Optimal Strategy Routing in LEO Satellite Network Based on Cooperative Game Theory

Songjie Wei[1], Hao Cheng[1](✉), Meilin Liu[2], and Milin Ren[3]

[1] School of Computer Science and Engineering,
Nanjing University of Science and Technology,
200 Xiaolingwei, Nanjing 210094, China
{swei,115106000709}@njust.edu.cn

[2] Shanghai Institute of Satellite Engineering,
Shanghai Academy of Spaceflight Technology,
3666 Yuanjiang Rd, Shanghai 201109, China
meilinliu51@outlook.com

[3] Beijing Engineering Research Center of NGI & Its Major Application
Technologies Co. Ltd., 1 East Zhongguancun Rd,
Beijing 100084, China
rmilin@163.com

Abstract. To overcome the network difficulty such as long propagation delay and traffic load imbalance when forwarding data packets through multiple hops in LEO satellite network, we propose an optimal strategy based routing algorithm for LEO satellite network using the cooperative game theory. With the idea of cooperation for mutual benefit, a LEO satellite node has the motivation of improving its own network performance gain by cooperation with neighbors to accomplish the multi-hop forwarding task of data packets. A satellite node compares the benefits of joining various routing coalitions, and tends to choose a more powerful next-hop coalition member node for data packet forwarding, which effectively distributes and balances the traffic load of the popular nodes. Such preference also improves the utilization of the satellite network resources, and reduces the average network delay of data packets. Our simulation results show that compared with the traditional satellite routing algorithms based on the shortest path, the average packet routing delay using the proposed algorithm is reduced by 18.5% and the traffic load balance of the network is increased by 65.6%. By replacing the shortest routing path with a path of satellite nodes with the expected optimal routing performance benefit, the proposed routing algorithm outperforms the existing algorithm on both the temporal and spatial network performance.

Keywords: Satellite network · Cooperative game theory
Optimal strategy routing

1 Introduction

With the rapid advance in satellite industry, satellite mobile communication is becoming more indispensable to humans' daily life. Compared with the traditional terrestrial mobile communication systems, a satellite mobile communication system is

© Springer Nature Singapore Pte Ltd. 2018
Q. Yu (Ed.): SINC 2017, CCIS 803, pp. 159–172, 2018.
https://doi.org/10.1007/978-981-10-7877-4_14

characterized by the fast deployment to cover a large area without a lot of ground-based supporting infrastructures. For communications in wild mountainous areas, offshore islands, disaster-stricken areas, cruising vessels and voyage aircraft, Satellite-based communication network has unique irreplaceable advantage [1]. Communication satellites can be classified into low-orbit LEO satellites, medium-orbit MEO satellites and geostationary orbit GEO satellites. GEO satellite is more suitable for broadcasting services and stationary users for high-rate data service. Although GEO satellites have been widely used in radio and television services, they are not suitable for real-time communication services due to the long propagation delay of hundred milliseconds. The distance between LEO satellites and ground users is comparably shorter, and the propagation delay of satellite-ground links is thus reduced to the order of milliseconds. A terrestrial mobile terminal only needs a smaller than dish antenna to setup a space-terrestrial link. LEO satellites is time and cost efficient in manufacturing, launching, and operating, which makes it a natural choice in many communication scenarios of service-oriented systems. In 1998, the first truly LEO-based satellite communication network Iridium is deployed with on-board switching and on-board processing capabilities. After that, the heat of academic study and industrial capital investment in LEO satellite networking grows for two decades.

Users of the LEO satellite network have desires real-time data communication with low packet delay, low packet loss ratio and optimal bandwidth utilization. The LEO satellites forms a multi-hop routing, self-organizing network with dynamic topology change by a series of inter-satellite links within the same orbit or between different orbits. However, compared with the random motion of nodes in the ground mobile ad hoc network, the motion of a LEO satellite node has a significantly periodic regularity. The dynamics of a satellite network topology predictable and schedulable. Such regularity can greatly improve the satellite network routing efficiency and resource utilization [2].

In the study of routing algorithms for LEO satellite networks, Werner et al. proposed a routing algorithm for satellite networks based on virtual topology for the first time. They carried out a great deal of in-depth research and discussion on this routing algorithm [3]. The main characteristic of this algorithm is to make full use of the periodic motion regularity of satellite nodes, converting the dynamic topology of LEO satellite network into a series of static topology on time, and conducting the calculation operation of all time slices routing tables in advance. The algorithm does not require too much computing capability onboard in satellite nodes. Ekici et al. designed a satellite network routing algorithm based on virtual nodes [4]. The basic idea is to divide the earth surface into regions and allocate a logical address for each region. The address of the LEO satellite node over each region area uses the same logical address. On this basis, each satellite node calculates its routing table according to the current logical address. Because a satellite node can infer the position of any satellite node in the whole network according to the logical address, it can avoid the link state information interaction among the nodes in the network. This idea shields the impact of satellite motion in the network. There are also a class of satellite network routing algorithms called satellite network dynamic routing algorithm. Its essence is based on the similarity between the satellite network and the ground mobile network. This kind of algorithm migrates the dynamic routing algorithm in the terrestrial network to the satellite network, which is an improvement and extension to the traditional terrestrial network routing algorithm. For example, the LAOR (Location-Assisted On-demand Routing Algorithm) proposed by Karapantazis is to apply the AODV routing algorithm in the mobile ad hoc network to the LEO satellite network [5].

On the basis of the above three categories of satellite routing strategies, other researchers put forward several novel satellite network improved routing protocols [6]. Aiming at the problem that the static route in the virtual topology routing algorithm cannot adapt to the dynamic network traffic, Song et al. proposed a traffic-light-based intelligent routing strategy (TLR) based on traffic signal mechanism [7]. The routing strategy firstly combines the predictability and periodic motion characteristics of the satellite network topology, and calculates multiple routing paths from the source satellite node to the destination satellite node in advance with the propagation delay as the routing cost. Then each satellite node periodically broadcasts its status information such as the queue occupancy rate to the neighbors, which is the traffic light information of the node. In the data packet relay forwarding process, the first routing path is adjusted locally according to the traffic signal information of the neighbor nodes, so as to bypass the congested satellite nodes and inter-satellite links as much as possible. This strategy uses the multi-path routing mechanism combined with static and dynamic planning to avoid and reduce network congestion, so as to balance the network traffic load. However, the application of the routing strategy has a prerequisite that the author believes in which the satellite node congestion can only happen in one or two inter-satellite links. With the progress of satellite network technology and the increasing degree of social informatization, the trend of the rapid increase of satellite network traffic makes this assumption not practical. Local optimization of routing path cannot achieve satisfactory results in the real satellite network. In the following simulation experiments, we compare this routing strategy with the optimal strategy routing algorithm based on cooperative game proposed in this paper, and the result analysis and discussion of these two strategies illustrates this limitation in local optimization.

In recent years, many researchers begin to apply the game theory in economics, especially the non-cooperative game theory to the network resource allocation problems such as bandwidth, power and channel. For example, Baig et al. applied the non-cooperative game theory to mobile ad hoc networks to establish a selfish node incentive mechanism, which makes the selfish nodes tend to participate in the relaying of data packets to get higher returns [8]. Paramasivan and Zheng et al. tried to solve the network security problem in mobile ad hoc networks by dynamic Bayesian signal game [9, 10]. Jiang et al. introduced the Stackelberg game into a hybrid multi-layer satellite network composed of GEO and LEO satellites to implement data packet routing, relay forwarding and network traffic load balancing [11].

In this paper, routing in a LEO satellite constellation network is taken as the problem study scenario, and an optimal strategy routing algorithm based on cooperative game is proposed. Cooperative game can make LEO satellite nodes have better cooperation initiative. According to the predictable topology of the LEO satellite constellation network, a number of routing paths between the source satellite node and the destination satellite node are constructed. The coalitional game is introduced into the data packet forwarding process of the LEO satellite node. The ground of LEO satellite relay nodes on the routing path are treated as an alliance, and the cooperative benefits of the routing alliance are defined by using the nodes' real-time status information and the performance of network routing path. The Shapley value of the coalitional game is used as the solution of the cooperative game and determines the individual benefits of LEO satellite relay node. In the process of forwarding data packets, the LEO satellite nodes independently calculate, compare the gains that can be obtained from each routing game alliance, and then determine the next hop of the data packet. In order to improve its own revenue, LEO satellite nodes tend to join more profitable routing alliances, and select the next hop member node of the alliance to forward the data packets. Therefore, it can bring better node traffic load balancing effect, shorten the network delay of data packets, and significantly improve the utilization rate of satellite resources.

The rest of this paper is organized as follows. Section 2 discusses the proposed coalition routing game. Section 3 presents NS-2 simulation results for the proposed approach and compares the results with those of TLR. Section 4 provides the conclusion and some discussion on future works.

2 Cooperative Gaming Routing Model

The periodic motion of LEO satellite nodes makes the LEO satellite network natural with multipath routing attributes. How to use the multipath routing in LEO satellite network to realize the efficient utilization of satellite resources, and the effective improvement of network performance has become an important subject of current research on satellite networking.

Game theory is a mathematical tool used to solve the cooperation and conflict between individuals. In this paper, we introduce the cooperative game theory to analyze the routing and forwarding of data packets in LEO satellite network, and to solve the typical problems such as unbalanced traffic load, network congestion and low resource utilization rate in LEO satellite network due to the uneven distribution of population on earth.

According to the three elements of game theory: player, strategy space and utility function, this paper defines the relay forwarding behavior of data packets in LEO satellite network as a cooperative game, and achieves the game revenue maximization, a reasonable allocation of resources, network performance optimization through the cooperation between nodes.

2.1 Coalitional Gaming Routing Model

In this paper, a coalitional game [12] is introduced in the data packet forwarding process of the LEO satellite node. A plurality of LEO satellite relay nodes from the source node to the destination node are treated as an alliance. As mentioned earlier, due to the natural multipath routing attributes of the LEO satellite network, a LEO satellite node usually has multiple associations as choices to join. In order to maximize its own benefit, a node tends to join the game alliance that can achieve the highest revenue. A satellite node chooses to join the optimal routing alliance based on the revenue that the node can achieve when joining the alliance, which is the revenue that the routing alliance allocates to the node based on the contribution of the node to the alliance, and the contribution of the satellite node to the routing alliance can be quantified by the Shapley value [13]. This paper uses the Shapley formula as the solution of the coalitional game, that is, the allocation scheme of the coalitional game utility, which can effectively guarantee the rationality and fairness of the cooperative revenue allocation.

In the above cooperative game model, the players of the game are defined as LEO satellite nodes, and the strategy space includes the next hop of the data packet forwarding, or the neighbor node of the current LEO satellite node. Next, we define the revenue of the alliance and the revenue of the node in detail. The alliance's revenue describes the gains that can be obtained by all nodes on a routing path. The revenue of a single node is closely related to the revenue of the alliance, and the higher the revenue of the alliance, the higher the revenue that the node receives from the alliance. In this paper, we use the data packet routing performance and the overall performance of the network to measure the revenue of the routing alliance, because our ultimate goal is to improve the forwarding efficiency of data packets and the overall performance of the network through the cooperative game between satellite nodes. Therefore, the revenue of the alliance is positively correlated with routing performance and network performance, and it is feasible and reasonable to measure the effect of cooperative game with observable routing performance and network performance parameters.

2.2 Routing Coalition Revenue Function Definition

The performance parameters of the LEO satellite node n described in this paper mainly include the current remaining available bandwidth of the node, namely the throughput attribute $throughput(n)$, the node queue delay attribute $queuedelay(n)$, the network packet loss rate attribute $packetloss(n)$, and the node buffer capacity attribute $bufferlength(n)$. These attributes are critical to network routing performance. For a routing path $P = (s, n_1, n_2, \ldots, d)$ from the source satellite node to the destination, its routing performance parameters are computed as follows:

$$throughput(P) = \min_{n \in p}\{throughput(n)\} \tag{1}$$

$$delay(P) = \sum_{n \in P} queuedelay(n) \tag{2}$$

$$packetloss(P) = 1 - \prod_{n \in P}(1 - packetloss(n)) \tag{3}$$

$$bufferlength(P) = \min_{n \in P}\{bufferlength(n)\} \tag{4}$$

Consider the grouping problem for satellite networks as a coalitional game. Every route from the source to the destination is treated as a coalition. The satellite nodes are the players and the game is concerned with whether a node should join a group or not. How the node may select the best group to join, we need a utility function which reflects the benefit for the node's joining a coalition. Here we use the quality of routing to measure the payoff for a participation node, because quality of routing is shared among every participation node. The payoff function of a path P can be expressed as follows:

$$f(P) = \alpha(throughput(P) - T_{min}) + \beta(D_{max} - delay(P)) + \gamma(1 - packetloss(P)) + \lambda(bufferlength(P) - B_{min}) \tag{5}$$

where $throughput(P)$, $delay(P)$, $packetloss(P)$, and $bufferlength(P)$, respectively, denote throughout, delay, packet loss ratio, and buffer capacity for the path as defined in (1), (2), (3), and (4). T_{min}, D_{max} and B_{min} indicate the path's minimal tolerable throughput, maximal tolerable delays and minimal buffer size available, respectively. α, β, γ and λ are the weighting factors for normalizing these requirements. That is to say, the value of α, β, γ, λ itself is of no significance, and the ratio between them is meaningful. By adjusting the ratio between α, β, γ and λ, different routing QoS requirements can be achieved, and different network performance requirements can be improved to meet the needs of different data traffic for different service quality.

2.3 Routing Coalition Revenue Allocation Mechanism

The most important thing in the cooperative game is the allocation of the cooperative revenue, as it relates to whether the cooperative coalition can be maintained steadily. A reasonable, fair and equitable coalition revenue allocation scheme ensures that any one of the participants in the coalition is reluctant to leave the current coalition and join another coalition. Because even if the participant leaves the current coalition to join another coalition, it cannot get higher returns. Based on individual rationality, it has no incentive to leave the current coalition.

As a widely applicable concept, the Shapley value is a solution that assigns a single benefit allocation to benefit sharing games. We choose this solution to a cooperative game since the computational complexity is small and the Shapley value provides relatively anonymous solution by a random ordering of the nodes. It had been proved that the Shapley value is the unique value on the set of games satisfying anonymity, dummy, and additivity. The benefits of the nodes in the coalition are calculated as follows:

$$\varphi_i(f) = \sum_{S \subseteq A \backslash \{i\}} \frac{|S|!(n-1-|S|)!}{n!} (f(S \cup \{i\}) - f(S)) \tag{6}$$

In (6), $S \subseteq A \backslash \{i\}$ denotes all coalitions S of A not containing node , where A is a finite set of nodes. $\frac{|S|!(n-1-|S|)!}{n!}$ represents the probability that the participant joins the coalition S, and $|S|$ represents the number of participants in the coalition S. Therefore, $\varphi_i(f)$ indicates the benefit allocation in the benefit sharing game for node i in the coalition $S \cup \{i\}$. There are two coalitions in (6): one is S and the other is $S \cup \{i\}$, and they are all routing coalition. In coalition S, the routing probe cannot arrive at destination node, so the payoff of S is 0. Then the benefit allocation in the cooperative game for node i in the coalition $S \cup \{i\}$ can be written into:

$$\varphi_i(f) = \sum_{S \subseteq A \backslash \{i\}} \frac{|S|!(n-1-|S|)!}{n!} (f(S \cup \{i\})) \tag{7}$$

In (7), the benefit allocation in the benefit sharing game for node i decreases with the number of participation being increased and with coalition benefits being decreased. So as a rational node, in order to maximize the benefits, the node tends to join the coalition which has less participation number and more benefits.

2.4 Cooperative Gaming Routing Cost Problem

Although the topology of a satellite network is dynamic, its change is not random, but can be determined in advance according to the laws of the constellation movement. In order to make full use of the periodic motion law of LEO satellite constellation and to reduce the routing control overhead of cooperative game routing algorithm, this paper transforms the dynamic topology of LEO satellite network into static topologies in several time slices by referring to the virtual topology routing mechanism in satellite network. In a certain time slice, we firstly calculate multiple node-disjoint routing paths as the alternative routing coalitions in the cooperative game routing algorithm based on the Dijkstra shortest path algorithm, so as to avoid spending too much unnecessary control overhead to collect network topology information.

The above-mentioned satellite network topology is predictable, but the traffic distribution in the network is unpredictable. We want to construct an adaptive optimal revenue routing algorithm based on cooperative gaming to deal with the dynamic network traffic distribution. In order to collect this dynamic traffic change information and avoid the large additional routing overhead, this paper uses the data piggyback mechanism to collect the state information of satellite nodes and inter-satellite links. These network state information is encapsulated into the data packet traffic, which gradually spreads over the entire LEO satellite network with the relay forwarding of the data packets. Finally, a satellite node uses the collected network state information to calculate the revenue of each routing coalition, and forwards the data packets according to the routing path determined by the routing coalition with the best revenue.

In the network state awareness scheme used in this paper, each satellite node needs to be aware of the state of all its inter-satellite links, which are connected to the neighbor nodes of the satellite. By adding additional piggyback information such as throughput, queue delay, and packet loss ratio to the data packets, LEO satellite nodes can obtain these information in real time during the forwarding of data packets and estimate the traffic load status of other network nodes based on these information [14]. This paper focuses on the cooperative game routing modeling process rather than the network state awareness and its cost analysis. The detailed description of the network state awareness scheme and the analysis of the routing cost can be found in the above referred literature.

3 Experimental Evaluation

To evaluate the performance of the proposed cooperative gaming routing protocol for LEO satellites, we benchmark the new protocol with the two mostly referred and studied ones, the Dijkstra shortest path routing algorithm based on propagation delay and the intelligent multi-path routing strategy TLR based on the traffic light signal mechanism. The corresponding LEO satellite network routing protocols simulation program is implemented on the ns-2 (Network Simulation Version 2) platform. The LEO satellite constellation model uses a polar orbital constellation model of Iridium-like systems.

3.1 Constellation Model Construction

Figure 1 shows the structure of the Iridium-like constellation model experimented in this paper. The LEO satellite constellation model is designed with 6 orbital planes, each with 11 LEO satellites for a total of 66 LEO satellites with an orbital inclination of 86.4° and an orbit height of 780 km. Each LEO satellite has four inter-satellite links connected to the neighbor nodes. An ISL between neighbor satellites in the same plane (orbit) is an intra-plane link, while one connecting cross-plane (cross-orbit) satellites is an inter-plane link. The relative inter-satellite distance and angle is constant inside the same orbit, so that intra-plane ISLs can be built and maintained continuously. The relative distance, speed and angle of satellites are time varying between different orbits. In general, the relative angular velocity between satellites at both ends of the inter-satellite link is significantly increased in the bipolar region, and the satellite antenna cannot maintain satellite communications on different orbits at an ever-changing angular velocity. Therefore, in order to reflect the characteristics of LEO satellite network operation with high fidelity, when a LEO satellite runs to a high latitude area above 60°, it closes its inter-plane links. The cost of building and maintaining cross-seam links is very expensive. Previous research indicates that cross-seam links only have trivial impact on network performance when doing satellite networking and communication, so our experiments do not consider the cross-seam links as others [15].

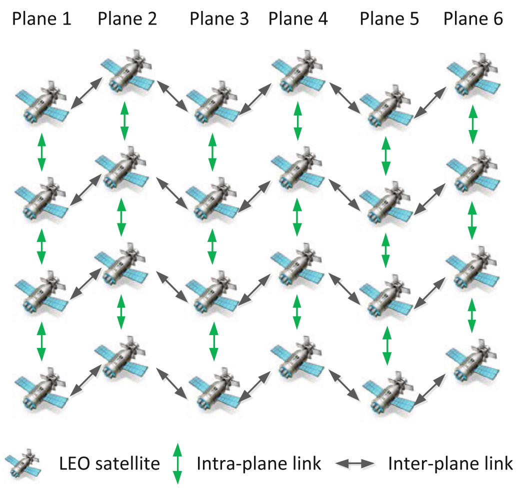

Fig. 1. Network topology with nodes and links in satellite constellation

3.2 Simulation Parameter Configuration

In the above LEO satellite constellation network model, the optimal revenue routing algorithm of cooperative game is simulated. With theoretical analysis and empirical evidence, we determine the ratio of weighting factors α, β, γ and λ as 4:3:2:1, for network traffic load balancing. Therefore, in the simulation experiment, the values of α, β, γ and λ are normalized and then set to 0.4, 0.3, 0.2 and 0.1 respectively. The simulation time for each experiment is 7200 s, which is about one satellite network running period. The data results are the mean of 100 simulation experiments. In order to more directly reflect the performance of the routing algorithm under different network load conditions, 200 data flows are established at the network application layer. The transmission time of each data flow is 15–25 s, and the distribution of data flows is in accordance with the Pareto distribution characteristics. That is, only a small number of satellite nodes transmit and receive data packets, and most of others are only responsible for relaying and forwarding data packets.

Note that this paper only considers inter-satellite routing, assuming that the terrestrial user node has sent the data packet to the source satellite node, and then the data packet is routed by the LEO satellite relay node to the destination satellite node. The main parameters of the LEO satellite network simulation are shown in Table 1.

Table 1. Network simulation parameter setting

Simulation parameters	Value
Packet type	CBR (Constant Bit Rate)
Packet size	512 Byte
Packet rate	1000, 2000, 3000, …, 10000
Link bandwidth	25 M
Queue length	50

3.3 Results and Discussion

In order to fully verify the performance of the cooperative game routing algorithm in the LEO satellite constellation network, especially its ability to balance the traffic load, respectively to measure the network performance of Dijkstra shortest path algorithm, TLR routing algorithm and the optimal revenue routing algorithm under different network loads. The network performance index measured in the experiment mainly includes the packet delivery ratio and the average end-to-end delay. The former reflects the reliability of the routing strategy, while the latter reflects the efficiency of the routing strategy. Finally, we compare the real-time node load variance of the three algorithms in the simulation process. This result is more intuitive to show the traffic load balancing ability of the optimal revenue routing algorithm. In this paper, the network load is divided into three states, including mild network load, moderate network load and heavy network load. The data packet sending rate of mild network load is less than 4000 per second, and the data packet sending rate of heavy network load is higher than that of 7000 per second. The data packet sending rate of moderate network load is between the two.

The packet delivery ratio of the three routing algorithms under different network loads is shown in Fig. 2. When the traffic load is light, the performance of the shortest path routing algorithm, the traffic light intelligent routing algorithm and cooperative game routing algorithm is quite similar with no significant gap. This is because at this point, whether the routing coalition with the best revenue in the cooperative game or the first routing path chosen by the traffic light routing policy is the routing path determined by the shortest path routing algorithm. When the network load is further aggravated, the packet delivery ratio of the three routing algorithms begins to decline. At this point, the input and output buffers of the LEO satellite nodes are gradually filled, and the excess data packets cannot get enough buffer space, or the waiting time in the queue is too long to be discarded.

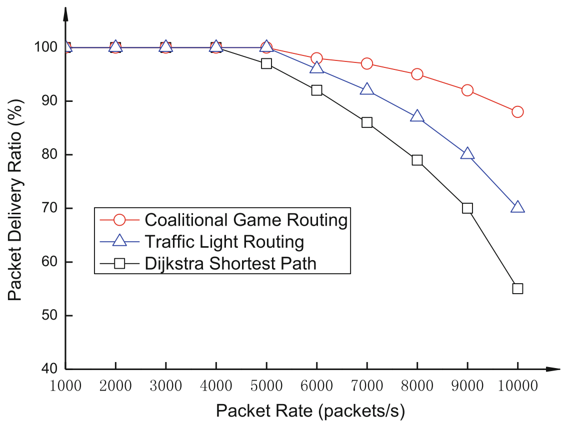

Fig. 2. Packet delivery ratio under different network loads

The shortest path routing algorithm simply uses the minimum hop counts as the routing basis, ignoring the real-time status information of the satellite nodes and the inter-satellite links, such as whether the satellite node is already in the congestion. Traffic light intelligent routing algorithm considers the real-time status of the neighbor nodes when selecting the next hop, and bypasses some congestion nodes by dynamically adjusting the local route, thus improving the packet delivery ratio to a certain extent. The cooperative game routing algorithm implements the maintenance of multiple routing alliances in real time. It evaluates the quality of the routing path by real-time calculation of the cooperative benefit of the coalition. It takes full advantage of the existing network resources to achieve load balancing of traffic, which greatly improves the packet forwarding rate and packet delivery ratio, and reduces the possibility of network congestion. Even if network congestion occurs, the cooperative game routing algorithm can also alleviate network congestion to some extent, especially to improve the performance of the network under heavy load conditions. Therefore, the average packet delivery ratio of cooperative game routing algorithm proposed in this paper is obviously higher than that of shortest path routing algorithm and traffic light intelligent routing algorithm.

Figure 3 shows the average end-to-end delay of the three routing algorithms under different network loads. The end-to-end delay in the LEO satellite network is the sum of the propagation delay of the data packet in the inter-satellite links and the queue processing delay of the data packet in the nodes. The shortest path routing algorithm is based on the number of hops in the routing, only considering the propagation delay of the data packets regardless of its queue processing delay. The traffic light intelligent routing algorithm dynamically selects the next hop relay node according to the real-time queue occupancy rate of each neighbor node, and avoids the over-congestion neighbor node as the next hop. When the network load is heavy, the algorithm can achieve the goal of reducing the overall end-to-end delay by reducing the queue processing delay of data traffic. The cooperative game routing algorithm takes into account the status information of each LEO satellite node and inter-satellite link in the routing coalition in the process of selecting the route. In particular, the algorithm not only considers the number of hops in the choice of routing path, but also takes into account the real-time data packet processing capability such as throughput, queue delay and packet loss ratio of LEO satellite nodes. Therefore, the routing established by cooperative game routing algorithm is more stable, and the algorithm can effectively reduce the end-to-end delay. Especially in the case of heavy network load, the satellite node compares the gains obtained from different cooperative game coalitions, and then selects the routing path determined by the coalition with the highest revenue to forward the data packets, which greatly reduces the waiting latency of the data packets in the queue.

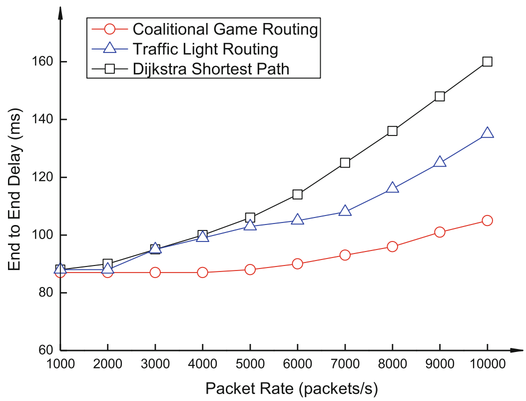

Fig. 3. End to end delay under different network loads

Figure 4 shows the average routing path length of data packets forwarded from a source satellite node to a destination satellite node under different network loads, which is consistent with the results shown in Figs. 2 and 3. With the increasing network load, the number of popular satellite nodes and inter-satellite links increases, and the performance of each routing path is damaged to varying degrees. The traffic light intelligent routing algorithm needs to dynamically adjust the local routing path in most LEO

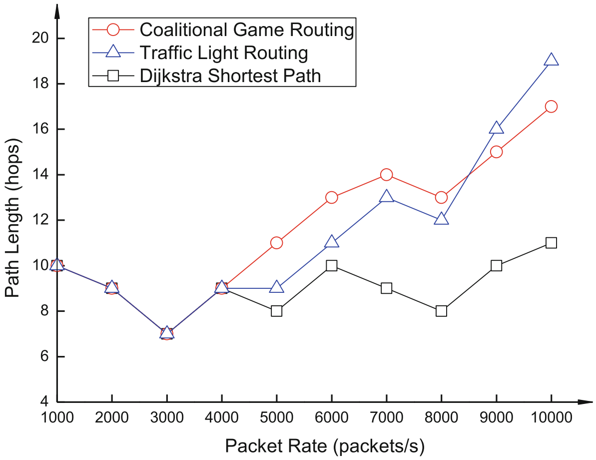

Fig. 4. Path length under different network loads

satellite relay nodes, which results in a significant increase in the average number of hops. The cooperative game routing algorithm proposed in this paper can select the current optimal routing path according to the real-time status of LEO satellite nodes and inter-satellite links in multiple routing alliances, thus improving the satellite network resource utilization and network throughput performance. The cost is also an increase in the number of inter-satellite routing hops, since the selected routing path must bypass some hot nodes and inter-satellite links that are prone to network congestion as much as possible to ensure routing performance. The simulation results show that when the LEO satellite network is in moderate network load, the cooperative game routing algorithm increases the average packet delivery ratio by 6.7% and decreases packet transmission delay by 21.2%, compared with the shortest path routing algorithm with an average increase of about 3 hops. Especially in the heavy network load conditions, the cooperative game routing algorithm with an average increase of about 5 hops to achieve an excellent routing performance that the average packet delivery ratio is increased by 23.7% and the packet transmission delay is reduced by 31.8%.

Figure 5 shows the average load variance values of the satellite nodes under heavy network load varying with the simulation time. The figure shows the traffic load balancing capability of the routing algorithm more intuitively. The Dijkstra shortest path algorithm always chooses the shortest path to forward data packets, which can easily cause the congestion of popular satellite nodes and inter-satellite links. Therefore, the load variance of satellite nodes is not only large but also dramatic. The traffic light intelligent routing algorithm can dynamically adjust the local routing path through the relay nodes to avoid aggravating the congestion of the hot nodes and inter-satellite links. The traffic light intelligent routing algorithm can dynamically adjust the local routing path through the relay nodes to avoid aggravating the congestion of the hot nodes and inter-satellite links. The load variance of satellite nodes is smaller and gentler than the shortest path routing algorithm by locally balancing the network traffic load. The cooperative game routing algorithm proposed in this paper dynamically adjusts the optimal routing path according to the cooperative revenue and balances the network traffic load from the global point of view. Therefore, the traffic load can be distributed evenly across the whole satellite network and the load variance of satellite nodes is the smallest and the most gentle in the three routing algorithms.

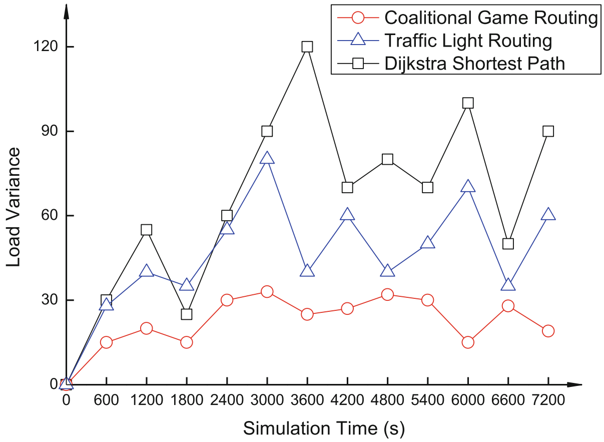

Fig. 5. Traffic distribution under heavy network load

4 Conclusion and Future Work

This paper presents an optimal revenue strategy routing algorithm for LEO satellite network based on cooperative game theory. The motivation of this algorithm design is to reduce the data transmission delay of LEO satellite network and to balance the traffic load of network nodes effectively. The algorithm is based on cooperative game theory to study the collaboration between LEO satellite nodes for data packet forwarding. LEO satellite nodes are more likely to cooperate with their best neighbor nodes to form an alliance, thereby increasing their own benefits. By comparing the benefits of joining the various coalitions, the node tends to select the lighter neighbor node as the next hop for data packet forwarding, which can effectively balance the nodes' traffic load. It can be seen from the experimental results that the cooperative game routing algorithm has significant effectiveness on reducing the transmission delay and balancing the network traffic load.

Acknowledgments. This material is based upon work supported by the CASC Innovation Fund (F2016020013), the CERNET Next-Generation Internet Innovation Project (NGII20160601), and Innovation Projects of Beijing Engineering Research Center of Next Generation Internet and Applications. Opinions and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

References

1. Wu, W.W., Miller, E.F., Pritchard, W.L., et al.: Mobile satellite communications. Proc. IEEE **82**(9), 1431–1448 (1994)
2. Li, C., Liu, C., Jiang, Z., et al.: A novel routing strategy based on fuzzy theory for NGEO satellite networks. In: IEEE Vehicular Technology Conference, pp. 1–5 (2015)
3. Werner, M.: A dynamic routing concept for ATM-based satellite personal communication networks. IEEE J. Sel. Areas Commun. **15**(8), 1636–1648 (1997)
4. Ekici, E., Akyildiz, I., et al.: A distributed routing algorithm for datagram traffic in LEO satellite networks. IEEE/ACM Trans. Networking **9**(2), 137–147 (2001)
5. Karapantazis, S., Papapetrou, E., Pavlidou, F.N.: On-demand routing in LEO satellite systems. In: IEEE International Conference on Communications, pp. 26–31 (2007)
6. Lu, Y., Zhao, Y., Sun, F., et al.: Satellite network routing technology. J. Software **5**, 1085–1100 (2014)
7. Song, G., Chao, M., Yang, B., et al.: TLR: a traffic-light-based intelligent routing strategy for NGEO satellite IP networks. IEEE Trans. Wireless Commun. **13**(6), 3380–3393 (2014)
8. Baig, O., Ai-Harthi, Y.S., Al-Tubaishi, E.: Game-theoretic algorithm stimulating cooperation in multi-hop wireless networks. In: International Conference on Game Theory for Networks, pp. 1–5. IEEE (2015)
9. Paramasivan, B., Prakash, M.J.V., Kaliappan, M.: Development of a secure routing protocol using game theory model in mobile ad hoc networks. J. Commun. Netw. **17**(1), 75–83 (2015)
10. Zheng, D., Tang, H., Yu, F.R.: A game theoretic approach for security and quality of service (QoS) co-design in MANETs with cooperative communications. In: IEEE Military Communications Conference, pp. 1–6 (2013)
11. Jiang, L., Cui, G., Liu, S., et al.: Cooperative relay assisted load balancing scheme based on Stackelberg game for hybrid GEO-LEO satellite network. In: IEEE International Conference on Wireless Communications & Signal Processing, pp. 1–5 (2015)
12. Saad, W., Han, Z., Debbah, M., et al.: Coalitional game theory for communication networks. IEEE Signal Process. Mag. **26**(5), 77–97 (2009)
13. Shapley, L.S.: A value for N-person games. In: Roth, A.E. (ed.) The Shapley Value, pp. 31–40. University of Cambridge Press, Cambridge (1988)
14. Cheng, H., Liu, M., Wei, S., Zhou, B.: A distributed algorithm for self-adaptive routing in LEO satellite network. In: Yu, Q. (ed.) SINC 2016. CCIS, vol. 688, pp. 274–286. Springer, Singapore (2017). https://doi.org/10.1007/978-981-10-4403-8_24
15. Gavish, B., Kalvenes, J.: The impact of intersatellite communication links on LEOS performance. Telecommun. Syst. **8**(2), 159–190 (1997)