

Multi-layer Orbit-weave Optical Satellite Networks with Cross-layer Routing for Stable Service Delivery

Hua Wang¹, Yongli Zhao², Massimo Tornatore³, Wei Wang², and Jie Zhang²

¹School of Computer Science and Technology, Nanjing Tech University Nanjing Tech University, Nanjing, 210000, China

²School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing, 100876, China

³Department of Electronics Information and Bioengineering, Politecnico di Milano, 20133, Milan, Italy

*yonglizhao@bupt.edu.cn

Abstract: We propose a multi-layer constellation for optical satellite networks and a cross-layer path-aggregation routing strategy to establish persistent links. Our proposal reduces blocking probability (12.6%) and link utilization (10.2%) with respect to a state-of-the-art single-orbit solution. © 2024 The Author(s)

1. Introduction

The number of Low Earth Orbit (LEO) satellites is rapidly increasing, and latest LEO constellations are starting to be deployed across multiple orbital altitudes, as exemplified by constellation projects like Starlink V1.0 and V2.0, with satellite altitudes around 300 km, 400 km, and 500 km. Inside these multi-layer constellations, satellites can connect to their neighbor satellites by using laser communication. Hence, satellites can establish both *intra-orbit satellite links (Intra-OSLs)* with satellites in the same orbit and *inter-orbit satellite links (Inter-OSLs)* with satellites in adjacent orbits. Additionally, the satellites can establish cross-layer links (CLLs) with nearby satellites located on layers at different altitudes of different orbits under certain visibility angles and distances. These links play a critical role in improving coverage and increase network capacity. As several constellation projects (i.e., Starlink, Kuiper, and Telesat) plan to use high-bandwidth laser links [1], multi-layer optical satellite networks are regarded as a promising trend.

Intra-OSLs can feature high stability and long holding times due to the slow relative mobility of co-directional satellites [2]. Instead, the stability of Inter-OSLs and CLLs faces great challenges due to the high relative mobility [3] (approximately 7.5 km/s), which exacerbates the difficulty of acquisition, tracking, and pointing (ATP) [4]. This results in frequent interruptions of Inter-OSLs, which may cause a higher service disconnection probability. Inspired by the stability of Intra-OSLs, we observe that designing a constellation with multi-layer co-directional orbits can reduce the interruptions of Inter-OSLs by slowing their relative mobility. The stability of Inter-OSLs in multi-layer constellation can be enhanced by setting the orbits in different layers with co-directional satellites adjacent to each other. Therefore, how to design the optimized multi-layer optical satellite networks is a problem worth studying.

This paper proposes a new constellation comprising multiple LEO layers, that is capable of establishing persistent cross-layer links (CLLs). We simulated the proposed constellation using a 3-layer constellation and compared it to a single-layer constellation. Our numerical results illustrate that the proposed constellation outperforms the single-layer in terms of the prolonged holding time of links (6433.36s) and reduced coverage time (50.853s). To evaluate the networking performance of the proposed constellation, we designed a cross-layer path aggregation routing (CPAR) scheme to optimize link utilization by grouping service paths across multiple layers. The proposed CPAR strategy in the 3-layer outperforms the benchmark in the single-layer by reducing blocking probability by 12.6%, while decreasing link utilization by 10.2% and increasing bandwidth utilization by 5.8%.

2. Multi-layer Orbit-weave Optical Satellite Networks (MO-OSNs)

To mitigate the impact of the relative satellite mobility on CLL stability, we must ensure that adjacent orbits maintain the same flight direction in the constellation design phase. To achieve this goal, we introduce the concept of woven orbits, which refers to the adjacent orbits in different layers sharing the same direction. Accordingly, we

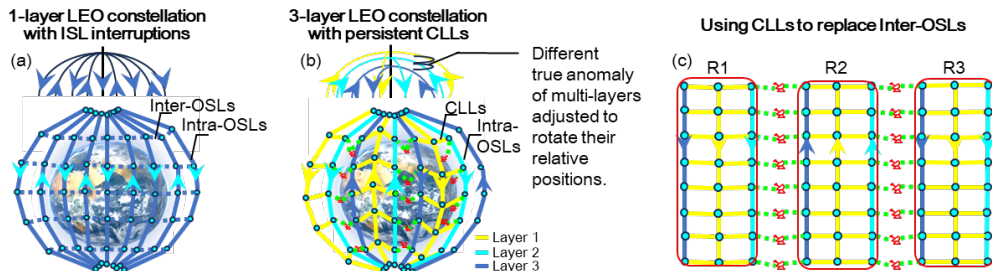


Fig. 1. 3-dimension presentation of (a) a single-layer OSN and (b) a 3-layer MO-OSN. 2-dimension presentation of (c) the 3-layer MO-OSN.

propose a *multi-layer orbit-weave constellation in optical satellite networks* (MO-OSNs). In MO-OSN, the true anomaly of satellites in different layers can be adjusted (a true anomaly is an angular parameter indicating the relative positions of satellites along their orbit). The true anomaly of satellites across different layers is adjusted to rotate within differed angles to align their co-directional orbits as the adjacent neighbors, thus creating an interleaved multi-layer structure.

For instance, if the n -th orbital plane in the m -th layer moves in a clockwise direction, its adjacent orbits will be the $(n-1)$ -th orbital plane in the $(m-1)$ -th layer, and the n -th orbital plane in the first layer, both also moving in the clockwise direction. These adjacent orbits with consistent flight directions form cohesive regions. Within a cohesive region, satellites at different layers can establish CLLs, which have persistent connections due to the adjacent codirectional orbits to guarantee stability. These cohesive regions can offer the advantage of paths composed entirely of CLLs when the service access and feeder satellites are within the region. Regarding the areas out of the regions, satellites in adjacent orbits flying opposite can be relayed by ground stations.

An example of our proposed MO-OSN (in the case of 3 orbit layers) is sketched in Fig. 1(b), as opposed to a traditional 1-layer Walker constellation shown in Fig. 1 (a). LEO satellites, marked as blue dots in Fig. 1(b), are located at different LEO altitudes in multiple layers. Supposed there are m constellation layers, each consisting of n orbital planes, with k evenly spaced LEO satellites distributed along each orbital plane. The orbital plane in different layers is configured with a fixed difference in their initial true anomaly, uniformly positioning them to interlace with each other. Several interlaced adjacent orbits can form a region, like R1, R2 and R3, as shown within the red boxes in Fig. 1 (c). These regions can communicate with each other via ground station relays, represented by green lines.

3. Cross-layer Path Aggregation Routing (CPAR) Scheme

As the number of CLLs is limited in MO-OSNs, a CPAR scheme is designed to optimize link utilization across multiple layers. The CPAR scheme is designed to optimize path selection and link utilization for dynamic service requests. Given the current network topology and bandwidth utilization, when a service request arrives at the source ground station, the CPAR needs to calculate the aggregated path for the requests.

First, when the satellite receives a service request, the CPAR checks the destination ground station, identifies its connected feeder satellite, and determines the region to which it belongs. If the access and feeder satellites are located within the same region, a stable transmission path can be established through CLLs. If they are in adjacent regions, at least one ground station relay is required. Subsequently, based on this regional topology, the system calculates multiple candidate paths. Based on the regional topology, multiple candidate paths between the satellites can be computed, and the paths are incorporated into a path set for bandwidth evaluation. Next, the scheme proceeds to calculate the total bandwidth utilization of each path with Eqn. (1) in Fig. 2 (b). The links in each path in the set undergo a bandwidth utilization evaluation. The paths with higher bandwidth utilization to the other alternative paths are prioritized for aggregation.

Fig. 2 illustrates an example of aggregated path computation for service requests (S1, S2, and S3). Fig. 2 (a) shows the input of the scheme. Three service requests originate from ground stations, and are represented by red lines extending from the access satellites to their feeder satellites. Fig. 2 (b) shows the path aggregation for the individual paths for S1, S2, and S3 which are aggregated to prioritize paths with higher CLL utilization. Fig. 2 (c) shows the output of the path aggregation, with an optimized path for all three service requests. The common links are highlighted in red to indicate shared links between requests. Furthermore, an index of bandwidth utilization of a path (U_{path}) is designed to evaluate aggregation performances with the ratio of the occupied bandwidth of the i -th link ($B_{used,i}$) to the total bandwidth of the i -th link ($B_{total,i}$) in a service path. n refers to link numbers of a service path. Higher U_{path} means more efficient aggregation of a path.

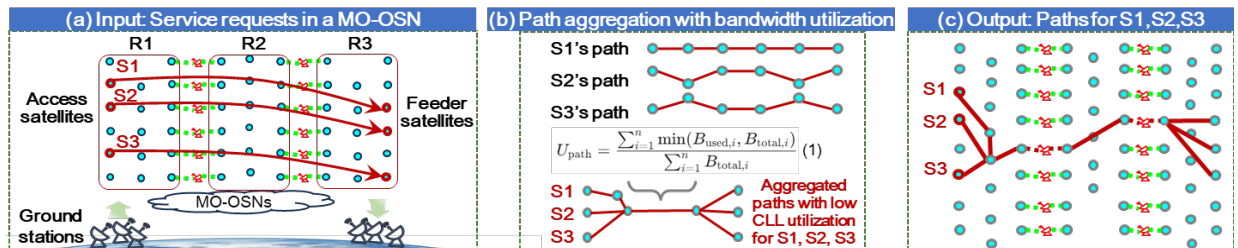


Fig. 2. CPAR scheme: (a) Input illustration, (b) Path calculation with bandwidth utilization, (c) Output illustration.

4. Simulation Results

To evaluate the proposed MO-OSNs, we simulated a 3-layer LEO constellation (i.e., 3 layers, 3 orbits and 7 satellites/orbit) and a 1-layer constellation (i.e., 1 layer, 9 orbits and 7 satellites/orbit) in System Tool Kit (STK)

software with 7200s holding time. The two constellations feature the same number of satellites. Two nodes were randomly selected from 30 ground stations to serve as source and destination nodes for 7,000 service requests. The detailed setting parameters are listed in Table 1. The shortest hop algorithm (SHA) is selected as a benchmark due to its relative low time latency, which helps mitigate frequent link interruptions. It compares to the proposed CPAR in 4 situations, i.e., with/without path aggregation respectively in 3-layer/1-layer constellations.

Table 1. Simulation settings.

Parameter	Value	Parameter	Value
LEO satellites	63	Ground stations	[1, 30]
Satellite layers	3/1	Service numbers	7000
Orbital planes	3/9	Service hold time	[1,10]
Orbital altitudes	850,1000, 800/750 km	Bandwidth of CSL	32
Inclination angle	89°	Bandwidth of ISL	32
True anomaly	22.5°/0°	Bandwidth of SGL	32

Fig. 3. 3-dimensional views of (a) 3-layer and (b) 1-layer constellations.

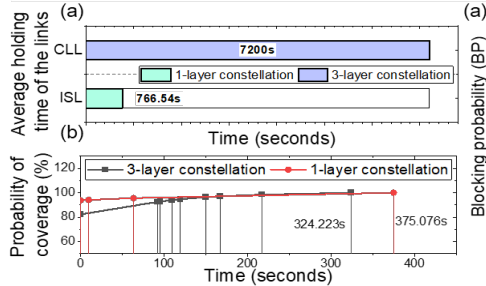
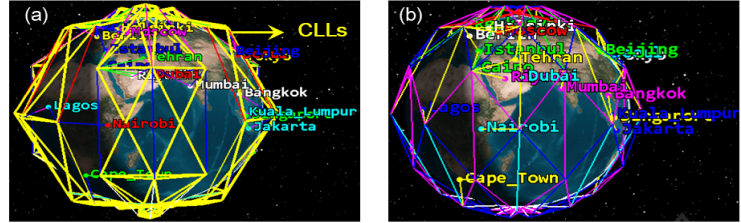


Fig. 4. (a) Average holding time of links and (b) probability of coverage of 3-layer and 1-layer constellations.

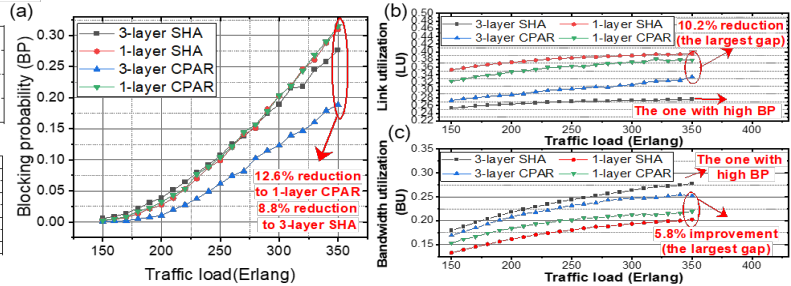


Fig. 5. (a) Blocking probability (BP), (b) link utilization (LU) and (c) bandwidth utilization (BU) of the proposed strategies to the benchmark.

Fig. 3 (a) and (b) are the 3D presentations of the two constellations in STK. Fig. 4 (a) compares the average holding time of the links obtained by STK, that means the time can maintain connections. It shows that the CLLs has the holding time 7200s, and the Inter-OSLs has the average holding time 766.64s. This indicates that Inter-OSLs suffer an average link interruption every 766.64s over the whole duration due to relative mobility. In contrast, CLLs can maintain a continuous connection, with an increased link duration by 6,433.36 seconds to that of Inter-OSLs. It means the 3-layer constellation has higher probability of link stability than the 1-layer. Also, the two constellations' probability of coverage on a certain area was evaluated via the data obtained from STK in Fig. 4(b). Fig. 4(b) shows the coverage time of 3-layer constellation (i.e., 324.223s) is 50.853s quicker than that of the 1-layer constellation (i.e., 375.076s) to reach and maintain the full coverage of the area. Therefore, these results above show that the proposed 3-layer constellation has stabler link connectivity than the 1-layer, which benefits network performance.

Fig. 5 shows three performance metrics (i.e., blocking probability (BP), bandwidth utilization (BU) and link utilization (LU)) for service requests in the two constellations. BU refers to the average ratio of the bandwidth of all links in a network to the total bandwidth. LU is the ratio of the number of occupied links to the total number of links. Generally, for increasing in traffic load, the possibility of concurrent arrival increases, and the BP and LU also increase. As expected, Fig. 5(a) shows the 1-layer SHA and CPAR have similar values of BP, while the 3-layer SHA and CPAR can achieve different reductions of BP. The largest reduction of BP is 12.6% achieved by 3-layer CPAR compared to the 1-layer CPAR, indicating the 3-layer CPAR strategy can serve a larger number of concurrent services. In Fig. 5 (b), link utilization (LU) of the 3-layer PA strategy has the largest reduction of 10.2% to the others while the 3-layer SHA strategy also has relatively low BP. Fig. 5 (c) shows that 5.8% bandwidth saving was achieved by the 3-layer CPAR with 12.6% BP reduction. The results above indicate that the multi-layer constellation has a significant improvement not only on the holding time of links but also the CPAR in the 3-layer has better network performance for service requests.

Acknowledgment

This work has been supported in part by the NSFC project under Grant No. 62425105 and 62350001, the Fundamental Research Funds for the Central Universities under Grant 530424001.

References

[1] Y. Hauri, et al., "“Internet from Space” without Inter-satellite Links," 19th ACM Workshop on Hot Topics in Networks, (2020).
 [2] A. U. Chaudhry, H. Yanikomeroğlu, "Laser intersatellite links in a starlink constellation: A classification and analysis," IEEE Veh. Technol. Mag. **16**, 48-56 (2021).
 [3] M. Y. Abdelsadek, et al., "Future space networks: Toward the next giant leap for humankind," IEEE Trans. Commun. **71**, 949-1007 (2022).
 [4] G. Wang, et al., "Free Space Optical Communication for Inter-Satellite Link: Architecture, Potentials and Trends," IEEE Commun. Mag. **62**, 110-116 (2024).