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APPLICATION OF 5G+EDGE COMPUTING IN REAL-TIME DATA TRANSMISSION FOR SMART MINES

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Abstract: Smart mining represents the core direction of the intelligent transformation in the coal and mining industry, and real-time data transmission is the vital lifeline for the efficient operation and safety management of smart mines. Traditional mine data transmission modes suffer from pain points such as insufficient bandwidth, high latency, poor anti-interference performance and limited access for massive terminals, making it difficult to adapt to the complex underground operating environment and intelligent operation requirements. 5G technology, with its core advantages of high bandwidth, low latency, massive connectivity and high reliability, provides communication support for the high-speed transmission of massive mine data. Edge computing sinks computing power to network edge nodes, enabling local data processing and rapid instruction delivery, which further reduces transmission latency, alleviates cloud computing pressure and ensures the stability of data transmission. Focusing on the integrated 5G+edge computing technology, this paper analyzes the core requirements for real-time data transmission in smart mines, expounds the technical characteristics and integration logic of 5G and edge computing, explores in depth the practical applications of this technology in scenarios such as environmental monitoring, remote equipment control, unmanned mining and emergency rescue, and analyzes the current technical challenges and optimization paths in its application. It aims to provide theoretical reference and practical guidance for the upgrading of the data transmission system in smart mines and the high-quality development of mining intelligence.
Keywords: 5G; Edge computing; Smart mine; Real-time data transmission; Intelligent mining

1 INTRODUCTION

As a major mining production country, China’s coal and metal ore mining occupies an important position in the national economy. The traditional mining environment is harsh, with numerous potential safety hazards and low production efficiency, making intelligent and smart transformation an inevitable trend for the industry. Relying on technologies such as the Internet of Things, 5G and artificial intelligence, smart mines realize intelligent operations throughout the whole process of mining, monitoring and management. The real-time collection, high-speed transmission and efficient processing of massive data are the core prerequisites for the implementation of various smart mine applications, and data transmission capacity directly determines the effect of application implementation. The complex underground environment results in traditional wired and 4G/WiFi transmission modes facing pain points such as insufficient bandwidth, high latency and poor anti-interference performance, which make it difficult to meet the real-time application requirements of remote control and emergency early warning. Centralized cloud processing further exacerbates network congestion and delays decision-making responses. 5G features high bandwidth, low latency and massive connectivity, while edge computing achieves local processing through computing power sinking. The in-depth integration of the two not only breaks the bottleneck of data transmission but also improves the security of data processing and transmission, providing a brand-new solution for the implementation of core applications in smart mines. Focusing on this integrated technology, this paper explores the core application requirements and application scenarios of real-time data transmission in smart mines, so as to boost the intelligent transformation of the mining industry.

2 CORE APPLICATION REQUIREMENTS FOR REAL-TIME DATA TRANSMISSION IN SMART MINES AND PAIN POINTS OF TRADITIONAL MODES

2.1 Core Application Requirements for Real-Time Data Transmission in Smart Mines

Smart mines cover various business application modules such as environmental monitoring, equipment operation and maintenance, mining operations and emergency rescue. Each scenario has significantly different requirements for data transmission rate, latency and reliability, presenting the overall characteristics of diverse data types, massive transmission traffic, stringent latency requirements and large-scale connected terminals. The core transmission requirements focus on three aspects. First, the demand for high-bandwidth and large-traffic transmission: massive data such as underground high-definition videos, 3D geological modeling and intelligent inspection images require ultra-large bandwidth support to avoid data congestion and jamming and ensure the smooth operation of visual applications. Second, the demand for ultra-low latency and high-reliability transmission: high-risk scenarios such as remote equipment control, autonomous driving of unmanned mining trucks and disaster emergency response require the transmission latency to be controlled within 20ms and the reliability to reach 99.999%, so as to prevent safety accidents

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caused by delayed application responses. Third, the demand for concurrent access of massive terminals: tens of thousands of sensing, monitoring and positioning devices in mines need to be connected to the network synchronously, and the network is required to support the access of massive terminals to avoid data loss and monitoring blind spots and ensure the normal operation of global scheduling applications [1-3].

2.2 Pain Points of Traditional Mine Data Transmission Modes

Traditional mine data transmission is mainly based on wired communication and 4G/WiFi wireless communication, combined with a centralized cloud processing mode, which is difficult to adapt to the intelligent operation requirements of smart mines with prominent application pain points. Wired transmission has poor flexibility; tunnel excavation and equipment movement underground are prone to cause line damage, with high maintenance costs, and it cannot adapt to dynamic scenarios such as mobile operations and unmanned mining, resulting in limited application scope. 4G and WiFi have insufficient transmission performance: 4G has limited uplink bandwidth, leading to severe jamming in high-definition video backhaul and an end-to-end latency of up to hundreds of milliseconds, which cannot meet the low-latency requirements of remote precise control. WiFi has a narrow signal coverage and weak anti-interference performance; the signal attenuation is obvious in complex underground tunnels, and parallel multi-scenario operations are prone to cause network congestion. Centralized cloud processing is inefficient: the long-distance transmission of massive raw data occupies a large amount of bandwidth, and the data processing and instruction delivery link is lengthy, resulting in delayed responses of core applications such as emergency early warning and remote control. At the same time, the traditional transmission network has weak security protection, making data vulnerable to eavesdropping and tampering, and electromagnetic interference underground also reduces transmission stability, restricting the safe implementation of core production applications.

3 TECHNICAL CHARACTERISTICS AND INTEGRATED ADAPTIVE APPLICATIONS OF 5G AND EDGE COMPUTING

3.1 Core Technical Characteristics of 5G and Its Adaptive Applications in Mines

Compared with previous generations of mobile communication technologies, 5G technology has achieved leaping improvements in communication performance, and its three major application scenarios accurately adapt to the data transmission and actual application requirements of smart mines with prominent core advantages. Enhanced Mobile Broadband (eMBB) has a peak rate of 10Gbps and sufficient uplink bandwidth, which can carry the real-time backhaul of large-traffic information such as high-definition videos and 3D geological data, adapting to applications such as underground visual supervision and 3D modeling. Ultra-Reliable and Low-Latency Communication (uRLLC) has an air interface latency as low as 1ms and a transmission reliability of 99.999%, meeting the low-latency and high-reliability requirements of equipment remote control and emergency early warning. Massive Machine-Type Communication (mMTC) can support the concurrent access of millions of terminals per square kilometer, adapting to the networking requirements of massive sensing and positioning devices in mines. Meanwhile, relying on technologies such as Massive MIMO, beamforming and network slicing, 5G realizes precise underground signal coverage and on-demand allocation of network resources, further improving transmission adaptability and stability, and conforming to the differentiated application requirements of mines in multiple scenarios [4, 5].

3.2 Core Technical Characteristics of Edge Computing and Its Adaptive Applications in Mines

As a distributed computing architecture, the core of edge computing is to sink computing and storage resources to network edge nodes such as underground edge gateways and base station edge servers, enabling local data processing and on-site decision-making without backhauling to remote clouds, which is highly adapted to the actual application requirements of smart mines. Its core characteristics are in line with mine application scenarios: first, low latency—edge nodes directly connect to terminals to complete data processing and instruction delivery, which greatly shortens the transmission and processing latency and significantly improves the response speed, adapting to millisecond-level response scenarios such as remote control and emergency early warning. Second, lightweight processing—it can filter and screen raw data and only upload high-value data, effectively alleviating network bandwidth pressure and adapting to lightweight applications such as regular monitoring of massive sensors. Third, high reliability—edge nodes have independent computing capabilities and can still ensure the operation of core businesses in case of network disconnection, adapting to scenarios such as continuous underground operations and key equipment control. Fourth, better security—local data processing reduces remote transmission links, lowers the risk of leakage and tampering, and facilitates local protection, adapting to the transmission requirements of core confidential data in mines.

3.3 Integration Compatibility of 5G and Edge Computing

5G and edge computing have inherent integration compatibility, and their collaborative efforts can realize a closed loop of "high-speed transmission + local computing", perfectly solving the problem of real-time data transmission in smart mines. 5G provides an efficient and reliable wireless transmission channel for edge computing, solving the data transmission bottleneck between edge nodes and data sources as well as the cloud, and ensuring the real-time performance and connectivity of edge computing. Edge computing makes up for the deficiency of centralized cloud processing in 5G networks, alleviates the bandwidth pressure of 5G networks, reduces transmission latency and improves the utilization rate of 5G network resources. Through integrated deployment, an integrated data transmission and processing system of "terminal collection - 5G transmission - edge computing - cloud collaboration" can be constructed, which not only meets the core requirements of real-time data transmission and processing in mines but also realizes hierarchical data management and efficient utilization, providing a solid support for the intelligent operation of smart mines in all scenarios [6-8].

4 APPLICATION SCENARIOS OF 5G+EDGE COMPUTING IN REAL-TIME DATA TRANSMISSION FOR SMART MINES

4.1 Intelligent Underground Environmental Monitoring and Early Warning

Underground environmental safety is the top priority of mine production. Relying on 5G+edge computing, all-time, high-precision real-time monitoring and hierarchical early warning of environmental data can be realized. Sensors for gas, carbon monoxide, dust, roof pressure and other parameters are deployed in all underground working faces, tunnels and chambers, and the monitoring data is transmitted to edge computing nodes in real time through 5G networks. The edge nodes conduct real-time analysis of the data and quickly judge the risk level by comparing with safety thresholds. When the data exceeds the standard and triggers the early warning threshold, the edge nodes immediately issue control instructions such as acousto-optic alarm, fan start-up and power-off interlocking to achieve millisecond-level emergency response; at the same time, the early warning data is uploaded to the cloud to generate risk disposal plans and push them to the terminals of managers. Compared with the traditional mode, the data transmission latency in this scenario is reduced to less than 10ms, and the early warning response speed is increased by more than 90%, which can effectively prevent safety accidents such as gas explosions and roof collapses.

4.2 Remote Precise Control of Mining Equipment

The operating environment of large underground equipment such as shearers, roadheaders and hydraulic supports is dangerous, and manual control has extremely high risks. 5G+edge computing can realize remote precise control on the ground to ensure operational safety. The equipment is equipped with high-definition cameras and attitude sensors, which transmit real-time operation videos and operating parameters to the edge computing layer through 5G networks. The edge nodes complete video decoding and data processing, and push clear images and real-time data to the ground control console synchronously; the control instructions issued by operators are transmitted to the edge nodes with ultra-low latency through 5G networks and then quickly sent to the equipment terminals, realizing an intelligent operation mode of "one-click control and real-time response". Benefiting from the ultra-low latency of 5G and local processing of edge computing, the equipment control is free of delay and jamming, and the control precision is greatly improved, truly realizing the intelligent operation mode of "unmanned on duty and remote control" and significantly reducing the number of underground operators.

4.3 Unmanned Mining and Intelligent Transportation Scheduling

Unmanned operation is the core symbol of smart mines, and 5G+edge computing provides data transmission support for unmanned mining and intelligent transportation. Unmanned equipment such as shearers, roadheaders and mining trucks are equipped with various types of sensors and positioning modules, which collect real-time operation data, position information and surrounding environment data, and transmit them to edge computing nodes through 5G networks. The edge nodes conduct real-time analysis of the data, plan the optimal operation and transportation routes, and automatically issue driving and operation instructions to realize autonomous equipment operation and intelligent obstacle avoidance. For the scenario of collaborative operation of multiple devices, the edge computing layer can centrally schedule the operating status of each device to avoid operational conflicts and improve mining and transportation efficiency. At the same time, the cloud optimizes the operation scheduling model based on the data uploaded by the edge, realizes the global collaborative management and control of unmanned operations, greatly improves mine production efficiency, and reduces labor costs and safety risks [9,10].

4.4 Precise Positioning of Underground Personnel and Emergency Rescue

The safety management and emergency rescue of underground personnel have stringent requirements for personnel positioning accuracy and real-time data transmission. Underground operators are equipped with 5G intelligent mining lamps and positioning terminals, which transmit real-time personnel position and vital sign data to edge computing nodes through 5G networks. The edge nodes update personnel position information in real time to achieve centimeter-level precise positioning; in the event of a safety accident, the edge computing layer quickly locks the personnel position, analyzes the trapped environment, pushes the optimal rescue route to rescuers through 5G networks, and issues evacuation guidelines to the trapped personnel at the same time. Compared with traditional positioning technologies, 5G+edge computing realizes real-time transmission of positioning data and dynamic update of position information, greatly improving the emergency rescue response speed and maximizing the safety of trapped personnel's lives.

4.5 Full-Lifecycle Intelligent Operation and Maintenance of Equipment

Large mining equipment has a high cost, and equipment operation and maintenance directly affect production continuity. By deploying monitoring terminals for vibration, temperature, current and other parameters on key equipment, real-time operating data of the equipment is collected and transmitted to edge computing nodes through 5G networks. The edge nodes conduct real-time analysis of the data using preset algorithms to judge the equipment operating status and identify early potential faults; for minor faults, the edge nodes issue early warning instructions to remind maintenance personnel to handle them in a timely manner; for serious faults, they immediately issue shutdown instructions to avoid the expansion of faults. At the same time, the edge nodes upload equipment operating data and fault data to the cloud, where the cloud constructs an equipment operation and maintenance model, predicts the remaining service life of the equipment and formulates preventive maintenance plans, realizing the transformation from "post-failure maintenance" to "preventive maintenance", reducing equipment failure rates and extending equipment service life.

5 PROBLEMS AND OPTIMIZATION STRATEGIES OF 5G+EDGE COMPUTING IN REAL-TIME DATA TRANSMISSION FOR SMART MINES

5.1 Existing Problems in Large-Scale Application

Although 5G+edge computing has prominent application advantages in real-time data transmission for smart mines and has been piloted in large mines, its large-scale promotion still faces many challenges due to factors such as the special mine environment, technical adaptability, cost and industry standards. The twisted underground tunnels and high dust concentration lead to severe 5G signal attenuation, and there are signal blind spots in remote working faces and blind tunnels, which are prone to cause data transmission interruption and hinder application implementation; some old equipment in traditional mines is not equipped with 5G and intelligent sensing modules, with incompatible interfaces, resulting in high cost and great difficulty in intelligent transformation, making it difficult to integrate into the integrated application system; the lack of targeted computing power planning for edge nodes leads to the inability to match the application requirements of each scenario, resulting in the imbalance between computing power supply and demand and affecting application operation efficiency; the openness of 5G and the distributed deployment of edge computing amplify potential safety hazards such as data leakage and network attacks, and the existing protection system is difficult to ensure application security; in addition, the high investment in equipment procurement and operation and maintenance, as well as the shortage of professional operation and maintenance talents, make it difficult for small and medium-sized mines to afford, further restricting the popularization and application of the technology.

5.2 Optimization Strategies for Application Implementation

In view of the existing problems in the large-scale application of 5G+edge computing in real-time data transmission for smart mines, combined with the actual mine scenarios and application requirements, optimization strategies can be formulated from five aspects to facilitate the global implementation and promotion of the technology. Realize full underground signal coverage and eliminate transmission blind spots by optimizing 5G network deployment and combining micro base stations, leaky cables and signal repeaters; promote the modular transformation of existing equipment, unify industry access standards, and install general 5G and sensing modules to reduce transformation costs and improve equipment compatibility; finely allocate edge computing power relying on intelligent computing power scheduling algorithms to meet the application requirements of each scenario and improve computing power utilization; build an all-round security protection system with end-to-end encryption and multiple identity authentication to prevent network attacks and data leakage and ensure application security; implement a lightweight hierarchical application mode, and reduce the investment threshold for small and medium-sized mines with the help of policy support and technical cooperation to promote the popularization and application of the technology.

6 CONCLUSION

The integrated 5G+edge computing technology effectively breaks the bottlenecks of bandwidth, latency and reliability in traditional smart mine data transmission, builds an integrated data transmission and application system, adapts to the complex underground operating environment, and provides core support for the intelligent transformation of mines. The pilot application of this technology in scenarios such as environmental monitoring, remote control, unmanned mining and emergency rescue has achieved remarkable results, which greatly reduces transmission latency, improves operational efficiency, strengthens safety management and control, and drives the transformation of mine mining towards intelligence and refinement. Although the current large-scale application still faces challenges such as signal coverage, equipment adaptability and cost investment, these can be solved one by one through optimized deployment and technological upgrading. In the future, with the in-depth integration of 5G-A/6G, digital twin and other technologies with edge computing, the efficiency of data transmission and applications will be continuously upgraded, unmanned and visual smart mines will be gradually implemented, and this technology will also be popularized and applied in various mines, helping the mining industry achieve safe, green and intelligent sustainable development.

COMPETINGINTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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