



# Wavelength Routing Assignment of Different Topological Optical Networks Based on Typical LEO Satellite Constellations

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**Abstract.** Inter-satellite laser communication can fulfill the requirements of huge-capacity transmission of satellite communication. The space-wide all-optical network is a key way to solve problems such as low-latency, huge-capacity transmission and low-cost on-orbit real-time route switching processing through technologies of Wavelength Division Multiplexing (WDM) inter-satellite links (ISLs) and wavelength routing. Then routing and wavelength assignment (RWA) become its core and main technology. Aiming at the RWA issue, this paper takes the typical LEO satellite constellations Iridium and NeLS as examples, establishes a regular ISLs topology, and proposes a simulation model based on the minimum cost routing strategy and wavelength demand. The results of simulations demonstrate that, compared with the link arbitrary topology, the NeLS constellation with regular network topology can save nearly half of the wavelength resource requirement under the condition of slightly sacrificing node connectivity, and the Iridium constellation has the better connectivity with the same wavelength resource demand. Both NeLS and Iridium constellations show a more stable trend in the link duration, wavelength volatility, and node connectivity volatility.

**Keywords:** Wavelength assignment · Regular ISLs · Wavelength routing · WDM

## 1 Introduction

Nowadays, the inter-satellite microwave transmission has been difficult to fulfil the communication capacity demand. And space all-optical communication technology has the benefits of high communication rate, robust anti-interference capability, powerful security and confidentiality [1–4]. The European Data Relay System (EDRS) [5], the Japanese laser relay satellite system [6], and the Quantum Experiments at Space Scale (QUESS) launched in China in 2016 [7] all accomplished higher-rate optical communication. With the mature development of WDM technology and related optical

equipment, optical wavelength switching has been widely introduced commercially. Thus, using the wavelength routing technology based on WDM on satellite networks is a fairly advanced and practical solution for building future space-wide networks [8].

The RWA problem of optical networks has been studied currently in ground fiber optic networks. However, there exist relative motions of two satellites of distinct orbital planes, and the inter-satellite distance typically changes with period. And the position of satellites in the non-synchronous orbit constellation is continuously time-varying relative to the earth. So, this key issue of satellite optical networks is more complex than the ground. Therefore, this paper chose the regular ISLs topology, which has lower algorithm complexity and better stability than the link-arbitrary topology.

The LEO constellation has become a preferred option for countries to construct space-based networks because of its low transmission delay and expense. The LEO constellation system's design is commonly divided into the polar orbit constellation and the Delta constellation. Consequently, this paper chooses the representative  $2\pi$  constellation NeLS [9] and the  $\pi$  constellation Iridium [10], and analyzes the RWA topic of these two constellations in detail.

In the past domestic and foreign research, some academics have proposed a number of algorithms for satellite network traffic, blocking rate and wavelength utilization analysis and improvement [11–14], but they lacked the analysis of wavelength demand and node connectivity. Sun et al. proposed that the deployment of LEO  $\pi$ -type polar orbit constellation is in line with the development trend of China's future integrated satellite network [15], and Tan et al. proposed a wavelength routing model based on  $2\pi$ -type NeLS constellation, lacking the comparison with the  $\pi$ -type constellation [16].

In this paper, the model of regular potential ISLs is established, and the ISLs topology is generated under the condition of time-varying ISL nodes, which supplies link support for the RWA procedure. This paper also improves the Dijkstra routing algorithm strategy, simulates the number of wavelength resource required in the optical satellite network, and compares it with the arbitrary ISL topology [19].

## 2 Optical ISLs Model

### 2.1 Introduction to NeLS and Iridium

The Iridium constellation is the only near-polar orbit constellation at present that can achieve global seamless coverage even including Antarctic and Arctic. NeLS is the first global satellite network that prepares to take advantage of WDM ISL technology, which belongs to the typical Delta type [17]. The 3D orbits map of NeLS and Iridium can be obtained by STK simulation software (see Fig. 1).

At the same time, using STK satellite simulation software to analyze the 2D planar columnar expansion of the two constellations, we can see the difference between the two constellations and their respective advantages more intuitively (see Fig. 2). The coverage of the NeLS constellation on the ground is better and evenly distributed, especially in densely populated areas. While the Iridium constellation takes care of the polar regions and achieves global seamless coverage.

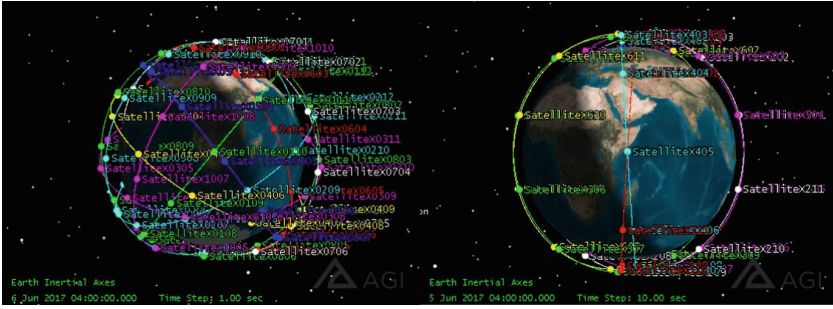


Fig. 1. 3D orbits map of NeLS (left) and Iridium (right) constellation.

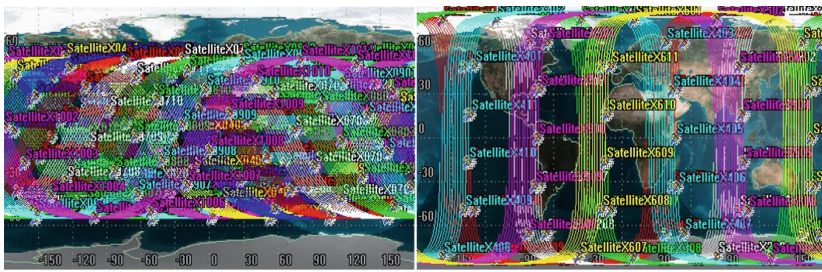


Fig. 2. 2D planar expansion map of the NeLS constellation (left) and Iridium constellation (right).

### 2.2 Mathematical Modeling of Satellites of the Constellations

According to the Walker representation [16, 18], the distribution of satellites in the constellation is expressed as N/P/F, where N stands for the total number of satellites in the constellation, P denotes the total number of orbits contained in the constellation, F means the phase factor of the constellation, and S represents the number of satellites in each orbit. According to the spatial geometric relationship, the following relationship can be obtained between the location of the k-th satellite in the i-th orbit of the constellation and the constellation parameters:

$$\begin{aligned}
 x_{ik}(t) = & -R\cos\theta \sin\left(\frac{2\pi i}{P}\right) \sin\left[\omega t + 2\pi\left(\frac{k}{S} + \frac{iF}{PS}\right)\right] + \\
 & R\cos\left(\frac{2\pi i}{P}\right) \cos\left[\omega t + 2\pi\left(\frac{k}{S} + \frac{iF}{PS}\right)\right]
 \end{aligned}
 \tag{1}$$

$$\begin{aligned}
 y_{ik}(t) = & R\cos\theta \cos\left(\frac{2\pi i}{P}\right) \sin\left[\omega t + 2\pi\left(\frac{k}{S} + \frac{iF}{PS}\right)\right] + \\
 & R\sin\left(\frac{2\pi i}{P}\right) \cos\left[\omega t + 2\pi\left(\frac{k}{S} + \frac{iF}{PS}\right)\right]
 \end{aligned}
 \tag{2}$$

$$z_{ik}(t) = R \sin \theta \sin \left[ \omega t + 2\pi \left( \frac{k}{S} + \frac{iF}{PS} \right) \right] \tag{3}$$

Where:

$$0 \leq i \leq P - 1, 0 \leq k \leq S - 1.$$

Where:

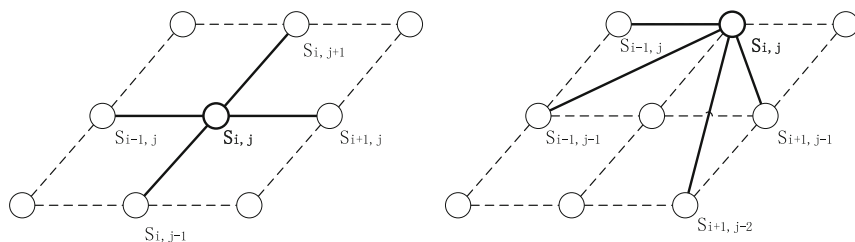
- R - Distance between the satellite and the earth's center;
- $\omega$  - Orbital angular velocity of the satellite;
- $\theta$  - Orbital inclination of the satellite.

Supposing that the k-th satellite in the i-th orbit of the constellation requires to build an ISL with the l-th satellite in the j-th orbit, we can obtain the link distance  $D(t)$  between the two satellites:

$$D(t) = \sqrt{[x_{ik}(t) - x_{jl}(t)]^2 + [y_{ik}(t) - y_{jl}(t)]^2 + [z_{ik}(t) - z_{jl}(t)]^2} \tag{4}$$

### 2.3 Regular ISL Network Topology and Arbitrary ISL Network Topology

In the planar structure of the regular ISL network topology, each node establishes ISL with 2–4 satellites adjacent to the same orbit and 2–4 satellites in the front and behind adjacent orbits, and the topological shape is regular and stable. In the arbitrary ISL network topology, under the limitation of the number of satellite optical terminals, the ISLs can be established between all the potential link satellites within the allowable laser terminal link distance, while its topology shape is complicated and the link duration is unstable (see Fig. 3).



**Fig. 3.** Regular ISL network topology (left) and arbitrary ISL network topology (right) in some moment.

### 2.4 Regular ISL Network Topology and Its Time Stability

On the basis of the mathematical model obtained in part 2.3, we analyzed the link topology characteristics of a single satellite in the constellation, and select the regular

link topology that can be used as a permanent link for simulation analysis. The simulation orbit parameters are based on the NeLS constellation and the Iridium constellation (see Table 1). We presented a two-dimensional model of the regular ISL topology at a certain time, verified and analyzed the stability characteristics of the potential communication links of a single satellite in one cycle in the system.

**Link Topology Characteristics of a Single Satellite**

Since each satellite of the constellation system is equivalent in the network, the motion characteristics of a single node are representative and universal, so we only analyze the link topology characteristics of one satellite. The link distance of the optical terminals on the satellite determines the communication coverage of the satellite, so we analyzed all satellites that can enter the satellite communication range and establish an ISL.

**Table 1.** Chief parameters of the NeLS constellation and Iridium constellation.

Parameters	NeLS	Iridium
Orbit inclination	55°	86.4°
Orital altitude	1200 km	780 km
Orbit period	6565 s	6660 s
Number of orbits	10	6
Number of satellites per orbit	12	11
Number of ISL terminals per satellite	4	4
Intraorbit ISL distance	3922 km	4029 km
Interorbit ISL distance	≤ 4909 km	≤ 4909 km
Inter plane spacing	3°	3°

**Table 2.** NeLS constellation potential link and its link duration.

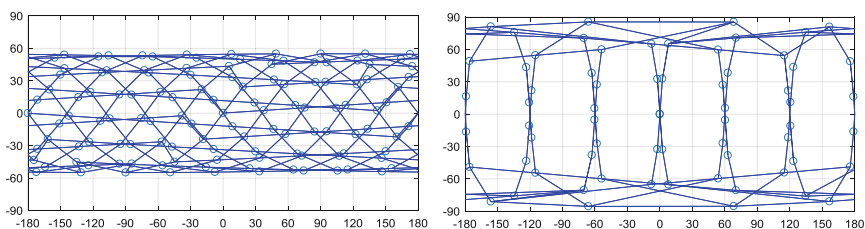
	Satellite number	Duration(s)	Satellite number	Duration(s)
Intraorbit	0001	6566	0011	6565
Interorbit	0100	6566	0506	1653
	0110	2207	0507	1235
	0111	6566	0602	1247
	0209	1263	0603	1747
	0210	3006	0604	1714
	0211	2605	0605	1120
	0308	1526	0701	1814
	0309	2127	0702	2127
	0310	1814	0703	1526
	0406	1120	0800	2605
	0407	1714	0801	3006
	0408	1747	0802	1263
	0409	1247	0900	6566
	0504	1235	0901	2207
	0505	1653	0911	6566

**Table 3.** Iridium constellation potential link and its link duration.

	Satellite number	Duration(s)	Satellite number	Duration(s)
Intraorbit	0101	6600	0110	6600
Interorbit	0000	3126	0403	1480
	0001	2694	0404	1426
	0010	1216	0405	1430
	0200	3126	0406	1459
	0201	1214	0407	1480
	0210	2692	0408	1474
	0300	1650	0409	1466
	0301	1240	0410	1464
	0308	770	0500	1718
	0309	1460	0501	1460
	0310	1718	0502	770
	0400	1464	0509	1238
	0401	1466	0510	1650
	0402	1474		

Tables 2 and 3 show the satellite numbers of NeLS and Iridium in all communication ranges of satellite s0000 during the constellation period and the total duration of the corresponding links in detail. The satellite s0000 can establish an ISL with the two satellites before and after the same orbit in the whole period, and can also establish a permanent interorbit link with the remaining four satellites of different tracks (see Table 2). Therefore, in the simulation work of this paper, the satellite s0000 is selected to establish a regular link topology with four satellites, which are s0001, s0011 in the same orbit and s0100, s0900 in the different orbits. The satellite s0100 can establish an ISL with the two satellites in front and rear of the same orbit at any time during the entire period, and can also establish a half-cycle ISL with two satellites of different orbits (see Table 3). Therefore, in the simulation work of this paper, the satellite s0100 is selected to establish a regular link topology with four satellites, which are s0101, s0110 in the same orbit and s0000 and s0200 in the different orbits.

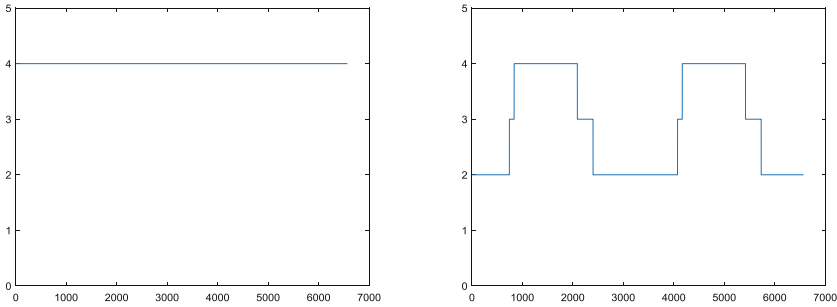
This type of regular topology conforms to the setting of the maximum degree of freedom of a single satellite node of 4, and the requirements of the optical terminals carried on the satellite are lower (see Fig. 4).



**Fig. 4.** 2D simulation of the potential link of the satellite network at a certain moment in the NeLS constellation (left) and the Iridium constellation (right).

### Time Characteristics of Regular ISL Topology

For a single satellite, the quantity of potential links for NeLS is stable at four, and it lasts for the entire 6565 s period; the quantity of potential links for Iridium changes from 2 or 4 within a period, and the time of the number of links is 2 or 4 basically reached the entire 6660 s period (see Fig. 5).



**Fig. 5.** The stability variation of the number of satellites in the potential link set of the NeLS constellation and the Iridium constellation within a period.

### 3 Optical ISLs Topology and RWA Algorithm

This paper defines the Satellite Connection Matrix (SCM):

$$C = \begin{pmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,N} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{N,1} & c_{N,2} & \cdots & c_{N,N} \end{pmatrix} \tag{5}$$

Where  $C \in \{0, 1\}^{N \times N}$ ,  $c_{m,n} = 0$  means the satellite m to satellite n does not have an ISL, and  $c_{m,n} = 1$  means the satellite m has an ISL with satellite n. N represents the total quantity of satellites.

In this paper, we consider bidirectional connections, so  $c_{m,n} = c_{n,m}$ , i.e. C is a symmetric matrix. We proposed  $\alpha$  to measure the proportion of active terminals in a satellite optical network link topology. The calculation formula is as follows:

$$\alpha = \frac{1}{N} \sum_{i=1}^N \sum_{j=1}^N \frac{c_{i,j}}{\phi_{max}} = \frac{\|CE_1\|_1}{N \cdot \phi_{max}} \tag{6}$$

Where  $E \in \{1\}^{1 \times N}$  is an all-one matrix of size  $1 \times N$ .  $\|CE_1\|_1$  is a 1-norm, which is the quantity of working terminals occupied by the established optical ISLs. N is the total number of satellites, and  $\phi_{max}$  means the maximum degree of satellite node freedom(in this paper,  $\phi_{max} = 4$ ). So  $N \cdot \phi_{max}$  means the total of terminals in the optical ISL network.

### 3.1 Establish ISLs Topology of the Satellite Optical Network

When all satellites have established their sets of potential ISLs during the constellation period, our work will focus on the choice from sets to determine the topology of the satellite optical network. Our algorithm is based on the following rules:

- An ISL is randomly chosen from all potential links as an established ISL. The entire topology generation rules should follow: (1) Every potential link can only be chosen once; (2) The node degrees of freedom of the two satellites must be within the interval defined by the minimum and maximum values; (3) Confirm whether the connectivity of the satellite network topology satisfies the full link and whether  $\alpha$  satisfies the demands.
- Repeat the above steps until the full topology is established.

In reality, there are always some pairs of satellite nodes that are not connectable because they may need to establish many ISLs to access each other. This situation will undoubtedly have a negative impact on network performance. Therefore, under the premise of complying with the wavelength continuity limit rule, the ISL hop count of the satellite optical network should not exceed an upper limit, that is, the maximum allowable link hop count of a single satellite, which we define as  $N_{maxhops}$ . After defining the hop limit between satellite nodes, the topology connectivity of the satellite optical network will be affected accordingly. For a more intuitive description, we define  $\beta$  as the normalized number of interconnectable node pairs relative to all the node pairs in the optical network.

$$\beta = \frac{2\mathcal{L}}{N(N-1)} \quad (7)$$

Where  $\mathcal{L}$  represents the quantity of satellite node pairs that have interconnected and  $N$  denotes the total number of all satellites in the constellation.

### 3.2 The RWA Algorithm

To solve the RWA issue, the continuity and dissimilarity constraints of wavelength routing must be considered. Under the premise of satisfying the above two constraints, the idle communication wavelength can be allocated when the optical connection request arrives. In the RWA algorithm for satellite optical networks, different routing schemes mean the performance of the network because it is directly affected by the allocation of wavelength resources between satellites. Finding the optical path with the least link cost is the core issue of the routing algorithm. Based on the research of reference [4], this paper comprehensively considers the influence of on-board processing time and ISL distance on link cost, and establishes the optical path set of source-target satellites optical connection request based on Dijkstra algorithm. In order to make the simulation results more accurate, we consider the time-varying characteristics of the satellite constellation, and perform a random network topology simulation over thousands of times at each moment in the constellation cycle, and finally obtain the best optical path set of all source-target satellites and the result of wavelength assignment.

The total cost of the optical routing link has two major factors, one is the link cost of a single ISL, and the other is the on-board processing cost of the satellite node, which is calculated as follows.

$$W_{total}(t_i) = \sum_{j=1}^{N_{hops}} \left[ \frac{d_j(t_i)}{c} + t_{j,p} \right] \quad (8)$$

Where  $N_{hops}$  is the jump numbers of the ISLs included in the optical path,  $d_j(t_i)$  represents the  $j$ -th ISL distance of the path,  $c$  represents the speed of light, and  $t_{j,p}$  is the processing cost of the terminals on the satellite node of the  $j$ -th ISL.

The detailed process is as follows:

- Establish the lowest cost optical path set and second lowest cost set;
- We sort the links in the optical path from high to low total cost and randomly select one of the costliest links in the optimal optical path set (because there may be several links have the same cost). The selected optical path is then assigned a dedicated wavelength that satisfies the wavelength dissimilarity constraint, in which case it is necessary to check whether the wavelength is free and has the smallest wavelength number in all ISLs through which the optical path passes;
- If the maximum number of channels in an ISL in the lowest cost optical path is greater than the second lowest cost optical path, in this situation, the lowest cost optical path currently requested will be replaced with the second lowest cost light path;
- According to the above steps, until all the link wavelength assignments are accomplished, the last calculated maximum wavelength number is the wavelength demand of the satellite optical network.

## 4 Simulation and Analysis of Results

Taking NeLS constellation and Iridium constellation as examples, this section analyzes and compares the wavelength resource demand and the node pairs connectivity  $\beta$  in a constellation cycle in the regular inter-satellite topology. In all simulation experiments we set  $t_{j,p}$  10 ms and  $N_{maxhops}$  is [1, 6].

### 4.1 The Performance of Node Connectivity with $N_{maxhops}$

The dotted line in the figure indicates the change in the mean value of  $\beta$ , and the vertical line indicates the range of variation of  $\beta$  at the hop count (see Figs. 6 and 7). This is because for the same  $\alpha$ , we generated 2600 different network topologies for the NeLS constellation and 4000 different kinds of network topology for the Iridium constellation, which is very convincing and representative. It can be concluded that when  $N_{maxhops}$  increases, the average value of  $\beta$  and the overall trend will show an upward trend. For a fixed  $N_{maxhops}$  value, it is desirable to increase the node connectivity  $\beta$  by increasing the  $\alpha$ . In the same network case (with the same  $\alpha$  and  $N_{maxhops}$ ), the Iridium constellation displays a better  $\beta$  than the NeLS constellation.

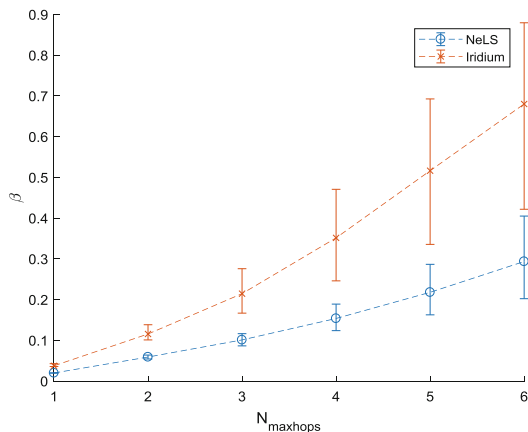


Fig. 6. The performance of  $\beta$  with  $N_{maxhops}$  ( $\alpha = 0.6$ ).

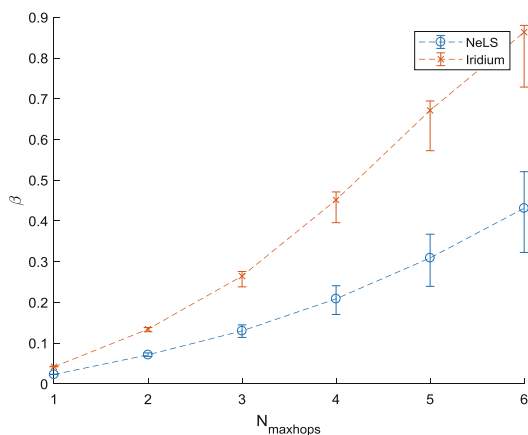
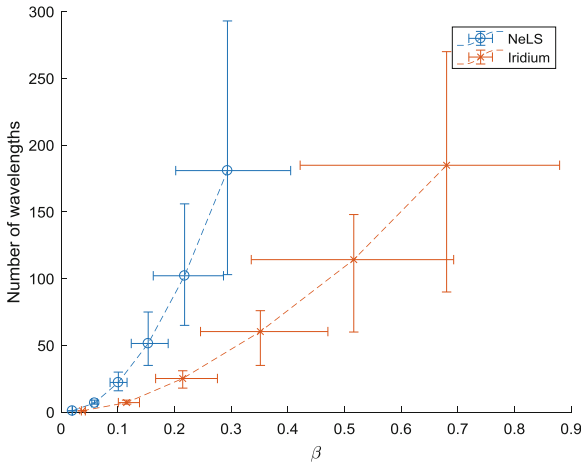


Fig. 7. The performance of  $\beta$  with  $N_{maxhops}$  ( $\alpha = 0.7$ ).

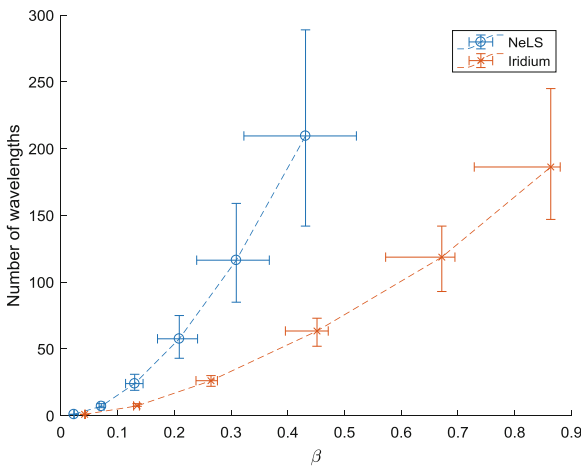
### 4.2 The Performance of Requirement of Wavelengths with $\beta$ and $\alpha$

The dotted line indicates the trend of the average value of the number of wavelengths, the vertical line indicates its range of variation, and the horizontal line indicates the range of variation of the node connectivity (see Figs. 8 and 9). As can be concluded from the picture, when the node connectivity  $\beta$  is higher, the wavelength demand increases. For the same  $\beta$ , increasing  $\alpha$  can effectively save wavelength resources. In the same network case (with the same  $\alpha$  and  $\beta$ ), the Iridium constellation requires fewer wavelength resources, apparently related to its smaller constellation system. As  $\alpha$  increases, the rate of change in  $\beta$  and wavelength demand is smaller.

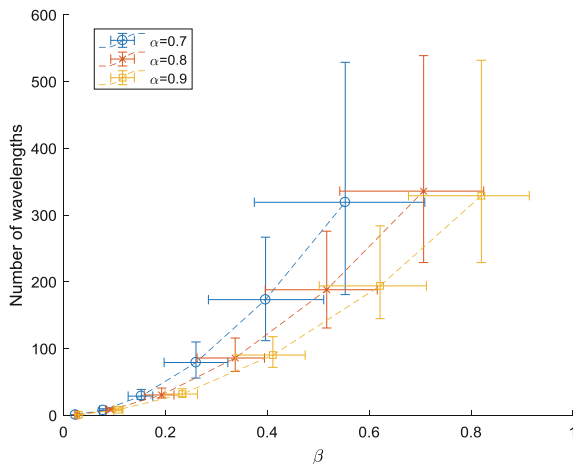
Comparing with Figs. 8 and 9, it can be seen that for the same  $\alpha = 0.7$ , the arbitrary topology of the NeLS constellation requires a maximum of 550 wavelengths, while the regular topology requires only a maximum of nearly 300 wavelengths, saving nearly half of the wavelength resources (see Figs. 10 and 11). The connectivity of the Iridium constellation in regular topology can reach a maximum of nearly 0.9, while in arbitrary link topology can only reach nearly 0.7, which improves the connectivity of 0.2 while reducing the wavelength requirement by nearly 100. It can be seen that the regular topology has a great improvement in wavelength demand and connectivity, especially for Iridium constellation.



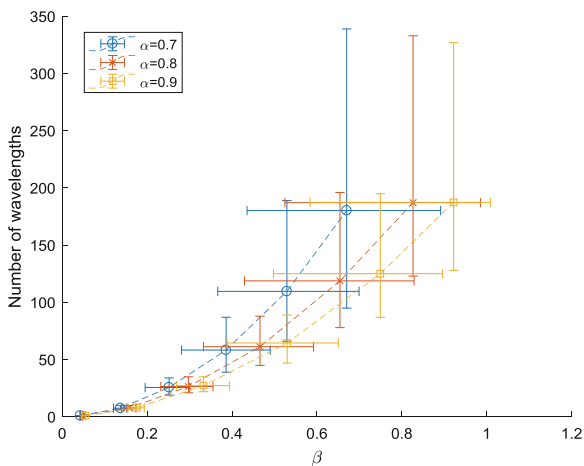
**Fig. 8.** The performance of the number of wavelengths with  $\beta$  when  $\alpha = 0.6$  in the rule of regular ISLs topology.



**Fig. 9.** The performance of the number of wavelengths with  $\beta$  when  $\alpha = 0.7$  in the rule of regular ISLs topology.



**Fig. 10.** The performance of the number of wavelengths with  $\beta$  in the rule of arbitrary ISLs topology (NeLS constellation).

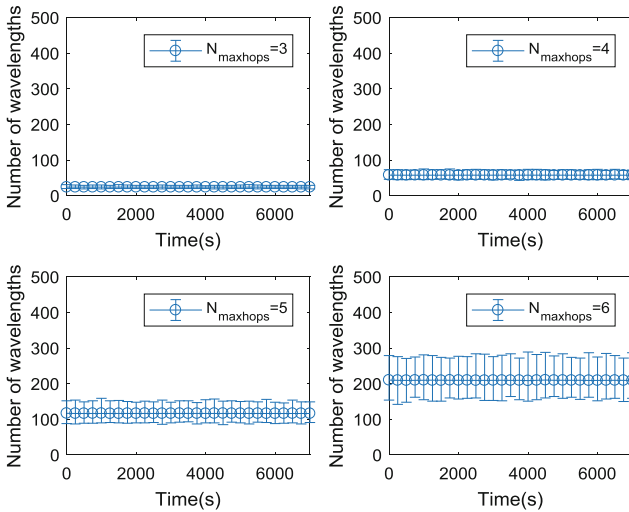


**Fig. 11.** The performance of the number of wavelengths with  $\beta$  in the rule of arbitrary ISLs topology (Iridium constellation).

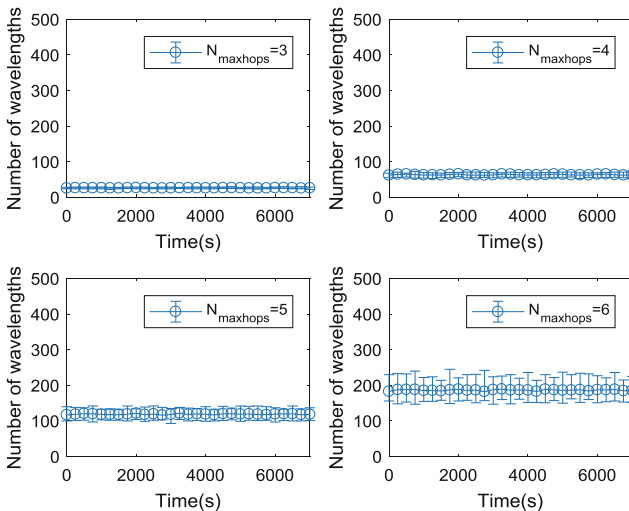
### 4.3 The Performance of Wavelength Requirements and $\beta$ with Different $N_{maxhops}$ in a Constellation Period ( $\alpha = 0.7$ )

It can be seen from the comparison that the regular topology has a large reduction of wavelength requirement for the NeLS constellation than the arbitrary topology, and the wavelength requirements of these two constellations fluctuate less (see Figs. 12, 13, 14 and 15).

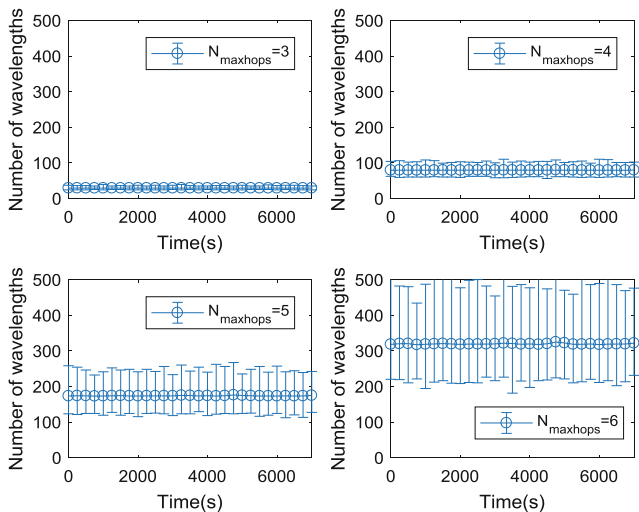
The comparison shows that under the regular network topology, the connectivity of the NeLS constellation is slightly lower than that of the arbitrary link topology, and the connectivity of the Iridium constellation has a significant improvement when  $N_{maxhops} > 4$  (see Figs. 16, 17, 18 and 19).



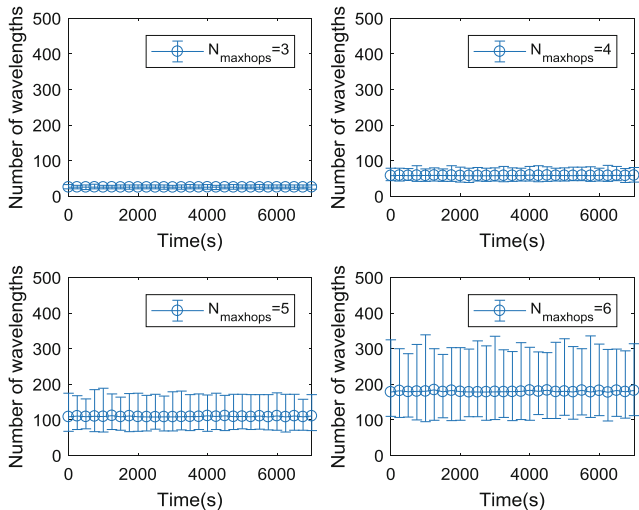
**Fig. 12.** The performance of the number of wavelengths with  $N_{maxhops}$  in a constellation period in the rule of regular ISL topology (NeLS constellation).



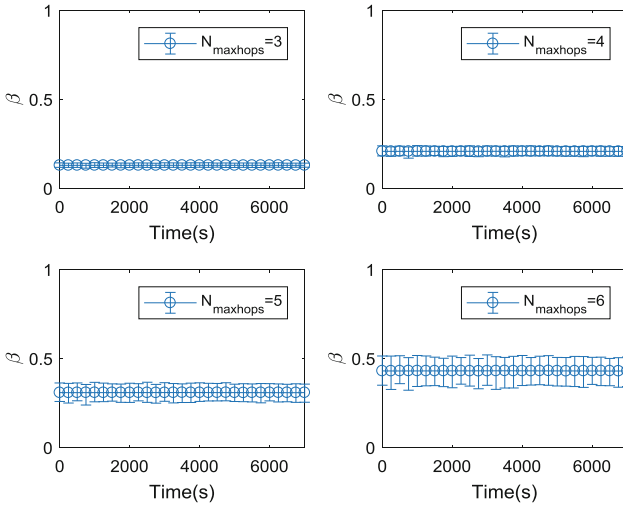
**Fig. 13.** The performance of the number of wavelengths with  $N_{maxhops}$  in a constellation period in the rule of regular ISL topology (Iridium constellation).



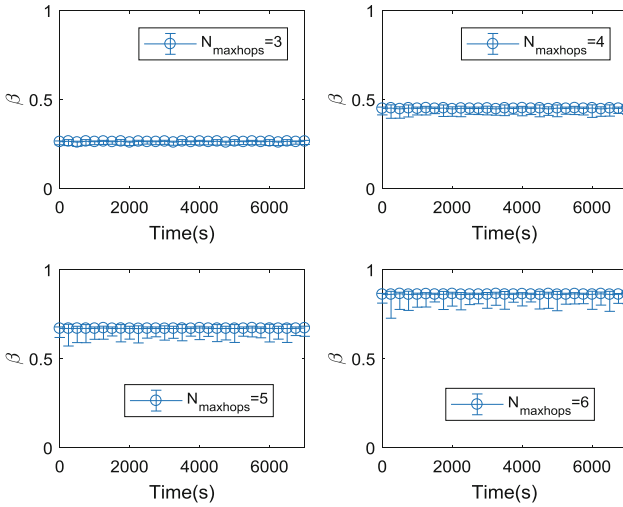
**Fig. 14.** The performance of the number of wavelengths with  $N_{maxhops}$  in a constellation period in the rule of arbitrary ISL topology (NeLS constellation).



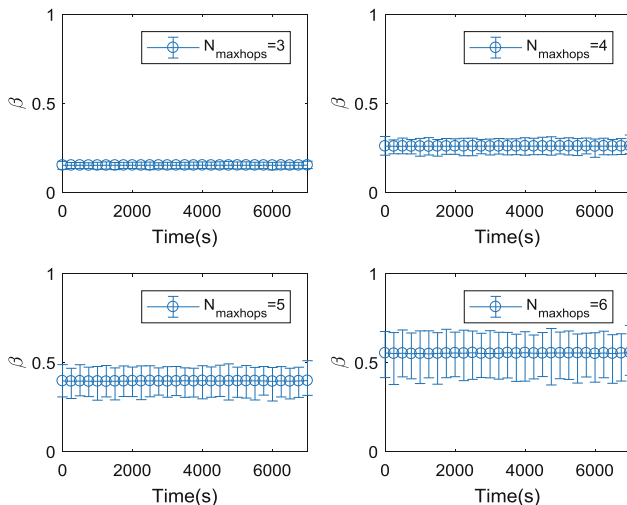
**Fig. 15.** The performance of the number of wavelengths with  $N_{maxhops}$  in a constellation period in the rule of arbitrary ISL topology (Iridium constellation).



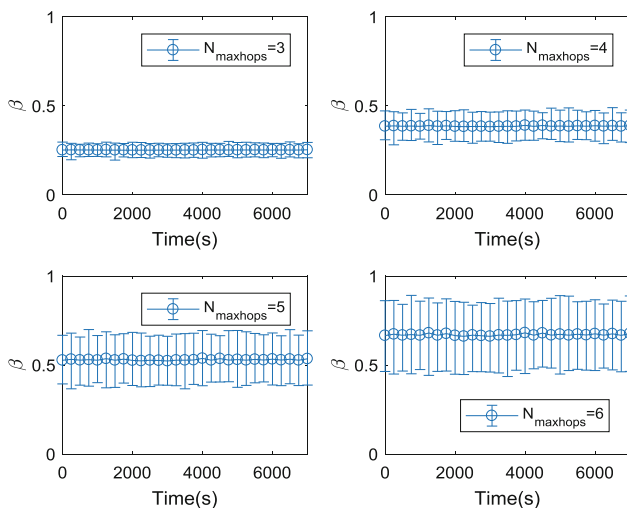
**Fig. 16.** The performance of  $\beta$  with  $N_{\max\text{hops}}$  in a constellation period in the rule of regular ISL topology (NeLS constellation).



**Fig. 17.** The performance of  $\beta$  with  $N_{\max\text{hops}}$  in a constellation period in the rule of regular ISL topology (Iridium constellation).



**Fig. 18.** The performance of  $\beta$  with  $N_{maxhops}$  in a constellation period in the rule of arbitrary ISL topology (NeLS constellation).



**Fig. 19.** The performance of  $\beta$  with  $N_{maxhops}$  in a constellation period in the rule of arbitrary ISL topology (Iridium constellation).

## 5 Conclusions

In this paper, a network topology model for satellite optical networks with  $\pi$ -type and  $2\pi$ -type constellations is established, which has a wide application space. And the RWA algorithm and wavelength demand analysis are carried out for the specific parameters of NeLS constellation and Iridium constellation. The correlation model and algorithm simulations given in this paper demonstrate that when we compare the regular network topology similar to the grid-like streets of Manhattan Island with the arbitrary link topology, the NeLS constellation can save nearly half of the wavelength resource requirement under the condition of slightly sacrificing node connectivity. And the Iridium constellation has better connectivity with the same wavelength resource requirements. The link duration, wavelength volatility and node connectivity volatility of the two constellations show a more stable trend.

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