Routing Core and Spectrum Allocation Algorithm for Inter-Core Crosstalk and Energy Efficiency in Space Division Multiplexing Elastic Optical Networks

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ABSTRACT Elastic optical networks (EONs) and space-division multiplexing (SDM) have emerged as a promising technology to accommodate the high-capacity and dynamic bandwidth demands of next-generation network. However, the problems of high energy consumption and inter-core crosstalk (ICXT) in space-division multiplexing elastic optical networks (SDM-EONs) are also particularly prominent. In this paper, we proposed an energy efficient grooming and hybrid crosstalk solution (EEG-HCS) algorithm. Firstly, in the routing strategy, a candidate path sorting formula combined the path length and path load state is designed to select the candidate paths and balance the network load. According to the sorting result, whether the current candidate path satisfied the energy efficiency grooming condition or not is determined. When the candidate path meet the energy efficiency grooming condition, the energy efficiency grooming algorithm is used to reduce the transmission energy consumption. For traffic request that do not satisfied the grooming condition, a new optical path is established. Through the core priority grouping, combined with crosstalk avoidance strategy and ICXT aware algorithm, the impact of inter-core crosstalk is minimized, and the probability of successful transmission is improved. In order to evaluate the performance of proposed algorithm, ICXT improvement index is defined. The simulation results show that the proposed algorithm can significantly reduce the energy consumption of space-division multiplexing elastic optical network system while ensuring the optimal blocking probability performance.

INDEX TERMS SDM-EONs, dynamic resource allocation, Energy efficiency grooming, Inter core crosstalk.

I. INTRODUCTION

In recent years, with the rapid development of 5G mobile network, Internet of Things, cloud computing and other emerging technologies, diversified network traffics have led to an exponential growth in the volume of traffics represented by IP requests, and the annual growth rate of global network traffics exceeding 30% [1]. Traffic requests need transmission network to provide more flexible and high-capacity services. Researchers have proposed a number of feasible technologies to solve the increasingly severe flexibility and capacity problems faced by optical transmission networks. Elastic Optical Networks based on Orthogonal Frequency Division Multiplexing (OFDM) technology can adaptively select modulation level and flexibly allocate spectrum bandwidth, so it is widely considered to be next-generation optical network [2]. Space Division Multiplexing technology can expand the optical transmission network from the spatial dimension, making the transmission capacity of optical transmission network exceed the physical limit of traditional single-mode single-core optical fiber [3]. Multi-Core Fiber (MCF) technology is a research hotspot and recognized as one of the most effective way to achieve SDM.
The combination of elastic optical network and space division multiplexing technology can adapt to the high speed development of traffic types and network traffic. At the same time, due to the increase of spatial dimension, the traditional routing spectrum allocation (RSA) problem has become a more complex routing spectrum core allocation problem (RSCA) [4]. Based on the previous routing and spectrum allocation problem, space dimension obviously increase the complexity of resource allocation algorithm. In addition, due to the structural characteristics of multi-core fiber, there is a leakage of optical power between the cores, which inevitably lead to the problem of inter-core crosstalk. Moreover, the ICXT problem will become more serious with the increase of transmission distance and the number of MCF cores, which affect the transmission quality of the network and reduce the capacity advantage brought by the space division multiplexing technology.

Optical signal is usually subjected to physical impairment caused by non-ideal devices during transmission, and with the increase of the transmission distance, the physical impairment will continue to accumulate, which seriously affected the transmission quality of the optical path. An established optical path may not transmit the request due to severe signal impairment. ICXT and nonlinear impairment in physical impairment are the focus of research. T. Mizuno et al. introduced a non-linear damage aware algorithm for anycast services, and proposed a complete resource allocation algorithm [5]. In order to highlight the MCF characteristics, this paper only considered the ICXT problem, nonlinear impairment will be studied in future work.

S. Fujii et al. firstly proposed that in the process of resource allocation, the ICXT was reduced to a certain extent by prioritizing the cores in MCF to avoid sequential allocation, and the problem of spectrum fragmentation was limited by spectrum partitioning [6]. However, the algorithm proposed only suitable for traffics with specific traffic type, and the core priority arrangement has poor ICXT avoidance effect when the traffic load was heavy. Y. Zhao et al. proposed a crosstalk-aware spectrum defragmentation (C ASD) algorithm based on spectrum compactness formula, which defined to measure the spectrum status in the SDM-EONs [7]. F.-J. Moreno-Muro et al. proposed core continuity Reconfigurable Optical Add/Drop Multiplexer (ROADM), combined with RSA algorithm, can reduce the structural complexity of ROADM and improve the blocking probability and spectrum utilization performance [8]. A path-based static route spectrum allocation algorithm was proposed in [9], the difference between path-based and link-based core exchange was analyzed. Different core exchange methods are provided on the basis of core-continuity. M. Yang et al. systematically introduced several types of ICXT, by design node-arc ILP model, routing, core and spectrum allocation can be achieved [10]. Compared with other crosstalk solution strategies, it can avoid over-protection and effectively suppress the impact of ICXT. However, the First-Fit (FF) principle adopted in the process of spectrum allocation in that literature still has a lot of room for improvement. In [11], the author presented a comprehensive model to address three-dimensional resource assignment in SDM-EONs, consider all spectral and spatial diversity types, it’s a valuable reference in SDM-EONs resource allocation algorithm.

With the explosive growth of network traffics, new types of energy-consuming devices are increasing, and the problem of network energy consumption was becoming increasingly prominent [12]. L. Chiara vigli o et al. designed ILP model and heuristic algorithm to reduce energy consumption under low traffic load by turning off some network components. However, close some components in the backbone network will affect the connectivity of the network, and frequent switch components had a great impact on network performance [13]. G. Zhang et al. introduced traffic grooming algorithm into the elastic optical network, reduce the use of spectrum resources through integer linear programming, and also reduced the number of transponders [14].

In [15], a virtual graph was considered for a given network topology graph, whereby the cost functions of virtual graph was computed according to the energy consumption of the corresponding links and intermediate routers, the arrived connection request was served by finding the most energy-efficient path among the possible candidate paths. Unlike the static topology, the traffic request in [16] varied with time and region, the literature reflected the relatively real traffic distribution and energy consumption distribution. An energy efficient procedure use geometric convexification technique was proposed in [17] to provide convex formulations for the signal-to-interference plus noise ratio, transponder power consumption, and transponder configuration problem. In [18], based on the Architecture on Demand (AoD), the energy consumption control was added by sacrificing the flexibility of some node exchange for higher energy efficiency, and cooperated with the resource allocation strategy proposed in this paper, the energy consumption of the network can be greatly reduced. However, this literature does not quantitatively calculate the power consumption, and the proposed algorithm at the expense of flexibility has obvious shortcoming when facing new business expansion in the future.

Based on the existing literature review, we found that the energy consumption of SDM-EONs is rarely studied. At the same time, the research of ICXT in MCF can be divided into two kinds, which is passive avoidance solution and ICXT aware. Considering that the passive avoidance solution is not effective under medium and high traffic load, and the complexity of ICXT aware is too high. Combining the above energy consumption and ICXT problems, this paper proposed an energy efficiency grooming and hybrid crosstalk solution (EEG-HCS) algorithm, which can reduce the fixed energy consumption and guard bandwidth by sharing the existing optical path. A hybrid ICXT solution of passive avoidance and ICXT aware is proposed. According to the resource utilization of the optical path, the passive avoidance ICXT solution is used to reduce the computational complexity of
when optical path under high traffic load, which can minimize the network energy consumption while ensuring the minimum impact of ICXT on bandwidth blocking rate.

The rest of this paper is organized as follow. In section II, energy consumption and ICXT are mathematically formulated in SDM-EONs architecture. In section III, a RSCA algorithm based on energy effective grooming and hybrid crosstalk solution is proposed. In section IV, numerical results are thoroughly discussed before concluding in section V.

II. PROBLEM STATEMENT

A. ICXT FOR SDM-EONs

According to the crosstalk calculation model proposed in reference [10], the ICXT increment $h$ per unit transmission length is calculated by formula (1), where $k$, $r$, $\beta$, $c_p$ represent the coupling coefficient, bending radius, propagation constant and core pitch, respectively. The average crosstalk of a particular core in MCF is calculated by substituting $h$ into formula (2), in which $XT_{av}$ represents the average crosstalk, $n$ represents the number of adjacent cores of the specified core, and $L$ represents the transmission length. Note that the selection of different ICXT calculation parameters will result in different $h$ values, and the calculated ICXT values will also be different. This formula is mainly used to quantitatively analyze the influencing factors of ICXT.

$$h = \frac{2k^2r}{\beta c_p}$$

$$XT_{av} = \frac{n - n \cdot \exp[-(n + 1) \cdot 2hL]}{1 + n \cdot \exp[-(n + 1) \cdot 2hL]}$$

The above average crosstalk calculation formula regarded all the adjacent cores of the specified core as active core which will cause ICXT, but the actual situation is not so. Therefore, this calculation method will cause over-protection phenomenon. In order to solve this problem, the calculation model of ICXT is further optimized, formulas (3) and (4) are shown in reference [10]:

$$XT_{cc_a} = \frac{1 - \exp(-2hL)}{1 + \exp(-2hL)}$$

$$XT_c = \sum XT_{cc_a}$$

$XT_{cc_a}$ represent the crosstalk between a core and its adjacent core $c_a$, which occupies the same spectrum domain. $XT_c$ is the total crosstalk, and its value is the sum of all crosstalk values on the transmission path.

In Fig. 1, since there are some frequency slots overlap between the traffic R1 and R2, traffic R2 and R3, so there is an ICXT problem between them. At the same time, R2 overlaps with R1 and R3 respectively, so the presence of the R2 may cause a crosstalk superposition phenomenon. In contrast, traffic R4 does not cause any ICXT because its adjacent core has no other traffic corresponding to the frequency slot.

B. ENERGY CONSUMPTION MODEL

As shown in Fig. 2, the schematic diagram of the space division multiplexing elastic optical network node architecture is given. The traffic in the network came from the IP router of the electrical layer, which determined the type and size of the traffic request, and is also the main energy consumption device. The bandwidth variable transceiver (BVT), select an appropriate output port according to the type and rate of the request, and convert the electrical signal into an optical signal and then send it to bandwidth variable optical cross connector (BV-OXC). Due to the introduction of space division multiplexing, the BV-OXC is mainly composed of core multiplexer or demultiplexer (Mux/DeMux) and spectrum selection switch (SSS), which can realize multi-core fiber multiplexing or demultiplexing and flexible cross-connect functions. In addition, in order to overcome the problem of signal degradation and distortion on the transmission path, an Erbium Doped Optical Fiber Amplifier (EDFA) is usually placed every 120KM [14].

In summary, the main energy consumption devices are as follows: IP Router, BVT, BV-OXC and OA. The energy consumption of transmission traffic can be divided into
two parts: the inherent energy consumption of devices which is not related to traffic type and request rate, and the load energy consumption which is positively related to traffic type and rate. Next, the energy consumption calculation model of each device is introduced.

1) POWER CONSUMPTION MODEL OF IP ROUTER

In [13], it is pointed out that IP router working in the IP layer is the main energy-consuming device. It mainly processed the data from the network, and its energy consumption model designed as follows:

\[ P_{IP}^i = P_{IP}^{Fix} + P_{IP}^{Traffic} \]  \hspace{1cm} (5)

\[ P_{Traffic}^{i} = R_{cos1} \times (T_r + G \times B) \]  \hspace{1cm} (6)

Formula (5) is the energy consumption calculation formula of IP router in node \( i \), where \( P_{IP}^{Fix} \) is the inherent energy consumption of IP router and its power consumption is 1329.33W[13]. The value of \( P_{Traffic}^{i} \) is related to the type of traffic and request rate. Formula (6) \( R_{cos1} \) represent the energy consumption per unit Gbit of request sent by IP router and its value is 0.465 (W/Gbit)[13]. \( T_r \) is the traffic volume of traffic request (Gbit), and B is the unit transmission bit which value is 12.5 Gbit. And G is the guard frequency gap between traffics.

**TABLE 1.** Power consumption, transmission reach and capacity of a subcarrier with different modulation format.

| Modulation format | Capacity (Gb/s) | Power (W) | Reach (Km) |
|-------------------|----------------|-----------|------------|
| BPSK              | 12.5           | 112.374   | 4000       |
| QPSK              | 25             | 133.416   | 2000       |
| 8QAM              | 37.5           | 154.457   | 1000       |
| 16QAM             | 50             | 175.489   | 500        |
| 32QAM             | 62.5           | 196.539   | 250        |
| 64QAM             | 75             | 217.581   | 125        |

2) POWER CONSUMPTION MODEL OF BVT

Bandwidth-variable transponder play an important role in the whole transmission process, and the energy consumption is closely related to the type of traffic, request rate and the selected modulation format. Combined with literature [14], the maximum transmission distance and transponder energy consumption under different modulation formats are obviously different for different network backgrounds and different MCF types. Table 1 shown the relationship between modulation format, energy consumption and maximum transmission distance in 7-core optical fibers.

Similar to IP routers, the energy consumption of BVT can be divided into fixed power consumption and traffic-related energy consumption:

\[ P_{BVT}^i = P_{Fix}^{BVT} + P_{Traffic}^{BVT} \]  \hspace{1cm} (7)

\[ P_{Traffic}^{BVT} = P_{Sub}^m \times (Sub^m + G) \]  \hspace{1cm} (8)

Formula (7) is the energy consumption of BVT in node \( i \). The fixed energy consumption is about 32W [14], and \( P_{Traffic}^{BVT} \) is the dynamic energy consumption related to traffic. The \( P_{Sub}^m \) in formula (8) is the energy consumption per unit sub-carrier transmission traffic when the modulation format is \( m \), the Sub\(^m\) is the number of bands requested by the traffic in \( M \) modulation format, and the \( G \) is the number of guard bands.

3) POWER CONSUMPTION MODEL OF BV-OXC

In SDM-EONs, a bandwidth variable optical cross connector is composed of spectrum selection switches to meet the need of core switching and fine granular bandwidth switching. In addition to the fixed energy consumption, the total energy consumption is also related to the degree of the node and the traffic types.

\[ P_{BVOXC}^i = Ni \times (P_{Fix}^{OXC} + P_{Traffic}^{OXC}) \]  \hspace{1cm} (9)

\[ P_{Traffic}^{OXC} = \sum_{j=1}^{C} \left( \left\lfloor \frac{FS_{j-Total}}{} \right\rfloor \times d_i \times 85 \right) \]  \hspace{1cm} (10)

Formula (9) is the energy consumption of cross-connector in node \( i \), and \( Ni \) is Boolean variable. When there is a traffic pass through the node, its value is 1, and the fixed power consumption is about 150W. Dynamic energy consumption is related to the node degree and request rate. \( FS_{j-Total} \) is the total bandwidth capacity of all the cores in the links which the traffic pass, \( C \) is the number of cores, and \( d_i \) is the degree of node \( i \).

4) POWER CONSUMPTION MODEL OF OPTICAL AMPLIFIER

In optical transmission networks, an optical amplifier (OA) is usually placed every 120KM to compensate for the loss of optical signals. Its energy consumption mainly depends on the transmission distance of traffic requests.

\[ P_{OA}^l = P_{Fix}^{OA} \times \left( \left\lfloor \frac{d_l}{120} \right\rfloor + 1 \right) \]  \hspace{1cm} (11)

The fixed energy consumption \( P_{Fix}^{OA} \) is 140 W and \( d_l \) is the path length.

5) TOTAL POWER CONSUMPTION

According to the analysis of the above four energy consumption models, the energy consumption model of transmitting a traffic \( r \) between source and destination nodes \( (s, d) \) is presented.

\[ P_r = P_{IP}^i + P_{IP}^d + P_{BVT}^i + P_{BVT}^d + \sum_{r \in V_r} P_{BVOXC}^i + \sum_{l \in L_r} P_{OA}^l \]  \hspace{1cm} (12)
III. PROPOSED FORMULATION AND ALGORITHM

In this section, we propose an overall framework of the main algorithm first. Then we introduce MCF priority grouping, spectrum partitioning strategy, candidate path sorting formula, energy efficiency grooming algorithm and crosstalk aware algorithm mentioned in the main algorithm.

Main Algorithm Energy Efficiency Grooming and Hybrid Crosstalk Solution (EEG-HCS)

**Input:**
1. The network topology $G(V, E)$, $V$ is a set of network nodes, $E$ is a set of fiber links.
2. Traffic $r_i(s, d, r)$, $s$ is the source node, $d$ is destination node, $r$ is the requested bandwidth;
3. ICXT threshold;

**Output:**
Resource allocation result;

Initialize the system and complete the **Crosstalk avoidance** strategy.

while a connection request $r_i(s, d, r)$ arrives do

Update network light path state $U_p$, Find $K$ shortest paths Path from source to destination (Invoke KSP-Algorithm)

Invoke **Candidate Path Sorting Formula**. Reordering candidate path based on path load, available resources and hops.

For (each candidate path $p$):

Find the optimal modulation format and calculate the number of FS required.

Invoke **Energy Efficiency Grooming Algorithm**.

If (Energy Efficiency Grooming Algorithm return **Success**) Resources allocated successfully, **Return**

Else (Create a new light path for the request)

For (All $c$ in $C$):

If (formula(15) result $\geq 0.8$) Invoke **ICXT-Aware Algorithm**.

If ($XT_{max} < XT_{threshold}$) New optical path is established.

Accept the request, **Return**

Else if (exist available FS resources) Accept the request under Crosstalk avoidance strategy, **Return**

End For

Block the request $r(s, d, r)$

A. CROSSTALK AVOIDANCE STRATEGY

According to [10], crosstalk can be avoided by adjusting the order and rules of core and FS allocation in the initial stage of network. Under light and medium loads, crosstalk can be avoided.

We proposed a MCF priority grouping and spectrum partitioning strategy. In this strategy, MCF is first grouped by core priority. Using vertex shading principle, adjacent cores are allocated to different groups to ensure that the cores in each group are not adjacent. As shown in Fig. 3, for 7-core and 19-core MCF, different colors represent different groups, numbers on the core represent the order in which they are selected. Taking 19-core fiber as an example, in order to avoid the influence of ICXT, when allocating core for requests, try to avoid sequentially assigning adjacent cores. The core number 1-7 in the figure is the first group of non-adjacent cores. No matter how they allocate the FS resources between groups, ICXT will not occur. Next, the remaining 12 cores are inevitably adjacent to the cores in other groups due to the physical structure of the fibers. In order to avoid the sequential assignment of adjacent cores, the second group is divided into 8-13 cores. Similarly, the third group and the fourth group are 14-16 and 17-19 cores, respectively.

A unified spectrum allocation scheme is adopted for the core in the same group. Because the core of the same group is not adjacent to each other, ICXT will not be generated in the same group. The spectrum partitions corresponding to each group are calculated by formula (13).

$$S_i = S_{i-1} + F \times \frac{G_{i-1}}{C}$$  \hspace{1cm} (13)

where $S_i$ is the initial frequency slot index of the cores corresponding to the $i$ th group, where $i \in (1, s)$, $s$ is the total number of groups, $S_0$ is initialized to 1. $F$ is the total number of frequency slots in a core, $C$ is the total number of cores in MCF, $G_i$ is the number of cores in group $i$, and $G_0$ is 0.

Taking 19-core optical fibers as an example. In Fig. 4, the colors in different spectral partitions correspond to the grouping colors in Fig. 3. The initial FS index values of groups in different colors are different, the arrow represents the FS allocation direction.

The above-mentioned core priority grouping and spectrum partition belong to crosstalk avoidance operation. This traffic-independent passive ICXT solution can effectively avoid crosstalk in medium and low traffic load. It only needs to prioritize and partition the MCF in the initialization stage, and the whole operation only needs to be executed once.
the candidate paths are arranged according to the results. The path set, which can reflect the current load of the network, and calculate the shortest paths and the number of available slots in the shortest path. The formula proposed in this paper not only considers the number of hops, but also use spectrum occupancy and remaining conditions, and link utilization rate as parameters for candidate path selection.

According to the path sorting formula below, the load of current candidate paths is calculated, and penalty coefficients are designed for the currently overloaded paths. Then the sorting formula is calculated according to the number of shortest paths and the number of available slots in the shortest path set, which can reflect the current load of the network, and the candidate paths are arranged according to the results.

For the traffic request \( r(s, d, r) \), candidate path sets are calculated by KSP algorithm. Based on the results of the KSP algorithm, we designed formula (14) to reorder the set of candidate paths, breaking the traditional concept of the “shortest path”, and further considered some important indicators such as remaining available FS resources, traffic load balance condition, and link utilization rate as parameters for candidate path selection.

In formula (14), the larger the calculation result is, the higher the probability that the path should be selected first. Formula (14) first use idle available spectrum blocks as the numerator. The more available idle spectrum resources, the greater the probability that the path can successfully serve the request. At the same time, the formula take the spectrum utilization rate of the candidate path as an important parameter and we also considered the constraint of spectrum continuity. Finally, the number of the shortest paths pass through each link is used to determine whether the path selection strategy will cause bottlenecks. By quantitatively calculating the influence of these parameters on the candidate path sorting results, we can find the most suitable candidate path in the context of current network resources.

To be more specific, \( W_{P_k} \) represents the sorting value of the candidate path \( k \) for request rate \( r \). \( f_s \) represents the number of frequency slots required in the current modulation format. \( N_{A_k} \) represent an idle spectrum block in the current path \( k \) that satisfies the \( f_s \) corresponding to the request \( r \). \( d_{i}^{num} \) denotes the number of shortest paths passing through link \( l \). \( N_{num} \) denotes the number of nodes in network topology. \( U_{P_k} \) denotes the spectral utilization of path \( k \), \( Hop_{P_k} \) denotes the hops of path \( k \).

Formula (15) and (16) are the calculation formulas of path utilization \( U_{P_k} \) and \( F \) represent the total number of cores and the number of FS in each core, respectively. When the spectral utilization of the calculated candidate path \( P_k \) exceeds 80%, the overall evaluation results are affected by multiplying a penalty coefficient \( \beta \) (greater than 1). When the utilization ratio exceeds 95%, it shows that the current path load is close to the limit, and the utilization ratio is set to infinite, that is, the path is not selected to avoid the whole path being paralyzed by full load.

\[
W_{P_k} = \frac{\sum_{A_i \in F.A_i \geq f_s} N_{A_i}}{\sum_{l \in P_k} (d_{i}^{num}/N_{num}) + U_{P_k} \times Hop_{P_k}}
\]  

(14)

\[
U_{P_k} = \begin{cases} 
\frac{\max \{U_{link[l,link_i \in P_k]\}, \quad \text{Max} \leq 0.8} 
\frac{\max \{U_{link[l,link_i \in P_k]\} \times \beta, \quad \text{Max} \in (0.8, 0.95)} 
\infty, \quad \text{Max} > 0.95
\end{cases}
\]  

(15)

\[
U_{link_i} = \frac{\sum_{c=1}^{F} f^c}{F \times C}
\]  

(16)

FIGURE 4. 19-MCF spectrum partition.

B. CANDIDATE PATH SORTING FORMULA

In the stage of resource allocation, the transmission path should be selected for the coming request. The traditional shortest path algorithm can only calculate the shortest hop or the shortest physical distance candidate path according to the source and destination nodes of the request.

For flexible dynamic traffic request, a routing algorithm that only considered the number of physical hops cannot reasonably select a suitable candidate path. The path sorting formula proposed in this paper not only considers the number of hops, but also use spectrum occupancy and remaining conditions, and link utilization rate as parameters for candidate path selection.

For the traffic request \( r(s, d, r) \), candidate path sets are calculated by KSP algorithm. Based on the results of the KSP algorithm, we designed formula (14) to reorder the set of candidate paths, breaking the traditional concept of the “shortest path”, and further considered some important indicators such as remaining available FS resources, traffic load balance situation and link utilization rate. For the \( k \)-th candidate path, the path sorting formula is as follows.

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W_{P_k} = \frac{\sum_{A_i \in F.A_i \geq f_s} N_{A_i}}{\sum_{l \in P_k} (d_{i}^{num}/N_{num}) + U_{P_k} \times Hop_{P_k}}
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\infty, \quad \text{Max} > 0.95
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(16)

FIGURE 5. Example of candidate path sorting.

In the stage of resource allocation, the transmission path should be selected for the coming request. The traditional shortest path algorithm can only calculate the shortest hop or the shortest physical distance candidate path according to the source and destination nodes of the request. The path set, which can reflect the current load of the network, and calculate the shortest paths and the number of available slots in the shortest path. The formula proposed in this paper not only considers the number of hops, but also use spectrum occupancy and remaining conditions, and link utilization rate as parameters for candidate path selection.

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\infty, \quad \text{Max} > 0.95
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\]  

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U_{link_i} = \frac{\sum_{c=1}^{F} f^c}{F \times C}
\]  

(16)

Fig. 5 shows an application example of the path evaluation formula. The network topology consists of 6 nodes and 9 links. The number (a, b) on the link indicates that the physical distance between nodes is a, and the number of shortest paths through the link is predicted to be b. Suppose there is a new request (1,6,2). After KSP algorithm, it is assumed that there are four candidate paths. The right side of the graph is the spectrum occupancy of the current candidate paths (assuming c is 1) and the path is sorted by formula (14) separately. We can see that the path with the
biggest sorting value is W1, because it has shortest physical path and the path FS resource is abundant. Although the number of hops in W4 is 4, the sorting value is higher than that of path 2 and path 3 of 3 hops because the parameter $d_{\text{min}}^k$ and the number of available free spectrum are considered in this sorting formula. Therefore, the final path sorting result is $[W1 > W4 > W3 > W2]$.

C. ENERGY EFFICIENCY GROOMING ALGORITHM

This algorithm is an important part of EEG-HCS. Based on candidate path sorting result, the energy consumption is taken as the first optimization objective. Through the energy efficiency grooming algorithm, the utilization of guard band is effectively reduced.

For request $r_i (s, d, r)$, find out whether there are optical path which have same source node and destination node with request $r_i$, and check whether there are available spectrum blocks that can grooming request $r_i$. The EEG-HCS first used a leftward grooming strategy and determined whether the ICXT-aware algorithm need to be invoked by judging the link FS utilization. When the link is under heavy load (the maximum value exceeds 0.8), ICXT is more serious. At this time, ICXT calculation and evaluation will be accurately performed for each request through the ICXT-aware algorithm. Otherwise direct grooming the request $r_i$ to the available free spectrum block. When the leftward grooming strategy does not meet the conditions, the rightward grooming strategy is executed. The algorithm will eventually return success or fail.

D. ICXT-AWARE ALGORITHM

In order to further reduce the impact of ICXT, this paper proposed an ICXT-aware algorithm. The ICXT of each FS is calculated in turn, and the XT impact of new request on assigned requests and the impact of assigned requests on new request are calculated respectively, and the maximum ICXT value is return to the main algorithm.

The Fig. 6 is an example of ICXT aware. For simplification purposes, a 7-core optical fiber is taken as an example. It is assumed that there are 12FS on each core. As shown in the figure, there are 3nodes and 2 links. When new request (a, b, 3) arrive, assuming that the request needs to be transported through a new optical path.

Firstly, core and spectrum are allocated according to core priority grouping and spectrum partition. As shown in the figure, core 1 and 2 do not have enough FS resources to satisfy continuity constraint, and core 3 is found according to core priority. The spectrum is allocated according to the result of spectrum partition, and the crosstalk aware algorithm is implemented. According to the algorithm, core 3 adjacent to core 4, 6 and 7, so the occupied FS blocks that overlap with the spectrum block $V_{B_i}$ will be found. As shown in the dotted frame.

The time complexity of the EEG-HCS in this paper is mainly composed of routing selection and spectrum core allocation. The time complexity of the routing phase is $O(K (|E|C |V| \log |V|))$. $E$ represents the set of physical links in the network topology, $V$ represents the set of physical nodes in the network topology, and $K$ is the number of candidate paths. The time complexity of the strategy proposed in the spectrum core allocation phase can be divided into two parts. At low and medium loads, i.e. when the value of...
Sub Algorithm ICXT-Aware

Input:
- Candidate path set \( P \), Selected Core \( C \) and FS blocks \( V_B \) based on MCF priority grouping and spectrum partitioning;
- Total network light path state \( U_p \);

Output:
- For each FS in \( V_B \)
  - For each adjacent core \( c \) in \( C \)
    - If FS in \( V_B \) overlaps with previously assigned transmission request;
      - Invoke formula (3) and (4) to calculate \( XT_{\text{New}} \)
        
        \[
        XT_{\text{Adjacent}}' = XT_{\text{New}} \\
        XT_{\text{Self}}' = XT_{\text{New}}
        \]
  
End if
End for

\[
XT_{\text{FS}} = \max\{XT_{\text{Adjacent}}, XT_{\text{Self}}\}
\]
End for

\[
XT_{\text{Max}} = \max\{XT_{\text{FS}}, FS \in V_B\}.
\]
Return \( XT_{\text{Max}} \)

![Figure 6](image.png)

**FIGURE 6.** Example of ICXT-aware.

formula (15) does not exceed 0.8, the ICXT-aware algorithm does not need to be used for spectrum core allocation, and the time complexity is \( O(K |E| |S| |C|) \). When the path is under high traffic load, the algorithm will invoke ICXT-Aware algorithm, and the time complexity is \( O(2^K |E| |S|^2 |C|) \).

IV. SIMULATION AND ANALYSIS

A. SIMULATION ENVIRONMENT ANALYSIS

In order to verify the performance of the proposed energy efficiency grooming and hybrid crosstalk solution algorithm (EEG-HCS), simulation is carried out under the NSFNET topology with 14 nodes and 21 links and USNET topology with 24 nodes and 43 links, respectively, shown in Fig. 7.

Two types of MCFs are considered in the simulation experiments, which are 7-core MCF and 19-core MCF (for ICXT improvement instances). Assume that each core has 360 FS, the FS granularity is 12.5GHz, the guard bandwidth between traffic is 1FS, and \( K \) is set to be 3 in the KSP algorithm.

Where the connection request generation rate follows a Poisson process with coefficient \( \lambda \). The holding time of each established connection takes values from a negative exponential distribution with coefficient \( \mu \). The traffic size is uniformly distributed between 50 Gbps, 100 Gbps, 200 Gbps, and 400 Gbps. The number of request is set to 100000. The penalty coefficient \( \beta \) in formula (15) is 1.5. The normalization formula of traffic load is as follows:

\[
\text{Traffic Load} = \frac{\lambda}{\mu \times F \times C}
\]

(17)

\( F \) is the number of frequency slots in one core, \( C \) is the number of cores in MCF.

ICXT calculation parameters and XT thresholds are shown in Table 2. In order to comparison, the ICXT calculation parameters in this simulation use fixed values.

Because the energy consumption and blocking rate will be considered simultaneously in this simulation, the classic ksp-ff resource allocation algorithm with SDM attribute is taken as the benchmark algorithm. In the simulation results, the benchmark algorithm is used as the maximum reference value for the total energy consumption under different traffic loads, and the \( XT_{\text{improve}} \) is also based on the benchmark algorithm. And other comparison algorithms are AoD-EERSA in [18] with fixed low energy consumption and advanced AoD structure. We also use ICXT-aware algorithm in [7] using core grouping to resolve ICXT.
B. TARGET MEASUREMENT FORMULA

In the second section of this paper, the energy consumption formula (12) for request \((s, d, r)\) is proposed. Because most of the current studies mainly focus on the optical layer. Moreover, the energy consumption of IP routers in the electrical layer mostly comes from the fixed energy consumption. In this paper we only considers the optical layer on the basis of formula (12), that is, the energy consumption of IP routers is not calculated when statistical energy consumption is used. Formula (12) is simplified as follows:

\[
P_r = P^s_{BVT} + P^d_{BVT} + \sum_{i \in V_r} P^i_{BVT-OXC} + \sum_{l \in L_r} P^l_{OA} \tag{18}
\]

Formula (18) is suitable for calculating the total energy consumption when a new optical path is built for request \(r\). \(V_r\) represent all BV-OXC that the request \(r\) passed. \(L_r\) represent all the links that request \(r\) passed. Based on the energy efficiency grooming algorithm proposed in section 3, a formula (19) is proposed to calculate the total energy consumption of grooming requests:

\[
P^G_r = P_r - 2 \times (P^{Fix}_{BVT} + G \times P^{m}_{Sub}) - \sum_{i \in V_r} [P^{Fix}_{OXC} + (G/\sum_{j=1}^{C} F_{S_j-Total} \times d_i \times 85)] \tag{19}
\]

Because of the energy efficiency grooming strategy, the newly arrived request can share some or all of the optical paths of the ongoing traffics, thus reducing the use of protection bandwidth. The inherent energy consumption is reduced by sharing BVT, OXC and other physical devices. To more specific, based on the energy consumption calculated by the formula 18, formula 19 first reduces the fixed energy consumption on the source and destination ports and the energy consumption required for guard bandwidth, and then reduces the fixed energy consumption of BV-OXC and the energy consumption required for switching the guard bandwidth.

Formula (20) is the total power consumption of the whole network, which is the first important optimization objective of this paper.

\[
P_{Total} = \sum_{r \in R} P_r + \sum_{r' \in R} P^G_{r'} \tag{20}
\]

We propose formula (21) to calculate the bandwidth blocking rate. It is also the second optimization goal in this paper. \(BT_{Block}\) is the bandwidth blocked by all traffics in the network, and \(BT_{Total}\) is the total bandwidth of all requested traffics in the network.

\[
BBP = \frac{BT_{Block}}{BT_{Total}} \tag{21}
\]

At the same time, in order to reflect the improvement of the proposed algorithm on ICXT, a crosstalk improvement
formula is proposed.

\[ \text{\( XT_{\text{improve}} = \frac{|BT_{\psi}^{\text{XT}} - BT_{KSP-FF}^{\text{XT}}|}{BT_{KSP-FF}^{\text{XT}}} \)} \tag{22} \]

Equation (22) compares with the benchmark algorithm KSP-FF to calculate the difference between blocking bandwidth caused by ICXT in Comparison algorithm \( \psi \) and in KSP-FF. \( \psi \) in formula (22) represent the algorithm to be compared with the benchmark algorithm. The difference is divided by the blocking bandwidth in KSP-FF, and the improvement of algorithm \( \psi \) in ICXT is obtained.

C. SIMULATION RESULTS

Fig. 8 simulates the total power consumption of the algorithm and the comparison algorithms mentioned above under two kinds of network topologies. The power calculation method is given by the formula (20). Figure (a) is NSFNET and figure (b) is USNET. Because USNET has a larger network topology, more nodes and links, the total power consumption is larger than that of NSFNET. With the increase of network load, the overall power consumption shows a rising trend except AoD-EERSA. The benchmark KSP-FF has the highest power consumption and the rising trend is obvious, while the ICXT-Aware algorithm which focuses on ICXT avoidance is similar to the benchmark algorithm in power consumption. Neither of them has done the corresponding power optimization for SDM-EONs.

The comparison algorithm AoD-EERSA has the lowest overall power consumption due to the adoption of the on-demand node structure and sacrificing flexibility in exchange for energy efficiency. The total power consumption of AoD-EERSA remains essentially the same regardless of the traffic load. The algorithm proposed in this paper uses energy efficiency grooming, at low traffic load, the total power consumption is lower than AoD-EERSA. As the traffic load increases, the total power consumption of the algorithm increased slowly. Compared with the benchmark algorithm, the energy saving effect is obvious, and the total energy consumption is not increased much compared to AoD-EERSA. Although the performance of our proposed algorithm is only close to that of AoD-EERSA in energy saving. That’s because the comparison algorithm replaced part of SSSs with passive devices that affect the flexibility of nodes and reduced energy consumption by reducing throughput and blocking performance. And the ICXT problem is not considered in AoD-EERSA. This paper considers ICXT and guarantees the performance of bandwidth blocking rate, while reducing the total power consumption of the system as much as possible. So the comprehensive performance of our algorithm is better.

Fig. 9 shows the performance of bandwidth blocking probability under two network topologies. By comparing figure (a) and (b), we can find that the blocking probability of the USNET is lower than that of NSFNET because USNET have a greater number of nodes and links, so the average degree of nodes is larger. With the increase of traffics, the bandwidth blocking probability increases obviously. Taking Figure (a) as an example, the benchmark algorithm KSP-FF has the highest bandwidth blocking rate, while the energy efficiency comparison algorithm AoD-EERSA is only slightly better than the KSP-FF algorithm in terms of blocking probability performance due to its focus on high energy efficiency. The comparison algorithm ICXT-Aware divides the non-adjacent cores into one group and reduces the influence of ICXT by crosstalk avoidance. Its blocking performance is better than that of benchmark algorithm and AoD-EERSA, but its shortcomings are also obvious. Because of the passive crosstalk avoidance, the performance of the algorithm will deteriorate as the traffic load becomes larger. The proposed algorithm performs well in blocking probability performance, and its bandwidth blocking probability is significantly lower than other comparison algorithms under the same traffic load. Because the proposed algorithm not only considers energy efficiency and prioritizes the use of traffic grooming, it also takes the impact of ICXT as an important metric. In the new optical path sub-algorithm, the joint
ICXT solution is adopted, not only adopt the passive crosstalk avoidance method, but also the active crosstalk aware algorithm is designed to further improve the bandwidth blocking probability performance.

Fig. 10 shows the ICXT improvement effect of the 7-cores and 19-cores MCF in the USNET for different algorithms compared to the benchmark KSP-FF, calculated by equation (22). Since the formula is based on the KSP-FF algorithm, when the traffic load is low, the resources in the MCF are abundant, and there is no shortage of resources. Therefore, when the initial load is 0.1, the proposed algorithm and the ICXT-Aware algorithm are only about 20% higher than the benchmark. With the growth of traffic, the ICXT problem will become increasingly serious and the gap between the benchmark algorithms will become more and more obvious. Compared with the passive crosstalk avoidance scheme adopted by the comparison algorithm ICXT-Aware, the performance is basically the same as the proposed algorithm at medium and low load, but after the higher load (load is greater than 0.6), its advantage is reduced significantly. Because the passive crosstalk avoidance scheme can only group the cores and the frequency slots in the initial stage of the network. When the traffic load is large, all the non-crosstalk groups are fully loaded, and the performance of the algorithm will be severely limited. The comparison algorithm AoD-EERSA does not consider the ICXT problem. Compared with the benchmark algorithm KSP+FF, its performance advantage only comes from the routing performance of its AoD node structure. The proposed algorithm in this paper is more effective in 19-core fiber, and its highest ICXT improvement rate is close to 1.5.

V. CONCLUSION

Aiming at energy consumption and inter-core crosstalk in SDM-EONs, a resource allocation algorithm based on energy efficiency grooming and hybrid crosstalk solution (EEG-HCS) is proposed. Firstly, a candidate path sorting formula is designed to comprehensively sort candidate path sets. Then, according to the candidate path set, the algorithm judges whether it is suitable to implement the energy efficiency grooming algorithm. By grooming the traffic, the algorithm reduces the inherent energy consumption of the devices and the energy consumption of transmit guard bandwidth, and judge the ICXT through the crosstalk aware algorithm. If the business is not suitable for grooming, a new optical path will be built for it. Combined with passive crosstalk avoidance strategy and dynamic crosstalk sensing algorithm, the impact of ICXT is reduced as much as possible. The simulation results show that the algorithm achieves remarkable results in energy efficiency and crosstalk solution, reduced network energy consumption as much as possible while guarantee low bandwidth blocking probability.

For future work, we can further study the energy consumption problem in SDM-EONs, especially to reduce energy consumption dynamically. At the same time, for crosstalk problem, inter-mode crosstalk and other non-linear signal impairment can be further considered.

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