International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

Design of a Wireless Underground Sensor Networks for Tunnel Rescuing

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***Abstract*— In challenging tunnel scenarios, conventional communication methods employing radio frequency (RF), ultra-wideband (UWB), or Wi-Fi signals often encounter limitations, including low reliability, high interference, and restricted coverage. Additionally, the use of wired communications proves impractical due to its high cost, low mobility, and maintenance complexities. Recognizing these shortcomings, the proposed soil communication system introduces a paradigm shift by harnessing advanced soil communication modules to establish a robust and efficient network. This approach overcomes the shortcomings of traditional communication methods, providing a reliable means of communication between trapped individuals and rescue teams. This technology not only ensures real-time information exchange but also significantly enhances coordination during rescue operations, thereby increasing the likelihood of successful outcomes. The gathered data is wirelessly transmitted through a wireless underground sensor network (WUSN) transmitter module, received on the surface by an ESP8266 Wi-Fi module, and connected to the internet of things (IoT) network. This information, including location, air quality, and user messages, becomes accessible remotely, empowering rescue workers to precisely locate individuals, understand potential hazards, and strategize efficient rescue operations. The scope involves the development of specialized communication devices tailored for soil communication. By addressing the challenges associated with conventional communication in tunnel environments, the soil communication system aims to revolutionize emergency services, acting as a vital lifeline for individuals trapped below ground and improving the overall effectiveness of rescue missions.**

Keywords*— WUSN, LCD, IoT Interfacing, ESP8266 Module

I. Introduction

The collapse incident at the Silkyara Bend-Barkot tunnel in Uttarakhand, where 41 workers were trapped for 17 days [5], serves as a poignant catalyst for this soil communication module to revolutionize emergency services in tunnels through the integration of WUSNs. Traditional methods of communication in underground areas, such as soil, have long been hampered by the inefficiencies of electromagnetic waves, which struggle with low penetration power and are prone to high attenuation from materials like sand and rock. In response to these formidable challenges, this paper introduces magnetic induction (MI), a wireless communication standard specifically tailored for underground environments. MI technology utilizes transmitters equipped with multiple magnetic coils connected to universal asynchronous receiver / transmitter (UART) modules, enabling robust serial data communication. By implementing MI, this paper not only mitigates attenuation levels, thereby facilitating more efficient data transmission and optimizes system parameters to enhance the channel capacity of weak links. This augmentation not only increases data rates but also extends the transmission distance of the MI waveguide, bolstering overall performance.

Moreover, WUSNs, fortified by a multitude of sensors strategically deployed throughout the underground environment, enable real-time monitoring of critical parameters such as temperature, humidity, and air quality. This heightened accuracy and timely data acquisition are pivotal in enhancing emergency response capabilities within tunnels, ensuring swift and effective interventions during crises. However, despite the potential benefits afforded by WUSNs, significant challenges persist. Factors such as temperature fluctuations, adverse weather conditions, varying soil compositions, moisture levels, and soil homogeneity significantly impact the reliability and efficacy of underground communication. Furthermore, burial depth and the frequency of electromagnetic waves exert a profound influence on communication success. To overcome these hurdles, innovative techniques such as the spread resonance method are deployed, effectively extending the transmission distance of MI-based waveguides and mitigating the effects of multipath fading and radio frequency (RF) interference.

Ultimately, this paper aims to bridge these technological gaps by facilitating the seamless transmission of stored data through soil as a medium, integrated with IoT technology to ensure swift and accurate delivery to the intended recipients. By harnessing the power of WUSNs and innovative communication technologies like MI, this paper endeavors to usher in a new era of enhanced safety and efficiency in underground environments. Through this approach, the system mitigates risks and empowers emergency responders to effectively manage crises with confidence.

II. LITERATURE REVIEW

Zhang et al. (2023) proposed recent advancements in IoT implementation for environmental, safety, and production monitoring in underground mines [3]. The research focused on utilising IoT technology for real-time monitoring of environmental parameters, safety, and production within underground mines. A Mine IoT system was introduced, along with a classification of sensors and an overview of wired and wireless communication technologies. Challenges highlighted include operation disruption, investment requirements, limited battery life, poor communication quality, and difficulties in data management. The paper emphasises the need for further research on advanced techniques to enhance the applicability and effectiveness of IoT applications in underground mines.

Salam et al. (2020) proposed a statistical impulse response model based on the empirical characterization of the wireless underground channel [1]. This research aimed to design resilient underground (UG) channel systems using soil characteristics. Experiments were conducted in indoor and field testbed environments, focusing on three soil types with varying sand and clay contents. Variations in soil texture and moisture were studied to offer adaptable control. The study also examined time-domain channel characteristics, including RMS delay spread, coherence bandwidth, and multipath power gain. The results led to the development of a statistical channel model for wireless underground channels, which lays the foundation for data harvesting, sub-carrier communication, and beamforming techniques.

Reddy et al. (2020) proposed a WUSN utilising MI technology [13]. While electromagnetic waves are commonly used for long-distance communication, they struggle to penetrate soil due to their composition, leading to high diffraction and attenuation and resulting in data loss. To overcome this challenge, WUSNs have been introduced.

Tran Quoc Vinh et al. (2024) introduced a machine learning-based approach for fault detection and localization in WUSNs deployed for tunnel monitoring [8]. This study presents a framework that utilises sensor data to train predictive models capable of identifying and pinpointing faults or anomalies in underground infrastructure. Experimental results demonstrate the effectiveness of the proposed method in enhancing tunnel safety and maintenance.

Sadeghioon et al. (2020) designed and developed a WUSN for pipeline monitoring [10], particularly in water supply networks. This paper addresses the need for infrastructure monitoring and reviews current methods while introducing an ultra-low-power WUSN with sensor nodes and a data management system. Additionally, it presents a non-invasive relative pressure sensor assembly based on force-sensitive resistors to overcome challenges associated with RF transmission through soil in WUSNs.

III. EXISTING SYSTEM

In tunnel environments, the current methods of transmitting data, including the use of fibre optic cables or wireless technologies like long-range wide-area networks (LoRaWAN), encounter various challenges. These include complexities in installation, limitations in bandwidth, scalability, and latency. Additionally, when converting analogue signals to digital signals suitable for transmission, variations in soil composition can lead to data loss due to difficulties in wave penetration over long-distance communication. To address these issues, this paper proposes a novel soil communication system tailored specifically for tunnels. By employing advanced soil communication modules, this paper aims to overcome these challenges and establish a reliable network. This innovative approach has the potential to significantly improve emergency services by facilitating dependable communication between trapped individuals and rescue teams. It promises to enhance coordination and effectiveness in rescue missions.

IV. PROPOSED SYSTEM

In the proposed system, electromagnetic waves are replaced with MI. Sensor data may be extracted from the tunnel surface and sent through the soil using the MI technique. And in this case, soil may be used as a medium to transfer data in the form of serial data and display it using the IoT interface.

A. Materials Overview

a. Arduino UNO

Fig. 1. Arduino UNO

Figure 1 showcases the Arduino Uno, a versatile microcontroller board designed to streamline the prototyping phase of electronic projects. Featuring an ATmega328P microcontroller, it offers a comprehensive range of digital and analog inputs and outputs, catering to the requirements of hobbyists and professionals alike. Its user-friendly development environment simplifies programming tasks and enables smooth integration with various sensors and actuators, making it an attractive choice for individuals with varying skill levels and application domains.

b. Vibrator Sensor

Fig. 2. Vibrator Sensor

Figure 2 illustrates the vibration sensor's function of detecting oscillations and vibrations within its environment. With its high sensitivity and broad frequency response, this sensor proves invaluable across various applications, ranging from structural health monitoring to seismic activity detection, and plays a critical role in ensuring equipment operates at its optimal performance level.

c. MQ2 Gas Sensor

Fig. 3. MQ-2 Gas Sensor

Figure 3 showcases the MQ-2 gas sensor, renowned for its capability to detect a variety of gases in the environment, including combustible gases, smoke, and harmful substances. Operating on the principle of conductivity change in its semiconductor material when exposed to different gases, this sensor finds extensive use in gas leakage alarms, safety systems, and air quality monitoring devices. Its integration with Arduino facilitates real-time monitoring and automation, enhancing its utility in safety and environmental monitoring applications.

d. RFID Sensor

Fig. 4. RFID Reader Module

Figure 4 introduces the radio-frequency identification (RFID) reader module, which employs radio waves to communicate with and retrieve data from RFID tags or cards. When an RFID tag enters the reader's antenna range, it wirelessly receives power and sends back data to the reader. This module processes the data, enabling object or personnel identification, tracking, and authentication. Integration of RFID reader modules with microcontrollers like Arduino allows for seamless incorporation into electronic projects, enhancing their functionality and applicability.

e. GPS Module

Fig. 5. GPS Module

Figure 5 introduces the global positioning system (GPS) module, which integrates with electronic systems to deliver precise geographic location data. These modules receive signals from satellites orbiting the Earth, determining latitude and longitude coordinates. Widely employed in navigation systems, vehicle tracking, and location-based applications, GPS modules provide real-time positioning information. Typically comprising a GPS receiver, antenna, and often a microcontroller interface, these modules seamlessly integrate with platforms like Arduino. This integration empowers developers to craft projects ranging from GPS-based navigation systems to location-aware IoT devices, thereby enhancing functionalities in transportation, outdoor activities, and asset tracking.

f. ESP8266 Wi-Fi Module

Fig.6. ESP8266 Module

Figure 6 highlights the ESP8266 Wi-Fi module, a pivotal component in embedded electronics and IoT applications. This module incorporates a microcontroller with built-in Wi-Fi capabilities, enabling effortless connectivity to the internet. Renowned for its affordability, low power consumption, and compatibility with popular development platforms like Arduino, the ESP8266 finds applications across various domains, including smart home devices, industrial automation, and wireless sensor networks. Its programmability and connectivity make it a preferred choice for developers seeking to integrate Wi-Fi functionality into their projects in a compact and cost-effective manner.

B. WUSN Data Transmission

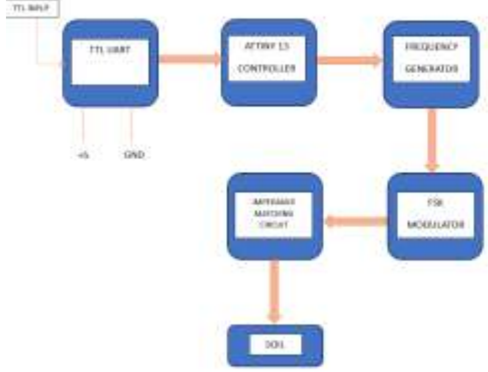

Fig.7. Block Diagram of WUSN Transmitter

From Figure 7, it's evident that data is initially encoded by the sensor or microcontroller, then converted to serial format through transistor-transistor logic (TTL) and UART interfaces, connected to both ground (GND) and a +5V power source. TTL levels adhere to standards where 0 bits correspond to 0 volts and 1 bit corresponds to 5 volts. The ATTINY 13 Controller interfaces with this setup, operating at a maximum clock frequency of 16.8 MHz. It's accompanied by a frequency generator capable of producing digital, analog, or non-repeating electrical signals. During transmission, it generates an analog signal, employing frequency-shifting key (FSK) modulation. This modulation facilitates data transfer through the generation of magnetic induction waves.

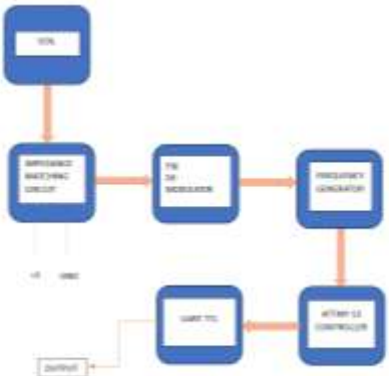

Fig.8. Block Diagram of WUSN Receiver

Figure 8 illustrates the receiver side of the system, where information is transmitted through the soil medium. The receiving portion mirrors the transmitter, but in reverse. MI waves are directed to the impedance matching circuit to minimize signal reflection from the load, and efforts are made to minimize the electrical load of the signal source. Next, the signal undergoes FSK demodulation, a process that converts it into binary signals. These signals are then fed into a frequency generator, which produces digital electrical signals. These signals are then processed by an ATTINY 13 controller and subsequently connected to a UART TTL interface, which interfaces with an IoT system to display the output.

C. System Design

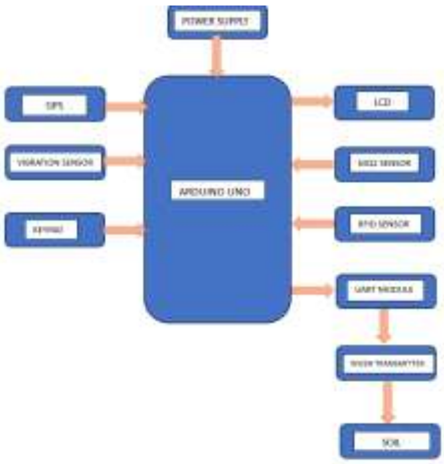

Fig.9. Block Diagram of Transmitter

Figure 9 illustrates the operational framework of the soil communication system transmitter, tailored specifically for tunnel rescue operations. At its core, an Arduino Uno acts as the central hub, gathering data from a variety of sensors. These sensors include an RFID sensor for identifying individuals equipped with tags, a vibration sensor for detecting movements or tremors, and an MQ-2 sensor for continuous monitoring of air quality, alerting rescuers to potential gas hazards. Additionally, a GPS module provides precise location data, aiding in targeted assistance efforts. On-site, an LCD screen connected to the Arduino Uno displays real-time sensor readings, while a keypad allows trapped individuals to transmit basic signals or messages. Subsequently, all collected data is wirelessly transmitted via a WUSN transmitter module embedded in the soil.

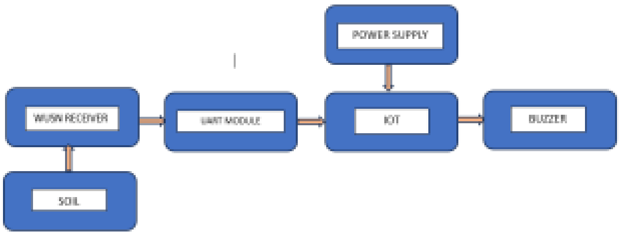

Fig. 10. Block Diagram of Receiver

In Figure 10, the data transmitted by the soil communication system's transmitter is received by a WUSN receiver module situated on the ground's surface. This received information is subsequently processed by an ESP8266 microcontroller. An IoT module is then integrated with this processed data to facilitate remote access and visualization. Finally, rescuers can monitor vital sensor readings on a computer or mobile device through the IoT platform, with an additional alert sounded by a buzzer.

Working: In the event of a tunnel collapse, when a signal is received from a vibration sensor, the Arduino Uno swiftly gathers data from all sensors. It then displays real-time readings on an LCD screen and allows users to send basic messages. Following this, the collected data is wirelessly transmitted through a WUSN transmitter module. Once transmitted, the data is translated and integrated into the IoT network. This seamless connection enables rescue personnel to monitor the data on either a computer or mobile phone. Instant access to real-time information assists in devising the most efficient rescue strategies while prioritising safety measures.

V. Results and Discussion

An innovative system designed to address tunnel collapse emergencies has been successfully implemented, significantly improving rescue operations. It integrates a range of essential components, including a vibration sensor, MQ-2 sensor, RFID sensor, keypad, WUSN transmitter module, and ESP8266 receiver. These components collectively detect collapses, identify gas leaks, and locate individuals in distress. The gathered data is seamlessly transmitted to the IoT network, enabling remote monitoring and facilitating the implementation of efficient rescue strategies.

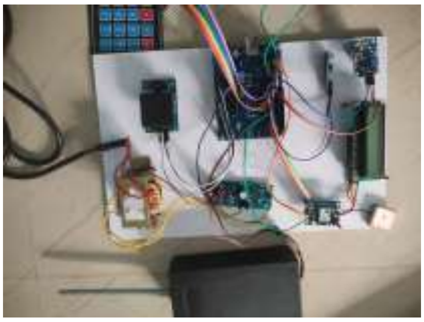

Fig.11. Transmitter module

Figure 9 illustrates the connections of essential components to the Arduino Uno. These include the vibration sensor for detecting tunnel collapses, the MQ-2 sensor for monitoring dangerous gas leaks, the RFID sensor for scanning signals from rescue tags, and the GPS module for providing precise location data. Interaction with the system is facilitated through a keypad, allowing for the transmission of coded messages. Utilizing a dedicated WUSN transmitter, all these components operate wirelessly, delivering crucial information to rescue workers for swift and effective response to emergencies.

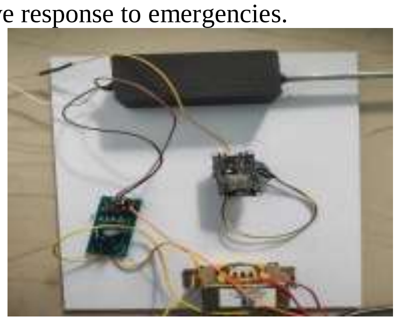

Fig. 12. Receiver module

The figure 12 illustrates the receiving end of our project, wherein the ESP8266 interprets and decodes transmitted data from the WUSN transmitter, incorporating information from various sensors. Upon decoding, the ESP8266 seamlessly integrates this data into the broader IoT network. This connectivity enables rescue workers to remotely monitor real-time insights via computer or mobile device, facilitating efficient decision-making for successful rescue operations. The ESP8266's efficient processing and translation of transmitted information contribute to timely and effective responses.

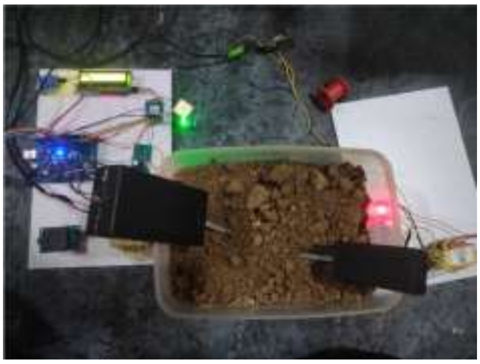

Fig.13. Prototype Model

The figure 13 depicts the prototype configuration, where multiple components connect to the Arduino. These components include sensors for detecting tunnel collapses, measuring gas levels, and assessing air quality. Additionally, the Arduino interfaces with a GPS module for precise location tracking, a keypad for user interaction, and an RFID sensor for tag recognition. Real-time information is displayed on an LCD screen. The data collected by these components is wirelessly transmitted through soil using a specialized prototype, highlighting the adaptability and effectiveness of our communication system in challenging underground environments.

Fig. 14. Tunnel Collapsed

Figure 14 illustrates the tunnel vibrations triggered by the vibration sensor. Upon detection, the arduino uno swiftly processes the data, facilitating its transmission through the WUSN transmitter via soil to the WUSN receiver. Subsequently, the conveyed information is seamlessly integrated into the IoT interface, providing immediate awareness of vibration occurrences within the tunnel environment.

Fig. 15. An Abnormal Gas Detected

Figure 15 showcases the system's swift response to abnormal gas detection within the tunnel, initiated by the MQ2 gas sensor. Upon detection, the sensor promptly relays crucial data to the Arduino Uno, initiating a sequential transmission process through the WUSN data transmitter via soil. The transmitted details are then received by the WUSN data receiver and seamlessly presented at the IoT interface, ensuring rapid identification and response to potential gas hazards.

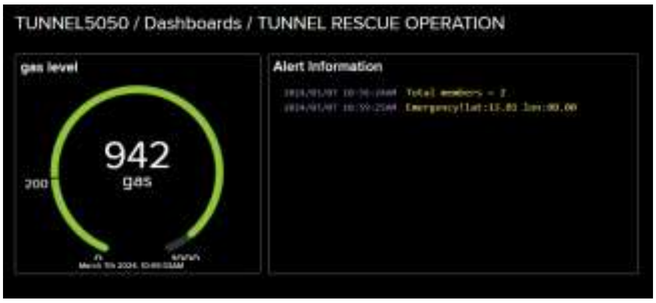

Fig. 16. People Count and GPS Location Display

The figure 16 illustrates the interface displaying real-time location coordinates, facilitated by the GPS module relaying latitude and longitude data to the Arduino Uno. Concurrently, the RFID sensor accurately counts and records the total number of individuals within the tunnel. This integrated information is effectively communicated through the WUSN Data Transmitter and showcased in the IoT interface, enhancing situational awareness for effective management of tunnel scenarios.

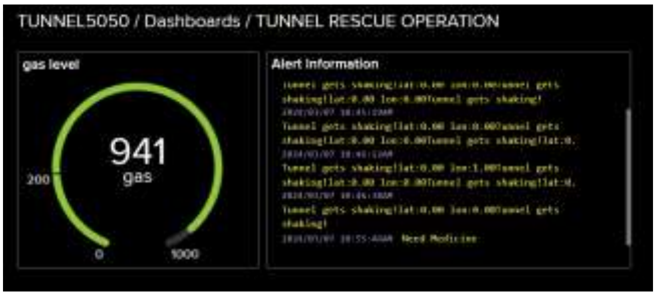

Fig. 17. Getting information from trapped individuals

The figure 17 showcases the system's capability to facilitate effective communication between trapped individuals using the keypad. By selecting predefined options, trapped individuals convey their basic needs, which the Arduino Uno processes and displays on the LCD screen. This enables timely assistance and contributes to efficient rescue operations.

VI. Conclusion and Future Scope

The proposed system seamlessly integrates a variety of sensors tailored for tunnel safety, including collapse detection, gas level monitoring, and air quality assessment. Through efficient processing by the Arduino Uno, the system enables wireless transmission of data via the WUSN transmitter through soil. Additionally, it provides real-time readings, facilitates communication through a keypad and LCD screen, and ensures accurate location tracking via GPS. This prototype demonstrates the feasibility of effective rescue operations in challenging environments, promising potential application in broader emergency scenarios.

The future trajectory of the soil communication system is highly promising, particularly with the envisioned integration of artificial intelligence and autonomous sensor networks. This advancement will significantly enhance the system's predictive analysis capabilities for various emergency scenarios. Moreover, the system's applicability is expected to extend beyond tunnels, finding utility in diverse underground environments. As research progresses, further exploration of advanced materials and communication protocols will fortify the system's robustness, enabling it to effectively navigate a broader spectrum of soil conditions and emergency situations.

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