A multicast routing restoration algorithm based on the n-person non-cooperative game in multi-domain optical networks

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Abstract. Aiming at the restoration problems for multicast service in multi-domain optical networks, a multicast routing restoration algorithm in multi-domain optical networks based on the n-person non-cooperative game is proposed by adopting the Breadth First Search (BFS) strategy and n-person non-cooperative game theory. This algorithm optimizes the searching sequence of BFS algorithm and reduces the searching scope by the competitive selection relation of the game theory. The algorithm analysis and experimental results show that the algorithm has low time complexity, reduces the computational time of the restoration path, and reduces the blocking rate of the multicast restoration service.

1. Introduction

With the continuous development of optical networks, many branch networks do not have the conditions to reserve a large amount of redundant resources. In this case, how to ensure the survivability of the network becomes a problem. In the face of optical networks without reservation protection mechanism, only the recovery mechanism can be constructed in the network to solve the problem of rapid recovery of services after failure [1-3]. Optical network survivability mechanism is divided into protection and recovery. Compared with the protection mechanism, the recovery mechanism studies the available path at the expense of a certain service recovery time, but it can save a lot of network resources [4]. At present, the research of optical network recovery mechanism is mainly divided into single-domain and multi-domain.

For the single-domain optical network multicast recovery algorithm, domestic and foreign researchers have made good research progress. Among them, the literature [5] compares the FRR-based and RTs-based end-to-end protection schemes. If the redundancy of resources is not considered, the FRR algorithm-based scheme can recover the service more quickly. Literature [6] proposed a hierarchical adaptive recovery algorithm, but the efficiency of the algorithm to generate a multicast tree will decrease as the number of multicast requests increases. The recovery scheme proposed in literature [7] overcomes the QoS limitation of recovery technology, and can solve link failure and node failure at the same time, but the scheme performs recovery time longer. Under the condition of
ensuring the same survivability, the MMRA algorithm proposed in literature [8] distinguishes four kinds of network faults, which contains route fault, OXC fault, fiber fault and hybrid fault, and solves the recovery problem separately. However, the spectrum utilization of this algorithm is poor.

There are few researches on multi-domain optical network multicast recovery algorithms at home and abroad. Literature [9] proposed a Dual-Weight Recovery (DWR) algorithm based on the Path Computation Element (PCE), which can adjust the link weights in time and provide a certain priority for recovery services. However, the distributed PCE-based computing solution lacks a core and cannot coordinate the resource allocation of the entire multi-domain optical network. The literature [10-13] proposed related multi-domain recovery algorithms based on networks such as Software-Defined Networks (SDN), Generalized Multi-Protocol Label Switching (GMPLS) and Elastic Optical Networks (EON), but these algorithms did not take into account the groups. Considering the particularity of multicast communication, these algorithms cannot be directly applied to the restoration of multicast services.

To sum up, there are many researches on the multicast recovery of single-domain optical networks at home and abroad, but relatively few achievements have been made specifically for the multicast recovery of multi-domain optical networks. Some results have higher costs while achieving better recovery performance. At the same time, due to the lack of a dedicated path calculation unit, the calculation load of a multi-domain optical network is likely to be excessive. Therefore, this paper will make full use of the efficiency of the computational path of the layered PCE architecture and combine n-person non-cooperative game theory to propose a new multicast recovery algorithm in multi-domain optical network. It is called GMMR (n-person non-cooperative Game based Multi-domain Multicast rerouting Restoration) algorithm.

2. Problem description
This paper combines the hierarchical PCE structure to locally recover faulty services in each domain. The BFS algorithm and the non-cooperative game are used to explore the multi-domain optical network multicast routing recovery mechanism. The related definitions and assumptions are as follows:

Definition 1: Define a multi-domain optical network topology as \(G(V,E)\), \(V=\{V_1,\ldots,V_n\}\) is a collection of all the nodes in the network. The link between node \(V_i\) and node \(V_j\) is expressed as \(e_{ij}\). \(E=\{e_{ij}|i,j\leq n\}\) is a collection of links in the network. Define the light path set as \(P \subseteq E\). Define the optical path set of the multicast working tree as \(P_w\), and define the recovery path set as \(P_r\).

Definition 2: For game \(G’=(N,S,U)\), \(N=\{n_1,n_2,\ldots,n_n\}\) is the collection of people in the game. In the multi-domain optical network multicast recovery process, all the next hop nodes of the direct upstream node of the fault link are the players in the game bureau. The strategy set of the player \(n_i\) in the game is \(S_i=\{1,2,\ldots,j\}\). Where \(j\) represents the node to select the \(jth\) access, and the policy set of all next hop nodes is \(S=\{S_1,S_2,\ldots,S_n\}\).

Definition 3: The set of utility functions \(U=\{U_1,U_2,\ldots,U_n\}\) is a collection of the income functions of the players in the game. Define the benefit function as follows: \(U_i=\alpha h + \beta L + \delta ber + T_{wait} + T_r\).

Where \(\alpha, \beta, \delta\) is the control variable, \(h\) is the number of neighbors of the current node (excluding the upstream node), \(L\) is the length of the fiber on the link, \(T_{wait}\) is the time to wait for the recovery operation to occur after the failure occurs in the network, and \(T_r\) is started in the network. The time from recovery operation to recovery success. The bit error rate is as follows: \(ber=\frac{N_{err}}{N}\).

The mathematical model constraints are as follows: \(U_i \rightarrow \min U_i, \alpha + \beta = 1, 0 \leq \alpha \leq 1, 0 \leq \beta \leq 1, \delta \geq 0, T_{wait} \leq T_0, T_r \leq T_1\).
3. Algorithm steps

3.1 The GMMR algorithm

The GMMR algorithm steps are as follows:

Step 1: Given a multi-domain optical network \( G(V, E) \), a multicast request \( R = \{ s: d_1, d_2, \ldots, d_m \} \), defining a multicast tree as \( PW \) and a recovery path set as \( PR \). Let the number of next hop neighbors of any node (excluding the upstream node) be \( h \).

Step 2: Initialize the multi-domain optical network \( G(V, E) \) and perform topology aggregation, and use the MPH algorithm to generate the multicast tree \( PW \).

Step 3: When the link \( e_{ij} \) fails, the location of the link is detected. If the link \( e_{ij} \) is an intra-domain link, turn to Step 4; if the link \( e_{ij} \) is an inter-domain link, turn to Step 5.

Step 4: Node \( V_i \) sends a fault message to the local domain child PCE (cPCE). The n cPCE starts the recovery process and sends a local rerouting instruction to node \( V_i \).

Step 4.1: Start with node \( V_i \) and find all next-hop neighbors \( V_i, V_j, \ldots, V_k \). If it contains the node \( V_j \), then go to Step 8, otherwise the node \( V_i, V_j, \ldots, V_k \) starts the game as the player in the game, calculates the utility function \( U \), determines the sequence, and then uses the BFS algorithm to search.

Step 4.2: Use \( V_i, V_j, \ldots, V_k \) as the starting point to find all the next hop neighbors of each node. If the neighbor of one of the nodes contains the destination point \( V_j \), go to Step 8. Otherwise, use all the next hop neighbors of each node as the player in the game. Start the game, calculate the utility function \( U \), determine the order, and then use the BFS algorithm to search. Repeat until you find node \( V_j \).

Step 5: The node \( V_i \) sends a failure message to the local domain cPCE (assuming the domain is domain 2), and the cPCE sends a message to the pPCE requesting to start the recovery process. The pPCE sends a rerouting instruction to the cPCE of the domain in which the node \( V_i \) is located (assuming the domain is domain 1). pPCE analyzes the topology. If there is another inter-domain link \( e_{ab} \) in domain 1 and domain 2 (where node \( V_a \) is in domain 1 and node \( V_b \) is in domain 2), turn to Step 6. Otherwise, find domain 3 in which domain 1 and domain 2 are connected together and turn to Step 7. If you can't find such a domain 3, return to block and output.

Step 6: First, look for the intra-domain path \( e_{ia} \) in domain 1. Starting from node \( V_i \), find all next-hop neighbor nodes \( V_i, V_j, \ldots, V_k \), start a game with \( V_i, V_j, \ldots, V_k \) as the player in the game, calculate the utility function \( U \), determine the order, and then use the BFS algorithm to search. Then take \( V_i, V_j, \ldots, V_k \) as the starting point, find all the next hop neighboring nodes of each node, repeat the operation until the destination node \( V_a \) is found, and record the path \( e_{ia} \). Similarly, look for the intra-domain path \( e_{bj} \) in domain 2. Finally, pPCE searches the topology between domain 1 and domain 2 to find the inter-domain path \( e_{ab} \), thereby establishing a recovery path from \( e_{ia} \) to \( e_{ab} \) to \( e_{bj} \), and then turn to Step 8.

Step 7: First, the inter-domain link between domain 1 and domain 3 is \( e_{cd} \), and the inter-domain link between domain 3 and domain 2 is \( e_{df} \). Then, in domain 1, look for the intra-domain path \( e_{ic} \). Starting with node \( V_i \), find all next-hop neighbor nodes \( V_i, V_j, \ldots, V_k \), start a game with \( V_i, V_j, \ldots, V_k \) for the game player, calculate the utility function \( U \), determine the order, and then use the BFS algorithm to search. Then take \( V_i, V_j, \ldots, V_k \) as the starting point, find all the next hop neighboring nodes of each node, repeat the operation until the destination point \( V_i \) is found, and record the path \( e_{ic} \). Similarly, in the domain 2, the intra-domain path \( e_{di} \) is found, in the domain 3, the intra-domain path \( e_{fd} \) is found, and finally the pPCE searches the topology between the domain 1 and the domain 2 to find the inter-domain path \( e_{db} \), and between the domain 2 and the domain 3 The inter-domain path \( e_{de} \) is established to establish recovery paths \( e_{ic} \) to \( e_{cd} \) to \( e_{de} \) to \( e_{df} \), and then turn to Step 8.

Step 8: Update the route, record the recovery path to \( PR \), and output \( PR \).

3.2 The BFS algorithm

The GMMR algorithm combines the idea of the BFS algorithm, which is a blind search algorithm that systematically expands and searches all nodes to find the destination node. The advantage is that it can
effectively solve the shortest or least problem, and the search depth is small. The main implementation steps of the BFS algorithm are as follows:

Step1: Given undirected graph $G(V, E)$, source node $V_s$, destination node $V_j$.

Step2: Mark node $V_s$ as the source node.

Step3: From $V_s$, access all downstream nodes $V_1, V_2, \ldots, V_n$ of $V_s$.

Step4: Start from $V_1, V_2, \ldots, V_n$ and access all the untouched neighbors of $V_1, V_2, \ldots, V_n$. If all neighbors are accessed or reach $V_j$, turn to Step5. Otherwise, turn to Step3.

Step5: Output the path from the source node $V_s$ to the destination node $V_j$.

4. Algorithm example

Combined with the actual situation, an example of the recovery scheme generated by the GMMR algorithm under the burst condition is illustrated.

It is assumed that there are three autonomous domains, Figure 1 is a multi-domain optical network structure, and Figure 2 is a topology diagram after full mesh aggregation. A multicast request is $R_1 = \{2, 5, 8, 10, 12, 13, 15, 17, 18\}$. Design recovery for the session if the network resource is not rich and the protection mechanism cannot be calculated in advance. The solution ensures that the business recovery can be completed within a certain period of time even if a failure occurs.

Figure 1. Multi-domain optical network     Figure 2. Multi-domain optical network topology

Figure 3. Multicast request $R_1$      Figure 4. Start recovery

The blue path in Figure 3 is the multicast working tree (2-5-9-15-17, 2-5-9-15-18, 2-5-9-8-10, 2-5-9-8-12, 2-5-9-8-13). Assuming that the link from node 8 to node 10 fails, the search is performed in domain 2 according to the GMMR algorithm, and the search direction is as shown in Figure 4Node 8 acts as a direct upstream node. In addition to its upstream node 9, there are three directions for searching, including purple dotted links 8-7, 8-12, 8-13. The game is played by the three directions to determine the order of the algorithm search, and then the game selection search is continued from the three nodes. The final search recovery path is 8-12-10 (purple solid path). Similarly, if there is a failure between domains, first look for other links between the two domains. If it exists, the search is performed from the inter-domain fault link node to the new inter-domain link node in the two domains.

5. Analysis of algorithms

Theorem 1: The time complexity of the GMMR algorithm is $O(ln^2 + m^3 n + e)$.
Proof: It is assumed that there are \( n \) nodes and \( l \) link in the multi-domain network, and a multicast request \( R \) with \( m \) leaf nodes is given. The time complexity of the MPH algorithm is \( O(mn^2 + e) \). The BFS algorithm needs to search all possible paths, so its time complexity is \( O(nl) \), and it is the horizontal development of horizontal selection. In the worst case, the GMMR algorithm is needed to play a game for each node, and the time complexity of the GMMR algorithm is \( O((n^2 + m^2n + e)) \).

Theorem 2: \( G'=(N,S,U) \) is a non-cooperative game of \( n \) people in the GMMR algorithm. It is defined that when a player chooses a strategy in each game, the situation formed at this time is called a situation. Let \( x^* \) be a situation of \( G'=(N,S,U) \), then when \( U_i(x^*_i) \leq U_i(x'_i), \forall i \in N, \forall s_i \in S \) is established, \( x^* \) is the Nash equilibrium point of the game.

Proof: If \( x^* \) can satisfies the condition: \( U_i(x^*_i) \leq U_i(x'_i), \forall i \in N, \forall s_i \in S \). That is to meet the conditions: \( U_i(x^*_i) \leq U_i(x'_i), i=1,2,\ldots,n, k=1,2,\ldots,n \). Then for the formula \( \forall x_i=(x'_1',x'_2',\ldots,x'_k') \in S \), the formula \( \sum_{i=1}^{n} U_i(x_i^*_i) \leq \sum_{i=1}^{n} U_i(x'_i) \) must be established. So, \( x^* \) is the Nash equilibrium point of the game.

6. Simulation

6.1 Network structure and parameter settings
In this paper, a multi-domain optical network system is designed by using VPI simulation software to verify the effectiveness of the GMMR algorithm. The extended multi-domain optical network DWR algorithm and MMRA algorithm strategy are selected for comparative analysis. Figure 5 is a multi-domain optical network VPI system diagram, and Figure 6 is an enlarged view of the domain 1. In the multi-domain optical network system, the fault module is designed to be used to manufacture network faults. The path conversion module is designed for the signal switching path in the network. In addition, the transmission of the multicast request satisfies the Poisson distribution, and the duration satisfies the exponential distribution. The main parameters of the experiment are as shown in Table 1.

![Figure 5. VPI system diagram](image1)
![Figure 6. VPI system diagram in domain 1](image2)

| Parameter               | Value       |
|-------------------------|-------------|
| Bit rate                | 10e9 bit/s  |
| Time window             | 64/10e9 s   |
| Sampling rate           | 160e9 Hz    |
| Signal average power    | 1.0e-3 W    |
| Fiber attenuation value | 0.2e-3 dB/m |
| Critical attenuation value | 30 dBm  |
| Integration time        | 0.1e-3 s    |
| Feedback gain           | 1.5 dBm     |
| Number of channels      | 16          |
| Continuous attenuation  | 20.8dB      |
| Channel Spacing         | 100e9 Hz    |
6.2 Experiment analysis
Figure 7 shows the power variation of the GMMR algorithm during the recovery mechanism operation. It can be seen that between 1ms and 2ms, the network output power value begins to drop. At this time, the attenuation module applies a 30 dBm attenuation to a certain link of the network, indicating that the service on the link is interrupted and the recovery mechanism is started in time. After about 6ms, the power slowly rises and eventually restores the link, thus restoring the transmission of the service.

Figure 8 shows the comparison of recovery times for the DWR algorithm, the MMRA algorithm, and the GMMR algorithm. The GMMR algorithm uses the shortest recovery time. The DWR algorithm adopts the dual-weight method. When a fault occurs, the weight is updated first to ensure that the subsequent service does not collide with the current recovery service, resulting in the slowest recovery time. The MMRA algorithm uses the shortest path search algorithm for global blind search after the fault, so the recovery speed is faster than the DWR algorithm. The GMMR algorithm combines the BFS algorithm with the n-person non-cooperative game mechanism to enhance the search targeting through the game competition selection mechanism, thus speeding up the process of finding the recovery path, and finally generating the recovery path for the shortest time.

Figure 9 is a comparison of blocking rates for the DWR algorithm, the MMRA algorithm, and the GMMR algorithm. As can be seen from the figure, as the number of faulty links increases, the blocking rate of each algorithm gradually increases. The MMRA algorithm has the highest blocking rate, followed by the DWR algorithm, and the lowest blocking rate is the GMMR algorithm. The MMRA algorithm includes an inter-domain grooming algorithm for inter-domain link search, and the domain is the shortest path search in the domain. The resource distribution changes in each domain are not considered, and the possibility of blocking is greatly increased. The dual-weighted scheme designed by the DWR algorithm provides real-time update of link weights, which does not affect the normal transmission of subsequent work services and reduces the blocking rate. And the GMMR algorithm has lower blocking rate because it determines the path-finding order through the non-cooperative game mechanism. For example, if the link is unavailable, it will be excluded in the game.

7. Conclusions
This paper proposes a multicast routing restoration algorithm in multi-domain optical networks, which optimizes the path-finding sequence and reduces the path-finding scope through the non-cooperative game competition mechanism. Compared with the DWR and MMRA algorithm, it has better
performance in terms of the computation time of recovery path and the blocking rate of multicast recovery service.

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