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APPLIED RESEARCH

Design and Study of LoRa-Based IIoT Network for Underground Coal Mine Environment

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ABSTRACT The paper presents a novel LoRa-based IIoT system for monitoring the underground coal mine environment. Additionally, a new adaptive data rate algorithm for mesh network topology is proposed to optimize the data rate and maximize the coverage distance. Maximum coverage distance is achieved with a minimum number of repeaters. However, unlike previous works, the current work takes into account the power constraints in the underground coal mine environment, and most low-power consumption system is presented with an intelligent design approach. The implementation of the proposed adaptive data rate algorithm achieves 1.46 Kbps data rate at spreading factor 9, bandwidth 125 KHz, and transmitted power 11 dBm and extended the battery life of the deployed end nodes. The deployed end nodes achieved a maximum of 180 m under diffused line-of-sight condition at the roadway region of the operational mine. The relevant parameters are measured from the operational mine. Finally, the hardware is fabricated and the proposed system is validated in an operational underground coal mine.

INDEX TERMS Adaptive data rate, IIoT, LoRaWAN, LoRaPHY, underground coal mine.

I. INTRODUCTION

Integrating wireless technology in the underground coal mine (UCM) industry ensures mobility, flexibility, scalability, cost-effectiveness, and reliability [1]. However, the design and implementation of a wireless network in the UCM environment is challenging as it is always threatened by the precarious geological structure [2] and also by the presence of toxic and poisonous gases in the atmosphere along with suspended coal dust particles [3]. Further, such difficulty is enhanced by the working area of a UCM, which is dynamic and depends on the excavation process as explained in [4]. Thus, a flexible, scalable, and reliable industrial internet of things (IIoT) based monitoring system for the UCM is essential [3], [5] yet quite challenging due to multiple factors mentioned above.

Using radio frequency (RF) signals for wireless communication is a standard and well-accepted solution. However, such conventional systems are not at all a good choice for IIoT systems in UCM because RF signals experience fast attenuation while propagating through such an extreme environment due to the presence of thick rough walls, and suspended dust particles [6], [7]. Another significant constraint to design system for UCM is the restriction of power consumption [8], [9] as enforced by mine authorities. No mine can afford high-power systems due to issues like sparking [10], overloading [11] etc. Therefore, traditional RF antenna loaded systems are not suitable for the UCM environment. Recently some attempts have been made using some alternative technologies, such as wireless fidelity (WiFi) [12], or ZigBee [13], to solve the practical problem that exists in the

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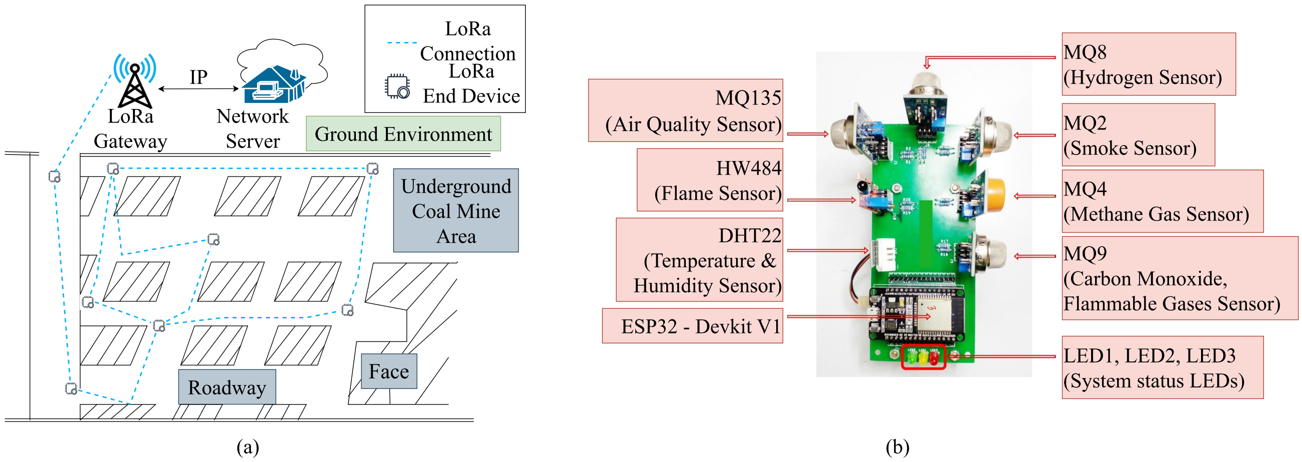

FIGURE 1. LoRa-based IIoT-UCM system model: (a) Schematic representation of the architecture of the UCM along with deployment strategy of the system modules, (b) the developed circuit board of the deployed LoRa end device.

UCM environment. However, these technologies have several limitations; most importantly all of them offer low coverage distance in an actual operational mine [14]. Further, these technologies need deployment of a large number of repeaters to increase the range and thereby increasing the overall complexity, cost, and chances to exceed the intrinsically safe power limit [8], [11].

Recently long range (LoRa) technology has evolved as a promising solution for some underground systems like in-soil propagation [15], drainage system [16], pipeline monitoring [17] etc. Following this trade some attempts have been made to utilize LoRa for the underground mine industry as well [18], [19], [20], [21]. However, successful and efficient design and implementation of a LoRa-based system in a UCM environment is still missing.

For example,

- The network of the LoRa communication system described in [18] needs a booster in every 15 m inside the model UCM tunnel to work successfully, and thus fundamental problems like complexity, cost, and power restriction remain unaddressed. Moreover, as the mine area is ever-changing space, scalability (addition or subtraction of the communication module) is an important requirement. However, scalability is not supported by the system in [18] due to the inefficient design of system topology.
- A system model is proposed in [19] to monitor temperature, humidity, and gas concentrations in the underground mine environment, but no guideline is provided for practical implementation of the system and it lags experimental validation.
- A simple design strategy using LoRaWAN is presented in [20] by gathering location data of miners, however, the deployment strategy of tags, generates the location information, and relays, transfers the information to a headend, is not mentioned.
- Only a simulation study has been conducted in [21] by varying the LoRa communication parameters, however, the full system design methodology is missing.

To the best of our knowledge, none of the previous works have designed a LoRa-based network to monitor the UCM environment from scratch. Motivated by this requirement, a comprehensive design strategy with proper network architecture, suitable algorithm development, and performance analysis of a deployed network is thoroughly investigated in order to fully utilize the LoRa-based system for the UCM environment. The key contributions of the present study are outlined as follows:

1) The present work proposes and provides a complete design methodology of a LoRa-based IIoT-UCM system that ensures network flexibility, scalability, and reliability.
2) A mesh network topology is judiciously chosen and implemented to achieve maximum coverage distance and minimum network maintenance overhead. Also use of mesh network topology for a LoRa-based IIoT-UCM system is not yet reported.
3) A simple yet effective adaptive data rate (ADR) optimization algorithm has been proposed to optimize the data rate and coverage distance of the network.
4) Real-time deployment and experimental validation are performed in an operational UCM in order to establish the effectiveness of LoRa in the UCM environment. None of the existing works validate LoRa-based system in a UCM.

II. DESIGN OF THE PROPOSED LoRa-BASED IIoT-UCM ARCHITECTURE

The schematic architecture of the proposed LoRa-based IIoT-UCM system has been depicted in Fig. 1(a). The system is composed of three modules: (i) LoRa end devices, (ii) LoRa gateways, and (iii) network servers. Additionally, Fig. 1(a)

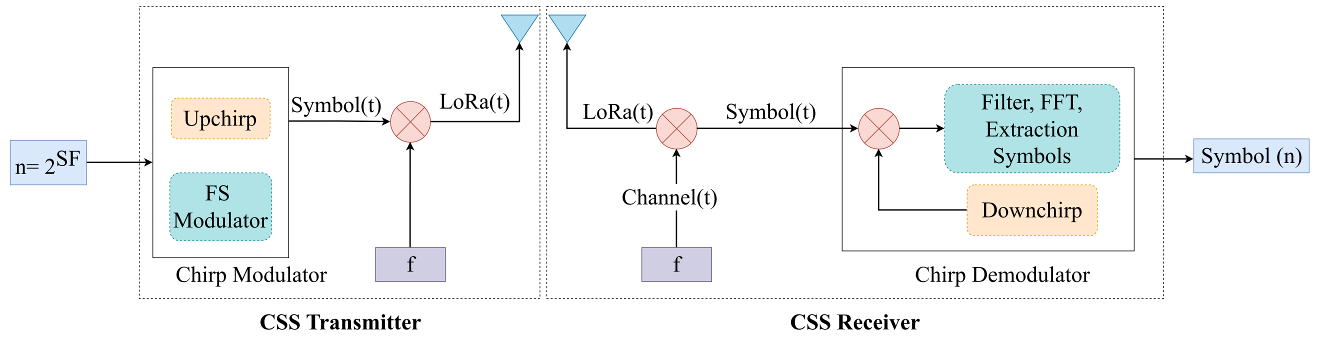

FIGURE 2. Block diagram of the LoRa transceiver consisting of CSS transmitter and receiver.

presents the deployment strategy of the system modules. LoRa end devices are deployed at three critical locations of the UCM, such as: (a) face region, where the actual excavation of coal is ongoing, (b) roadway that represents a network of tunnels, providing the pathway to carry mining machinery, extracted coal materials, and miners, and the (c) shaft which is a vertical tunnel, occupied by an elevator, providing access to the underground region from the ground region.

At the ground region, the LoRa gateway is deployed. This gateway wirelessly collects the underground sensor data from the deployed LoRa end devices and uploads the data to the network server. The network server shares the data with the mining authority at the ground level.

A. SYSTEM DESCRIPTION

The LoRa end devices comprise a sensor unit, a controller and transceiver unit, a display unit, and a rechargeable battery unit. The sensor unit, presented in Fig. 1(b) is designed to measure the concentration of hydrogen gas, methane gas, and carbon monoxide gas while also monitoring air quality, the presence of flame and smoke, and temperature and humidity. The functionality of the sensors is controlled by the ESP32 microcontroller and the collected sensor data is transmitted through the attached sx1276 LoRa transceiver module. The LoRa transceiver module is equipped with a 2 dBi LoRa omnidirectional antenna with vertical polarization. The transceiver unit of the end devices enables in-mine wireless communication using 433 MHz frequency (f) and a bandwidth (B) of 125 KHz with a spreading factor (SF) varying from 7 to 12 and coding rate (EC) of 2 [22].

The display unit, integrated with the deployed end devices, presented the required communication parameters such as the received signal strength indicator (RSSI), signal-to-noise ratio (SNR), and the counts of the total number of packets transmitted and received.

Due to the power constraint of the UCM environment, the LoRa end devices are designed to consume minimum power to maximize battery life. Each device is equipped with a 2000 mAh 18650 Li-ion rechargeable battery, along with a heat sink to ensure safe, reliable, and efficient operation.

LoRa gateway comprises an sx1276 LoRa transceiver module and the ESP32 microcontroller that acts as a bridge in the IIoT-UCM system. Gateway receives the packet from the underground deployed end devices through a LoRa network using 433 MHz frequency. At the ground region, the received LoRa packets are uploaded to the network server using an IP backhaul network [23]. The network server receives the packets, runs a redundancy check, discards the redundant packet, and authenticates the packets [24].

B. LoRa NETWORK

The mesh network is intentionally designed for application inside the UCM area because, in conventional star networks, end nodes are restricted from leaving or joining the network without maintenance overhead. Moreover, if a node fails to transmit in a star network, the packet is more likely to be lost. However, in a mesh network, because of the multi-hop facility, packet loss is minimal, thus ensuring scalability, reliability, and increased coverage distance. Mesh networks for other environments are well known and can be found in other literature [16], [25]. However, the employment of mesh networks using LoRa in the UCM environment has not yet been reported.

In this work, the deployed LoRa end devices form a mesh network to wirelessly transmit the collected sensor data packet to the LoRa gateway, stationed at the ground region. The physical layer foundation like modulation, bandwidth, data rates, and signal robustness, essential for designing the wireless mesh network in the UCM is provided by the LoRaPHY. Although, the mesh networking capabilities such as routing protocols, and secure communication, are controlled by the LoRaWAN [26].

LoRaPHY [27] defines the modulation scheme, such as the chirp spread spectrum (CSS), making the LoRa signal more resilient to multipath fading and interference within the mesh network. The block diagram of a LoRa transceiver is presented in Fig. 2. At the transmitter, first, n bit LoRa data is encoded, and 2^{SF} number of symbols are generated which forms a LoRa packet. These symbols are the input to the chirp modulator. The frequency shift (FS) modulator then modulates the signal in accordance with

FIGURE 3. The UCM environment exhibiting (a) Line-of-sight (LOS), (b) diffused-LOS (DLOS), and (c) non-LOS(NLOS) link condition.

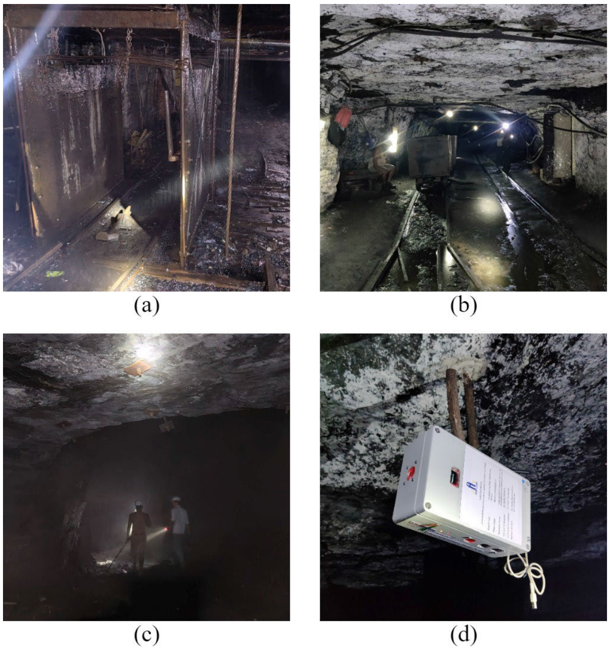

FIGURE 4. The extreme environment of an operational UCM area at (a)the shaft region, (b) the roadway region, (c) the face region, and (d) the deployed LoRa end node.

the up-chirp frequency. An omnidirectional LoRa antenna is used to transmit this modulated spread spectrum signal. At the receiver side, the demodulator performs frequency despreading operation by multiplying the received signal with the down-chirps. Then the received signal is processed to derive the estimated symbol from which the LoRa packet is recovered.

LoRaWAN [24] facilitates the in-mine wireless transmission of the LoRa packet through the designed mesh network. This protocol supports the implementation of the ADR algorithm for the mesh network and relays data through a multi-hop facility. A unique ADR algorithm is proposed, in Section IV to optimize the bit rate while maximizing the coverage distance with minimum power consumption by the LoRa end devices [28]. The performance of the LoRa mesh network in the IIoT-UCM system is evaluated by attaining maximum coverage distance with a satisfactory level of RSSI and SNR while maximizing the overall battery life of the deployed LoRa end devices, for the given area of the cross-section.

III. VALIDATION OF THE PROPOSED WORK

The developed LoRa-based IIoT-UCM system was deployed in an operational UCM at Madhaipur Colliery Eastern Coalfield Limited, West Bengal, India, Pit no. 9, and Seam - R II/III to evaluate its performance. The coordinates of the mine site are 23° 71' 0'' N and 87° 34' 0'' E.

The operational environment of the test site was completely enclosed by coal seams and underlying and overlying strata. The depth of the shaft at Madhaipur Colliery was 64 m. The cross-section of the mine was rectangular shaped and the mining operation was extended horizontally, starting from the shaft level, inside the underground area. Three different link conditions were considered to test the in-mine LoRa signal propagation, line-of-sight (LOS), non-LOS (NLOS), and diffused-LOS (DLOS), as shown in Fig. 3. The LOS link was defined as the unobstructed link between the transmitter and receiver. When the signal was obstructed by the presence of thick walls or heavy machinery, the link was then defined as NLOS, whereas, partial obstruction, due to the presence of pillars or slight curvature, has been defined as a DLOS link condition.

A. DEPLOYMENT STRATEGY

The field experiment was conducted at the shaft, roadway, and face regions, as shown in the Fig. 4(a),(b), and (c) respectively, where the LoRa end devices were deployed. The cross-sectional area of the roadway and face region was not uniform and was measured as 22.5 sqm and 25 sqm respectively. The height from the mine floor at which the LoRa end device was deployed at the roadway region was 4.2 m, whereas, at the broad face region the device was deployed at a height of 1.8 m from the mine floor. The elevator and the long tunnel-like structure of the shaft region demand a unique deployment arrangement. Thus, the device was deployed at the side wall of the shaft at a distance of 5 m from the mine floor.

Deployment of the LoRa end devices in these UCM regions was impeded by the extreme humidity and presence of coal dust which might cause significant damage to the hardware if not properly protected. Additionally, poor visibility, transmission power restriction to 14dBm, as mandated by the mine regulatory authorities [29], and the irregular shape of the mine tunnel complicated the deployment process.

These deployment challenges were addressed by encapsulating the end devices in a special casing of aluminum and polycarbonate material to protect against dust and water, as shown in Fig. 4(d), and a cooling fan was added inside the box to prevent the overheating of the circuitry.

To achieve low-power operation the circuit boards of the deployed devices were carefully designed incorporating an ESP32 microcontroller and sx1276 LoRa chip with a receiver sensitivity of -148 dB. The transmission power was limited to 11 dBm i.e., within the intrinsic safe limit to ensure safe and reliable operation. Additionally, a battery management system (BMS) was integrated for efficient battery usage. Moreover, the deployed end devices were designed to operate as class A LoRaWAN devices [24] which have unique low-power operating mode with bi-directional communication capability.

B. EXPERIMENTAL OBSERVATIONS

The experimental data is presented in Table 1. The purpose of the field experiment was to measure the communication distance across multiple locations of the UCM. Due to the dynamic environment of the UCM, each region offered distinct environmental factors and link conditions. The RSSI and SNR were measured at different distances. The maximum coverage distance was estimated when satisfactory RSSI and SNR were received with minimum or no packet loss.

TABLE 1. Observation from the field test.

Mine Region	Location	Link Condition	Maximum Coverage Distance Obtained (m)	RSSI (-dBm)	SNR (dB)
Shaft	Entry to the underground	NLOS	100	90	13
Roadway	4D-5D/0L	LOS	125	100	7
	8D/0L	NLOS	95	120	2
	8D/0L-11L	DLOS	180	90	5
Workface	34D/0L	LOS	90	73	-2
		NLOS	50	89	-4

The data presented in Table 1 justifies that LoRa propagation experiences less attenuation at the shaft region,even under NLOS link condition, as the noise level of the area was minimal, resulting highest SNR of 13 dB. Moreover, at the roadway, a maximum distance of 180 m was achieved under DLOS link condition with the SNR of 5 dB. Additionally, under the NLOS link condition, the roadway region offered a maximum distance of 95 m with SNR 2 dB, whereas at the face only 50 m coverage distance was achieved with -4 dB SNR value.

The improved propagation at the roadway was obtained compared to the face region because mining activities like blasting and rock bolting were underway at the face during the field test. Substantial noise was generated due to the high concentration of coal dust and humidity at the face, thereby deteriorating the LoRa signal propagation as compared to the roadway region.

IV. PROPOSED ADR ALGORITHM FOR LoRa MESH NETWORK

ADR algorithm is conventionally designed for LoRa star network [23], [30], where ADR is initiated by the network server. A multi-hop mesh network with flexible deployment

TABLE 2. Parameters used during the field experiment.

Category	Component	Description
Communication Parameters	Frequency	433 MHz
	Spreading Factor (SF)	Variable: 7 to 12
	Bandwidth (B)	125 KHz
	Coding rate (EC)	Variable: 1 to 4
	Transmission power P_t	11 dBm
	Payload size	Minimum 140 Bytes
	Duty cycle	1%
	Channel used	433.175 MHz
	End device class	Class A
	Gateway capacity	Scalable, up to 50 end devices
	Link Budget	Maximum 168 dB
	Receiver Sensitivity	Down to -148 dBm
	Data rate	Variable: upto 3 Kbps
Environmental Parameters	Temperature Range	30°C to 40°C
	Humidity Range	More than 95% RH

of LoRa end devices has been adopted as a trade-off of computational overload by the present work while adopting a new strategy to perform the proposed simple but effective ADR algorithm.

Each LoRa end device, present in the mesh network, transmits the packet to its next hop node. The receiving node receives the LoRa packet with a maximum noise margin (NM) of 6 dB. After receiving the new LoRa packet, the algorithm reads the communication parameters such as SF, EC, and RSSI. Among them, SF is used to derive the sensitivity (S) and link budget (LB) of the transmission.

The flowchart given in Fig. 5 presents a detailed description of the designed ADR algorithm. According to the designed ADR algorithm, the success of the reception is determined by comparing the obtained RSSI value with the measured value, (S-NM). For a successful reception, the ADR algorithm calculates the coverage distance (d) and bit rate (R_b) and transmits the ADR_ACK_Success packet back to the transmitter, which contains the optimized value of d and R_b.

Additionally, for an unsuccessful reception, the receiver sends a retransmission request to the transmitter by transmitting the ADR_ACK_RetransREQ packet. The transmitter then retransmits the LoRa packet by reducing the SF value by 1. If the SF value reaches its minimum value of 7, this indicates the communication link between the transmitter

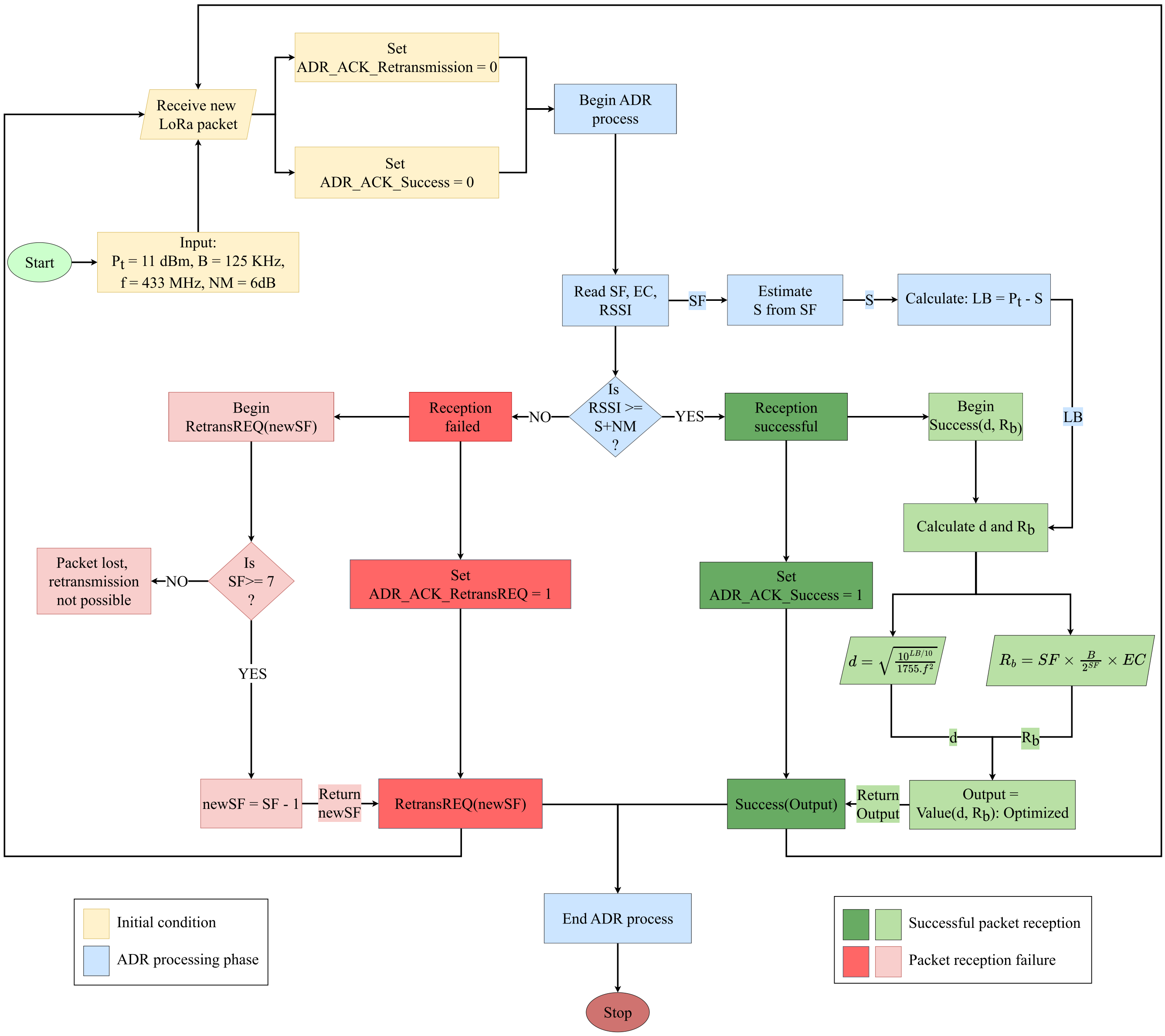

FIGURE 5. Proposed ADR algorithm for LoRa-based IIoT-UCM network.

and the receiver can not be established. In such a scenario, the transmitter must attempt to transmit the packet to an alternate receiver node, present in the mesh network, in order to establish a successful communication link for packet transmission.

At the inception of the LoRa network, each node executes the designed ADR algorithm, to determine and optimize the link parameters, such as; d and R_b. Adjacent nodes within the mesh network share these optimized parameters. As long as the position of the end nodes remains unchanged, these parameters are maintained by the neighboring nodes for future transmissions. This strategic approach significantly reduces the need for retransmissions, thereby decreasing the overall active time of the end nodes. Adapting this ADR optimization technique helps in power conservation by the end nodes, increasing battery life and ensuring reliable network performance.

V. RESULTS AND DISCUSSIONS

This section presents the in-mine LoRa propagation characteristics and also the performance analysis of the proposed LoRa-based IIoT-UCM system. Table 2 summarizes the communication and environmental parameters considered during the evaluation of the performance of the designed system. Additionally, the performance of the proposed LoRa-based IIoT-UCM system has been analyzed based on criteria like; mine cross-section, operational status, mine region, and RSSI.

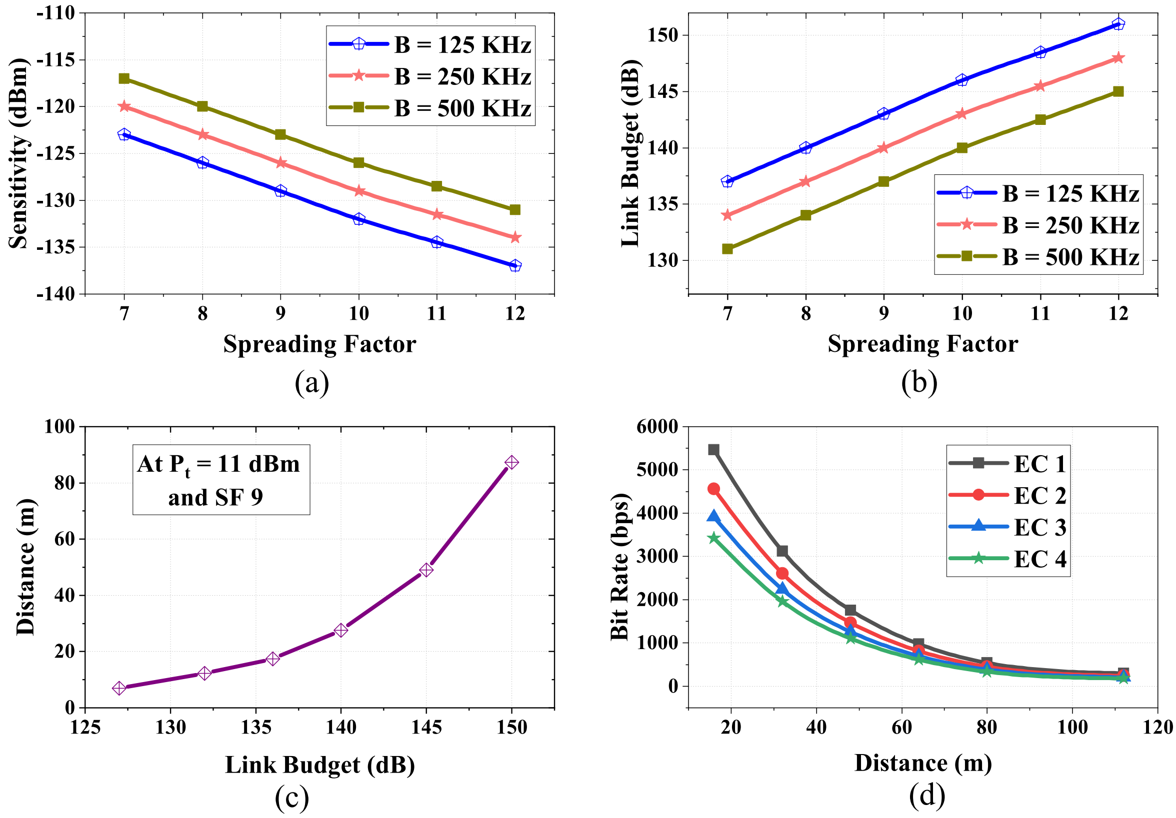

FIGURE 6. Characteristics of LoRa signal propagation: (a) Sensitivity vs. spreading factor, (b) link budget vs. spreading factor, (c) distance vs. link budget, and (d) bit rate vs. distance.

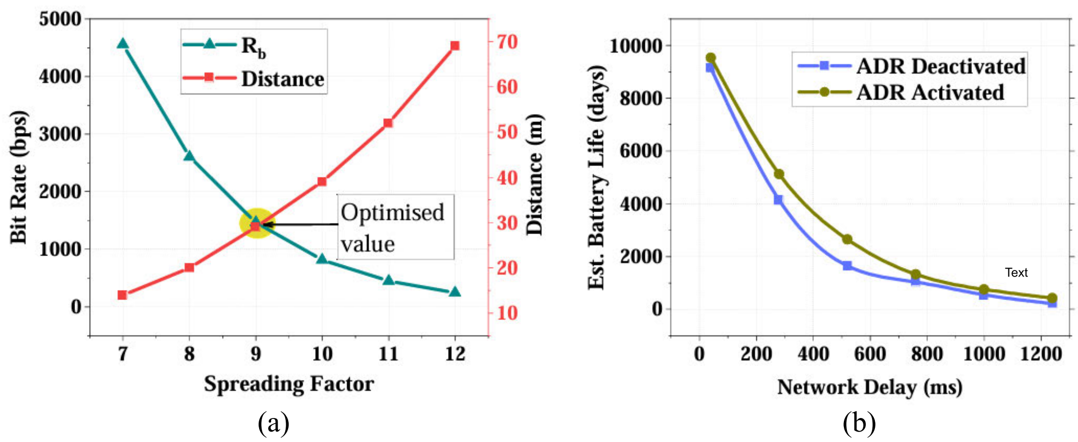

FIGURE 7. Performance of ADR algorithm: (a) trade-off between bit rate and distance with respect to spreading factor, and (b) maximizing the battery life of LoRa end nodes for consistent network delay.

A. PERFORMANCE OF THE PROPOSED ADR ENABLED LoRa NETWORK

The characteristics of LoRa signal propagation entail a linear modulation of receiver sensitivity in response to varying SF, as shown in Fig. 6(a), consequently leading to fluctuations in the link budget, presented in Fig. 6(b). This phenomenon, in turn, influences changes in transmission distance, as depicted in Fig. 6(c) for a fixed P_t of 11 dBm and SF 9. Finally, the trade-off between coverage distance and bit rate is presented in 6(d).

These characteristics of LoRa signal propagation is exploited by the proposed ADR algorithm in order to achieve maximum coverage distance with an optimum bit rate. The designed LoRa network attained the desired trade-off between the coverage distance and the bit rate by varying the SF, as presented in Fig. 7(a). The optimized bit rate achieved

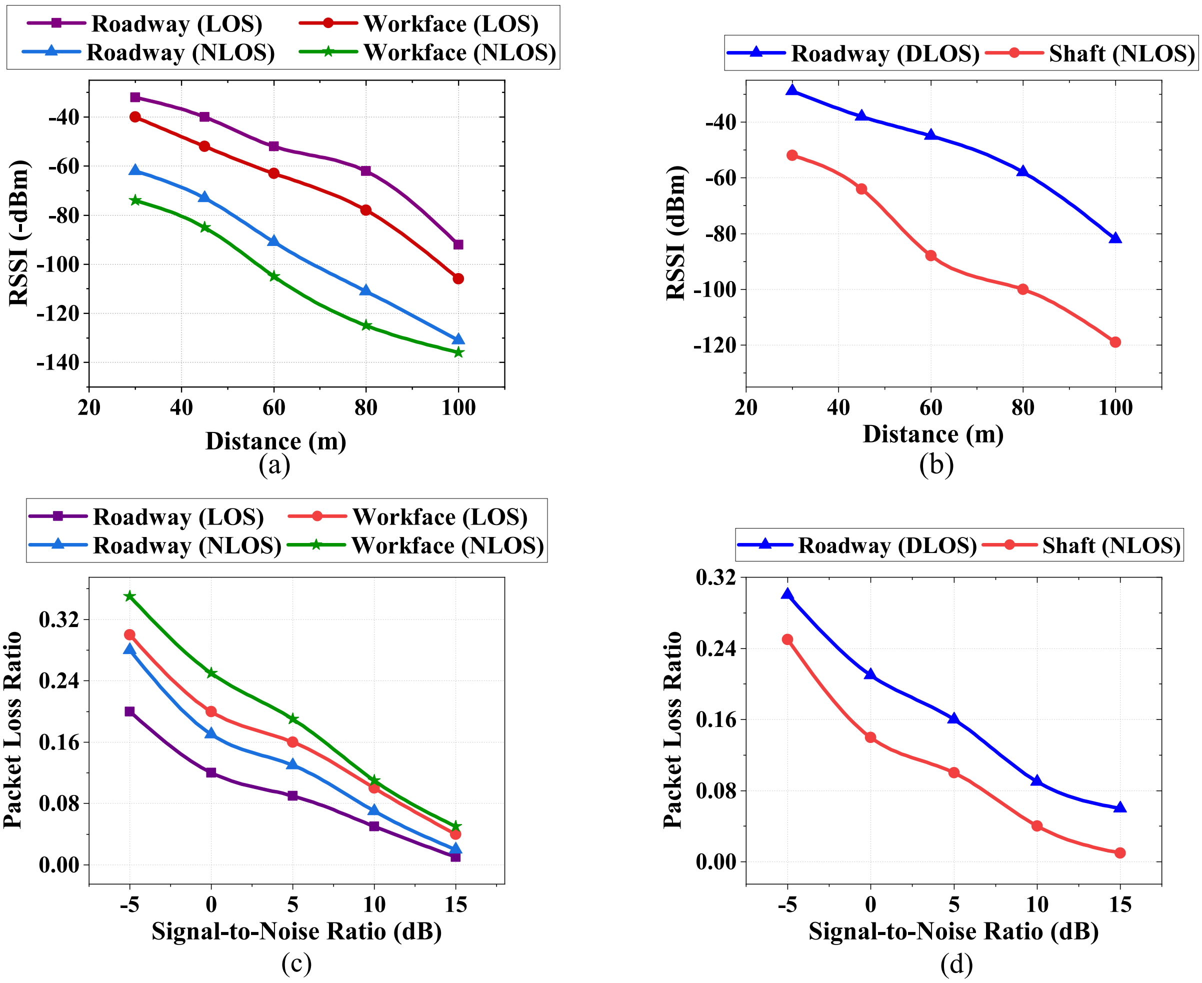

FIGURE 8. RSSI vs. coverage distance variation observed at (a) LOS and NLOS condition at roadway and face region respectively, and (b) DLOS condition at roadway and NLOS condition at shaft region. PLR vs. SNR variation observed at (c) LOS and NLOS condition at roadway and face region, and (d) DLOS condition at the roadway and NLOS condition at shaft region.

by the network is 1.46 Kbps at SF 9 and EC 2 with transmitted power of 11 dBm and 125 KHz bandwidth.

Moreover, as the system performance is evaluated based on providing a higher coverage distance, it subsequently increases the network delay, accelerating the depletion of the battery life of the end device. However, the implementation of the ADR algorithm reduces the requirement of retransmission, thereby decreasing the overall active time of a device which helps in power conservation. Thus, for a fixed network delay, it is observed that the power consumption of an ADR enabled LoRa end device is much lower than the ADR disabled device. This comparative analysis is illustrated in Fig.7(b).

B. PERFORMANCE OF THE PROPOSED LoRa-BASED IIoT SYSTEM

The performance evaluation of the proposed LoRa-based IIoT system has been done by deriving the relation between RSSI and the obtained coverage distance under LOS, and NLOS conditions at the roadway, and face region inside an operational UCM. The loss in RSSI over distance has been presented in Fig. 8(a).

Along with RSSI, the system specifies the SNR at the roadway, and face region of the mine considering LOS and NLOS conditions. To exemplify the challenging environmental conditions of the UCM, SNR measurements at ground level are also provided for both LOS and NLOS conditions. The comparative analysis of the SNR variation across varying distances under diverse link conditions is shown in Fig. 9.

From the obtained results it can be implied that at the roadway, the packet reception was successful with SNR 9 dB, even the RSSI drops to -92 dBm at 100 m under LOS conditions. While under NLOS link condition, as the RSSI decreases to -131 dBm at 100 m distance, successful packet reception was not assured at the roadway. Additionally, at the face region, the RSSI was -106 dBm and -136 dBm, at 100 m distance, under the LOS and NLOS link conditions respectively. High noise power and low RSSI restricted the packet reception beyond a distance of 90 m under LOS

TABLE 3. Comparison with state of the art.

Paper	Technology	Test at Operational Underground Mine	Deployed Region	Area (sqm)	RSSI (-dBm)	d (m)	Remarks
[31] 2015	ZigBee	No	Face	–	–	45	1. No mining activities were undergoing during testing and validation. 2. Link condition not derived and tested.
			Tunnel			65	
			Tunnel			85	
[6] 2015	–	No	Tunnel	6, 8.1, 12, 16.2	–	–	1. No mining activities were undergoing during testing and validation. 2. Confirms that RF propagation decreases with increasing tunnel cross-sectional area. 3. No information regarding the UCM communication system is available.
[12] 2022	WiFi	No	Tunnel	4	80	140 (LOS)	1. No mining activities were undergoing during testing and validation.
		Yes	Tunnel	14	60	130 (NLOS)	1. Active mining operation at distant places. 2. The shaft and face region was excluded. 3. Slightly more coverage distance was achieved under NLOS, for narrow tunnel.
[32] 2020	IEEE 802.15.4	Yes	Tunnel	12	85	132 (LOS) and 39 (NLOS)	1. The mine tunnel was straight and empty while the LOS link was considered. 2. The used 2.4 GHz frequency failed to penetrate the thick wall, resulting in low coverage under NLOS link condition.
		Yes	Face	10	88	90 (LOS)	1. NLOS link condition was not considered.
[18] 2023	LoRa	No	Tunnel	5.28	56	150 (LOS) and 15 (NLOS)	1. No mining activities were undergoing during testing and validation. 2. Requires more boosters within short distances under NLOS condition.
[33] 2022	LoRa	Yes	Tunnel	20	100	40 (NLOS)	1. Collected data was not transmitted to ground monitoring station and optimization along with mesh network deployment were absent. 2. Work was done in an underground gold mine. LoRa propagation in UCM was not recorded.
Proposed Work	LoRa	YES	Shaft	20	90	100 (NLOS)	1. Measurement was taken when rock bolting at roadway, and blasting at face was underway. 2. Achieved bit rate 1.46 Kbps at SF 9 and EC 2 with bandwidth 125 KHz and transmitted power 11 dBm.
			Tunnel (Roadway)	22.5	80	180 (DLOS)	
			Face	25	73	90 (LOS)	

conditions and 50 m under NLOS conditions at the face region.

Moreover, the experimental data has been used to calculate the packet loss ratio (PLR), defined as the ratio of unsuccessful to successful transmissions at different regions of the UCM. A low PLR with a high SNR value is desired for optimal performance of the LoRa-based IIoT-UCM system. Fig. 8(c) summarises the PLR and SNR relation for LOS, and NLOS conditions at roadway, and face region. However, as evident in Fig. 8(c) substantial noise interference at the face results in more than 5% PLR, even for high SNR.

The present study also evaluates the performance of the LoRa-based IIoT-UCM system at the shaft region under NLOS conditions and at the roadway region under DLOS conditions. It is observed in Fig. 8(b) and 8(d), that the proposed LoRa network achieves RSSI of -82 dBm at the roadway under DLOS condition, whereas shaft region offered -119 dBm RSSI at 100 m distance. However, due to low noise power at the shaft, the PLR was 0.01 whereas, the roadway region exhibits PLR of 0.06 under DLOS conditions. The observations highlight the challenging and unpredictable nature of the UCM environment.

C. COMPARISON WITH STATE OF THE ART

A comparative study has been presented in Table 3, in order to investigate the superiority and uniqueness of the proposed work. The performance of the systems has been compared based on mine cross-section, operational status, mine region, and obtained satisfactory RSSI value. It has been observed that the LoRa-based technology offers significant advantages compared to the other technologies [6], [12], [31], [32]. However, the field experiment in [32] achieved better coverage distance at the tunnel under LOS conditions than the present work. This increased coverage distance was attributed to the significantly narrow cross-sectional area, with the tunnel being straight and empty during the experiment. However, in the current study, no such favorable conditions were selected, making the work more resilient to typical UCM scenarios. Moreover, reliable packets were received with RSSI -82 dBm in [32], while the present work can receive reliable packets with -100 dBm.

Further compared to other LoRa-based designs (which were not targeted for operating mine systems) the current work offers significant advantages in terms of various operating parameters. Only the design in [33] offers better performance in some aspects, however, sensor communication is

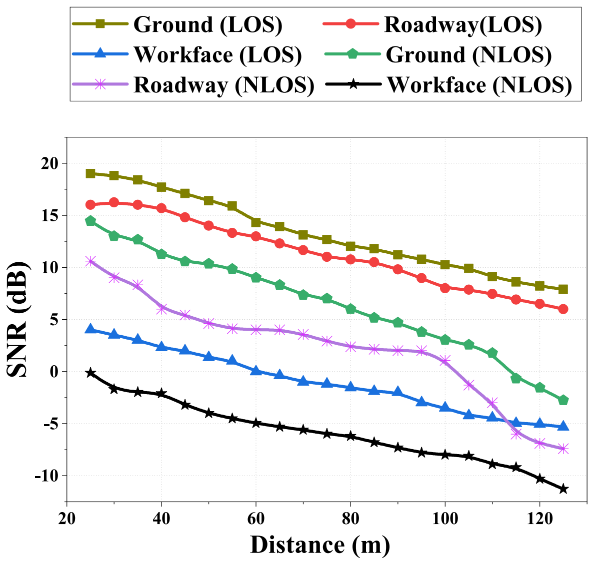

FIGURE 9. SNR vs. distance as obtained from the LoRa-based IIoT-UCM system.

TABLE 4. Hardware and software used in the proposed system.

Category	Component	Description
Hardware	Microcontroller	Type: ESP32 Processor: dual-core Tensilica LX6 microprocessor, Clock: upto 240 MHz, Memory: 520 KB SRAM, 448 KB ROM, and up to 16 MB of external flash
	Transceiver	Module: sx1276 LoRa module, Receiver sensitivity: -148 dB, Modulation scheme: chirp spread spectrum (CSS)
	Antenna	2 dBi omnidirectional antenna Polarization: vertical
	Sensors	MQ4: methane, MQ9: carbon-mono-oxide, MQ2: smoke, MQ8: hydrogen, MQ135: air quality, HW484: flame, DHT22: temperature and humidity.
	Power Supply	Supply: 3.7 V, Capacity: 2000 mAh battery
Software	Operating System	FreeRTOS v10.2.1
	LoRaWAN Stack	LoRaMAC-node v4.4.1
	Development Environment	Arduino IDE 1.8.13
	Libraries	LoRaLib v2.3.2
	Application Platform	MQTTBox, enables message queueing telemetry transport (MQTT) protocol

restricted within the mine and data cannot be communicated to the outside base station.

VI. CONCLUSION

Development of LoRa-based IIoT network for UCM environment is designed, analyzed, and tested. The designed IIoT-UCM network supports flexibility, scalability, and reliability. A suitable ADR algorithm is also developed and

Algorithm 1 Proposed ADR Algorithm

The ADR Initiates at every LoRa packet reception.

Inputs :
Transmitted power (P_t) = 11 dBm,
Bandwidth (B) = 125 KHz,
Operating frequency (f) = 433 MHz,
Noise Margin (NM) = 6 dB.
Sensitivity (S) = depends on transmission parameter, SF.

Initialization :
ADR_ACK_Success = 0
ADR_ACK_RetransREQ = 0

Output :
Optimized coverage distance (d) and Bit rate (R_b).

// ADR process initiates
BEGIN *// Read inputs*
SF = Read_SF()
EC = Read_EC()
RSSI = Read_RSSI()
S = Estimate_S()
LB = P_t - S *// Calculate LB*
// Compare RSSI with the threshold limit for successful reception
if RSSI ≥ (S + NM) **then**
  Print **Reception successful**
  ADR_ACK_Success = 1 *// Setting flag*
  Success(Output) *// Output*
else
  Print **Reception failed**
  ADR_ACK_RetransREQ = 1 *// Setting flag*
  RetransREQ(SF-1) *// Request retransmission with reduced SF*
end if
Repeat for next reception of LoRa packet.
END

//Output function for successful reception
function Success(Output)
$\mathbf{d} \leftarrow \sqrt{\frac{10^{LB/10}}{1755 f^2}}$ *// Optimized coverage distance*
$\mathbf{R_b} \leftarrow SF \times \frac{B}{2^{SF}} \times EC$ *// Optimized bit rate*
Output = Value(d, R_b): Optimized
Return **Output**
end function

// Retransmission request function
function RetransREQ(newSF)
if SF ≥ 7 **then**
  newSF = SF - 1
  Return **newSF**
else
  Print **Packet lost, retransmission not possible**
end if
end function

integrated with the system and a trade-off between the data rate and coverage distance has been obtained. The present work is expected to solve the IIoT network design challenge in operating mine conditions. This implementation can be further extended to applications, such as machine health monitoring, condition of strata monitoring, and location-based systems while integrating artificial intelligence (AI) to enable predictive and decision-making approaches to enhance safety measures for miners.

APPENDIX A PROPOSED ADR ALGORITHM

See Algorithm 1.

APPENDIX B HARDWARE AND SOFTWARE USED IN THE PROPOSED WORK

See Table 4.

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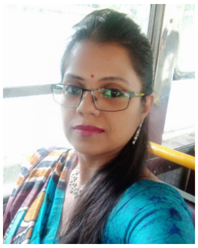

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