Optimization of Backbone Optical Network for Power Communication Based on Critical Link

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Abstract. The existing optimization algorithms for power communication backbone optical networks do not comprehensively consider the real-time performance of power communication services and the difference of substation voltage levels, and the optimization results are difficult to meet the actual needs of power communication networks. Firstly, this paper uses the link critical comprehensive index to express the characteristics of critical links, and designs a critical link identification algorithm; then, on the basis of link critical ranking, the network performance is optimized by using link redundancy and link expansion methods; finally, the feasibility and correctness of the method are verified by an example of provincial power backbone optical network. The research results have reference value for the planning, design and operation management of power communication network.

1. Introduction

Power communication backbone optical network is an important support of power communication service, and its performance will directly affect the real-time, reliability and security of power communication service. Critical link refers to the set of optical links which play a key role in the quality of communication services in the backbone optical network of power communication. Link criticality not only has reference value for the planning and design of power optical network, but also can improve the efficiency of network operation and maintenance and reduce the risk of business operation.

In recent years, link criticality identification methods have aroused widespread interest in the research field of optical networks. The research contents are mainly manifested in two aspects: link criticality measure optimization and efficient identification of critical links. Reference [1] gives an analytical expression of network performance, which is used as a link criticality measure. Reference [2] gives another link criticality measure considering service requirements and link traffic. The research achievements in this field also include: link criticality based on dielectric centrality [3] and network efficiency measurement based on current principle [4]. The research achievements of critical link identification mainly include: accelerated identification technology based on edge node pruning [5], link importance identification method based on weighted natural connectivity [6], key link identification of power communication network based on multi-attribute decision making [7] and critical link identification method based on shortest path sensitivity [9]. Literature [8] also applies the
critical link identification results to the capacity design of optical networks. The above research work shows that although the critical link measurement and identification method can solve the optimization problem of general network to a certain extent, the research results on the optimization problem of power communication private network are few. Literature [9] only studies the identification method of critical links, but does not study the network optimization problem.

In this paper, the shortest path delay between nodes is taken as the efficiency measure of power communication backbone optical network, and the comprehensive identification of key links is realized by considering the sensitivity of path delay and the importance level of nodes. On this basis, this paper also studies the method of network optimization through link redundancy and link expansion.

2. Comprehensive Index of Critical Link Identification

2.1. Path Delay Sensitivity

The backbone optical network of power communication can be expressed as an acyclic and weighted undirected graph, \( G = (V, E, R, W) \). Among them, \( V \) is a node set and the number of nodes is \( |V| = m \); \( E \) is a link set, and the number of links is \( |E| = n \); \( R \) is node importance and \( |R| = m \), which is related to substation voltage level; \( W \) is the link delay and \( |W| = n \), which is defined as the overall delay of the link and node.

According to the definition of link shortest path sensitivity in reference [9], the path delay sensitivity of link \( d \) is expressed as

\[
\Delta_d = \frac{2}{m(m-1)} \sum_{s,t \in V} \sum_{r \in SP(s,t)} \frac{\partial}{\partial W_d} w_r
\]

(1)

Where, \( SP(s,t) \) is the shortest path set between nodes \( s \) and \( t \); \( w_r \) is the delay of link \( r \), \( w_r \in W \); \( \sum_{r \in SP(s,t)} w_r \) represents the shortest path delay between nodes \( s \) and \( t \); \( w_d \) is the delay of link \( d \), \( w_d \in W \). Make \( \tau(d,r) = \frac{\partial}{\partial W_d} \sum_{r \in SP(s,t)} w_r \). If \( d \in SP(s,t) \), then \( d = r \), and \( \tau(d,r) = 1 \); otherwise, \( \tau(d,r) = 0 \).

It can be seen that the path delay sensitivity \( \Delta_d \) represents the average number of times that link \( d \) has been passed by the shortest path between all node pairs, which is equivalent to the intermediate centrality of link \( d \). The larger the value of \( \Delta_d \), the more critical the link \( d \) is. It indicates the criticality of links and can be used as one of the identification indicators of critical links.

2.2. Node Importance

The importance of communication stations affects the criticality of links between nodes. Critical links are usually required to be deployed between communication stations with high importance. According to the service quality requirements, service deployment scale and bandwidth requirements of communication stations, the node importance is given by multi-attribute decision-making method. The value range of node importance in typical power communication backbone optical network is \([0.4, 1]\). Among them, the node importance of "provincial dispatching center" is the highest, with a value of 1; the node importance of "local dispatching center" is the second, with a value of 0.9; the importance of other nodes decreases in turn according to voltage level, service scale and bandwidth requirements.

2.3. Comprehensive Quantitative Index of Critical Link

According to the distribution principle of node importance, \( R \) in the graph \( G = (V, E, R, W) \) represents node importance. Considering the path delay sensitivity \( \Delta_d \) of the link in formula (1) and the link end node importance \( R \), the link key comprehensive quantification index is
\[ I_d = \Delta_d \cdot \min_{i,j \in \mathbb{R}} (r_i(d), r_j(d)) \]  

Wherein, \( \Delta_d \) is the path delay sensitivity of the link \( d \); and \( r_i(d) \) and \( r_j(d) \) are node importance degrees at both ends of link \( d \), respectively. The larger the value \( I_d \), the stronger the link criticality. The key links of power communication backbone optical network can be sorted by \( I_d \), so as to realize the identification of key links.

2.4. Critical Link Identification and Network Optimization

2.4.1. Critical link identification. The identification process of critical links is the process of sorting links by using comprehensive quantitative indicators. If the collation is in descending order, the link in front is the more critical link. The arrangement order of critical links can express the influence degree of links on network performance. For the whole network, the lower the average value of link key indicators, the better the network performance.

2.4.2. Network optimization. If the number of network nodes remains unchanged, adding a certain number of links can reduce the average index, which is equivalent to improving the network performance and optimizing the network. The network optimization in this paper is to find a scheme to maximize the performance of the network with the minimum link cost. Generally, link redundancy and link expansion are two effective optimization methods.

1) Link redundancy method

Link redundancy refers to the redundant configuration of a link with similar length on the identified most critical link, so as to relieve the traffic flow of the critical link, thus achieving the purpose of improving reliability and network performance. From equation (1), it can be seen that link redundancy can significantly reduce the critical link’s \( \Delta_d \). In the case of equal probability, link redundancy can reduce \( \Delta_d \) by 50%.

2) Link extension method

Link expansion refers to selecting a certain number of alternative links to add to the network, so as to achieve the purpose of reducing the average index of critical links. In the link expansion method, the basis for optimizing the selection of alternative links is the ranking result of \( I_d \).

3. Critical Link Identification and Network Optimization Method

The flow chart of critical link identification and optimization of power communication backbone optical network is shown in Fig. 1. As can be seen from Fig. 1, the critical link identification and optimization method mainly includes three links.

3.1. Initialization

In this link, network parameters are input, and link delay, shortest path delay and initial network efficiency \( Q \) (average value of shortest path delay between nodes in the whole network) are calculated respectively.

3.2. Path delay Sensitivity Calculation

In this link, for each link \( d \), the path delay sensitivity \( \Delta_d \) of the link is calculated by using equation (1). Then, the importance of nodes is integrated, and the key link quantification index \( I_d \) is calculated by equation (2).
3.3. Network Optimization
According to the key indicators $I_d$ of alternative links, the link can significantly improve the performance of the network, and add it to the network to improve the network performance, to achieve the purpose of network optimization.

![Flowchart of Key Link Identification and Optimization](image)

Figure 1. Key links identification and optimization flowchart.

According to the flow in Figure 1, this paper designs and implements critical link identification and network optimization algorithms based on MATLAB R2014a environment. By calling `graphallshortestpaths(G)` function, the shortest path calculation of the whole network is realized, and the iterative process of path delay sensitivity $\Delta_d$ calculation is avoided. The developed program can meet the critical path identification and optimization requirements of medium-scale power communication backbone optical network.

4. Examples

4.1. Example Description
The instance network includes 144 nodes and 163 initial links. Among them, there are 1 provincial dispatching center, 14 prefecture-level dispatching centers and the number of 750kV substations is 12,
in addition to which there are 330kV, 220kV and 110kV substations of different grades. The instance network has 27 important nodes and 117 general nodes. The importance of each node is selected in the range of [0.4, 1]. The physical length of the optical link is distributed over [2.7, 344] km. The network topology is shown in Figure 2.

![Figure 2. Example power optical network topology.](image)

In Figure 2, red indicates 27 important nodes, and the others are general nodes. The thick lines represent the critical links identified by the algorithm. The thick dotted lines represent the 10 extended links used for optimization.

4.2. Result Analysis

4.2.1 Initial critical link identification. This paper uses the designed method to identify the critical links of the instance network. The links ranked in the top 15 bits of comprehensive key indicators are shown in red and blue thick solid lines in Figure 2. It can be seen that the critical link belongs to the backbone link of the instance network and runs through the whole network, and most important nodes are connected through the critical link.

4.2.2 Critical link optimization. According to the grid structure associated with the example network, this paper determines 20 alternative links. Firstly, the algorithm identifies the key of 20 alternative links. Then, on the basis of the identification results, the first 10 alternative links are selected as extended links, as shown by thick dotted lines in fig. 2; finally, the algorithm identifies the critical links of the network with extended links to verify the optimization effect. Table 1 shows the key link numbers in the top 15 positions before and after optimization. should be numbered with a dot following the number and then separated by a single space:
Table 1. Critical link ranking (top 15).

| Number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
|--------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Before | 66 | 53 | 40 | 77 | 163| 21 | 121| 18 | 75 | 79 | 80 | 82 | 122| 108| 110|
| After  | 66 | 53 | 40 | 75 | 79 | 167| 121| 107| 18 | 180| 181| 132| 77 | 129| 36 |

As can be seen from Table 1, the link expansion method changes the ranking of some key links, but the main key links still remain in the top 15 positions. After link expansion optimization, the key links are divided into levels, as shown by thick lines with different colors in Figure 2.

The basic idea of power communication backbone optical network optimization based on critical link is to select the most critical link among the alternative links and add it to the network, so as to relieve the flow of the original critical link, make the critical link of the whole network tend to balance, and further realize the best overall performance of the network.

5. Conclusion
The comprehensive quantitative index of critical links is the product of link delay sensitivity and node importance, which integrates the comprehensive information of nodes and links. We realize critical link identification by sorting the indicators. The performance of power optical network can be further improved by using link redundancy method and link expansion method. This paper verifies the feasibility and correctness of the proposed method through a provincial power backbone optical network example. The research results have reference value for the planning, design, operation and maintenance of power communication network. The next step will focus on the in-depth study of critical link optimization algorithms.

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