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Analysis of queuing delay in optical space network on LEO satellite constellations

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ABSTRACT

Low earth orbit (LEO) satellite constellations using laser inter-satellite links (ISLs) are recognized as a promising technology to provide global broadband network services. In this paper, the queuing delay model of an optical space network built on LEO satellite constellations is established. It is assumed that the optical space network employs wavelength division multiplexing ISLs with wavelength routing technology to communication satellites and makes routing decisions. With consideration of the network task characterizations such as distribution of task arrival time and task holding duration, simulation experiment results are analyzed and the expression of optical space network queuing delay is given. Both theoretical analysis and simulation results show that features of queuing delay vary with distribution characterizations of the network tasks. It is hoped that the study can be helpful to evaluate the design of constellation networking.

1. Introduction

Optical space network based on wavelength division multiplexing (WDM) architecture and wavelength routing technology has emerged as the befitting backbone for the dramatic increase in bandwidth demand of emerging applications [1]. Several optical space network have been proposed such as Celestri [2], Teledesic [3], and NeLS [4]. These satellite systems built on non-geosynchronous orbits, use a single wavelength or WDM laser inter-satellite links (ISLs) for broadband inter-satellite communications. In contrast to single wavelength ISLs, WDM ISLs with onboard wavelength routing equipment perform better by offering more routing selection and by reducing processor delays in high bandwidth communications [5].

The key factor of optical space network transmission feasibility is the transmission delay, also called network delay, which is the duration of the signal passage from the source satellite transmission to the destination satellite. In optical space networks based on WDM technology, network delay is mostly decided by the queuing delay. Queuing delay indicates the duration from one signal transmission network task arrived at the source satellite to the time when this signal was ready to be transmitted. During queuing delay, the satellite system is expected to assign the light path for communication and the wavelength for the corresponding network task, and check the light path and wavelength till they are available. Due to the periodic motion of the satellites, each network task has a waiting limitation until it can be executed. Thus, the increase of the queuing delay will be a destructive defect to the optical satellite network. For this reason, it is necessary to research the generative mechanism and characterization of the queuing delay in the optical space network in order to reduce it to an acceptable range.

Previous study has mainly focused on the network structure in LEO satellite communication system, in order to optimize the orbit parameters to enhance the performance of communication service [6]. In these feasibility studies on the LEO satellite networks, Walker constellations with optical ISL are employed to form a global satellite network and the constellation parameters such as orbits altitudes, number of orbital planes, number of satellites in the orbital plane and the orbital inclination were studied for optimization [7]. However, to the best of our knowledge, no previous work concerned the performance of queuing delay in random network tasks on the LEO satellite networks. In this paper, on the assumption that WDM architectures with wavelength routing were available for the ISLs, and in view of random network tasks, queuing delay in the optical space network is analyzed for the Walker constellation with optical ISLs.

The paper is organized as follows. Section 2 describes the system model and theoretical analysis of the queuing delay in the optical space network. Section 3 is devoted to the simulation and numerical analysis with discussion. Section 4 states the conclusions of this work.

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2. Model and analysis of the network

2.1. Logical connections of LEO space network

In optical space network employing low earth orbit (LEO) satellite constellations, the geographic topology of the network changes periodically. This dynamic network architecture is considered as a great challenge to the light path routing and wavelength assignment of the WDM based optical network. Therefore, in order to improve the effectiveness of routing and wavelength assignment, the topology of the network has to be simplified.

Through the use of continuous ISL connections, a typical LEO optical space network in the Walker constellation can be seen as a modified Manhattan network [8], as is shown in Fig. 1, an example of a typical LEO satellite network with five orbital planes and six satellites in each orbital plane is given. Each satellite in the network is connected to four adjacent satellites by optical ISLs. However, in addition to the model shown in Fig. 1, there are also several different logical connection architectures studied by researchers, corresponding to different schematics of the network.

When a network task, also called connection request, arrives at the LEO satellite network, a sequence of ISLs which starts from the source satellite and ends in destination satellite is generated and assigned to this connection request. Each generated sequence of the ISLs is a specific route to the corresponding connection, and each specific route needs a customized wavelength to meet the communication requirement.

A practical problem is that the amount of available wavelengths is finite in the network, which means the number of connections simultaneously operating on the network is limited. Some network tasks arriving at the network have to wait for an accessible route along with an unoccupied wavelength in this route to accomplish communication mission. On this occasion, the time spents on the waiting is called queuing delay. Obviously, queuing delay is associated with the network capacity, routing principle, temporal distribution of network tasks and some other network parameters.

2.2. Theoretical analysis of network traffic parameters

Since queuing delay in the optical space network is relevant to network capacity, clearly are expression of network capacity should be given. Considering a LEO satellite network with L orbital planes and M satellites in each orbital plane, total number of ISLs in the network can be written as

$$P_{all} = 2 \times L \times M \tag{1}$$

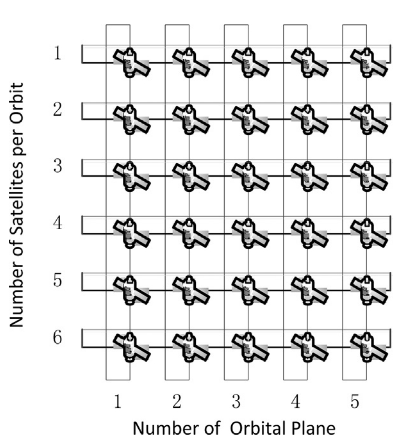

Fig. 1. Logical connections for LEO satellite network.

In number of ISLs, the average connection length count between network node pairs can be expressed as

$$P_{av} = \frac{1}{L \times M - 1} \cdot \sum_{i=1}^{L \times M - 1} p_i = \frac{Mf(L)(L-1) + Lf(M)(M-1)}{ML - 1}$$
$$\text{where} \quad f(x) = \begin{cases} \dfrac{x+1}{4} & x, \quad \text{odd} \\[2ex] \dfrac{x^2}{4(x-1)} & x, \quad \text{even} \end{cases} \tag{2}$$

where p_i is the connection length count in number of ISLs between the reference satellite and ith satellite in the network. What should to be point out is that the average connection length count P_{av} shown in Eq. (2) is computed with assigning the shortest path to each node pair.

The network capacity can be measured by the number of connections operating on the network simultaneously. With average connection length shown in Eq. (2) and total number of ISLs shown in Eq. (1), the theoretical network capacity N_{TL} can be depicted as

$$N_{TL} = \frac{P_{all} \times n_\lambda}{P_{av}} \tag{3}$$

where n_λ is the number of available wavelengths in the optical satellite network. Practically, not all of the ISLs and their wavelengths can be utilizing at the same time, and then the practical network capacity can be written as

$$N_{PL} = N_{TL} \times \eta_{av} \tag{4}$$

η_{av} means the average ISLs utilization ratio. As ISLs utilization ratio is a function of time, η_{av} can be expressed as

$$\begin{cases} \eta_{av} = \overline{\eta(t)} \\ \eta(t) = \dfrac{P(t)}{P_{all} \times n_\lambda} \end{cases} \tag{5}$$

where $P(t)$ stands for the number of occupied ISLs at time t in the network.

In general, in the care of identical temporal distribution of the network tasks, increasing network capacity can decrease the number of queuing connections. On the other hand, under the condition of certain network capacity, increasing network task generation rate will lead to a boost of the queuing delay.

Distribution of the arrival time determines the amount of connection requests per unit duration, while service time distribution affects the operating speed of connection requests. To build a reasonable temporal distribution model of network tasks, arrival time and service time of connection requests generated on certain distributions should be considered. Actually, plentiful approaches have been proposed in order to model large network flows as well as their superposition properties [9].

In this paper, arrival times with Poisson distribution [10] and service times with lognormal distribution [11] were chosen both for their simplicity and because they provide rather general and realistic representation of large network systems.

Under these assumptions, the mean arrival time can be defined as λ and mean service time is assumed as μ. Since the expression of network capacity is depicted and network model is built, queuing delay of the network in unit duration can be written as

$$D_{un} = \begin{cases} \dfrac{1}{\lambda} - \dfrac{N_{TL}}{\mu}, & \dfrac{1}{\lambda} \geq \dfrac{N_{TL}}{\mu} \\[2ex] 0, & \dfrac{1}{\lambda} < \dfrac{N_{TL}}{\mu} \end{cases} \tag{6}$$

In order to estimate the average queuing delay for every connection requirement, the total number of connection requirements