

Dynamic routing and wavelength assignment algorithm of optical satellite networks based on cross-layer design^①

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Abstract

In order to overcome the adverse effects of Doppler wavelength shift on data transmission in the optical satellite networks, a dynamic routing and wavelength assignment algorithm based on cross-layer design (CL-DRWA) is introduced which can improve robustness of the network. Above all, a cross-layer optimization model is designed, which considers transmission delay and wavelength-continuity constraint, as well as Doppler wavelength shift. Then CL-DRWA is applied to solve this model, resulting in finding an optimal light path satisfying the above constraints for every connection request. In CL-DRWA, Bellman-Ford method is used to find an optimal route and a distributed relative capacity loss method is implemented to get an optimal wavelength assignment result on the optimal route. Moreover, compared with the dynamic routing and wavelength assignment algorithm based on minimum delay strategy (MD-DRWA), CL-DRWA can make an improvement of 5.3% on the communication success probability. Meanwhile, CL-DRWA can meet the requirement of transmission delay for real-time services.

Key words: cross-layer design, Doppler wavelength shift, dynamic routing and wavelength assignment, optical satellite network

0 Introduction

Driven by data traffic demand (especially Internet) and successes of laboratory, atmosphere, and space demonstrations of free-space optical communications, there is no doubt that free-space optical communication will be a key building block for wide-area space backbone networks of the future^[1-3]. Optical satellite networks offer many potential advantages compared to radio frequency (RF) satellite networks, including a very wide bandwidth, unlicensed spectrum, no need for frequency allocation, security, and resistance to jamming^[4-6], which makes them attractive for both civil and military applications. Furthermore, optical networking techniques based on wavelength division multiplexing (WDM) can not only simplify routing decisions but also minimize processing delays, and it is important that the technologies to be employed on board the satellites have to be space-qualified^[1,3,7]. The routing and wavelength assignment (RWA) prob-

lem, especially under the wavelength-continuity constraint, is the most challenging issue in the wavelength-routed optical satellite WDM networks^[8].

RWA problem is proved to be nondeterministic-polynomial-hard (NP-hard)^[9] and some methods have been carried out on the RWA problem in optical satellite networks. Using the minimum delay (MD) cost strategy, the fixed-alternate routing method and the first-fit (FF) wavelength assignment method is proposed to estimate the bounds of wavelength requirements in the optical transport networks over nongeosynchronous satellite constellations^[3,10]. An algorithm with multi-hop grooming and waveplane-based RWA for IP over WDM optical satellite networks is raised, and the costs used for searching a route are physical distance and routing hops respectively^[11]. Based on subcarrier layered-graph (SLG), a novel dynamic routing and wavelength/subcarrier assignment (RWSA) algorithm is put forward to find the shortest path with limited costs in the corresponding layered-graph^[12]. A perfect match model-based link assignment scheme

① Supported by the National Natural Science Foundation of China (No. 61675033, 61575026, 61675232, 61571440) and the National High Technology Research and Development Program of China (No. 2015AA015504).

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Received on Sep. 7, 2016

(LAS-PMM) is introduced to design an appropriate topology such that shorter path could be routed and less wavelengths could be assigned for each inter-satellite link (ISL) along the path^[13].

Although the methods mentioned above can provide better solutions from different aspects, there are still problems when significant Doppler is observed by the onboard terminals on the inter-satellite links (ISLs). As a matter of fact, the relatively rapid movement between each pair of establishing ISL satellites in the constellations can cause inevitable Doppler shift to the signal wavelengths^[14]. Furthermore, Doppler wavelength shift leads to ascending of crosstalk power and descending of signal power which directly makes bit error rate (BER) increased^[15]. Therefore, in order to overcome the adverse effects of Doppler wavelength shift on data transmission in the optical satellite network, a cross-layer optimization model is established, which takes into account transmission delay, wavelength-continuity constraint and Doppler wavelength shift simultaneously. The solution of the cross-layer optimization model is to select an optimal route and assign an available wavelength in setting up a lightpath for every source-to-destination connection request. For the sake of adapting to the dynamic changes of satellite networks, a dynamic routing and wavelength assignment algorithm based on cross-layer design (CL-DRWA) is used to solve the cross-layer optimization model. In CL-DRWA, Bellman-Ford (BF) algorithm is carried out to find an optimal route from the source to the destination using the transmission delay and Doppler wavelength shift information, which is suitable for satellite networks^[16]. And then a distributed relative capacity loss (DRCL) algorithm is implemented to get an optimal wavelength assignment result on the optimal route for the source-to-destination connection request, which can reduce the calculation upon receiving the connection request and have a good performance on blocking probability^[9].

The remainder of this paper is organized as follows. Section 1 presents a system architecture and theoretical model for dynamic RWA in optical satellite networks, while Section 2 describes the mechanism of CL-DRWA in detail. Section 3 is devoted to the analysis of CL-DRWA through extensive simulations, and finally, Section 4 summarizes the main conclusions of the paper.

1 System architecture and theoretical model

1.1 System architecture

The system architecture of this paper is shown in Fig. 1.

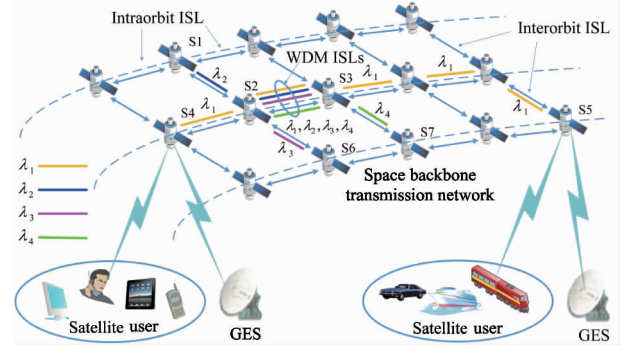


Fig. 1 The system architecture

As shown in Fig. 1, the system architecture consists of the space backbone transmission network, the gateway earth station (GES) and the satellite user. The space backbone network is formed by a Walker constellation with optical ISLs, which can achieve a global space-based communication service. Walker constellation can be expressed as $\theta; N/P/F$ ^[17], where θ is the inclination of orbital plane, N is the total number of satellites, P is the number of orbital planes and each orbit consists of S satellites, F is the phasing factor. There are two types of ISLs for the network connectivity: intraorbit ISLs and interorbit ISLs. The former interconnects satellites belonging to the same orbit, and the latter interconnects satellites belonging to different orbits. Since the relative distance of two intraorbit ISL satellites are fixed, no Doppler shift can be detected. However, as the relative distance between two interorbit ISL satellites varies from moment to moment, the Doppler wavelength shift is assignable. On the assumption that WDM architectures with wavelength routing are available for the ISL and there is no wavelength converter in the intermediate nodes, a light path should be set up under the wavelength-continuity constraint.

1.2 Theoretical model

The cross-layer optimization can integrate layers of the protocol stack into a comprehensive classification framework, which can improve the performance of the satellite networks^[18]. In CL-DRWA, the architecture of cross-layer design for dynamic RWA under the wavelength-continuity constraint in optical satellite networks is illustrated in Fig. 2. It is comprised of two main parts: quality of service (QoS) requirements for applications, and cross-layer optimization model.

As shown in Fig. 2, transmission delay and BER are two important factors of the QoS requirements for applications^[19]. In order to satisfy the QoS requirements for applications, a cross-layer optimization model

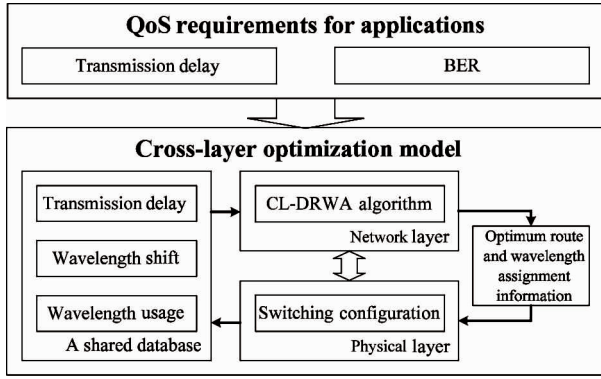


Fig. 2 The architecture of cross-layer design for dynamic RWA

is established. That is, the physical layer provides transmission delay, wavelength usage and Doppler wavelength shift information to a shared database, while the network layer gets the three kinds of information in the shared database^[20]. Then the network layer implements CL-DRWA algorithm to select a route and assign a wavelength in setting up a lightpath for every source-to-destination connection request. Next, the physical layer uses the optimum route and wavelength assignment information to accomplish the switching configuration. Eventually, the data is transmitted and switched. The schematic diagram of CL-DRWA algorithm is presented in Fig. 3. It can be seen that CL-DRWA algorithm mainly consists of two parts: BF algorithm and DRCL algorithm. BF is implemented periodically to update the routing table by using the transmission delay and Doppler wavelength shift information, which can provide an optimal route from the source to the destination. And DRCL is carried out cyclically to renew the relative capacity loss (RCL) table using the route information in the routing table and the wavelength usage information, which can get an optimal wavelength assignment result on the optimal route for the source-to-destination connection request.

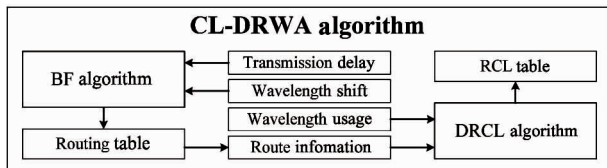


Fig. 3 The schematic diagram of CL-DRWA algorithm

Suppose $P(s, d)$ is a light path from satellite s to satellite d . i and j denote two interconnecting satellites on $P(s, d)$. $link_{ij}$ means optical ISL from i to j , $cost_{ij}(t)$ is the cost of $link_{ij}$ at moment t . $TD_{ij}(t)$ indicates the transmission delay from i to j at moment t . $BER_{ij}(t)$ is the BER when the packet passes through $link_{ij}$ at moment t . TD_{th} and BER_{th} represent the trans-

mission delay threshold and the BER threshold in the optical satellite network respectively. $w_{ij}(t)$ is the wavelength used on $link_{ij}$ of $P(s, d)$ at moment t . $\Omega = \{w_1, \dots, w_W\}$ is the wavelength resource on each ISL and W is the total number of wavelength candidates in the network. $w_k \in \Omega$ is the wavelength assigned at the beginning of establishing $P(s, d)$. An ISL is assigned to a source-destination satellite connection based on minimizing the total cost of the specific route. And the specific route should satisfy the constraints of the transmission delay, wavelength-continuity as well as Doppler wavelength shift. Therefore, the cross-layer optimization model proposed in this paper is represented by

$$\begin{aligned} \min \quad & \sum_{(i, j) \in P(s, d)} cost_{ij}(t) \\ \text{s.t.} \quad & \sum_{(i, j) \in P(s, d)} TD_{ij}(t) \leq TD_{th} \\ & \forall link_{ij} \quad w_{ij}(t) = w_k \\ & \forall link_{ij} \quad BER_{ij}(t) \leq BER_{th} \end{aligned} \quad (1)$$

In the optical satellite network, BER is effected by Doppler shift. Doppler shift leads to ascending of crosstalk power and descending of received signal power which directly increases BER^[15]. The relationship between BER and Doppler wavelength shift is that the more wavelength shift Doppler-effect induced, the more rapidly BER increases. Therefore, the constraint $\forall link_{ij} \quad BER_{ij}(t) \leq BER_{th}$ can be expressed as $\forall link_{ij} \quad |\Delta\lambda_{ij}(t)| \leq \Delta\lambda_{th}$, where $|\Delta\lambda_{ij}(t)|$ is the Doppler wavelength shift from i to j at moment t , and $\Delta\lambda_{th}$ represents the Doppler wavelength shift threshold in the optical satellite network.

The cost is the weighted sum of transmission delay and Doppler wavelength shift from i to j . So $cost_{ij}(t)$ can be expressed as

$$\begin{aligned} cost_{ij}(t) &= \omega_d \times \frac{TD_{ij}(t)}{TD_{max}} + \omega_w \times \frac{|\Delta\lambda_{ij}(t)|}{|\Delta\lambda_{max}|}, \\ \omega_d + \omega_w &= 1 \end{aligned} \quad (2)$$

where, ω_d and ω_w are the weights for transmission delay and Doppler wavelength shift respectively. TD_{max} and $|\Delta\lambda_{max}|$ are the maximum transmission delay and the maximum Doppler shift of the optical ISLs in the whole network respectively. $|\Delta\lambda_{ij}(t)|$ can be calculated according to formulas in Ref. [14]. $TD_{ij}(t)$ can be computed by

$$TD_{ij}(t) = PD_{ij}(t) + PRD_{ij}(t) \quad (3)$$

In Eq. (3), $PD_{ij}(t)$ is the propagation delay from i to j at moment t . $PRD_{ij}(t)$ is the on-board processing delay (which relates to the data switching/routing and queuing) at moment t in the WDM optical satellite net-

works.

2 Mechanism of CL-DRWA

In this section, the mechanism of CL-DRWA is described. Firstly, routing table and RCL table on each satellite are particularly introduced. And then the implementation of CL-DRWA is recommended in detail.

2.1 Routing table and RCL table

In an optical satellite network with N satellites, K links and W wavelengths, the state of link k , $1 \leq k \leq K$ at time t is represented by $w_k(t)$, which is defined as

$$w_k(t) = (w_k^1(t), w_k^2(t), \dots, w_k^W(t))^T \quad (4)$$

If wavelength i , $1 \leq i \leq W$ on link k is utilized by some connection at time t , then $w_k^i(t) = 0$; otherwise $w_k^i(t) = 1$. So the network status at time t can be described by constructing matrix $w(t) = (w_1(t), \dots, w_K(t))$. An example of the state of a simple network with 7 satellites, 10 links and 4 wavelengths at time t is illustrated in Fig.4(a).

The routing table on satellite s is represented by **ROUTE** _{s} , which can be defined as

$$\mathbf{ROUTE}_s = [\text{cost}_s(d), \text{prec}_s(d)]_N \quad (5)$$

here, **ROUTE** _{s} contains two rows and N columns. Each column corresponds to a destination satellite. $\text{cost}_s(d)$ indicates the cost of optical ISL from satellite s to satellite d ; $\text{prec}_s(d)$ means the previous node of satellite d in establishing a light path from satellite s to satellite d . $\text{cost}_s(d)$ and $\text{prec}_s(d)$ are used to calculate the route and update the routing table. An example of routing table at satellite 1 in the simple network is shown in Fig.4(b).

The RCL table of satellite s is represented by **RCL** _{s} , which can be defined as

$$\mathbf{RCL}_s = [rcl_s(w, d)]_{W, N} \quad (6)$$

where, **RCL** _{s} has W rows and N columns. Each row corresponds to an available wavelength and each column corresponds to a destination satellite; $rcl_s(w, d)$ means the probability of wavelength w which is selected by the light path from satellite s to satellite d . An example of the RCL table at node 1 in the simple network is illustrated in Fig.4(c). When a connection request from satellite 1 to satellite 6 occurs, the RCL table is looked up. Then the total relative capacity loss (TRCL) on each wavelength are 0.25 | _{$w=w1$} , 0.58 | _{$w=w2$} , 2.08 | _{$w=w3$} and 2.08 | _{$w=w4$} . Therefore, the minimum TRCL is 0.25 | _{$w=w1$} and w_1 is selected.

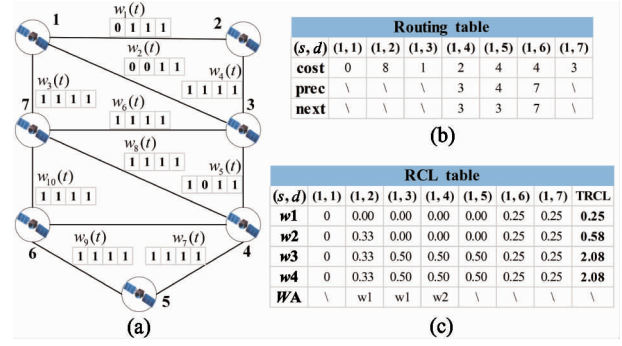


Fig. 4 A simple network topology with routing table and RCL table at satellite 1

2.2 Procedure of CL-DRWA

The pseudo code of CL-DRWA is shown in Fig. 5. CL-DRWA is composed of routing table updating, RCL table updating and request arrival. At First, the routing table updating process is carried out periodically by using BF algorithm, which can renew the routing table on each satellite according to the real-time status of the optical satellite network. Then RCL table updating procedure is implemented cyclically using the DRCL algorithm, leading to refreshing the RCL table with the wavelength usage status of the network. Eventually, when the connection request reaches the source satellite, the routing table will be looked up to get the route and the RCL table will be checked to assign the wavelength. Therefore, a light path is set up for the connection request. This process will be repeated until reaching the maximum simulation time.

2.2.1 Routing table updating

Assuming $link_{ij}(t)$ is the link connected state at time t from i to j , if the link at time t from i to j is connected, then $link_{ij}(t) = 1$; otherwise $link_{ij}(t) = 0$. When the renewal period of routing table updating is up, the operation is as follows: for each link which satisfies $link_{ij}(t) = 1$, $TD_{ij}(t)$ is calculated by Eq. (3), as well as $|\Delta\lambda_{ij}(t)|$. $cost_{ij}(t)$ is computed by Eq. (2). And then the routing table on each satellite is initialized. Next, the BF algorithm is implemented to find an optimal path for every satellite s from itself to the other satellites in the optical satellite network. N_s is the set of neighboring satellites for every satellite s . Each satellite receives the routing table from its neighboring satellites and refreshes its routing table and this will be repeated until reaching the iteration times.

2.2.2 RCL table updating

Assume W_i^j is the set of available wavelength candidates on the light path from i to j , which satisfies $W_i^j = \{w \in W | rcl_i(w, j) \neq 0\}$. For each satellite s in the network, $rcl_s(w, d)$ is initialized to $1/W$. When the

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{ Routing table updating }
for each  $link_{ij}(t)=1$  do
  calculate  $TD_{ij}(t)$ ;
  calculate  $|\Delta\lambda_{ij}(t)|$ ;
  calculate  $cost_{ij}(t)$ ;
end for
initialize each  $ROUTE_s, s \in N$ ;
repeat
  for each source satellite  $s \in N$  do
    for each neighbor  $n \in N_s$  do
      for each destination satellite  $d \in N$  do
        if  $(cost_s(d) = \infty) \wedge (cost_n(d) \neq \infty)$  then
           $cost_s(d) \leftarrow cost_n(d) + cost_n(d)$ ;
           $prec_s(d) \leftarrow prec_n(d)$ ;
        else if  $cost_s(d) > cost_s(n) + cost_n(d)$  then
           $cost_s(d) \leftarrow cost_s(n) + cost_n(d)$ ;
           $prec_s(d) \leftarrow prec_n(d)$ ;
        end if
      end for
    end for
  end for
until (reach iteration times);
{ RCL table updating }
repeat
  for each source satellite  $s \in N$  do
    for each destination satellite  $d \in N_s$  do
       $k$  is the number of elements in  $W_s^d$ ;
      if  $w \in W_s^d$  then
         $rcl_s(w, d) \leftarrow 1/k$ ;
      else if  $w \in W - W_s^d$  then
         $rcl_s(w, d) \leftarrow 0$ ;
      end if
    end for
  for each destination satellite  $d \in N - N_s, n \in N_s$  do
     $W_s^d \leftarrow W_s^n \cap W_n^d$ ;
     $k$  is the number of elements in  $W_s^d$ ;
    if  $w \in W_s^d$  then
       $rcl_s(w, d) \leftarrow 1/k$ ;
    else if  $w \in W - W_s^d$  then
       $rcl_s(w, d) \leftarrow 0$ ;
    end if
  end for
until (reach iteration times);
{ Request arrival }
if  $ArrivalTime(s, d) = t$  then
  optimal route  $\leftarrow prec_s(d)$ ;
  for each  $w \in \{w \in W \mid rcl_s(w, d) \neq 0\}$  do
    calculate  $TRCL(w)$ ;
  end for
  calculate  $TRCL_{min}$  and select the wavelength  $w_0$ ;
  if  $w_0 \in \emptyset$ 
     $ComSuccess \leftarrow false$ ;
  else
    if  $(\sum_{(i,j) \in P(s,d)} TD_{ij}(t) \leq TD_{th}) \wedge (\forall link_{ij} |\Delta\lambda_{ij}(t)| \leq \Delta\lambda_{th})$ 
       $ComSuccess \leftarrow true$ ;
    else
       $ComSuccess \leftarrow false$ ;
    end if
  end if
until (reach the maximum simulation time ).

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Fig. 5 The pseudo code of CL-DRWA

renewal period of RCL table updating is up, the operation is as follows: each satellite receives the RCL table from its neighboring satellites and refreshes its RCL ta-

ble. This will be repeated until reaching the iteration times.

2.2.3 Request arrival

When a connection request from satellite s to satellite d arrives at time t , the routing table on satellite s is checked and the optimal route can be derived from $prec_s(d)$. Subsequently, the RCL table on satellite s is looked up. TRCL on each available wavelength is computed by summing the RCL values for each wavelength over all destinations excluding destination d , and then wavelength w_0 will be selected, which has the minimum TRCL. Ultimately, data transmission begins. If the wavelength of each ISL on the optimal light path is available, and the transmission delay and Doppler wavelength shift of each ISL on the optimal light path satisfy the constraints in Eq. (1), then the flag ComSuccess is set to true; otherwise it is set to false. ComSuccess means that a reliable communication is set up between source and destination.

3 Simulation results

In this section, an Iridium-like satellite constellation is considered for our study, which is expressed by using a Walker notation of $86^\circ: 66/6/0$. There are two intraorbit ISLs and two interorbit ISLs. Intraorbit ISLs are maintained permanently throughout the orbital movement of the satellites, while interorbit ISLs are broken as satellites come close to the poles (Latitude $> 60^\circ$) due to adverse pointing and tracking conditions, when satellites move to lower latitudes, interorbit ISLs are re-established. Moreover, cross-seam ISLs, namely links between satellites in counter-rotating orbits, are not used^[21]. The number of wavelengths on each optical ISL is 16. All the wavelength routing have the same processing delay PRD_{ij} , which is set to 10ms^[3]. The transmission threshold TD_{th} is 300ms^[18]. As the sources and destinations are generated randomly, all the results are obtained by statistical averaging. In the following subsections, the Doppler wavelength shift threshold is given through simulation firstly. Then the performance of CL-DRWA is simulated and analyzed.

3.1 Doppler wavelength shift threshold

Ignoring the background light power and supposing that the receiving detector is thermal noise limit, as in Ref. [15], the BER of optical communications using an on-off keying (OOK) modulation format is

$$\begin{aligned}
 BER = & \frac{1}{2}Q(\sqrt{SNR}) + \frac{1}{4}Q(\sqrt{SNR}(1 + \frac{2}{\varepsilon})) \\
 & + \frac{1}{4}Q(\sqrt{SNR}(1 - \frac{2}{\varepsilon})) \quad (7)
 \end{aligned}$$

here, SNR is the signal-to-noise ratio and ε is the ratio of signal power P_s to crosstalk power P_{CT} . They can be described by

$$SNR = \left(\frac{e\bar{g}\eta P_s T_b}{2hf_0\sigma_n} \right)^2 \quad (8)$$

$$\varepsilon = \frac{P_s}{P_{CT}} = \frac{\int_{-\infty}^{\infty} S(f) |H(f)|^2 df}{\int_{-\infty}^{\infty} S(f+f_d) |H(f)|^2 df} \quad (9)$$

where, f_0 is the central frequency of the light wave. σ_n^2 means the variance of thermal noise. e denotes the electronic charge and h is the Planck constant. For convenience, $\eta = 0.8$, $T_b = 0.4\text{ns}$ ($1/T_b = 2.5\text{GHz}$), and $\bar{g} = 10$ have been taken, f_d indicates the frequency spacing for WDM channels, $S(f)$ and $H(f)$ are the power spectral density of signal and filter spectrum respectively. They can be expressed as

$$S(f) = \frac{P_r}{2\pi} \frac{B_s}{(B_s/2)^2 + [f - (\Delta f + f_{Lc})]^2} \quad (10)$$

$$H(f) = \frac{(B_f/2)^2}{(B_f/2)^2 + (f - f_{Dex})^2} \quad (11)$$

where, Δf denotes Doppler frequency shift, P_r is the mean receiving power of the signal, B_s is 3dB bandwidth of the laser, f_{Lc} represents central frequency of the laser. And B_f is 3dB bandwidth of the filter, f_{Dex} means central frequency of the filter.

Suppose c represents the velocity of light. The relationship between Doppler wavelength shift $\Delta\lambda$ and Doppler frequency shift Δf is

$$\Delta\lambda = \frac{c}{\Delta f} \quad (12)$$

$f_0 = f_{Lc} = f_{Dex} = 193.55\text{THz}$ (1550nm), $f_d = 200\text{GHz}$ and $B_f = 2B_s = 20\text{GHz}$ are taken. The variation of BER with Doppler wavelength shift is shown in Fig. 6. It can be seen from the relationship between

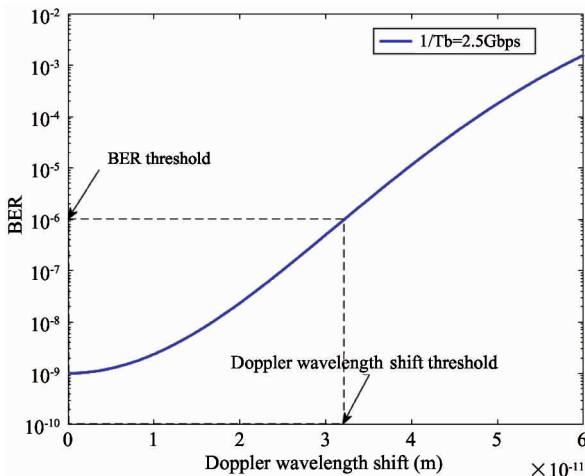


Fig. 6 Variation of BER with Doppler wavelength shift

BER and Doppler wavelength shift that the more wavelength shift Doppler-effect induced, the more rapidly BER increases. For the inter-satellite communication systems, BER is usually up to a magnitude of 10^{-7} [22], that is, BER must satisfy $BER < 1 \times 10^{-6}$, so the BER threshold BER_{th} is 1×10^{-6} . According to Fig. 6, the Doppler wavelength shift threshold $\Delta\lambda_{th}$ can be obtained, which is $3.22 \times 10^{-11}\text{m}$.

3.2 Performance analysis of CL-DRWA

In the simulation, in order to compare CL-DRWA results, the dynamic routing and wavelength assignment algorithm based on minimum delay strategy (MD-DRWA) is used throughout the simulation. Before simulation, several definitions are given. The traffic intensity is the product of the number of wavelength channels occupied per hour in the network and the average time for each occupation [8]. The communication success probability is defined as the ratio of the number of the established light paths, which satisfy the demands of transmission delay and BER in Eq. (1), to the number of total connection requests.

The effect of weighted values in the cost expression of CL-DRWA is illustrated in Fig. 7, where weight ω_d and ω_w are varied from 0.9 to 0.1 and communication success probability as a function of traffic intensity is captured. The results show that the ratio of the weighted values greatly affects the communication success probability. It can be seen that, when ω_d takes the value of 0.9, 0.8 and 0.7, the changing trend of the curves is basically the same in these three cases and the communication success probability is about 90%. The communication probability degrades when ω_d varies from 0.4 to 0.1, and the curves have a rapid downward trend with the increase of the traffic intensity. The reason is that, the larger the value of ω_w , the larger the probability to choose the interorbit ISLs with small Doppler wavelength shift, which causes no available wavelength resources at these interorbit ISLs and makes the request blocked. What's more, the communication success probability can reach about 94% as the value of ω_d is 0.6. And when the value of ω_d is equal to the value of ω_w (0.5), the communication success probability is about 95% and the performance of the algorithm is the best. This is because, when setting up a light path, the link cost caused by the transmission delay in Eq. (2) makes the route not too long, meanwhile, the link cost caused by the Doppler wavelength shift in Eq. (2) have a good effect on avoiding the ISL which has a large Doppler shift. When the values of ω_d and ω_w have little difference, it can achieve a better tradeoff between the transmission delay and the

Doppler wavelength shift, and make a high probability of the established light path to satisfy the constraints in Eq. (1).

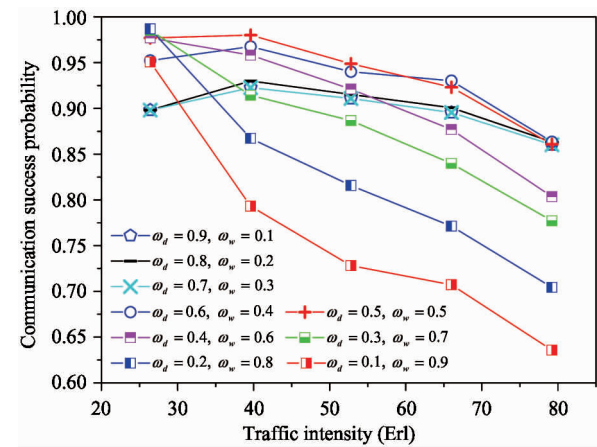


Fig. 7 The communication success probability of various ratios of weighted values in CL-DRWA

Fig. 8 is the communication success probability for both MD-DRWA and CL-DRWA. In CL-DRWA, ω_d and ω_w both take the value of 0.5. It can be clearly seen that as the traffic intensity increases, the communication success probability of the two algorithms are going down slowly, due to the growth of the wavelength resource utilization. Moreover, the communication success probability of CL-DRWA is higher than that of MD-DRWA and the growth increment is 5.3%. Table 1 illustrates the simulation data on the communication success probability of different algorithms so as to make the growth increment more clear. The growth increment (%) is the percentage of the communication success probability of CL-DRWA higher than that of MD-DRWA in the case of each traffic intensity. The average value of the growth increment is taken, which is equal to 5.3%. The reason is that CL-DRWA reduces

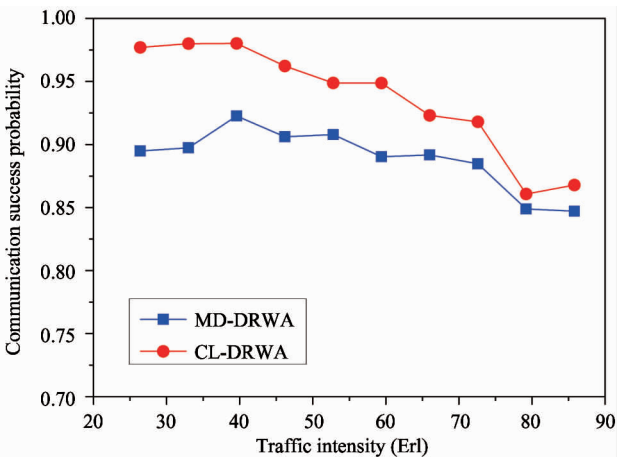


Fig. 8 The communication success probability of different algorithms

| Table 1 The communication success probability of different algorithms | | | | | |
|---|--------|--------|--------|--------|--------|
| Traffic intensity (Erl) | 26.4 | 33 | 39.6 | 46.2 | 52.8 |
| MD-DRWA | 0.8949 | 0.8973 | 0.9227 | 0.9061 | 0.9079 |
| CL-DRWA | 0.9770 | 0.9800 | 0.9801 | 0.9623 | 0.9488 |
| Growth increment (%) | 9.17 | 9.22 | 6.22 | 6.20 | 4.50 |
| Traffic intensity (Erl) | 59.4 | 66 | 72.6 | 79.2 | 85.8 |
| MD-DRWA | 0.8904 | 0.8917 | 0.8847 | 0.8489 | 0.8472 |
| CL-DRWA | 0.9487 | 0.9231 | 0.9180 | 0.8608 | 0.8679 |
| Growth increment (%) | 6.55 | 3.52 | 3.76 | 1.40 | 2.44 |

the possibility to select the interorbit ISLs which has a large Doppler shift and makes a high probability of the established light path to satisfy the constraints in Eq. (1). Furthermore, CL-DRWA enriches the choices of light path, so wavelength resource usage is balanced.

Fig. 9 shows the transmission delay performance as a function of traffic intensity when MD-DRWA and CL-DRWA are utilized in the network respectively. In CL-DRWA, ω_d and ω_w have the value of 0.5. It can be seen clearly from these two plots that there is a gap between the two algorithms with the increasing traffic intensity, but the gap is small. The reason is that, CL-DRWA can avoid selecting the interorbit ISLs which has a large Doppler shift, leading to an increase of the number of hops of the route, but the transmission delay constraint of CL-DRWA limits the number of hops not

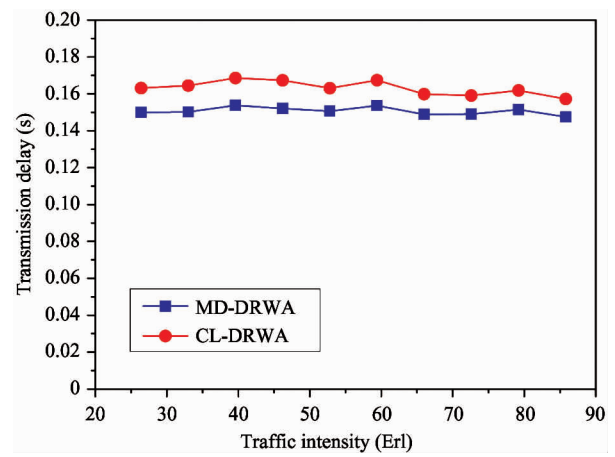


Fig. 9 The transmission delay of different algorithms

to be too large. As shown in Fig.9, operating CL-DRWA in the network increases the transmission delay, but the delay is basically stable at around 160ms, which can meet the needs of real-time traffic transmission^[23].

4 Conclusions

In this paper, CL-DRWA is put forward for the sake of improving the robustness of the optical satellite networks. Since Doppler wavelength shift has a negative impact on the quality of communication, a cross-layer optimization model is designed, which takes into account not only the constraints of the maximum transmission delay and Doppler wavelength shift the optical satellite networks can tolerant but also the wavelength continuity. In consideration of the dynamic state changes of the satellite network, CL-DRWA is used to solve the cross-layer optimization model, bringing about an optimal light path which satisfies the above constraints for every connection request. In setting up a light path, BF is used to find an optimal route and DRCL algorithm is implemented to get an optimal wavelength assignment result on the optimal route. The performance of CL-DRWA has been evaluated through extensive simulations with very promising results. Firstly, the effect of weighted values in the cost functions of CL-DRWA is analyzed. When the value of ω_d is equal to that of ω_w , the performance of the proposed algorithm is optimal as a result of a better tradeoff between the transmission delay and the Doppler wavelength shift. Furthermore, compared with MD-DRWA, CL-DRWA can enhance the communication success probability by about 5.3%. Meanwhile, CL-DRWA can meet the requirement of transmission delay for real-time services. These works contribute to the design of wavelength routing strategy with consideration of the Doppler wavelength shift factor in the WDM optical satellite networks.

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