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Temperature and humidity monitoring and communication system for coal mine working based on LoRa

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Abstract: Aiming at the complexity of the underground coal mine environment and the safety of workers facing geothermal disasters, a LoRa-based communication system for real-time monitoring and control of temperature and humidity in the working environment of underground coal mines is studied and designed. Based on the introduction of the fair-access criterion of MAC protocol, the time division multiplexing protocol is adopted and improved, and the nodes complete the self-clock synchronisation after sending the information packets by redesigning the LoRa data frame structure. While adopting linear topology networking, LoRa relay nodes are adopted and designed for packet sensing, transmission and forwarding functions and the distance arrangement of LoRa relay nodes is experimentally investigated. The experimental test proves that the system realises the expansion of the transmission distance and the improvement of the success rate of packet reception, which meets the wireless communication requirements in underground coal mines.

Keywords: LoRa technology; wireless communication technology; coal mine environmental monitoring; low power consumption.

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1 Introduction

It is well known that coal resources are still the main demand resource for industrial development today. China is still a large energy consumer, and with the rapid growth of the economy, the energy demand is also growing. Coal is China's main energy consumer and an important chemical raw material, so ensuring the safe and smooth mining of coal is very important (Li et al., 2011). Coal mines need to combine new technologies, such as the internet of things (IoT), wireless network transmission, and so on, to strengthen the management of coal mine safety production. Reducing the occurrence of coal mine accidents and protecting the lives of mining workers is the guarantee of safe production in coal mines and the prerequisite for the healthy development of the coal industry. Due to the

complexity of the working environment of coal mines, a set of complete and high-quality coal mine monitoring and communication systems is crucial for coal mine production work and workers' life safety (Suganthi et al., 2021).

At present, half of China's proven coal weight is located below 1,000 metres underground, and to ensure the normal supply of coal for a long time in the future, the depth of domestic coal mining is increasing yearly. It was pointed out that deep mining mainly faces 'three high' environments, i.e., high ground pressure, high ground temperature, and high pore pressure (Zhao, 2002). Among them, the most overlooked safety hazard is high ground temperatures. Underground geothermal disasters in coal mines in the central and eastern parts of China are very serious. If cooling measures are not taken in time, the temperature of the working environment in most of the

working faces reaches 28~30°C. The temperature of the outlet holes in some of the working faces reaches 50~62°C, and the relative humidity is close to 100%. According to statistics, the accident rate when the working face temperature is 30~40°C is 3.6 times higher than the accident rate below 30°C (Cao et al., 2022). Underground workers in high-temperature and high-humidity environments have serious safety and production hazards. The establishment of a set of communication systems for the underground environment temperature can be for the underground high temperature and high humidity environment to formulate more reasonable safety standards and timely make the corresponding cooling measures, to reduce the incidence of accidents and to ensure the production of safety has a subtle and important role.

The complex environment under the mine is dynamic because the working area is continuously extended with coal mining, resulting in the need for frequent movement of equipment, and the equipment arranged in the working area is exposed to high temperatures and humidity. For wired transmission, wiring is difficult on some working surfaces, and the lines are also likely to be damaged, affecting the communication system's normal operation. The huge network system in the underground, coupled with the many sensors deployed, creates the status quo of site management cluttered with cables. For example, the number of cables on the support is as thick as the 'thigh', which makes it extremely difficult to maintain and troubleshoot in the field. Wired transmission deployment has the problems of high cost, difficult maintenance, and poor scalability. Mines are particularly concerned about this 'braid-cutting' project, so the demand for wireless data transmission is obvious.

In this paper, for the characteristics of the current traditional wired communication system and wireless transmission system in coal mines, combined with the requirements of smart mines (Ye et al., 2015) and coal mine safety management, a temperature and humidity monitoring communication system based on LoRa technology for the working environment of underground operation in coal mines is proposed and designed by designing a self-clocking synchronisation of TDMA protocols and LoRa relay nodes. An experimental study was conducted for the optimal arrangement of LoRa relay nodes. Through the simulation environment experiments, the system is proved to be successful in the underground tunnel environment to realise the expansion of the transmission distance and the improvement of the success rate of data packet reception. The main contributions of this paper are:

- A set of wireless communication systems with low power consumption and long distance, low cost, simple system equipment, easy to build and occupies little space is independently designed for monitoring the temperature and humidity of the underground working face of coal mines, which realises the monitoring of geothermal hazards and the improvement of the underground communication system.

- By designing the LoRa data frame structure, self-clock synchronisation is achieved when each node transmits data, and the communication conflict problem caused by the simultaneous transmission of data packets by multiple source nodes at the downhole working face is alleviated after time slot allocation.
- A linear topology with LoRa relay nodes is used in the system construction, which is simple to build and suitable for the alleyway environment. The distance arrangement of relay nodes in this network structure is also studied. Meanwhile, the fair-access criterion in the MAC protocol is introduced to ensure that the TDMA protocol meets the network's specified utilisation and delay requirements.
- It is proved by experiments that the success rate of packet reception between the source node and the gateway of this system can reach 99% in the range of 500 m to 700 m. It successfully realises the expansion of transmission distance and the improvement of packet reception success rate, which is suitable for the working environment of underground coal mines.

The paper is organised as follows. Section 2 describes the communication system for coal mine applications and the related work on LoRa technology. Section 3 gives a detailed description of LoRa technology. Section 4 presents the hardware and software design of the proposed communication system. Section 5 and Section 6 test the experiments and analyse the results. Section 7 concludes the paper.

2 Related work

In response to the problem of non-stop digging in the working face of coal mines and the mobility of underground workers, China has successively developed leaky cable communication systems, PHS, Zigbee, WiFi, 3G, 4G, 5G, and other mine mobile communication systems (Sun, 2015). The function of a leaky cable communication system is to carry out voice communication, and it does not support the transmission of underground monitoring data to the ground. PHS communication technology has low security and reliability, and it is not suitable to face the strict requirements for safety in coal mines nowadays. Zigbee system has a short communication distance of up to 100 metres, the communication rate is low, and the stability of the network is limited due to the limited number of devices connected to its network. 3G has been replaced by WIFI and 4G technology. WIFI and 4G can realise underground voice, image, and video communication transmission due to the long transmission distance and high bandwidth, which is currently widely used in coal mines. Still, the communication environment is not ideal due to the corners in the underground tunnel. It is necessary to reduce the transmission distance between the wireless transmitting base stations to ensure good quality of communication, which increases the number of wireless transmitting base

stations and the cost of the communication system. The newly developed 5G technology has higher transmission rates, lower latency, and large connections and intelligence. However, its application is still in the exploratory stage, and its cost is extremely high (Nie et al., 2016).

There is a great interest in applying LoRa, a novel LPWAN wireless communication technology, to communication systems in underground mines. Yadav et al. (2021) proposed a slope monitoring system for the mining industry based on LoRa technology and conducted experiments in non-line of sight (NLoS) areas to prove that LoRa can meet the mining industry's needs. Still, they only applied LoRa in open-cast mines. Abrardo and Pozzebon (2019) found that the signal strength of LoRa faded badly underground and adopted LoRa as a multi-hop relay technology. Still, their focus was on minimising energy consumption. Branch and Cricenti (2020b) utilised LoRa as a multi-hop messaging system applied in explosives detonation for underground mining. They demonstrated that LoRa can propagate a considerable distance underground through measurements of underground signal strength. Chowdhury et al. (2023) successfully developed a smart coal mine underground environment monitoring system based on WSN with LoRa technology and established end-to-end data transmission so that the data monitored by the sensors can be successfully transmitted to the application server. Still, the optimal transmission distance of LoRa in their system is only 14 m. Piyare et al. (2018) proposed an efficient on-demand time division multiple access (TDMA) communication protocol for IoT. This ultimately achieves a 100% packet transmission rate for LoRa by eliminating the possibility of packet conflicts.

3 LoRa technology

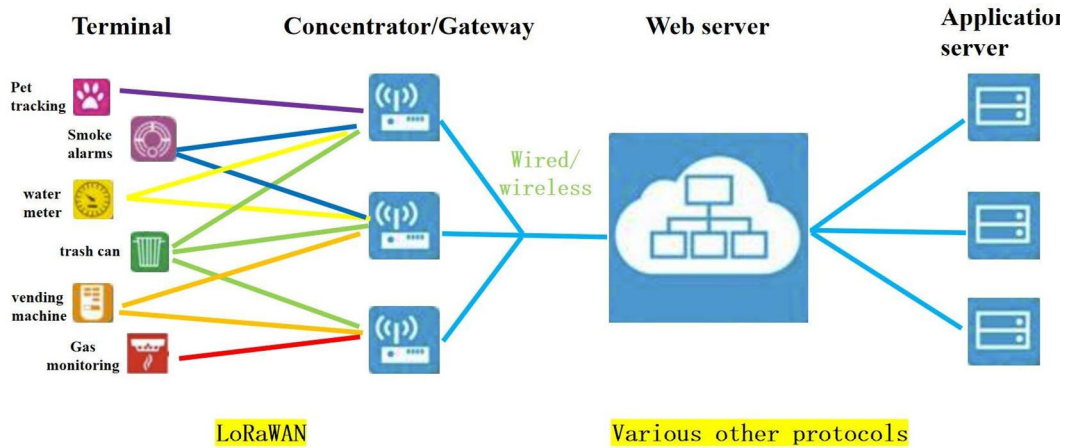
LoRa is a wireless physical layer technology developed and promoted by Semtech, Inc. in the USA. It can provide a low-power, long-range, two-way communication platform in the IoT channel. The use of chirped spread spectrum

(CSS) modulation technology enhances the distance and performance of wireless communication, and the transmission distance can reach several kilometres when a monopole antenna is used and more than 10 kilometres when a directional antenna is used (Branch and Cricenti, 2020b).

LoRa has higher interference immunity than other LPWAN technologies, such as Sigfox, NB-IoT, and LTE-M. Its battery life is increased by ten times compared to cellular networks. Unlike Sigfox and NB-IoT, LoRa supports adaptive data rates and allows private networks. In IoT applications, it can support multiple independent users or organisations to share the same LoRa network infrastructure, which makes it versatile. LoRa supports connecting many devices and transmitting data simultaneously, accommodating a huge public network. It has minimal infrastructure equipment and is simple to install (Yadav et al., 2021). LoRa can communicate wirelessly in free frequency bands around the world without paying for the spectrum, e.g., 868 MHz is commonly used in Europe, 915 MHz is commonly used in the USA, and 433 MHz is commonly used in Asia (Reddy et al., 2023).

The LoRa network architecture comprises four parts: terminal nodes (containing LoRa modules), gateways (or concentrators), network servers, and application servers. As shown in Figure 1, the networking scheme of LoRa is similar to a cellular system, and a typical LoRa network can be formed using star topology (Gao et al., 2023). Gateways star topology connecting various terminal nodes and the terminal nodes can transmit data with single or multiple gateways. The gateways are connected to a network server via standard IP protocol (Aslam et al., 2020). The network server functions include organising, analysing, and saving all data packets, managing and configuring the gateways, and displaying the status of each part of the communication system. The application server obtains all the organised data from the network server, displays what each terminal node monitors, and warns instantly (Zhang, 2019).

Figure 1 LoRa network architecture (see online version for colours)



The significant advantages of LoRaWAN are the ability to communicate over long distances with low power consumption and the fact that it operates in free ISM bands such as 433 MHz, 470 MHz, etc., which makes the cost of use much lower (Jethwa et al., 2021).

LoRa chip provides three categories of devices used to piggyback on the communication system for LoRa-based wireless monitoring terminals, which can realise different functions and cope with different environments, thus improving the quality of communication. As shown in Table 1 (Lavric and Popa, 2017).

Table 1 LoRa terminal equipment classification

Class	Function	Power consumption
Class A	Bidirectional communication, wake by sensor, with two short receiving windows after data transmission.	Lowest
Class B	Bidirectional communication It has an additional timed receive window.	Median
Class C	Bidirectional communication The receiving window is always open.	Highest

LoRa data frame consists of leading code, optional header, payload, and cyclic redundancy check (CRC), as shown in Figure 2 (Balatsouras et al., 2023).

Figure 2 LoRa data frame structure

Preamble	Header	CRC	Payload	Payload CRC
	(explicit mode only)			

The leading code synchronises the receiver with the incoming data stream, ensuring the correct reception of the data. By default, it is generally 12 symbols in length. The optional header contains information such as payload length, encoding rate, and CRC. When the above information is fixed, or the spread factor is 6, the optional header can be set to the hidden mode, reducing transmission time and improving data transmission efficiency. The payload carries the actual data content, and its symbol number, $N_{payload}$, is not fixed (Mugerwa et al., 2023).

$$N_{payload} = 8 + \max \left[\left\lceil \frac{8PL - 4SF + 28 + 16 - 20H}{SF - 2DE} \cdot \frac{1}{CR} \right\rceil, 0 \right] \quad (1)$$

where PL represents the payload bytes; SF is the spreading factor, with a value range of 6–12. $H = 0$ when there is a header; otherwise, we have $H = 1$. When the low data rate optimisation bit is set to 1, we have $DE = 1$; otherwise, we have $DE = 0$, and CR indicates the encoding rate, ranging from 1 to 4.

Let the LoRa packet time be T_{packet} , then:

$$T_{packet} = T_{preamble} + T_{payload} \quad (2)$$

where $T_{preamble}$ is the leading code time; $T_{payload}$ indicates the payload time.

$$T_{preamble} = (N_p + 4.25) \cdot T_{symbol} \quad (3)$$

where N_p is the length of the leading code, T_{symbol} is the symbol period:

$$T_{symbol} = \frac{2^{SF}}{BW} \quad (4)$$

where SF is the spreading factor, and BW indicates the bandwidth.

In formula (2), the payload time $T_{payload}$ is:

$$T_{payload} = N_{payload} \cdot T_{symbol} \quad (5)$$

By bringing formulas (3), (4) and (5) into formula (2), we can get:

$$T_{packet} = (N_{payload} + N_p + 4.25) \cdot \frac{2^{SF}}{BW} \quad (6)$$

The bit rate R_b is:

$$R_b = \frac{SF}{T_{symbol}} \cdot CR \quad (7)$$

By substituting formula (4) into (7), we get:

$$R_b = SF \cdot \frac{BW}{2^{SF}} \cdot CR \quad (8)$$

4 Overall system design scheme

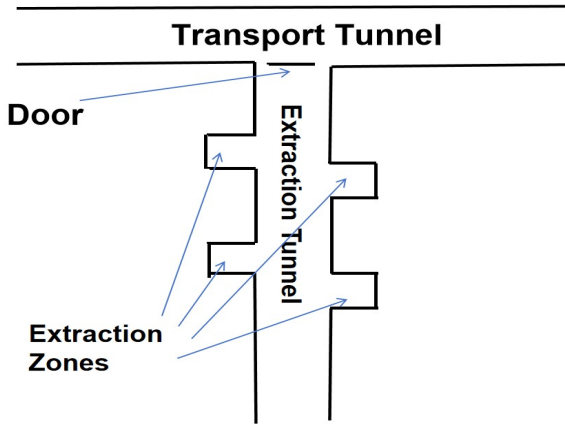
4.1 System design idea

Because accidents caused by high ground temperatures differ from ordinary regional safety accidents, they can result in a wider range of incidents and involve more personnel. Over time, the accident rate gradually increases without notice, seriously affecting mine safety production (Gao, 2018). Given the small data packages of underground ambient temperature and humidity, the low monitoring frequency, the coal mine's emphasis on 'cutting braid engineering' (reducing wired transmission), and cost considerations, a LoRa-based monitoring communication system for underground ambient temperature and humidity in the coal mine was designed. Flexibly arranging terminal detection nodes allows a wide range of environmental data in coal mines to be monitored. The sensor collects data, and the LoRa module wirelessly transmits the data to the underground gateway. The gateway then transmits all the data collected in the mine to the computer's cloud service information processing platform through the network server, completing the analysis, processing, and recording of the data from the underground coal mine working environment.

In the coal mine underground, due to the need to arrange multiple monitoring terminals, then in the whole communication system work, there will be multiple wireless communication devices at the same time to try to use the same channel for communication, which may lead to communication conflicts, packet loss and communication

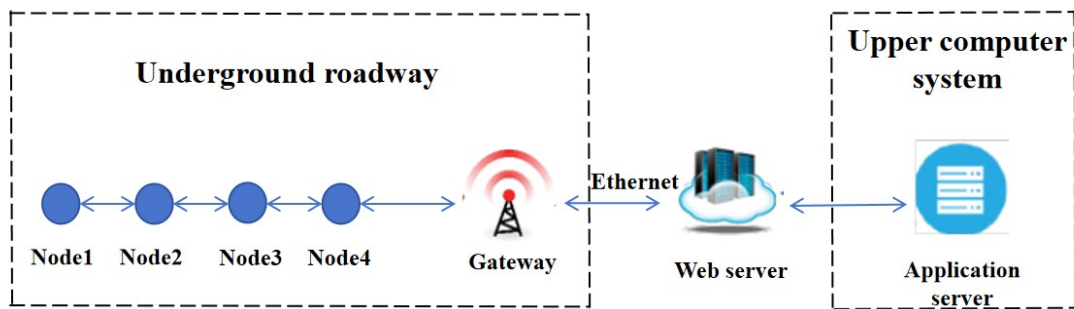
efficiency degradation of the problem. LoRa's TDMA scheme effectively avoids channel conflicts by dividing the time under the same channel into different and non-overlapping time slots, which are called time slots. Under the same channel, each time slot has a specific serial number, which is used to determine whether the time slot has been occupied. Based on this scheme can effectively realise orderly data transmission and efficient bandwidth utilisation. At the same time, considering the simplification of the system, low power requirements, and clock synchronisation accuracy, instead of clock synchronisation settings in the system, the self-clock synchronisation of LoRa nodes is designed to make the system more advantageous in application scenarios.

Figure 3 Mine tunnel structure (see online version for colours)



As shown in Figure 3, the underground mine consists of extraction zones, extraction tunnels, and transport tunnels. The extraction zone is a small branch area in the extraction tunnel, while the extraction tunnel is separated from the transport tunnel by a large steel gate. Although LoRa can successfully transmit data wirelessly in the 200-metre-long mining channel, the signal strength decreases rapidly in NLoS areas. Therefore, one or more relay nodes are designed and arranged in the transmission process of the system, and using broadcast communication, the relay receives and forwards messages within the range to ensure the success rate of receiving data packets and also expands the transmission distance of the system.

Figure 4 Construction diagram of downhole temperature and humidity monitoring communication system (see online version for colours)



4.2 Basic system architecture

The overall structure of the underground environment temperature and humidity monitoring communication system proposed in this paper is shown in Figure 4.

The underground communication system comprises a monitoring terminal, relay node, and gateway. The system is designed through hardware and software to meet the whole system, expand the transmission distance under stable transmission data, and exert a good low-power long-distance advantage. Each monitoring node comprises an STM32F103 microcontroller with a DHT11 temperature and humidity sensor and an SX1278 chip wireless RF module powered by an 18650 lithium battery pack.

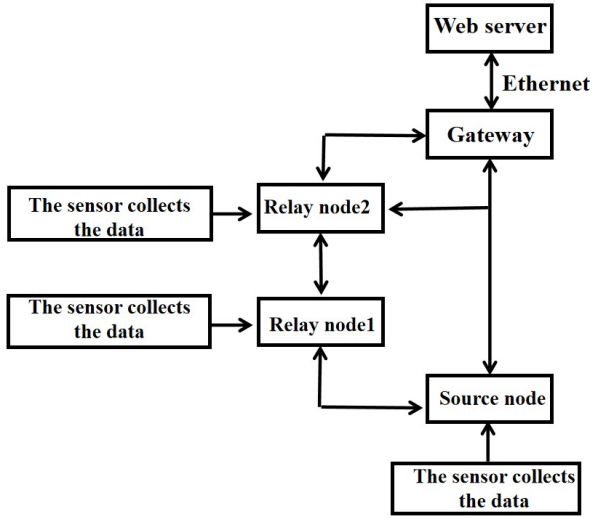
Node 1 in Figure 4 is arranged as a monitoring source node at the deepest working face and is only responsible for collecting and transmitting temperature and humidity data of this environment. Node 2, node 3, and node 4 in Figure 4 are evenly arranged between the monitoring source node and the gateway as relay nodes, possessing the ability to regularly collect and transmit the data collected by their sensors and forward the data received from the monitoring source node. The overall functional diagram of the downhole communication system is shown in Figure 5.

4.3 System software design

This system mainly designs the software for monitoring the source and relay nodes.

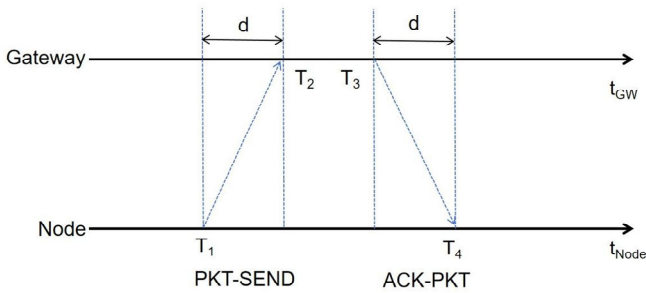
4.3.1 Low power design

By burning the program for the STM32F103 microcontrollers and the SX1278 chip, the microcontrollers can wake up regularly and control the power-up of the DHT11 temperature and humidity sensor and the LoRa radio frequency module. The sensor then collects environmental temperature and humidity data. Meanwhile, the LoRa RF module begins to read the data collected by the sensor and enters the transmission state. After receiving the ACK message, the LoRa RF module enters a dormant state, awaiting the next wake-up signal. In this manner, the monitoring nodes can be dormant for most of their daily operations, resulting in low power consumption.

Figure 5 Overall function diagram of lower computer communication system

4.3.2 Time division multiple access design

Currently, TDMA time slot allocation protocols are mostly used in ad hoc networks, such as the five-phase reservation protocol, ATST, and N-TDMA. Still, less research has been done on TDMA time slot allocation protocols for LoRa networks (Li et al., 2019). In this system, each terminal node is set to obtain the time slot according to the order the gateway sets and then takes turns communicating with the gateway. The terminal node transmits its packet without conflict in its allocated time slot and enters dormant mode outside its time slot to realise the purpose of low power consumption.

Figure 6 Clock synchronisation process (see online version for colours)

TDMA requires a clock synchronisation setup to achieve time slot allocation. Most of the current researches design the clock synchronisation process separately in the system, but this requires additional synchronisation protocols to ensure the consistency of the clocks of each node and is affected by the performance limitations of the synchronisation protocols themselves as well as the network conditions, which leads to relatively poor real-time performance. The system needs more resources to maintain the synchronisation state. Therefore, in this paper, instead of designing a separate time synchronisation process in the protocol, we set up the clock synchronisation process every time a LoRa node uploads data by designing the LoRa data

frame structure. As shown in Figure 6, if a node uploads data at local clock T_1 , the gateway receives the data at local clock T_2 , replies with an ACK message at local clock T_3 , and receives an ACK message at local clock T_4 .

Suppose the propagation delay from node to gateway and gateway to node are d , and the clock deviation between the gateway and the node is Δt . In that case, the gateway packs the information of T_2 and T_3 in the ACK packet, and the node receives the ACK message and then calculates the deviation through formula (9), thus correcting the local clock. Then, it can realise the time synchronisation with the gateway.

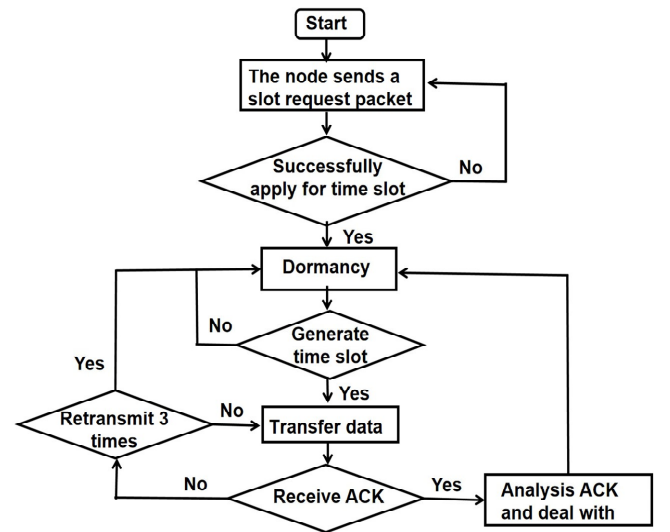
By

$$T_2 = T_1 + d + \Delta t; \quad T_4 = T_3 + d - \Delta t$$

Obtain

$$d = \frac{(T_2 - T_1) + (T_4 - T_3)}{2}; \quad \Delta t = \frac{(T_2 - T_1) - (T_4 - T_3)}{2} \quad (9)$$

In the time slot allocation process, first, the node sends a time slot request packet, which includes fields such as source device number and destination device number. After the gateway receives the time slot request packet sent by the node, it extracts the source device number from it and stores it in the memory in chronological order. The offset address of the source device number of each node in the gateway memory is their respective time slot numbers. When the allocation is completed, the gateway sends a time slot response packet, which includes fields such as the number of nodes n , the time slot period T , the time slot starting clock t_0 , the static time slot number i , the time slot length l , and the reporting period t (the size of t is an integer multiple of $2l$). When initialising the gateway, these fields can be configured according to the user's needs. The node time slot allocation process is shown in Figure 7.

Figure 7 Flow of node time slot allocation

Since the MAC protocol requires each sensor node to have an equitable opportunity to send its collected and received data to the gateway, the fair-access criterion in the MAC

protocol is introduced: the data frame size is assumed to be fixed, the propagation and processing delays are negligible, and the transmit rates are equal. Under this criterion, it can be ensured that the data from all nodes can reach the base station equally, and the performance bounds of the specific implementation of the linear network topology can be known to ensure that the TDMA protocol meets the specified utilisation and delay requirements of the network (Gibson et al., 2007). The performance bounds obtained therein apply to any MAC protocol, while these performance bounds can be realised by a self-TDMA protocol (Xiao et al., 2012).

4.3.3 Design of DATA frame and ACK frame

By specifying a uniform frame format, the sender and receiver can adhere to the same rules to ensure that the data will not be misunderstood or confused during the transmission process, thus guaranteeing the accuracy and reliability of data transmission. Here, the data frame (DATA frame) and the confirmation frame (ACK frame) are designed.

The maximum number of bytes of a DATA frame is 69, which consists of a frame type, frame sequence number, destination address, source address, frame check sequence (FCS), and a payload of up to 64 bytes. As shown in Table 2, the frame type is represented by the lower four bits of a byte, where 0010 represents the normal data frame, and 0111 represents the broadcast frame (in this case, the destination address is 0).

Table 2 DATA frame structure

Frame type	Frame sequence number	Destination address	Source address	Payload	FCS
1B	1B	1B	1B	Variable length	1B

The gateway sends an ACK frame to indicate whether the data has been successfully received and carries the information to realise the clock correction of each node, which can realise the time synchronisation between each node and the gateway. The ACK frame consists of frame type, destination address, payload, and FCS, where the frame class is represented by the low four bits of the byte(0011), and the payload contains the correction information to achieve the time synchronisation between the node and the gateway as shown in Table 3.

Table 3 ACK frame structure

Frame type	Destination address	Payload	FCS
1B	1B	Variable length	1B

When the device successfully receives the data, it will immediately send an ACK frame to the packet's source. When the monitoring node that sent the packet receives the ACK frame, it does not need to reply and ends the current transmit task.

5 Experimental tests

This experiment uses an STM32F103 microcontroller with an SX1278LoRa wireless RF module and a DHT11 temperature and humidity sensor to form a monitoring terminal. It uses an STM32F407 microcontroller equipped with an SX1278LoRa wireless RF module to form a summarising node instead of the gateway to network with each monitoring node and complete the reception and statistics of all data.

Considering that the width of the underground working surface of the large coal mine is about 300 m, the limit distance between the gateway and the terminal source node is temporarily arranged to be 1.5 km, which not only ensures the stable reception of the data but also relieves the wiring pressure of the coal mine underground. A simulated experimental test was carried out on a road similar to a roadway in the school (1 km away from the distance in the tunnel by the Fenhe River). The aggregate node was used to directly connect to the computer via D/A converter instead of the gateway for the total reception and observation of data. The relay node was arranged between the terminal source node and the gateway, as shown in Figure 8.

Figure 8 LoRa communication experiment terrain map (see online version for colours)

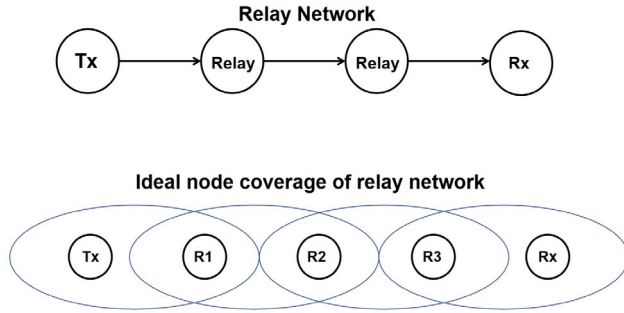


All device channel frequencies are set to 433 MHz, i.e., the same channel. The source nodes are set to a maximum of two in this experiment, which is only used to observe the effect of channel conflicts and the effect of the TDMA scheme. The monitoring nodes are set to collect the temperature and humidity data of the surrounding environment once every hour. By dividing the one hour into a series of equal 1-minute time slots, each of which is assigned to a specific LoRa monitoring node for communication, each monitoring node knows when it is ready for data sending. Each node sends data in the time slot assigned to it, and the sensors of the other monitoring nodes remain dormant, waiting for their time slots to arrive, thus avoiding conflicts among the monitoring nodes.

The LoRa relay network used in this paper is a wireless communication network constructed using LoRa

technology, which realises long-distance data transmission through relay nodes. As shown in Figure 9, this network structure has the advantages of low power consumption, long distance, and high reliability, which is especially suitable for communication between IoT devices. As a special type of mesh structure, the topology of the relay network is long and thin, which is very suitable for application in communication systems in tunnels (Branch and Cricenti, 2020a).

Figure 9 LoRa relay network structure diagram (see online version for colours)



Packet reception success rate is one of the important indexes to measure the performance of a wireless communication system, which directly reflects the reliability of the network transmission. A higher success rate means that the user can receive the required information faster and more accurately, so the statistical packet reception success rate is chosen as the evaluation criterion of the system performance in this experiment. Three experiments are conducted under different schemes and distances; 100 packets are sent in each experiment, and the average packet reception success rate of the three experiments is taken for statistics.

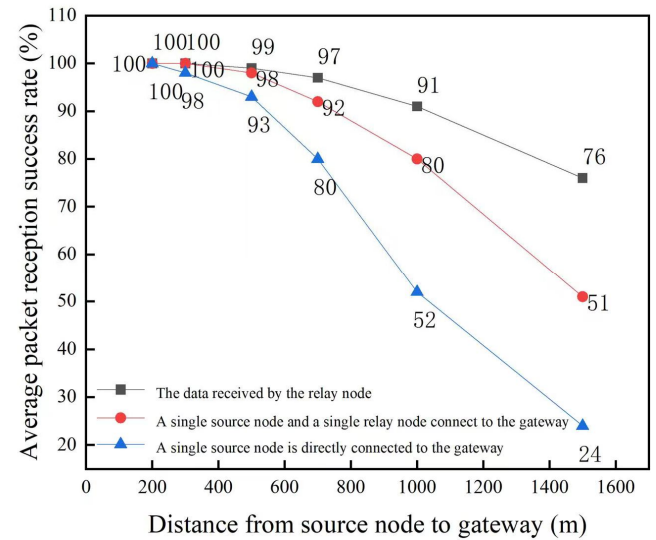
6 Experimental results and analysis

Firstly, the success rate of packet reception under different distances between the source node and the summary node in the TDMA-free design was tested. A single relay node was arranged between the source node and the summary node to observe the influence of the relay node on the packet reception success rate. The experimental results are presented in Figure 10.

As shown in Figure 10, when a single source node sends data directly to the gateway, the success rate of packet reception decreases faster and faster with the increase of distance because the attenuation of signal strength increases with the increase of transmission distance. The impact of environmental noise on the signal is also increasing; simultaneously, due to the multipath effect, signal superposition and interference are also reducing the packet transmission success rate. When a relay node is added between the source node and the gateway for packet forwarding, the success rate of packet reception is improved. Still, due to the influence of channel conflict, it can be seen that the improvement of packet reception success rate is not significant in short distances. Still, it is

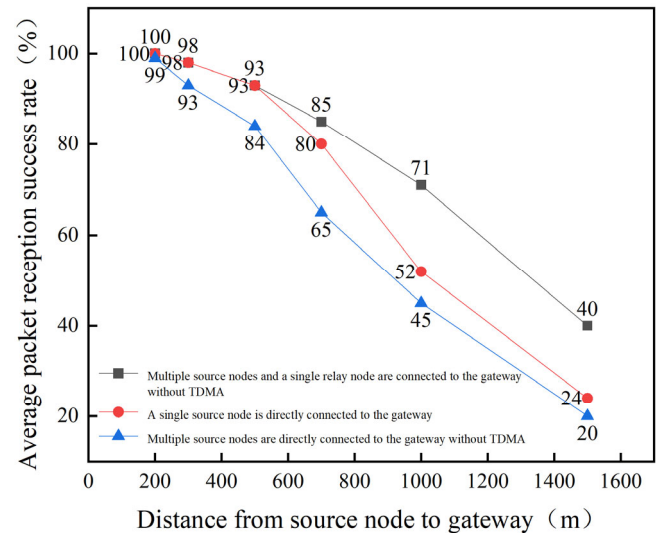
more significant in long distances. Due to channel conflict, the success rate of relay nodes sending data monitored by their sensors is slightly lower than that of a single node sending data directly to the gateway at the same distance.

Figure 10 Experimental results of different distances and schemes without TDMA design (see online version for colours)



The influence of channel conflict on the wireless transmission of this system is also tested. The data transmission experiment is carried out by arranging multiple source nodes to connect to the gateway directly and adding a relay node in the middle of them. The experimental results are shown in Figure 11.

Figure 11 Experimental results of the impact of channel conflict on the success rate of data packet reception (see online version for colours)



It can be seen from Figure 11 that when multiple source nodes transmit data to the gateway at the same time, due to channel conflicts, the average data packet transmission success rate will be lower than the data packet transmission success rate of a single source node directly transmitting to

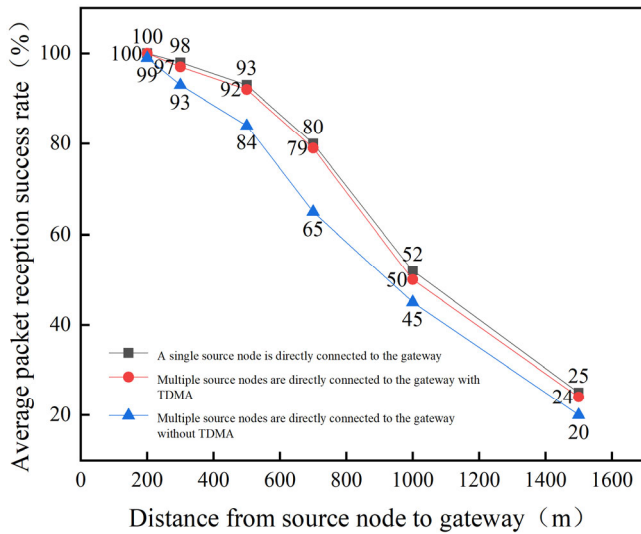
the gateway. At the same time, compared with Figure 10, it can be concluded that due to the influence of channel conflicts, the success rate of data packet transmission from multiple source nodes plus one relay node to the gateway is also lower than that of a single source node plus one relay node to the gateway.

We also conducted experiments on reducing the impact of channel conflicts using the TDMA scheme. The experimental results are shown in Figure 12.

It can be seen from the experimental results that when the system adopts the TDMA scheme, the average data packet transmission success rate of multiple source nodes is improved compared to the non-TDMA scheme and is similar to the data packet transmission success rate of a single node to the gateway. This is because after adopting the TDMA scheme, channel conflicts are avoided. Only one source node is transmitting in a random time slot, which can be regarded as a single node transmitting data packets directly to the gateway.

Next, the impact of the TDMA solution and a single relay node on the system transmission work was tested. The experimental results are shown in Figure 13.

Figure 12 Experimental results of the impact of the TDMA scheme on reducing channel conflicts (see online version for colours)



As shown in Figure 13, after adopting the TDMA scheme and adding a relay node, the transmission success rate of data packets has been significantly improved, reaching 99% within the range of 500 m. However, as the distance between the source node and the gateway gradually increases, the distance between the relay node and both nodes increases, so the data packet reception success rate still fails to meet expectations. Therefore, increasing the number of relay nodes between the source node and the gateway is decided to ensure the success rate of data packet transmission while achieving the expansion of transmission distance.

Finally, the impact of the TDMA solution and two relay nodes on the system transmission work was tested. The experimental results are shown in Figure 14.

Figure 13 The impact of using the TDMA solution and a single relay node at the same time on data packet transmission (see online version for colours)

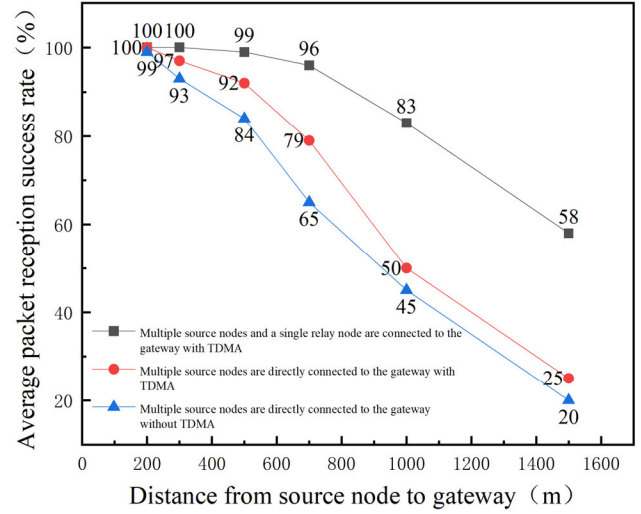
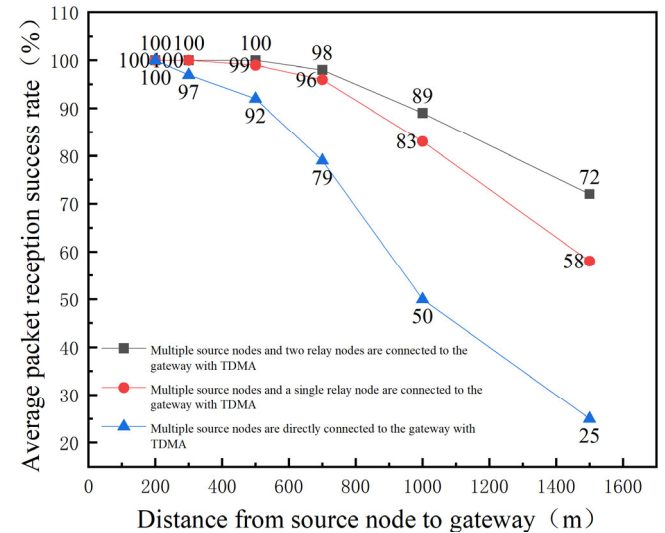
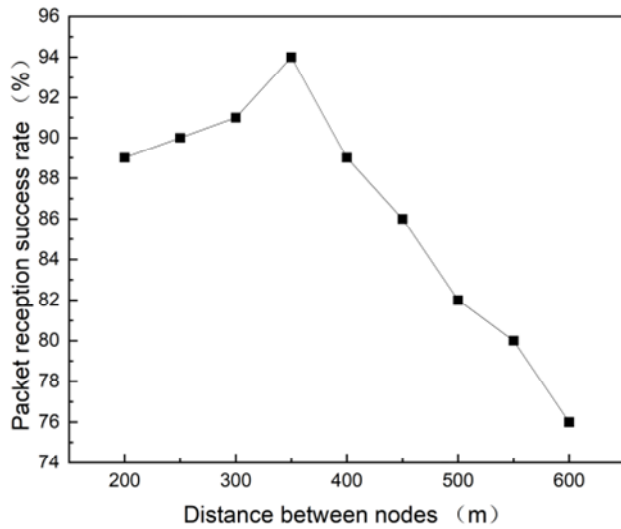


Figure 14 The impact of using the TDMA solution and two relay nodes at the same time on data packet transmission (see online version for colours)



It can be seen from the experimental results that increasing the number of relay nodes can improve the data packet transmission success rate of the system. The improved efficiency gradually increases as the distance between the source node and the gateway increases.

When adopting the TDMA scheme and using two relay nodes simultaneously, the data packet reception success rate reaches 100% within 500 m from the source node to the gateway. Within the range of 500 m to 700 m, the data packet reception success rate can reach 99%. Although the packet loss rate increases as the distance continues to increase, the system can meet the requirements for environmental temperature and humidity monitoring in coal mines (Liu, 2017) and can also expand the communication distance by adding relay nodes to cope with the needs of different working faces underground.

Figure 15 Effect of distance between nodes on data transmission

When multiple relay nodes are used, the number of relay nodes and their distance from the source node will have an impact on the packet reception success rate of the system, so we conducted experiments for the effect of distance between nodes on the packet reception success rate within a range of 1 km from the source node to the aggregation node. The results of the experiments are shown in Figure 15.

From the experimental results, it can be seen that the source node is 1 km away from the summary node. When the relay nodes are 200 m apart, the success rate of data packet reception but only 89%. This is because there are five relay nodes in the range; since relay nodes carry out the work of forwarding the data, it will cause channel congestion data packet loss, but instead of the result is not ideal, which also illustrates that it is not the more, the more, the better the relay nodes are. When the relay nodes are 350 m apart, the distance between the nodes is ideal for LoRa node data transmission. In addition, because there are only two relay nodes, the more distant relay nodes are more likely to receive the message forwarded by the nearest relay node, mitigating the impact of channel conflicts and repeated packet sending so that the packet reception success rate reaches a maximum of 94%. As the distance between the nodes continues to increase, although the number of relay nodes is decreasing, regardless of channel conflicts, the distance between the nodes does not reach the optimal distance for LoRa transmission, which still causes an increase in the packet loss rate. Therefore, this experiment also proves that the optimal distance between the nodes of the LoRa relay network in this system is 350 m.

Since the relay node sends more packets and consumes more power compared to the source node, in the course of the experiment, we used the UT70 USB tester to test the current of a single relay node of the system in dormant mode, collecting data and transmitting data. All the working hours are estimated longer when calculating to lower the actual power consumption than the calculation results to cope with the challenge of a complex environment for power consumption as shown in Table 4.

Table 4 Relay node power consumption experimental results

Working status	Current	Working hours
Dormancy	0.12 mA	58.5 min
Collect data	81 mA	57 s
Send data	105.7 mA	18 s

Suppose a single relay node wakes up once in 1 hour for data collection, the working time is 1 minute, and sends data 3 times at a sending rate of 1 time/second. Also, assume that there are five source nodes, and each of them takes 3 s to send data, then the relay node forwards the packets from the source node with a working duration of 15 s, then the average power consumption of a single relay node for 1 hour is $(105.7 \times 18 + 81 \times 57 + 0.12 \times 58.5 \times 60)/3,600 = 1.92$ (mAh). The adopted lithium battery capacity is 6,800 mAh. Considering the battery's self-discharge issue, if we estimate its capacity at 85%, the estimated number of days that the battery can power devices is $6,800 \times 0.85/(1.92 \times 24) = 125.4$. Therefore, the power consumption of terminal nodes in the system meets the requirements of a coal mine (Li, 2020).

7 Conclusions

This article comprehensively analyses the current demand for geothermal disaster monitoring in coal mine underground environments and the existing communication technologies. Considering the infrequent monitoring cycle of environmental temperature and humidity in underground mines, as well as the small data packets, combined with the novel LoRa wireless communication technology, which has the advantages of long communication distance, low energy consumption, and low cost, a temperature and humidity monitoring communication system for coal mine working environments based on LoRa technology has been researched and designed. By designing the node self-clocking synchronisation process of TDMA protocol with LoRa relay node, after testing in the simulated environment, it is proved that this system can meet the index requirements for the actual use in coal mines and realise the improvement of the transmission distance and packet receiving success rate of the LoRa communication system, which provides a new technological solution for the remote monitoring and control of coal mines underground, wireless communication and coal mine safety.

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