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Wavelength dimensioning for wavelength-routed WDM satellite network

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KEYWORDS

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Abstract Internet and broadband applications driven by data traffic demand have become key drivers for satellite constellations. The key technology to satisfy the high capacity requirements between satellites is optical satellite networks by means of wavelength division multiplexing inter-satellite links (ISLs) with wavelength routing (WDM-OSN). Due to the limited optical amplifier bandwidth onboard the satellite, it is important to minimize the wavelength requirements to provision requests. However, ISLs should be dynamically established and deleted for each satellite according to its visible satellites. Furthermore, different link assignments will result in different topologies, hence yielding different routings and wavelength assignments. Thus, a perfect match model-based link assignment scheme (LAS-PMM) is proposed to design an appropriate topology such that shorter path could be routed and less wavelengths could be assigned for each ISL along the path. Finally, simulation results show that in comparison to the regular Manhattan street network (MSN) topology, wavelength requirements and average end-to-end delay based on the topology generated by LAS-PMM could be reduced by 24.8% and 12.4%, respectively.

1. Introduction

Internet and broadband applications driven by data traffic demand have become key drivers for satellite constellations.[1] In order to provide broadband communications to consumers, several satellite low-earth-orbit (LEO) constellations, which exhibit significantly low earth-to-space delay[2,3], were constructed such as Orbcomm-2,[4] Globalstar-2,[5] Iridium-Next.[6] In these satellite constellations, Iridium-Next adopts inter-satellite links (ISLs) technology, while the others do not. The key technology to satisfy the high capacity requirements between satellites is optical satellite networks (OSN) by means of wavelength division multiplexing ISLs with wavelength routing (WDM-OSN), where WDM technology could satisfy the high bandwidth requirements by establishing multiple wavelength channels in each ISL and wavelength routing could guarantee simple routing of the optical channels in the optical domain.[7,8] In order to accommodate a request, a path is routed based on certain topology and the same wavelength should be assigned for each ISL along the path, namely the wavelength-continuity constraint. However, optical amplifier bandwidth onboard the satellite is limited and the wavelength spacing should maintain

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a safety margin for the Doppler effects. As a result, the amount of available wavelengths is finite. Thus, it is important to minimize the wavelength requirements to provision requests.

Different from terrestrial WDM optical network, each satellite could establish WDM ISL with its visible satellites until all the laser communication terminals (LCTs) onboard are assigned in WDM-OSN. Moreover, the satellite's relative position to the earth and the set of its visible satellites change continuously as it moves along its orbit. Therefore, ISLs for each satellite should be dynamically established and deleted according to its visible satellite set. Different link assignment schemes will result in different network topologies, hence yield different routings and wavelength assignments. Thus, a link assignment scheme (LAS) should design an appropriate topology such that shorter path could be routed and less wavelength could be assigned for each link along the path.

However, wavelength dimensioning of the previous works does not consider the impact of topology on routing and wavelength assignment,[7,9–11] and LAS of the previous works does not consider minimizing the wavelength requirements to provision requests.[8,12,13] For example, wavelength dimensioning is optimized on some simple regular network topologies with all LCTs active, such as ring network topology[9] and Manhattan street network (MSN) topology.[7,10,11] These regular topologies have large average inter-node distance in hops, resulting in large wavelength requirements. Some other studies focus on the target of link assignment to generate an arbitrary connected network topology,[8] maximize the remnant capacity of ISLs[13] or maximize the connectivity of network topology.[14] The other studies could only design topology for satellite networks with two planes.[12,15,16]

This paper mainly focuses on the relationship among link assignment, routing and wavelength assignment. In order to minimize the wavelength requirements to provision requests in WDM-OSN, we propose a novel link assignment scheme based on perfect match model (LAS-PMM) to design an appropriate network topology such that a shorter path could be routed and less wavelengths need to be assigned for the ISL along the path. Based on network topology generated by LAS-PMM, the partition coloring model is used to find the lowest label of wavelength channel for the assigned routing paths to provision request set. Finally, simulation results for Next-generation LEO System constellation (NeLS[17]) show that wavelength requirements to provision requests under network topology generated by the LAS-PMM and average end-to-end delay can be reduced by 24.8% and 12.4%, respectively, in comparison to that of the regular MSN topology.

The rest of this paper is structured as follows. Section 2 presents problem statement. Section 3 presents perfect match model-based link assignment and wavelength dimensioning. Section 4 demonstrates the effectiveness of our proposed LAS-PMM through computer simulations. Finally, concluding remarks are presented in Section 5.

2. Problem statement

In WDM-OSN, there are usually N LEO satellites evenly placed in P orbits. Each orbit consists of S satellites. The jth satellite belonging to ith orbit is denoted as $v = S_{i,j}$, $1 \leqslant i \leqslant P, 1 \leqslant j \leqslant S$. At each time interval, two satellites are defined to be visible from each other if they are within line-of-sight, communication ability and pointing acquisition and tracking (PAT) ability during the whole time interval. The visibility graph and network topology of WDM-OSN are denoted as $M = (V, E)$ and $G = (V, E)$ respectively, where $V(G)$ and $V(M)$ are the same node set consisting of $|V(G)|$ satellites, $E(M)$ and $E(G)$ are the link set consisting of $|E(M)|$ visibility links and $|E(G)|$ established ISLs assigned from visibility links respectively, namely $V(G) = V(M)$ and $E(G) \subseteq E(M)$. As a network node, each satellite v requires $f(v)$ LCTs to maintain the network connectivity. Each ISL $e \in E(G)$ has w wavelength channels with equal channel bandwidth capacity. $W = \{1, 2, \ldots, w\}$ is the wavelength set. A light path defined on a WDM-OSN is a route of the graph G with each link assigned a wavelength channel. It is assumed that the WDM-OSN does not have wavelength converters and so wavelength continuity constraint applies.

Each visibility link $e = xy, \forall e \in E(M)$ represents that satellites x and y are visible from each other, while each ISL $e = xy, \forall e \in E(G)$ represents an ISL between satellites x and y. Each ISL $e = xy$ will occupy one LCT on satellites x and y. $\boldsymbol{M}$ and $\boldsymbol{G}$ are the matrix expression form of the visibility graph $M = (V, E)$ and topology $G = (V, E)$ respectively. As a result, $\boldsymbol{M}(x, y) = 1$ represents $e = xy$ and $\boldsymbol{M}(x, y) = 0$ otherwise. Node degree $d_M(v)$ of visibility graph M represents that there are $d_M(v)$ satellites visible from satellite v, and its visible satellites are usually more than LCTs equipped, namely:

$$d_M(v) = \sum\nolimits_{x \in V(M), x \neq v} \boldsymbol{M}(x, v) \geqslant f(v) \tag{1}$$

$\boldsymbol{G}(x, y) = 1$ represents $e = xy$, and $\boldsymbol{G}(x, y) = 0$ otherwise. Node degree $d_G(v)$ of network topology G represents that there are $d_G(v)$ active LCTs of satellite v assigned to establish ISLs and active LCTs are limited to the specified number of LCTs, namely:

$$d_G(v) = \sum\nolimits_{x \in V(G), x \neq v} \boldsymbol{G}(x, v) \leqslant f(v) \tag{2}$$

The LCT utilization is defined as

$$\alpha_G = \sum\nolimits_{v \in V(G)} d_G(v) \Big/ \sum\nolimits_{v \in V(G)} f(v) \tag{3}$$

Therefore, the link assignment problem of assigning LCTs to establish ISLs is to find a spanning subgraph and satisfy the node degree constraints $d_G(v) \leqslant f(v)$.

Under the network topology $G = (V, E)$ generated by link assignment, there is a set of requests to be accommodated. It contains N requests denoted by R. We assume that all requests ask for the same bandwidth which is the capacity of a wavelength channel. Thus, each request $r \in R$ is represented as $r = (s, d)$, where s and d are the source and destination satellite respectively. For practice consideration, we only consider k shortest paths for each request and the routing paths which are δ longer than the shortest one are not considered. To satisfy a request r, we should find a path p_r and assign a wavelength label c_r for path p_r. There are d_r hops of routing path for request r from satellite s to satellite d, therefore, the average end-to-end delay is represented as

$$\bar{d}_R = \sum\nolimits_{r \in R} d_r / |R| \tag{4}$$

The objective of wavelength dimensioning is to minimize the maximum wavelength channel number, i.e.

$$C = \min_{r \in R}\{\max_{r \in R}\{c_r\}\} \tag{5}$$