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Routing, Core and Wavelength Allocation in Multi-Core-Fiber-Based Quantum-Key-Distribution-Enabled Optical Networks

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ABSTRACT Quantum-key-distribution (QKD) enabled optical networks can provide secure keys for different kinds of applications to ensure the high security of communication processes. As the number of wavelength channels in a single-core fiber is limited, space division multiplexing (SDM) has been considered to be a valuable technique to provide more wavelength resources, which solves the problem of insufficient channel capacity. Due to the rapid expansion of data volume, the SDM-based QKD network has been regarded as an important paradigm. At the same time, resource allocation in multi-core optical networks is a problem worthy of studying. In this work, four routing, core, and wavelength allocation (RCWA) algorithms are proposed in the multi-core optical network for quantum service requests and classical service requests, which are referred to as RCWA without perception (RCWA-WP), RCWA with crosstalk perception (RCWA-XTP), RCWA with spectrum perception (RCWA-SP), and RCWA with core perception (RCWA-CP). Simulations are carried out to evaluate the network performance in terms of blocking probability, key utilization, and average crosstalk intensity. The comparative results indicate that the RCWA-SP algorithm can improve network performance and reduce the blocking probability, while the RCWA-XTP algorithm can reduce inter-core crosstalk during transmission.

INDEX TERMS Quantum key distribution, space division multiplexing, routing and resource allocation.

I. INTRODUCTION

Currently, the demand for data security in networks becomes increasingly important. Among many aspects of data security, key distribution is widely regarded as an important part of symmetric encryption [1]. Quantum key distribution (QKD) gradually becomes a research hotspot in the field of network information security. Its security is guaranteed by the basic laws of quantum mechanics such as Heisenberg uncertainty principle and no-cloning theorem [2]. Therefore, the information transferred in backbone networks can be effectively secured by QKD [3]. With the further research of QKD and the exploration of resource allocation in optical networks, the QKD-enabled optical network (QKD-ON) is promising to be more widely used [4]–[6].

In almost all the previous experiments reported, QKD was realized using separate fibers as opposed to allowing coexistence with the classical signals. However, due to the high cost of installing fiber resources, there is an increasing demand for multiplexing QKD with classical data information in a single fiber. In the current development of QKD-ON, wavelength division multiplexing (WDM) technology plays a crucial role in data transmission. The quantum signals generated by QKD are usually situated at the C-band (1530–1565 nm)

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and O-band (1260–1360 nm) [7]–[9]. Quantum signals and classical data signals are transmitted in the same fiber relying on different wavelength channels [10]. With more and more data carried by optical networks, the capacity of existing standard single-core single-mode fiber may no longer satisfy the increasing capacity demand. In order to reduce network costs and increase network capacity, the space division multiplexing (SDM) technology has been proposed [11]. In the SDM research, multi-core fiber (MCF) is widely used, which includes the following technologies, such as weakly-coupled multicore fiber (WC-MCF) [12], strongly-coupled multicore fiber (SC-MCF) [13], and few-mode multicore fiber (FM-MCF) [14]. Among these fibers, WC-MCF has the advantage of relatively low crosstalk [15]. Figure 1 shows the coexistence of the quantum and classical signals in the MCF. Given the nonlinear noise from classical signals, such as Raman scattering and Four-Wave Mixing (FWM) may affect the quantum signals in the same core strongly, the quantum signals and the classical signals are placed in different cores [16]. However, the inter-core crosstalk (IC-XT) is also generated between signals distributed in different cores, which is the main impairment of QKD in multi-core optical networks as it decreases the signal transmission quality between the quantum and the classical signals. MCF is already playing an important role in the backbone of optical networks. With the development of quantum communications in optical networks, deploying QKD in MCF networks will become a trend in the future.

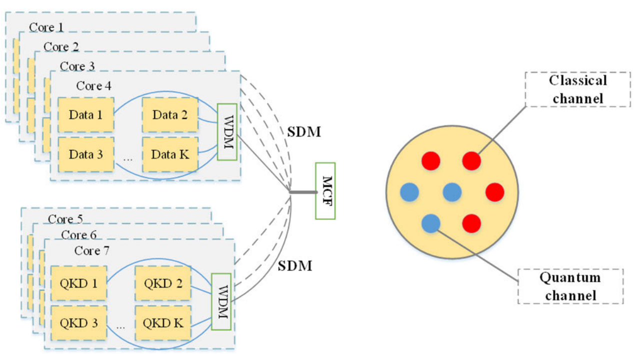


FIGURE 1. Coexistence of quantum and classical signals in the MCF.

In this work, how to design a reliable resource-allocation algorithm is noteworthy when quantum and classical signals coexist in an MCF. The major contributions of this study are three-fold:

1) Four algorithms for routing, core, and wavelength allocation (*RCWA*) are presented. These algorithms are referred to as *RCWA* without perception (*RCWA-WP*), *RCWA* with crosstalk perception (*RCWA-XTP*), *RCWA* with spectrum perception (*RCWA-SP*), and *RCWA* with core perception (*RCWA-CP*) according to different core-allocation schemes.

2) A core-distribution matrix based on an auxiliary matrix (CDAM) to address the dynamic core-allocation problem for QKD-ON is established in the *RCWA-XTP* algorithm.

3) A comparative evaluation of RCWA-based QKD-ON solutions considering two MCF types in terms of service request blocking probability, quantum-key resource utilization, and average crosstalk intensity (AXTI) of the quantum signals.

The rest of this paper is organized as follows. In Section II, the related research on QKD networks and SDM technology is described. Then, an analytical model is presented to address the problem of inter-core crosstalk in the multi-core optical network in Section III. In Section IV, the network model is described, it includes the process of dynamic resource allocation of quantum service requests and classical service requests in a multi-core optical network. Meanwhile, four *RCWA* algorithms for different requests are proposed in a multi-core optical network. The comprehensive analyses of the results of the *RCWA* algorithms are carried out in Section V. Finally, this work is concluded in Section VI.

II. RELATED WORKS

This section briefly reviews the QKD-ON from different perspectives, including the deployment and management of QKD networks and the current research progress of multi-core optical networks.

A. QKD NETWORK CONSTRUCTION

The first QKD protocol (i.e., BB84 protocol) was proposed by Bennett and Brassard [17] in 1984. The BB84 protocol solves the process of key exchange and negotiation, but it requires the deployment of trusted relays in long-distance QKD scenarios. Recently, the measurement device-independent QKD (MDI-QKD) protocol has attracted a lot of research interests due to its natural advantage of immunity to all detector attacks, and thus, the QKD can be a strong candidate for network security [18]. However, compared to the implementation and deployment of the physical layer, the control, management, and construction of the QKD network is also important.

From the perspective of QKD network control and service provisioning, experts and scholars have done a lot of research work [19]–[25]. Aguado *et al.* [26] discussed the impact of SDN on QKD-device deployment and proposed a quantum sensing SDN architecture by dividing the network into three layers, i.e., application layer, control layer, and infrastructure layer. In addition, Yu *et al.* [27] proposed an architecture of QKD networks named software-defined QKD network to solve the problem of complex management caused by excessive resource consumption. In terms of spectrum resource allocation, Cao *et al.* proposed a resource assignment strategy in optical networks integrated with QKD [28]. In addition, they also proposed a quantum-key-pool construction method to solve the problem of insufficient secure keys in the QKD network [25].

From the perspective of QKD network construction, there have been many mature field trials for QKD, including SECOQC [29], Tokyo [30], and Beijing-Shanghai [31] QKD networks. They have been successfully deployed and have provided strong support for researchers' analysis. At present, the main problems confronted with the QKD network include network capacity, construction cost, optimized strategies for resource allocation, etc. In the future, WDM may not suffice network requirements, and SDM promises to be the preferred technology in QKD networks.

B. SDM-BASED QKD-ON

In recent years, the research on multi-core optical networks has gradually increased. Dynes *et al.* [11] performed the first QKD experiment in MCF in 2016. They demonstrated that weak QKD signals can coexist with classical data signals launched at full power in a 53 km 7-core fiber while showing negligible degradation in performance, and performed additional simulations highlighting that classical data bandwidths beyond 1Tb/s can be supported with high-speed QKD in the same fiber. However, in a high-capacity transmission system, this transmission scheme fixed the quantum core (i.e., the core in MCF through which only quantum signals are transmitted) in a certain position, which is not conducive to the flexible core distribution. And in 2018, Lin *et al.* [32] integrated the QKD with the SDM-enabled optical communication network for cybersecurity. They confirmed that the impact of the high-speed data channels on the quantum channel can be divided into two main categories. On the one hand, photons transmitted in one spatial channel can transfer into adjacent channels through evanescent field coupling, which is defined as IC-XT. On the other hand, Raman photons are generated in one spatial channel by the strong data signals and contaminated the quantum channel, which is defined as Raman scattering. Recently, Cai *et al.* proposed a wavelength-space division multiplexing scheme for quantum and classical signals [16]. In this scheme, quantum signals are transmitted in an outer core while other cores are used to transmit classical signals. In addition, Urena *et al.* proposed a model to evaluate the performance of multiple QKD channel transmissions under few-mode fibers (FMF) [33]. It verifies the feasibility for the hybrid transmission of quantum and classical signals in multi-core optical networks.

In most of the previous research works, scholars concentrated on solving the technical problems of the physical layer in multi-core optical networks [34]. Quantum and classical signals coexistence in the same channel with WDM technology will generate complex nonlinear effects, such as Raman scattering and FWM [35]. Moreover, in the multi-core optical networks, the same spectrum segment of adjacent cores will lead to IC-XT which has a severely complicated impact on the quantum signals. However, the problem of resource allocation has not been solved yet. In the previous work, it paid more attention to the influence of IC-XT on the quantum service requests in optical networks [36]. In this work, the resource allocation scheme was improved in the multi-core optical networks.

III. INTER-CORE CROSSTALK

IC-XT is a major problem in multi-core optical networks. Once the IC-XT is generated, the quantum bit-error rate increases with distance. In this section, an analytical model for the IC-XT of quantum signals was proposed in multi-core optical networks. According to the analytical model, it can evaluate the AXTI of quantum signals in the multi-core optical networks. In multi-core optical networks, the non-linear noise is the main factor that affects the quality of quantum-signal transmission, which includes Raman scattering, FWM, IC-XT, and so on. In the process of the independent allocation of quantum cores and classical cores, Raman scattering and FWM have a relatively weak influence on the quantum channel [16]. Therefore, the analysis of IC-XT is particularly important in multi-core optical networks. In the scenario where the quantum signals and the classical signals are co-fiber, it evaluates the IC-XT between quantum and classical signals through the analytical model in [33]. When quantum signals are transmitted in multi-core-fiber-based optical networks, they are subject to photons which are infiltrated by adjacent cores. The average Power Coupling Coefficient (PCC) between cores m and n is expressed as $\bar{h}_{mn}$, which is calculated in Eq. (1) [33]. PCC represents the degree of influence of light intensity on the current quantum channel.

$$\bar{h}_{mn} = \sqrt{2}\kappa_{mn}^2 d \left| \frac{1}{\sqrt{a(b+\sqrt{ac})}} + \frac{1}{\sqrt{c(b+\sqrt{ac})}} \right| \quad (1)$$

where the parameter κ_{mn} is defined as the mode-coupling coefficient, d refers to the correlation length, a, b, c are three functional expressions as depicted by Eqs. (2), (3), and (4) respectively. In Eq. (5), the factor B_{mn} is depicted as a correction factor when it considers the MCF is bent at a constant bending radius R_b while being twisted at a constant rate γ [33].

$$a = 1 + \left(\Delta\beta_{mn}\mathrm{d} - \frac{B_{mn}d}{R_b}\right)^2 \quad (2)$$

$$b = 1 + (\Delta\beta_{mn}\mathrm{d})^2 - (\frac{B_{mn}d}{R_b})^2 \quad (3)$$

$$c = 1 + \left(\Delta\beta_{mn}\mathrm{d} + \frac{B_{mn}d}{R_b}\right)^2 \quad (4)$$

$$B_{mn} = \sqrt{(\beta_m x_m - \beta_n x_n)^2 + (\beta_m y_m - \beta_n y_n)^2} \quad (5)$$

where $\Delta\beta_{mn} = \beta_m - \beta_n$ and x_m, y_m are the coordinates of the center of core m at $z = 0$ in Eqs. (2-5). Finally, it can derive the crosstalk between adjacent cores m and n for an L-km fiber link as follows:

$$XT = \tanh\left(L * \bar{h}_{mn}\right) \quad (6)$$

Meanwhile, the value of $\bar{h}_{mn}$ is formulated as:

$$\bar{h}_{mn} = \frac{2K_{mn}^2 R_b}{\beta_m \Lambda_{mn}} \quad (7)$$

where R_b is the radius of curvature of the bent fiber, Λ denotes the core distance, and β_m is the propagation constant, where R_b and β_m are constants, which represent the properties of the fiber. In this work, the impact of IC-XT on quantum signals is characterized as the impact on quantum service requests in the QKD network. At the same time, it adjusted the resource-allocation strategy accordingly. On the basis of the above equations, the IC-XT will change with the selection of the cores and distance, so it chooses proper routes and cores to minimize the effects of IC-XT as shown in Eq. (8).

$$Min\,(XT) = \tanh\,(Min(L * ACN) * R * A) \tag{8}$$

Here L is the path length (km), Adjacent Core Number (ACN) is the number of adjacent cores with different types in each link, R is the reciprocal of the core distance, and A is the coefficient of the basic constant parameters in MCF fiber. Finally, the appropriate core and route can be selected through Eq. (8) to reduce the impact of IC-XT on the quantum channel. In this paper, a benchmark value is selected for comparison in the simulation under different scenarios, i.e., different percentage of service requests with encryption requirements, and different core models. The selection of the benchmark value is based on the first set of data in the simulation. In the multi-core optical network, the IC-XT can produce a certain intensity of crosstalk to the quantum signals in the channel, which will increase the error rate of the quantum signal and cause irreparable losses. According to Eq. (6), the IC-XT can be quantified to optimize the resource-allocation problem.

IV. ROUTING, CORE AND WAVELENGTH ALLOCATION

A. NETWORK MODEL

In this section, the relevant mathematical model is established to describe the resource-allocation problem. The notations and their definitions in this paper are listed as follows.

Considering that channels accommodate not only quantum service requests but also classical service requests, in this work, by data request, it refers to the resource request which is used to allocate the data signals transmitted in the network. In addition, there are two kinds of service requests, i.e., service requests with encryption requirements and without encryption requirements. Service requests with encryption requirements contain both quantum and classical service requests, while service requests without encryption requirements contain only classical service requests. In a multi-core optical network, the existing quantum signals' transmission rate is much less than the data transmission rate. Moreover, the quantum signals are not replicable by themselves. Therefore, it can increase the transmission capacity of quantum signals through the MCF.

B. RCWA IN MULTI-CORE OPTICAL NETWORKS

In this section, four *RCWA* schemes are proposed, which complete the resource-allocation process of service requests in multi-core optical networks. There are two points that need our consideration, on the one hand, it focus on how to alleviate IC-XT so that it can design an algorithm for different requests. On the other hand, it considers the optimum utilization of the network resources. With these considerations, an algorithm to optimize network resource allocation was proposed. The proposed *RCWA* algorithm for requests is shown as follows:

TABLE 1. Notations and definitions.

Notation	Definition
$G(V,E,C,W,Q)$	the topology for the QKD-over-multi-core optical network
$V = \{v_1, v_2, \dots, v_n\}$	the network node sets
$E = \{e_1, e_2, \dots, e_n\}$	the fiber links in network sets
$C = \{c_1, c_2, \dots, c_n\}$	the core in each link sets
$W = \{W, W_2, \dots, W_n\}$	the set of wavelengths on each link that reserved as data channels
$Q = \{Q_1, Q_2, \dots, Q_n\}$	quantum keys reserved by the node
R_Q	quantum service request
R_C	classical service request
S_E	service requests with encryption requirements
S_U	service requests without encryption requirements
$r(s_r, d_r, w_r, t_h, p_r)$	service request
s_r	the source node of service request r
d_r	the destination node of service request r
w_r	the wavelength demand of service request r
t_h	the occupying time of service request r
p_r	the path of service request r
c_r	the cores in each link in the current path
ACN	the number of adjacent cores with different types in each link
S	the pre-allocated wavelength resources set
M	the shortest *M* routes obtained by K-Shortest Path (KSP) algorithm
N	the available cores in each link
$a_{(i,j)}$	the elements in the matrix
c_{min}	the link set which has min(XT) path

C. RCWA FOR QUANTUM SERVICE REQUESTS

In multi-core optical networks, the accommodation of quantum service requests involves three dimensions, that is, paths, cores, and wavelength resources. When there is a quantum service request, it adopts the KSP algorithm to obtain the routing set M, core allocation methods to obtain the core set γ, and First Fit to allocate wavelength resources. The four algorithms that proposed for core distribution includes *RCWA-WP*, *RCWA-XTP*, *RCWA-SP*, and *RCWA-CP*. The proposed *RCWA* algorithm for quantum service requests is shown as follows:

The above algorithm consists of five sections. First, an appropriate algorithm is selected, such as *RCWA-XTP*. Second, the algorithm gets K paths and cores collection

TABLE 2. RCWA algorithm.

RCWA algorithm

Input: $G_v(V,E)$, $r(s_r,d_r,w_r,t_h,p_r)$
Output: ***RCWA*** solution for requests

Initialize the network $G(V,E,C,W,Q)$;
R comes, and the t_h obey the Poisson distribution;
if $S= S_E$ **then**
  Operate ***RCWA*** algorithm for quantum service requests;
  if R_Q allocation succeeded **then**
    Operate ***RCWA*** algorithm for classical service requests;
  else service requests with encryption requirements allocation failure;
  end if
else if $S= S_U$ **then**
  Operate ***RCWA*** algorithm for classical service requests;
  if R_C allocation failure **then**
    service requests without encryption requirements allocation failure;
  end if
end if

which can carry quantum service requests and available in K paths. After that, it calls the CDAM method to realize core pre-allocation which can get the candidate cores that could be allocated. Third, it uses Eq. (8) to analyze IC-XT for each path, the routing and core allocation strategy with the lowest IC-XT value is selected for the next step. Fourth, it implements the quantum service request deployment, it is worth noting that "NUM" means the number of free wavelengths in the current core that can satisfy resource allocation requirement. At last, if the wavelength resources are insufficient on the current path, the *RCWA-CP* algorithm is used for resource allocation. The reason that it chose *RCWA-CP* is that the other two methods will cause extremely high IC-XT during the core-selection process. According to these steps, the resource-allocation problem of the quantum service requests in the multi-core optical network is solved. Compared with other algorithms, the *RCWA-XTP* focuses more to relieve IC-XT. The proposed CDAM method for quantum service requests is shown as follows:

The aim of the CDAM method is to allocate the core based on the number of adjacent cores. It consists of 3 sections. First, it constructs two matrices of n*m based on the structure of the MCF. For example, the auxiliary matrix of 7-core fiber is 3*5, and the auxiliary matrix of 19-core fiber is 5*9 (it depends on the position structure of each core in the fiber to build the matrix of the same dimension), so n and m depend on the position of the core and the structure of the MCF. According to the position of the core, it initializes the matrix which means the position with the core distribution is assigned a value of 1, 0.01, 0 or MAX_VALUE. Otherwise, the MAX_VALUE represents the position occupied by no

TABLE 3. RCWA algorithm for quantum service requests.

RCWA algorithm for quantum service requests

Input: $G_v(V,E)$, $r(s_r,d_r,w_r,t_h,p_r), R_Q$
Output: ***RCWA*** solution for quantum service requests

R_Q comes, and the t_h obey the Poisson distribution;
if *RCWA-XTP* is selected;
  $p_r \leftarrow$ get $M \in G(V,E,C,W,Q)$;
  for p_i in p_r **then**
    $c_r \leftarrow$ get $N \in G(V,E,C,W,Q)$;
    for all c_i in c_r **then**
      $c_i \leftarrow$ core distribution computation with ***CDAM*** method;
    end for
  end for
  Evaluate each p_i in p_r IC-XT by ***Equation 8***, get c_{min};
  for c_i in c_{min} **then**
    $S \leftarrow$ get the available wavelength in c_i;
    if w_r<NUM(w=∅) && satisfy wavelength consistency
      Resource allocation successful and **return**;
    end if
  end for
  for all p_i in p_r **then**
    $c_r \leftarrow$ get $N \in G(V,E,C,W,Q)$;
    for all c_i in c_r **then**
      Select c_i of the same position in each link (*RCWA-CP*);
    end for
    $S \leftarrow$ get the available wavelength in c_r;
    if w_r<NUM(w=∅) && satisfy wavelength consistency
      Resource allocation successful and **return**;
    end if
  end for
  else select *RCWA-WP, RCWA-SP, or RCWA-CP*;
  end if

core, and it is a relatively maximum value, it can be replaced by 10^5 in this paper. Second, the total number of adjacent cores in each core can be obtained by mathematical calculation as shown in Eq. (9), after that the result will be recorded in the matrix β. At last, it selects the minimum value b for which a is not equal to 1. The CDAM method can be used to allocate cores for classical and quantum service requests so that it will have the least number of adjacent classical cores on quantum service requests.

$$a_{(i,j)} = \lfloor a_{(i+1,j+1)} + a_{(i+1,j-1)} + a_{(i-1,j+1)} + a_{(i-1,j-1)} + a_{(i,j-2)} + a_{(i,j+2)} \rfloor \quad (9)$$

D. RCWA FOR CLASSICAL SERVICE REQUESTS

Similar to the quantum service requests, the IC-XT also affects the classical service requests in multi-core optical networks. However, the performance on utilization of network resources needs to be improved. Therefore, *RCWA* for classical service requests is the same with *RCWA* for

TABLE 4. Core distribution based on auxiliary matrix method.

Core Distribution based on Auxiliary Matrix method

Input: $r(s_r, d_r, w_r, t_h, p_r),\ C(C_C, C_Q)$
Output: $C_i(C_C, C_Q)$

Create an empty auxiliary matrix A, β;
  for a (number in the matrix) in A **then**
    if candidate core in A is a classical core, $a \leftarrow 1$;
    else if candidate core in A is a quantum core, $a \leftarrow 0.01$;
    else if candidate core in A is a free core, $a \leftarrow 0$;
    else $a \leftarrow MAX\_VALUE$;
    end if
  end for
  for a in A **then**
    if a != MAX_VALUE
      b (number in β) ← Calculate ACN by ***Equation 9***, record b in β;
    else
      $b \leftarrow MAX\_VALUE$ (same as a), record b in β;
    end if
  end for
  for a in A **then**
    if a !=1
      Select min(b) in β as the quantum core;
    end if
  end for
return b;

quantum service requests. The proposed *RCWA* algorithm for classical service requests is shown in Table 5. The *RCWA* algorithm for classical service requests consists of 4 sections. First, an appropriate algorithm is selected, such as *RCWA-SP* or *RCWA-WP*. Second, it gets K paths and cores collection which can carry classical service requests and available in the current path. Third, if the *RCWA-SP* is selected, the algorithm looks for all the cores in the current path and select the one with the most number of free wavelengths as the pre-core, otherwise, the selected *RCWA-WP* algorithm which selects the core randomly (in order to reduce the probability of failure in resource allocation process, N-loop random selection method is set). At last, if the wavelength resources are sufficient in the current path, it will perform First Fit algorithm for wavelength resource allocation. According to these steps, the resource allocation problem of the classical service requests in the multi-core optical network is solved.

The time complexity of the four algorithms can be used as an indicator to evaluate each algorithm's performance. The time complexity of *RCWA* in the routing process is the same, so the core and wavelength allocation are worth noting. *RCWA-WP* is the easiest algorithm and its time complexity is $O(KV(E + VlogV))$ because it does not consider the allocation of core and wavelength. *RCWA-CP* considers the

TABLE 5. RCWA algorithm for classical service requests.

RCWA algorithm for classical service requests

Input: $G_v(V, E),\ r(s_r, d_r, w_r, t_h, p_r), R_C$
Output: ***RCWA*** solution for the classical service request

R_C comes, and the t_h obey the Poisson distribution;
  if *RCWA-XTP or RCWA-CP* is selected
    Same as *RCWA-XTP* for quantum service requests;
  else if *RCWA-SP or RCWA-WP* is selected
    $p_r \leftarrow$ get $M \in G(V, E, C, W, Q)$;
    for all p_i in p_r **then**
      $c_r \leftarrow$ get $N \in G(V, E, C, W, Q)$;
      for all c_i in c_r **then**
        if the algorithm is *RCWA-SP*
          if c_i has the most number of free wavelengths
            Select c_i as the per-core, $S \leftarrow$ get the available wavelength in c_i;
            if w_r<NUM(w=∅) && satisfy wavelength consistency
              Resource allocation successful and **return**;
            end if
          end if
        end if
        if the algorithm is *RCWA-WP*
          Select c_i randomly as the per-core, $S \leftarrow$ get the available wavelength in c_i;
          if w_r<NUM(w=∅) && satisfy wavelength consistency
            Resource allocation successful and **return**;
          end if
        end if
      end for
    end for
  end if

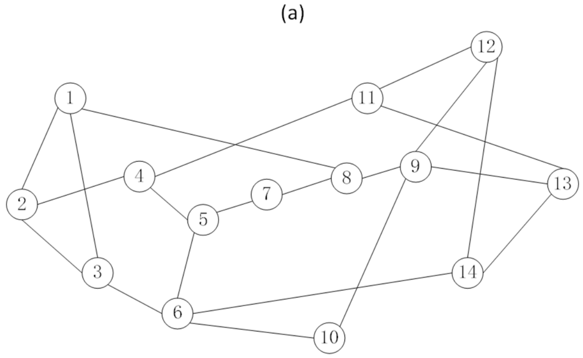
dimension of the link, and its time complexity is $O(KV(E + VlogV)logC)$. *RCWA-XTP* adopts the CDAM method to analyze the deployment state of the core, so the complexity will be relatively higher than *RCWA-CP* and its time complexity is $O(CKV(E+VlogV))$. The *RCWA-SP* algorithm combines the dimension of wavelength, and its magnitude is higher, so its complexity is the highest among all the *RCWA* algorithms and its time complexity is $O(WKV(E + VlogV)logC)$.

V. SIMULATION RESULTS AND ANALYSIS

In this section, it evaluates the performance of the proposed *RCWA* algorithm in terms of blocking probability, key utilization, and AXTI. Here, the key utilization indicates the ratio of the number of consumed quantum keys to the total number of generated quantum keys, and AXTI is defined as average crosstalk intensity of quantum signals in multi-core optical networks, and its calculation formula is Eq. (6). Compared with four different algorithms, it draws some conclusions and results. As shown in Figure 2, it describes our simulation parameters configuration and the NSFNET network topology. To compare the performance of these algorithms, it coordinates the proportion of percentage of service requests with encryption requirements under increasing traffic load. Secondly, it evaluates the impact of different resource-allocation methods on IC-XT and use the ACN of each core in the current path occupied by the quantum service requests established successfully as our evaluation index. At the same time, combined with this parameter, the AXTI of each request could be evaluated.

Network topology	NSFNET
Number of nodes	14
Number of bi-directional links	21
Number of wavelengths on each link	80
Number of requests	50000
Wavelengths of request occupied	1 / 2 / 3 / 4
Number of cores in a MCF	7 / 19
Request type	Date request / Quantum request
Distribution of request	Poisson distribution
Number of alternative paths	4
Wavelength allocation method	First Fit

(a)



(b)

FIGURE 2. (a) Simulation parameters; (b) NSFNET network topology.

Figure 3 shows blocking probability of the service requests with encryption requirements and without encryption requirements with different *RCWA* algorithms. The blocking probability increases with traffic load. It also varies with the percentage of service requests that require encryption. When the percentage of service requests with encryption requirements was set to 80%, there were more quantum service requests in the network. The *RCWA-WP* and *RCWA-XTP* have a higher blocking probability and *RCWA-SP* has a lower blocking probability in Figure 3. The reason is when *RCWA-SP* is performed, it considered the resource utilization efficiency in each core at first. In contrast, the *RCWA-XTP* algorithm could avoid the impact of different request types as much as possible. Although the *RCWA-XTP* also considers a part of the algorithm *RCWA-CP*, the blocking probability is still higher than *RCWA-SP*. When the percentage of service requests with encryption requirements is set to 20%, the number of key requests reduces in the network, the blocking probability still increases with increasing traffic load. In addition, when the percentage of service requests with encryption requirements is set to 20%, since *RCWA-WP* lacks regularity in the core-allocation process, the wavelength resources in the quantum core are partially wasted, and blocking probability is higher. In addition, *RCWA-WP* starts with a high contingency, and the blocking probability increases rapidly when the traffic load increases. It can be seen from Figure 3 that when the traffic load reaches 660 Erlang and the percentage of service requests with encryption requirements is 80% or traffic load reaches 540 Erlang and percentage of service requests with encryption requirements is 20%, the performance of the *RCWA-WP* algorithm fluctuates greatly. In fact, when the traffic load reaches a certain scale, quantum and classical service requests are allocated randomly, wasting a lot of resources, and then it reduces the efficiency of resource utilization and increases the network blocking probability. Therefore, when the network service scale is tiny, *RCWA-WP* can be adopted appropriately.

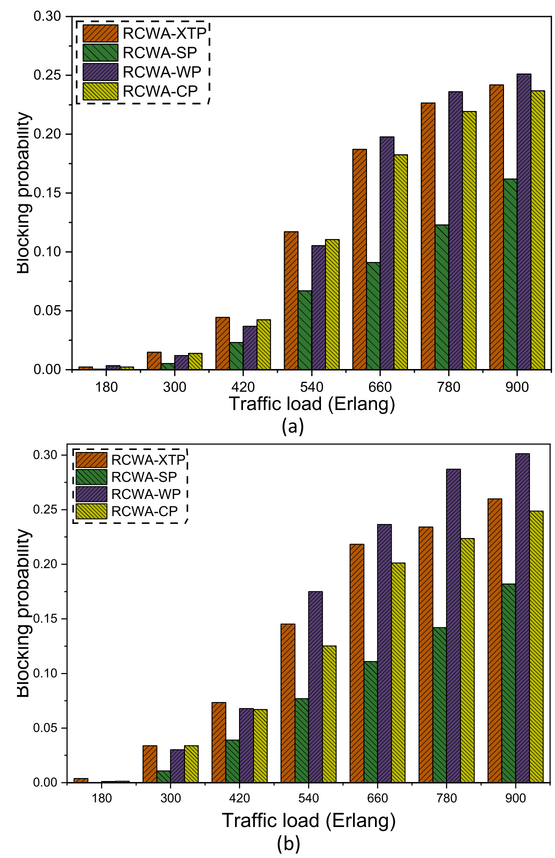


FIGURE 3. Blocking probability with different *RCWA* algorithms (a) percentage of service requests with encryption requirements is 80%; (b) percentage of service requests with encryption requirements is 20%.

Figure 4 shows the key utilization with different *RCWA* algorithms. As shown in Figure 4, the key utilization decreases for increasing traffic load under different percentages of service requests with encryption requirements. When the percentage of service requests with encryption

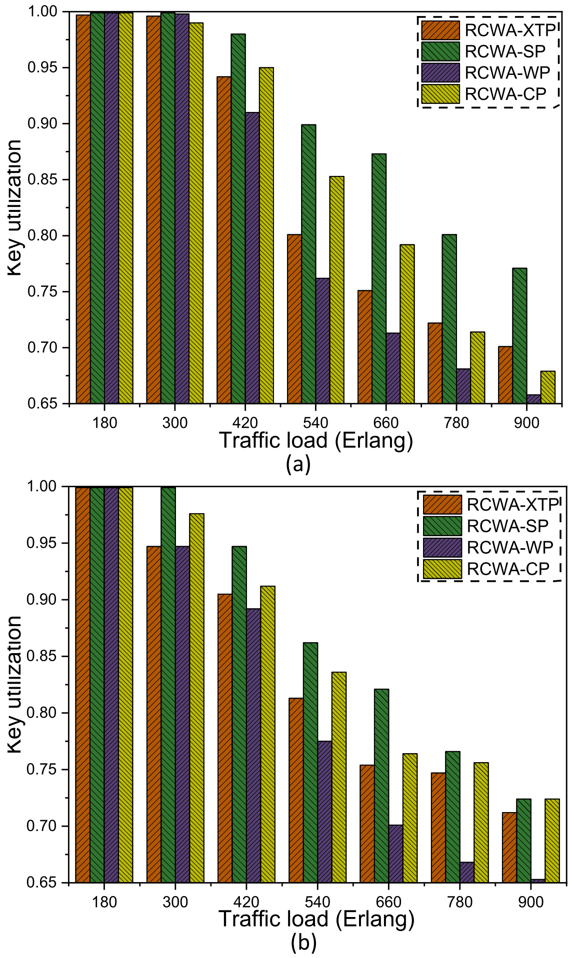


FIGURE 4. Key utilization with different *RCWA* algorithms (a) percentage of service requests with encryption requirements is 80%; (b) percentage of service requests with encryption requirements is 20%.

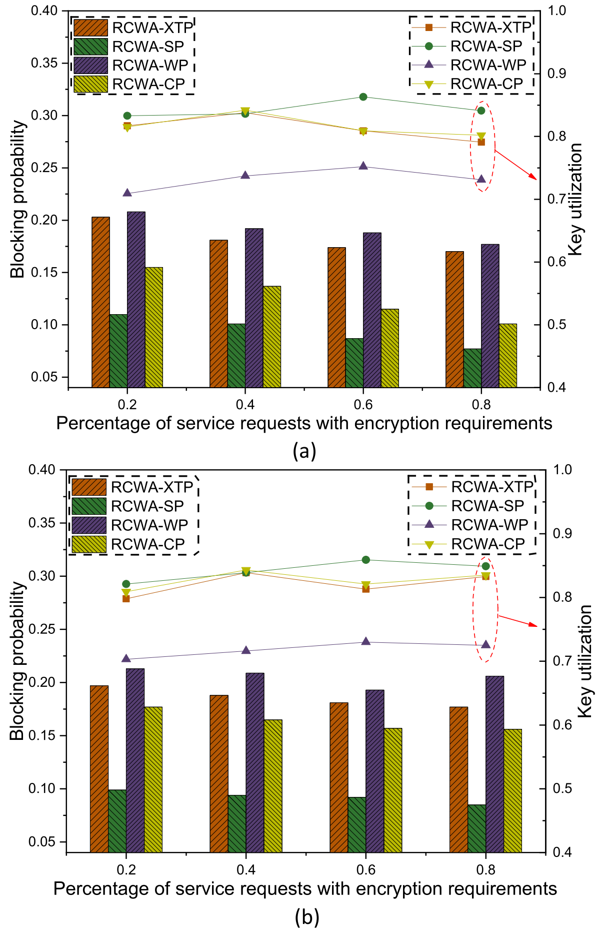


FIGURE 5. Blocking probability and key utilization with different *RCWA* algorithms (a) 7-core fiber under 600 Erlang; (b) 19-core fiber under 1500 Erlang.

requirements is set to 80%, *RCWA-SP* has the best performance. The reason is when the *RCWA-SP* is performed, it will select the channel with the idlest wavelength for resource allocation and it obtains a higher network resource utilization, key utilization will increase with it. When the percentage of service requests with encryption requirements is set to 20%, the key utilization still decreases with traffic load increasing, *RCWA-SP* shows more disadvantages compared to the case when percentage of service requests with encryption requirements is set to 80%. In addition, *RCWA-CP* led to an imbalance in resource allocation, so it is not as high performance as *RCWA-SP*. It can be seen from Figure 4 that when the percentage of service requests with encryption requirements was set to 80%, the key utilization of *RCWA-XTP* has dropped by 14% when the traffic load is 540 Erlang. Due to the fact that the *RCWA-XTP* deviates from the classical service request during the core-selection process, the interference of data signals to quantum signals is reduced, and classical service request blocking probability increases accordingly.

Figure 5 shows the blocking probability and key utilization with different *RCWA* algorithms. The simulation results show that with the increase of percentage of service requests with encryption requirement, the blocking probability is slightly decreased. First of all, the dimension of 19-core fiber is higher than that of the 7-core fiber in figure 5. With the *RCWA-CP*, higher-dimensional cores are deployed in more centralized locations during the core selection process, resulting in higher blocking rate. At the same time, in Figure 5(b), the *RCWA-WP* has a higher blocking probability when the percentage of service requests with encryption requirements is 80%. The reason for this phenomenon is that when the number of these two kinds of requests are close, the uncertainty of *RCWA-WP* will increase. In addition, it also indicates that more uncertainties should be considered when adopting *RCWA-WP*. The key utilization is affected by both the blocking probability and ratio between the quantum-to-classical cores. When the percentage of service requests with encryption requirements was set to 60%, blocking probability of *RCWA-SP* and *RCWA-WP* reached a higher value; however, when the percentage of service requests with encryption requirements was set to 40%, *RCWA-XTP* and *RCWA-CP* arrived a higher value. The reason is that when the percentage of service requests with encryption requirements increases, *RCWA-XTP* and *RCWA-CP* assign more quantum channels, resulting in a higher blocking probability of classical information data, while *RCWA-SP* and *RCWA-WP* receive quantum channels when the percentage is 80%. In addition, 19-MCF has a higher number of cores and higher randomness in multi-core optical network in terms of blocking probability and key utilization under the same network environment. In brief, the simulation results further demonstrates the feasibility of our algorithms in multi-core optical network.

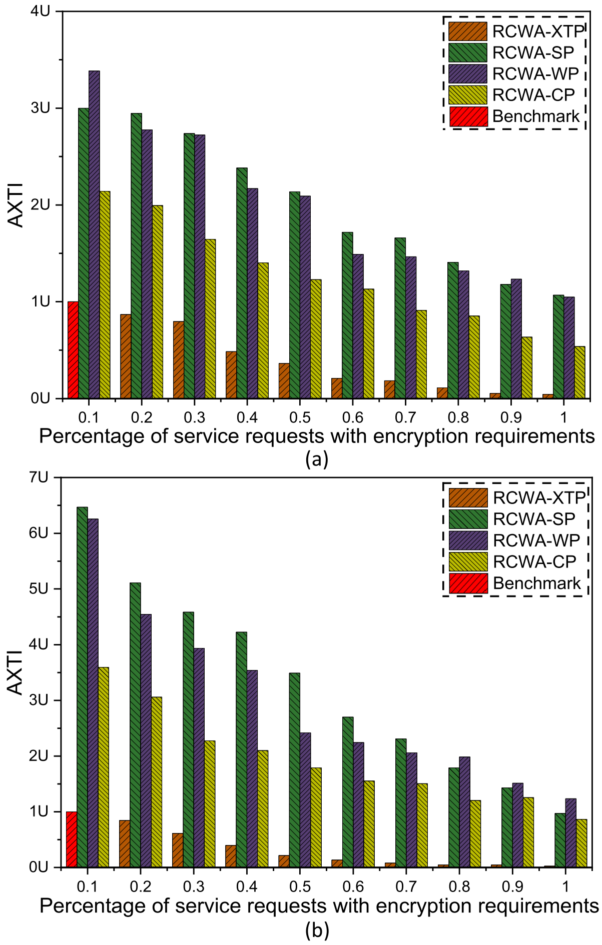


FIGURE 6. The AXTI with different *RCWA* algorithms (a) 7-core fiber under 600 Erlang; (b) 19-core fiber under 1500 Erlang.

Figure 6 shows the AXTI with different *RCWA* algorithms. The value of AXTI is used to evaluate the variation of quantum service requests due to IC-XT in the multi-core optical network. In Figure 6, the red one is our benchmark, which means a specific algorithm is selected under a certain condition as a comparison example, and then it compares its performance with other algorithms and conditions, finally, it takes the AXTI value under the reference condition as a unit, namely 'U'. Moreover, it sets the benchmark condition to be 10% service requests are with encryption requirements. Besides, the *RCWA-XTP* is the benchmark algorithm in Figure 6. Compared with the 7-core fiber, the 19-core fiber has lower IC-XT under different *RCWA* algorithms. In general, the advantage of *RCWA-XTP* in IC-XT is very obvious and as the number of cores increases, the crosstalk intensity decreases. However, the IC-XT of *RCWA-WP* and *RCWA-SP* is relatively stronger, the reason is that they are more flexible in the core-selection process. Through the above simulation, the appropriate *RCWA* algorithm could be selected from the perspective of network resource utilization and IC-XT.

VI. CONCLUSION

In this paper, the *RCWA* algorithms are proposed to address the problem of resource allocation in the multi-core optical network. A crosstalk-perception *RCWA* algorithm is presented to assign the pre-selected core to protect the quantum core channel and decrease the crosstalk of the classical core with respect to adjacent cores. A spectrum-perception *RCWA* algorithm is designed to make full use of the network resources by pre-computing the distribution of secure key and data information in the multi-core optical network. Compared with the above two algorithms, *RCWA-WP* and *RCWA-CP* have lower performance but less time complexity. The simulation results show that the *RCWA-SP* algorithm can improve the network performance more efficiently than others in terms of blocking probability and key utilization. Besides, the *RCWA-XTP* can guarantee more reliable quantum signals transmission, which is the lowest IC-XT strength. Therefore, it is more appropriate to adopt the *RCWA-XTP* algorithm when considering IC-XT; on the contrary, it is more appropriate to adopt the algorithm *RCWA-SP* to improve network resource utilization efficiency.

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