Load-Balancing Routing Algorithm Against Inter-Satellite Link Congestion in LEO Satellite Optical Networks

Yunxiao Ning[1], Yongli Zhao[1], Xin Li[1], Sabidur Rahman[2], Huibin Zhang[1] and Jie Zhang[1]
1: State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, China;
2: Sonoma State University, CA, USA.
yonglizhao@bupt.edu.cn

Abstract: A novel load-balancing routing algorithm based on satellite-ground cooperation is proposed to reduce the impact of inter-satellite link congestion in LEO satellite optical networks. Simulations prove that our proposal can significantly improve the network throughput.

OCIS codes: (060.4250) Networks; (060.4251) Networks, assignment and routing algorithms

1. Introduction

Laser communication [1] is one of the key technologies for low earth orbit (LEO) satellite networks, which has the capability of large-capacity service bearing and high-speed service transmission to help LEO satellite networks achieve global communication coverage. Due to the geographical condition and the population distribution, some gateway stations may be deployed in a limited region, such as a country, resulting in an even higher traffic load in the space section of the network above that region. Leading to the occurrence of inter-satellite link (ISL) congestion, this phenomenon becomes a bottleneck constraining further growth of throughput in the LEO satellite optical network (LSON).

The relative movement between satellites and ground gateways causes the distribution of traffic load to change rapidly. Hence, strategies used to avoid congestion in ground networks (e.g., setting up higher bandwidth for links with heavy traffic load) are not applicable for satellite networks. The load-balancing (LB) algorithm has provided a solution from the perspective of routing strategy. When a service request arrives, the LB algorithm [2-4] computes multiple connections from the source to the destination and distributes the traffic spatially on multiple paths based on its traffic load, thereby minimizing the traffic congestion. However, because of the frequent topology change in LSON, the multipath strategy used by the LB algorithm may cause more consumption of computing resources. Therefore, "how to accommodate as many services as possible without traffic congestion?" is one of the biggest problems faced by LSON.

To increase the throughput of the LEO optical network and avoid traffic congestion, we propose a novel load-balancing routing algorithm based on satellite-ground cooperation (SGC-LB). The SGC-LB algorithm considers the network topology, traffic distribution, and the traffic load of ground gateways. Simulations show that the SGC-LB algorithm can achieve higher throughput of the network and increase the network utilization rate.

2. SGC-LB algorithm

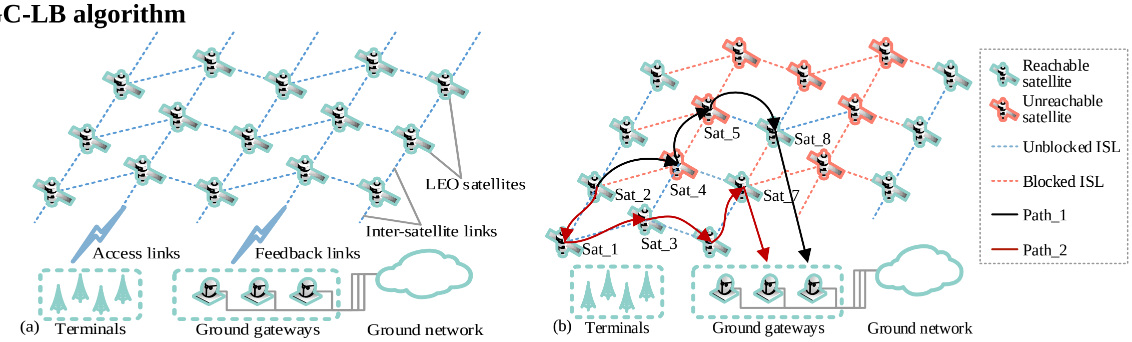
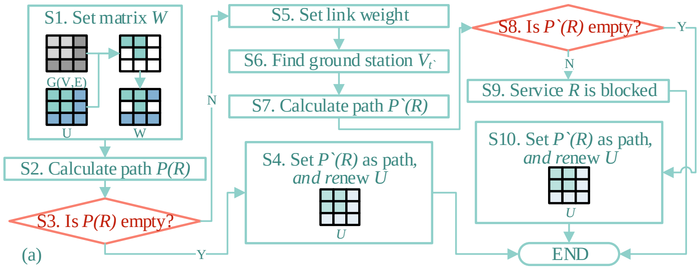


Fig. 1. (a) LSON infrastructure; (b) a LEO network service blockage scenario

Fig. 1(a) illustrates a typical LEO satellite optical network infrastructure, which consists of several terminals, satellites, and ground gateways. The service data is sent by the terminal to the ground gateway through the access link, ISLs, and the feedback link. The traditional shortest path routing which minimizes the latency by taking the minimum length of service path may cause traffic congestion and is unable to meet the high-throughput demand of LSON [5]. However, when the original destination is unreachable, there may still be reachable satellites that can be used to transmit the service data to ground stations. Fig. 1(b) shows a typical service blockage scenario in LEO satellite optical network, where a service packet will be sent from the source node Sat_2 to the destination node Sat_8. Sat_8 is unreachable because of the ISL blockages in its region. If we change the destination node from Sat_8 to Sat_7, the data will be successfully sent to a ground gateway.

In Fig. 2(a), we propose a novel method that can effectively increase the throughput of such networks. The method selects the ground gateway node with the least traffic load as the new service destination when the original service request is blocked. Figure 2(a) shows how the proposed SGC-LB algorithm works.



(b)

Parameter	Values
The number of orbits	12
The number of satellites per orbit	24
The inclination of orbits	89°
Satellite orbit height	1050km
Number of gateways	16
Number of terminals	100
The bandwidth of inter-satellite link	10GB
The bandwidth of feedback link	16GB

Fig. 2. (a) Load balancing algorithm based on satellite-ground cooperation; (b) simulation settings of LSON

Considering the highly dynamic nature of LSON, we divide the changing topology into slices, and each slice represents a period, during which the satellite network topology remains unchanged. Let $G(V,E)$ denote the network topology of the current slice. In LSON, $V=\{V_1,V_2,\ldots,V_m\}=\{V_o \cup V_x\}$ is the set of m nodes, where V_o is n satellites and V_x is the collection of $(m-n)$ ground gateways. $E=\{E_{jk}|\forall j,k\in[1,m], j\neq k\}$ is the set of directional links, where E_{jk} represents an existing link from V_j to V_k. Let set $U=\{U_{jk}|\forall j,k\in[1,m], j\neq k\}$ denote the traffic load where U_{jk} donates the traffic load of link E_{jk}. Let $R(s,t,b)$ denote a service request which originates from node V_s to node V_t, and its bandwidth requirement is b.

Since there may be links in the network that cannot carry the service，the SGC-LB algorithm first sets the weight matrix $\mathbf{W}$ according to the topology and the traffic load. For ISLs, we set link weight w_{ij} as follows: $w_{ij}=u_{ij}(u_{ij}+d\le B_{isl}), w_{ij}=0(u_{ij}+d>B_{isl})$, where B_{isl} is the bandwidth of the ISL. For feedback links, we set w_{ij} as follows: $w_{ij}=u_{ij}(u_{ij}+d\le B_{feed}), w_{ij}=0(u_{ij}+d>B_{feed})$, where B_{feed} is the bandwidth of the feedback link. Then we calculate the minimum weight path set $P(R)$ using Dijkstra algorithm. If $P(R)$ is not an empty set, we use $P(R)$ as the data transmission path for service R and renew U. Otherwise, we set link weight as $\{w_{ij}=0\,|\,i\in[1,n], j=t\}$ to indicate that the ground gateway V_t is unreachable in current network topology. To make better use of existing transmission resources to transmit the current service, we change the original destination from V_t into $V_{t`}$ which has the least traffic load in matrix $U$ and then calculate the minimum weight path set $P`(R)$ for service R. If $P`(R)$ is not an empty set, we use $P`(R)$ as the data transmission path for service R and renew U. Otherwise, we declare service R is blocked to prevent further performance deterioration of the algorithm incurred by further routing calculation.

Based on the above algorithm, we can perform a dynamic LEO network routing. The objective of the LEO network routing is to efficiently find service routing paths in the dynamic LEO network topology such that the network can bear as many services in the changing network topology without service blockage. The algorithm complexity of the SGC-LB algorithm comes mainly from Dijkstra algorithm [6]. The algorithm complexity of the SGC-LB is $O(m^2)$, m is the quantity of network nodes in the slice topology $G(V,E)$.

3. Simulation studies

To evaluate the performance of the proposed routing algorithm, extensive simulations were performed on a 288-satellites Walker constellation with satellite links. The simulation settings of LSON are shown in Fig. 2(b). To better evaluate the network throughput under different algorithms, we assume a static service model, where all service requests arrive at the beginning of a simulation and stay until the end of the simulation. The bandwidth of each service is 50 MB. 80% of the destination of the services are in China, and 20% of the services flow to other ground gateways. For each service request, if there is no transmission resource available, it will be blocked. If there is a link down in the original service transmission path and the destination node is unreachable, the service will also be blocked. We compare SGC-LB with two routing algorithms: shortest-path routing (SP) [5], and load balancing-routing algorithm (LB) [7].

In the simulation process, different service models have different effects on the actual number of services carried by the network. To reasonably evaluate the capacity changes of the LEO laser network, the network minimum cost maximum flow method is used to solve the network capacity corresponding to the slice topology:

$C_{therory} = f_{\max flow}(G(V,E), B_{isl}, B_{feed})$, $f_{\max flow}$ is Boykov-Kolmogorov (BK) algorithm [8] which is used to calculate the maximum flow from a collection of satellite access nodes to the ground network through the feedback links in $G(V,E)$, B_{isl} and B_{feed} is the bandwidth of the ISL and the feedback link). We consider the minimum $C_{therory}$ as the network capacity in an orbit period. Based on the simulation settings, the network capacity is 7600.

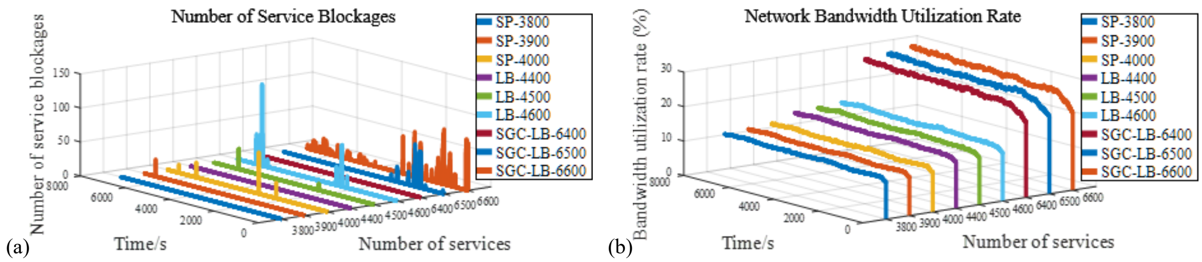


Fig. 3. (a) Number of service blockages; (b) network bandwidth utilization rate

Fig. 3(a) shows the traffic congestion of the network under different number of services. We consider the max-throughput as the maximum number of services the network can accommodate without service blockages in an orbit period. The max-throughputs of SP, LB, and SGC-LB algorithms are 3,800, 4,400, and 6,400 respectively, which are 50%, 58%, and 85% of the theoretical network capacity. The comparison shows that the proposed SGC-LB algorithm can improve the max-throughput of the network. The reason is that the services, supposed to be blocked when using the SP or LB algorithm, are successfully transmitted to ground gateways by using the SGC-LB algorithm.

In order to better describe the usage of network resources at time i , we define the network bandwidth utilization rate: $BUR = (\sum_{j=1}^{RS} h_j * b) / B_i$, where RS is the set of current services under transmission, h_j is the hops of the data transmission path for a service rs_j and B_i is the total bandwidth of the current topology slice. Assuming an ideal service model and an ideal deployment of ground gateways, the max-throughput can reach the network capacity of 7,600, the average R_u is approximately 48% under this ideal circumstance. However, due to the particularity of the service model and the uneven deployment of ground gateways, the BUR is unable to reach 48%.

Fig. 3(b) shows how the network BUR changes with time. When the network is running at max-throughput status, the network using the SP algorithm can accommodate 3,800 services and the average BUR is 12%. When the traffic distribution is considered, the network can accommodate more services using the LB algorithm and the average BUR of LB is 15% (4,400 services), which is higher than using the SP algorithm. As for the SGC-LB strategy, by utilizing the remaining transmission resources, more services can be accommodated, and the average BUR can reach 26% (6,400 services). The comparison shows that the SGC-LB algorithm can effectively utilize network bandwidth resources. While ensuring most of the original service transmission requirements, the SGC-LB algorithm can transmit more service using the link resources of reachable satellites, and further improve the utilization of network resources.

4. Conclusion

This paper studies the traffic congestion problem in LSON and proposes a SGC-LB algorithm to tackle the impact of traffic congestion on the network throughput. Simulations show that the proposed SGC-LB algorithm can improve the network throughput and effectively utilize the network bandwidth resources. *(This work has been supported in part by National Key Research and Development Program of China (2020YFB1805602), and National Natural Science Foundation of China (NSFC) (62021005).)*

5. References

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