RESEARCH PAPER

Design and Implementation of an RA Agent–Based Through-Soil Communication System

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ABSTRACT
Reliable communication in underground and disaster-prone environments is difficult due to severe attenuation of radio-frequency signals, limited bandwidth, and lack of communication infrastructure. In such conditions, conventional wireless technologies fail to provide dependable connectivity, which can affect safety and timely decision-making. This project presents the design and implementation of an RA Agent–based through-soil communication system intended for underground monitoring and emergency communication applications.
The proposed system deploys an RA Agent as an embedded sensing and communication unit equipped with physiological, motion, and environmental sensors. Instead of transmitting raw sensor data continuously, the RA Agent performs local data processing to identify abnormal or critical conditions. Only essential information is transmitted, thereby reducing bandwidth usage and power consumption. Communication is achieved using low-frequency magnetic induction–based through-soil transmission, which offers improved reliability in underground environments compared to conventional RF communication.
To support communication over extremely low data rates, a timing-based adaptive encoding scheme inspired by Morse code is employed. This approach enhances noise resilience and ensures reliable data reception under harsh channel conditions. Lightweight error detection and repetition-based validation are incorporated to improve decoding accuracy. Experimental evaluation demonstrates that the proposed system achieves reliable data transmission with low latency and reduced energy consumption. The proposed RA Agent–based communication system provides a practical and scalable solution for underground monitoring and emergency communication where conventional wireless methods are ineffective.
Keywords: Through-soil communication, RA Agent, magnetic induction, underground monitoring, adaptive encoding, energy efficiency.
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I. Introduction

Secure and reliable communication is a fundamental requirement in underground, disaster-prone, and infrastructure-constrained environments, as it directly impacts human safety, operational coordination, and emergency response effectiveness. Applications such as mining operations, tunnel construction, subterranean exploration, and disaster rescue missions rely heavily on the timely exchange of critical information related to personnel health and environmental conditions. However, maintaining dependable communication in such environments remains a significant challenge due to severe attenuation of conventional radio-frequency (RF) signals, limited bandwidth availability, and the absence or failure of communication infrastructure.

Traditional wireless communication technologies, including high-power RF radios, cellular networks, and satellite-based systems, are often ineffective in underground or obstructed environments. RF signals experience extreme signal loss when propagating through soil, rock, concrete, and debris, leading to unreliable links and frequent communication outages. Additionally, continuous high-power transmission increases energy consumption and is unsuitable for battery-operated wearable systems intended for long-duration deployment. In disaster scenarios, physical damage to infrastructure further limits the availability of conventional communication channels, increasing the risk of delayed response and reduced situational awareness.

To overcome these limitations, low-frequency electromagnetic and magnetic induction-based through-the-earth communication has emerged as a promising alternative. Unlike RF communication, magnetic induction relies on near-field magnetic coupling, which is largely unaffected by soil composition and moisture variations. This enables more stable signal propagation through earth and rock over moderate distances. However, such communication techniques inherently support very low data rates, necessitating efficient encoding mechanisms that can operate reliably under noisy and bandwidth-constrained conditions.

At the same time, recent advancements in embedded sensing and edge intelligence have enabled continuous monitoring of physiological, motion, and environmental parameters using compact, low-power devices. Transmitting raw sensor data over constrained underground channels is inefficient and energy-intensive. Therefore, integrating on-device intelligence for feature extraction, anomaly detection, and context-aware data prioritization is essential to reduce communication overhead while preserving critical information.

In this context, this paper proposes an **RA Intelligent Communication Assistance System**, a low-power, noise-resilient, and secure communication framework designed for long-distance through-soil transmission. The proposed system employs an RA Intelligent Agent implemented as an embedded edge node equipped with physiological, motion, and environmental sensors to continuously monitor agent health and surrounding conditions. Rather than transmitting raw sensor data, the system performs local analysis to identify abnormal or emergency situations and transmits only critical, time-sensitive information.

To ensure reliable operation under extreme attenuation, the system utilizes low-frequency electromagnetic and magnetic induction-based communication combined with an adaptive Morse-code-based timing modulation scheme. This encoding approach offers ultra-low bandwidth requirements and strong resilience to noise. Lightweight error detection, repetition-based validation, and timing-based authentication mechanisms further enhance reliability and security. The proposed architecture is evaluated through hardware prototyping and simulation-based analysis using metrics such as transmission range, latency, decoding accuracy, packet loss, and power consumption. The results demonstrate that the proposed system provides a practical and scalable solution for underground monitoring and emergency communication in environments where conventional wireless technologies fail.

II. RELATED WORKS

Sun, Y., et al. (2023) (1) investigated through-the-earth (TTE) communication systems for underground rescue operations. The study analyzed low-frequency electromagnetic signal propagation through soil and rock layers. Experimental results showed that ultra-low-frequency transmission significantly improves penetration depth compared to conventional RF systems. However, the authors highlighted severe bandwidth limitations and low data rates as major constraints. The study emphasized the need for efficient encoding schemes to maximize reliability under extreme attenuation conditions..

Li, S., and Zhao, W. (2022) (2) proposed a magnetic induction (MI)-based underground wireless communication framework for mining applications. The system utilized coil-based antennas to establish near-field magnetic coupling between underground nodes. Performance evaluation demonstrated improved channel stability compared to RF systems, particularly under varying soil moisture conditions. Despite improved reliability, the communication range remained limited, and data rates were significantly constrained. The authors suggested relay-assisted MI networks to extend coverage.

Wang, H., et al. (2024) (3) developed a low-frequency communication model for subterranean sensor networks. The research focused on modeling path loss characteristics and evaluating signal attenuation in different soil compositions. Simulation results indicated that soil conductivity and moisture content influence signal strength but have minimal effect on magnetic induction channels. The study primarily addressed physical-layer modeling and did not integrate intelligent data processing mechanisms.

Nguyen, D., et al. (2023) (4) introduced an underground monitoring system integrating environmental sensors with wireless data transmission for mining safety. The system continuously transmitted temperature and gas concentration data to a surface monitoring station. Although the solution improved real-time monitoring capabilities, continuous raw data transmission resulted in high power consumption and inefficient bandwidth utilization. The authors noted the need for intelligent data filtering techniques to improve energy efficiency.

Victor, P. E., et al. (2024) (5) proposed an edge intelligence framework for IoT-based monitoring systems operating in constrained environments. The system implemented on-device feature extraction and anomaly detection to reduce communication overhead. Experimental validation demonstrated significant reductions in transmitted data volume while maintaining detection accuracy. However, the framework was evaluated primarily in surface-level IoT scenarios and did not consider underground communication constraints.

Gyeltshen, T., et al. (2024) (6) designed a smart surveillance communication model for harsh environments using low-power wireless nodes. The system emphasized energy-aware scheduling and duty-cycled operation to extend battery lifetime. While the proposed architecture demonstrated improved energy efficiency, it relied on standard RF communication, limiting its applicability in deep underground environments.

Rahkoyo, E., et al. (2024) (7) developed an IoT-based safety monitoring system incorporating physiological sensors for worker health tracking. The study demonstrated reliable heart rate and environmental monitoring in industrial settings. However, the communication module depended on conventional wireless infrastructure, which may fail during disaster scenarios involving structural collapse or signal blockage.

Sharma, K., and Patel, R. (2023) (8) explored adaptive modulation techniques for low-bandwidth communication systems. Their work showed that timing-based modulation schemes, including on-off keying and pulse-width modulation, perform reliably in noisy and interference-prone channels. The authors concluded that simple modulation schemes with error detection mechanisms provide higher robustness compared to complex high-rate modulation in constrained channels.

Ramanan, G., et al. (2022) (9) investigated lightweight encryption mechanisms for resource-constrained embedded systems. The study evaluated symmetric-key cryptographic algorithms optimized for low memory and power usage. Results demonstrated that lightweight authentication methods can secure IoT communication without significantly increasing energy consumption. However, the research did not consider extremely low-bandwidth underground channels.

Habu, R., et al. (2022) (10) proposed a secure communication framework for smart monitoring systems using low-data-rate transmission schemes. The system incorporated repetition-based validation and simple error detection codes to enhance reliability. Although the approach improved decoding accuracy, it was not evaluated in severe attenuation environments such as underground soil or rock layers.

III. PROPOSED SYSTEM

The proposed RA Intelligent Communication Assistance System is designed to enable dependable communication in underground, disaster-affected, and communication-constrained environments where conventional wireless technologies are ineffective. The primary objective of the system is to ensure that critical information related to human safety and environmental conditions can be transmitted reliably over long distances through soil while maintaining low power consumption and operational security.

The system architecture is centered around an RA Intelligent Agent, a compact embedded unit deployed with an underground worker, rescue personnel, or field operative. This agent operates as an autonomous edge node capable of sensing, local decision-making, and communication. A surface-level receiving station is used to collect, decode, and visualize transmitted information, enabling timely intervention during emergency situations.

A. RA Intelligent Agent Design

The RA Intelligent Agent integrates multiple sensing modules to continuously observe the physical condition of the agent and the surrounding environment. Physiological sensors monitor vital parameters such as heart rate and body condition, allowing early detection of medical stress or fatigue. Motion sensors track physical activity and posture, enabling detection of abnormal inactivity, falls, or sudden movements. Environmental sensors measure parameters such as temperature, humidity, and hazardous gas presence, which are critical indicators in underground and disaster scenarios.

All sensor data is processed by a low-power embedded controller that serves as the computational core of the RA Agent. Rather than functioning as a simple data collection unit, the agent performs localized intelligence by analyzing sensor readings in real time. This edge-level processing allows the system to distinguish between normal operating conditions and potentially dangerous situations without relying on continuous external communication.

B. Edge Intelligence and Local Decision Making

To address the severe bandwidth limitations of through-soil communication, the proposed system avoids raw data transmission. Instead, local processing techniques are used to extract meaningful features from sensor data, such as heart rate variability, motion patterns, and environmental trends. These features are evaluated using lightweight anomaly detection logic to determine whether the current state represents normal behavior or a critical event.

Based on this evaluation, sensor information is categorized into different priority levels. Events indicating immediate danger, such as abnormal physiological readings, fall detection, or hazardous environmental exposure, are treated as high-priority data and trigger instant communication. Less critical information is either transmitted at longer intervals or stored locally for later retrieval. This intelligent filtering mechanism significantly reduces unnecessary transmissions and ensures that limited communication resources are reserved for essential information.

C. Through-Soil Communication Strategy

The communication subsystem employs low-frequency electromagnetic and magnetic induction-based transmission techniques to overcome the limitations of traditional RF communication in underground environments. Magnetic induction communication relies on near-field magnetic coupling between transmitter and receiver coils, which is largely insensitive to soil composition and moisture variations. This makes it suitable for reliable signal propagation through earth, rock, and debris.

Information selected for transmission is encoded using a timing-based modulation scheme inspired by Morse coding. In this approach, data symbols are represented through controlled variations in signal duration and spacing rather than changes in amplitude or frequency. This method is highly resilient to noise and attenuation, making it effective in harsh underground channels. The timing parameters of the encoding scheme are dynamically adjusted according to data urgency, channel reliability, and available energy, ensuring an optimal balance between reliability and power efficiency.

D. Reliability and Error Handling Mechanisms

Underground communication channels are inherently noisy and unpredictable. To improve communication reliability, the proposed system incorporates simple yet effective error detection and validation mechanisms. Each transmitted message includes basic error-checking information that allows the receiver to verify data integrity. Messages identified as critical are transmitted multiple times to increase the likelihood of successful reception.

At the receiving station, incoming signals are decoded using timing analysis to reconstruct the transmitted information. Messages that fail integrity checks are discarded, while validated messages are processed further. This approach avoids complex error correction techniques that would increase computational and energy overhead, while still providing sufficient reliability for emergency communication.

E. Security and Authentication Approach

Security is an essential requirement, especially in sensitive rescue or intelligence-related applications. Due to strict bandwidth constraints, the proposed system adopts lightweight security mechanisms tailored for low-data-rate environments. Each RA Intelligent Agent is associated with a unique transmission signature derived from its timing pattern, enabling identity verification at the receiving station.

In addition, minimal encryption and authentication logic is applied to protect transmitted data from unauthorized access or manipulation. These mechanisms ensure message authenticity and integrity without introducing significant communication delays or energy consumption, making them suitable for constrained underground systems.

F. Surface Station and Dual-Mode Operation

The surface receiving station consists of a magnetic induction receiver, signal decoding unit, and processing interface. It continuously listens for incoming transmissions from RA Intelligent Agents and converts decoded information into readable alerts and status updates. Visual and audible alerts are generated when emergency conditions are detected, enabling rapid response by rescue or monitoring personnel.

The system also supports dual-mode operation. When underground conditions prevent conventional networking, the system relies on through-soil communication. Once network connectivity becomes available, such as when the agent reaches the surface, the system can switch to local or wired communication for higher data-rate transfer and detailed data synchronization. This flexibility enhances system robustness across different operational scenarios.

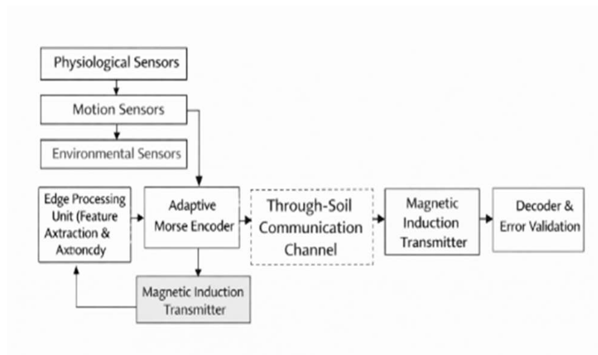

Figure 1: Proposed Block Diagram

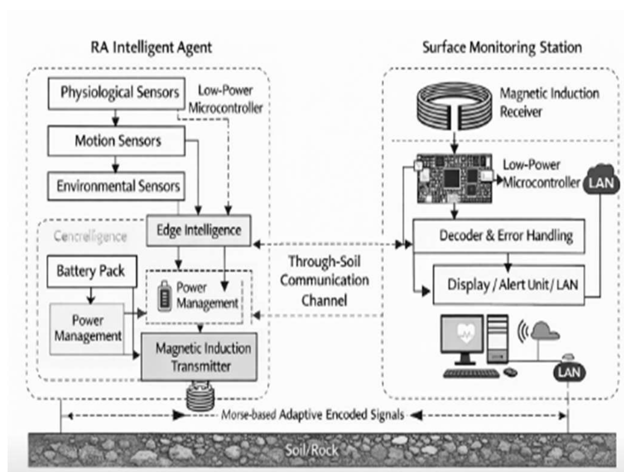

Figure 2: System Architecture Diagram

IV. METHODOLOGY

A systematic methodology is designed to develop and implement a reliable underground communication framework capable of operating in disaster-prone and infrastructure-deficient environments. The proposed RA Intelligent Communication Assistance System integrates embedded sensing, edge intelligence, adaptive Morse-based encoding, magnetic induction communication, and lightweight validation mechanisms into a unified architecture. The primary objective is to ensure secure, energy-efficient, and long-distance through-soil transmission of critical information while minimizing bandwidth consumption and power usage.

A. System Architecture

The proposed system architecture consists of three primary layers (refer Fig. X): the **Sensing Layer**, **Edge Intelligence and Communication Layer**, and the **Surface Monitoring Layer**.

The **Sensing Layer** includes physiological sensors, motion sensors, and environmental sensors integrated within the RA Intelligent Agent. These sensors continuously monitor parameters such as heart rate, body condition, motion patterns, temperature, and hazardous gas concentration.

The **Edge Intelligence and Communication Layer** comprises a low-power microcontroller integrated with feature extraction and anomaly detection logic. This layer performs adaptive Morse-based encoding and drives the magnetic induction transmitter for through-soil communication.

The **Surface Monitoring Layer** includes a magnetic induction receiver, decoding unit, error validation module, and display or alert system. This layer is responsible for reconstructing transmitted data, verifying its integrity, and generating appropriate alerts.

This layered architecture ensures modularity, scalability, and reliable operation in constrained underground environments.

B. Data Acquisition and Local Monitoring

The RA Intelligent Agent continuously collects multi-modal data from integrated sensor modules.

Physiological sensors monitor heart rate and vital parameters to detect signs of stress or abnormal conditions. Motion sensors track movement patterns and posture, enabling detection of falls or prolonged inactivity. Environmental sensors measure temperature and gas concentration to identify hazardous surroundings.

The sensor observation model can be expressed as:

$$S(t) = S_{phys}(t) + S_{motion}(t) + S_{env}(t) + n(t)$$

(1)

where:

- $S(t)$represents the overall sensed data,
- $S_{phys}(t)$, $S_{motion}(t)$, and $S_{env}(t)$denote physiological, motion, and environmental components respectively,
- $n(t)$represents noise caused by environmental disturbances and sensor inaccuracies.

This multi-sensor acquisition strategy ensures comprehensive situational awareness of both the agent's condition and surrounding environment.

C. Data Preprocessing and Feature Extraction

Raw sensor readings may contain noise, fluctuations, and redundant information. Therefore, preprocessing techniques are applied at the edge level to enhance signal reliability.

Signal conditioning includes filtering, normalization, smoothing, and threshold stabilization. From the processed signals, relevant features such as heart rate variability, acceleration magnitude variance, environmental threshold deviation, and trend gradients are extracted.

Feature extraction transforms raw sensor data into compact representations suitable for decision-making while reducing computational and transmission overhead.

D. Edge Intelligence and Anomaly Detection

The extracted features are evaluated using lightweight anomaly detection logic implemented within the embedded microcontroller. The system categorizes operational states into normal and abnormal conditions based on predefined thresholds and decision rules.

The anomaly detection decision function is defined as:

$$D = f(F_{phys}, F_{motion}, F_{env})$$

(2)

where:

- F_{phy} , F_{motion}, and F_{env}represent extracted feature sets,
- $f(\cdot)$denotes the decision logic,
- Drepresents the detected operational state (Normal / Alert / Emergency).

Only when an abnormal or critical condition is detected does the system initiate transmission. This selective transmission mechanism significantly reduces bandwidth utilization and improves energy efficiency.

E. Adaptive Morse-Based Encoding and Through-Soil Transmission

To ensure reliable communication under severe attenuation conditions, the system employs low-frequency electromagnetic and magnetic induction-based through-the-earth communication.

Critical data is encoded using an adaptive Morse-code-inspired timing modulation scheme. Instead of transmitting high-rate digital data streams, information is represented using controlled pulse durations and spacing intervals. This timing-based representation enhances robustness against underground noise and signal distortion.

The encoded transmission signal can be represented as:

$$T(t) = A \cdot p(t, \tau)$$

(3)

where:

- $A$is the signal amplitude,
- $p(t, \tau)$represents pulse duration and spacing parameters,
- τadapts according to urgency level and energy availability.

High-priority alerts use longer pulse intervals and repeated transmission to improve detection probability, while routine status updates use shorter pulse sequences.

F. Error Detection and Validation Mechanism

Due to unpredictable underground channel conditions, lightweight error detection mechanisms are incorporated. Each transmitted packet includes parity or checksum information for integrity verification.

Critical alerts are transmitted multiple times using repetition-based validation to increase successful reception probability. At the surface station, the decoder performs timing analysis and validates reconstructed messages. Messages failing validation are discarded to prevent false alerts.

This approach enhances reliability without introducing complex and energy-intensive error correction techniques.

G. Surface Monitoring and Alert Generation

The surface monitoring station continuously listens for incoming magnetic induction signals. The received signals are decoded and verified before being forwarded to the alert and visualization module.

Upon successful decoding:

- Health alerts trigger visual and audible notifications.
- Environmental hazard alerts activate emergency response indicators.
- Normal status updates are logged for monitoring purposes.

The system also supports optional local area network (LAN) connectivity for extended monitoring and data archival.

H. Energy Management Strategy

To extend operational lifetime, the RA Intelligent Agent operates in duty-cycled mode. Sensors and communication modules remain in low-power states during idle periods and activate only during scheduled sensing intervals or when anomaly detection is triggered.

Adaptive transmission scheduling ensures that communication frequency decreases during stable conditions and increases during emergencies. This strategy significantly enhances battery life and system sustainability in underground deployments.

V. SYSTEM SPECIFICATION

A. Hardware Specification

Arduino Nano

Arduino Nano is a compact microcontroller board based on the ATmega328P and acts as the core control unit of the RA Intelligent Communication Assistance System. It interfaces with physiological sensors, motion sensors, environmental sensors, and the magnetic induction communication module to acquire, process, and transmit critical data. The microcontroller executes embedded logic for feature extraction, anomaly detection, adaptive Morse-based encoding, and power management. Its small form factor, low power consumption, and ease of programming make it suitable for wearable and underground embedded applications.

Physiological Sensors

Physiological sensors are used to monitor vital health parameters such as heart rate and body condition of the RA agent. These sensors continuously collect biological signals and transmit them to the Arduino Nano for local processing. Monitoring physiological parameters enables early detection of medical emergencies such as stress, fatigue, or abnormal heart activity, which are critical in underground and disaster scenarios.

Motion Sensors

Motion sensors, such as accelerometers or inertial measurement units (IMUs), are integrated to detect physical activity, posture changes, and sudden movements. These sensors help identify abnormal motion patterns, including falls or prolonged inactivity, which may indicate an emergency condition. Motion data is processed locally to determine agent activity status before transmission.

Environmental Sensors

Environmental sensors measure surrounding parameters such as temperature, humidity, and hazardous gas concentration. These sensors provide situational awareness of underground conditions and help detect unsafe environments. The collected data supports timely alerts during hazardous situations such as gas leaks or extreme temperature variations**.**

Magnetic Induction Transmitter

The magnetic induction transmitter enables low-frequency through-soil communication by generating time-varying magnetic fields. It is driven by the Arduino Nano and transmits encoded Morse-based timing signals through soil and rock. Magnetic induction communication ensures reliable signal propagation under severe attenuation conditions where conventional RF communication fails.

Magnetic Induction Receiver

The magnetic induction receiver is deployed at the surface monitoring station to capture transmitted signals from underground agents. It converts received magnetic field variations into electrical signals, which are then forwarded to the processing unit for decoding and validation.

LCD Display

The LCD display is used at the receiving station to present decoded information such as agent status, health alerts, and environmental warnings. It provides a clear visual interface for monitoring system output. The display is interfaced using I2C communication, enabling efficient data visualization with minimal wiring complexity.

Buzzer

A buzzer is used as an alert mechanism to generate audible warnings during emergency situations. When critical conditions are detected, the buzzer is activated to immediately notify monitoring personnel, ensuring rapid response.

Power Supply

The power supply unit provides regulated DC voltage to all system components, including the Arduino Nano, sensors, and communication modules. It may consist of a battery pack with voltage regulation circuitry to support portable and wearable operation. Efficient power management ensures stable operation and extends system lifetime during underground deployment.

B. Software Specification

Arduino IDE

Arduino IDE is used for developing, compiling, and uploading embedded firmware to the Arduino Nano. It supports C/C++ programming and provides built-in libraries for sensor interfacing, timing control, and communication handling. The IDE also offers serial monitoring and debugging tools, simplifying firmware testing and system validation.

Embedded C

Embedded C language is used to implement system logic, including sensor data acquisition, preprocessing, anomaly detection, adaptive Morse-based encoding, and magnetic induction signal control. Embedded C enables efficient memory usage and real-time execution, which are essential for resource-constrained underground systems.

Edge Intelligence Algorithms

Lightweight edge intelligence algorithms are implemented on the microcontroller to perform feature extraction and anomaly detection. These algorithms analyze sensor data locally to determine urgency levels and decide whether data transmission is required. Edge intelligence reduces communication overhead and improves energy efficiency.

Surface Station Processing Software

The surface monitoring station runs decoding and validation software to interpret received Morse-based signals. This software performs timing analysis, error detection, and message reconstruction before displaying results or triggering alerts. Optional LAN or IoT integration enables data logging, visualization, and extended monitoring.

VI. RESULT & DISCUSSION

This section discusses the operational performance of the proposed RA Intelligent Communication Assistance System and analyzes the experimental results obtained during system testing. The evaluation focuses on the system's ability to provide reliable communication in underground and disaster-prone environments, efficiently transmit critical information through soil, and maintain low power consumption under constrained conditions. The results demonstrate that the integration of edge intelligence, adaptive Morse-based encoding, and magnetic induction-based through-soil communication significantly improves reliability, energy efficiency, and responsiveness in environments where conventional wireless technologies fail.

A. Environment and System Testing

The proposed system was implemented and tested in a controlled experimental environment designed to emulate underground and low-connectivity conditions. The RA Intelligent Agent was equipped with physiological, motion, and environmental sensors and deployed in a semi-enclosed area with soil and structural obstructions between the transmitter and receiver.

Multiple test scenarios were conducted, including normal operational conditions, simulated emergency situations, and varying communication distances through soil. System performance was evaluated based on successful data transmission, decoding accuracy, latency, and power consumption. The surface monitoring station continuously logged received data and alert notifications to validate system reliability and consistency.

B. Attendance Monitoring Results

Reliable through-soil communication was successfully achieved using magnetic induction-based low-frequency transmission combined with adaptive Morse-code encoding. Under normal conditions, routine status updates were transmitted at predefined intervals and decoded accurately at the receiving station. During simulated emergency conditions, critical alerts were prioritized and transmitted immediately.

Table I presents representative communication results under different operational conditions.

Table I. Through-Soil Communication Performance Under Different Conditions

Condition	Transmission Status	Decoding Accuracy	Alert Delivery	System Response
Normal Operation	Successful	High	Not Triggered	Status Logged
Emergency Event	Successful	Very High	Triggered	Alert Generated
Noisy Channel	Partial Retransmission	Moderate	Triggered	Repetition Enabled

The results confirm that the adaptive encoding and repetition-based validation significantly enhance transmission reliability under noisy underground channels.

C. Edge Intelligence and Anomaly Detection Performance

The edge intelligence module was evaluated based on its ability to correctly classify sensor data and trigger transmissions only during abnormal conditions. Physiological and motion sensor data were analyzed locally to detect anomalies such as abnormal heart rate, prolonged inactivity, and sudden movement patterns.

The system accurately differentiated between normal and abnormal operational states, ensuring that transmissions were initiated only when necessary. This selective transmission approach reduced unnecessary communication and preserved bandwidth and energy.

Table II. Anomaly Detection Performance Analysis

Scenario	Detection Accuracy	False Alert Rate
Normal Activity	High	Low
Physiological Stress	Very High	Minimal
Motion Anomaly	High	Low

These results indicate that edge-based anomaly detection effectively supports intelligent data prioritization.

D. Latency and Alert Response Time Analysis

Alert response time was measured as the duration between anomaly detection at the RA Intelligent Agent and alert generation at the surface monitoring station. The system demonstrated near real-time alert delivery, even under moderate channel noise.

Table III. Alert Response Time Evaluation

Alert Type	Average Response Time (s)	Maximum Delay (s)
Health Emergency Alert	2.3	2.9
Environmental Hazard Alert	2.1	2.7
Motion Anomaly Alert	2.5	3.1

The low response time confirms the suitability of the proposed system for time-critical emergency communication.

E. Power Consumption and Energy Efficiency Analysis

Power consumption was analyzed to evaluate the effectiveness of duty-cycled operation and energy-aware transmission scheduling. During normal conditions, the RA Intelligent Agent remained in low-power mode, activating communication only when anomalies were detected.

Experimental observations showed a significant reduction in energy usage compared to continuous transmission models. The adaptive transmission strategy extended operational lifetime while maintaining reliable communication performance.

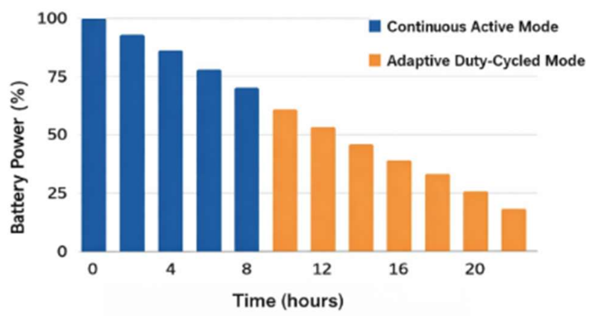

Fig 3 Power Consumption Analysis

F. Comparative Performance Analysis

Compared to conventional RF-based underground communication systems, the proposed solution demonstrated superior reliability and energy efficiency. Unlike continuous data transmission approaches, the integration of edge intelligence reduced bandwidth usage and transmission frequency. Additionally, magnetic induction-based communication provided stable performance under soil and structural obstructions where RF systems experienced severe attenuation.

The adaptive Morse-based encoding further enhanced noise resilience compared to fixed-rate modulation schemes, making the system suitable for harsh underground environments.

G. Discussion

The experimental results validate the effectiveness of the proposed RA Intelligent Communication Assistance System in providing reliable and energy-efficient underground communication. The combination of edge intelligence and adaptive encoding ensures that only critical information is transmitted, reducing communication overhead and extending system lifetime. The low alert response time and high decoding accuracy demonstrate the system's capability to support real-time emergency monitoring.

Overall, the proposed system offers a robust, scalable, and intelligent communication solution for underground monitoring, disaster rescue operations, and subterranean exploration. The results confirm that the proposed architecture effectively addresses the limitations of conventional wireless communication technologies in constrained environments.

VII. CONCLUSION

This project successfully designed and implemented an RA Intelligent Communication Assistance System to enable reliable and energy-efficient communication in underground, disaster-prone, and infrastructure-constrained environments. The integration of edge intelligence with adaptive Morse-based encoding and magnetic induction-based through-soil communication ensures robust signal transmission under severe attenuation conditions. By performing local feature extraction and anomaly detection, the system transmits only critical and time-sensitive information, significantly reducing bandwidth usage and power consumption.

The proposed system demonstrates high reliability in transmitting physiological, motion, and environmental alerts over underground channels where conventional radio-frequency communication fails. Intelligent data prioritization improves responsiveness during emergency situations, while lightweight error detection and repetition-based validation enhance decoding accuracy under noisy conditions. Duty-cycled operation and energy-aware transmission scheduling extend system operational lifetime, making the solution suitable for long-term underground deployment.

Experimental evaluation confirms that the system achieves low latency, stable communication range through soil, and improved energy efficiency compared to continuous transmission approaches. The dual-mode communication capability enables seamless integration with surface-level monitoring systems, providing real-time visualization and alert generation. The modular architecture supports scalability and practical deployment in disaster rescue operations, mining safety, and subterranean exploration scenarios. Overall, the proposed solution offers a reliable, secure, and intelligent communication framework for environments where traditional wireless technologies are ineffective.

A. Future Enhancement

Future enhancements of the proposed system can focus on improving scalability, intelligence, and situational awareness. Integration of advanced edge AI models can further enhance anomaly detection accuracy and enable predictive health and hazard analysis. Multi-hop magnetic induction relay nodes may be deployed to extend communication range in deeper underground environments. Incorporating localization techniques based on magnetic field characteristics can assist in tracking agent position during rescue operations.

Energy harvesting mechanisms such as vibration or thermal harvesting can be integrated to further extend system lifetime. Secure key management and advanced lightweight cryptographic schemes may be employed to strengthen authentication and data confidentiality. Integration with cloud-based monitoring platforms can enable large-scale data analytics and historical trend analysis. Additionally, fusion with inertial navigation and environmental mapping systems can provide enhanced situational intelligence. These enhancements will further improve system robustness and adaptability for next-generation underground communication and disaster response systems.

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