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Fault Detection and Localization in Optical Transport Network Using Machine Learning Technique: A Review

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ABSTRACT: Optical transport networks (OTNs) play an important role in achieving high-speed data transport. But rising complexity and traffic increase inefficiency in fault management using conventional rule-based approaches due to the inability of precise fault detection and identification. Machine learning (ML) can serve as a promising tool for the automation of fault analysis. This paper provides a comprehensive literature review of fault detection and localization methods in OTNs based on machine learning techniques, including supervised learning, unsupervised learning, deep learning, ensemble learning, and graph-based learning approaches. Several machine learning algorithms such as SVM, ANN, CNN, LSTM, random forest, and XGBoost are compared by network parameters, like BER, OSNR, QoT. Also, several open research questions are discussed, along with possible ways to solve them in future research.

KEYWORDS: Optical Transport Network, Fault Detection, Fault Localization, Machine Learning, Optical Network Management, Alarm Correlation, BER, OSNR, Quality of Transmission.

I. INTRODUCTION

The Optical Transport Networks (OTN) are used today in advanced communication infrastructures where high amounts of information are transferred over long distances. Because it provides efficient, transparent, and reliable transport of massive data volumes, such as 100G, 400G, and beyond. The OTN layered structure allows to carry different traffic type of client traffic (Ethernet, SDH/SONET) over optical channels. It enables It has three primary layers Optical Channel (OCh), Optical Multiplex Section (OMS) and Optical Transmission Section (OTS) which provides the network flexibility and scalability but at the same time, it creates problems for the monitoring and fault management process. [1–3]. Even though optical networks come with their own strengths, they can be easily affected by failures ranging from fiber cuts, equipment failure, signal degradation and even improper configuration settings. In Optical Transport Networks (OTN), often triggers a cascade of interrelated alarms across different network layers, creating an "alarm storm" that complicates the root cause. The current approach relies on the manual investigation & due to increase in network size and complexity of optical networks, manual investigation of alarm logs and performance metrics, manual method that takes a lot of time which result in in delayed fault localization and increased service downtime and also needs domain knowledge [4–7].

The recent advancements in the field of ML have led researchers to explore its use in the effective management of faults in optical networks. ML algorithms can be trained to examine huge amounts of data generated by network & identify the unusual patterns that might lead to network failure. Alarms, performance parameters like BER, OSNR, and QoT can be given as inputs to the machine learning models to identify abnormal behavior and anticipate faults. Several different methods, including SVMs, ANN, CNN, LSTM, and ensemble learning, have been used in this domain to improve the fault detection and monitoring in optical networks [8–15].



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However, current research in most cases concentrates more on fault detection than localization. Also, some studies use only a few monitoring metrics or simulation data sets, making them less effective in practical scenarios. Hence, it is necessary to propose a more intelligent framework that integrates multiple layers of monitoring data, correlates alarms from the network, and uses intelligent algorithms to detect and localize faults in an Optical Transport Networks [16].

Fault detection and localization of faults is important to ensure reliability and continuity of services in Optical Transport Networks. Because of the complexity of network topology and high volume of monitoring data, conventional approaches become ineffective. Using machine learning algorithms, automation of processing network parameters and fault detection and localization can be achieved [1, 2, 4, 6].

II. CONTRIBUTIONS OF THE SURVEY

The scope of this paper includes the review of machine learning methods used in fault detection and localization within Optical Transport Networks (OTNs). Due to the growing complexity of modern optical communication systems, there are some difficulties in using conventional rule-based methods for fault detection and fault localization. As a result, the development of machine learning methods can be seen as one of the effective tools for processing large amounts of data regarding network faults and enabling intelligent fault management in OTNs. The purpose of this survey is to highlight the current trends and challenges in machine learning methods for fault detection and localization.

To summarize, the survey includes the following contributions:

- A brief description of optical transport networks (OTN) and their typical faults is presented, along with the application of machine learning techniques in fault detection and localization.
- Qualitative analysis of machine learning techniques for optical network fault management via alarm information, network parameters, and performance.
- Categorizes recent researches on ML-based fault detection and localization techniques into supervised learning, unsupervised learning, and deep learning.
- Comparison between different papers based on machine learning techniques, datasets used, implementations, and evaluation criteria. Concluding remarks with discussion on challenges faced and future research directions.

III. RELATED WORK

A number of scholarly works have explored the use of machine learning algorithms for better failure management in optical networks.

Musumeci et al. Machine learning tutorial for optical network failures management that includes performance measurement, prediction, detection, localization, and identification was presented. While the proposed method demonstrated high efficiency in performing all these functions, the study mainly concentrated on theory development and did not propose an actual OTN fault localization model [1].

A study by Musumeci et al. discussed machine learning approaches like neural networks, SVM, and clustering algorithms for Optical Network Management. But there was no discussion on fault localization in OTN networks with multiple layers [2].

Jiao et al. introduced the FACT-FL algorithm to detect the location of faulty optical device boards in OTN networks through alarm correlation and integer linear programming. While the algorithm enhances fault localization, it is only concerned with device board failure detection and does not employ machine learning for multi-source monitoring [3].

Cruzes on how failure management is done in optical networks, while also emphasizing how machine learning can be used in order to automate some of the processes in network management. Several techniques were identified in the paper regarding the use of machine learning, which included the use of neural networks, support vector machines, and generative approaches. Nevertheless, the research did not come up with an intelligent framework for fault detection in OTN [4].

Michel et al. have explored the issue of alarms' classification and correlation in SDH/WDM optical networks. Unsupervised learning methods such as K-Means clustering and DBSCAN have been used in this study to detect any



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possible correlations between the alarms and to pinpoint the source of the network failure. Even though this technique enhances the effectiveness of alarm analysis, it fails to take into account the performance monitoring data [5].

Mohammed et al. This paper has utilized Machine learning algorithms like Decision Tree, Gradient Boosting, and XGBoost were applied to automatically classify network faults. While high precision in fault detection was attained, most emphasis was put on network status classification instead of determining the actual cause of faults. [6].

Patri et al. studied the application of machine learning techniques for detecting failures in optical spectrum-as-a-service systems. This research compares artificial neural networks with one-class support vector machines by analyzing monitoring data that was collected through flexible bandwidth transceivers. Although this technique enables successful detection of network anomalies, its effectiveness is limited due to insufficient monitoring data [7].

Abdelli et al. An approach to detect and localize the anomalies present in optical fibers using Autoencoder and BiGRU models is proposed. This method performs well in terms of accuracy but has been applied mainly to detect fiber-level anomalies and not network-level faults [8].

Machine Learning for Prediction of QoT in DWDM Optical Network has been analyzed by Sakthivel et al. In their study, different methods such as Support Vector Machine, Neural Networks have been used to predict BER and other parameters of transmission quality. Although the proposed technique helps in estimating performance and planning of the optical network, it does not directly address the detect and localize any faults within the network [9].

Titouni et al. presented a novel approach named CNN-Ensemble, which combines convolutional neural networks for feature extraction along with ensemble classifiers including random forest, support vector machine, and XGBoost for classifying fiber faults. Experimental studies showed significant fault detection accuracy; nevertheless, the research mainly concentrated on fiber fault detection rather than fault localization OTN in network [10].

Soothar et al. performed a comparative analysis of various machine learning and deep learning approaches to detect optical fiber faults. In this research, the classifiers used were logistic regression, support vector machine, random forest, and the hybrid approach of CNN and LSTM for the detection of different types of fiber faults. Despite the fact that the outcomes indicate significant classification performance, it does not discuss any fault correlation among the network [11].

A deep learning technique based on convolutional neural networks was developed by Lun et al. in order to detect soft failures in optical networks used for long-distance communication. This method makes use of the power spectrum density information extracted by the coherent receiver in order to detect the causes that led to the failure. Although the technique has been successful, it needs lots of data to generalize across other environments [12].

Pardhi et al. discussed the design of fault identification systems in optical transport network systems with the use of neural networks. In their review paper, they pointed out the current methods used to detect faults and the advantages that can be achieved by utilizing artificial neural networks for fault location. However, their discussion is mostly theoretical [13].

Pardhi and Dhande proposed model is based on CNN for identifying faults in optical transport network was proposed. The proposed CNN model identifies and localizes faults through analysis of network parameters. Even though CNN method exhibits promising results, the work is based on few fault conditions only and lacks multilayered monitoring data [14].

The Abdula et al. group carried out a systematic literature review on the applications of machine learning for fault diagnosis and detection in optical fiber communication systems. The review involved an analysis of several machine learning algorithms such as neural networks, SVMs, and LSTM. Despite offering useful information on machine learning applications, the review is primarily concerned with optical fiber communication systems and not OTNs [15].

Fault localization technique based on knowledge graphs and graph neural networks was presented by Li et al. According to their research, the new technique uses knowledge graphs to model the connections between alarms and employs graph neural networks for root cause analysis of network faults. Even though this technique is efficient in modeling alarm associations, it necessitates significant knowledge base creation efforts [16].



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IV. RESEARCH GAP

Paper	ML Model	Input Features	Dataset	Fault Type	Research Gap
[1]	ML framework	Monitoring parameters	Conceptual	Network faults	No practical OTN implementation
[2]	SVM, Neural Networks	Network telemetry data	Survey datasets	Network monitoring	Does not address fault localization in multi-layer OTN architecture
[3]	FACT-FL	Alarm correlation patterns	Alarm datasets	Device board failures	Does not incorporate machine learning models for prediction
[4]	ML overview	BER and QoT metrics	Conceptual analysis	Network failures	Provides conceptual discussion without implementation
[5]	K-Means, DB-SCAN	Alarm logs and timestamps	Optical network logs	Alarm fault detection	Does not integrate Topology and performance parameters
[6]	Decision Tree, XG-Boost	Network performance metrics	Emulated datasets	Network status faults	Limited root-cause analysis for optical transport networks
[7]	ANN, OneClass SVM	Optical signal parameters	Telemetry datasets	Signal anomalies	Uses limited monitoring features for fault localization
[8]	Autoencoder + Bi-GRU	OTDR signal characteristics	Fiber monitoring datasets	Fiber anomalies	Focuses mainly on physical fiber layer monitoring
[9]	SVM-based model	BER and Q-factor	DWDM simulation datasets	QoT degradation	Does not address fault detection or localization
[10]	CNN + Ensemble Learning	Optical signal characteristics	OTDR datasets	Fiber faults	Limited to fiber-level fault detection
[11]	RF, CNN-LSTM	Optical signal parameters	Fiber datasets	Fiber classification faults	Does not analyze network-wide fault correlations
[12]	CNN-based model	Spectral signal features	Receiver monitoring datasets	Soft failures	Requires extensive monitoring data
[13]	ANN-based survey	Alarm monitoring parameters	Literature review	OTN fault analysis	No experimental validation provided
[14]	CNN-based model	Network performance parameters	Simulated OTN datasets	OTN faults	Limited number of fault scenarios considered
[15]	ML review framework	Monitoring data	Multiple datasets	Fiber communication faults	Focus mainly on Fiber networks rather than OTN architecture
[16]	Knowledge Graph + GNN	Alarm relationship graphs	Network alarm datasets	Root-cause faults	Requires complex knowledge base construction



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V. OPTICAL TRANSPORT NETWORK ARCHITECTURE

Optical Transport Network (OTN), defined by the ITU-T G.709 standard, ensures effective and reliable transfer of high-speed data using an optical network system. The OTN makes use of digital wrapping to transfer client traffic such as Ethernet, SONET/SDH, and IP services as Optical Data Units (ODUs). OTN not only enables effective transfer but also offers functionality for fault detection and protection.

5.1 Overview of Optical Transport Network

An Optical Transport Network is made up of transponders, multiplexers, optical switches, and DWDM systems which carry out the functions of signal creation, multiplexing, switching, and transmission. The client signals are transformed into optical signals by transponders, while DWDM allows the multiplexing of several optical channels to facilitate the concurrent transfer of data via one fiber optic cable.

Nodes of OTN networks like optical cross connects and ROADMs provide the facility of switching and routing the optical channels throughout the network, as illustrated in Fig. 1. This design allows for optimized use of the available bandwidth and traffic management.

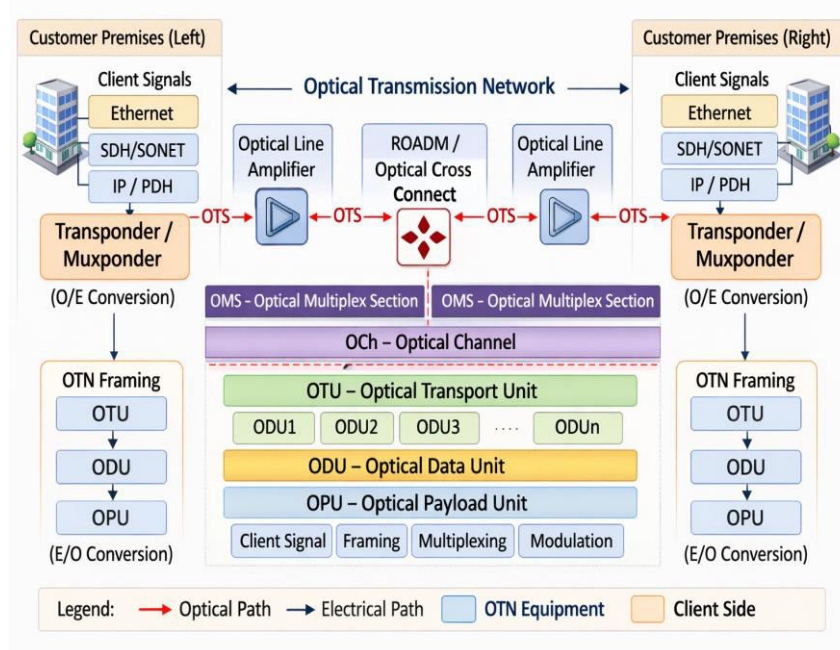


Figure 1: Optical Transport Networks

5.2 Fault Monitoring in Optical Transport Networks

Fault detection is a crucial part of Optical Transport Network (OTN) systems, where abnormal situations and faults can be identified. OTN equipment provides alarm notifications and performance monitoring information about network components, including transponder units, multiplexer units, optical switches, and Reconfigurable Optical Add-Drop Multiplexers (ROADMs). Some alarms include loss of signal (LOS), loss of frame (LOF), and degrading signal alarms. The optical power, Optical Signal to Noise Ratio (OSNR), and Bit Error Rate (BER) can also be monitored to measure the quality of signals. However, in large optical networks, a single hardware fault can cause multiple correlated alarms in various network components.

Monitoring solutions like Element Management System (EMS) and Network Management System (NMS) combine alarm and performance information from many devices in the network. Such solutions provide centralized monitoring facilities and allow the NOC operators to evaluate the performance of the network as illustrated in Fig. 2.



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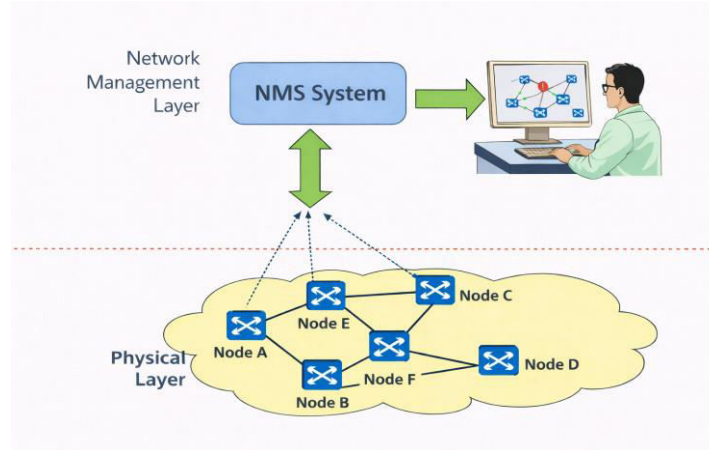


Figure 2: Optical Transport Networks

5.3 Fault Types in Optical Transport Networks

Failures within optical transport networks may take place in various layers in the network architecture and can have serious impacts on the communication system.

Common faults in OTN include:

- Physical optical link failures or Fiber cuts
- Degradation in optical signal
- Malfunctioning of Optical Switch/Transponder.
- Malfunctioning of Optical Line Driver/Optical Amplifier.
- Board/Equipment Failure
- Configuration Issue.

These faults leads to total signal loss, errors in transmission line or complete signal transmission disruption which resulted in network failure if not detected correctly.

5.4 Challenges in Fault Detection and Localization

Detection of faults is done by finding out any unusual status within the network, and localization is the process of identifying the faulty network component. OTNs are faced with difficulties during fault localization due to their complicated structure and dependencies. Fault management using conventional methods involves rule-based alarm correlation and human intervention, which tends to be less efficient in a large network environment. With massive amounts of data being monitored, the complexity of fault diagnosis is greatly elevated.

VI. MACHINE LEARNING APPROACHES FOR FAULT DETECTION AND LOCALIZATION IN OPTICAL TRANSPORT NETWORKS

Machine learning methods have become more popular lately as part of efforts to enhance the process of detecting and locating faults within optical transport networks. In contrast to traditional rule-based systems used for monitoring the network, ML techniques can process vast amounts of information to discover patterns of faults.

OTN elements' monitoring information generally includes alarm messages, signal power, bit error rates, optical signal-to-noise ratio, and other parameters. Such information can be processed by ML methods to discover abnormal patterns in network behavior and locate the source of such faults.

Fig. 3, Both supervised and unsupervised learning methods can be applied for anomaly detection. In addition, graph-based and deep learning methods play an important role in the accurate identification of network faults and alarms' correlations in optical networks.



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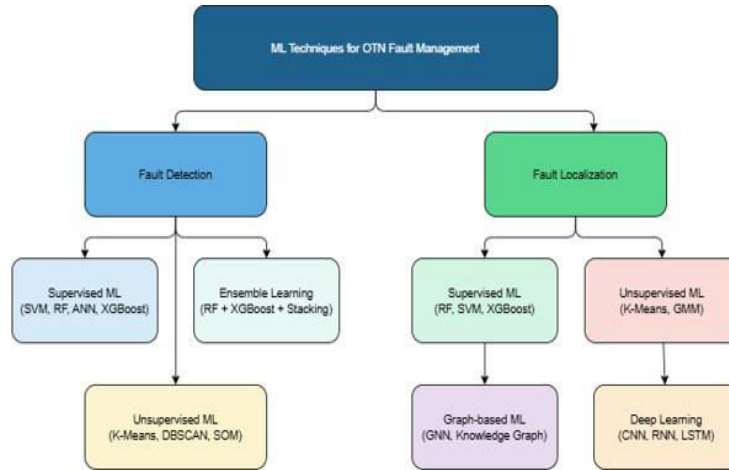


Figure 3: ML for Fault Detection and Localization in Optical Transport Networks

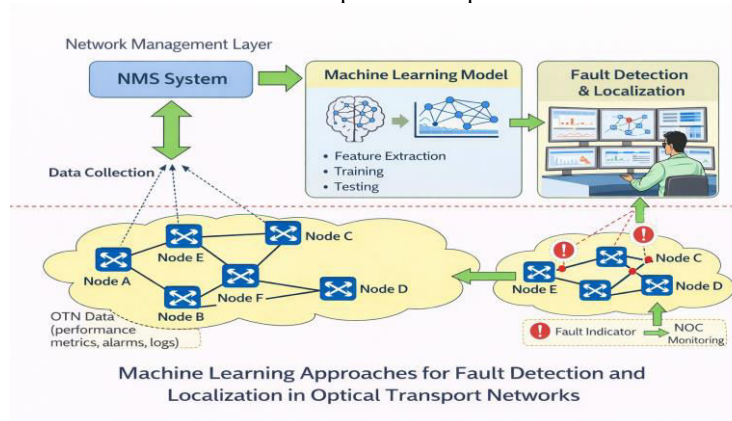


Figure 4: Fault Management with ML

The network visualization shown in Fig. 4 provides a clear picture of the fault localization output provided by the machine learning algorithm, with the key nodes and impacted connections being indicated. The output facilitates rapid problem identification and resolution by the NOC user.

6.1 Supervised Learning-Based Approaches

Supervised learning techniques have been employed by many researchers to classify and localize faults in an optical network. The technique helps in establishing correlations between monitoring parameters and faults such as fiber cuts, degraded signals, or equipment failure. The effectiveness of the technique, however, relies greatly on the availability of quality training data.

6.2 Unsupervised Learning-Based Approaches

Unsupervised machine learning techniques identify anomalies within an optical communication network using unlabeled datasets by recognizing deviations from the norm within patterns. The clustering technique involves forming clusters based on network behavior and then finding clusters that contain abnormal patterns due to network problems.

6.3 Deep Learning-Based Approaches

CNN and RNN-based techniques are popular choices for fault detection and localization within optical transport networks. These approaches can detect intricate patterns in fault data and the non-linearity within them without any prior knowledge. The RNN-based technique is highly proficient at handling sequential data from networks. Deep learning algorithms need huge amounts of data and high computational power for processing.



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6.4 Comparative Discussion of Machine Learning Techniques

Various machine learning methods have their own benefits in diagnosing and localizing faults in Optical Transport Networks. Supervised learning helps diagnose fault location based on labeled data, whereas unsupervised learning diagnoses problems by detecting anomalies using unlabeled datasets. Deep learning can diagnose complex faults by analyzing big data including alarms and network performance.

VII. FUTURE RESEARCH DIRECTIONS

Despite advances in machine learning algorithms that enhance fault detection and localization in optical transport networks, many problems still exist.

7.1 Real-time Fault Detection and Localization

Further research should be dedicated to creating real-time fault detection and localization systems that will allow for immediate processing of data from network monitoring.

7.2 Scalable Network Monitoring Framework

With the expansion and increased complexity of optical transport networks, it is essential to create scalable frameworks that will allow for efficient processing of massive amounts of data from networks.

7.3 Intelligent Fault Detection and Recovery

The combination of machine learning and SDN can lead to the creation of intelligent networks that detect, localize, and recover faults in optical transport networks.

7.4 Dataset Standardization for Optical Network Faults

The absence of open source datasets containing information about optical network faults is one of the key barriers to research in this field. Dataset standardization would greatly facilitate research.

7.5 XAI for Root Cause Analysis

Deep learning algorithms employed in fault prediction face the challenge of being a black box, which hinders explainability and interpretability. The future direction of this area should focus on the integration of Explainable Artificial Intelligence (XAI), which will allow for increased explainability of the deep learning algorithms. XAI algorithms generate interpretable results that enable effective fault identification and management.

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