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ABSTRACT

The developed method of optimal design of flexible optical networks takes into account various factors and goals to ensure efficient use of resources, high performance, scalability, and adaptability. A mathematical model is developed to determine the key parameters of the fiber optic linear network route. The topology of the route of a fiber-optic linear network based on the proposed matrix model is proposed. An algorithm for using the matrix model of parameters based on the proposed variant of the fiber-optic linear network route is developed. The application of a systematic approach using the proposed method will allow network designers to achieve optimal design of flexible optical networks that efficiently use resources, provide high performance, as well as scalability and adaptability necessary for future growth and technological progress.

Keywords: flexible optical network, fiber-optic linear network path, fiber-optic communication system, matrix model

1. INTRODUCTION

The utilization of coherent ultra dense wavelength division multiplexing (UDWDM) in the PON system enables the transmission of multiple high-speed signals over a single optical fiber, resulting in increased network capacity. With the ability to transmit 4 × 25-Gb/s signals, the system can support a substantial number of subscribers (more than 1,000) over a significant distance (50 km)[1]. Achieving a downlink power budget of more than 44 dB indicates that the system has sufficient optical power to ensure signal quality and accommodate the required number of subscribers. This power budget refers to the difference between the received signal power and the minimum power required for proper detection and decoding at the receiver. A higher power budget allows for better signal integrity and supports reliable communication. Considering the achievements, coherent technologies are considered a future-proof option for next-generation optical access networks. Their ability to deliver high capacity, long reach, and support for a large number of subscribers positions them as a viable and promising solution. As data demands continue to grow and access networks require higher performance, coherent technologies offer the potential to meet these evolving requirements[1].

The deployment of coherent optics in access networks offers high bandwidth capabilities that surpass other optical technologies. To fully leverage this technical superiority, it is crucial to explore various use cases that can make the most of the enhanced capabilities provided by coherent optics.

Enterprises, network operators, and data centers are examples of high bandwidth users that can directly benefit from the substantial capacity enabled by coherent optics. These entities may have specific requirements for high capacity connections to support their operations efficiently.

For access-network operators, a common approach is to aggregate multiple end points into a single large pipe, capitalizing on the scalability offered by coherent optics. By consolidating multiple connections, access-network operators can efficiently utilize the high capacity provided by coherent optics and cater to the increasing demands of their subscribers. Initially, point-to-point (P2P) Coherent Optics links are used for aggregation purposes in access networks.

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These links connect individual endpoints to a central aggregation point. However, it is expected that P2P Coherent Optics will evolve into point-to-multipoint (P2MP) Coherent Optics in the near future. This transition will enable access-network operators to efficiently serve multiple endpoints from a single central location, further optimizing network resources[2].

1.1 Research objectives and tasks

The aim of this work is to develop a universal method for the efficient design of fiber optic network transmission paths based on a matrix model of key parameters of linear paths. To achieve the given goal, the following tasks need to be solved:

- to develop a mathematical model for determining the key parameters of the fiber-optic linear network path;
- to propose the topology of the fiber-optic linear network path based on the proposed matrix model;
- to propose an algorithm for using the matrix model of the parameters of the developed version of the fiber-optic linear network path.

2. BASIC RESEARCH MATERIAL

The development of the component base in optical transport networks is crucial for building network elements that possess several desirable characteristics such as flexible functionality, high throughput speed capabilities, energy efficiency, and compact mass-size indicators. These components serve as the foundation for the construction of optical transport network infrastructure[3,4,5].

Among the multiplexers, CDC-ROADM (Reconfigurable Optical Add-Drop Multiplexer) type multiplexers stand out. These multiplexers offer maximum flexibility in optical connections, ensuring there is no blocking of connections. This means that optical channels can be added, dropped, or rerouted without any disruption to the existing connections. The CDC-ROADM multiplexers enable efficient and versatile optical network operations.

In terms of routing, both static and dynamic routing techniques are utilized for optical channels with different bandwidths. Static routing involves predetermined paths that remain fixed, while dynamic routing provides even more effective resource utilization. Dynamic routing allows for the optimization of optical connections between network nodes by dynamically adjusting the paths based on demand. This ensures the most favorable use of optical resources within the network. In summary, the development of the component base in optical transport networks enables the construction of network elements with flexible functionality, high throughput speeds, energy efficiency, and compact sizes. The integration of electronic and optical components has led to the creation of advanced transponders and multiplexers, including CDC-ROADM multiplexers that provide maximum flexibility and eliminate connection blocking. Furthermore, the use of static and dynamic routing techniques optimizes the utilization of optical resources in the network[6].

In the development of a flexible optical network, utilizing solutions that maximize the use of optical fiber resources is important. This includes considering wavelength ranges for optimal resource utilization, ensuring non-blockable connections in switches, and employing suitable modulation schemes and error correction techniques in the construction of optical modules. Additionally, choosing forward error correction (FEC) and coding schemes for linear signals can improve transmission speeds and channel organization distances.

One of the most promising directions for the development of communication network management, regardless of scale, is based on Transport Software-Defined Networking (T-SDN) technology. T-SDN allows for centralized control and programmability of network resources, offering significant benefits in terms of flexibility, scalability, and resource optimization. At present, T-SDN is in the process of being adopted as part of international standards and protocols.

Currently, T-SDN technology is in the experimental stage of operation within the networks of individual operators, utilizing equipment from various manufacturers. This experimental operation allows operators to evaluate and fine-tune the technology under real-world conditions.

Notably, many leading manufacturers in the industry, catering to transportation networks, mobile networks, mobile communication networks, data centers, and other types of networks, have integrated SDN/T-SDN controllers into their equipment. These controllers provide advanced capabilities for network management, enabling operators to efficiently configure and control their networks. To fully benefit from T-SDN technology and the capabilities of SDN/T-SDN controllers, it is essential for network operators and administrators to study and understand the functionalities and features of these controllers. By doing so, they can effectively implement T-SDN in their networks, leading to improved network performance, better resource utilization, and enhanced overall network management.

In conclusion, the constant improvement of control systems in transport communication networks is driven by the development of innovative software products and control protocols. T-SDN technology represents a highly effective direction for managing communication networks of any scale, and its adoption is progressing through international standards and experimental operation by individual operators with diverse equipment. Utilizing SDN/T-SDN controllers in the equipment offered by leading manufacturers is key to successfully harnessing the potential of T-SDN technology in practice. By leveraging T-SDN management functions, data center interconnection schemes can achieve efficient resource utilization, dynamic provisioning, optimized traffic engineering, and effective management of service-level agreements. This enhances the overall performance, scalability, and flexibility of the interconnected data centers, leading to improved data center operations and better user experience (fig. 1)[7].

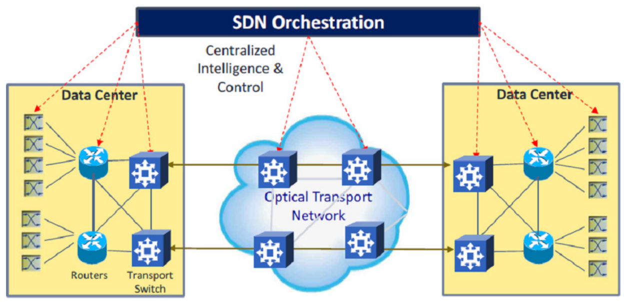

Figure 1. The data center interconnection scheme via a transport network with T-SDN management functions.

When designing optical networks, it is essential to consider the parameters of energy and frequency characteristics of the fiber-optic linear path. Here are some key peculiarities to keep in mind: Link Budget Analysis; Dispersion Compensation; Wavelength Division Multiplexing (WDM); Nonlinear Effects Mitigation; Fiber Quality and Characterization; Network Scalability[8].

By taking into account the parameters of energy and frequency characteristics in the design process, optical networks can be optimized for efficient and reliable signal transmission, meeting the specific needs of the application and supporting future network requirements.

To determine the optimal parameters of fiber optic linear paths, a matrix model can be used. In this context, the matrix model refers to a mathematical representation that helps analyze the performance of the fiber optic system based on various parameters.

It's important to note that creating a comprehensive matrix model for fiber optic systems can be complex and may require expertise in optical communication and signal processing. Additionally, real-world fiber optic systems may involve other practical considerations, such as environmental factors and manufacturing tolerances, which may need to be incorporated into the model for more accurate results.

3. MATHEMATICAL MODEL FOR DETERMINING THE OPTIMAL FREQUENCY-ENERGY PARAMETERS

The proposed mathematical model for determining the optimal frequency-energy parameters of fiber-optic linear paths can be represented by the expression

$$A_{mn} = \begin{pmatrix} a_{ij} & \cdots & a_{in} \\ \vdots & \ddots & \vdots \\ a_{mj} & \cdots & a_{mn} \end{pmatrix} \qquad (1)$$

where a_{ij} – parameter of energy and frequency characteristics of the fiber optic linear path;

i – the number of the accumulated dispersion correction node on the regeneration section of the fiber-optic linear path, the range of values $(1 \div n)$;

j – number of the energy potential correction node on the optical amplification section of the fiber-optic linear path, range of values $(1 \div m)$.

As a general guideline, the number of dispersion compensation nodes on the regeneration section can range from a few nodes for shorter distances to several nodes for longer distances. It is essential to perform detailed link budget analysis, taking into account the dispersion characteristics of the fiber and the specific network requirements, to determine the optimal placement and number of dispersion compensation nodes.

Network designers and operators should consider these factors and work with experienced optical engineers to optimize the dispersion compensation strategy and ensure reliable signal transmission over the entire fiber-optic linear path.

In the optical amplification section of a fiber-optic linear path, the number of energy potential correction nodes, commonly known as optical amplifiers, depends on various factors such as the length of the amplification section, signal attenuation, and the desired signal quality.

The normalized matrix of parameters of the fiber-optic linear network path can be determined using the following formula:

$$A_{mn}^{N} = A_{mn} \cdot Q \cdot K \tag{2}$$

where Q – the reliability factor of a fiber-optic linear network path;

It is important to note that the specific form of the matrices and the normalization procedure may vary depending on the specific parameters being considered and the characteristics of the optical system under investigation. The above formula provides a general framework for normalizing the matrix of parameters but may need to be adapted to suit the specific requirements of the fiber-optic linear network path.

Reliability in fiber-optic networks is a critical aspect as disruptions or failures in the network can lead to data loss, service interruptions, and significant financial consequences. The reliability factor is commonly expressed as a percentage, representing the likelihood of the network path being operational over a specified time frame.

The reliability factor of a fiber-optic linear network path can be calculated through reliability analysis, taking into account the reliability metrics of individual components and considering the redundancy and topology of the network. The goal is to design and maintain the network in a way that maximizes reliability and minimizes the risk of failures or downtime.

To evaluate and optimize the error rate in a fiber-optic linear network path, thorough testing and performance analysis are necessary. Bit error rate (BER) testing is a common method used to measure the error rate in fiber-optic communication systems. Additionally, careful network design, component selection, and maintenance practices are essential to ensure low error rates and reliable data transmission in the network.

4. THE TOPOLOGY OF A FIBER-OPTIC LINEAR PATH BASED ON THE MATRIX MODEL

The topology of a fiber-optic linear path based on the matrix model of a telecommunications network is typically a point-to-point or point-to-multipoint configuration. This means that there is a direct transmission path from a single transmitter to one or more receivers, with no intermediate branching or looping of the fiber.

The topology of a fiber-optic linear path based on the matrix model of a telecommunications network is shown in Fig. 2.

In the matrix model, the fiber-optic linear path is represented as a sequential arrangement of optical elements, where each element has a corresponding matrix that describes its properties and effects on the transmitted signal. These elements can include transmitters, fiber links, amplifiers, dispersion compensation modules, and receivers.

The topology can be visualized as a linear progression of the optical elements, where the signal flows from the transmitter to the receiver(s) in a unidirectional manner. Each element in the path affects the signal as it passes through, and the composite matrix multiplication captures the cumulative transformation of the signal.

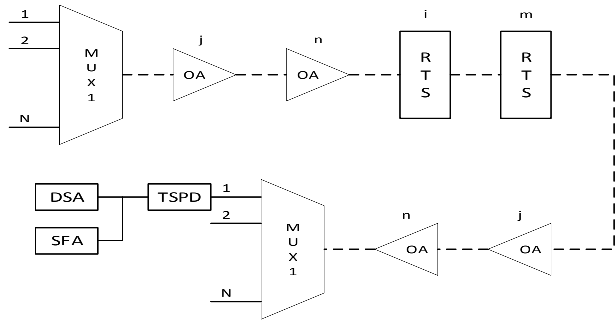

Figure 2. The topology of a fiber-optic linear path based on the matrix model of a telecommunications network

The matrix model can accommodate various network topologies by incorporating the appropriate matrices for each optical element. This enables the analysis and optimization of the overall performance of the fiber-optic network, including signal quality, power levels, and dispersion management.

It is essential to strike a balance between coding efficiency (adding redundancy) and the overall data rate, as more redundancy can reduce the effective data transmission rate.

The algorithm for applying the proposed matrix model in developing the optimal topology of the fiber-optic linear path of a telecommunications network is shown in Fig. 3.

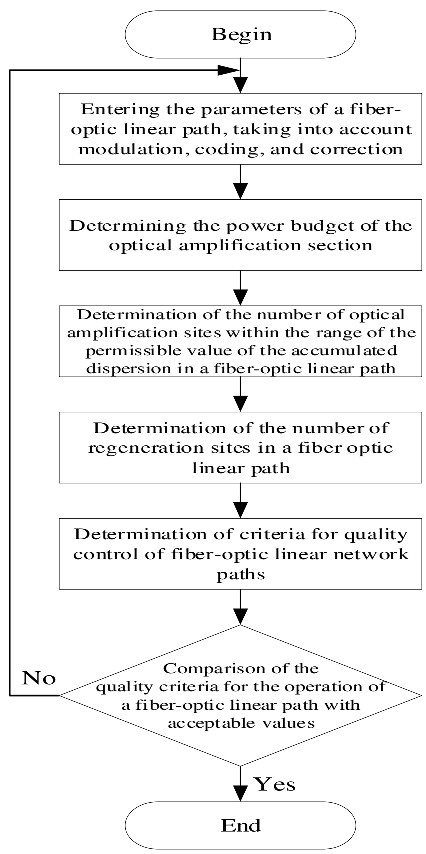

Figure 3. The algorithm for applying the proposed matrix model in developing the optimal topology of the fiber-optic linear path of a telecommunications network.

When designing a fiber-optic linear path, factors such as the length of the fiber, the quality of the optical components, the signal-to-noise ratio, and the complexity of the system will influence the choice of modulation, coding, and error correction techniques to ensure reliable and efficient data transmission. The specific parameters chosen for a given system will depend on the application requirements and the available resources.

Designing a fiber-optic communication system with a suitable power budget is crucial to maintain signal integrity and achieve reliable data transmission over the desired distance.

It's important to note that dispersion management in a fiber-optic system is a complex task, and multiple factors, including signal rate, modulation format, and fiber characteristics, can affect the overall system performance. Additionally, practical considerations, such as amplifier spacing and signal quality requirements, also play a role in determining the number and placement of amplification sites.

5. DISCUSSION OF RESULTS

It's important to note that regeneration sites amplify and reshape the optical signal, effectively resetting its quality to its original state. This process helps mitigate the effects of signal attenuation and other impairments that accumulate over long transmission distances.

Comparison of quality criteria for the operation of a fiber-optic linear path with acceptable values depends on the specific application, transmission distance, and technology used. It's important to note that the acceptable values can vary depending on the network's specific requirements, technology, and application. Additionally, as fiber-optic technology advances, acceptable values may change over time.

Developing the optimal topology of a fiber-optic linear path in a telecommunications network using the proposed matrix model involves an iterative process that considers various factors and objectives. While there is no fixed algorithm, here is a general outline of steps that can be followed.

Begin by clearly defining the requirements and objectives of the telecommunications network. This includes considerations such as data rate, transmission distance, reliability, signal quality, and budget constraints. Understanding these requirements will help guide the optimization process.

Identify the key elements that will be part of the fiber-optic linear path, such as transmitters, fiber links, amplifiers, dispersion compensation modules, and receivers. Determine the properties and characteristics of each element and represent them as matrices in the matrix model.

Start with an initial topology based on the defined network requirements and available resources. This may involve connecting the elements in a linear fashion from the transmitter to the receiver(s). Assign the corresponding matrices to each element in the topology.

Use matrix multiplication to calculate the composite matrix representing the overall transformation of the optical system. This composite matrix captures the cumulative effects of the elements in the path. Analyze the parameters derived from the matrix, such as transmission coefficients, reflection coefficients, dispersion, and polarization effects, to evaluate the performance of the initial topology.

Assess the performance of the initial topology against the defined network requirements. Identify areas where improvements are needed, such as optimizing signal power, minimizing attenuation, managing dispersion, or maximizing reliability. Use the parameters derived from the matrix calculations to quantify the performance.

Modify the topology by adjusting the arrangement and properties of the elements based on the evaluation from the previous step. This can involve adding or removing elements, changing their characteristics, or introducing redundancy. Update the matrices accordingly and repeat the matrix calculations.

Analyze the performance of the optimized topology using the matrix model. Compare the performance metrics with the network requirements and evaluate if they meet the objectives. Iterate this process by making further adjustments to the topology until the desired performance is achieved.

Once an optimized topology is obtained, verify its performance through simulation or practical testing. Measure the actual parameters and compare them with the predicted values from the matrix model. Fine-tune the topology if necessary based on the verification results.

It's important to note that the algorithm may vary based on the specific network requirements and the complexity of the fiber-optic linear path. Additionally, real-world considerations such as cost, scalability, and compatibility with existing infrastructure should be taken into account during the optimization process.

Please note that the actual implementation of the algorithm will depend on the programming language and tools you choose. Additionally, real-world fiber-optic network design may involve more complex considerations, such as dispersion, nonlinear effects, and network redundancy, which are not covered in this simplified model. Professional network planning software and consultation with experts are recommended for practical network design.

6. CONCLUSIONS

The developed method for optimal design of flexible optical networks takes into account various factors and goals to ensure efficient use of resources, high performance, scalability, and adaptability. The effectiveness of the method is due to the proposed mathematical model of the key parameters of the fiber-optic linear network path. The practical significance of the model is analyzed on the topology of the fiber-optic linear network path. An algorithm for using the matrix model of the parameters of the fiber-optic linear network path is proposed. The application of a systematic approach using the proposed method will allow achieving the optimal design of flexible optical networks that efficiently use resources, provide high performance, as well as scalability and adaptability necessary for future growth and technological progress.

By implementing flexible optical networks with dynamic bandwidth management, operators can achieve cost-effectiveness, energy efficiency, and high adaptability. Such networks are particularly valuable in connecting base stations for 5G generation mobile communications, where the demand for bandwidth and flexibility is significantly higher compared to previous generations.

In conclusion, the flexibility of optical transport networks relies on the combination of physical components and advanced algorithmic software, with T-SDN being a promising solution. As data traffic and connectivity demands continue to rise, the development of these technologies will play a crucial role in building efficient, adaptive, and future-proof optical networks, especially in access networks and their application in 5G mobile communications.

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