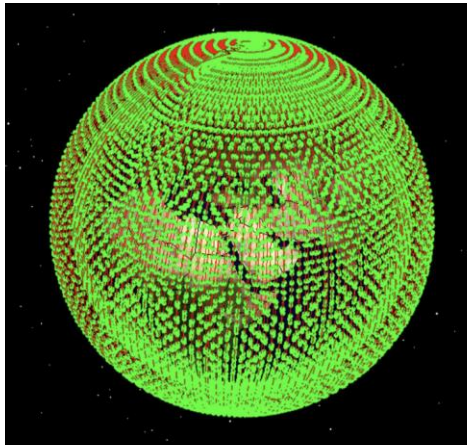
Background

- Commercial Satellite Constellations

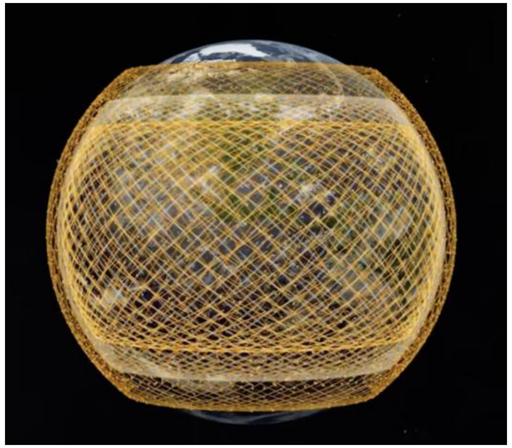
STARLINK

amazon | project kuiper

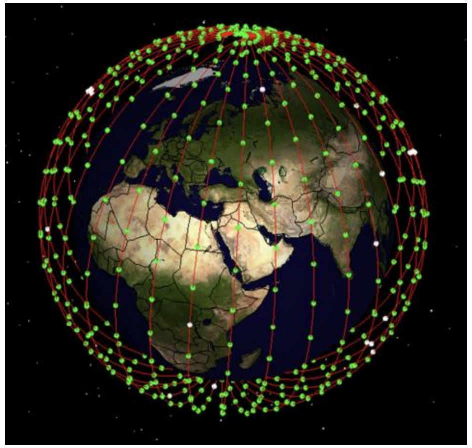
OneWeb



11,943 satellites



3,236 satellites



648 satellites

Figures are obtained from https://www.google.com/, https://www.aboutamazon.com/what-we-do/devices-services/project-kuiper
X. Yang, “Low Earth Orbit (LEO) Mega Constellations – Satellite and Terrestrial Integrated Communication Networks”.

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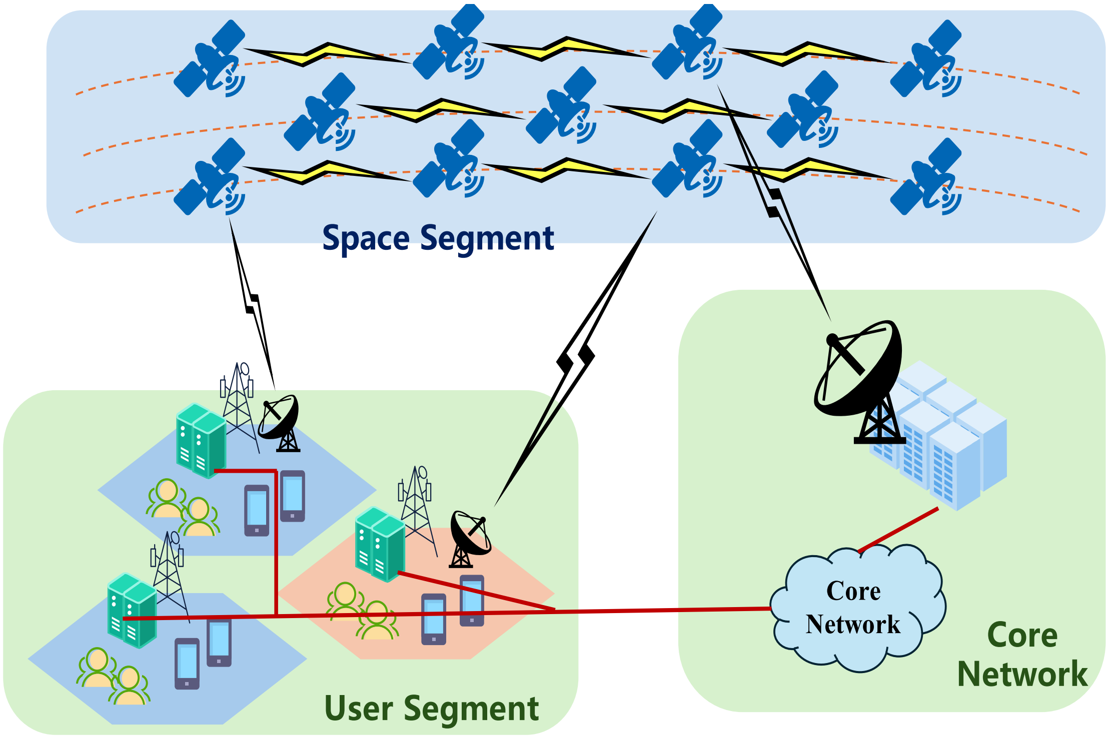
LEO SC Network



❑ What are Satellite Constellations (SC)?

- Groups of artificial satellites working together
- Provide nearly continuous global coverage
- With similar altitude, orbital eccentricity and inclination
- Medium Earth orbit (MEO) and low Earth orbit (LEO) SCs

❑ The advantages of SC:

- Low latency
- Broadband communications
- Lower path losses and power requirement

[1] Fang Fang, Wu Mingge. Research on the development of Global Low Earth Orbit Satellite constellation [J]. Flying Missile,2020,(05):88-92+95.
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Routing Algorithms

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Table: Typical routing algorithms in LEO satellite constellation networks

Routing Algorithm		**Typical representative**
Based on graph theory	Converage area division	FHRP
	Topology structure	CGR
	QoS assuran	STAG
Based on Artificial intelligence	Heuristic algorithms	HMWM
	Machine learning	LBQR
		GR

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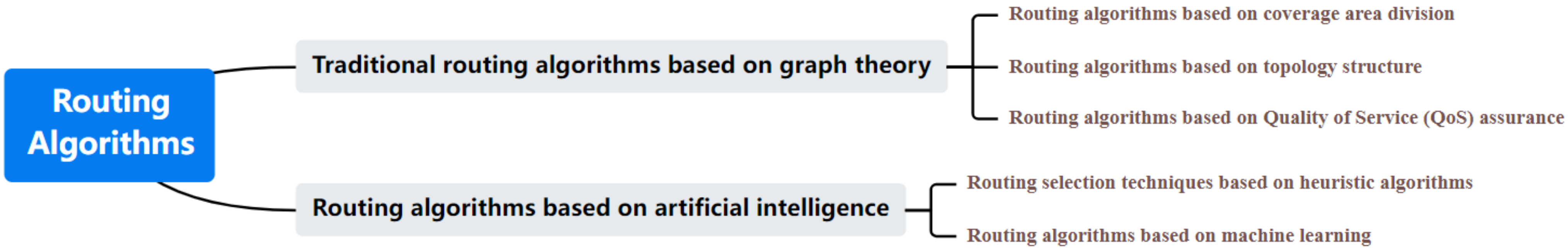


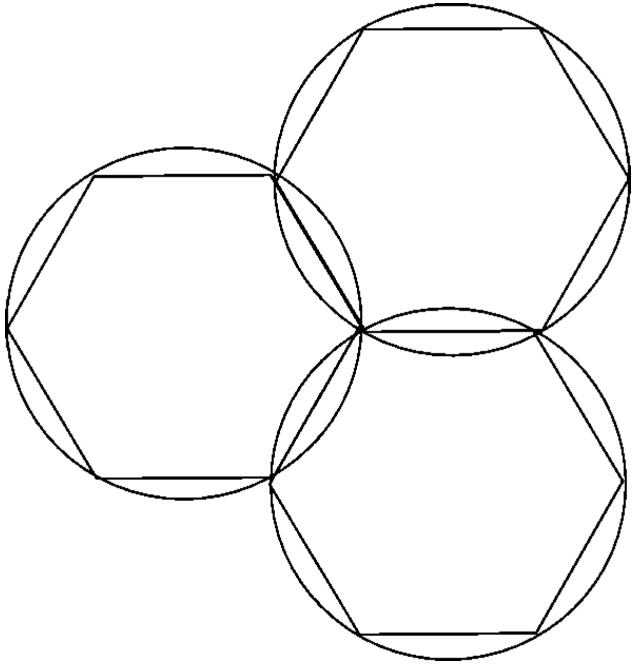
Routing algorithms based on coverage area division

- Contact Graph Routing (CGR) algorithm

1.Coverage Area Division: FHRP routes based on LEO satellite network coverage.

2.Route Augmentation and Rerouting: FHRP consists of two phases: Route Augmentation and Footprint Rerouting.

3.Optimizing Initial Path: FHRP maintains the optimality of the initial path without re-executing the routing algorithm.



The footprints of the LEO satellites

Uzunalioglu H, Akyildiz I F, Yesha Y, Yen W. Footprint handover rerouting protocol for LEO satellite networks[J]. ACM Baltzer Journal of Wireless Networks, 1999, (10): 327-337.

Routing Algorithms

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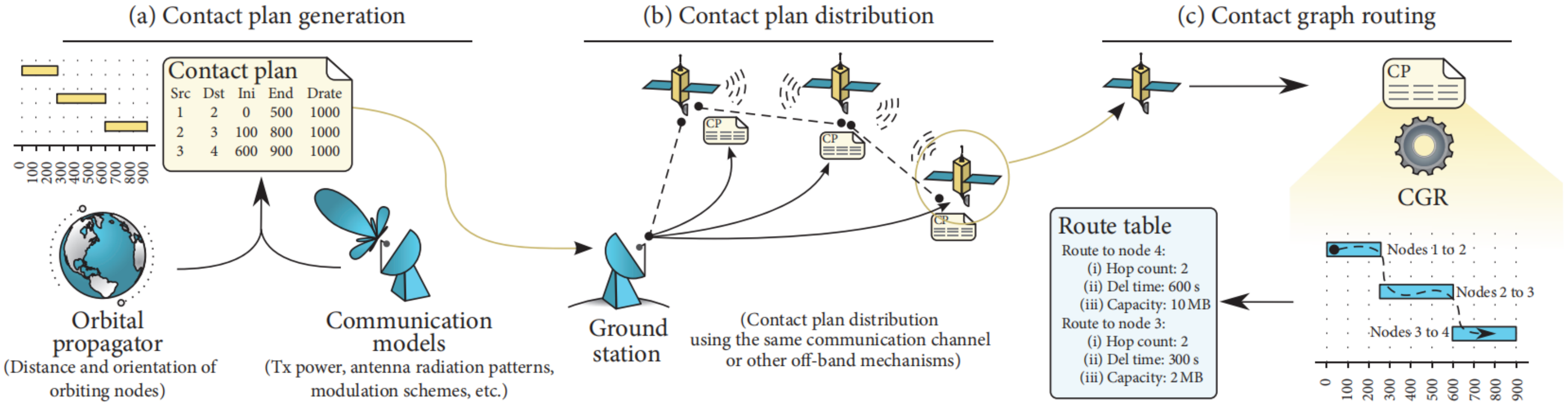
Routing algorithms based on topology structure

❑ Contact Graph Routing (CGR) algorithm

1. **Topology-Based Routing**: CGR is based on LEO satellite network topology.
2. **Static Routing**: CGR partitions the LEO network in the time-space domain.
3. **Masking Dynamic Topology**: CGR masks the dynamic characteristics of network topology.



Fraire J A, Madoery P, Burleigh S, et al. Assessing contact graph routing performance and reliability in distributed satellite constellations[J]. Journal of Computer Networks and Communications, 2017.

Routing Algorithms

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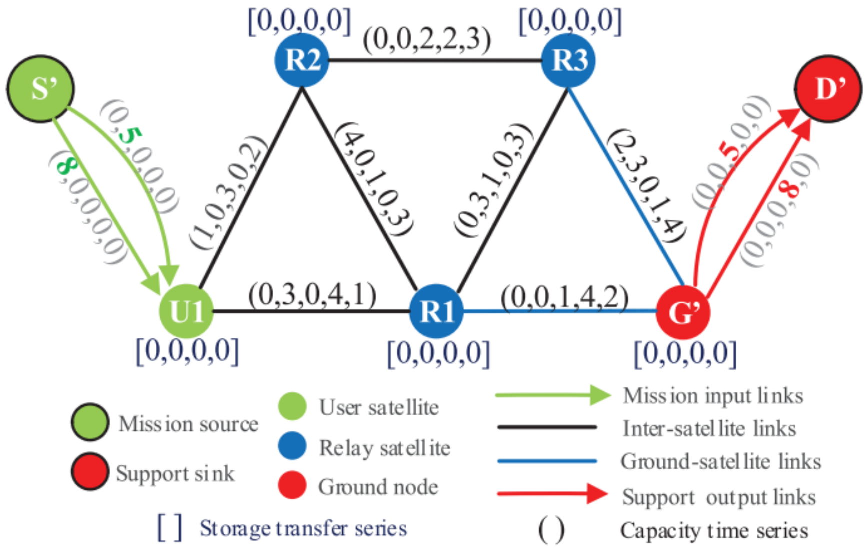
Routing algorithms based on QoS assurance

❑ Storage Time Aggregated Graph (STAG) algorithm

1.QoS-Based Routing: STAG ensures task QoS, improving task completion rates and resource utilization.

2.Solving Maximum Flow Problem: STAG identifies multiple paths that maximize flow for task data transmission within acceptable latency.

3.Adapting to Network Dynamics: The core of STAG is its ability to adapt to dynamic network changes.



STAG algorithm model

Zhang T, Li H, Zhang S, et al. STAG-based QoS support routing strategy for multiple missions over the satellite networks[J]. IEEE Transactions on Communications, 2019, 67(10): 6912-6924.

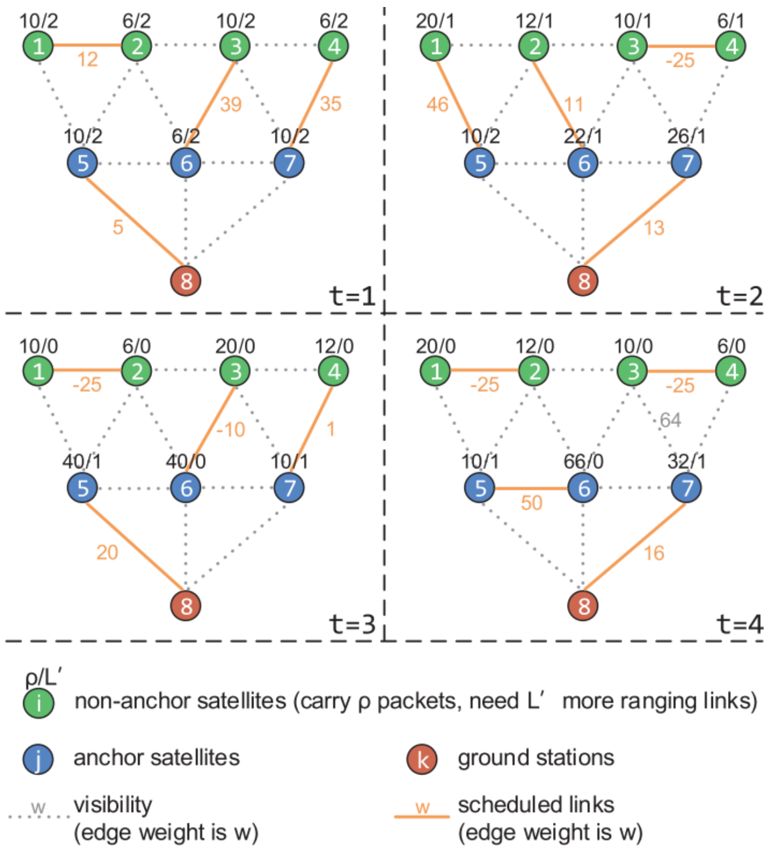
Routing selection based on Heuristic algorithm

❑ Maximum Weight Matching (HMWM) algorithm

1.Heuristic Algorithm: Heuristic Algorithm: HMWM is an intuitive approach that offers near-optimal solutions.

2.Maximum Weight Matching: HMWM assigns weights to potential links to prioritize beneficial data flow.

3.Reduced Computational Complexity: HMWM, compared to ILP, exhibits reduced computational complexity and minimizes network delay.



Yan Z, et al. Topology Design for GNSSs Under Polling Mechanism Considering Both Inter-Satellite Links and Ground-Satellite Links[J]. IEEE Transactions on Vehicular Technology, 2022, 71(2): 2084-2097.

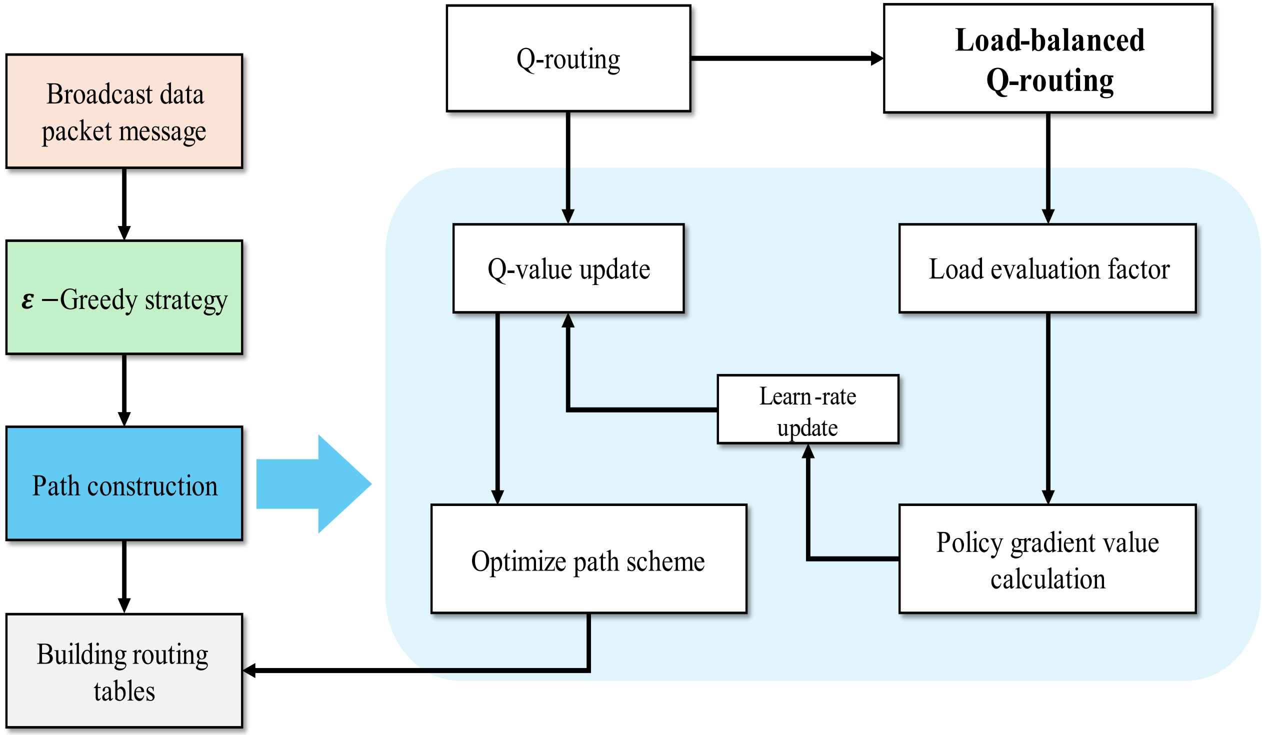
Routing algorithms based on machine learning

- ❑ Load Balancing Routing Algorithm Based on Q-routing in LEO satellite network (LBQR)

1.Solves Traffic Load Imbalance: LBQR reduces network congestion risk and achieves load balance.

2.Q-routing and Load Evaluation: LBQR uses randomness and remaining buffer space in Q-routing.

3.Dynamic Learning Rate Adjustment: LBQR includes gradient calculation for adapting to environmental changes.



Lin Wucheng. Research on low earth orbit satellite network routing algorithm based on reinforcement learning[D]. Guangzhou University, 2023.

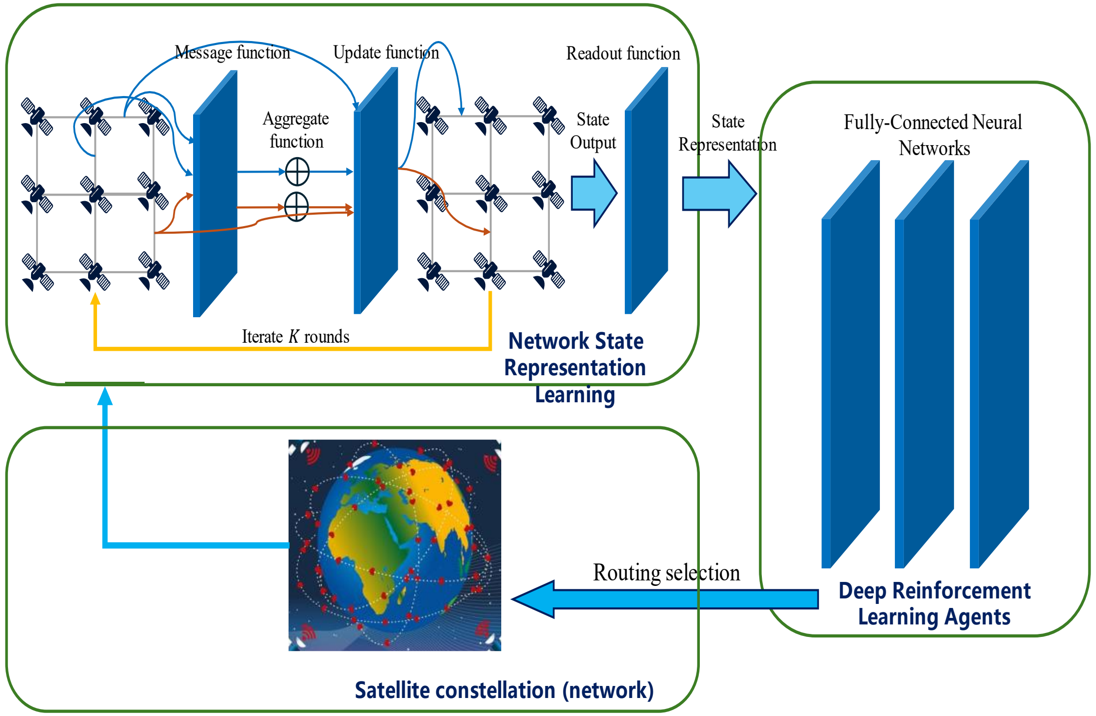
Routing algorithms based on machine learning

❑ Graph-based routing (GR) algorithm

1.Solves Routing Challenges: GR uses DQN and Graph Neural Networks to optimize routing selection.

2.Considers Various Constraints: GR considers topology, bandwidth, and delay constraints.

3.Improves Network Performance: GR improves throughput, reduces packet loss, and ensures low latency.



Wang Hao, Ran Yongyi, Zhao Lei, et al. Dynamic routing algorithm for low earth orbit satellite networks based on deep graph reinforcement learning[J]. Journal of Chongqing University of Posts and Telecommunications (Natural Science Edition), 2023, 35(04):596-605.

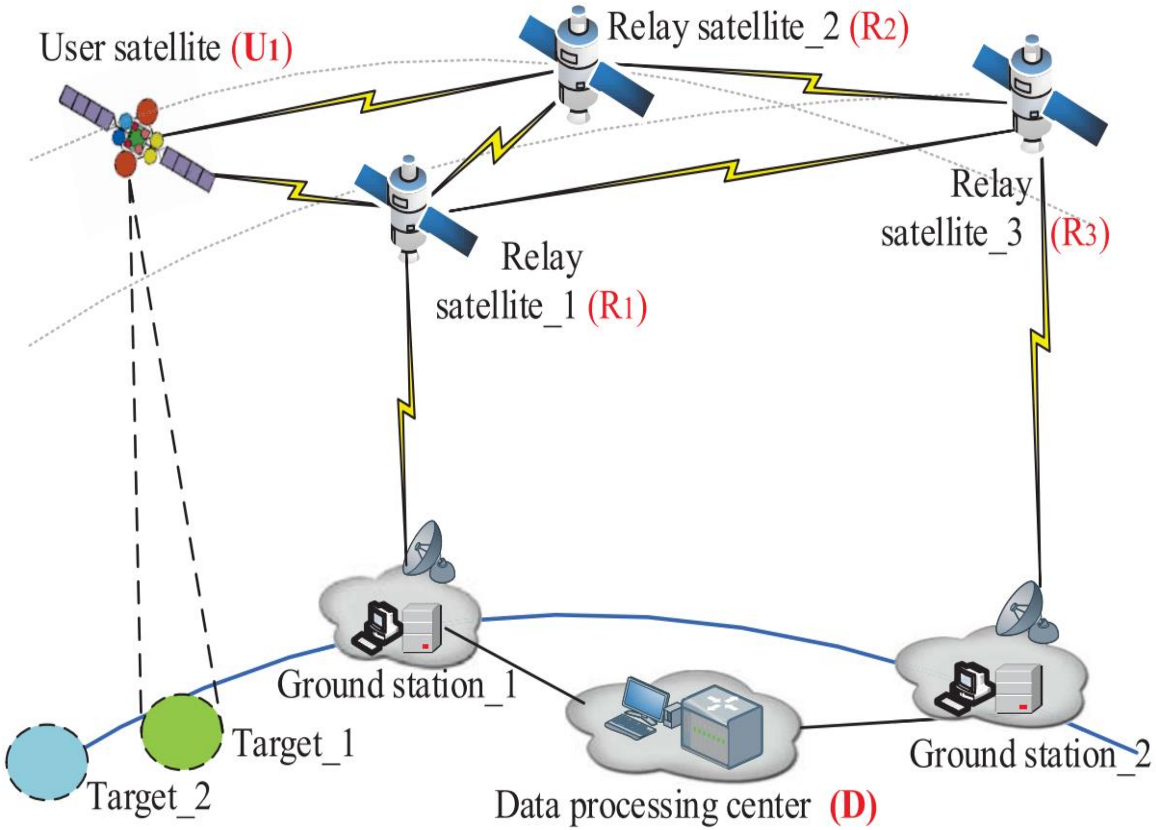
Conclusions

❑Challenges:

- Dynamic Topology Structure
- Latency and Quality of Service Issues
- Computational Complexity
- Storage Overhead

❑Directions:

- AI-Based Routing Algorithms
- Data-Driven Routing Optimization
- Hybrid Routing Algorithms
- Multi-Task Transmission Optimization
- ……



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