IEICE TRANS. COMMUN., VOL.E103–B, NO.6 JUNE 2020

PAPER

Bee Colony Algorithm Optimization Based on Link Cost for Routing and Wavelength Assignment in Satellite Optical Networks

Yeqi LIU[†], **Qi ZHANG**[†a)], **Xiangjun XIN**[†], **Qinghua TIAN**[†], **Ying TAO**[††], **Naijin LIU**[††], ***Nonmembers***,
and **Kai LV**[†], ***Member***

SUMMARY Rapid development of modern communications has initiated essential requirements for providing efficient algorithms that can solve the routing and wavelength assignment (RWA) problem in satellite optical networks. In this paper, the bee colony algorithm optimization based on link cost for RWA (BCO-LCRWA) is tailored for satellite networks composed of intersatellite laser links. In BCO-LCRWA, a cost model of intersatellite laser links is established based on metrics of network transmission performance namely delay and wavelengths utilization, with constraints of Doppler wavelength drift, transmission delay, wavelength consistency and continuity. Specifically, the fitness function of bee colony exploited in the proposed algorithm takes wavelength resources utilization and communication hops into account to implement effective utilization of wavelengths, to avoid unnecessary over-detouring and ensure bit error rate (BER) performance of the system. The simulation results corroborate the improved performance of the proposed algorithm compared with the existing alternatives.

key words: *routing and wavelength assignment, satellite optical networks, bee colony algorithm optimization, link cost, fitness*

1. Introduction

1.1 Background and Motivation

Driven by the continuous development of satellite optical communication, acquisition tracing and pointing (ATP) technology of space optical signaling has developed from the experimental stage to the practical engineering stage. In recent years, inter-satellite laser link (ISL) is replacing microwave links as the preferred physical link for inter-satellite communication [1]. The traditional satellite network is gradually becoming incapable of meeting the enormous data transfer speeds [2] in military, meteorological, remote sensing and other fields. So, the satellite optical network with laser links is being developed to support a bunch of applications [3] because of its flexible global communication capability, low power consumption, strong confidentiality and survivability. Besides, the merits of miniaturization and lightweight of laser terminals provide its potential practicability of all-optical networks in the future. Specifically, in satellite optical networks, wavelength routing with coarse switching granularity can create multi-wavelength channels between satellites so as to avoid frequent multiplexing and demultiplexing, which improves the efficiency of resource utilization.

Due to the limitation of onboard resource and complexity of network, satellite optical networks place greater demands on solutions for routing and wavelength assignment (RWA). To tackle with RWA problem, it is imperative to establish an optimal combination of routing and wavelength for a set of connection requests in the demand matrix, with consideration of network objectives and constraints. Whether in terrestrial networks or satellite networks, wavelength continuity constraints and wavelength conflict constraints must be satisfied [4]. Since RWA has been proved to be a non-deterministic-polynomial-hard (NP-hard) problem [5], conventional solutions in existing literatures include mathematical integer linear programming (ILP) model, the shortest path method, heuristic algorithm and intelligent algorithm. Notwithstanding, frequent switching of links, low communication success rate, long delay and high bit error rate (BER) induced by satellite optical networks make the routing a tremendous challenge. In the status of difficulties for establishing inter-satellite links, designing an effective routing algorithm can provide support to significantly improve communication quality of the network and enhance resource utilization. Based on the considerations mentioned above, a bee colony algorithm optimization based on link cost (BCO-LCRWA) is designed to solve RWA problems in satellite optical network. Firstly, the link cost model comprised of delay and wavelength utilization is constructed as the criteria for initial path establishment of bees, bounded by some necessary constraints. Secondly, we formulate a fitness function by taking into consideration wavelength resources occupation and communication hops of candidate paths to further select the optimal route with better adaptability. Afterwards, by way of searching, comparison and recruitment of bees, BCO-LCRWA can achieve rapid expansion of the superior solutions and maintain capability of multiple exploration at the same time. Simulation results corroborate that it effectively alleviates the deficiency of long delay and high BER in satellite optical networks with diminishing adverse effect of Doppler wavelength shift, especially, the proposed algorithm has advantages in rational utilization of wavelength resources in the context of low blocking rate.

The remainder of this paper is organized as follows. We briefly review related works in Sect. 1.2. Section 2 formu-

---

Manuscript received April 24, 2019.
Manuscript revised October 16, 2019.
Manuscript publicized December 18, 2019.

[†] The authors are with Beijing University of Posts and Telecommunications, Beijing, China.

[††] The authors are with China Academy of Space Technology, Beijing, China.

a) E-mail: zhangqi@bupt.edu.cn

DOI: 10.1587/transcom.2019EBP3097

lates a network model for RWA based on satellite optical networks. We present detailed procedure of BCO-LCRWA in Sect. 3. Performance evaluations of proposed algorithm are presented in Sect. 4. Finally, we conclude this paper in Sect. 5.

1.2 Related Works

Non-synchronous satellite constellation of laser links highlights the need for wavelength routing in the future, and some research has been conducted on RWA of satellite optical networks. [6] considers physical ISL topologies of nongeosychronous satellite constellations with WDM ISLs and wavelength routing, on this basis, its time-variant optical ISL topology is analyzed while many distinct topologies are investigated to estimate the bounds of wavelength requirements. But, utilization efficiency of wavelength resources in the network is not considered. Yi Dong et al. [7] propose an ant colony algorithm based on small window strategy for RWA problem of satellite optical networks, which introduces the intersatellite distance, link duration and wavelength idle ratio to heuristic functions. By employing the small window strategy, the optimized algorithm promotes the convergence speed, especially, blocking rate is significantly reduced and the utilization of resource is greatly improved. Notwithstanding enhancement of optimized algorithm, the author neglects the physical factors of link establishment on network performance. In [8], the characteristics of crosstalk in WDM laser ISL constellation network is analyzed and quantified, meanwhile, Doppler wavelength offset caused by transport layer is taken into account to analyze its influence on system power consumption. However, no consideration is given to the transmission state of data packets over the network. Tengyun Dong et al. [9] presents different traffic grooming algorithms, which required for establishing optical virtual topology and the optical RWA algorithm on the IP layer. The results show that multi-hop grooming and waveplane-based RWA would be able to significantly reduce the number of required wavelengths and keep end-to-end transmission delay to the minimum at the same time. But traffic grooming algorithms build on the assumption of high traffic flow and not even concerned about the stability of communication. In summary, numerous efforts focusing on RWA in satellite optical networks have been made from perspectives of resource constraints, physical transmission performance impacts and unfair traffic distribution. More specifically, analysis of routing problems based on physical layer and transport layer qualifies related physical factors in detail but barely take account of factors from the network itself. In addition, some research neglects the phenomenon of traffic overload in the network for only considering the problem of traffic grooming, so that the blocking rate may not be qualified to the requirements of practical demand. As a result, it is indispensable to design an effective algorithm that would be able to meet requirements of the network by taking different parameters into account as comprehensively as possible.

Bee colony algorithm [10] is inspired by the intelligent foraging behavior of honeybee swarm, who manifests five distinct characteristics, namely, simple structure, parallel computing, fast convergence, less control parameters and strong robustness. In this context, it has attracted more and more attention and research. An artificial bee colony (ABC) algorithm put forward by Arash Rashedi [11] has proved to effectively solve the RWA problem in real-time terrestrial optical networks and has further been extended to the dynamic RWA scheme in real-time applications. To the best of our knowledge, there is no correlational research on employment of bee colony algorithm or optimized algorithm for RWA problem in satellite optical networks.

2. Network Model

Satellite optical network consists of satellite constellation with ISLs, that is, an ISL performs as a transmission channel between adjacent satellites. Without loss in generality, we consider a regular satellite constellation generally possesses 4~8 ISLs, which is realized by a pair of optical communication terminals carried by corresponding satellites respectively, so each satellite is supposed to take 4~8 optical communication terminals to shape a satellite optical interconnection network. Since the network topology is determined by satellite constellation, for Iridium-like constellation [12], it encompasses $S = P * Q$ satellites, where P represents the number of orbits and Q is the number of satellites in each orbit. In such constellations, contiguous satellites can be interconnected through two kinds of ISLs: links between neighboring satellites in the same orbital plane, termed intra-plane ISLs, and links between neighboring satellites in adjacent orbital planes, called inter-plane ISLs, as shown in Fig. 1. Both intra-plane ISLs and inter-plane ISLs are regarded as optical paths including W available wavelengths.

In general, the RWA problem in satellite optical networks can be divided into two subproblems: a routing subproblem and a wavelength assignment subproblem. To clarify the problem mathematically, the directed weighted graph $G\,(V, E, C)$ is modeled to represent the basic structure of the satellite network topology, where $V = \{v_1, v_2, \ldots v_N\}$ represents the set of satellite nodes in the network (N denotes the

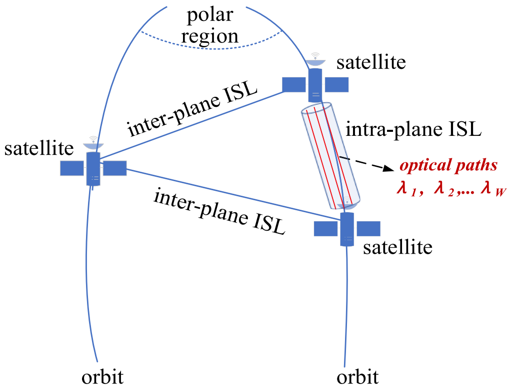


Fig. 1 The architecture of satellite optical network system.

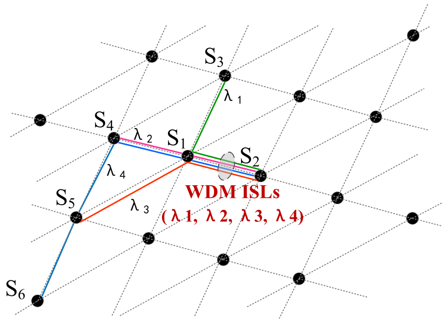


Fig. 2 Topology of satellite optical network for transmission.

total number of satellites), $E = \{e_1, e_2, \ldots e_M\}$ represents the set of ISLs for the entire satellite network (M demotes the number of edges of the whole topology), and C represents the cost of the link. Moreover, there are W wavelength resources expressed as $\lambda_1, \lambda_2, \ldots, \lambda_W$, where W is the number of total wavelengths in every link. The topology of satellite optical network for transmission is illustrated in Fig. 2. $S_1 \sim S_6$ represent six satellite nodes of the network respectively, and assuming that optical paths have been established for four pairs of satellite nodes, namely S_3-S_1-S_2, S_4-S_1-S_2, S_5-S_1-S_2, and S_6-S_5-S_4-S_1-S_2. Wavelength of λ_1, λ_2, λ_3 and λ_4 are occupied by the above four optical paths, respectively. As can be seen from Fig. 2, the intersatellite laser link between S_1 and S_2 contains four optical paths with wavelengths of λ_1, λ_2, λ_3 and λ_4. Similarly, the ISL between S_4-S_1 have two optical paths with λ_2 and λ_4.

To describe utilization of wavelength resources on links, each link $e_i \in E(i \in [1, M])$ is characterized by a binary vector $U = [u_1, u_2, \ldots, u_W]$, with a jth element equal to 1 if the jth wavelength is available and 0 if it has already been occupied by a path or a request connection. In view of the above-mentioned model, the RWA problem can be formally stated as follows: When a ground terminal issues a connection request or user-to-satellite handover occurs, the RWA algorithm is performed to select the next hop for data transmission. That is to say, the access satellite node should select a feasible optical path, and also choose appropriate wavelength resources to be reserved on the optical path.

3. RWA Based on Bee Colony Algorithm Optimization

The original bee colony algorithm is inspired by the foraging process of bees in a swarm, which provided with socialized division of labor and cooperation. The colony of bees contains three groups of bees: employed bees associated with specific food source, unemployed bees (also known as onlooker bees) watching the swaying dance of employed bees within the hive to choose a food source and scouter bees searching for food source randomly. The process steps of cooperatively searching for nectar source by different types of bees are listed as follows.

- Initialization phase: The locations of a series of food sources are randomly allocated to employed bees, who then measure the nectar amount of source. The employed bee returns to the hive after completing the mission of collecting nectar, and shares the information of the source with other bees waiting in the hive by swaying dance.

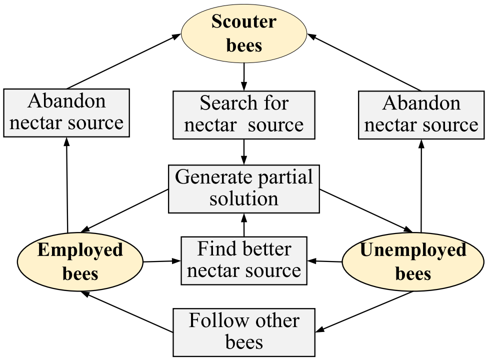


Fig. 3 Behavior transition of three kinds of bees.

- The second phase: Each unemployed bee chooses a food source based on the information shared by employed bees. The greater the amount of nectar, the higher the probability of being selected by unemployed bee. After information interaction between bees, each employed bee flies to the previous searched source in compliance with its memory and chooses a new nectar in the vicinity of the original one, while onlooker bee that follow the employed bee behaves similarly.
- The third phase: When the employed (or onlooker) bee in the second phase cannot find a updated nectar with better quality within the limited search times, the unimproved nectar source is abandoned. Meanwhile, the location of a new source is randomly searched by a scouter bee and replaces the abandoned source.

In the bee colony algorithm, the roles of bees can be transformed under different conditions as shown in Fig. 3, and the optimal location of nectar source can be obtained by iteratively search eventually. Thereinto, employed bees have the ability of tapping high quality food sources. Unemployed bees can attract a larger number of bees corresponding to better food sources and accelerate convergence speed of the algorithm. Scouter bees randomly search for new food sources to make the algorithm break away from the local optimum. Thus, in collaboration with three types of bees, bee colony algorithms have been used extensively in optimization problems. In other words, the process of seeking a high-quality food source is the process of solving the optimal solution, where the location of nectar source indicates the feasible solution of the optimization problem, and the nectar amount of source represents the quality (fitness) of the feasible solution. Besides, the searching speed of bees equates to the optimization efficiency, and the maximum amount of nectar obtained by a bee colony denotes the optimal solution.

In the actual satellite optical network, we build a virtual routing platform to act as a honeycomb, so that the interaction of local and global path information, as well as the update on routing information can be carried out by the bee colony algorithm. The platform for bee colony distribution is deployed on certain satellites, which are ingress satellites of service requests designated by users. Similar to mobile agents [13], bees in a colony can migrate autonomously from one node to another in the network, and hence have the capability to perform routing decisions dynamically. Generally, the number of employed bees accounts for half of the total, while the number of other types of bees is adjusted flexibly according to the realistic condition, and the total number of bees in a colony remains unchanged.

3.1 Global Routing Pre-Calculation and Initialization

Since the motion of satellites in a certain constellation is deterministic, and the variation of satellite network topology is highly periodic and predictability, the shortest path for each source and destination pair can be calculated periodically. At first, for the sake of simplicity, the operation period of satellite network is discretized into several time slots, in which the topology is supposed to be unchanged. Then, the K-Dijsktra [14] algorithm is applied to create initial alternative paths during each time interval. In such way, the routing table is pre-computed by the principle of shortest path in each time slot. When data packets are in transmission, the information of next hop along the route can be easily found from the pre-computed routing table in current satellite, as shown in Table 1, in where n_i ($i \in [1, N]$) refers to the next hop of current node for current time slot t_i, that is, the neighboring satellite of current node. N represents the total number of neighboring nodes here. Due to the limited on-board processing capacity, the above calculation procedure is normally operated by the ground gateway stations, which not discussed in detail in our article. Once switching to the next time slot, the new information of routing table is uploaded to satellite nodes accessed by gateway stations and then notify all satellites in the whole network to update routing tables. Except for the pre-computed routing table, each satellite is additionally equipped with a local information routing table as shown in Table 2, which is obtained by periodically collecting the path information of adjacent links from the satellite. The parameters in Table 2 are significant measurements of the link cost in the next section (3.1) and are updated immediately after the interaction with a bee who passing through the current satellite node.

In the phase of initialization, the related parameters of routing problem are initialized, including parameters of bee colony algorithm and statistical variables of the network. Also, the candidate set of wavelengths is initialized to W.

3.2 Path Search Based on Link Cost Function

As we mentioned above, the original bee colony algorithm employs the way of stochastic search in global scope during path reconnaissance, which is more suitable for small amount nodes or the uniform distribution of solutions. Whereas for the satellite network with massive nodes, it will be guaranteed to aggravate the overhead of routing algorithm greatly with more bees and more frequent collaboration. To alleviate complexity of path searching and decease convergence time of algorithm, the link cost function is adopted to optimize the bee colony algorithm. When a connection request arrives, a certain number of scouter bees proceed from the source satellite to perform the mission of routing and wavelength assignment. In the process, the bee access routing tables (Table 1 and Table 2) of the current satellite to obtain the path information of the next hop. Although the shortest path criterion has advantages to reduce transmission delay, only considering the length of path may lead to high risks on network congestion and end-to-end delay with the increase of communication requests. Considering that unbalanced resource allocation will lower the efficiency of the network under a heavy load. And in a satellite network composed of optical links, due to high relative velocities of two satellites between adjacent orbits, Doppler wavelength drift, leading to communication ineffective, cannot be ignored.

Table 1 Pre-computed routing table.

time slot	current node	destination node	node of next hop
t_i	n	dest	n_1
			n_2
			…
			n_N

Table 2 Local information routing table.

current satellite node	neighboring ISLs	transmission delay	wavelength resource utilization	Doppler wavelength shift
S_n	L_1	D_1	WR_1	$\Delta\lambda_1$
	L_2	D_2	WR_2	$\Delta\lambda_2$
	…	…	…	…
	L_N	D_N	WR_N	$\Delta\lambda_N$

Therefore, we must establish a comprehensive criterion for guiding bees to select links from all feasible optical paths. Since delay and wavelength occupancy ratio of links are regarded as two important indicators to assess the preference of network, our cost (target) function is to minimize the delay and wavelength occupancy of links subject to the wavelength continuity and contiguity constraints, as well as Doppler wavelength drift and transmission delay, so they are defined as Eq. (1).

$$\begin{aligned} &\min C = \frac{Delay_{link}}{Delay_{\max}} + \frac{WR_{link}}{WR_{\max}} \\ &subject\ to \\ &Delay_{link \in P(sour,dest)} \le D_{th}, \\ &\forall \omega_{link \in P(sour,dest)} = \lambda_k, \\ &\forall |\Delta\lambda|_{link \in P(sour,dest)} \le \Delta\lambda_{th} \end{aligned} \tag{1}$$

In the $G\ (V, E, C)$ of a satellite optical network, a sequence of nodes and edges alternated from the source node *sour* to the destination node *dest*, called optical path, is referred to as $P(sour, dest)$. $Delay_{max}$ and WR_{sum} represent the maximum transmission delay of all links and total number of wavelength resources in the whole network respectively. It should be pointed out that $Delay_{max}$ can be calculated by constellation parameters. $Delay_{link}$ is transmission delay of the link, including propagation delay and processing delay, collected by the satellite node next to the link. WR_{link} indicates the number of occupied wavelengths on the link, that is, the number of 0 in binary vector U defined above. $Delay_{link \in P(sour,dest)}$ denotes delay of the current link, and D_{th} denotes the transmission delay threshold tolerated by transmission of real-time traffic in satellite optical networks. $\omega_{link \in P(sour,dest)}$ represents the wavelengths occupied by $link \in P(sour, dest)$, and λ_k denotes the kth wavelength resource. $\forall \omega_{link \in P(sour,dest)} = \lambda_k$ reveals the constraints of wavelength continuity and contiguity, which concretely means that the wavelength occupied by each link on $P(sour, dest)$ must be the same, and neither of the two requests occupies the same wavelength resource. $|\Delta\lambda|_{link \in P(sour,dest)}$ represents the Doppler wavelength shift of the ISL. [15] has proved that the larger the Doppler wavelength shift is, the worse the bit error rate (BER) will be, and the variation of BER with Doppler wavelength shift is described quantificationally as well. On this account, the threshold value of Doppler wavelength shift $\Delta\lambda_{th}$ can be easily obtained by the tolerance of BER in real network. More specially, $\Delta\lambda_{th}$ reflects the limit set for guaranteeing BER of the system not to deteriorate.

In the process of time, with the traffic demand in the network tending to rise, some satellite nodes and ISLs are occupied, and part of wavelength resources in the network are consumed. Moreover, the network topology may also change with high-speed movement of satellites. Thus, the network delay and resource utilization are bound to have changed. In this phase, the scouter bee launched from ingress satellite will choose the satellite included in available neighbor set and the link with minimum cost as the direction of the next hop based on Eq. (1) during the path migration. The intermediate satellites and links who violate the constraints are supposed to be excluded. Afterwards, scouter bees arrived at egress satellites migrate along the same paths but in the opposite direction, meanwhile, the local routing information of intermediate satellites is updated. By following procedure aforementioned, a certain number of solutions satisfying locally great-adaptability with the restrictions are produced, in other words, the paths for source and target satellites pair are implemented by searching of bees. To avoid bees being trapped in endless-loop during path searching, every time a bee passes through a satellite node, it adds the visited node to taboo table until it is blocked or reaches the destination. The process of path searching by bees is blocked when one or more of the following conditions occur: a) No available wavelength resources on link to the next hop. b) The Doppler wavelength drift is worse than the threshold. c) Set of potential next hop is empty. Once path searching accomplished, the information of path explored by each bee in each iteration is recorded in routing table, which includes satellite nodes contained by available paths, transmission delay, wavelength resource utilization and Doppler wavelength shift.

In the next phase of the original bee colony algorithm, all feasible solutions are divided into two parts with the same number based on the descending order of fitness values. Bees with larger fitness are transformed into employed bees, and the remaining half are unemployed bees. However, we propose a novel behavior transition mechanism to optimize the bee colony algorithm in Sect. 3.4, which is different from the one shown in Fig. 3.

3.3 Comparison of Solutions

After partial solutions being generated by path searching, all of bees return to the hive to compare the quality of feasible solutions for selecting the optimal route with the best adaptability globally. The object of comparison is the quality of the feasible solution defined as $Fitness$ in Eq. (2), which takes into consideration wavelength resource utilization and communication hops in route to deal with the deficiency of low resource utilization and BER of satellite optical network.

$$Fitness = \frac{1}{a_1 \times \dfrac{WR}{WR_{sum}} + a_2 \times \dfrac{PH}{PH_{\max}}} \tag{2}$$

WR denotes the number of all wavelength resources occupied in the path by communication request and WR_{sum} has the same meaning as that in Eq. (1). The number of hops underwent by a path is expressed as PH, and the maximum hops of all alternative paths in the network is expressed as $PH_{\max}$. The coefficient a_1 and a_2 are the weighted parameters ($a_1 \in [0, 1], a_2 = 1 - a_1$), which used to regulate the importance among two indexes of wavelength utilization and hops respectively. Eq. (2) shows that for a certain route, the lower utilization of wavelength resources and the fewer communication hops contribute to the route with greater $Fitness$.

To make full use of network resource and reduce BER effectively, bees having achieved better quality solutions are supposed to be more inclined to keep their own routes. Consequently, we reassign roles to bees having returned to their hives, and define that bees keeping loyal to the solutions created by their own become recruiter bees, so the rest of bees in the colony are uncommitted bees. The role of recruiter bees is to further expand their solutions by attracting more uncommitted bees to follow the explored routes to the destination node in the recruitment process. As such, each uncommitted bee must determine whether to follow the route obtained by the recruiter bee or to transform into a scouter bee for exploring new solutions. At the instant bees begin to compare solutions, the selection of optimal route mainly depends on recruitment strategy. Specifically, to select the better solutions in an appropriate manner and to make them have more opportunities to be chosen by uncommitted bees, we devise the probability $p_{i,loyal}$ defined by Eq. (3) to express the likelihood that the ith bee becomes a recruiter bee who loyal to its own solution, where B represents the total number of bees.

$$p_{i,loyal} = 1 - \log[1 + (NF_{\max} - NF_i)], \quad i = 1, 2, \ldots, B \tag{3}$$

NF_i denotes the normalized objective function value of *Fitness* calculated by the ith bee, and $NF_{\max}$ denotes the maximum value of all normalized objective function values. Note that the definition of normalized objective function value NF_i is derived as Eq. (4). It can be seen from Eq. (3) that $p_{i,loyal}$ lies in the relative *Fitness* instead of *Fitness* itself, which contributes to suitable global ability of optimization.

$$NF_{\mathrm{i}} = \frac{Fitness_i - Fitness_{\min}}{Fitness_{\max} - Fitness_{\min}} \tag{4}$$

Where $Fitness_{\max}$ and $Fitness_{\min}$ are the maximum and minimum values of *Fitness*, respectively. *Fitness* of all feasible solutions are recorded in the routing table with corresponding path, and $Fitness_i$ donates the *Fitness* value of the path explored by ith bee in the colony. If the $Fitness_i$ value is greater, the normalized objective function value NF_i is greater, and thus the $p_{i,loyal}$ is higher, in other words, the bee with better fitness is more likely to maintain its own solution, so the better partial solution is more likely to be followed. As can be concluded from Eq. (3), the introduction of relative *Fitness* alleviates the congestion and resource overload caused by the high following probability of the first-found path. Once $p_{i,loyal}$ of each employed bee is evaluated, the rest of bees in hive are assigned to division by combination of a random number (*rand*) and Eq. (3). If $rand \leq p_{i,loyal}$, the ith bee becomes a recruiter to stay loyal to its own solution and thus further expands its superiority within the procedure of recruitment, otherwise, it will transform into an uncommitted bee, which will become a follower of recruiter bee to inherit previously created partial solution or wait to explore new solutions in global range.

3.4 Recruitment Phase

Based on the process above, the bees who are loyal to their own solutions will transform into recruiter bees and recruit more bees for developing the more competitive routes. Meanwhile, uncommitted bees must determine which recruiter bee to follow in accordance with a probability $p_{i,recruitment}$ that is proportional to the *Fitness* value of all optional routes. The probability referred to above is evaluated by Eq. (5).

$$p_{i,recruit} = \frac{Fitness_i}{\sum_{t=1}^{RB} Fitness_t}, \quad i = 1, 2, \ldots, RB \tag{5}$$

Where RB represents the total number of recruiter bees. Each uncommitted bee joins to one recruiter bee based on roulette wheel method. If there are no logical *Fitness* value among all feasible solutions, the uncommitted bee will abandon following the recruiter and fly back to hive so that it can wait for the next literation to conduct path exploration as a scouter bee. As for recruiter bees, they continue to search paths locally for better nectar sources near the original source in each loop by the rule shown in Eq. (6).

$$v_j = x_j + \alpha \cdot (x_j - x_k) + \beta \cdot (x_{global} - x_j), \quad j \neq k \tag{6}$$

Where v_j and x_j represent the coordinate of subsequent solution and original solution attributed to the jth source respectively. Specifically, x_k donates the kth solution ($k \neq i$), and x_{global} donates the coordinate of global optimal solution. α is neighborhood search coefficient which equal to a random number between -1 and 1. The coefficient β is a random number between 0 and 1.5, which can balance the searching and developing ability of bee colony algorithm very well.

During the procedure of local search, recruiter bees calculate the *Fitness* values of the routes newly discovered according to Eq. (2). Immediately the *Fitness* value of the subsequent solution is greater than the original one, the original route will be replaced by the route with better adaptability according to Eq. (7), where $Fitness_v$ and $Fitness_x$ indicate the *Fitness* value of new and original solution.

$$x_{j+1} = \begin{cases} v_j, & Fitness_v > Fitness_x \\ x_j, & Fitness_v \leq Fitness_x \end{cases} \tag{7}$$

For each follower bee, while choosing the recruiter bee to follow, it executes the local search similar to that of recruiter bees mentioned above based on Eq. (6)~Eq. (7). If the subsequent route has stronger adaptability, the original route will be replaced, otherwise, the original route is maintained. However, once the bee fails to update the route with better fitness while consecutive search times are running over the threshold *Limit*, which clarified before the execution of algorithm, the operation of locally searching is compulsively suspended. Afterwards, the role of the losing bee is transformed into a scouter bee to randomly explore a new route substituting for the poorer solution in the overall range. Bearing in mind the above procedure, we summarize the proposed algorithm as shown in Fig. 4.

BCO-LCRWA is performed whenever a traffic request is received by the network, then the bee colony saves the optimal nectar source location with maximum nectar yield (i.e. the route with the greatest *Fitness*), which created within the period of iteration and use it as the initial solution in the next iteration. At last, the best solution is chosen as the global optimal solution until all the scheduled iterations are completed. It should be noted that the proposed algorithm starts when the communication requests arrive and executes independently according to the sequence of the above stages.

4. Simulation Results and Analysis

4.1 Simulation Setup

In this section, a series of experiments are carried out to evaluate the performance of BCO-LCRWA and to compare it with other three algorithms. Meanwhile, to prove adaptability of the proposed algorithm, our experiments are conducted on Iridium-like constellation with 66 satellites and NeLS (Next-generation Low-earth-orbit System) constellation [16] with 120 satellites. Table 3 shows the key parameters of two constellations. Specifically, for Iridium-like constellation,

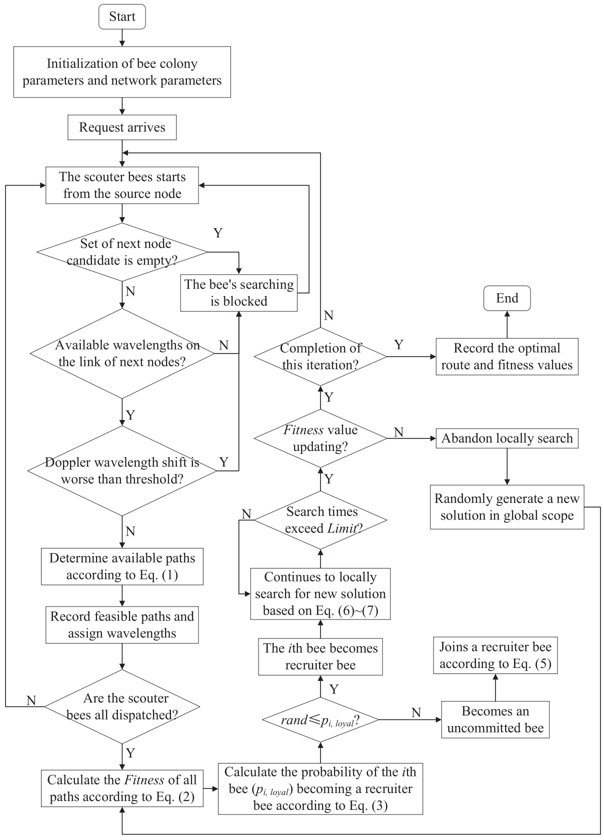


Fig. 4 The algorithm flow of BCO-LCRWA.

Table 3 Parameters for iridium constellation and NeLS constellation.

	Iridium	NeLS
Configuration	π	2π
orbit inclination	86°	55°
Number of planes	10	6
Number of satellites per plane	12	11
Altitude	1200km	780km
Orbital period	6565s	6072s
ISLs connectivity	Nonpermanent	Permanent

most satellites maintain four ISLs with adjacent satellites, except those at high latitudes (±60°) whose inter-plane ISLs are turned off, and those along the seam whose cross-seam ISLs are switched off. However, for NeLS constellation, due to its symmetrical physical topology, each satellite establishes ISLs with four directions and maintains connectivity permanently.

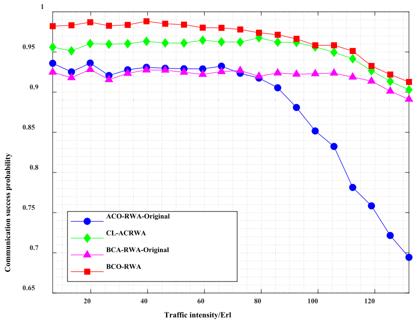
In order to eliminate the influence of channel error, we assume that all links are error-free so that we can focus our attention on the algorithm itself. In the experiments, the simulation time interval is set to 7200s. The initial number of available wavelength resources in the constellation is 16 [17], and each satellite has the same processing delay, which is set to 10 ms [18]. The threshold of Doppler wavelength drift is designed to 3.22×10^{-11} for guaranteeing the tolerance for BER of communication system. Rules of arrival for each user's request obeys Poisson distribution, and waiting time of traffic arriving obeys exponential distribution. The target user of connection request randomly chooses from the rest of users [19]. Assuming that the connection request is a real-time service so that the transmission delay threshold of the service is set to 300 ms [20]. Original ant colony optimization algorithm (ACO-RWA-Original) [21], bee colony algorithm (BCA-RWA-Original) [22] and ant colony RWA based on cross-layer design (CL-ACRWA) [23] are used to make comparison with bee colony algorithm optimization based on link cost for RWA (BCO-LCRWA), which we simplify the representation as BCO-RWA in the following simulation diagrams and description for convenience. The reason why selects algorithms above is that ant colony optimization (ACO), proposed by Marco Dorigo [24] of Italy in 1992, represents a mature heuristic algorithm, which has a lot of research achievements in routing of satellite networks. CL-ACRWA intensifies original ant colony algorithm preference by cross-layer awareness mechanism of perceiving the information of physical layer to cope with the RWA problem. As a swarm intelligence optimization algorithm, bee colony algorithm (BCA) has been widely used in a mass of optimization problems and has been applied to routing and wavelength assignment problems in terrestrial networks. The heuristic algorithms mentioned above act in a corresponding manner in finding the optimal route with BCO-LCRWA proposed in this paper. Thus, we discuss the network performance of ACO-RWA-Original, CL-ACRWA, BCA-RWA-Original and BCO-LCRWA in terms of communication success rate, transmission delay, communication hops, blocking rate and wavelengths utilization ratio. Noted that convergence is a neglectable index to measure the performance of the algorithm itself, which also has effect on end-to-end delay of the network. Simply stated, the algorithm with rapid convergence has strong ability to select the optimal route with fewer iteration times and lower complexity.

4.2 Simulation Results

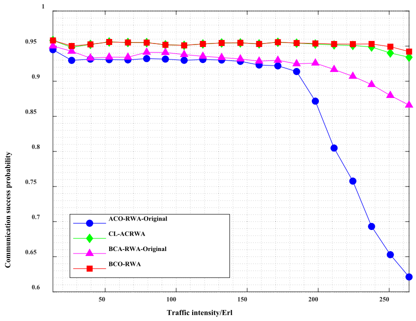
In order to validly indicate the effect of the algorithms on network performance, we introduce the traffic intensity, which equates to the product of the number of wavelengths occupied for an hour and the average elapsed time of traffic when occupancy occurs in the network. Due to the number of nodes and links in Iridium-like constellations is different from that in NeLS constellation [25], the variation range of traffic density we set is different under the condition of two constellations, so that it is more comprehensive to analyze the proposed algorithm. Hence, the varied curves of network performance parameters in following simulation are almost based on the growth of traffic density.

4.2.1 Communication Success Probability

Under the background of the issues discussed in this paper, the success rate of communication is defined as the ratio of the number of optical paths satisfying the constraints of delay and Doppler wavelength drift to the total number of connection requests in the established optical paths. Comparison of BCO-RWA, BCA-RWA-Original, ACO-RWA-Original and

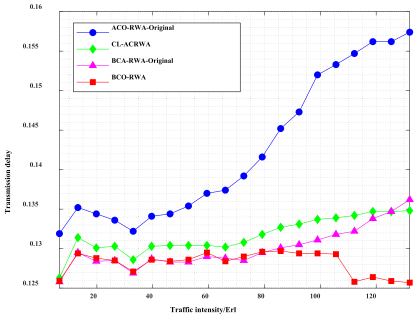


(a) Iridium-like constellation

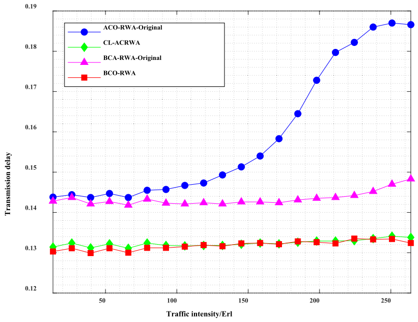


(b) NeLS constellation

Fig. 5 Comparison of communication success probability of four different algorithms.



(a) Iridium-like constellation



(b) NeLS constellation

Fig. 6 Comparison of transmission delay of four different algorithms.

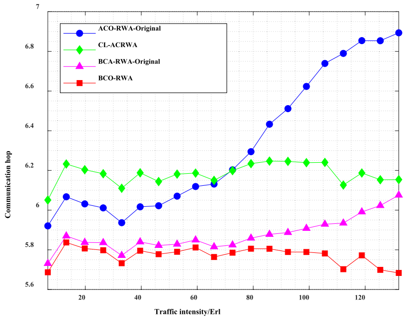
CL-ACRWA in communication success probability is depicted in Fig. 5(a) and (b). As can be seen from figures, the communication success probability of BCO-RWA outperforms the other three algorithms and shows relatively smooth decline with the increase of traffic density. This fact proves that BCO-RWA keeps the more powerful and stable capability of communication. Due to its strong global search ability, it achieves rapidly resources allocation for traffic requests with heavy load. As *Fitness* value updates during the implementation of iterative process, BCO-RWA constantly excludes the routes with low fitness and with inferior Doppler wavelength shift, meanwhile, the algorithm mechanism of BCO-RWA is inclined to strength the preference of solution with better quantity, and to ultimately develop more adaptive routes, so that in an Iridium-like constellation the communication success probability remains at a high level, which even higher than CL-ACRWA, who achieves fast convergence through positive and negative feedback mechanism of ant colony pheromone concentration in searching process to establish the optical path. However, the communication success probability of CL-ACRWA is slightly lower than BCO-RWA as a result of the restriction upon routing mechanism of ant colony algorithm. When the traffic density is lower than 80Erl (150Erl), the communication success probability of BCA-RWA-Original and ACO-RWA-Original are very close. Whereas when the traffic density is higher than 80Erl (150Erl), the success probability of ACO-RWA-Original decreases rapidly while the success probability of BCA-RWA-Original varies with a relatively slow downward trend. This is because ACO-RWA-Original fails to consider the utilization of wavelength resources and influence of Doppler wavelength drift on communication performance. Furthermore, the accumulation of pheromone gives rise to path search being easily lost in a local optimum, which leads to the blocking of links, so the communication success probability decreases as low as 69.4% (62.1%) when traffic intensity is 132Erl (264Erl). Although BCA-RWA-Original only considers the length of paths in the network, it is good at distributed routing to avoid congestion. From above all, it could be noticed that bee colony algorithm has inherent superiority in solving such problems, so it does make sense to optimize bee colony algorithm for RWA in satellite optical networks, the optimized bee colony algorithm we proposed has proved its superiority as well.

4.2.2 Transmission Delay

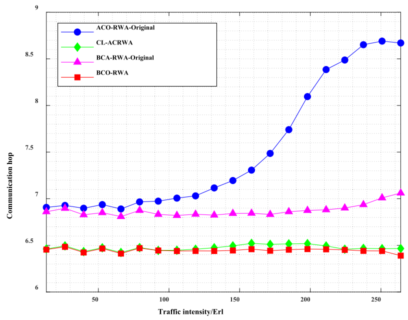
Transmission delay here is the average time of the data packet being successfully transmitted to the destination with execution of the algorithm. Figure 6(a) and (b) plot the transmission delay for various traffic density. We can see that in Fig. 6(a) BCO-RWA precedes a lot in delay compared to the other algorithms, but in Fig. 6(b), the delay of BCO-RWA is slightly lower than CL-ACRWA and far lower than the other two original algorithms. As increasing of traffic density in the network, the delay values of two optimization algorithms (BCO-RWA and CL-ACRWA) intend to keep at a relative stable level. For BCO-RWA, the value of transmission delay sustains within the range of 125 ms to 130 ms in an Iridium-like constellation, which satisfies the requirement of real-time traffic. In a NeLS constellation, both BCO-RWA and CL-ACRWA can achieve stable delay performance no more than 135 ms. Nevertheless, ACO-RWA-Original exhibits the worst latency performance, and its transmission delay increases sharply as traffic intensity growths. This result attributes to the fact that the original ant colony algorithm is liable to cause blockage, meanwhile, it only bases its routing on finding paths with the shortest distance, while the utilization ratio of wavelength resources and the Doppler shift are ignored. Therefore, with heavy traffic load, link congestion occurs because that pheromones accumulate massively on certain paths, leading to the deterioration of ACO-RWA-Original in respect of latency. Due to the lack of comprehensive consideration of network performance, BCA-RWA-Original in an Iridium-like constellation shows an obvious deterioration trend when the traffic load increases. While in Fig. 6(b), the delay of BCA-RWA-Original is approximately 8.0% worsen than that of BCO-RWA. CL-ACRWA has better latency performance than ACO-RWA-Original, but in both Iridium-like constellation and NeLS constellation, it is not as good as BCO-RWA, whose low latency benefits from the global searching characteristics inherent from bee colony algorithm and the rational assignment of resources in virtue of optimization.

4.2.3 Communication Hops

Figure 7(a) and (b) show the variation curves of communication hops of BCO-RWA, BCA-RWA-Original, ACO-RWA-Original and CL-ACRWA with traffic density. It is obvious that fewer hops undergone along the path between source and destination can bring a significant reduction in delay, so the changing trend of communication hops with traffic density is quite similar to that of delay as shown in Fig. 6. As can be seen from Fig. 7, BCO-RWA achieves the least number of hops compared with the other three algorithms. As traffic density growing heavy, the hops of BCO-RWA is basically stable in two constellations. To explain, communication hops mentioned in figures is average communication hops of multiple iterations, thus it is not an integer. When the traffic density is no more than 80Erl in Fig. 7(a), the hops of BCA-RWA-Original and BCO-RWA varies in almost the same trend, but when traffic density is higher than 80Erl, there is an evident tendency for the hops of BCA-RWA-Original to increase. In Fig. 7(b), the hops of BCA-RWA-Original is always more than that of BCO-RWA. It is because the path length is regarded as the only criterion to routing during selection of paths in BCA-RWA-Original, but BCO-RWA we proposed comprehensively considers the length of paths and resources utilization to solve routing problem. So, the BCO-RWA can complete more efficient transmission with fewer hops under heavy load. Compared with bee colony algorithms, the hops of ACO-RWA-Original tend to go up drastically with the increase of traffic density, whereas the hops of CL-ACRWA stabilizes in a certain range. For ACO-RWA-Original, when the traffic is heavy, the intermediate nodes with shorter distance from source to destination satellites have been occupied on account of the shortest path criterion, so ants need to travel more nodes to reach the target satellite. But for CL-ACRWA, since there are considerations for premature convergence, hops tend to be stable while the surge in traffic occurs. Generally, the proposed algorithm BCO-LCRWA minimizes the number of communication hops and thus improves the BER performance of the system.



(a) Iridium-like constellation

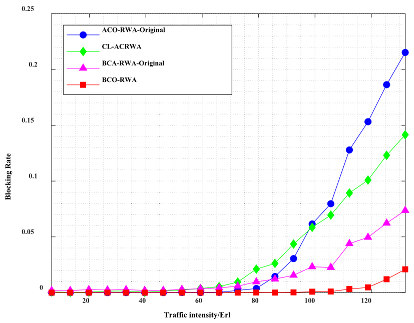


(b) NeLS constellation

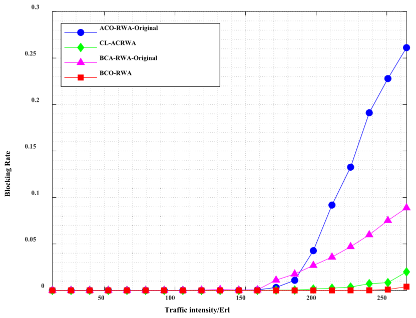
Fig. 7 Comparison of communication hops of four different algorithms.

4.2.4 Blocking Rate

When a communication request reaches the network, an available path and an idle communication wavelength will be allocated on certain route, otherwise, blockage will occur in the network. Figure 8(a) and (b) show the blocking rates of BCO-RWA, BCA-RWA-Original, ACO-RWA-Original and CL-ACRWA with traffic density. As shown in the figure, the blocking rate of BCO-RWA is the lowest, and it grows smoothly with the increase of traffic density, while the blocking rate of ACO-RWA-Original increases faster than other curves. The results need to be analyzed from two aspects. From the perspective of routing selection, the factors of path length and delay are considered synthetically in BCO-RWA with the constraint of service demand, so the algorithm can quickly complete path searching at a minimum cost with its strong global search capability. From the aspect of wavelength assignment, BCO-RWA selects the routes with high fitness, which takes utilization of wavelength resources and Doppler wavelength shift into account, so it is not easy to cause conflicts in wavelength resource assignment, and si-

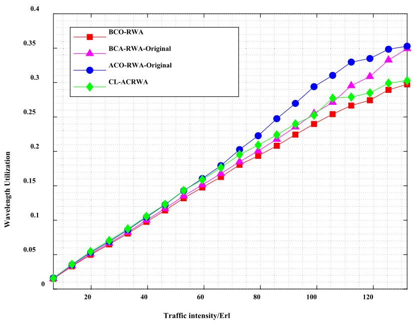


(a) Iridium-like constellation

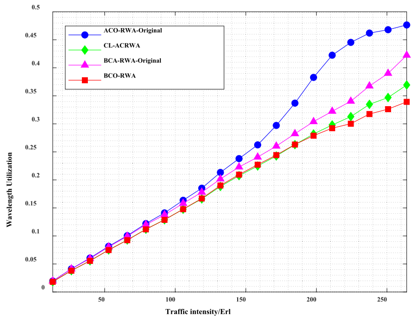


(b) NeLS constellation

Fig. 8 Comparison of blocking rate of different algorithms.



(a) Iridium-like constellation



(b) NeLS constellation

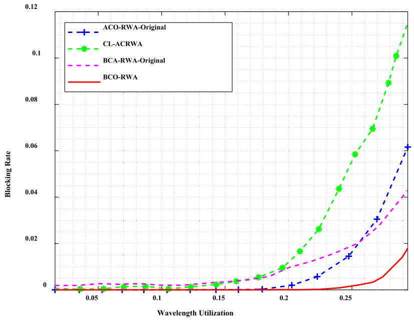
Fig. 9 Comparison of wavelength utilization of different algorithms.

multaneously avoid the influence of wavelength shift effect on the BER of communication. That is why BCO-RWA shows the best performance in blocking rate of the network. The blocking rate of BCA-RWA-Original is worse than that of BCO-RWA but greater than ACO-RWA-Original and CL-ACRWA in Fig. 8(a). However, the blockage of BCA-RWA-Original is inferior to CL-ACRWA in Fig. 8(b), which indicates that BCA-RWA-Original is more suitable for an Iridium-like constellation. The two original heuristic algorithms (ACO-RWA-Original and BCA-RWA-Original) do not consider wavelengths already occupied by earlier reached traffic requests in the network when a latter one arrives, so it is prone to be caught in path blockage owning to that there are no available wavelength resources for more traffic on some paths. Besides, the Doppler wavelength shift of unoptimized algorithms mentioned above is not taken into account, so links with wavelength drift exceeding threshold are unused and directly lead to related paths blocked.

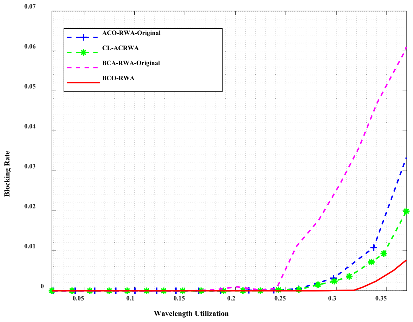
4.2.5 Wavelength Utilization

Figure 9(a) and (b) show the variation curve of wavelength resource utilization of BCO-RWA, BCA-RWA-Original, ACO-RWA-Original and CL-ACRWA with traffic density. With the increase of traffic density, the utilization rate of wavelength resources of the four algorithms is not significantly different, but BCO-RWA is rising slower than the other two algorithms, and its values of wavelength utilization are the smallest all the time. The reason is that the route with lower wavelength utilization has higher *Fitness* value, and it is more likely to be followed by uncommitted bees according to Eq. (5). Meanwhile, as shown in Fig. 8, the blocking rate remains at a relatively low level, i.e. there being almost no traffic blocking occurs. That is to say, the most wavelength savings could be achieved without extra data loss by using BCO-RWA. Furthermore, in circumstance of attaining the same utilization ratio, BCO-RWA can satisfy more traffic demands than the other algorithms. However, when the traffic density increases, the blocking rate of ACO-RWA-Original increases significantly, and the wavelength resource utilization also presents rapid growth trend. The performance of BCA-RWA-Original and CL-ACRWA are moderate. From the above analysis, we can see that it is meaningless to only consider the wavelengths utilization or blocking rate. So next we give an analysis of the blocking rate of four algorithms varying with the utilization of wavelength resources.

Figure 10(a) and (b) plot the blocking rate versus wavelength utilization. It can be seen that the blocking rate of BCO-RWA growths slowly with the increase of wavelength utilization while the other algorithms growth rapidly. Therefore, BCO-RWA achieves the best performance, whose assignment mechanism of the wavelength resources always be achieved at cost of the lowest blocking rate of the network. Since there are enough available wavelengths to meet connect requests of traffic under light load, the blocking rate of four algorithms in Curves of Fig. 10 not change drastically when the utilization rate of wavelength resources is less than 0.20 (0.25) in the Iridium-like constellation (NeLS constellation). But with the continuous increase of traffic load, as a result of a growing number of communication requests

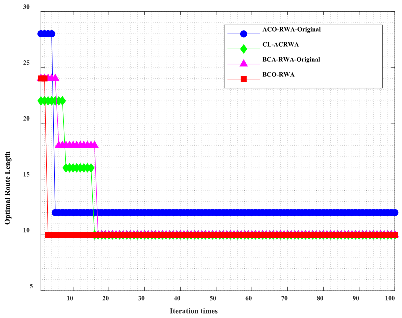


(a) Iridium-like constellation

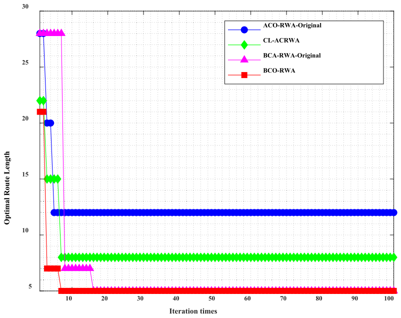


(b) NeLS constellation

Fig. 10 Curve of blocking rate with wavelength resources.



(a) Iridium-like constellation



(b) NeLS constellation

Fig. 11 Comparison of convergence of different algorithms.

competing for the wavelength resources, the rationality of resource allocation is particularly of importance. Except for BCO-RWA, blocking rates of three algorithms mentioned above are in an exponential growth with the increase of wavelength utilization. The advantage of low blocking rate mainly benefits from the optimization for routing mechanism of bee colony, which avoids choosing the links with high wavelengths occupancy when searching for an optical path and give priority to the path with more idle wavelength resources. In this way, BCO-RWA can prevent congestion on route to a certain extent and thus enhance the communication performance of satellite optical network. It is not hard to see that under the same blocking rate, the wavelength resources utilization of BCO-RWA is much greater than that of BCA-RWA-Original, ACO-RWA-Original and CL-ACRWA, which indicates that BCO-RWA has the maximum utilization rate of network resources on the premise of guaranteeing a certain degree of unblocking.

4.2.6 Convergence and Complexity

Figure 11(a) and (b) show the convergence performance of four different algorithms. In order to evaluate the convergence speed of the algorithm, we choose a pair of source and destination satellite nodes to access and observe the change of the optimal route length from source to destination with the number of iterations at a given traffic intensity. It should be noted that route length here is equivalent to the number of hops passing from source satellite to destination satellite. Since the convergence mainly represents the speed of seeking the optimal route instead of distracting frequent traffic, the traffic intensity is set to a relatively small value, that is 66Erl in the Iridium-like constellation and 132Erl in the NeLS constellation. As can be seen from Fig. 11(a), all of four algorithms tend to be stable within 20 iteration times. BCO-RWA has the fastest speed of convergence with the shortest optimal route length of 10, who shows the best convergence performance compared with other algorithms, while the convergence speed of BCA-RWA-Original is the slowest. As for Fig. 11(b), BCO-RWA has the same convergence speed as CL-ACRWA, but the optimal route length of the former is shorter than that of the latter. Although BCA-RWA-Original and BCO-RWA converge to the optimal route of the same length, BCA-RWA-Original converges more slowly. The reason why is that the original bee colony algorithm primarily focusses on discovering the optimal route from the global context, so BCA-RWA-Original cannot realize optimum routing in a short period of time. However, the problems mentioned above have been well overcome in BCO-RWA with the application of Eq. (3)~Eq. (5), which accelerates extension of dominant solutions and thus realize quick convergence. ACO-RWA-Original also has fast convergence speed, but the optimal route length is the worst of all algorithms because that ant colony are easy to fall into local optimum and thus fails to find the global shortest one. CL-ACRWA optimizes the original ant colony algorithm based on cross-layer, so it can find the best path faster than ACO-RWA-Original, but not as good as BCO-RWA we proposed. Therefore, the superiority of convergence performance proves applicability and effectiveness of BCO-RWA applied to RWA problem in satellite optical networks.

To prove the availability of the proposed algorithm in satellite optical networks, except for the simulative analysis of the algorithm convergence as shown in Fig. 11, we give a theoretical analysis of the algorithm complexity for supplementary explanation. As we known, the ISL topology dynamics is deterministic and periodic, so that the cost of links can be easily obtained according to the constellation geometry, even computed in advance and stored in satellites. Moreover, each bee in the virtual routing platform can independently evaluate *Fitness* when candidate paths are available. Hence, the algorithm completely depends on the local information, in which the routing calculation does not require any exchange of link status among neighboring satellites. Thus, the signaling overhead of the proposed algorithm is almost zero. Note that another instinct character is that the computation and storage complexity is also negligible since the aforementioned formulas are only involved in simple mathematical operation.

5. Conclusion

In this paper, we apply the bee colony optimization algorithm based on link cost to the RWA problem in satellite optical networks. First of all, we establish a cost function model of the link, which considers transmission delay and wavelength occupancy synthetically with constraint of Doppler wavelength drift, wavelength continuity and contiguity in optical path. Afterwards, we take wavelength resource utilization and hops into account in fitness function of BCO-LCRWA, and thus improve adaptability of the selected route. At the same time, BCO-LCRWA realizes the effective utilization of wavelength resources and reduces the impact of BER on network performance by avoiding choosing routes with degraded Doppler wavelength drift and reducing hops from source to destination satellite nodes. Lastly, the simulation results show that compared with the ant colony algorithm, the bee colony algorithm has better application prospects in solving RWA problems based on satellite optical networks because of its strong global search ability. The improved bee colony algorithm proposed in this paper not only maintains the global search ability of the original bee colony algorithm, but also has advantages in developing predominant solutions. The fast convergence of the optimal solution and low complexity certify the availability of BCO-LCRWA. Through the cooperation of local search and global search, the optimal route selection and reasonable utilization of wavelength resources are efficiently achieved at the cost of low blocking probability, as well as improvements in network communication performance.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC) under grant No. 61775237, 61571440, 61675033.

References

[1] V.W.S. Chan, "Optical satellite networks", J. Lightwave Technol., vol.21, no.11, pp.2811–2817, 2003.

[2] B. Liu, L. Zhang, and X. Xin, "Enhanced secure 4-D modulation space optical multi-carrier system based on joint constellation and Stokes vector scrambling," Opt. Express, vol.26, no.6, pp.6890–6898, 2018.

[3] Y. Dong, S. Zhao, and Y. Li, "Research on routing and wavelength assignment based on ant colony optimization in distributed satellite optical network," J. Electron. Inf. Technol., vol.37, no.11, pp.2650–2656, 2015.

[4] A. Rashedi, Y.S. Kavian, K. Ansari-Asl, and Z. Ghassemlooy, "Dynamic routing and wavelength assignment: Artificial bee colony optimization," Transparent Optical Networks (ICTON), 2011 13th International Conference on, 2011.

[5] D. Karaboga, "An idea based on honey bee swarm for numerical optimization," Technical Report-TR06, Erciyes University, Engineering Faculty, Computer Engineering Department, 2005.

[6] L. Tan, Q. Yang, J. Ma, and S. Jiang, "Wavelength dimensioning of optical transport networks over nongeosychronous satellite constellations," IEEE/OSA Journal of Optical Communications and Networking, vol.2, no.4, pp.166–174, April 2010.

[7] Y. Dong, S. Zhao, H.D. Ran, Y. Li, and Z. Zhu, "Routing and wavelength assignment in a satellite optical network based on ant colony optimization with the small window strategy," IEEE/OSA J. Opt. Commun. Netw., vol.7, no.10, pp.995–1000, Oct. 2015.

[8] Q. Yang, L. Tan, and J. Ma, "Analysis of crosstalk in optical satellite networks with wavelength division multiplexing architectures," J. Lightwave Technol., vol.28, no.6, pp.931–938, March 2010.

[9] T. Dong and G. Shen, "Traffic grooming for IP over WDM optical satellite networks," 2014 13th International Conference on Optical Communications and Networks (ICOCN), pp.1–6, Suzhou, 2014.

[10] D. Karaboga and B. Basturk, "A powerful and efficient algorithm for numerical function optimization: Artificial bee colony (ABC) algorithm," J. Global Optim., vol.39, no.3, pp.459–471, 2007.

[11] A. Rashedi, Y.S. Kavian, and Z. Ghassemlooy, "Artificial Bee Colony model for routing and wavelength assignment problem," 2011 13th International Conference on Transparent Optical Networks, pp.1–5, Stockholm, 2011.

[12] R.J. Leopold and A. Miller, "The IRIDIUM communications system," IEEE Potentials, vol.12, no.2, pp.6–9, 1993.

[13] X. Dong and H. Shi, "A shortest path algorithm based on mobile agent in LEO satellite network," 2008 4th International Conference on Wireless Communications, Networking and Mobile Computing, pp.1–5, Dalian, 2008.

[14] G.C. Cabrera-Celi, E.G. Novoa-Guaman, and P.F. Vasquez-Miranda, "Design of secondary circuits of distribution networks using clustering and shortest path algorithms," 2017 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America), pp.1–6, Quito, 2017.

[15] Q. Yang, L. Tan, and J. Ma, "Analysis of Doppler-effect on satellite constellations with wavelength division multiplexing architectures," Chin. Opt. Lett., vol.7, no.1, pp.19–22, 2009.

[16] R. Suzuki, I. Nishiyama, S. Motoyoshi, E. Morikawa, and Y. Yasuda, "Current status of NeLS project: R&D of global multimedia satellite communications," Proc. 20th AIAA International Communication Satellite Systems Conference and Exhibit, pp.2002–2038, 2002.

[17] N. Karafolas and S. Baroni, "Optical satellite networks," J. Lightwave Technol., vol.18, no.12, pp.1792–1806, 2000.

[18] L. Tan, Q. Yang, J. Ma, and S. Jiang, "Wavelength dimensioning of optical transport networks over nongeosychronous satellite constellations," IEEE/OSA J. Opt. Commun. Netw., vol.2, no.4, pp.166–174, 2010.

[19] L. Franck and G. Maral, "Routing in networks of intersatellite links," IEEE Trans. Aerosp. Electron. Syst., vol.38, no.3, pp.902–917, 2002.

[20] W. Houtian, Z. Qi, X. Xiangjun, T. Ying, and L. Naijin, “Cross-layer design and ant-colony optimization based routing algorithm for low earth orbit satellite networks,” China Commun., vol.10, no.10, pp.37–46, 2013.

[21] F. Wang, B. Liu, L. Zhang, Q. Zhang, Q. Tian, F. Tian, L. Rao, and X. Xin, “Dynamic routing and spectrum assignment based on multilayer virtual topology and ant colony optimization in elastic software-defined optical networks,” Optical Engineering, vol.56, no.7, 076111, July 2017. doi: 10.1117/1.OE.56.7.076111.

[22] A. Singh and S. Sundar, “An artificial bee colony algorithm for the minimum routing cost spanning tree problem,” Soft Comput., vol.15, no.12, pp.2489–2499, 2011.

[23] G. Wen, Q. Zhang, H. Wang, Q. Tian, and Y. Tao, “An ant colony algorithm based on cross-layer design for routing and wavelength assignment in optical satellite networks,” China Commun., vol.14, no.8, pp.63–75, 2017.

[24] M. Dorigo, G.D. Caro, and L.M. Gambardella, “Ant algorithms for discrete optimization,” Artificial Life, vol.5, no.2, pp.137–172, April 1999. doi: 10.1162/106454699568728.

[25] L. Franck and G. Maral, “Routing in networks of intersatellite links,” IEEE Trans. Aerosp. Electron. Syst., vol.38, no.3, pp.902–917, 2002.

Yeqi Liu received B.S. degree in Electronic Engineering form Sichuan University, China in 2016. She is currently pursuing her Ph.D. of Electronic Science and Technology in Beijing University of Posts and Telecommunications (BUPT). Her research interests include routing and resource management in the optical satellite networks.

Qi Zhang received the Ph.D. degree from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2005. She is currently a Professor with the School of Electric Engineering, BUPT. Her research interests include optical access network, optical fiber communication and satellite communication. Within this area, she has authored or co-authored over 60 SCI and EI papers.

Xiangjun Xin was born in HeBei, China, in 1969. He received the Ph.D. degree from the School of Electric Engineering, Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2004. He is currently a Professor with the School of Electric Engineering, BUPT. He is a member of the State Key Laboratory of Information Photonics and Optical Communications, BUPT. His main research interests focus on broadband optical transmission technologies, optical sensor, and all-optical network. Within this area, he has authored or co-authored over 60 SCI papers.

Qinghua Tian received the Ph.D. degree from Beijing University of Posts and Telecommunications (BUPT) in 2013. She is working in the school of electronic engineering, BUPT. Her main research interests focus on deep learning and optical communication and satellite communication. Email: tianqh@bupt.edu.cn.

Ying Tao received her B.S. and Ph.D. degrees from Beijing Jiaotong University in 1997 and 2004, respectively. She is currently working in the Institute of Telecommunication Satellite, China Academy of Space Technology (CAST). Her research interests include satellite communication and satellite networks and she has resulted in many research papers, patents and experimental systems.

Naijin Liu received the Ph.D. degree in communication and information systems from the University of Science and Technology of China, Hefei, China, in 2007. He is currently working in Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology. His research interests include satellite communication, space network and cognitive radio.

Kai Lv received the B.S. degree in optical information science and technology the School of Electric Engineering, Beijing University of Posts and Telecommunication, Beijing, China, in 2014. He is currently pursuing the Ph.D. degree in optical engineering from the Beijing University of Posts and Telecommunication. His research interests include optical fiber communication, probabilistic shaping, digital signal processing and high-order modulation.