Research and Design of Intelligent Operation and Maintenance Management System for Communication Equipment Rooms

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Abstract. With the rapid development of communication networks, traditional operation and maintenance (O&M) practices for communication equipment rooms face numerous challenges. This paper proposes an intelligent management system design for communication equipment rooms based on a hierarchical architecture and intelligent-driven technologies. By constructing a three-dimensional collaborative framework of "management domain–business domain–technical domain," the system achieves an O&M mode upgrade from passive response to active prediction and from experience-driven to model-driven approaches. Through practice, this system will directly promote the improvement of the operation and maintenance efficiency of the communication room.

Keywords: Intelligent O&M; Communication equipment room; Management system; System design

1 Introduction

As an important component of modern communication networks, communication rooms are responsible for the aggregation and exchange of network data, and their safety and stability directly affect communication service quality and user satisfaction. In communication networks, communication rooms vary greatly in function and equipment types. They can be divided into large, medium, and small communication rooms based on the volume of business. Large communication rooms, serving as backbone nodes of communication networks, handle massive data processing and cross-regional connectivity functions. Medium-sized communication rooms serve counties, cities, or specific regions and need to balance performance and scalability. Small rooms, mainly located at community or enterprise endpoints, are the "last mile" connecting users. In traditional O&M management, large communication rooms have a large scale of equipment and low efficiency of manual control; medium-sized rooms have diverse systems, making fault location and disposal difficult; and small rooms are scattered, lacking professional O&M personnel. With the development of the Internet of Things (IoT), big data analytics, and artificial intelligence (AI) technologies,

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seeking an efficient and intelligent new O&M management system for communication rooms has become an important aspect of communication network reconstruction [1].

2 Requirements Analysis

To improve the O&M efficiency and stability of communication room equipment, intelligent construction is needed from the dimensions of system sensing capability, decision-making efficiency, control mode, and resource scheduling.

2.1 Comprehensive Online Monitoring of Situational Awareness

The operating environment of communication room equipment is complex, and hazards such as power fluctuations, temperature and humidity imbalances, and equipment overload can lead to major communication failures [2]. Online monitoring of the situational awareness of communication rooms refers to the use of deployed IoT sensor clusters (such as infrared thermal imaging, vibration monitoring, and micro-environment acquisition modules) to build a real-time sensing network capable of collecting tens of thousands of data points per second. Combined with edge computing, multi-dimensional correlation analysis is performed on power, temperature and humidity, equipment load, etc. For example, relying on power and environment monitoring equipment to achieve online real-time monitoring of room environments, power supply and distribution, batteries, and other room infrastructure; relying on security monitoring equipment to achieve real-time collection of room images and personnel access records [3]; relying on cable maintenance and intelligent patching equipment to achieve real-time monitoring of the status of optical cable lines, 2M lines, telephone lines, and network lines [4]. Combined with management interfaces such as situational presentation and GIS maps, the goal of online monitoring of room elements' situational awareness is achieved.

2.2 Precise Fault Warning and Root Cause Tracing

Traditional fault handling in communication rooms highly relies on manual experience, with an average fault location time of 2.5 hours, resulting in low maintenance efficiency. By constructing a three-layer fault management model of "prediction-diagnosis-tracing" in communication rooms and using neural networks to analyze and process real-time monitoring data and historically stored data from power and environment, video security, cable maintenance, intelligent patching, etc. [5], potential equipment faults, line faults, or service interruptions can be identified in advance, and alerts can be issued promptly, with possible causes of alerts displayed, significantly improving the efficiency of precise fault warning and handling [6,7].

2.3 Remote Business Control and Automated Handling

With the intelligent reconstruction and upgrade of communication rooms, small and medium-sized rooms are gradually advancing towards "unmanned" operation. However, for sudden faults or emergency business scheduling, remote control and automated handling of business are necessary. For example, remote control means can be used to achieve remote battery charging and discharging, remote setting of ordinary (precision) air conditioning, and remote door opening of access control. Remote scheduling technologies for 2M lines and telephone lines can solve the tedious, time-consuming, and error-prone issues of traditional manual jumper wiring for DDF, VDF, etc. At the same time, it has the ability to test the quality of optical fiber lines, 2M lines, telephone lines, and network lines to ensure normal service provisioning [8].

2.4 Resource Visualization and Dynamic Optimization of Management Domains

The utilization rates of communication rooms of different types or in different regions vary significantly. For example, the utilization rate of 5G core network rooms during nighttime traffic troughs is less than 50%, resulting in resource waste. A resource dynamic optimization system should be built based on digital twins and AI scheduling engines [9]. For example, using laser point cloud scanning of communication rooms to construct digital twin rooms, real-time mapping of equipment location, temperature and humidity, equipment resource utilization, etc.; conducting finer-grained virtual simulation of asset parameters and maintaining them from a full lifecycle management perspective to achieve visual management of O&M resources; using GIS maps to show the routing of optical cable points, combined with intelligent patching resource management, to construct visualization of ODF, VDF, DDF, and NDF patching ports.

3 System Design

Through in-depth analysis of the current construction status and business needs of communication rooms, the main directions for the intelligent construction of communication rooms have been accurately identified. The intelligent management system architecture for communication rooms is constructed at three levels: management domain, business domain, and technical domain. It fully considers intelligent technology requirements, integrates existing management processes and norms, closely focuses on core businesses of stations, and focuses on the application and integration of cutting-edge technologies, striving to comprehensively improve the intelligent management level of communication rooms. The system architecture diagram is shown in Figure 1.

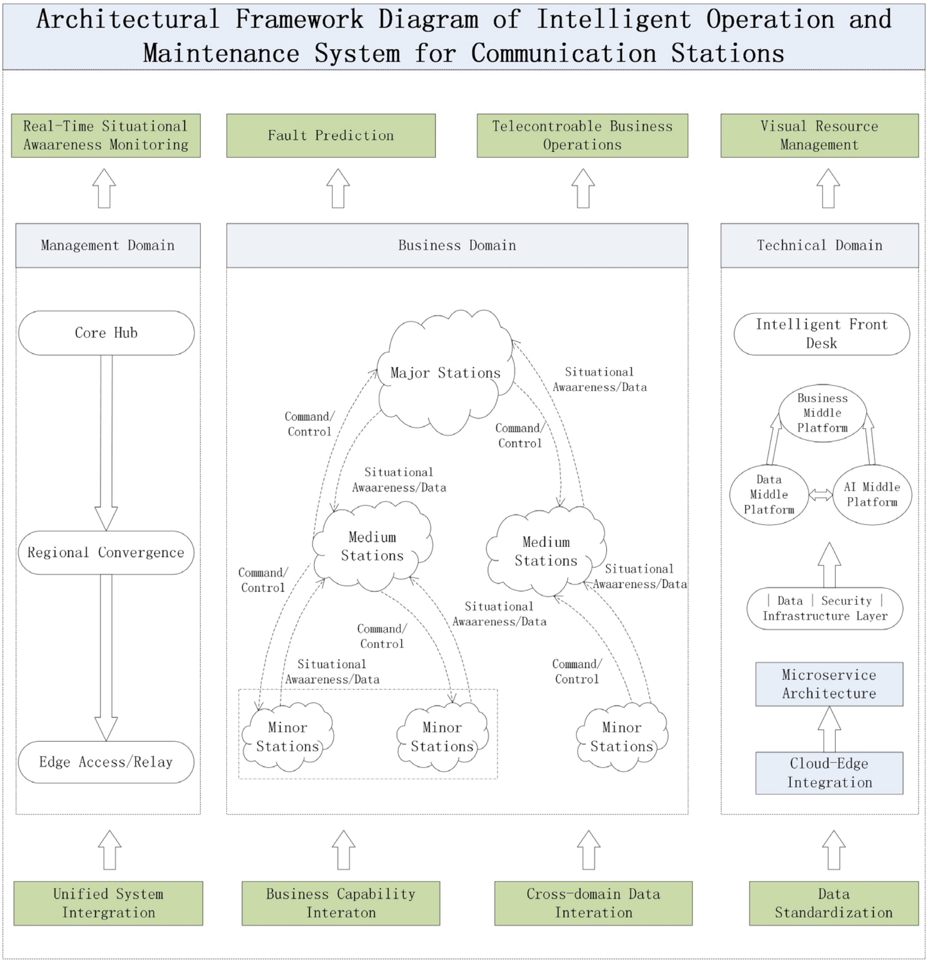

Fig. 1. Schematic Diagram of System Architecture

3.1 Management Domain: Layered Collaborative Architecture

Based on the layered characteristics and intelligent needs of large, medium, and small communication rooms, a three-tier management model of "core-convergence-access" should be established to achieve resource intensification and O&M agility. The first tier is the core hub, typically undertaken by large stations, responsible for managing itself and its subordinate regional convergence centers. It serves as the global resource scheduling hub, undertaking cross-regional disaster recovery and strategic decision-making. The second tier is the regional convergence center, usually undertaken by medium-sized stations, managing subordinate endpoint/relay stations at the end, supporting heterogeneous system compatibility and elastic scaling. The third tier is the endpoint/relay station, mostly unmanned small stations, serving as autonomous units for endpoint access, responsible for undertaking business from superior stations, and should achieve minimal deployment and unmanned operation [10].

3.2 Business Domain: Scenario-Based Business Adaptation

Differentiated O&M strategies and service guarantee mechanisms are designed for communication service connectivity needs. Large sites, as business center stations, monitor O&M situation data (covering business, equipment, etc.) of their own sites, while receiving key O&M situation data (business, equipment, etc.) from their subordinate regional sites, and are responsible for the allocation and issuance of various businesses. Their core functions include all-optical switching control, power supply and distribution resilience simulation, and cross-load balancing. Medium-sized sites, as regional centers, monitor O&M situation data (business, equipment, etc.) of their own sites, receive important O&M situation data (business, equipment, etc.) from their subordinate unmanned endpoint sites, and issue businesses downward. In addition, they need to report important O&M situation information (business, equipment, etc.) converged at their level to superior sites. Their core functions include elastic resource pools, multi-tenant isolation, and compliance audits. Small sites, as unmanned endpoint sites, monitor O&M situation data (business, equipment, etc.) of their own sites and report important O&M situation data (business, equipment, etc.) of their own level to superior sites. Their core functions include environmental adaptability, scan-and-deploy, and offline data continuation.

3.3 Technical Domain

The O&M technical system can be constructed based on principles such as layered collaboration, business/data drive, intelligent decision-making, automated O&M, and scalability and compatibility.

(1) The architecture foundation can choose mainstream cloud-edge integration technology. Through cloud-edge collaborative scheduling management, leveraging the powerful computing, storage, and data analysis capabilities of cloud computing, deploying complex AI computing, training, analysis, and other businesses on the cloud platform of large stations, and realizing in-depth mining and analysis of large-scale O&M data on the cloud to provide macro-level support for O&M decision-making. At the same time, utilizing the unique advantages of edge computing in local real-time processing and low-latency response, deploying O&M functions with high real-time requirements at medium or small stations. Edge devices process O&M data directly related to equipment in real time, quickly respond to equipment faults and anomalies, and ensure the timeliness and efficiency of O&M work.

(2) After determining the cloud-edge integration technology as the architectural foundation, the service deployment approach was selected to be a microservices-based elastic architecture. If the system contains n microservice modules, then the resource allocation for each module satisfies formula 1. R_i is the resource quota for the i-th microservice. B_i is the priority weight of business i.T_{max} is the total resource capacity. α is the elastic coefficient (0.8-1.2).

$$R_i = \alpha * \frac{B_i}{\sum_{j=1}^{n} B_j} * T_{max} \tag{1}$$

With its unique advantages, the microservices-based elastic architecture is gradually becoming the preferred mode for service deployment in modern complex systems. It breaks down the entire operation and maintenance system into multiple relatively independent microservices modules with single functions, each focusing on completing specific business functions and interacting through lightweight communication protocols. This architectural design not only significantly enhances the maintainability and scalability of the operation and maintenance system, allowing each microservice to be independently developed, tested, and deployed, thus reducing the difficulty of system upgrades and maintenance; it also possesses powerful elastic scaling capabilities, enabling flexible adjustment of resource allocation for each microservice based on actual business needs [11].

(3) Building a smart central platform on top of the cloud-edge integration architecture and the microservices-based elastic service deployment model has become a key step in achieving intelligent operation and maintenance. The smart central platform consists of a business central platform, a data central platform, and an AI central platform. The business central platform meticulously organizes operation and maintenance businesses, breaking them down into a series of standardized and reusable business components, integrating business capabilities, and providing unified external business service interfaces. The data central platform adopts advanced data governance technologies for unified collection, cleaning, storage, and analysis. The data storage architecture can adopt a hybrid structure, tailored to meet the requirements of various data computing tasks. Through a data management system driven by business scenarios, it taps into the potential value behind the data, providing solid data support for operation and maintenance decision-making. The AI central platform integrates various advanced artificial intelligence algorithms and machine learning models, combines them with actual operation and maintenance scenarios of communication stations, constructs algorithm units of different scales, and provides standard external interfaces to meet the requirements of elastic deployment and unified interfaces. Through the construction of the smart central platform, the entire operation and maintenance system can form unified, standardized, and efficient external service interfaces, achieving shared reuse of data, business, and capabilities, and providing strong support for operation and maintenance applications and business expansion at different levels.

(4) As an important window for direct interaction between the operation and maintenance system and operation and maintenance personnel as well as management personnel, the intelligent front-end leverages a series of advanced specific application technologies such as 3D visual scene perception and intelligent analysis to present the comprehensive operation and maintenance situation of the station to users in an intuitive and vivid manner. Visual scene perception technology can utilize virtual reality (VR), augmented reality (AR), and 3D modeling to construct virtual scenes that are highly realistic and similar to the actual operation and maintenance environment of the station. Intelligent analysis technology is based on advanced technologies such as

big data analysis and artificial intelligence algorithms provided by the smart central platform, conducting real-time and in-depth mining and analysis of operation and maintenance data to generate statistical analysis data on various operation and maintenance situations, providing users with intelligent and precise decision-making suggestions, and helping them take effective response measures in a timely manner. In terms of operation and maintenance interaction, the intelligent front-end integrates the business unit capabilities provided by the smart central platform, forms automated business processing flows, encapsulates them into different tasks, supports customization of task parameters, and provides users with remote rapid execution capabilities for operation and maintenance businesses through intuitive visual means.

4 Case Study and Performance Evaluation

Utilizing cloud edge integration and big data analysis for centralized operation and control of communication systems, real-time monitoring of the operating environment and equipment status in the data center, implementation detection, and comprehensive information display, to achieve timely warning and intervention of data center failures. Once a device malfunctions, the alarm information associated with the device can be located at different levels of the system, such as switching devices, servers, middleware, and cable equipment; It can also be located at specific physical locations, such as the computer room where the equipment is installed, achieving the transformation of operation and maintenance mode, as shown in Table 1.

Table 1. Comparison of Operation and Maintenance Methods

Operation and maintenance elements	Traditional operation and maintenance methods	Intelligent operation and maintenance mode
Number of inspectors	≥2	Unmanned
Data record	Handwritten transcription	Automatic storage
Data upload Real time	Manual upload	Automatic upload
Data upload performance	Non Real Time	Real time
Data reliability	Lower	Reliability
Fault diagnosis	Empirical analysis	Intelligent analysis (big data+experience)
Alarm response	Slow	Rapid
Equipment pre alert warning	Not have	Have
Environmental monitoring	Non Real Time	Real time

For our unit's large, medium, and small computer rooms, which are far apart from each other, on-site operation and maintenance take a long time and require manpower. By adopting integrated intelligent operation and maintenance technology for its dedicated renovation and upgrading, the average time for locating regional faults can be reduced from 65.3% to 15%, basically controlled within 10-15 minutes to locate the fault point, providing strong support for subsequent fault troubleshooting, shortening the business operation process, and shortening the closed-loop time for fault handling and troubleshooting. The comparison of fault handling time is shown in Figure 2.

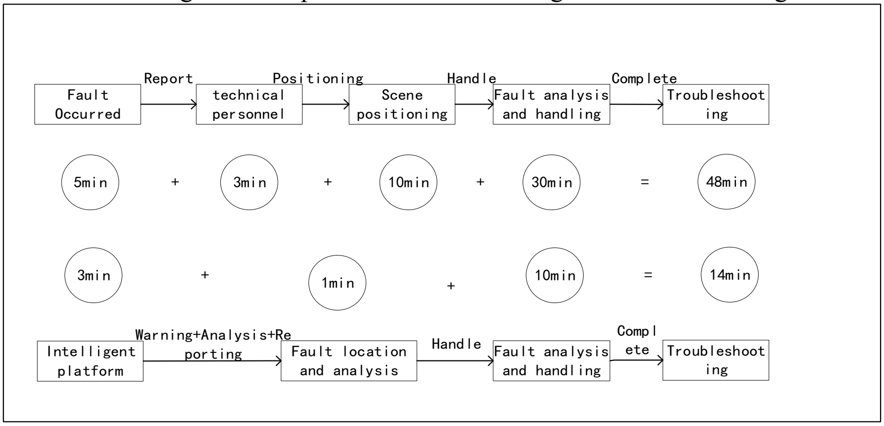

Fig. 2. Comparison of Fault Handling Processes

To validate the proposed system, we implemented it in a provincial communication network comprising 1 large core rooms, 2 medium-sized regional rooms, and 3 small endpoint rooms. Over a 2-month trial period, the system demonstrated significant improvements: Fault prediction accuracy: Achieved 92.3% precision using a hybrid LSTM-Random Forest model trained on historical data from power, temperature, and load sensors. Downtime reduction: Average service interruption duration decreased from 2.5 hours (manual O&M) to 15 minutes (intelligent system). Resource utilization: Dynamic optimization increased nighttime core room utilization from 48% to 76%. According to data statistics, its operational efficiency has been significantly improved, as shown in Table 2.

Table 2. Comparative Analysis of O&M Practices

Metric	Traditional O&M	Proposed System	Improvement
Fault Diagnosis Time	2.5 hours	15 minutes	83% ↓
Resource Utilization	48%	76%	58% ↑
O&M Labor Cost (Annual)	$320k	$180k	43.8% ↓
False Alarm Rate	22%	8%	64% ↓

5 Summary

This paper proposes an intelligent O&M management system for communication equipment rooms based on a hierarchical architecture and intelligent-driven technologies. Through a 2-month provincial deployment covering communication rooms of various scales, the system has demonstrated significant improvements: Operational efficiency: Fault diagnosis time decreased by 83% (from 2.5 hours to 15 minutes) through AI-driven root cause analysis, while resource utilization increased by 58% via dynamic optimization algorithms. Cost-effectiveness: Annual O&M labor costs were reduced by 43.8% through unmanned operations and remote control.

Despite these advancements, challenges remain in legacy system integration and heterogeneous device compatibility (e.g., Huawei/Cisco hybrid environments). Future research will focus on: Lightweight edge containers for scalable deployment in small rooms with limited resources. Federated learning frameworks to address data privacy concerns in multi-tenant scenarios. Energy-aware scheduling to further reduce power consumption during low-traffic periods. This system marks a critical transition from experience-driven to data-driven O&M practices, providing a replicable paradigm for intelligent infrastructure management in the 5G/6G era.

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