

A Secure, Scalable LoRa-Based TDMA Network with Dual-Frequency Three-Layer Architecture for Underground Miner Health Monitoring

Abstract

Underground miner health monitoring faces critical challenges due to the absence of cellular connectivity, limited wireless range, and harsh environmental conditions. This paper presents a robust three-layer LoRa-based wireless sensor network architecture comprising coordinator nodes, relay nodes, and wearable end devices to enable real-time health and environmental monitoring in mines extending up to 2 km and beyond.

The system employs a dual-frequency TDMA architecture (uplink and downlink) for collision-free communication, dynamic node joining using ALOHA, and Hop-to-Hop relay forwarding for scalable data collection.

Wearable end devices collect vital signs and RF-ID-based localization data, which are compressed into 16-byte payloads secured using AES-128 encryption with CRC-16 integrity checks. The coordinator node orchestrates dynamic joining, RTC synchronization, and TDMA slot management, while relay nodes extend range efficiently using an optimized SF7/BW125 kHz LoRa configuration.

The design balances scalability, security, and power efficiency while maintaining low-power standby, enabling a deployable safety system in GPS and cellular denied environments to enhance operational awareness and worker safety in real-world underground mining.

1. Introduction

Mining environments pose significant operational and safety risks, including gas leaks, structural collapses, and health emergencies requiring immediate detection and response. Continuous monitoring of miner vital signs (heart rate, SpO₂, body temperature) and environmental parameters (CO, methane levels) is critical but faces harsh connectivity challenges in underground tunnels:

- GPS signals do not penetrate underground, eliminating location tracking.
- Cellular and WiFi signals attenuate rapidly in rock and tunnel geometries, limiting coverage to a few meters.
- Bluetooth and Zigbee offer low power but fail due to their limited range and high packet loss in obstructed, metallic environments.

LoRa, operating at sub-GHz frequencies (410 MHz – 525 MHz typically used at 433 MHz in India), offers high link budgets and the ability to penetrate partially obstructed paths. To address these challenges, we systematically developed a secure, scalable LoRa-based TDMA network with a three-layer architecture (coordinator node, relay nodes, wearable end devices):

- Range Extension: Implementing hop-to-hop relay nodes, each with 150 meters forward and 150 meters backward underground coverage, extends the systems total operational range beyond 2 km while maintaining reliable packet delivery.
- Dynamic Node Joining: Using ALOHA-based joining on a separate downlink frequency (433.100 MHz), miners can dynamically join the network without disrupting active TDMA

transmissions on the uplink (433.300 MHz), supporting shift-based worker replacement and scalability.

- **Security and Data Integrity:** Data packets containing compressed health and environmental parameters (≤ 16 bytes) are secured with AES-128 encryption to ensure confidentiality, with CRC-16 ensuring data integrity even under noisy channel conditions.
- **Collision-Free Scheduling:** A TDMA protocol with guard bands (60–75 ms) ensures collision-free transmissions, accounting for LoRa propagation delays, RTC drift, and decryption time at relays. The system achieves slot times of ~ 200 ms per node, balancing latency and power efficiency.
- **RTC and Slot Synchronization:** A RTC synchronization broadcasts for clock alignment, dynamic slot realignment for efficient TDMA scheduling and the use of future RTC timestamps in TDMA start commands to maintain synchronization across the network while mitigating drift over long duration.

Through these design choices, I developed a practical, secure, low-power LoRa-based system capable of monitoring over 100 miners with sub-minute update cycles, enabling real-time safety and environmental awareness in underground mining environments.

2. System Design

2.1. Architecture

- **End Devices (Layer-1):** Wearable sensor nodes built using Arduino Nano and SX1278 LoRa modules collect and transmit compressed and encrypted health parameters (SpO_2 , heart rate, temperature), RFID tag IDs, and unique Node IDs during their assigned TDMA slots. A single LoRa module per device manages uplink and downlink operations, alternating between transmission and reception states as per the TDMA schedule. RFID beacons are installed at predefined tunnel zones and junctions to provide location referencing for miners. End devices read these beacon IDs during movement, enabling position tracking with zone-level granularity while maintaining low power consumption.
- **Relay Nodes (Layer-2):** Relay nodes are equipped with dual LoRa modules to simultaneously handle uplink and downlink frequencies, enabling hop-to-hop data forwarding while maintaining network scalability over long tunnel distances. Relays are strategically deployed at 300 m intervals, each covering ~ 150 m forward and backward, to extend system reach up to 2 km or beyond while preserving packet delivery reliability.
- **Coordinator Node (Layer-3):** The coordinator, also equipped with dual LoRa modules, serves as the network's aggregation and control hub. It collects data from miners via relay chains, manages dynamic node joining, performs RTC synchronization broadcasts, Slot realignment broadcasts and issues TDMA start and control commands. The coordinator connects to the cloud server or monitoring dashboard via Wi-Fi or Ethernet for real-time data access and analysis.

2.2. Workflow Table

Normal Operation Phase			
Step	Timestamp	Action	Why This Step
1. Join Attempt	T + 0s	New nodes sends join request via ALOHA protocol. [FREQ2]	Allows miners to dynamically join at system startup.
2. Coordinator ACK	T + 1s	Coordinator ACKs join and buffers node for future slot assignment. [FREQ2]	Prepares for seamless integration in the next cycle.
3. RTC Sync + TDMA Start Command	T + 1s - 8s	Coordinator issues RTC_SYNC + START_TDMA_AT for TDMA initiation. [FREQ2]	Enables synchronized, collision-free TDMA operation.
4. Miner TDMA Transmission	T + 9s - 29s	Miners transmit in 200 ms slots (slots 1–100). [FREQ1]	Enables reliable, low-power, collision-free health and location monitoring.
5. Relay-to-Relay Hopping	T + 30s - 76s	Relays forward data hop-by-hop (~6.54 s per relay) across 7 relays. [FREQ1]	Extends range up to 2 km in underground environments reliably.
6. Coordinator Reception	T + 76s	Coordinator receives complete data from Relay 1, including inactive node list. [FREQ1]	Aggregates all miner data and identifies inactive nodes for removal.
7. Data Upload to Cloud	T + 76s - 77s	Coordinator uploads data to cloud via Wi-Fi/Ethernet.	Enables real-time monitoring, alerting, and logging for safety systems.
8. Slot configuration	T + 77s - 88s	Coordinator removes inactive nodes, adds new joiners, and broadcasts updated slot table + encrypted RTC_SYNC [FREQ2].	Ensures clean, updated slot allocation and clock alignment for next cycle.
9. Next TDMA Cycle Begins	T + 88s	TDMA cycle resumes with updated slots, new joiners begin transmission.	Ensures continuous, scalable miner monitoring with updated participation.

2.3. Communication Setup

- ❖ Uplink (Freq1):
 - Miners transmit in 200 ms slots (SF7/BW125kHz: 139 ms ToA + 61 ms guard).
 - Payload: Encrypted 16-byte block (AES-128) with CRC-16.
 - Cycle: 100 miners = 20 sec.
- ❖ Downlink (Freq2):
 - Commands (RTC sync, slot allocation) sent with retry logic (3–5 attempts).
 - TDMA start: START_TDMA_AT avoids propagation and decryption misalignment.
- ❖ Dynamic Joining:
 - New miners send join requests on Freq2 via ALOHA (random backoff).
 - Coordinator assigns Node ID and TDMA slot; miner switches to Freq1 for uplink.
- ❖ Range Extension:
 - Relay Placement: 7 relays cover 2 km (positions: 0 m, 300 m, ..., 2100 m).
 - SF Optimization: SF7 (100–150 m range) for speed.
- ❖ Security
 - AES-128 Encryption: Encrypts payloads (sensor data + CRC) for confidentiality.
 - CRC-16 Integrity: Verified post-decryption to detect corruption.
 - Packet Structure: 13-byte data + 2-byte CRC + 1-byte padding → 16-byte encrypted block.
- ❖ Miner Localization
 - RFID readers on wearables scan tunnel-wall beacons.
 - Tag ID (4 bytes) transmitted with health data, mapped to zones (e.g., "Section A-12").

2.3. Performance Parameters

Table 1: System Parameter

Parameter	Value
Miners Supported	100+
TDMA Slot Duration	200 ms (139 ms ToA + 61 ms guard)
Uplink Cycle (100 miners)	20 sec
Relay Forwarding Time	6.5 sec/relay (20 packets × 302 ms)
Inter-Hop Guard Time	0.5 sec
Total Relay Forwarding (7 relays)	46 sec (6.5 sec × 7 relays)
Total Update Cycle	88 sec (20 sec uplink + 46 sec relay forwarding uplink + 22 sec control signal downlink)
Range per Relay (SF7)	150–200 m (practical underground range)
Frequency Bands (India)	Freq1: 433.100 MHz (uplink), Freq2: 433.300 MHz (downlink)
Power Consumption	20–50 mA (TX), 15–20 mA (RX), 10 µA (sleep)

Table 2: Uplink and Downlink Configuration

Aspect	Uplink	Downlink
Frequency	433.100 MHz	433.300 MHz
SF	SF7	SF8
Bandwidth	125 kHz	125 kHz
Purpose	Fast, power-efficient Tx	Reliable, robust Rx

Table 3: Payload Structure for Miner

Byte Index	Field	Size (Bytes)	Description
0	Heart Rate	1	0x48 = 72 BPM
1	SpO ₂	1	0x62 = 98%
2	Temperature	1	0x6F = 36.7°C (scaled ×10)
3	CO Level	1	0x01 = CO level
4	Methane Level	1	0x2C = Methane level
5	Battery	1	0x55 = 85%
6	Status Flags	1	Bitmask: 0x01 (SOS), 0x02 (fall detected)
7–10	RFID Tag ID	4	0x00001234 = Beacon zone "A-12"
11–12	Node ID	2	0x04D2 = Miner #1234
13–14	CRC-16	2	Checksum of bytes 0–12
15	Padding	1	0x00 (align to 16-byte AES block)
	Total	16 bytes	Encrypted using AES-128 before transmission

Table 4: LoRa Spreading Factor (SF) vs. Data Rate & Range Trade-off

Spreading Factor (SF)	Sensitivity (approx.)	Data Rate (bps)	Time per Symbol	Relative Range	Use Case Examples
SF7	-125 dBm	~5,500	1.28 ms	1×	High data rate, short-range, dense networks
SF8	-128 dBm	~3,125	2.56 ms	2×	Urban/suburban, medium data rate
SF9	-131 dBm	~1,760	5.12 ms	4×	Balance of range and data rate
SF10	-134 dBm	~980	10.24 ms	8×	Long-range, low data rate
SF11	-136 dBm	~440	20.48 ms	16×	Very long-range, low power
SF12	-137 dBm	~250	40.96 ms	32×	Extreme range, deep penetration

Table 5: LoRa virtual channel

Aspect	Detail
SF Orthogonality	SF7–SF12 are quasi-orthogonal
Gateway Demodulators	Multiple (typically 8), each can decode SF7–SF12 concurrently
Practical Result	All 6 SFs can be received simultaneously on 1 frequency
Limitation	Collisions occur if the same SF & frequency overlap in time

3. Results and Discussion

- ❖ Collision Avoidance: The system utilizes dual-frequency separation (Freq1 uplink, Freq2 downlink) and structured TDMA slotting to fully eliminate uplink/downlink collisions. Guard bands of 60 ms per slot reliably tolerate RTC drift of ± 5 ms across cycles, maintaining slot alignment even under temperature fluctuations underground.
- ❖ Scalability: ALOHA-based dynamic joining enables unlimited miner integration without disrupting active cycles. The system’s relay structure forwards $\sim 2,000$ bytes of aggregated miner data using 20 chunks of 100 bytes each, ensuring efficient hop-to-hop delivery across up to 7 relays for 2 km coverage.
- ❖ Latency: The system achieves a 67-second end to end update cycle for 100 miners, enabling better health and environmental monitoring while respecting LoRa duty cycle constraints and underground operational feasibility.
- ❖ Reliability: CRC-16 is applied pre-encryption to detect and discard corrupted packets before AES decryption, reducing processor waste. Downlink retries in control windows achieve $>99\%$ delivery success even under occasional interference.

Limitations:

- ❖ SF7’s practical range (150–200 m) requires additional relay density in tunnels with bends or heavy obstructions.
- ❖ AES-128 encryption adds ~ 2 ms processing per packet, which is negligible within 190–200 ms TDMA slots but relevant for firmware optimization.
- ❖ Relay placement planning impacts latency and hop reliability under harsh conditions.

3. Future work

- ❖ Field validation in active coal and metal mines across India to quantify reliability under real mining operations.
- ❖ Integration with cloud dashboards for real-time alerts and supervisor monitoring.
- ❖ Adaptive SF tuning using measured tunnel RSSI to dynamically balance range and data rates.

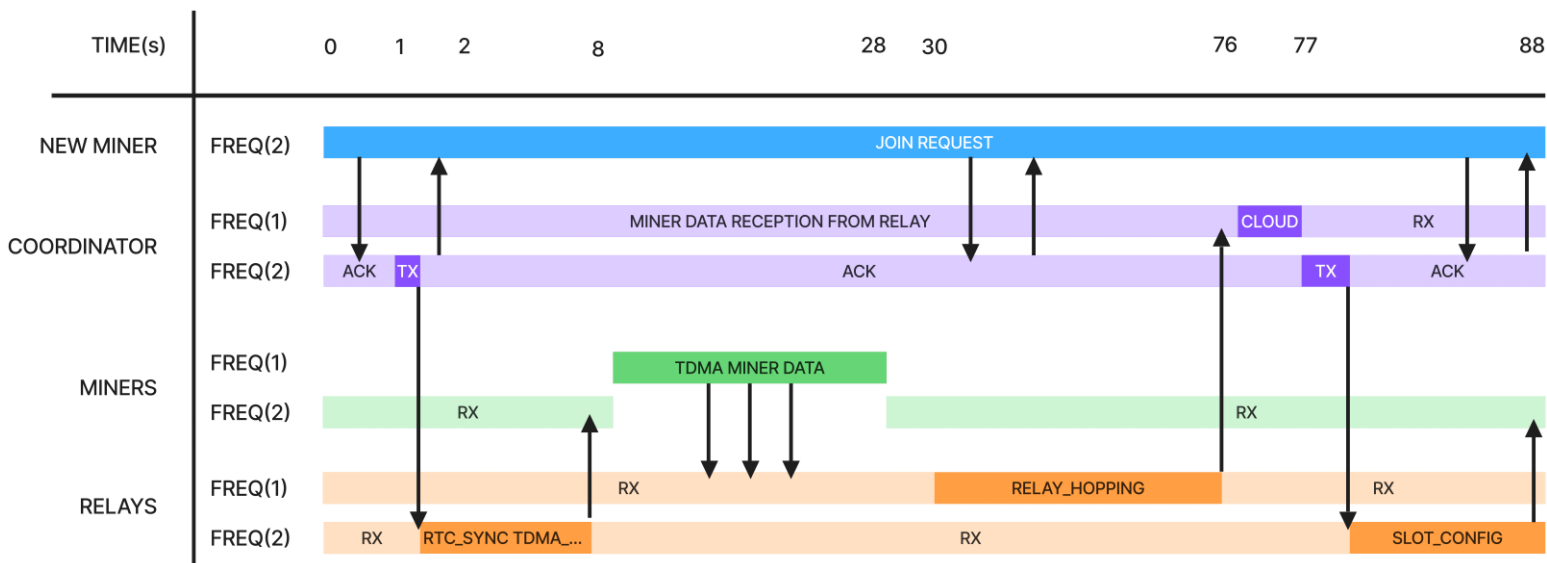


Fig1: Timing diagram