Research on Routing and Wavelength/Subcarrier Assignment Algorithm based on Layered-Graph Model in Optical Satellite Networks

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Abstract: In optical satellite networks with multi-wavelengths and multi-subcarriers, two-level switching mode replace single wavelength switching, achieving better flexibility and network performance with its disadvantages of more complex routing and network resource allocation. Based on subcarrier layered-graph (SL-G), a novel dynamic routing and wavelength/subcarrier assignment (RWSA) algorithm is proposed to find the shortest path with limited costs in the corresponding layered-graph. By defining different edge cost functions in SL-G, centralized resource allocation strategy and decentralized resource allocation strategy in dynamic RWSA are analysed for optical satellite networks with different types of constellations. Simulation results demonstrate that, no matter whether optical satellite networks has single constellation with uniform wavelength distribution or hybrid constellations with non-uniform wavelength distribution, the proposed RWSA algorithms are superior to traditional routing and wavelength assignment algorithms with lower network blocking probability.

1 INTRODUCTION

Optical satellite networks have been a research hotspot in the satellite communication field (Sodnik *et al*, 2010). With the performance improvement of optical inter-satellite laser link (OISL), it is a very important development direction to build an optical satellite networks by wavelength division multiplexing (WDM) and wavelength routing technology for the future broadband, high-capacity space communications (Yang *et al*, 2010; Yang *et al*, 2009). In order to establish OISLs, the required wavelength number has to grow nearly at the speed of square law while satellite nodes increases, which limited the scale of optical satellite networks severely (Baroni and Bayvel, 1997; Tan *et al*, 2010).

Considering microwave links are used between satellites and ground, a scheme of optical satellite networks with two-layered wavelength/subcarrier routing (TWSR-OSN) has been proposed (Guo *et al*, 2003) to resolve its serious insufficient of wavelength resources, which keeps its advantage of wavelength routing and its better flexibility.

In optical satellite networks, each OISL can have multiple wavelengths; and satellite nodes can perform switching of data streams by wavelength-routing algorithms. The issue is how to use fewer network resources, such as nodes, ports, wavelengths and so on, to obtain the most network throughput with minimum time delay and least blocking probability, so it becomes very critical to adopt a better routing and wavelength assignment algorithm (Poo *et al*, 2006; Cardoso *et al*, 2010).

In TWSR-OSN, wavelength and subcarrier are expensive network resources. When a subcarrier channel in a wavelength is established, two-layered routing is helpful to improve the network performance, so it is necessary to study its dynamic RWSA algorithm. But its logical hierarchy with double granularity switching is more complicated, some switching belongs to subcarrier layer while the others maybe belong to wavelength layer[6].

Distinguished to optical terrestrial networks with WDM, most optical satellite networks consist of different satellite constellations with its unique attributes and features, such as low earth orbit (LEO), medium earth orbit (MEO), geosychronons earth

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orbit (GEO), where its OISL distributions are asymmetry obviously. Therefore WRSA problem has to be studied respectively in two cases that OISLs have uniform or non-uniform wavelength distributions.

Based on a novel subcarrier layered-graph, dynamic RSWA algorithm is presented with centralized allocation strategy and decentralized allocation strategy on the network resources, In order to make the scheme more general, two types of TWSR-OSN are analyzed: one has OISLs with uniformly distributed wavelengths and the other has OISLs with non-uniformly distributed wavelengths.

The remaining sections are organized as follows. In section 2, two-layer switching structure is analyzed, and SL-G model is set up in section 3. In section 4, based on SL-G model, RSWA algorithms are proposed with two strategies for different types of TWSR-OSN. Section 5 shows the simulation results of RWSA algorithms. Section 6 concludes the work.

2 TWO-SWITCHING STRUCTURE & WORKING MECHANISM

Due to two relatively independent logical sub-layers of wavelength and subcarrier, TWSR-OSN can perform unique two-level switching, therefore satellite node's switching structure is a kind of hybrid granularity exchanging of wavelength and subcarrier. Its working mechanism is that each satellite node can demultiplex the OISL into a single wavelength, or a single subcarrier channel. Although its switching structure become complicated with higher cost, the traffic load can realize two-level switching by adding and dropping in wavelength layer or subcarrier layer, based on routing status in TWSR-OSN.

Figure 1 shows two-level switching structure. For the incoming wavelength link and subcarrier channel, wavelength switching matrix and subcarrier switching matrix act as a selector and a space division switch so that input traffic can select different switching granularity of wavelength or subcarrier according to the switching matrix configuration. Of course, switching matrix can switch wavelength and subcarrier simultaneously, as well as only wavelength.

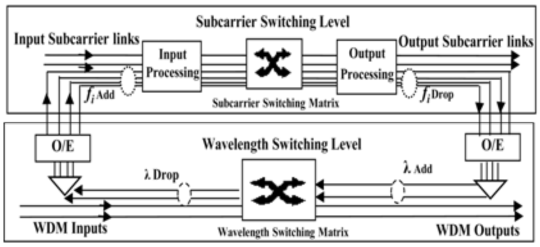

Figure 1: Two-level switching structure.

Because both of the same wavelengths cannot converge into one OISL at the same time while both of the same subcarriers cannot converge into one wavelength, both wavelength continuity constraints and subcarrier continuity constraints have to be met simultaneously. In Figure 1, wavelength switching matrix can only exchange the same wavelength from different OISLs, while subcarrier switching matrix can only exchange the same subcarrier from different wavelengths in different OISLs.

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3 SL-G MODEL

According to subcarrier continuity constraints, each available network path in multiple OISLs must be assigned the same subcarrier, namely, in the same subcarrier plane, each satellite node is divided into multiple virtual nodes with different sub-layers, where each sub-layer indicates only one wavelength in OISL, therefore, two-level switching structure can perform cross-connect between these virtual nodes, and each edge between virtual nodes is determined uniquely by one subcarrier and one wavelength.

Given a TWSR-OSN topology $\boldsymbol{G(N,L,W,S)}$, where $\boldsymbol{N}$ represents physical satellite node sets, and $\boldsymbol{L}$ is all directed link sets among satellite nodes, for any OISL, $\boldsymbol{l_{a,b}}$ is a link between node $\boldsymbol{a}$ and node $\boldsymbol{b}$ and $\boldsymbol{l_{a,b} \in L}$; $\boldsymbol{W_{a,b}}$ is its available wavelengths sets of $\boldsymbol{l_{a,b}}$, so all wavelength sets $W = \{W_{a,b}\}$; $\boldsymbol{S}$ is a subcarrier sets $\boldsymbol{S = \{S_1, S_2, S_3 .....S_K\}}$ in each wavelength channel. If $\boldsymbol{W^W}$ is a wavelength sets which are used for wavelength switching, and $\boldsymbol{W^S}$ is a wavelength sets that are used for subcarrier switching, then $\boldsymbol{W = W^W \cup W^S}$.

The subcarrier layered-graph (***SL-G)*** is a directed graph. For OISLs in a given TWSR-OSN with uniformly-distributed resources, each link $\boldsymbol{l_{a,b}}$ has the same wavelength sets ***W***, and each wavelength has the same subcarrier sets ***S***, so its ***SL-G*(*V*,*E*)** can be obtained by two steps.

Firstly, a subcarrier sub-graph can be made by the following steps:

1)Each node $a \in N$ is replicated $|W|$ times to get a virtual nodes sets $V = \{v_a^{s,1}, v_a^{s,2}, \cdots v_a^{s,w} \cdots v_a^{s,|W|}\}$, where $V = V^W \cup V^S$, V^W and V^S are two kinds of virtual node sets corresponding to wavelength switching ports and subcarrier switching ports respectively. For any virtual node $v_a^{s,w}$, when $w \in W^W$, $v_a^{s,w} \in V^W$, similarly, when $w \in W^S$, $v_a^{s,w} \in V^S$.

2)For an available link $l_{a,b}$, two virtual nodes $v_a^{s,i} = \{v_a^{s,1}, v_a^{s,2}, \cdots\cdots v_a^{s,|W|}\}$ and $v_b^{s,j} = \{v_b^{s,1}, v_b^{s,2}, \cdots\cdots v_b^{s,|W|}\}$ can be connected by two edges $e_{a,b}^{s,i,j}$ and $e_{b,a}^{s,j,i}$ in opposite directions, where $e_{a,b}^{s,i,j}, e_{b,a}^{s,j,i} \in E$ and E is defined as an all edge sets, and one edge corresponds to one possible path between node $\boldsymbol{a}$ and $\boldsymbol{b}$ in ***SL-G***(***V***,***E***).

3) In order to accomplish the adding/dropping requests in subcarrier layer, two virtual nodes have to be added for each node in $SL\text{-}G(V,E)$: source node $v_a^{s,o}$ denote a producing service entity of access node $\boldsymbol{a}$, and destination node $v_a^{s,d}$ represents an absorbing service entity of dropping node $\boldsymbol{a}$. Meanwhile two directed edges have to been added from source node $v_a^{s,o}$ to virtual nodes $v_a^{s,w^1}, v_a^{s,w^2}, \cdots\cdots v_a^{s,|w^{|S|}}$ and from virtual nodes $v_a^{s,w^1}, v_a^{s,w^2}, \cdots\cdots v_a^{s,|w^{|S|}}$ to destination node $v_a^{s,d}$, and $W^S = \{w^1, w^2, \cdots w^{|S|}\}$, where the costs of the two directed edges are set to 0.

Secondly, by duplicating above sub-graph $|S|$ times, $|S|$ sub-graphs can be achieved with $|S|$ different subcarrier planes, which make up a whole ***SL-G***(***V***,***E***) shown in Figure 2, where every subcarrier plane is equivalent with each other.

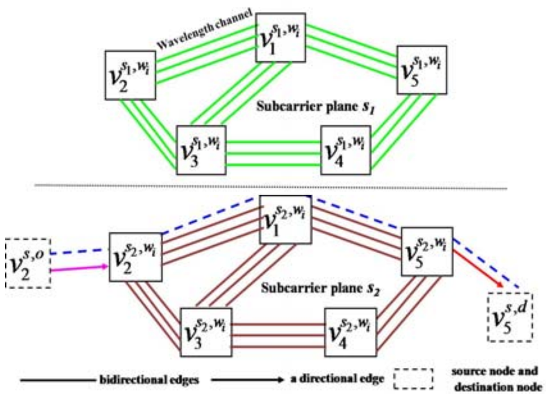

Figure 2: SL-G Model.

Assuming that each OISL is bidirectional in ***SL-G***(***V***,***E***), a subcarrier path corresponds to a pair of edges in opposite direction. Figure 2 shows a subcarrier path in subcarrier plane s_2 via a route $l_{2,1}l_{1,5}$ from node $V_2^{s_2,w_i}$ to node $V_5^{s_2,w_j}$, which corresponds to a pair of directed edges $e_{2,1}^{2,i,j}, e_{1,5}^{2,i,j}$ and $e_{5,1}^{2,j,i}, e_{1,2}^{2,j,i}$, and subcarrier s_2 and wavelengths $w_i, w_j \in W$ are assigned to them. Consequently, dynamic RWSA problem in optical satellite networks can be solved simultaneously by the proposed ***SL-G***(***V***,***E***) model.

Obviously, subcarrier continuity constraint in ***SL-G***(***V***,***E***) can be ensured by allocating different subcarrier channels in the different subcarrier planes correspondingly, then RWSA problem in TWSR-OSN is simplified to find a path with minimum cost from source node $v_a^{s,o}$ to destination node $v_b^{s,d}$, which will provide a desired routing in a determined subcarrier plane.

It is noticed that the edges of subcarrier channels in all subcarrier planes are independent in ***SL-G***(***V***,***E***), however, the edges of wavelength channels between virtual nodes in different subcarrier planes are dependent. Once a wavelength is used out in one subcarrier plane, the cost of all edges which the wavelength passes should be set to infinity, meanwhile, the costs of related edges with the same wavelength in else subcarrier planes are also set to infinity.

4 DYNAMIC RWSA ALGORITHM BASED ON SL-G MODEL

4.1 Definition of Edge Costs

In ***SL-G*** model, dynamic RSWA problem is equivalent to find a minimum cost path in TWSR-OSN, which should make full use of network resources, including wavelengths and subcarriers, and meet the service requests of network connection of subcarrier channels as far as possible.

In TWSR-OSN, the cost of each edge in ***SL-G*** is a scalar, which is much more complex and affected by many factors, including inter-satellite distances, QoS, different constellations and switching levels etc. Different definitions of each edge cost will lead to two different resource allocation strategies and the corresponding RSWA algorithms. The definition of different edges and its cost functions based on different strategies are followed.

For edge $e_{a,b}^{m,i,j}$, subscript $\boldsymbol{a}$ is source node number and $\boldsymbol{b}$ is terminal node number in satellite networks, $\boldsymbol{m}$ indicates the subcarrier plane which this edge belongs to in the ***SL-G***, $\boldsymbol{i}$ and $\boldsymbol{j}$ represent the wavelength number of virtual nodes; T^W is wavelength sets and T^S indicates subcarrier channel sets.

4.1.1 Centralized Strategy

When $i \in W^W$ and $j \in W^W$, $e_{a,b}^{m,i,j} \in T^W$

$$C(e_{a,b}^{m,i,j}) = \begin{cases} & \text{if flow is assigned to } e_{a,b}^{m,f_1,f_2},\ f_1 = i \text{ or } f_2 = j \\ \infty & \text{or to } e_{a,b}^{s,i,f},\ f \in W,\ f \neq j,\ s \in S,\ s \neq m \\ & \text{or to } e_{a,b}^{s,f,j},\ f \in W,\ f \neq i,\ s \in S,\ s \neq m, \\ C_{a,b}^W & \text{otherwise} \end{cases} \quad (1)$$

When $i \in W^S$ or $j \in W^S$, $e_{a,b}^{m,i,j} \in T^S$

$$C(e_{a,b}^{m,i,j}) = \begin{cases} & \text{if flow is assigned to } e_{a,b}^{m,f_1,f_2},\ f_1 = i \text{ or } f_2 = j \\ \infty & \text{or to } e_{a,b}^{s,i,f},\ i \in W^W,\ f \in W^W,\ s \in S,\ s \neq m \\ & \text{or to } e_{a,b}^{s,f,j},\ j \in W^W,\ f \in W^W,\ s \in S,\ s \neq m \\ C_{a,b}^S & \text{otherwise} \end{cases} \quad (2)$$

The constraint conditions are:

$$C(e_{a,b}^{m,i,j}) > 0,\ \forall m \in S,\ \forall i \in W,\ \forall j \in W,\ \forall a \in N,\ \forall b \in N \quad (3)$$

Where $C_{a,b}^W$ and $C_{a,b}^S$ are the initial cost constants of wavelength and subcarrier channel from node $\boldsymbol{a}$ to node $\boldsymbol{b}$ respectively. It is noticed that if each subcarrier plane is equivalent completely, cost function of different edges corresponding to the same link is exactly the same.

After the establishment of a new subcarrier channel, if there are idle subcarrier channels in the edge, its cost is $C(e_{a,b}^{m,i,j})$, otherwise, its cost is set to infinity. Concentrated strategy encourage optical path to use least network source by setting up subcarrier channels in less edges on the least subcarrier planes as far as possible, so more network resources can be reserved to meet much more service requests of subcarrier channels.

4.1.2 Decentralized Strategy

Under the decentralized strategy, the edge cost of $e_{a,b}^{m,i,j}$ is given as follows:

When $i \in W^W$ and $j \in W^W$, $e_{a,b}^{m,i,j} \in T^W$

$$C(e_{a,b}^{m,i,j}) = \begin{cases} & \text{if flow is assigned to } e_{a,b}^{m,f_1,f_2},\ f_1 = i \text{ or } f_2 = . \\ \infty & \text{or to } e_{a,b}^{s,i,f},\ f \in W,\ f \neq j,\ s \in S,\ s \neq m \\ & \text{or to } e_{a,b}^{s,f,j},\ f \in W,\ f \neq i,\ s \in S,\ s \neq m, \\ C_{a,b}^w + \delta_{a,b}^w \sum_{s \in S} O(e_{a,b}^{s,i,j}) & \text{otherwise} \end{cases} \quad (4)$$

When $i \in W^S$ or $j \in W^S$, $e_{a,b}^{m,i,j} \in T^S$

$$C(e_{a,b}^{m,i,j}) = \begin{cases} & \text{if flow is assigned to } e_{a,b}^{m,f_1,f_2},\ f_1 = i \text{ or } f_2 = j \\ \infty & \text{or to } e_{a,b}^{s,i,f},\ i \in W^W,\ f \in W^W,\ s \in S,\ s \neq m \\ & \text{or to } e_{a,b}^{s,f,j},\ j \in W^W,\ f \in W^W,\ s \in S,\ s \neq m \\ C_{a,b}^S + \delta_{a,b}^S \sum_{s \in S} O(e_{a,b}^{s,i,j}) & \text{otherwise} \end{cases} \quad (5)$$

Where $\delta_{a,b}^w$ is a coefficients used to adjust the changing trend of edge cost of a wavelength as its occupied subcarrier number changes, and $\delta_{a,b}^S$ is a coefficients used to adjust the changing trend of edge cost of a subcarrier channel as the occupied subcarrier number changes in the same wavelength. Both of them can be configured according to the network conditions.

$O(e_{a,b}^{s,i,j})$ is used to judge if its edge cost of $e_{a,b}^{s,i,j}$ is infinity, which is defined as follows:

$$O(e_{a,b}^{s,i,j}) = \begin{cases} 1 & \text{if } C(e_{a,b}^{s,i,j}) = \infty \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

Because of its action of δ_W and δ_S, no matter which kind of the shortest path algorithm is adopted, decentralized strategy will promote the existing calls to route in wavelength channel and subcarrier plane with lower utilization, so that all traffic loads will be distributed uniformly in all wavelength channels and all subcarrier planes as far as possible.

By setting different $C_{a,b} = C_{a,b}^W$ or $C_{a,b}^S$, two strategies can derive different RSWA algorithms suitable for different types of optical satellite networks.

A) TWSR-OSN with uniform wavelength distribution and different link costs

Set a link cost matrix $BC = \{BC_{a,b}\}_{|N|\times|N|}$, where $BC_{a,b}$ represents its basic cost of $e_{a,b}^{s,i,j}$. If $e_{a,b}^{s,i,j}$ doesn't exist, $BC_{a,b} = \infty$. For such a network, Let:

$$\begin{cases} C_{a,b} = BC_{a,b} \\ \delta_{a,b} = BC_{a,b} \end{cases} \quad (7)$$

Obviously, the network with uniformly distributed wavelengths and the same link costs is just a special case when $C_{a,b} = \delta_{a,b} = 1$.

B) TWSR-OSN with non-uniform wavelength distribution and the same link costs.

Matrix $WL = \{|W_{a,b}|\}_{|N|\times|N|}$ describes the wavelength number distribution among OISLs, $\boldsymbol{LCM(WL)}$ represents the least common multiple of all non-zero element in matrix. For such a network, Let:

$$\begin{cases} C_{a,b} = LCM(WL)/|W_{a,b}| \\ \delta_{a,b} = LCM(WL)/|W_{a,b}| \end{cases} \quad (8)$$

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In above formula, the less wavelength number an OISL has, the bigger its corresponding $C_{a,b}$ and $\delta_{a,b}$ are.

C) TWSR-OSN with non-uniform wavelength distribution and different link costs.

For such a network, two types of definition of $C_{a,b}$ and $\delta_{a,b}$ are given below.

$$\begin{cases} C_{a,b} = MCM(WL)/|W_{a,b}| + BC_{a,b} \\ \delta_{a,b} = MCM(WL)/|W_{a,b}| + BC_{a,b} \end{cases} \tag{9}$$

$$\begin{cases} C_{a,b} = BC_{a,b} \\ \delta_{a,b} = MCM(WL)/|W_{a,b}| \end{cases} \tag{10}$$

If a calling request from node $\boldsymbol{a}$ to node $\boldsymbol{b}$ arrives, let $\boldsymbol{P_{a,b}}$ represents all possible access path sets from v_a^o to v_b^d. If the edge $e_{a,b}^{s,i,j}$ exists in a path $\boldsymbol{p}$ ($p \in \boldsymbol{P_{a,b}}$), let indicating function $x(p, e_{a,b}^{s,i,j}) = 1$, otherwise, let $x(p, e_{a,b}^{s,i,j}) = 0$. If an new calling is established in path $\boldsymbol{p}$, let indicating function $y(p) = 1$, otherwise, let $y(p) = 0$.

The minimum cost function $C(p)$ of path $\boldsymbol{p}$ can be expressed as:

$$C(p) = \min\{\sum_{s\in S} \sum_{p\in P_{a,b}} \sum_{e_{a,b}^{s,i,j}\in E} c(e_{a,b}^{s,i,j}) \cdot x(p, e_{a,b}^{s,i,j}) \cdot y(p)\} \tag{11}$$

The following condition must be met.

$$\sum_{p\in P_{a,b}} y(p) = 1 \tag{12}$$

For $\forall \boldsymbol{p} \in \boldsymbol{P_{ab}}$, $x(p, e_{a,b}^{s,i,j}) \in \{0,1\}$ and $y(p) \in \{0,1\}$. Considering edge costs from source node v_a^o, destination node v_b^d to its own virtual nodes has been set to 0, formula (11) includes all edge sets $\boldsymbol{E}$ in ***SL-G***.

In summary, dynamic RSWA problem in TWSR-OSN can be resolved by the shortest path algorithm based on SL-G. If the shortest path with a limited cost can be found from v_a^o to v_b^d in corresponding ***SL-G***, the calling request will be accepted, otherwise, it will be rejected.

4.2 RWSA Algorithm Based on SL-G

By the shortest path algorithms, such as *Dijkstra* algorithm, according to decentralized strategy and centralized strategy, the dynamic RWSA based on ***SL-G*** can be performed by the following steps.

Step 1: Convert a given TWSR-OSN with ***G***(***N***,***L***,***W***,***S***) into ***SL-G(V,E)***. According to different types of satellite networks, proper $C_{a,b}$ and $\delta_{a,b}$ is defined by formula (7) to formula (10), and taken into formula (1) and (2) or formula (4) and (5) based on concentrated strategy or decentralized strategy , then initial cost of each edge $e_{a,b}^{s,i,j}$ can be achieved.

Step 2: Waiting for the input calling. If a request for subcarrier channel connection arrives, turn to Step 3; if a request for releasing a connection arrives, turn to Step 4.

Step 3: According to the pair of nodes requested by the input calling, the corresponding source node and destination node v_a^o and v_b^d, as well as its edges and its edge costs, are added into ***SL-G***. By the shortest path algorithm *Dijkstra*, search for the shortest path $\boldsymbol{p}$ from v_a^o to v_b^d.

(1) If the shortest path cost $\boldsymbol{C}(p)$ is infinity, reject the calling request, then turn to Step 2.

(2) If $\boldsymbol{C}(p)$ is limited, accept the request, and map the shortest path $\boldsymbol{p}$ into the corresponding subcarrier plane and wavelength channel in ***SL-G***:

a) Map the distribution of all virtual nodes and directed edges along the shortest path $\boldsymbol{p}$ into the nodes and links in the physical optical satellite networks, then a routing of the subcarrier path can be obtained;

b) If the shortest path $\boldsymbol{p}$ passes through the *k-th* subcarrier plane, assign subcarrier channel s_k to it;

c) According to the formula (1) and (2) or formula (4) and (5), refresh the edge costs of related links that the shortest path $\boldsymbol{p}$ passes through. Because $\boldsymbol{p}$ is a bidirectional path, edge cost functions of $e_{a,b}^{s,i,j}$ and $e_{b,a}^{s,j,i}$ must be refreshed at the same time, turn to Step 2;

Step 4: According to the formula (1) and (2) or formula (4) and (5), refresh the edge costs of related links that the subcarrier path passes through.

Step 5: Release subcarrier path, turn to Step 2.

Considering the complexity of RSWA algorithm, the influence of v_a^o and v_b^d and its edges connecting to SL-G are ignored. The complexity of Step 1 is proportional to the edge number of |E|, while the complexity of Step 4 is nearly proportional to the network diameter. Therefore the complexity of dynamic RSWA algorithm is mainly determined by the complexity of the shortest path algorithm adopted in Step 3. If the shortest path algorithm with the highest speed, such as *Dijsktra* algorithm, is adopted, its complexity is $\boldsymbol{O}(|\boldsymbol{V}|^2) = \boldsymbol{O}(|\boldsymbol{N}|^2|\boldsymbol{S}|^2)$.

5 SIMULATION RESULTS

Based on ***SL-G*** model, numerical simulation will be performed to compare the performance of two RWSA algorithms in different types of TWSR-OSN: one is denoted as RWSA-C derived from centralized

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strategy while the other is named as RWSA-D derived from decentralized strategy.

In simulations, two types of network topology are used. As shown in Figure 3(a), a regular ring-lattice topology represents TWSR-OSN with a single constellation (such as LEO), which consists of 4 orbits with 8 satellites at each orbit, where each satellite node has OISLs with four adjacent satellite nodes at the same orbit and at the adjacent orbit, meaning the whole network has 32 nodes and 64 OISLs. Figure 3(b) depicts an irregular network topology, representing optical satellite networks with hybrid constellations of LEO and MEO etc, which has 10 nodes and16 OISLs.

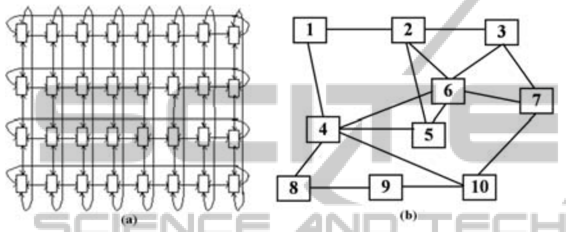

Figure 3: (a) Regular network topology, (b) Irregular network topology.

Assuming that requests for subcarrier channels arrive randomly in Poisson Process with the network arrival rate λ, traffic intensity among all satellite node pairs is distributed uniformly, while multiple subcarrier paths between a pair of nodes are permitted. After subcarrier paths are set up, its services time depends on negative exponential distribution with a mean value of $1/\mu$. The average service time in TWSR-OSN is set to an unit time, so it total network load is $\rho = \lambda/\mu$. Once a subcarrier channel connection request is rejected, it is discarded immediately without a waiting queue scheduling mode. In order to ensure the network into a stable running status, 1×10^6 connection requests are generated.

For comparison with the proposed RWSA algorithm, two routing and wavelength assignment algorithms are employed, including fixed routing and First-Fit wavelength assignment algorithm (FR/FF), fixed alternate routing and random wavelength assignment algorithm (AR2) which determines two alternate routes for each pair of nodes by its basic costs.

A: TWSR-OSN with uniform wavelength distribution and the same link costs

In TWSR-OSN with uniform wavelength distribution and the same link costs, wavelength number at each OISL is set to $|W_{ij}|=|\boldsymbol{W}|$. For simplicity, the basic cost $\boldsymbol{C}_{a,b}$ and $\delta_{a,b}$ of each edge in any link $\boldsymbol{l}_{a,b} \in \boldsymbol{L}$ in $\boldsymbol{SL\text{-}G}$ are all set to 1.

Based on the regular network topology above, the network performances of TWSR-OSN is simulated firstly, where wavelength number of each OISL is set to 4, 8 and 16 respectively, while each wavelength has 16 subcarrier channels. By RWSA-D algorithm, Figure 4 describes the network performances with different wavelength numbers. As expected, with the increasing wavelengths, its network blocking probability is degraded sharply at the same traffic load, while its network throughput increases greatly at the same blocking probability. For example, when the blocking probability is 0.01, its throughput with 8 wavelengths is over 3 times of that with 4 wavelengths, while its throughput with 16 wavelengths is over 8 times, that is, the network throughput appears to increase rapidly at a nonlinear rate, which reveals its advantage of the network performance improvement by introducing two-layered wavelength/subcarrier routing in optical satellite networks.

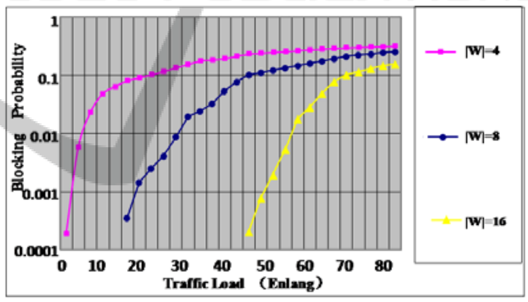

Figure 4: Network performance of TWSR-OSN with different wavelength numbers in the regular network topology.

It is assumed that the network traffic load is fixed, and its channel number in each ISL is set to $|\boldsymbol{W}|\cdot|\boldsymbol{S}|=32$, and the number of wavelengths |W| changes from 1 to 32. Figure 5 illustrates the network blocking probability by different algorithms. The simulation result shows that AR2 algorithm appears better network performance with lower blocking probability than FR/FF algorithm obviously; meanwhile, once the wavelength number |W| exceeds 4, the performance of RWSA-D algorithm is far superior to two other algorithms.

For a given irregular network topology of TWSR-OSN, the total channel number of each OISL is set to $|\boldsymbol{W}|\cdot|\boldsymbol{S}|=16$, while wavelength number |W| is set to 4 and 16 separately. In Figure 6, the blocking probability curve of RWSA algorithm based on SL-G is compared with other algorithms,

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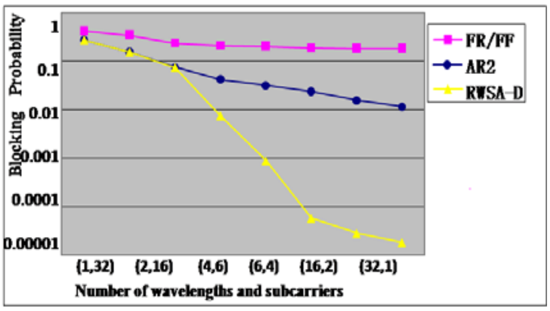

Figure 5: Network performance of TWSR-OSN with different algorithms in the regular network topology.

based on SL-G is compared with other algorithms, indicating similar simulation results to the regular network topology, that is, RWSA-D algorithm is far superior to FR/FF algorithm, and also better than AR2 algorithm. When the network blocking probability is 0.01, its throughput under RWSA-D is over 1.7 times that of FR/FF, as well as over 1.38 times that of AR2. If both wavelength number and subcarrier channel number are set to 4 with the traffic load of 80 Erlangs, the blocking probability by RWSA-D is only 1.1×10^{-3}, but the blocking probability by FR/FF reaches up to 5.3×10^{-1}, and the blocking probability by AR2 is 9.8×10^{-2}.

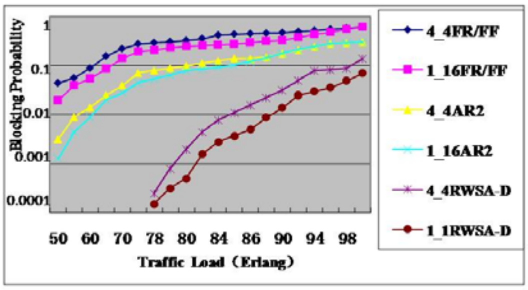

Figure 6: Network performance of TWSR-OSN with different algorithms in the irregular network topology.

Suppose that the total channel number of each OISL is still set to $|\boldsymbol{W}|\cdot|\boldsymbol{S}|=16$, while wavelength number |W| is set to 2, 4 and 8 separately, the performances of RWSA-D algorithm and RWSA-C algorithm are simulated in the irregular network topology. Figure7 shows the performance of RWSA-D algorithm with lower blocking probability is better than RWSA-C algorithm, while its actual difference gap enlarges rapidly with the increasing wavelengths |W|. For instance, when the blocking probability is 0.01, |S|=8 and |W|=2, the network throughput by RWSA-D algorithm is 1.27 times that of RWSA-C algorithm, while its corresponding ratio is 1.5 times as |S|=4 and |W|=4, as well as 1.63 times as |S|=2 and |W|=8.

RWSA-C algorithm prefers to concentrate the request callings on fewer subcarrier planes and fewer edges, which results in so rapid exhaustion of its channel resources that when an new calling arrives at a node, it becomes difficult to find an appropriate path in the subcarrier planes, even if a large number of idle channels exist in the other edges. Path length determined by RWSA-D algorithm for a new calling may exceed that of RWSA-C algorithm, but a long subcarrier path will not necessarily lead to congestion, yet better network performance probably.

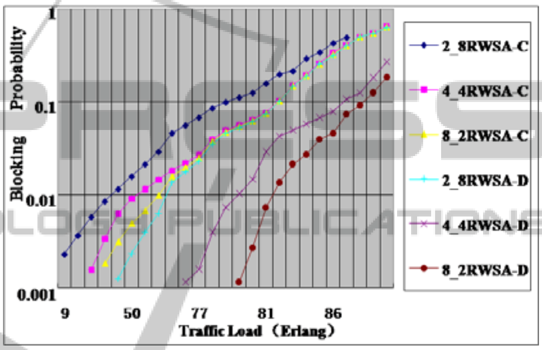

Figure 7: Network performance of TWSR-OSN by RWSA-D algorithm and RWSA-C algorithm in the irregular network topology.

B: TWSR-OSN with non-uniform wavelength distribution and the same link costs

In actual satellite networks of hybrid constellations, owing to its different functions and optical transceiver costs in different satellite constellations, different types of OISLs appears non-uniform wavelength distribution generally with its different number of wavelengths, including inter-satellite OISLs at the same orbit, different orbits and different constellations. An OISL wavelength-number matrix ***WL*** in the given irregular network topology is followed below. Herein each element indicates the wavelength number in the OISL of the corresponding pair of nodes, and its element 0 represents no OISL between the corresponding satellite node pair, meanwhile the subcarrier channel number in each wavelength is set to |S|=4.

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$$
WL = \begin{pmatrix}
0 & 8 & 8 & 4 & 0 & 2 & 0 & 0 & 0 & 4 \\
8 & 0 & 8 & 0 & 2 & 0 & 0 & 0 & 4 & 0 \\
8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 0 \\
4 & 0 & 0 & 0 & 4 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 & 4 & 0 & 4 & 0 & 0 & 0 \\
0 & 0 & 4 & 0 & 0 & 4 & 0 & 4 & 0 & 0 \\
0 & 0 & 4 & 0 & 0 & 0 & 4 & 0 & 4 & 0 \\
0 & 4 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 2 \\
4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0
\end{pmatrix} \qquad (13)
$$

Figure 8 depicts the network performance of different algorithms with non-uniform wavelength distributions. It is observed that RWSA-D algorithm and RWSA-C algorithm based on SL-G are still better than FR/FF and AR2 algorithms significantly. Especially, as the load is 75 Erlangs, the blocking probability by RWSA-D algorithm is merely 6.5×10^{-4}, however the blocking probability of AR2 and FR/FF algorithms are 1.05×10^{-2} and 9.5×10^{-2} respectively; as the load is reduced to 70 Erlangs, the blocking probability of RWSA-D algorithm is lower than AR2 by two orders of magnitude, and lower than FR/FF by three orders of magnitude.

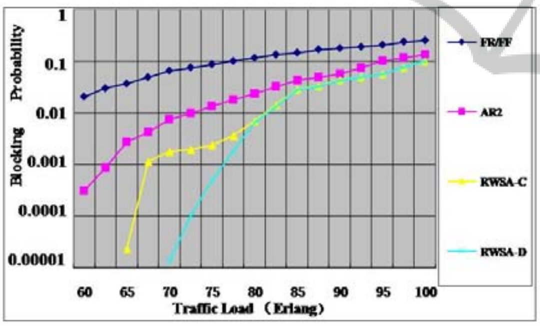

Figure 8: Network performance of different algorithms with non-uniform wavelength distributions.

6 CONCLUDING REMARKS

In this paper, a novel dynamic RWSA algorithm is proposed to realize its two-layered routing and wavelength/subcarrier assignment in TWSR-OSN. Based on the two-level switching, a new SL-G model is established, which can convert the RWSA problem into finding the shortest path with limited costs in the corresponding subcarrier layered graph, therefore TWSR-OSN not only can provide the end-to-end service access and aggregation for subcarrier channel connection requests, but also its dynamic RWSA problem can be achieved simultaneously.

By definitions of different edge cost functions in SL-G, two types of network resource assignment strategy of centralized strategy and decentralized strategy are analysed, while two RWSA algorithms are introduced, adapting to TWSR-OSN with different kinds of constellations. Simulation results demonstrate that, no matter whether TWSR-OSN has single constellation with uniform wavelength distribution or hybrid constellations with non-uniform wavelength distribution, the proposed RWSA algorithms based on SL-G model are superior to traditional routing and wavelength assignment algorithms, achieving lower network blocking probability; Meanwhile RWSA-D algorithm with balanced use of network resources is better than RWSA-C algorithm that encourage the centralized utilization of network resources.

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