# The Research of Ultra-Low Delay Gateway for Underground Remote Control

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***Abstract.*** *The existing systems for coal mine safety oversight, worker location tracking, and video surveillance face issues such as intricate network topologies, limited capacity for additional device connectivity, and significant latency. Aiming at the complex underground multi-source heterogeneous network, this paper compares and analyzes the defects and shortcomings of the current network, designs the time-sharing protocol mapping model based on MII (Media Independent Interface), SPI (Serial Peripheral Interface), DMA (Direct Memory Access) and other high-speed data exchange bus, and proposes a fusion gateway suitable for underground ultra-low delay. The actual operation results show that the gateway has the characteristics of rich interface, less packet loss and low delay, which can meet the real-time communication requirements of underground CAN (Controller Area Network) bus, IoT (Internet of Things) and Ethernet equipment.*

## Keywords

Integration gateway, ultra-low delay, high speed bus, coal mine gateway, time delay test

## 1. Introduction

With the implementation of intelligent mining and 5G technology in coal mines, the communication infrastructure for underground equipment is being integrated into high-speed networks. Underground mining equipment aims to enhance productivity by efficiently extracting ore from beneath the earth's surface, maximizing payload while minimizing waste. Safety monitoring, personnel positioning, and video surveillance systems play crucial roles in the status acquisition within coal mines. Various sensor devices, edge equipment, and Internet of Things wireless devices are interconnected to support these functionalities [1–4].

The rapid growth of underground network equipment has stimulated the development of mine APPs, underground edge equipment, and mine intelligent networks. Through the analysis, aggregation, and conversion of mine gateway, heterogeneous data with different protocols, different media, and different sources can be integrated and sent to an underground dispatching room or ground integrated information platform [5–7]. When compared to a standard industrial gateway, intelligent networks used in mining have a significant difference in access network type, application environment condition, and data exchange speed [8], [9].

In the challenging underground environment, the design of heterogeneous networks often encounters interference. Middleware is commonly used to achieve transparent access and communication between different networks, requiring high hardware specifications [10], [11]. To enable communication within the underground sensing network, wireless communication serves as a vital supplement to wired communication [12–14]. In a heterogeneous integration gateway structure, each node operates independently and can self-network, adapting to changes in network topology. When connecting a device with a heterogeneous protocol to Ethernet, signal conversion is performed through the gateway. In summary, optimizing the design of underground gateways is crucial to enhance anti-interference capabilities and real-time information transmission performance.

Scholars have conducted extensive research on heterogenous network integration, resulting in significant findings. For instance, Y. Gao et al. [15] proposed a novel end-to-end autonomous mining solution: Parallel Mining based on Internet of Things, which encompasses conceptual definition, the proposed solution, and specific implementation. P. K. Mishra et al. [16] developed an IP-based multimodal sensing platform using Zigbee-based wireless sensor networks, enabling the implementation of IoT applications in underground coal mines. A. Kychkin and A. Nikolaev [17] proposed a secure and energy-efficient ventilation control method, which

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specifically includes fundamental algorithms for computing the interrelations of general natural airflow physical parameters within the ventilation ducts. Fang Rui and Li Xudong [18] developed an IoT gateway compatible with different WSN terminals, utilizing Sqlite3 as an embedded database. A. H. Soomro and M. T. Jilani [19] proposed a system for sensor-based detection of methane and carbon monoxide gas concentrations in the air, along with measurements of mine temperature, humidity, and miner heart rate.

In the field of gateway communication protocols, researchers have explored various technologies. Blockchain technology has been employed to enhance communication network security by storing critical transmission data [20–26]. ZigBee technology, known for its short-range, low power consumption, and low-cost bidirectional wireless communication, has been integrated into devices and leveraged for geolocation functions [27–30]. In underground network environments, signal transmission characteristics such as attenuation, reflection, decay, and scattering have been studied to optimize communication quality and efficiency [31–36].

In summary, the authors of the literature have carried out a detailed analysis of the communication architecture, networking mode, communication protocol, algorithm efficiency and wireless communication mode of the high-speed gateway, but have not involved the communication performance research of the coal mine gateway. Aiming at the high reliability and real-time characteristics of downhole communication, this paper researches and tests the data transmission channel and protocol in the downhole, designs an ultra-low delay gateway, which is suitable for the heterogeneous network of the field bus of downhole equipment, and realizes the equipment prototype of the downhole gateway by using an embedded controller.

The paper is organized as follows: Section 2 describes the overall architecture of mine fusion gateway; Section 3 describes the hardware structure design and software program design. Section 4 describes the performance test process of mine gateway, such as delay test, packet loss rate test, etc. Finally, the general gateway summary and future research trends are discussed in Sec. 5.

## 2. Methods/Experimental

According to the '5G + Coal Mine Intelligent White Paper' released in October 2021, the underground business can be roughly divided into information collection, video monitoring, personnel positioning and remote control. The information collection service is mainly based on the small packet service of the upper line, the delay is not sensitive, and the packet loss rate can be controlled within 1%. The network requirements of the video surveillance class are large uplink bandwidth. Taking the 4K camera as an example, the bandwidth requirement is about 15–20 Mbps, the delay sensitivity is medium, the packet loss rate is high, and it must be guaranteed below 0.5%. The personnel positioning business has the same requirements for the uplink and downlink of the network. The network demand is about 4–8 Mbps, and the packet loss rate is controlled within 1%. For remote control services, the network requires large uplink bandwidth and low downlink delay. The uplink returns video or radar and other sensor data at the scene. According to the video resolution and the number of pictures returned, the bandwidth requirement is about 20–30 Mbps. The downlink transmits the control signal of the equipment, and the bandwidth requirement is not large, but it is sensitive to the delay. Generally, the delay is less than 50 milliseconds, and the packet loss rate is generally controlled within 0.5%. If it is remote control of vehicles such as rubber-tyred vehicles, the delay is further reduced to 20 ms. The business requirements of the network are shown in Tab. 1.

Take the network data of the underground personnel locator sensor as an example and carry on the gateway access and forward test record as shown in Tab. 2.

From the test data, it can be seen that after the aggregation of the gateway, the access delay of the underground sensor has been reduced by 10%–50%, and the ability to perceive the data has been greatly improved.

In this study, the experiments were conducted in a coal mine testing laboratory measuring 6 m × 4.5 m. The laboratory included tables, chairs, and relevant experimental instruments, as shown in Fig. 1. The experiment utilized a computer with Windows 10 operating system, a mining switch, two personnel positioning sensors, NFC (Near Field Communication) devices, a wireless router, and two mine gateways. A computer was connected to the mining switch, which was then connected to the mining gateway #01 via an Ethernet cable. Gateway #01 was connected to a personnel positioning sensor, while gateway #02 was connected to the

| Application classification | Scene description | RTT delay | Packet loss rate |
|---|---|---|---|
| Information collection | Equipment sensor acquisition | < 500 ms | 1% |
| Video surveillance | Distribution video of coal mining face | < 100 ms | 0.5% |
| Personnel positioning | Underground personnel information | < 500 ms | 1% |
| Remote control | Remote centralized control of shearer | < 50 ms | 0.5% |

**Tab. 1.** Communication requirements of coal mine underground business.

| Test number | Network interconnection types | Package size (Byte) | Average RTT (ms) | Packet loss rate |
|---|---|---|---|---|
| 1 | NFC transfer 485 | 420 | 450 | 0.4% |
| 2 | NFC transfer 485 summary | 260 | 310 | 0.2% |
| 3 | UWB transfer 485 | 90 | 420 | 0.4% |
| 4 | UWB to Ethernet | 240 | 45 | 0.6% |
| 5 | UWB passthrough | 110 | 486 | 0.2% |

**Tab. 2.** Human location gateway RTT delay data test.

NFC device and wireless router. The full-duplex asynchronous serial port had a speed of up to 25 Mbps, and the CAN bus operated at 500 kbps–1 Mbps.

The experiment involved four volunteers, including two males and two females. Ten different experimental scenarios were conducted as shown in Tab. 1 and Tab. 2. The fusion gateway processor was a 32-bit L7 with a working speed of 240 M. It integrated RF scheduling and supported low-power Bluetooth BLE5. The F407 main control chip used HAL (Hardware Abstraction Layer) migration Free-RTOS (free real-time operating system) system for software control, including initialization, reset, clocking, and communication data parsing of the connected devices.

**Fig. 1.** Mine gateway laboratory.

## 3. Mine Integration Gateway Architecture

The development trend of mine gateway is integration, compatibility, and intellectualization, which further integrates the automatic systems, sensors, and backbone transmission of coal mines and adapts to the complicated and severe environment of mines. The centralized gateway access architecture is shown in Fig. 2.

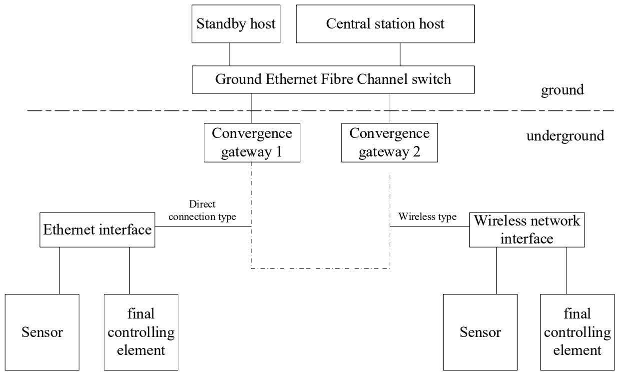



**Fig. 2.** Centralized gateway access architecture.

Centralized gateway has the advantages of simple data resolution, cascading of layers, and ease of forming a large data acquisition network. A communication enabler for a vehicle network system, serving as both a data router and

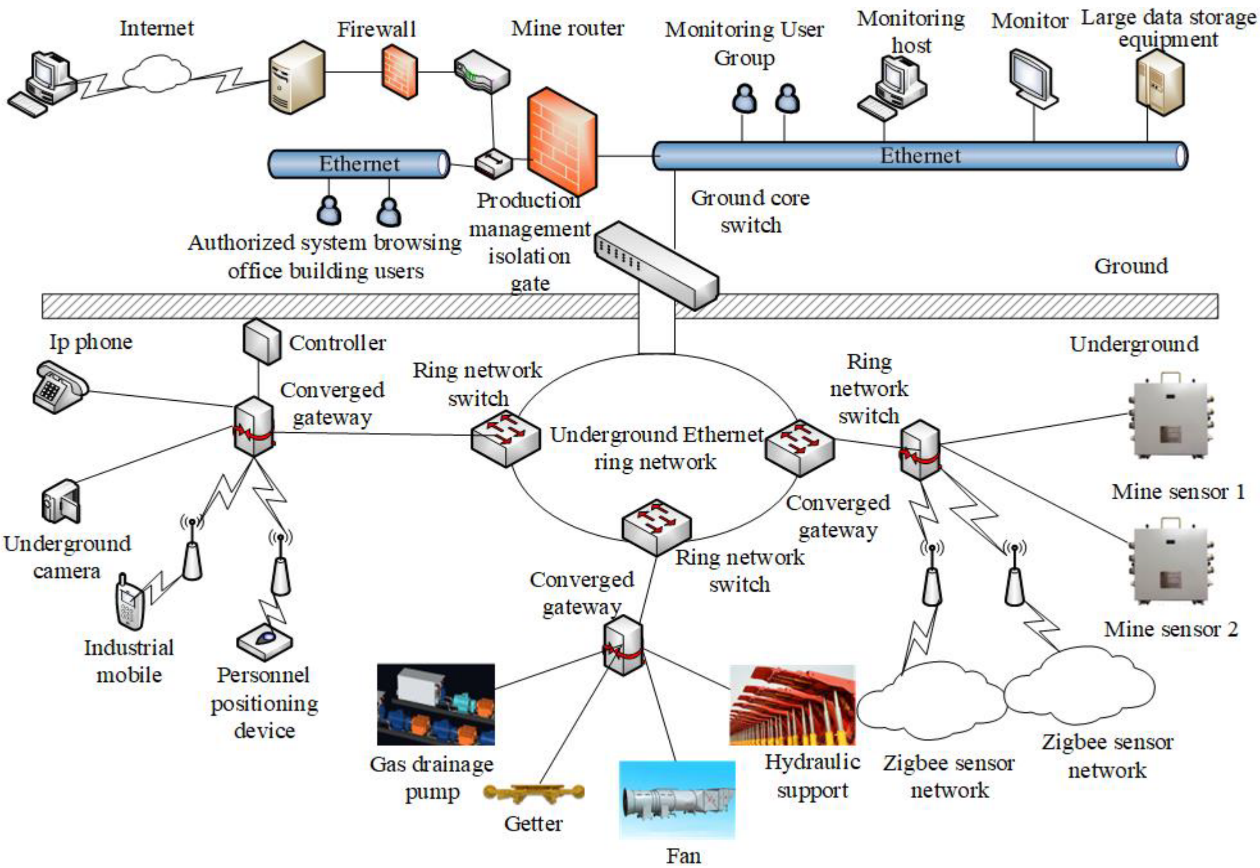



**Fig. 3.** Work architecture of fusion gateway.

a central processing hub for several vehicle network domains. Connected services and cross-domain communication are made possible via the Central Gateway. Within commercial vehicles, the Gateway serves as the main communication hub. However, the disadvantage is that the network is not effectively optimized between multiple data levels but relayed and transmitted through the network. Because, network optimization aims to boost a computer network's functionality and effectiveness. To ensure that data and other network traffic may move freely and swiftly throughout the network, this entails locating and fixing bottlenecks and other reasons of poor network performance. The time and pressure of resolution are done by the information platform. The smallest pressure increase that a sensor can detect is designated as pressure transducer resolution. In full scale output, or FSO, resolution is measured as a percentage. Centralized gateway is transmitted through multiple levels with high latency, severe network congestion, and poor outreach capability.

The distinction between the Mine Integration Gateway Architecture and the Centralized Gateway lies in their approach to addressing the protocol and architecture differences in the heterogeneous underground network. In the case of the Mine Integration Gateway Architecture, instead of independent access devices, the information platform utilizes a unified interface for gateway transmission. This enables on-site computing, analysis, integration, and network load optimization based on time delay considerations. Our focus is on achieving balanced transmission in the cloud computing layer, thereby reducing data communication latency. By addressing the issue of data transmission delay from edge devices to cloud servers and establishing an effective allocation matrix, we ensure efficient data allocation. The working architecture of the fusion gateway is shown in Fig. 3.

The integrated gateway architecture of coal mines should address three issues: 1) the coexistence and interconnection of heterogeneous networks. Underground networks are different from ground networks, and the main network types include Ethernet, CAN bus, RS 485, and 2.4 GHz. To solve the coexistence and interconnection problems of different types of networks, the integrated gateway architecture of mines needs to effectively integrate and manage various sensors and devices in the mine, and achieve centralized data collection, transmission, and processing. 2) Protocol exchange and interoperability, such as direct correspondence between MODBUS protocol and CIP (Common Industrial Protocol) registers, are used to reduce the computational complexity of gateways, improve communication response speed, and reduce latency of access devices. 3) Improving response speed: Network resource management is the process of network process management and resource allocation, which monitors and allocates resources globally to ensure data security.

This paper presents a design idea for the ultra-low latency gateway of the mine real-time control equipment working network. The gateway is equipped with an asynchronous serial port, a CAN bus, Ethernet, and a 2.4 GHz network.

# 4. Hardware and Software Design of Mine Integration Gateway Architecture

The design uses ST's M4 processor, STM32F407ZGT6, as the gateway's master chip. The chip has 1 M of built-in flash memory and 256 K of built-in RAM (Random Access Memory). To increase the capacity of a single data exchange, 4 M of SDRAM (Synchronous Dynamic Random-Access Memory) is extended for temporary data storage via a parallel bus. The F407 has a wealth of external synchronization interfaces, including six primary and secondary SPI interfaces, four full-duplex asynchronous serial interfaces, two CAN bus interfaces, one Ethernet MII interface, and one SDIO (Secure Digital Input and Output) interface. A Serial Peripheral Interface (SPI) in a computer is an interface that permits the exchange of serial data (one bit at a time) between two devices. The schedule performance index (SPI) gauges the extent that earned value (actual progress) adheres to the timetable (intended progress): SPI is equal to PV / EV. Through these external interfaces, the F407 can store and forward heterogeneous network data via high-speed RAM and a high-speed bus. The mine integration gateway architecture hardware architecture is shown in Fig. 4.

The main measures of CPU to improve network throughput are: 1) the speed of full duplex asynchronous serial port can reach 25 Mbps; 2) CAN bus works at 500 kbps–1 Mbps; 3) Wi-Fi and Bluetooth use SPI communication with a maximum speed of 150 Mbps; 4) SDIO interface works in high-speed mode at 48 Mbps; 5) The Ethernet uses a built-in MII interface with a maximum speed of 100 M; 6) Use of RAM as an exchange zone at a rate of 400 M; 7) Data exchange using DMA with a 99% bit rate and an improvement rate of more than 10 times.

The Ethernet controller is built into the F407, and the PHY chip in the external extension link layer enables Ethernet functionality. As an abstraction layer, the Ethernet physical layer, or PHY, sends and receives data without mistake at lengths more than 100 meters. The PHY has a specified modulation speed, transmission media type, and supported connection length when encoding data frames for transmission and decoding received frames. The chip used in this paper is DP83848. The Ethernet chip architecture is shown in Fig. 5.

DP83848 is an industrial-grade wide-temperature Ethernet chip suitable for downhole draconian environmental stabilization work. Green websites were once silenced by oppressive law. Sites that fight against the relaxation of environmental impact regulations are intended to turn an unpredictable and unstable environment for earth drilling are put on hold by the government. Key features include support for full and half-duplex automatic switching; Information can be transmitted between a switch and an endpoint simultaneously using full duplex (FDX) switches. One direction of communication is carried out at a time in a half-duplex (HDX) system. Support for network adaptation and adaptive arbitration; support for modification of MAC addresses and internal storage of 32 KB; self-testing in loop mode; and fast Ethernet transmission via DP83848, the Mine integration gateway architecture to a superior backbone high-speed switch.

Underground 2.4 GHz wireless communication mainly includes Wi-Fi, Bluetooth, and Zigbee, of which Wi-Fi is the main access mode for coal mine Internet of Things devices. The Gateway uses a single multi-mode 2.4 GHz wireless chip from Lexin in China. The ESP32 chart is shown in Fig. 6.

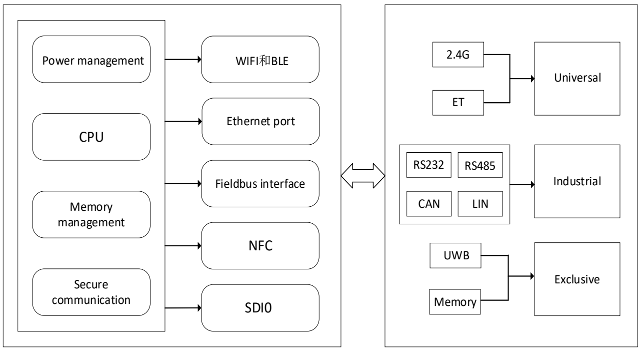



**Fig. 4.** Mine integration gateway architecture hardware architecture.

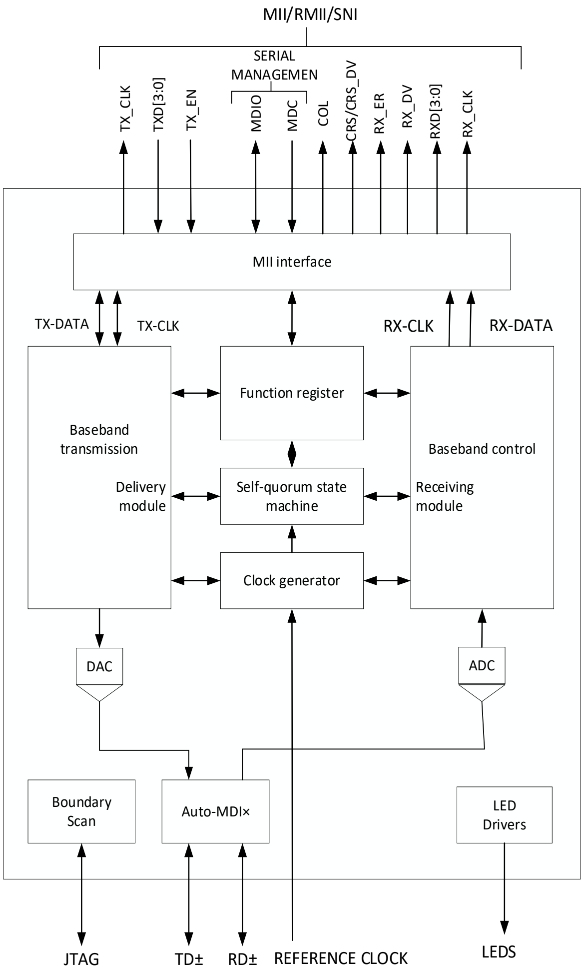



**Fig. 5.** Ethernet chip architecture.

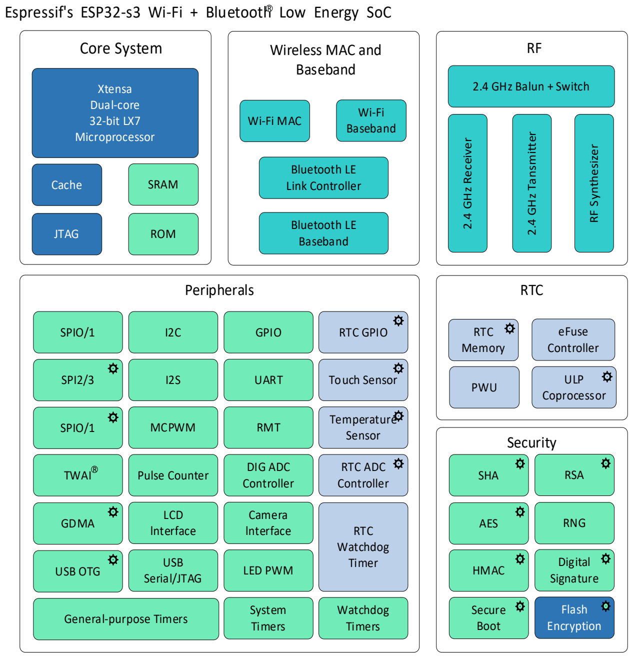



**Fig. 6.** ESP32 chart.

ESP32 has a full IEE802.11 BGN protocol built in and works in three modes: site, hotspot, or hybrid. The processor is a 32-bit L7 and works 240 M. RF scheduling integration with support for low-power Bluetooth BLE5; Built-in 512 K SRAM, with SPI support for a total of four, can be connected to external RAM or flash. Through ESP's GPIO and external interface, it is possible to connect all the functions of IOT device. An uncommitted digital signal pin on an electronic circuit (such as an MCU or MPU board) that can be used as an input, output, or both is recognized as a general-purpose input/output (GPIO).

On the F407 master control chip, it can complete the initialization, reset, clock, and other software controls of each device through the HAL transfer FreeRTOS system, and analyze the communication data of the connected device, a reusable hardware interface is implemented in software using a hardware abstraction layer (HAL). A class of RTOS identified as FreeRTOS is created to be compact enough to run on a microcontroller. The general architecture of the fusion gateway is shown in Fig. 7.

Heterogeneous network equipment of downhole equipment should first carry out network adaptation work. Because heterogeneous network is one in which the computers use various operating systems or where the devices come from several vendors. The original network data is parsed to the CPU in source format. If it is not a fieldbus, the configuration of the network also needs to consume delay. The network simulator offers a real-time method for more accurate time delay measurement across all network topologies in real-time applications. Applications requiring a very quick response from the control system refrain from employing Fieldbus. In order to minimize the delay of the overall network, a network configuration mapping table has been integrated inside the CPU, which already contains network segments, address intervals, slave station numbers and other

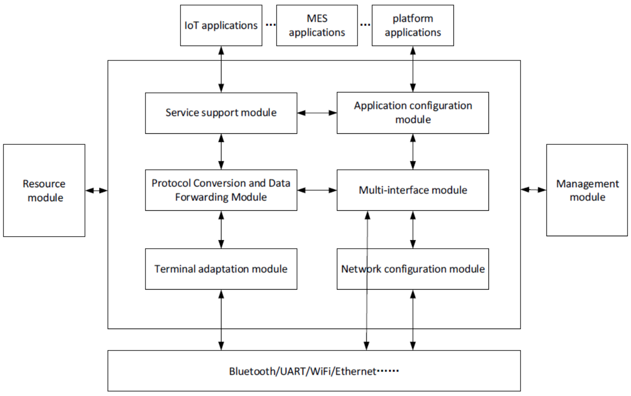



**Fig. 7.** General architecture of the fusion gateway.

information, and is preferentially carried out according to the built-in configuration when communicating. When communicating externally, the CPU configures a fixed application to avoid the time overhead of searching, retrying, etc.

The key task of heterogeneous networks is protocol conversion. The method adopted in this paper is to establish time-shared routing modules to implement peer-to-peer switching so as to save the time cost of communication data copying, unwrapping, storage, and so on. The most typical form of structured P2P (peer to peer) networks is a distributed hash table (DHT), in which a specific peer is given ownership of each file using a variation of consistent hashing ads services and directives to allow users to navigate between views created in an application. The isomeric protocol swap structure is shown in Fig. 8.

Within the Service Support Module and Application Configuration Module, a dynamic network interface timesharing map table is created, and users are prompted to configure the protocols and types of maps prior to system boot-up. These include the Transmission Control Protocol (TCP), Internet Protocol (IP), User Datagram Protocol (UDP), and Post Office Protocol (POP). The map table encompasses general-purpose, thematic, and chronometric maps. When a protocol switch occurs, the mapping relationships of the protocol registers are established based on the protocol's role, data flow direction, and read-write attributes. Subsequently, the message is parsed and directly written to the designated map area. The updated data in the map area is then transmitted to a specific port, which reduces CPU processing time for two sets of data unbundling and packetization, and removes inter-protocol threading locks, thereby significantly enhancing software performance. It has

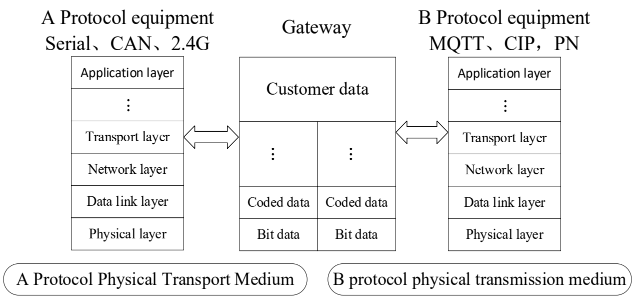



**Fig. 8.** Isomeric protocol swap structure.

been observed that the blind packet transfer between source and destination can lead to the proliferation of viruses; however, local routing protocols equipped with the (NNN) algorithm are found to be highly effective in preventing virus spread. The code for the main controller and radio frequency component of the driver has been managed on a public platform. You can find the link at https://gitee.com/arimmorton_admin/coal-gateway.

## 5. Performance Evaluation Test

In addition to regular ESD (Electrostatic Protection) and EMC (Electromagnetic Compatibility) protection, the gateway for working in the mine must be designed with an explosion-proof enclosure and an inherently safe design to ensure long and reliable work in the mine. The gateway shell and circuit processing installation design is shown in Fig. 9.

The Gateway case is made of polycarbonate with injection molding and lathe technology, and the cavity is designed with a pressurized front and back combination. The front key is a deformation pad, and the back leads to CTC4 and 10 cores. The ABS engineering plastic is embedded with copper pins. While electroless plating is frequently used in isolation, it can also serve as the foundation for a coating that has been electroplated. The professionals at SPC can inject an electric current into a plating solution to increase the thickness of your ABS plastic product as needed.

The entire case is explosion, dust, and water resistant. The design grade is IP67. When a camera has an IP67 classification, it signifies that it is secured against dust ingress and that it can be submerged for up to 30 minutes at a depth of 1 m without losing any functionality. The motherboard is designed for inherently safe circuits and is EMC-rated at 2500 V electrostatic test with a power rating of 7.5 W. Multiply the appliance's power rating (watts) by the number of hours it is used for, then divide the result by 1000 to get the kWh for that particular item.

The gateway initiates the testing process of the load-drive device and Message Queuing Telemetry Transport as shown in Fig. 10. As you can see from the launch process, the gateway registers all devices as configuration services,

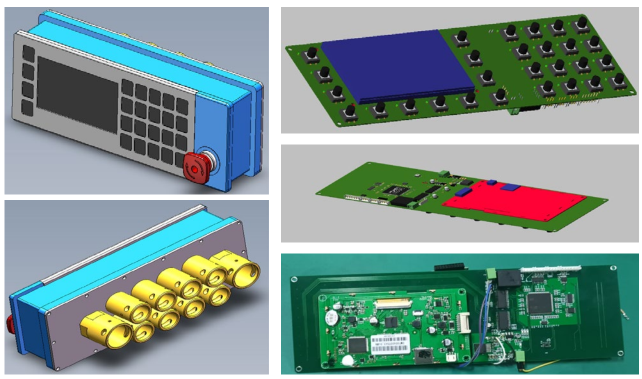


**Fig. 9.** Reality map (shell, motherboard 3D, motherboard physical in sequence).

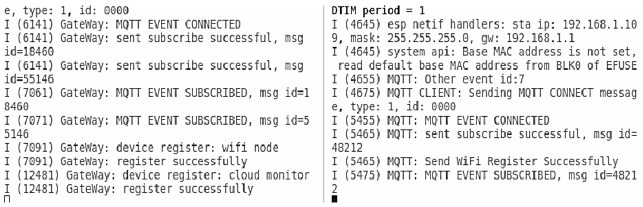



**Fig. 10.** Gateway launches Wi-Fi devices and MQTT protocol.

| Test number | Package size (Byte) | Number of packets | Average RTT (ms) | Packet loss rate |
|---|---|---|---|---|
| 1 | 50 | 100 | 2 | 0.3% |
| 2 | 200 | 100 | 3 | 0.2% |
| 3 | 1K | 100 | 9 | 0.5% |
| 4 | 2K | 100 | 9.5 | 0.3% |
| 5 | 3K | 100 | 10.1 | 0.5% |

**Tab. 3.** Backbone network RTT delay data test.

each hardware device is allocated address mapping space, and the protocol runs are logged.

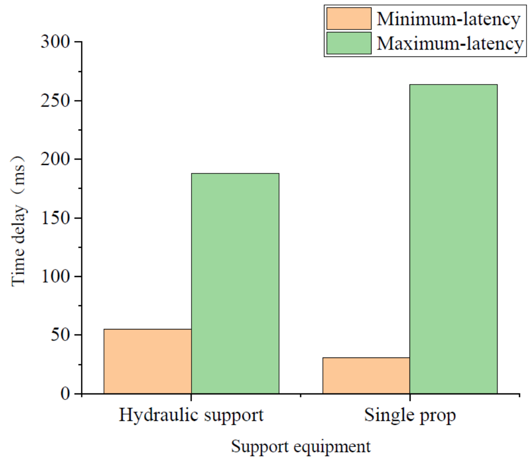
The data of a test transceiver connected to the integrated information platform is shown in Tab. 3.

The backbone switch is gigabit/hundred gigabit adaptive, the network cable is CAT6 six-line, and the transceiver test adopts continuous test mode. Through the test, it can be seen that the Fusion Gateway up platform communication speed is about 10 ms at a time, the network load is light, and communication is very smooth.

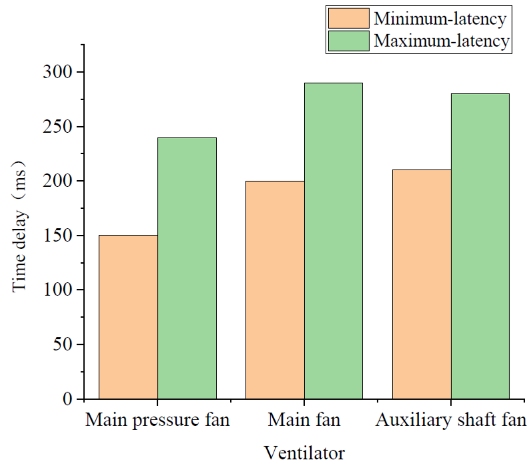
The experimental equipment we use can adjusts the baseband bandwidth. During the experiment, the 100 MHz bandwidth is turned on, and every 2.5 MHz is a sub band. Subbands can be reused and migrated between them. The coal mine deploys a four-channel station device in the 2.4 GHz frequency band. Each two channels are connected to an antenna. The two antennas are back-to-back. The output power of each channel is 250 mW, and the 100 MHz carrier is turned on. Coverage tests were carried out in pedestrian inclined shaft and fully mechanized mining face respectively. In the pedestrian inclined shaft test, at a distance of 200 meters from the antenna, the upload rate is 33.2 Mbps; at 250 meters, the upload rate dropped to about 15.5 Mbps. The coverage radius of single station is more than 200 meters.

The reliability testing of the designed gateway for underground communication transmission in this study is shown in Fig. 11. A comparison was made between the minimum and maximum delays for communication latency of support equipment, ventilation equipment, transportation equipment, and mining equipment. The minimum delay for communication latency of support equipment, transportation equipment, and mining equipment is around 50 ms, while the maximum delay is generally between 150 and 200 ms. For ventilation equipment, the minimum delay is around 150 ms, while the maximum delay is generally between 225 and 300 ms. Overall, the designed gateway in this study meets the communication transmission requirements for industrial equipment in underground settings.

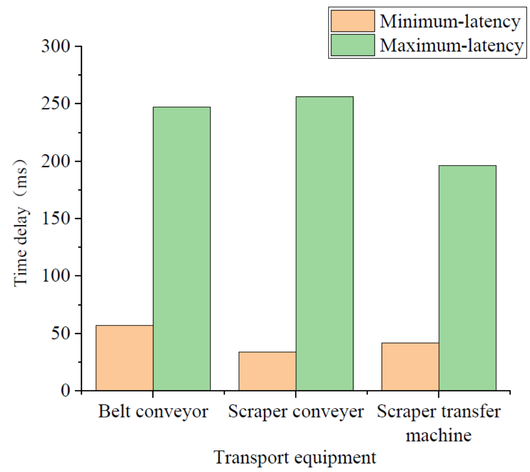
Furthermore, to comprehensively evaluate the communication performance of this gateway within a specific timeframe, statistical analysis was conducted on communication delay, packet loss rate, throughput, and communication jitter using Ethernet, CAN, Modbus, and Profibus data



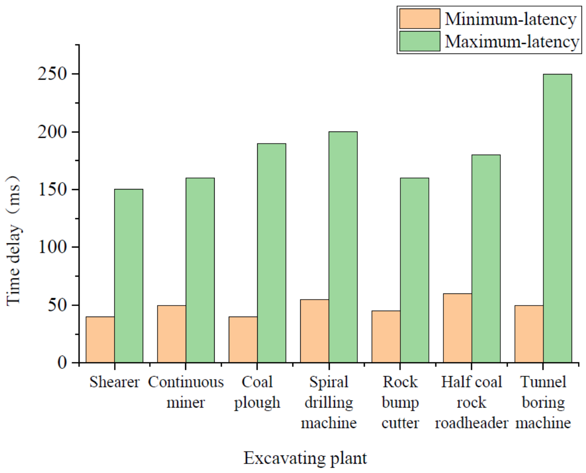

(a) The comparison of the minimum and maximum delays for support equipment




(b) The comparison of the minimum and maximum delays for ventilator




(c) The comparison of the minimum and maximum delays for transport equipment

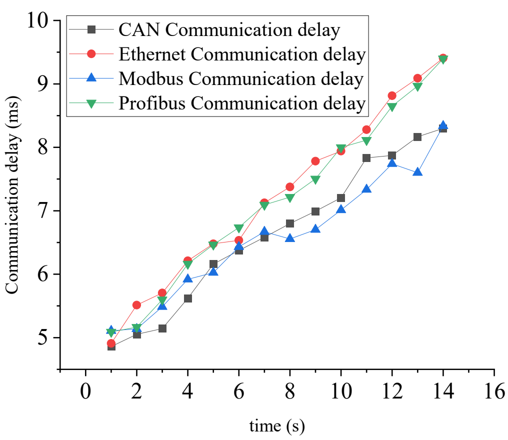



(d) The comparison of the minimum and maximum delays for excavating plant

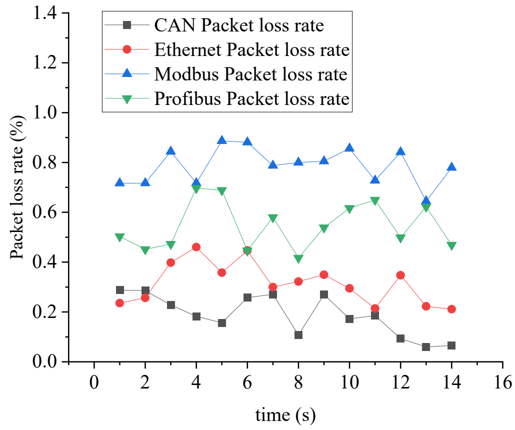
**Fig. 11.** The comparison of the minimum and maximum delays for underground equipment.

transmission protocols. The comparison of Ethernet, CAN, Modbus and Profibus as depicted in Fig. 12. When the gateway utilizes Profibus for data transmission, it exhibits the highest accumulation of parameters such as communication delay, throughput, and communication jitter over time, whereas the packet loss rate is 0.6%. Modbus demonstrates the highest accumulation of packet loss rate per unit time, reaching 0.8%. However, the accumulation values for communication delay, throughput, and communication jitter are comparatively lower. On the other hand, the CAN bus showcases the lowest accumulation of packet loss rate per unit time at 0.12%, ranking third in terms of the accumulation values for communication delay, throughput, and communication jitter. Ethernet, with a packet loss rate of 0.25%, ranks second in terms of accumulation. Apart from its higher delay accumulation, Ethernet performs at a relatively lower level regarding throughput and communication jitter.

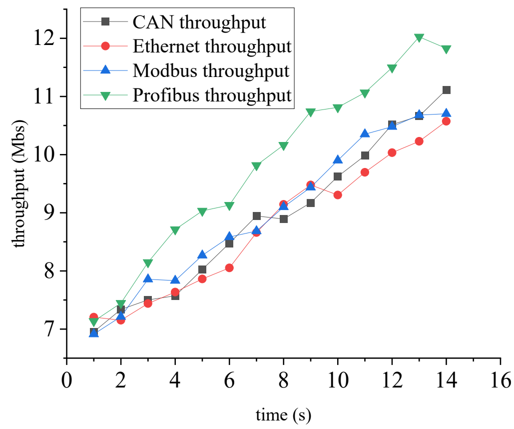
The Root Mean Square (RMS) delay jitter is a metric used to measure the variation in signal delay. In communication systems, delay jitter is typically caused by various factors such as changes in the transmission path and network congestion, which result in small random fluctuations in the



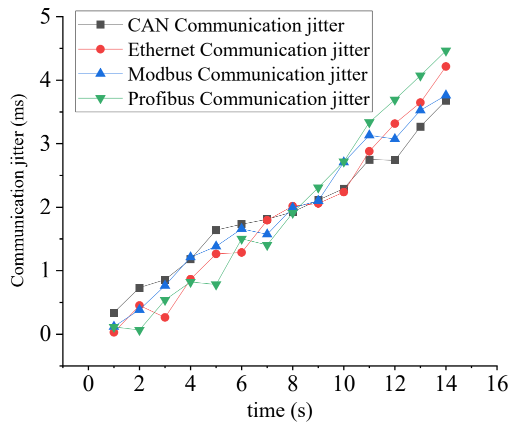

(a) The comparison of communication delays for Ethernet, CAN, Modbus and Profibus




(b) The comparison of pocket loss rate for Ethernet, CAN, Modbus and Profibus




(c) The comparison of throughput for Ethernet, CAN, Modbus and Profibus




(d) The comparison of communication jitter for Ethernet, CAN, Modbus and Profibus

**Fig. 12.** The comparison of Ethernet, CAN, Modbus and Profibus.

arrival time of the signal at the receiving end. The root mean square (RMS) delay jitter is shown in Fig. 13. The curve represents the delay jitter signal of the underground gateway communication, exhibiting a certain level of periodicity and randomness. The red dashed line represents the RMS value of the delay jitter signal, reflecting the average energy of the delay jitter signal.

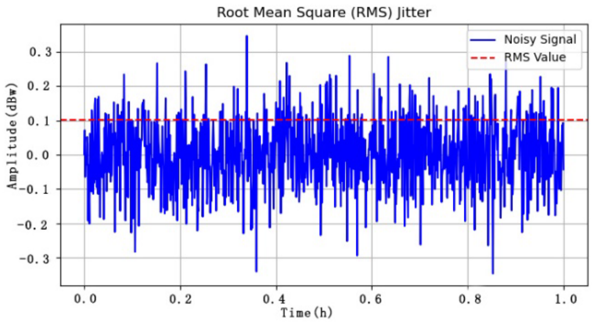



**Fig. 13.** Root Mean Square (RMS) delay jitter.

In summary, the RMS delay jitter chart of the underground gateway communication indicates that the delay jitter signal is a composite signal with both periodic and random components, which may be influenced by various factors such as network congestion, interference, and propagation environment. On the other hand, the RMS value of the delay jitter signal for the underground gateway communication is approximately 0.1, indicating network stability and reliable data transmission.

The power spectral density of delay jitter is used to represent the power distribution of a signal with respect to frequency. In the jitter power spectral density plot, the vertical axis typically represents power, while the horizontal axis represents frequency, displaying the power intensity of the signal at different frequencies. To visually assess the frequency distribution of delay jitter in the designed gateway, this study derived a bilateral power spectral density plot of delay jitter based on the communication frequency of the gateway in the underground environment, as shown in Fig. 14. As the communication baud rate increases, the frequency band load utilization is relatively balanced, and the power curve shows a slight downward trend, while the power spectral density is decreasing. In summary, the delay jitter of this gateway is within an acceptable range.

When multi-source data such as security monitoring, hydraulic support, and personnel positioning are mixed, WireShark is the packets on the network which represented by a moving line in WireShark's visualization of the traffic, and Source network analyzer are used to randomly capture packets of gateway Ethernet data for network pressure test data analysis, as shown in Fig. 15.

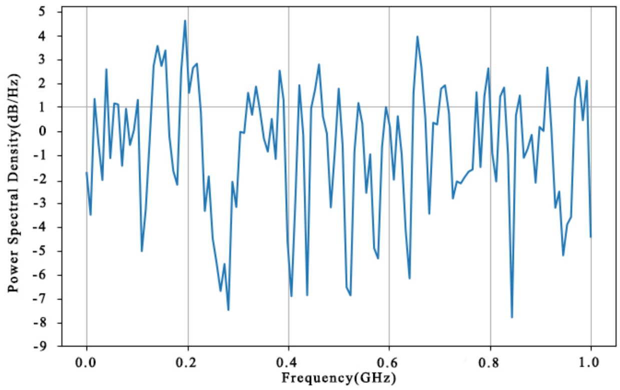



**Fig. 14.** Power spectral density plot of delay jitter.

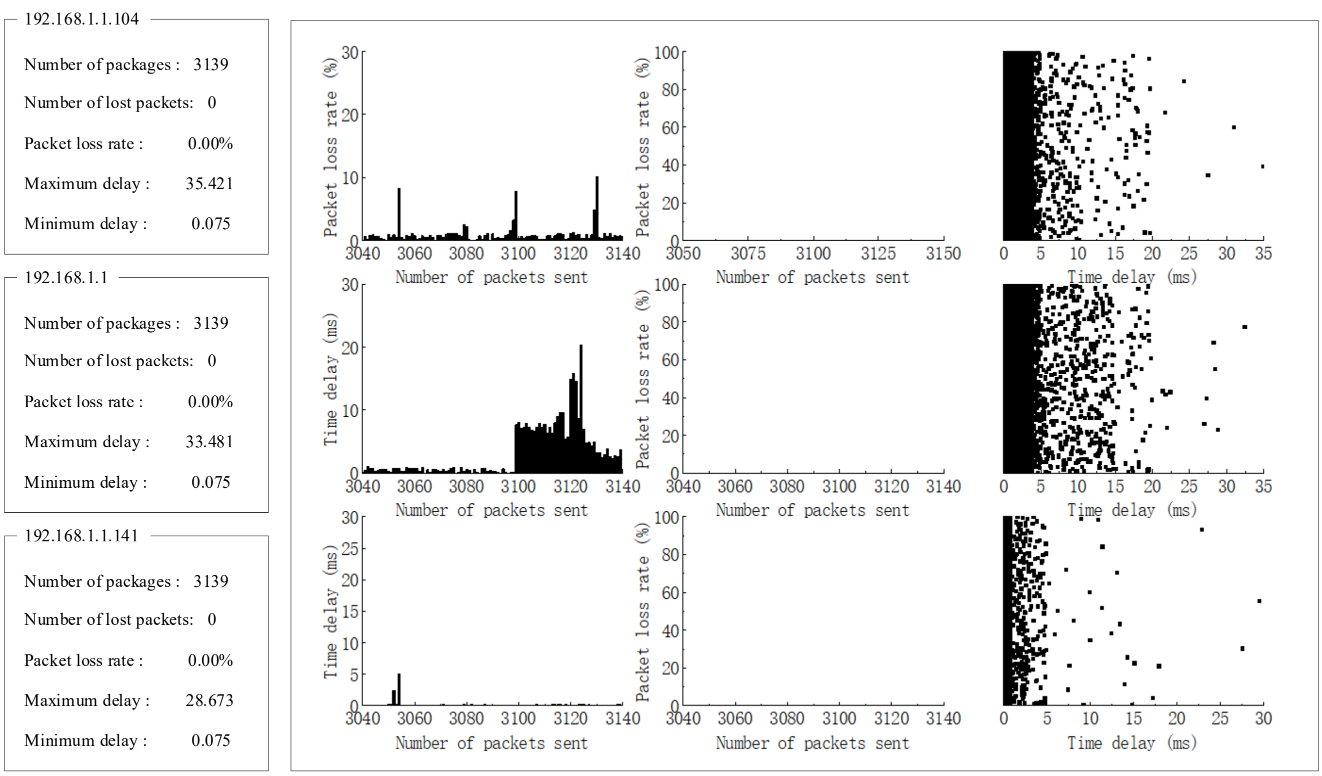



**Fig. 15.** Gateway stress test analysis chart.

# 6. Conclusion

In this paper, the main goal is to reduce the real-time communication latency of mine gateways, and a design method for multi-source isomeric fusion communication networks is proposed. The mine integration gateway architecture integrates the required industrial Ethernet, equipment operating network CAN bus, instrument interface RS 485 and Internet of Things interface 2.4 GHz to achieve multi-source heterogeneous multi-mode equipment access. A time-sharing protocol mapping model is established, and the key problems of long delays and low efficiency of coal mine equipment networks are solved by using MII, SPI, DMA, and other technologies. The test results show that the latency of mine intelligent network is less than 10 ms, which meets the control requirement of real-time communication. The integrated gateway of the mine will be applied in the coal mine production process within two years. In the future, the development of low-power mine gateways will focus on further improving energy efficiency, using advanced energy-saving technologies and self-powered solutions such as solar energy, energy harvesting, etc., to achieve long-term stable operation in harsh underground environments. At the same time, combined with the Internet of Things and artificial intelligence technologies, these gateways will have intelligent data processing capabilities, enabling real-time data analysis and decision support in the field, thereby improving the safety and efficiency of mine operations.

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