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Special Topic: Cohesive Clustered Satellites System for 5GA and 6G Networks

A sparrow search-based energy-adaptive routing scheme for satellite internet

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With the rapid development of satellite and terrestrial communication technologies, satellite internet has become a key component of future space-air-ground integrated information networks, providing comprehensive coverage and seamless connectivity [1]. However, the complexity of network structures and the instability of inter-satellite links (ISLs) pose significant challenges to designing stable and efficient routing schemes for satellite internet systems. Moreover, the highly dynamic nature of network topology and resource availability, combined with interference from the space environment, further complicates the technical design [2]. To address these challenges, more comprehensive and intelligent routing algorithms should be utilized to optimize resource allocation, improve transmission reliability, and enhance adaptability to dynamic network conditions, thereby ensuring accurate, continuous, and stable user services [3]. The related work can be found in Appendix A.

In this study, we propose an energy-adaptive multi-objective optimized routing scheme for satellite internet based on the sparrow search algorithm (SSA). The proposed scheme first constructs a satellite network architecture based on the Iridium constellation, then establishes a traffic model using historical data, divides the Earth's surface into multiple regions, and randomly generates source and destination nodes. Furthermore, dynamic weights for satellite energy, delay, throughput, and packet loss are normalized to calculate link cost [4]. After that, a multi-objective optimization model is formulated incorporating these parameters, and SSA is applied to develop an optimization strategy to minimize the link costs. Simulation results demonstrate that the enhancement of satellite residual energy can be significantly achieved through the proposed multi-objective optimization routing scheme.

System model. We adopt the Iridium constellation, whose dynamic characteristics exhibit both periodicity and variability over time. We evaluate transmission delay, throughput, and packet loss rate to assess satellite internet routing performance. Additionally, energy consumption is prioritized as the most important factor because LEO satellites operate under strict energy limitations, directly impacting network stability and longevity.

When the satellite performs transmission or reception services, its energy consumption includes the transmission and reception power, and the power consumed during regular operation. The following equation can express the total energy consumption:

$$E_C(t) = E_R(t) - E_N(t) - E_{\rm Tx}(t) - E_{\rm Rx}(t), \qquad (1)$$

where $E_C(t)$ denotes the residual energy at the end of the mission, $E_N(t)$ is the satellite's operating energy consumption at time t. $E_{\rm Tx}(t)$ is the energy consumed by the satellite to send data at time t, and $E_{\rm Rx}(t)$ is the energy consumed by the satellite to receive data at time t, $E_R(t)$ is the energy at the beginning of the mission, as expressed by the following equation:

$$E_R(t) = \min(W_{\max}, E_R(t) + E_{\rm cap}(t)), \qquad (2)$$

where $W_{\max}$ is the maximum energy of the battery, defined as 30 kJ in this letter, $E_{\rm cap}(t)$ is the energy captured by the solar panels and satellite battery at time interval t.

The average remaining energy of all satellites in a satellite internet snapshot can be calculated using the following equation:

$$\overline{E}_{Rn} = \frac{\sum_{i=1}^{M} E_{Rn}(i)}{W_{\max} M} \times 100\%,\ \forall n \in N, \qquad (3)$$

where $\overline{E}_{Rn}$ represents the average residual energy percentage of all satellites in snapshot n. M is the number of satellites in the snapshot, defined as 66 in this study. $E_{Rn}(i)$ is the remaining energy i in snapshot n. Other performance indicators can be found in Appendix B.2.

Algorithm design. In the design of LEO constellations, previous studies have mainly focused on optimizing a single performance metric. This can result in an incomplete assessment of the overall quality of service. In the existing studies, a single path routing-static weight (SW) algorithm is proposed as a multi-objective optimization approach that relies on fixed-weight evaluation schemes and considers multiple QoS dimensions simultaneously. However, this algorithm lacks the adaptability to accommodate evolving user

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demands and fails to address priority variations across different application scenarios.

Motivated by these limitations, this study proposes three key innovations. Firstly, a multi-objective optimization model is proposed, integrating critical metrics into a unified framework to balance competing objectives. Furthermore, a dynamic weight (DW) multi-objective evaluation scheme is introduced to adapt to real-time network topology changes and varying user demands. Lastly, an SSA-based path planning approach is proposed, effectively managing dynamic topology and resource constraints. The proposed methods aim to provide a comprehensive solution for enhancing the efficiency, reliability, and operational lifetime of LEO satellite internet systems by integrating intelligent algorithms into both the multi-objective evaluation and path planning processes.

In this study, satellite residual energy, transmission delay, throughput, and packet loss rate are considered key metrics, and the following link cost model is established between adjacent nodes [5]:

$$S_{x,y} = \omega_1 \frac{D_{x,y} - D_{\min}}{D_{\max} - D_{\min}} + \omega_2 \frac{E_{x,y} - E_{\min}}{E_{\max} - E_{\min}} + \omega_3 \frac{B_{x,y} - B_{\min}}{B_{\max} - B_{\min}} + \omega_4 \frac{P_{x,y} - P_{\min}}{P_{\max} - P_{\min}}, \tag{4}$$

where $S_{x,y}$ represents the link cost between adjacent satellite nodes x and y. ω is the weight factor assigned to different indicators. $D_{x,y}$ is the transmission delay between adjacent satellites, while $D_{\min}$ and $D_{\max}$ are the minimum and maximum transmission delays between satellites in the snapshot, respectively. Similarly, $E_{x,y}$ refers to the energy consumption for data transmission between adjacent satellites, $B_{x,y}$ is the throughput between adjacent satellites, and $P_{x,y}$ denotes the packet loss rate for data transmission between adjacent satellites.

We define a minimum energy threshold L_B, which is 50%. When a satellite's remaining energy is below this threshold, it is considered a failure state, and we dynamically adjust and reallocate the weights of the evaluation metrics as follows:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = \begin{cases} \begin{bmatrix} 0.2 & 0.3 & 0.2 & 0.3 \end{bmatrix}^{\mathrm{T}}, \\ \quad \text{if } \frac{B_x(t)}{B_{\max}} \geqslant L_B \text{ and } \frac{B_y(t)}{B_{\max}} \geqslant L_B; \\ \begin{bmatrix} \omega_1' & \omega_2' & \omega_3' & \omega_4' \end{bmatrix}^{\mathrm{T}}, \\ \quad \text{otherwise}. \end{cases} \tag{5}$$

To prevent any single parameter from overly influencing the results, we constrained the dynamic adjustment of metric weights, ensuring each metric's weight remained between 0.2 and 0.7.

While the proposed DW scheme adaptively adjusts link weights to improve resource allocation in satellite internet networks, it relies on the traditional Dijkstra algorithm, which can lead to suboptimal paths in dynamic environments. We integrate the SSA, a global optimization method inspired by sparrows' foraging behavior, to address this limitation. The sparrow search algorithm-dynamic weight (SSA-DW) multi-objective evaluation scheme evaluates link costs comprehensively and explores multiple solutions to avoid local optima, ensuring efficient and reliable path selection in complex, evolving satellite networks. Details of the SSA are provided in Appendix C.

Simulation results and analysis. The effectiveness of the proposed algorithm is validated by comparing the proposed SSA-DW algorithm with both the SW and DW schemes. The analysis focuses on four performance metrics: average transmission delay, average hop count, average throughput, and the average remaining battery energy percentage of the satellites.

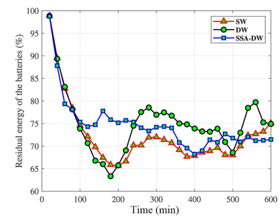

Figure 1 (Color online) Average percentage of energy remains in satellite batteries.

The average remaining energy percentage of satellite batteries in the snapshots is given in Figure 1. The minimum energy threshold L_B for satellite batteries is set to 50%. Obviously, the SW scheme results in an average remaining battery energy level of 71.89%, while the DW scheme achieves 74.68%. The SSA-DW scheme yields an average remaining energy level of 74.20%. The DW scheme demonstrates a 3.88% improvement in the average remaining battery energy percentage compared to the SW scheme. In addition, the SSA-DW scheme shows a 3.22% increase in the average remaining battery energy relative to the SW scheme. The rest of the simulation results for the indicators are provided in Appendix D.

Conclusion. This study proposes an energy-adaptive multi-objective optimized routing scheme for satellite internet based on the sparrow search algorithm, where satellite energy, transmission delay, throughput, and packet loss are all considered in the link cost. The proposed scheme integrates the dynamic multi-objective weighting scheme and the intelligent search algorithm to enhance routing efficiency and link performance. Simulation results demonstrate that the proposed SSA-DW scheme significantly improves the key performance metrics. Additionally, this solution provides reliable data transmission paths, satisfies diverse service requirements, and substantially enhances the overall utilization of network resources.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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