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Anycast Transmission in Routing Modulation Level Spectrum Assignment (RMLSA) Problem on Space Division Multiplexing (SDM) Elastic Optical Networks (EON)

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Abstract

With the rise of cloud computing in recent years, a large number of streaming media has yielded an exponential growth in network traffic. With the now present 5G and future 6G, the development of the Internet of Things (IoT), social networks, video on demand, and mobile multimedia platforms, the backbone network is bound to bear more traffic. The transmission capacity of Single Core Fiber (SCFs) may be limited in the future and Spatial Division Multiplexing (SDM) leveraging multi-core fibers promises to be one of the solutions for the future. Currently, Elastic optical networks (EONs) with multi-core fibers (MCFs) are a kind of SDM-enabled EONs (SDM-EON) used to enhance the capacity of transmission. The resource assignment in MCFs, however, will be subject to Inter-Core Crosstalk (IC-XT), hence, reducing the effectiveness of transmission. This research highlights the routing, modulation level, and spectrum assignment (RMLSA) problems with anycast traffic mode in SDM-EON. A multipath routing scheme is used to reduce the blocking rate of anycast traffic in SDM-EON with the limit of inter-core crosstalk. Hence, an integer linear programming (ILP) problem is formulated and a heuristic algorithm is proposed. Two core-assignment strategies: First-Fit (FF) and Random-Fit (RF) are used and their performance is evaluated through simulations. The simulation results show that the multipath routing method is better than the single-path routing method in terms of blocking ratio and spectrum utilization ratio. Moreover, the FF is better than the RF in low traffic load in terms of blocking ratio (BR), and the opposite in high traffic load. The FF is better than the RF in terms of a spectrum utilization ratio. In an anycast protection problem, the proposed algorithm has a lower BR than previous works.

Keywords

Anycast, Crosstalk, Elastic Optical Networks, Multi-Core Fibers, Routing Modulation Level and Spectrum Assignment, Space Division Multiplexing

1. Introduction

With the rise of cloud computing in recent years, a large number of streaming media has yielded an exponential growth in network traffic. With the future 5G/6G and the development of the Internet of Things (IoT), social networks, video on demand and mobile multimedia platforms the backbone network is bound to bear more traffic. At present, because of its high transmission rate and low energy consumption, optical fiber has replaced the coaxial cable and has become the best choice for backbone networks.

Traditional optical fiber network technology is based on Wave Division Multiplexing (WDM) technology and the used bandwidth is a fixed 50 GHz. The effective assignment of spectrum resources is limited as transmission requires a high-bandwidth rate [1]. In recent years, Elastic optical networks (EONs), because of their finer bandwidth 12.5 GHz (or 6.25 GHz), can provide a flexible assignment of spectrum resources in Space Division Multiplexing (SDM).

1.1. Elastic Optical Network

EONs are based on Optical Orthogonal Frequency Division (O-OFDM) Technology [1] [2] and the bandwidth can be adjusted flexibly according to demand [3]. Figure 1 is the architecture of EON, which is composed of Bandwidth-Variable Transponders (BVTs) and Bandwidth-Variable Wavelength Cross-Connects (BV-WXC) [2]. BVTs can adjust the corresponding bandwidth according to requirements [3]; BV-WXC is used as a switch to establish a node-to-node network to transmit the optical signal of BVT [3].

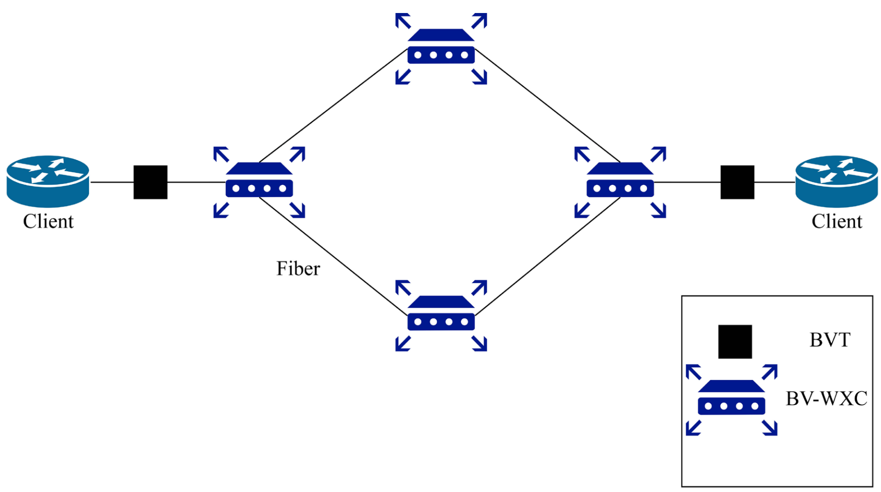


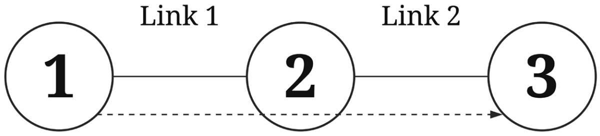
Figure 1. EON Network architecture.

1.2. Routing and Spectrum Assignment Configuration

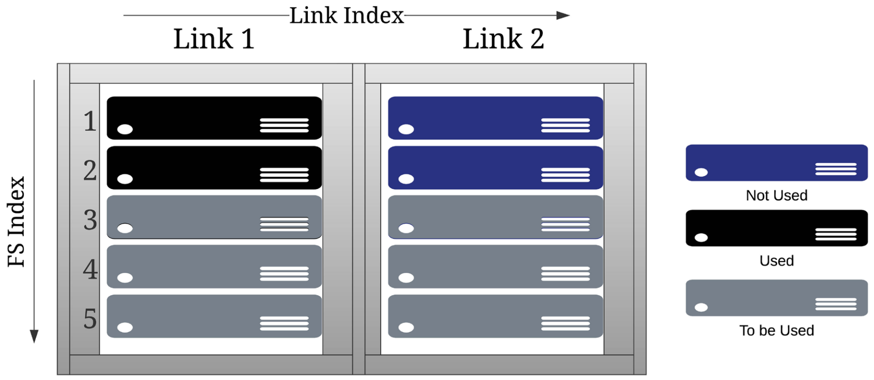
A traditional WDM network uses Routing and Wavelength Assignment (RWA). In EONs, the spectrum of EONs is divided into finer frequency slots (FSs) and the number of frequency slots required for the path configuration is appropriately selected according to the needs. Thus, this is also the case in Routing and Spectrum Assignment (RSA) [1] on EONs. Note that RSA must observe spectral continuity and must be adjacent to the spectrum [1] [2]. **Figure 2(a)** is a network topology (3 nodes and 2 links). If a single demand is sent from node 1 to node 3, the number of frequency slots required is 3. In **Figure 2(b)**, the vertical axis is the index value of the frequency slot, the horizontal axis is the index value of the link. The frequency slot is marked white as not used, marked with black as used, and marked Gray as intended for use. In Link 1, the available continuous frequency slot index values are 3 to 5; in Link 2, if the continuous frequency slots are allocated to positions 1 to 3, they cannot be successfully established because it does not meet the adjacency restriction. To comply with the limitation of adjacency, it should be placed in the range of frequency slots 3 to 5 before routing can be carried out, so this requirement can be established successfully.

1.3. Routing Modulation Level and Spectrum Assignment Configuration

With BVT, different modulation formats can be used for different needs according to the required transmission distance, and the modulation can be changed. The modulation level is added to RSA and the original RSA problem becomes the RMLSA problem [1] [2]. When needed, after the desired path is



(a)



(b)

Figure 2. (a) Example of flexible optical network RSA configuration. (b) RSA configuration problem.

determined, and before determining the number of spectrum slot configuration requirements, select the appropriate modulation mode. The higher the modulation level, the higher the number of bits that a frequency slot can transmit; the higher the number of frequency slots that are required to be configured, and the shorter the maximum transmission distance. RMLSA issues must also comply with the spectrum constraints on continuity and proximity [1] [2]. Choosing the appropriate modulation format according to the distance of the path is important, the higher the modulation and shorter the distance; the lesser the spectrum slots used. An illustration can be seen in **Table 1** in the problem definition section.

Table 1 introduces the limitation of the modulation level of the transmission distance [4], which is the distance required to establish the connection, the corresponding modulation mode, and the number of spectrum slots.

1.4. Anycast

With the rise of cloud computing in recent years, a large number of streaming media has yielded an exponential growth in network traffic and many data centers (DCs) is established. The synchronization and exchange of data between data centers require anycast. Therefore, the demand for anycast transmission is also increasing compared to multicast and broadcast. Anycast routing method is characterized by a single source node to multiple target nodes and only one connection between any target node can be established (**Figure 3**). This requirement requires different performances according to different strategies.

1.5. Space Division Multiplex Network (SDM)

Due to the limitation of the transmission capacity of Single Core Fiber (SCF), SDM technology has been developed to overcome the limitations. At present, most SDMs make use of MCFs to increase transmission capacity. Therefore, SDM is been regarded as an important transmission technology in the future Technology [5]. However, in (MCFs), the most critical factor is the influence of Inter-Core Crosstalk (IC-XT). Signal transmission between adjacent cores may occur and cause IC-XT effects [6]. In the red box in **Figure 4**, adjacent cores use λ1 for transmission, which will have the effect of crosstalk between cores; in the green box, λ2 across cores is used for transmission, so there will be no crosstalk between cores. Therefore, in an SDM network, Routing, Core, and Spectrum Assignment (RCSA) issues should not only follow continuity in addition to the limitations of proximity but also avoid the effects of crosstalk between cores.

1.6. Multipath Methods

Single path configuration is limited by bandwidth, and it is difficult to configure some larger bandwidth requirements, which eventually leads to congestions and an increase in the blocking rate. Therefore, with O-OFDM [7] flexibility characteristics, network nodes can easily adjust the demand into multiple paths, using the multipath method [8], making full use of spectrum resources and also effective configuration.

Table 1. Modulation level formula [4].

Demand Modulation Format	Number of required spectrum slots					Transmission Distance (km)
	10 Gbps	40 Gbps	100 Gbps	400 Gpbs	1000 Gpbs	
BPSK	2	5	9	33	81	4000
QPSK	2	3	5	17	41	2000
8-QAM	2	3	4	12	28	1000
16-QAM	2	2	3	9	21	500
32-QAM	2	2	3	8	17	250
64-QAM	2	2	3	7	15	125

Modulation format: BPSK (binary phase-shift keying), QPSK (quadrature phase-shift keying), QAM (Quadrature amplitude modulation).

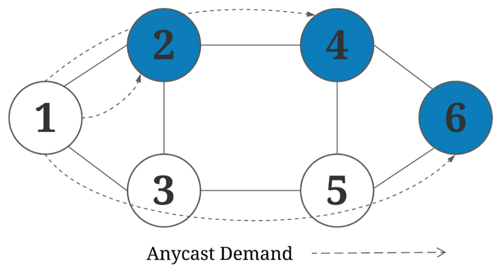


Figure 3. Example of an anycast transmission.

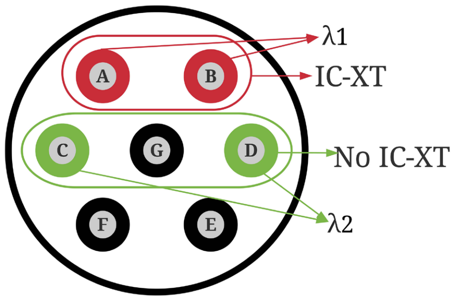


Figure 4. MCFs middle IC-XT.

Suppose there is a requirement in four-node network topology, the starting node is A, the destination node is D, and the required bandwidth is 4 frequency slots. Assuming from the network diagram shown in Figure 5, the numbers in the parentheses on the link represent the number of frequency slots that are still configurable, and the number outside the parentheses represents the number of frequency slots configured by the path. Figure 5(a) uses a Single path configuration, but because the long-dashed line (A-B-D) and short dashed line (A-C-D) of the path cannot meet the required bandwidth, the path cannot be configured and the transmission demand is blocked. Figure 5(b) uses a multi-path configuration, the path with dashed-dotted lines P1 (A-B-D) and P2 (A-C-D) are each configured with two frequency slots. The total bandwidth of the two frequency slots meets the required bandwidth, so it can be successfully configured.

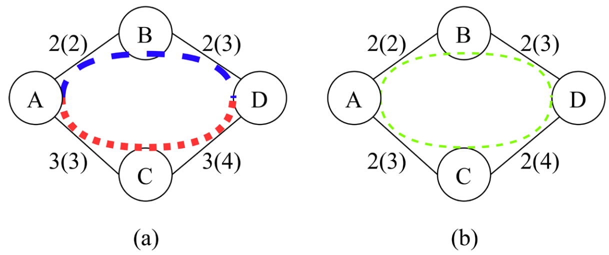


Figure 5. (a) Single-path configuration (b) multi-path configuration.

In the subsequent sections, the second section discusses and analyzes related documents; the third section describes the mathematical symbols, calculation formulas, and evaluation formulas of the research problem; the fourth section details the methodology used in the anycast demand transmission problems and candidate core selection strategies; fifth section presents the simulation results, further discussion, and analysis; the sixth section presents the conclusion of the thesis.

2. Literature Review

This section describes the keywords and discusses the literature related to the research question.

2.1. Elastic Optical Network

The traditional demultiplexing network divides the spectrum into 50 GHz spectrum segments, no matter how small the demand is, it is required to occupy a spectrum segment. Hence, the spectrum resources cannot be used efficiently [1]. For flexible optical networks, O-OFDM technology can be used in dividing the frequency spectrum finely, cutting the frequency spectrum into 6.25 GHz, 12.5 GHz, 25 GHz, or 37.5 GHz. It can also be equipped with an appropriate spectrum slot for smaller needs [3]. In turn, the usage of spectrum resources is improved.

2.2. Routing Modulation Level Spectrum Assignment Configuration Problem

In the flexible optical network, the RSA problem has become an RMLSA problem after adding the use of different modulation formats to the question. The RMLSA problem will select a suitable modulation format according to different paths and distances, then allocate the spectrum more efficiently. Literature [2], proposes the RMLSA algorithm to maximize the use of the best modulation format (MBM) in the flexible optical network. The RMLSA Algorithm of the best modulation format (MBM) can consolidate traffic and optical signals (traffic grooming, optical grooming) and adjust the modulation format. The experimental results show that MBM Algorithm and k shortest path are compared with ten different algorithms and the MBM bandwidth blocking ratio is relatively low.

Literature [9] proposed two RMLSA algorithms that use modulation level conversion (MLC), namely path modulation level conversion (Path-MLC) algorithm, and link modulation level conversion (link-MLC) algorithm. The experimental results show that when the MLC threshold is not limited, Link-MLC has a lower blocking rate and common spectrum utilization rate; when the MLC threshold value is lower, there will be a higher blocking rate and fewer spectrum resources will be occupied. In addition, the Path-MLC method saves resources compared to Link-MLC.

2.3. Anycast

With the rise of cloud computing in recent years, a large number of streaming media has yielded an exponential growth in network traffic and data centers (DC). Many DC has been established, and data synchronization and exchange between data centers need to be performed by anycast. Therefore, the demand for anycast transmission is becoming more and more important. In literature [10], the situation of anycast demand and unicast demand in the flexible optical network is studied.

Then in literature [11], a multi-path protection algorithm was further proposed. While using multi-path transmission, if one of the paths fails, the protection ratio set by the other paths can still be used to ensure the information transmitted by the original failed path can be transmitted from other paths

2.4. Space Division Multiplex Network

Due to the rise of webcasting and audiovisual streaming-related applications in recent years, Internet traffic has grown rapidly. The transmission capacity of single-core optical fibers may not be able to cope with the huge amounts of traffic. Space Division Multiplexing (SDM) technology currently includes single-mode fiber bundles, multi-core fibers (MCFs), few-mode multi-core fibers (FM-MCFs), and photonic crystal fibers (photonic bandgap fibers) [12] and is considered one of the solutions.

Most of the current research use MCFs to implement SDM Networks, but inter-crosstalk (IC-XT) has a great impact on the transmission of MCFs. in the literature [13], three methods to deal with IC-XT are proposed.

- XT-avoid: Try to avoid using spectrum slots with the same serial number between adjacent cores in an optical fiber link, and at the same time allocate FS and cores to different transmission requests.
- XT-WC: Taking into account the crosstalk between cores, make the maximum limit configuration.
- XT-aware: Accurate calculation of crosstalk between cores on the same frequency slot on the same link in adjacent cores

In literature [14], the RSA algorithm for anycast demand in the SDM flexible optical network was proposed. This algorithm will be used to compare with the algorithm proposed in this paper.

Routing Core Spectrum Assignment Configuration

In literature [6], a method of predefining the priority of core selection is proposed, which sorts the cores while avoiding the occurrence of crosstalk between cores in MCFs. However, if the method is applied to multi-core fibers with seven cores, the result is an out-of-the-core sequence of 1 – 3 – 5 – 4 – 6 – 2 – 7. The assigned priority core selection strategy proposed in this paper will also use this order to achieve the purpose of reducing crosstalk between cores.

Literature [15] uses the Connected Component Labelling (CCL) algorithm in the field of image processing to solve the Routing, Core, and Spectrum Assignment (RCSA) problem. The CCL algorithm is characterized by lower time complexity, and it can have a good effect when compared with a smaller topology or lower network traffic.

In [16], the RCSA algorithm crosstalk-aware in MCFs is proposed, which are First-Fit (FF) Crosstalk-Aware Routing, Core, and Spectrum Assignment (FF-CA-RCSA) and Random-Fit (RF) Crosstalk-Aware Routing, Core, and Spectrum Assignment (RF-CA-RCSA). The simulation results confirm that FF-CA-RCSA is better in terms of blocking rate and spectrum utilization.

Literature [17], Use Auxiliary Graph (AG) for traffic grooming and proposes the RCSA algorithm, and proposes five strategies Maximal Electrical Grooming (MEG), Maximal Optical Grooming (MOG), Maximal Space Grooming (MSG), Minimize Virtual Hops (MVH), and Minimize Physical Hops (MPH). The simulation results show that MPH has the lowest blocking rate, MEG saves the most use of transponders, and MSG uses the fewest cores for demand.

2.5. Routing Modulation Level Core Spectrum Assignment

Literature [18], proposed the Distance Adaptive Routing, Core and Spectrum Assignment (DA-RCSA). The algorithm selects the appropriate modulation level according to the path distance and then selects the core for spectrum slot configuration. The simulation results confirmed that because DA-RCSA uses different modulation formats, compared with the First-Fit Routing Core and Spectrum Assignment (FF-RCSA) algorithm with only a single modulation Format, the blocking rate is lower and the frequency spectrum usage rate is higher.

Literature [19], designed the optical transmission network of MCFs, trying to calculate the worst transmission distance of the optical signal under different modulation formats, and according to the Routing, Modulation format, Core, and Spectrum Assignment (RMCSA) problem design Integer Linear Programming (ILP) model and Simulated Annealing (SA) heuristic algorithm. The experimental results show that the effect of crosstalk between cores of the long-distance continental backbone network is more obvious, the maximum number of cores should be reduced to 12. This enables the performance of multi-core fiber to be utilized effectively.

Literature [20], in response to the problem of spectrum fragmentation due to different sizes on flexible optical networks, the paper proposes a crosstalk-aware Multi-Core Virtual Concatenation (MCVC) method to avoid fragmentation. Experimental results confirmed that in terms of blocking rate or spectrum utilization, MCVC Performance is better than Single-Core Virtual Concatenation (SCVC).

2.6. Multipath

Literature [8], considering the problem of multi-path transmission on the flexible optical network, and Hybrid Single/Multi-path Routing-Online Path Computation, (HSMR-OPC) core virtual concatenation (SCVC) algorithm is proposed. Algorithm and experimental results show that the multi-path method can reduce the blocking rate.

Literature [21] proposed the use of survivable multipath provisioning with content connectivity (MPC) RMLSA algorithm that adds content connectivity to the requirements. Note that, content links make the request more important and weighted, which can reduce the blocking rate. Compared with traditional protection methods, the results show that MPC has better performance.

3. Problem Definition

This section defines and describes the research symbols and problem.

3.1. Equation Definition

Mathematical models were used to propose an algorithm for this problem. The following is the symbol definition and description:

- $G(V,E,D)$: Denotes an EON network topology graph (G), where, (V) represents the Node set, (E) the link set, and link length function (D).
- $R_{anycast}$: A set of anycast requirements, where $r_i(s_i,d_i,b_i)$ represents anycast demand, which is composed of the start node ($s_i \in V$), the destination node ($d_i \in V$), and the bandwidth required (b_i). d_i consists of $\{d_{i1},d_{i2},\cdots,d_{ia}\}$, where a represents the number of anycast destination nodes.
- C: The set of candidate cores.
- FS: Frequency Slots.
- $XT_{Threshold}$: The threshold of crosstalk between cores.
- $$p_{s_i,d_i}^{(anycast)} = \left\{ p_{s_i,d_{i1}}^{(1)}, p_{s_i,d_i}^{(2)}, \cdots, p_{s_i,d_i}^{(k)}, p_{s_i,d_i}^{(1)}, p_{s_i,d_i}^{(2)}, \cdots, p_{s_i,d_i}^{(k)}, \cdots, p_{s_i,d_i}^{(1)}, p_{s_i,d_i}^{(2)}, \cdots, p_{s_i,d_{ia}}^{(k)}, s_i \neq d_{ia} \right\}$$: Anycast candidate path set ($p_{s_i,d_i}^{(1)}$), among them ($p_{s_i,d_i}^{(1)}$) It represents the jth candidate path from the starting node (s_i) to the destination node (d_{ia}) ($z = 1,2,\cdots,a$).
- m = {BPSK, QPSK, 8QAM, 16QAM, 32QAM, 64QAM}: A set of modulation modes, where m represents the modulation level of different modulation modes, corresponding to the modulation mode in set m {1, 2, 3, 4, 5, 6}.
- X: The number of multi-path branches upper limit, used to compare the performance of the algorithm in different X.

3.2. Modulation Level Equation

From the modulation mode generated {BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, the capacity of a spectrum slot corresponds to {12.5, 25, 37.5, 50, 62.5, 75} Gbps generated according to Equation (1). FS is the number of spectrum slots, BW_{sd} is the bandwidth required from the source node s to the destination node d, C_f is the basic modulation level corresponding to the bandwidth, m is the modulation level, and GB sets a spectrum slot for the protection bandwidth.

$$FS = \left(\frac{BW_{sd}}{C_f \times m}\right) + GB. \tag{1}$$

3.3. Crosstalk Calculation Equation and Threshold

This section introduces the threshold value [22] and equation [24] for calculating crosstalk between cores. In Equation (2), h represents the average crosstalk per unit length, κ is the coupling coefficient, R is the bending radius, β is the propagation constant, Λ is the distance between cores. XT in Equation (2) represents the average XT, n Is the number of adjacent cores and L is the length of the fiber.

$$h = \frac{2 \cdot k^2 \cdot R}{\beta \cdot \Lambda} \tag{2}$$

$$XT = \frac{n - n \cdot \exp[-)n+1) \cdot 2 \cdot h \cdot L}{1 + n \cdot \exp[-)n+1) \cdot 2 \cdot h \cdot L} \tag{3}$$

The threshold value is set to −30 dB. When the crosstalk value is higher than −30 dB, the transmission is easier to block. Therefore, many studies set the threshold value roughly at −30 dB.

3.4. Evaluation Equation

The following two evaluation equations are used to determine the effectiveness of the algorithm:

1) Blocking Rate (*BR*):

Represents the ratio of the total number of unsuccessfully established requirements to the total number of requirements rate.

$$XT = \frac{\text{total number of blocked requests}}{\text{total number of requirements}}$$

2) Spectrum Utilization Rate (*SUR*):

Represents the ratio of the total number of used frequency slots occupied by the demand to the ratio of the total number of frequency slots.

$$SUR = \frac{\text{total number of used frequency slots}}{\text{total number of frequency slots}}$$

4. Heuristic Algorithm

In this chapter, the problem of anycast demand transmission is explained, and the proposed RMLSA-M algorithm method is explained in section 4.1; section 4.2 is the flow chart of the single path of the RMLSA-M algorithm; section 4.3 is the RMLSA-M flow chart of the multi-path part of the algorithm; Section 4.4 describes the candidate core selection strategy for the research problem; Section 4.5 uses the RMLSA-M algorithm in a unicast example; Section 4.6 describes the process of using the RMLSA-M algorithm in an anycast example.

4.1. RMLSA-M Algorithm

This research proposes the need for anycast transmission in routing modulation level, spectrum assignment with multipath (RMLSA-M) problem on SDM-EON's MCFs, with a proposed RMLSA-M algorithm to simulate and get results. If the multipath stage is not included, then for Routing, Modulation Level, Spectrum Assignment with Single Path (RMLSA) only, is used to compare with the Routing, Modulation Level, Spectrum Assignment with Multi-path (RMLSA-M) algorithm.

Algorithm: Routing Modulation Level Spectrum Assignment - Multipath

Input: Network topology $G(V,E,D)$, demand set $r_i(s_i,d_i,b_i)$ in $R_{anycast.}$

Output: demand set $r_i(s_i,d_i,b_i)$ in $R_{anycast}$ established.

for each demand
Construct and compute the KSP algorithm
Sort path in ascending order of *j*
For the single path: select required parameters in descending order and calculate the required FS
If the spectrum space can be configured
    Configure the selected path combination, modulation mode *FS*, and core
else
    if the core limit is not exceeded
        Change to the next core and compute the single path
    else
            Confirm that the upper limit of the path is not exceeded
        If the upper limit of the path is not exceeded
            Change to the next core and compute the single path
        else
            end for
For the Multipath: *select the required parameters in descending order*, *calculate the required FS*
If the spectrum space can be configured according to the core selection strategy
    Configure the selected path combination, modulation mode *FS*, and core
else
    If the core limit is not exceeded
        Change to the next core and compute the single path
    else
            Confirm that the upper limit of the path is not exceeded
        If the upper limit of the path is not exceeded
            Change to the next core and compute the single path
        else
end for

4.2. Algorithm: RMLSA-M

Input: network topology $G(V,E,D)$, Number of anycast destination nodes *a*, anycast demand set $R_{anycast}$, core set *C*, crosstalk upper limit $XT_{Threshold}$, multipath upper limit *X*.

Step 1: Set the core selection strategy.

Step 2: The demand set $r_i(s_i,d_i,b_i)$ in $R_{anycast}$ are sorted in descending order of bandwidth demand.

Step 3: Use the *k*-shortest path algorithm [23] to generate the path and set $p_{s_i,d_i}^{(anycast)}$ for each demand. (Initial $p_{s_i,d_i}^{(anycast)}=\varnothing$), the first path generated to the destination node d_1 is $p_{s_i,d_{i1}}^{(1)}$, to the *k*th path $p_{s_i,d_{i1}}^{(k)}$, and then the corresponding nodes d_a produce *k* paths,

$$p_{s_i,d_i}^{(anycast)}=\left\{p_{s_i,d_{i1}}^{(1)},p_{s_i,d_i}^{(2)},\cdots,p_{s_i,d_i}^{(k)},p_{s_i,d_i}^{(1)},p_{s_i,d_i}^{(2)},\cdots,p_{s_i,d_i}^{(k)},\cdots,\right.$$
$$\left.p_{s_i,d_i}^{(1)},p_{s_i,d_i}^{(2)},\cdots,p_{s_i,d_{ia}}^{(k)},s_i\neq d_{ia}\right\}$$

Step 4: Select the shortest path $p_{s_i,d_{ia}}^{(j)}$ from the set $p_{s_i,d_i}^{(anycast)}$ (the set $p_{s_i,d_i}^{(anycast)}$ is sorted in ascending order (from short to long), $j = 1, 2, \ldots, 3k$.

Step 5: For Single path: First, select the shortest path $p_{s_i,d_{ia}}^{(j)}$, determine the distance, and start selecting the modulation level *m*, arranging *m* in descending order (from highest to lowest S_i, d_{ia}), calculate the required *FS*, confirm whether the spectrum space can be configured, and then configure according to the core selection.

Step 5.1: If yes, then confirm if the *XT* generated with the configured path will not exceed the upper limit.

1) If yes, go to step 7.

2) If not, go to step 5.2.

Step 5.2: If not, confirm if the core limit is not exceeded.

1) If yes, change to the next core according to the core selection strategy and repeat step 5.

2) If not, confirm that the upper limit of the path is not exceeded.

a) If yes, change to the next path and repeat step 5.

b) If not, end the loop of single-path configuration and go to step 6.

Step 6: For Multipath: Sort $p_{s_i,d_i}^{(anycast)}$, first, select the shortest path $p_{s_i,d_{ia}}^{(j)}$, determine the distance, and start selecting the key. Change the modulation mode *m*, arranged in descending order (from highest to lowest), calculate the required *FS*, and confirm if the spectrum space can be configured according to the core selection strategy, also confirm if the core can be configured.

Step 6.1: If yes, then confirm if the *XT* generated with the configured path will not exceed the upper limit.

1) If yes, determine the path, core, and modulation mode, then calculate how much *FS* is needed.

a) If *FS* is still required to be 0, go to step 7.

b) If *FS* is still not 0, confirm if it does not exceed the multipath upper limit *X*.

i) If yes, confirm if the upper limit of the path has been exceeded.

If yes, add a path $p_{s_i,d_{ia}}^{(j+1)}$ and repeat step 6.

If not, the demand will be marked as blocked

ii) If not, the demand will be marked as blocked.

2) If not, confirm if the core limit is not exceeded.

a) If yes, change to the next core according to the core selection strategy and repeat step 6.

b) If not, confirm if the upper limit of the path is not exceeded.

i) If yes, change the first path to $p_{s_i,d_{ia}}^{(j+1)}$, and repeat step 6.

ii) If not, mark the demand as blocked.

Step 6.2: If not, confirm if the core limit is not exceeded.

1) If yes, change to the next core according to the core selection strategy and repeat step 6.

2) If not, confirm if the upper limit of the path is not exceeded.

a) If yes, change the first path to $p_{s_i,d_{ia}}^{(j+1)}$, and repeat step 6.

b) If not, mark the demand as blocked.

Step 7: Finally, configure the selected path combination, modulation mode *FS*, and core for r_i, and change to the next r_i.

4.3. Single Path Flow Chat

The flow chart of Single-path transmission is shown in **Figure 6**;

4.4. Multipath Flow Chat

The flow chart of multi-path transmission is shown in **Figure 7**;

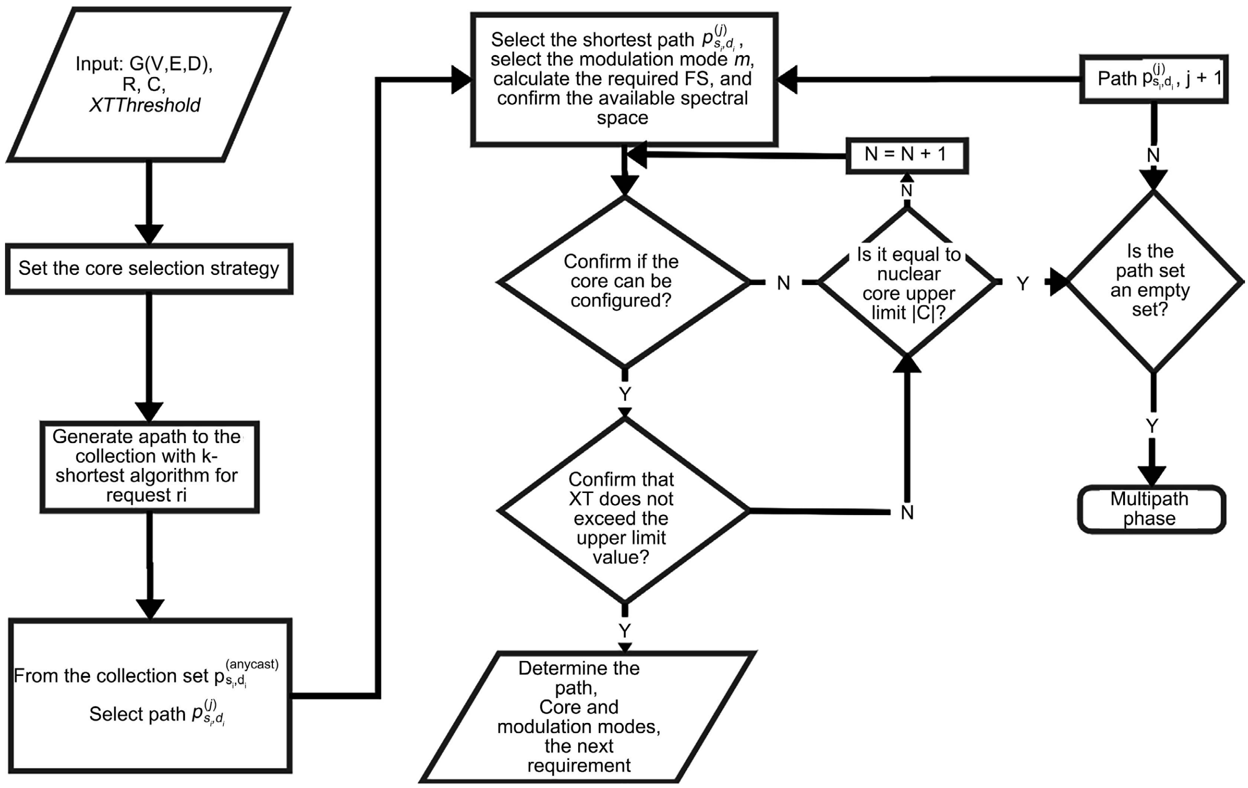


Figure 6. Single-path Flow chart.

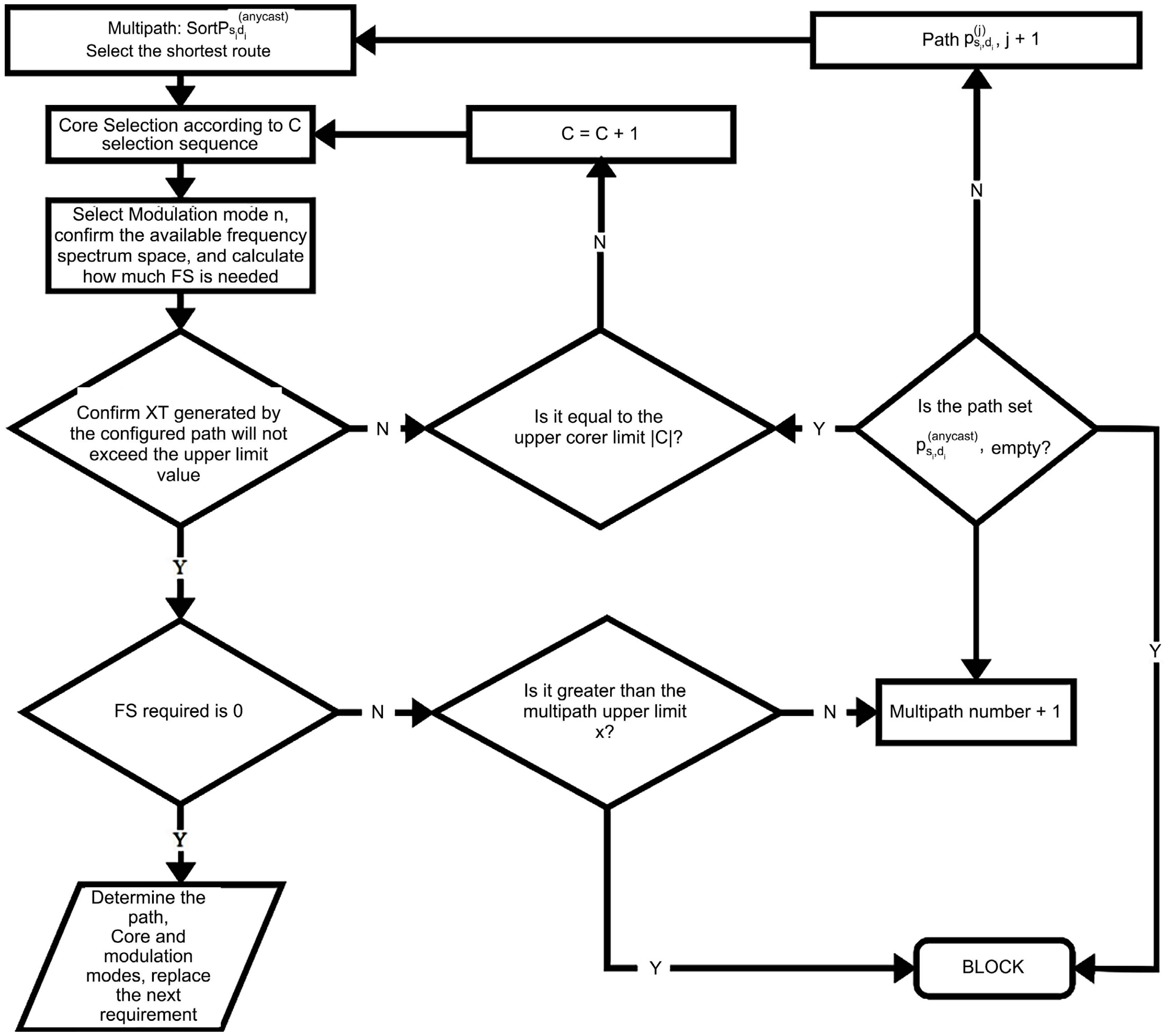


Figure 7. Multipath configuration flow chart.

4.5. Core Selection Strategy

This research and other studies use 7-core multi-core fiber. In terms of avoiding crosstalk problems, this paper uses two core selection strategies:

- First-Fit (FF): According to [6], to avoid crosstalk, non-adjacent cores will be selected first when core selection is required, according to 1 → 3 → 5 → 4 → 6 → 2 → 7, selected in order (**Figure 8**).
- Random-Fit (RF): Compared with First-Fit, Random-Fit selects 7 cores randomly during each core selection phase.

4.6. Unicast Example

As shown in **Figure 9**, when the demand *R* (1, 10, 980) arrives, through the *k*-shortest path algorithm [23], the candidate path ($k = 3$) found is [1] [8] [9] [10] with the distance 7800, the distance of [1] [7] [8] [10] is 9000, and the distance of [1] [3] [6] [10] is 8700. The candidate paths are stored in Psi, di according to the

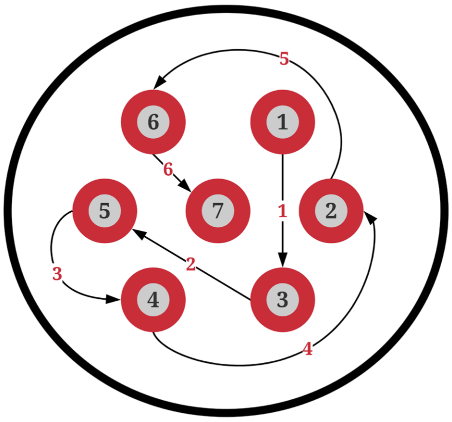


Figure 8. First-Fit sequence diagram of core selection strategy.

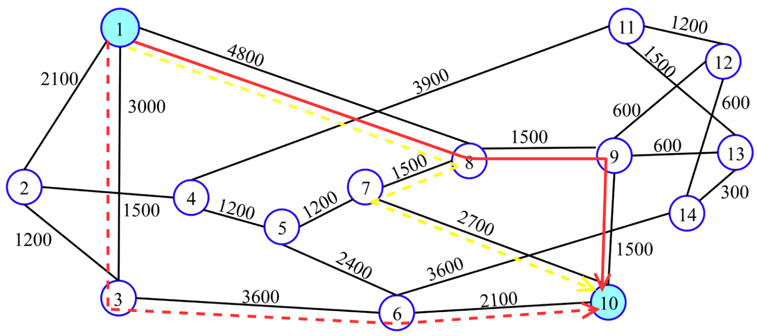


Figure 9. Example of unicast transmission.

distance from the smallest to largest, select the shortest path solid line [1] [8] [9] [10], and then select the modulation mode to calculate the required number of *FS* according to the distance of the selected path 7800. Then according to the order of candidate cores (*C*), select the first candidate core (core 1). If the core has available frequency slot resources, continue to check that the *FS* range to be configured is in the adjacent core (2, 6, 7). If there is an *FS* occupied and if the used *FS* is found in the *FS* range of core to be configured (core 2), it means that crosstalk will occur. The adjacent numbers are accumulated until all adjacent cores are checked. If this condition does not occur in the cores (2, 6, 7), the number of adjacent cores is 0. Then substitute the number of neighbors and the length of the path into formula (2) to obtain the *XT* value and judge by the set threshold value. If the threshold value is not exceeded, the configuration is performed, and the requirement is successfully established.

If all paths $p_{s_i,d_i}^{(1)} \sim p_{s_i,d_i}^{(k)}$ cannot be established, then perform multipath configuration. Select the path according to the above method and calculate the *FS*. If there is space (for example, bandwidth 300), it can be configured. If the *XT* value does not exceed the threshold value, subtract the configured bandwidth (980 - 300) from the required bandwidth, and select the next long dashed line [1] [3] [6] [10] to repeat the above actions until the required frequency returns to zero, then the demand is successfully established. If the selected path has exceeded the multipath upper limit X, and the required bandwidth still cannot be returned to zero, it needs to be blocked.

4.7. Anycast Example

As shown in **Figure 10**, anycast demand $R(1, \{10, 11, 14\}, 980)$ arrives, the k-shortest path algorithm is performed on each destination node, and the destination node 10 ($k = 3$) is found; The candidate path is [1] [8] [9] [10] with a distance of 7800, and [1] [7] [8] [10] with a distance of 9000, also [1] [3] [6] [10] with a distance of 8700; for the destination node 11 ($k = 3$); The candidate path found is [1] [2] [4] [11] with a distance of 7500, and [1] [8] [9] [11] [12] with a distance of 8100, also [1] [8] [9] [11] [13] with a distance of 8400; The candidate path found for the destination node 14 ($k = 3$) is [1] [8] [9] [13] [14] with a distance of 7200, and [1] [8] [9] [12] [14] with a distance of 7500, then [1] [5] [6] [7] [8] [14] with a distance of 13,500. The candidate paths are stored in $p_{s_i,d_i}^{(anycast)}$ according to the distance in ascending order (from the smallest to the largest). Therefore, the first selected path is the solid line [1] [8] [9] [13] [14], and the following is the same as the unicast content.

In the multi-path stage, the path is also selected according to the candidate path. If [1] [8] [9] [13] [14] does not meet the demand, the dotted line [1] [2] [4] [11] is selected as the second path, and so on, and the following is the same as the unicast content.

5. Simulation Results

In this section, examples of the Unicast and anycast experiment is illustrated and simulation experiments are conducted on the proposed RMLSA-M algorithm. The simulation environment is introduced and parameters presented.

5.1. Simulation Environment

The experiment environment of this work was performed on a computer with windows 10, Intel i7-2600, CPU 3.4 GHz, and RAM of 16 GB operating system, using python programing language, through commonly used simulation network topology NSFNet (**Figure 11**) and Pan-European-COST-239 (**Figure 12**) evaluates the effectiveness and performance of the proposed method.

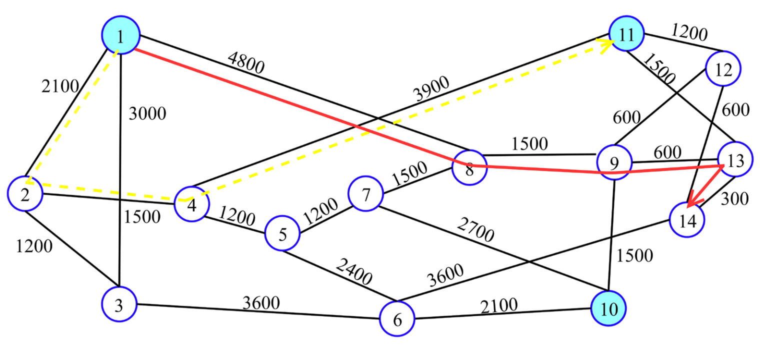


Figure 10. Example of an anycast transmission.

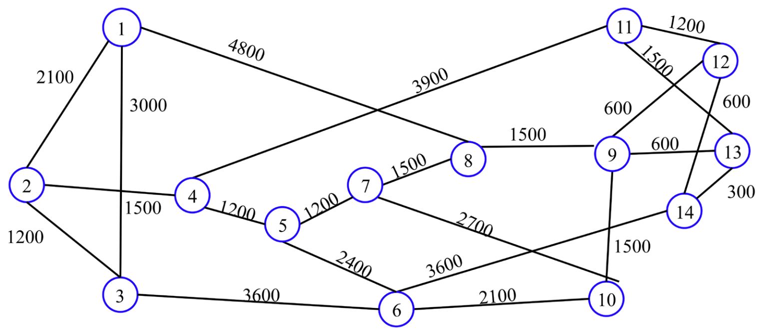


Figure 11. NSFNET Topology.

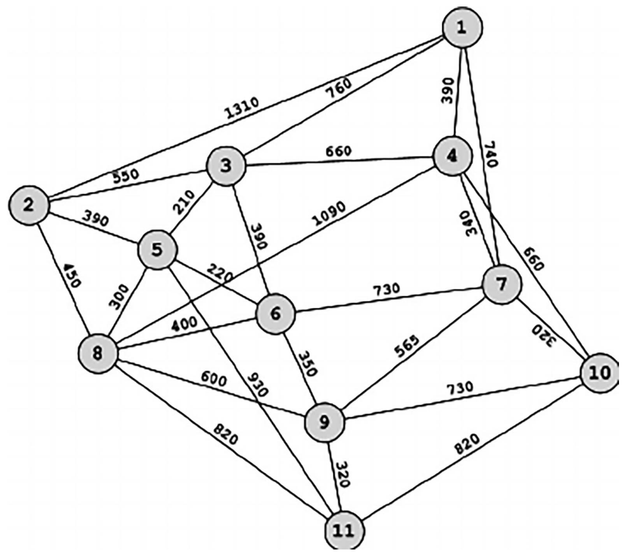


Figure 12. Pan-European-COST-239 Topology.

5.2. Simulation Parameters

There is a two-way link between NSFNet and any node In the Pan-European-COST-239 topology, and the distance of the link is in kilometers (km). In the multi-path part of the NSFNet topology, 100 - 1600 static requirements are randomly generated, and in the multi-path part of the COST-239 topology, increase the randomly generated static requirement to 200 - 3200, to enhance the execution of each requirement. The performance is compared with the average result of ten executions. The demand of anycast will randomly generate a different destination node, *a* contains 1, 2, 3, 4, 5 ($a = 1$, which means unicast transmission). This research presents *a* to 3. The frequency slot (*FS*) has a bandwidth of 12.5 GHz, and the required bandwidth requirements range from 10 Gbps to 1000 Gbps. The number of candidate paths *k* includes 3, 5, and 7. The candidate path *k* in the single-path mode is preset to 3, and the candidate path *k* in the multi-path mode is preset to 3. The Multipath upper limit *X* contains 1, 2, 3, 5, 10, and the default is 10. Modulation formats include BPSK, QPSK, 8 QAM, 16 QAM, 32 QAM, and 64 QAM, the number of cores is 7, and the parameters for calculating crosstalk between cores are set as follows in the paper [24]:

The Coupling coefficient, (κ) is 4×10^{-4}, the bending radius (R) is 0.05 m, the propagation constant, (β) is 4 × 106 1/m, and the distance between cores (core pitch, Λ) is 4×10^{-5} m, the threshold of crosstalk between cores is −30 dB, and the number of frequency slots in each core is 160.

5.3. Simulation Results

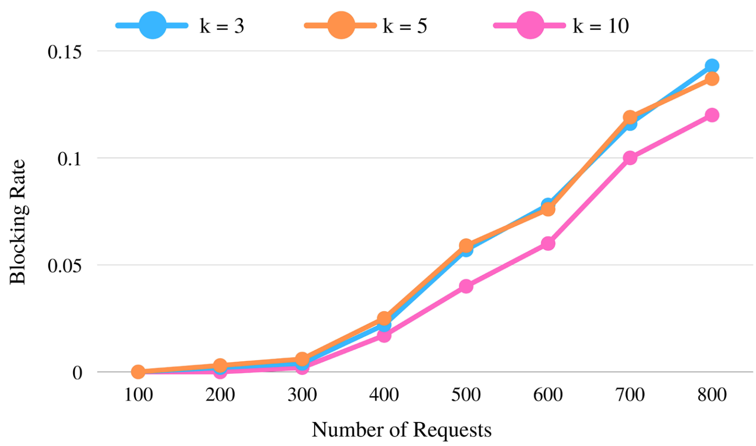
The performance is compared with the average result of ten executions.

1) Comparison of the number of different candidate paths (*k* value) of RMLSA-M on NSFNet

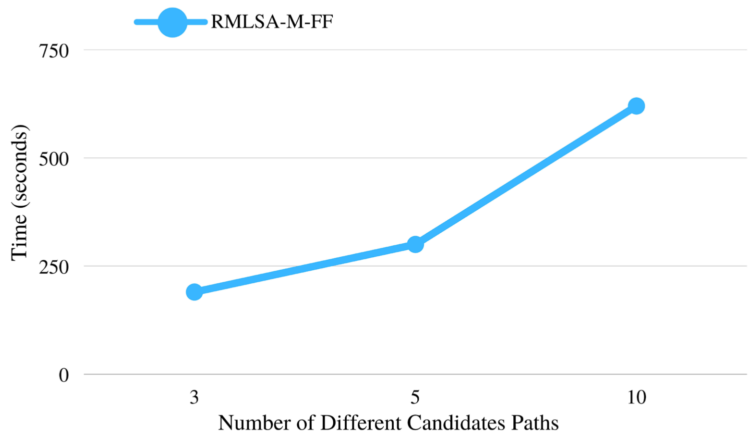
In Figure 13(a), the X-axis is the number of demands, and the Y-axis is the blocking rate. In Figure 13(b), the X-axis is the *k* value of the number of candidate paths, and the Y-axis is the execution time. Here, set the *k* values of the number of different candidate paths for the RMLSA-M algorithm (k = 3, 5, 10), using the FF core selection strategy. Compare whether the increase in the number of candidate paths on the topological graph NSFNet can improve the efficiency. The results show that in the case of low traffic (100 - 800), the more candidate paths, the lower the blocking rate; but in the case of high traffic (900 - 1600), the number of candidate paths does not have much impact on the blocking rate. (Due to similar experimental results when 900 - 1600 is required, this article only shows the results of 100 - 800 demand). As the number of candidate paths increases, the execution time also increases, which is roughly proportional.

2) Comparison of the number of the different destination nodes (a value) of RMLSA-M on NSFNet

Figure 14(a) shows X-axis as the number of demands, and the Y-axis as the blocking rate. Figure 14(b), X-axis is the number of destination nodes a value, Y-axis is the execution time. Here, the number *a*, of different destination nodes is set for the RMLSA-M algorithm (a = 2, 3, 4, 5), using the FF core selection strategy. An increase in the number of destination nodes on the NSFNet topological graph, shows a decrease in the blocking rate, an increase in the execution time, and an increase in the number of candidate paths.

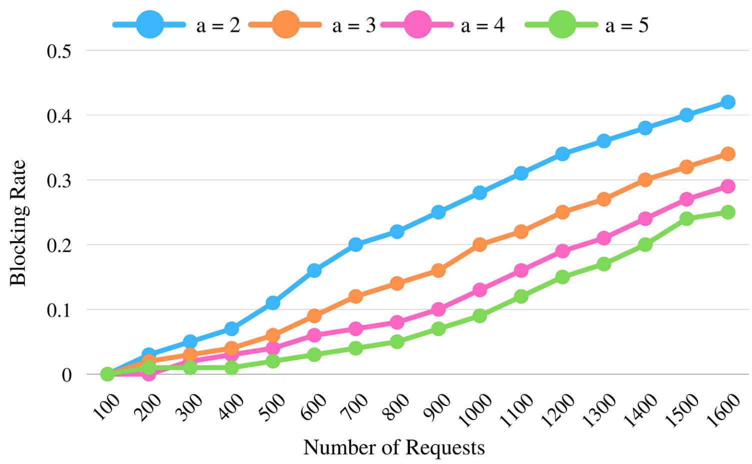


(a)

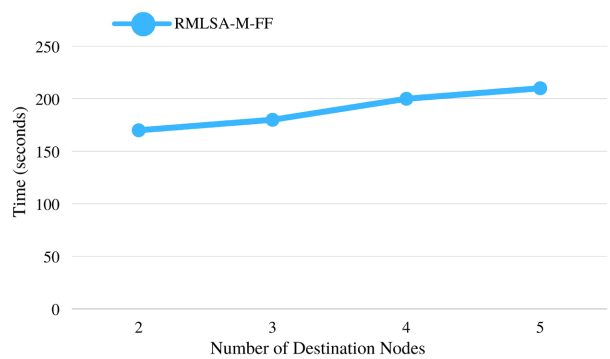


(b)

Figure 13. (a) Under the crosstalk threshold value of −30 dB between cores, compare the blocking rate of the number of different candidate paths (*k* value). (b) Time analysis of the number of different candidate paths under the threshold of −30 dB for crosstalk between cores.



(a)



(b)

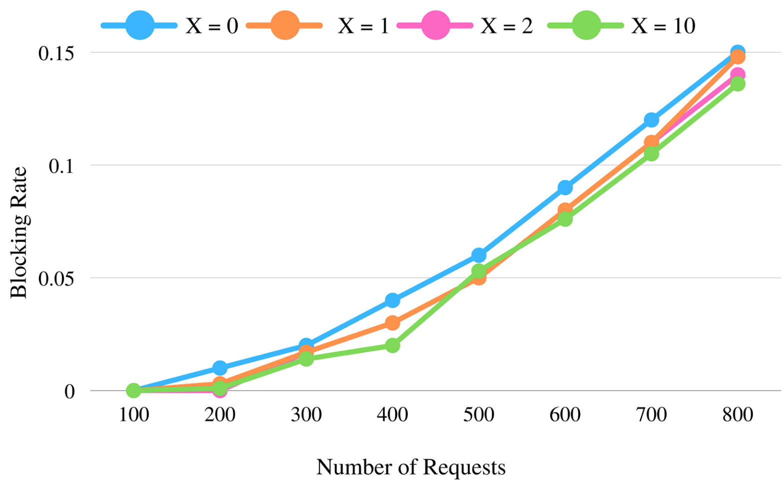
Figure 14. (a) Under the crosstalk threshold value of −30 dB between cores, compare the blocking rate of different destination nodes (*a* value). (b) Crosstalk threshold between cores −30 dB, the number of different destination nodes, the number of different destination nodes *a* value.

3) Comparison of RMLSA-M's different multipath upper limit X on NSFNet

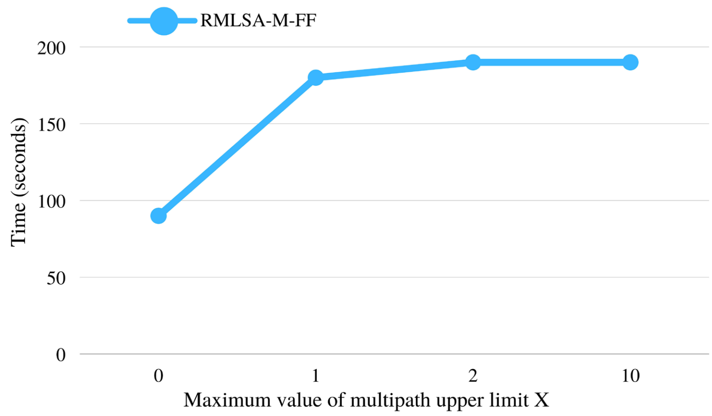
Figure 15(a), the X-axis is the number of demands, and the Y-axis is the blocking rate. In Figure 15(b), X-axis is the upper limit of the multi-path, Y-axis is the execution time. Here, different multipath upper limits (X = 0, 1, 2, 10) are set for the RMLSA-M algorithm, using FF core selection strategy, and X = 0 means that RMLSA-M uses the single-path algorithm. Compare if an increase in the upper limit of the multipath on the NSFNet topological graph can increase the performance. The results show that at a low flow rate of 100 - 800, an increase in the upper limit of multipath does have a lower blocking rate. Also, at high traffic 900 - 1600, the impact of the upper limit of multipath on performance is minimal. (Due to similar experimental results when 900 - 1600 is required, this article only shows the results of 100 - 800 demand). The execution time of a multi-path is more than twice that of a single path, and the execution time only rises slightly as the upper limit X rises. It is recommended to use 2. The need for more than one additional multipath is very small, so even if the upper limit is increased, the calculation time will not increase significantly.

4) Comparison of RMLSA-M anycast traffic and unicast traffic on NSFNet

In Figure 16(a), the X-axis is the number of demands, and the Y-axis is the blocking rate. In the case of unicast traffic for the heuristic algorithm proposed, the two core selection strategies (FF and RF) are used. Comparing the difference between flows in Unicast and Anycast on NSFNet topology, since anycast can select multiple destinations, the characteristics of the nodes are lower than those of RMLSA-M-FF-uni and RMLSA-M-RF-uni. In addition, in the case of low traffic (100 - 800), the blocking rate of RMLSA-M-FF is lower than that of RMLSA-M-RF and in the case of higher traffic (900 - 1600), the opposite is true. It can be judged that in anycast traffic, the higher the traffic, the more the core, and the lower the impact of crosstalk.

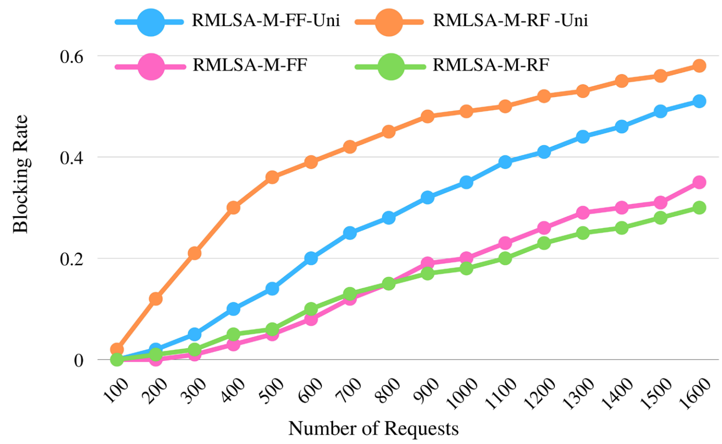


(a)

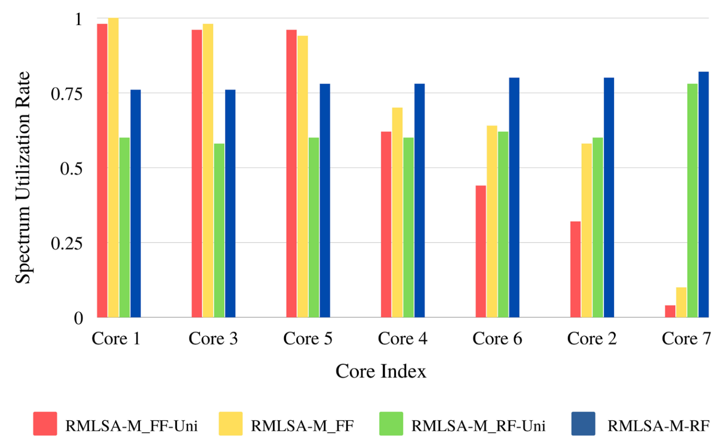


(b)

Figure 15. (a) Under the crosstalk threshold value of −30 dB between cores, compare the blocking rate of different multipath upper limit *X*. (b) Time analysis of different multipath upper limit *X* under the crosstalk threshold of −30 dB between cores.



(a)



(b)

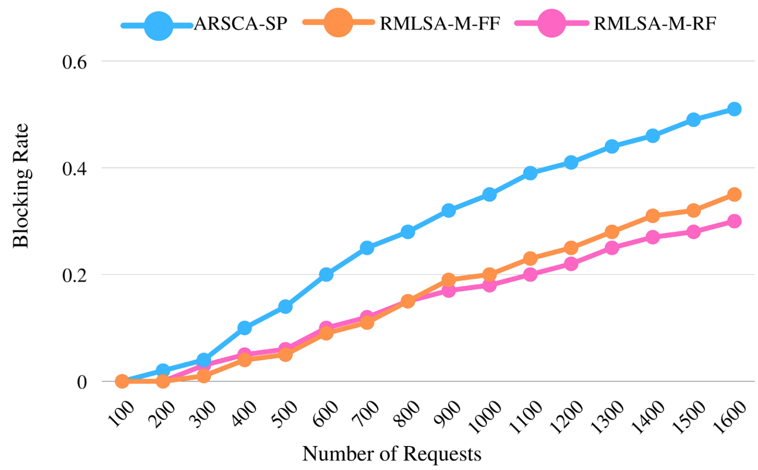
Figure 16. (a) Comparison of the blocking rate of unicast traffic and anycast traffic under the crosstalk threshold between cores −30 dB. (b) Under the crosstalk threshold of −30 dB. The comparison of the core spectrum utilization rate between unicast and anycast under the condition that the number of requirements is 1600.

In **Figure 16(b)**, the X-axis is the core index value, and the Y-axis is the spectrum utilization rate. Under the condition that the demand is 1600, compare the spectrum utilization rate of the algorithm proposed on the topology of NSFNet in unicast traffic and anycast traffic. It can be observed that using, First-fit (FF) or Random-fit (RF) core selection strategy with the algorithm proposed there is a slightly higher spectrum utilization rate for anycast traffic than unicast traffic.

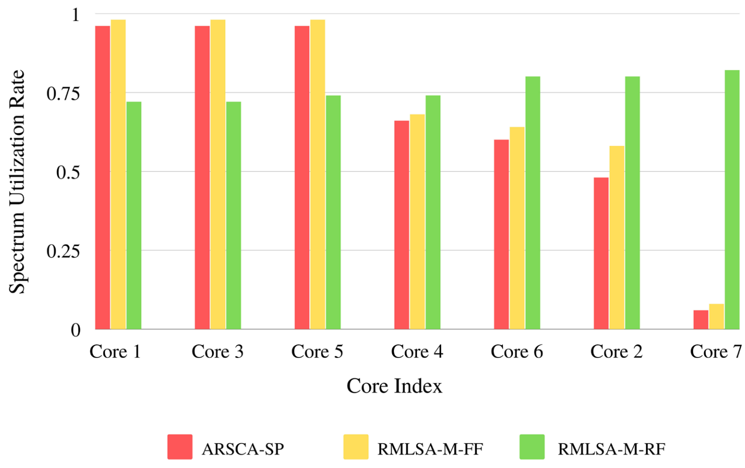
5) Comparison of RMLSA-M and ARSCA-SP on NSFNet

In **Figure 17(a)**, the X-axis is the number of demands, and the Y-axis is the blocking rate. ARSCA-SP uses a single path method for the paper [14]. The anycast RSA algorithm of the United States does not take into account the different modulation formats. With the two core selection strategies, and the heuristic algorithm proposed in the article, compare if the algorithm has better performance on NSFNet topological graph. As the number of demands increases, the blocking rate also increases. However, RMLSA-M-FF and RMLSA-M-RF use different modulation modes and multi-path methods, they have a significantly lower blocking rate than ARSCA-SP.

In **Figure 17(b)**, the X-axis is the core index value, and the Y-axis is the spectrum utilization rate. Under the condition that the number of requirements is 1600, compare the spectrum utilization rate of each core of the algorithm proposed in this paper on the topology NSFNet and the single-path RSA algorithm. The core index values are arranged in the order of the priority to which they will be assigned using the FF core selection strategy. Therefore, taking the observed spectrum utilization rate in descending order (highest to lowest) as the core 1, 3, 5, 4, 6, 2, 7, the RMLSA-M-FF has a higher spectrum utilization rate than ARSCA-SP. And in RF core selection strategy, the RMLSA-M-RF, a new sequence of candidate cores will be generated for each requirement, and then cores will be selected. This result shows that the spectrum usage of each core is relatively evenly distributed. In particular, Core 7 has a much higher spectrum utilization rate than the other two, because the random assignment can have a fairer distribution under high traffic.



(a)



(b)

Figure 17. (a) Under the threshold of −30 dB for crosstalk between cores, compare the blocking rate of single path and multipath. (b) The crosstalk threshold value of −30 dB single-path and multi-path comparison of core spectrum utilization rate under the condition that the number of requirements is 1600.

6) Comparison of RMLSA-M and ARSCA-SP on COST239

Figure 18(a) indicates X-axis is the number of requirements or demands and the Y-axis is the blocking rate. ARSCA-SP uses a single path method for this research [15]. Anycast RSA algorithm of RMLSA-M-FF, RMLSA-M-RF, does not take into account different modulation formats. The heuristic algorithms proposed in this research using these two core selection strategies; First-fit (FF) and Random-fit (RF) respectively. Compare whether the algorithm proposed in this paper has a better effect on the topological map COST239. As the number of demands increases, the blocking rate also increases while RMLSA-M-FF and RMLSA-M-RF because of the use of different modulation modes and the use of multi-path methods, there is a significantly lower blocking rate than ARSCA-SP.

In **Figure 18(b)**, X-axis is the core index value, Y-axis is the spectrum usage rate. Under the condition that the number of requirements is 3200 in this situation, compare the frequency of each core of the single-path RSA algorithm and the algorithm proposed in this research on the topology. In the frequency spectrum utilization rate of each core of the algorithm, the core index values are assigned according to First-fit (FF) core selection strategies. Therefore, it can be observed that the spectrum utilization rate goes from high to low for cores 1, 3, 5, 4, 6, 2, 7, and in contrast to NSFNet. What this proposes is the spectrum usage rate of RMLSA-M in this research is lower than ARSCA-SP. Use Random-fit (RF) RMLSA-M-RF for the core selection strategy, since a new sequence of candidate cores will be generated for each requirement, and then the cores will be selected, the result shows that the spectrum utilization rate of each core is relatively even. Also, in RMLSA-M's from the perspective of the low blocking rate, the method proposed will have higher spectrum utilization efficiency in a network topology with more links.

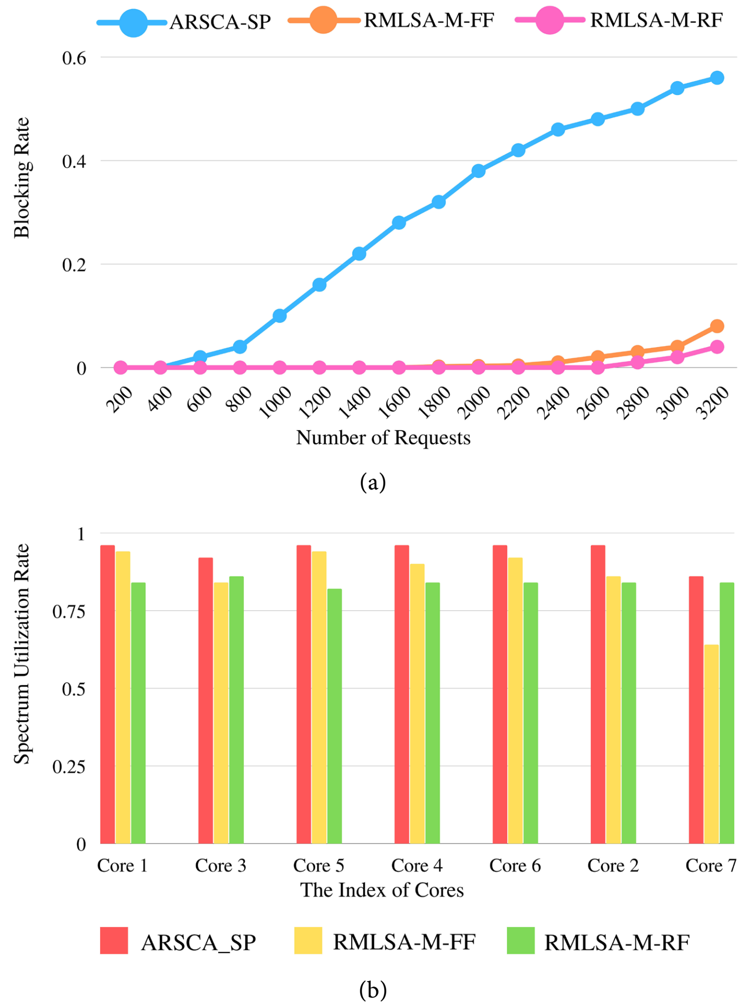
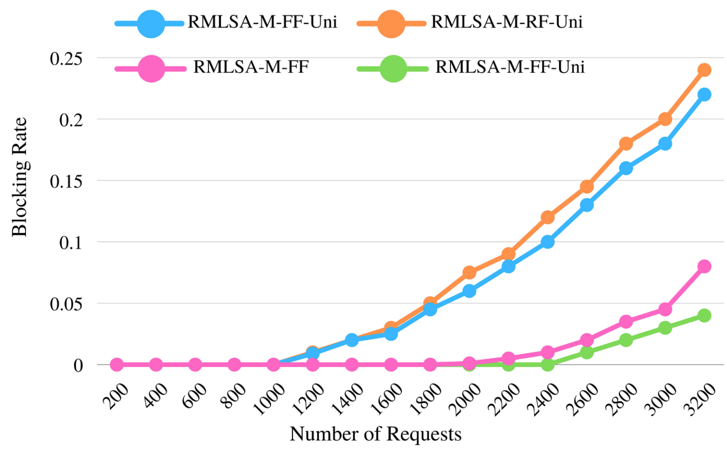


Figure 18. (a0 Under the threshold value of −30 dB for crosstalk between cores, compare the blocking rate of single path and multipath. (b) Crosstalk threshold value −30 dB Single-path and multi-path comparison of core spectrum utilization rate under the condition that the number of requirements is 3200.

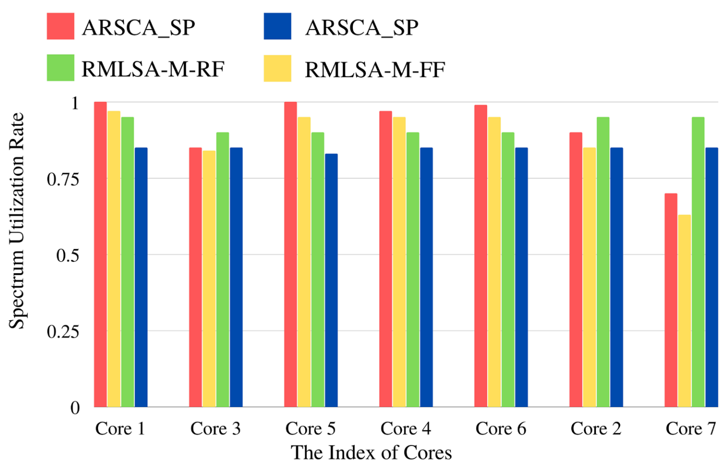
7) Comparison of RMLSA-M anycast traffic and unicast traffic on COST239

Figure 19(a) shows that X-axis is still the number of requirements, and Y-axis is the blocking rate. RMLSA-M-FF-uni and RMLSA-M-RF-uni are the heuristic algorithm proposed in this paper in the case of unicast traffic, First-fit (FF) is used followed up respectively with Random-fit (RF) two core selection strategies. The difference between the amounts is compared using unicast and anycast transmission on COST239 topology. It can be noticed that RMLSA-M- FF are RMLSA-M-RF are similar to NSFNet because of anycast. The characteristics of multiple destination nodes can be selected, which are lower than RMLSA-M-FF-uni and RMLSA-M-RF-uni blocking rates. The difference is that under unicast traffic, the blocking rate of RF is higher. If the interruption rate is low, it is judged that anycast transmission is more likely to generate inter-core crosstalk according to a fixed core sequence when there are more links to provide path selection. In addition, because COST239 has more links, the blocking rate of the same requirement is lower than in NSFNet.

In Figure 19(b), the X-axis is the core index value, and the Y-axis is the spectrum usage. RMLSA-M-FF-uni and RMLSA-M-RF-uni are the heuristic algorithms proposed in this paper in the case of unicast traffic. Under the condition that the number of requirements is 3200, compare the spectrum utilization rate of the algorithm proposed in this research for unicast traffic and anycast traffic on the topology map COST239. Quite on the contrary from NSFNet, it can be observed that regardless of the priority allocation First-fit, (FF) or Random-fit (RF) core selection strategies, the spectrum utilization rate of unicast traffic is higher than that of anycast traffic. In combination with the lower blocking rate of anycast traffic, it shows that anycast transmission is more efficient in using the spectrum utilization rate when there are more links to choose from and the utilization efficiency will be relatively higher.



(a)

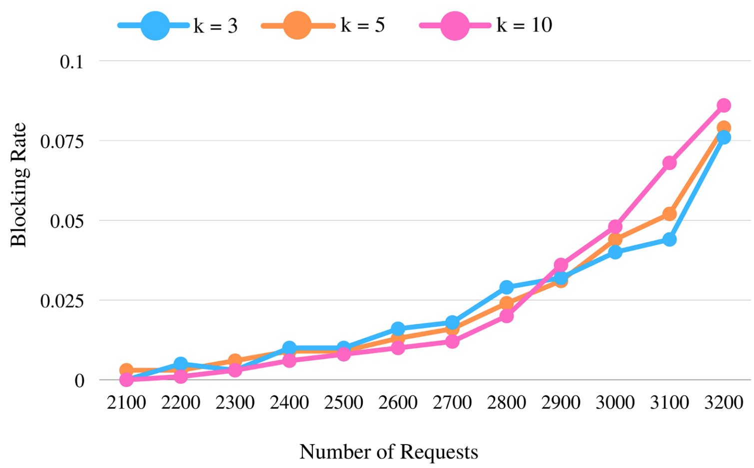


(b)

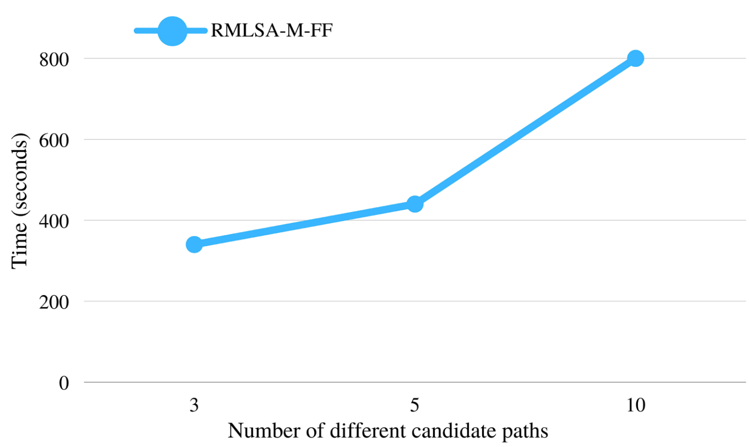
Figure 19. (a) Comparison of the blocking rate of unicast traffic and anycast traffic under the crosstalk threshold between cores −30 dB. (b) Crosstalk threshold value −30 dB, the comparison of core spectrum utilization rate between unicast and anycast under the condition that the number of requirements is 3200.

8) Comparison of the number of different candidate's path *k* of RMLSA-M on COST239

Figure 20(a), the X-axis is the number of requirements, and the Y-axis is the blocking rate. Figure 20(b), the X-axis is the number of candidate paths k, Y-axis is the execution time. Here, the number of different candidate paths k is set for the RMLSA-M algorithm ($k = 3, 5, 10$), so that the first-fit (FF) core selection strategy is used. Compare the number of candidate paths k on the COST239 topology if an increase in the number can improve performance. The results show that at the traffic of (100 - 2800), in the case of more number of candidate paths, the lower the blocking rate. However, at the higher traffic (2900-3200), the greater the number of candidate paths, the higher the blocking rate. This judgment is based on the topology of more links, the more the candidate paths, the higher the traffic occurs. On the contrary, subsequent demand will not get enough links to form the path and hence, will be blocked. (Due to the actual



(a)



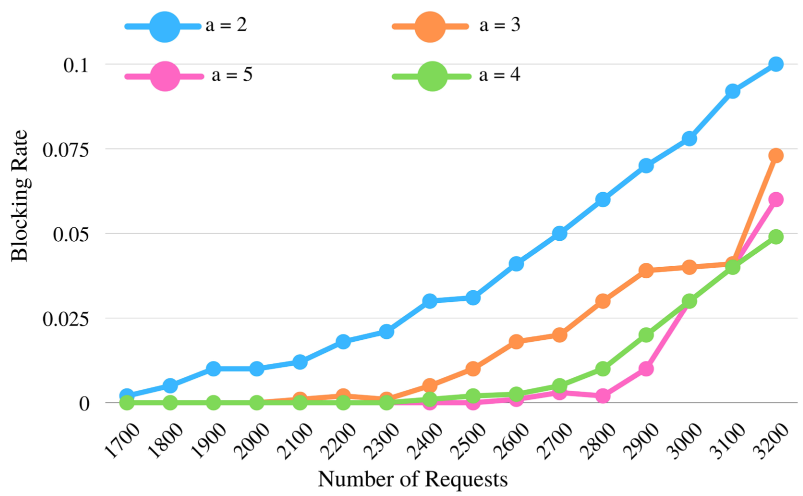
(b)

Figure 20. (a) Under the crosstalk threshold value of −30 dB between cores, compare the blocking rate of the number of different candidate paths k. (b) Time analysis of the number of different candidate paths k under the threshold of −30 dB for crosstalk between cores.

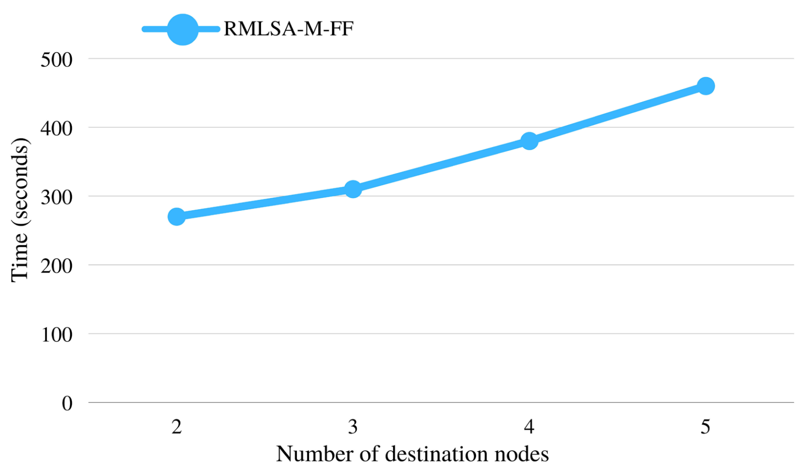
demand for 100 - 2000, the test results are too similar, so this research only shows the results of the 2100 - 3200 requirements). The execution time is the same as the previous data, as the number of candidate paths increases, the execution time also increases, showing a proportional relationship.

9) Comparison of the number of the different destination nodes (a value) of RMLSA-M on COST239

In Figure 21(a), The X-axis is the number of requirements, and the Y-axis is the blocking rate. In, Figure 21(b) X-axis is the number of destination nodes *a*, and the Y-axis is the execution time. Here, the number of different destination nodes *a,* for the RMLSA-M algorithm is set to (*a* = 2, 3, 4, 5) and the first-fit (FF) core selection strategy is used. Compare the destination node on the COST239 topological graph, does the increase in number have an impact? Similar to NSFNet, the results show an increase in the number of destination nodes will



(a)



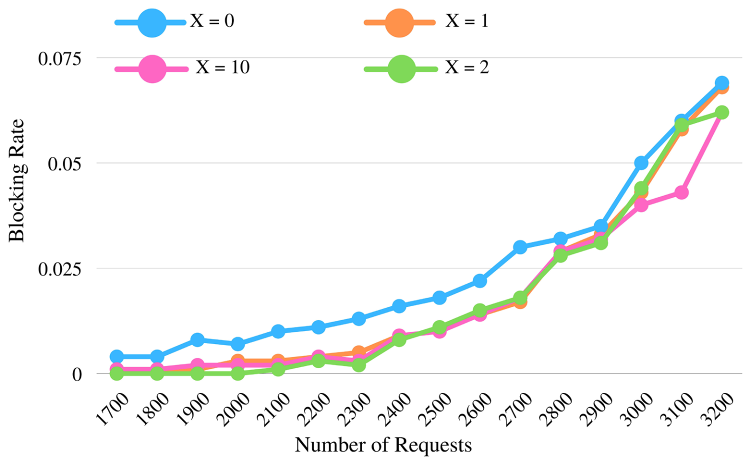
(b)

Figure 21. (a) Under the threshold value of −30dB for crosstalk between cores, compare the blocking rate of different destination nodes *a*. (b) Time analysis of the different destination nodes a, under the threshold value of −30 dB for crosstalk between cores.

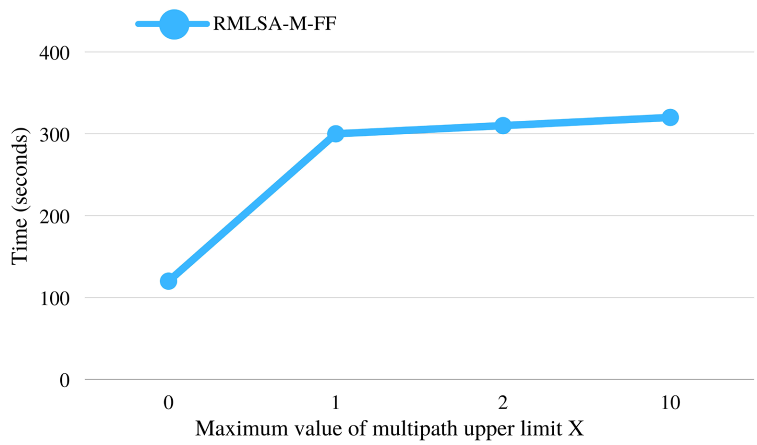
result in a low blocking rate. (Because the experimental results at 100 - 1600 requirements are too similar, this thesis only shows the result of 1700 - 3200 requirements). In addition, if anycast requires more than 4 destination nodes, the blocking rate is roughly the same after the traffic (3000) This can be considered that under extremely high traffic, the anycast demand of more than 4 destination nodes is not advantageous. The execution time is also similar to the previous data, an increase in the number of destination nodes also increases the execution time.

10) Comparison of RMLSA-M different multipath upper limit *X* on COST239

Figure 22(a), The X-axis is the number of requirements, and the Y-axis is the blocking rate. In Figure 22(b), X-axis is the upper limit of multipath X, Y-axis Is the execution time. Here, different multipath upper limits ($X = 0, 1, 2, 10$) are set for the RMLSA-M algorithm and first-fit (FF) core selection strategy is used, when $X = 0$ RMLSA-M uses the single-path algorithm.



(a)



(b)

Figure 22. (a) Under the threshold of crosstalk between cores −30 dB, compare the blocking rate of different multipath upper limit *X*. (b) Time analysis of different multipath upper limit *X* under the threshold of crosstalk between cores −30 dB.

Compare whether an increase in the upper limit of the multipath on COST239 topology can increase the performance? The results are shows that in the case of (100 - 2800) request, the blocking rate of multi-path is lower than that of single-path when ($X = 0$), but the difference in the upper limit is not large. In the case of high traffic (2900 - 3200) requests, the difference in blocking rate between single path and multipath is much smaller. (Because the experimental results of 100 - 1600 requests are similar, this thesis only shows the results of 1700 - 3200 requests). The execution time is also similar to the previous data, and the execution time of multi-path is more than twice that of single-path, and the upper limit X increases execution time slightly. It is considered that the requirement for more than 2 additional multipaths is very small, so the calculation time will not increase significantly if the upper limit is increased.

6. Conclusion and Further Research

6.1. Conclusion

This research considers the RMLSA problem of anycast requirements on the SDM-EON network and proposes a heuristic algorithm. The experimental results show that the proposed RMLSA-M in this paper when compared with ARSCA-SP has better performance. Under low traffic, the larger the upper limit of multipath, the lower the blocking rate; under high traffic, the effect of crosstalk is not much improved. In terms of core selection strategy, First-Fit considers crosstalk and the blocking rate at low traffic is lower than Random-Fit; Random-Fit uses spectrum utilization ratio and the blocking rate is higher than First-Fit.

6.2. Further Research

Future research will be conducted on the number of different multi-core fiber cores. Currently, most research is carried out on multi-core fibers with 7 cores. Although the 12 and 19 cores have specifications, there are not many relevant studies. Core-to-core crosstalk is a problem worthy of discussion.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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