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Energy Optimized Monitoring System for Underground Cave Environments

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ABSTRACT: Wireless sensor networks are essential for environmental monitoring, but their performance in underground cave environments is hindered by severe signal attenuation, multipath fading, and limited energy resources. This project proposes an energy-optimized monitoring system using Long Range (LoRa) communication with an adaptive long preamble to enhance data transmission reliability. Virtual sensors for temperature, humidity, and gas concentration are simulated in MATLAB to generate representative environmental data. LoRa modulation based on Chirp Spread Spectrum (CSS) is employed to ensure robust, long-distance communication. A high-loss, multipath channel model replicates underground conditions, while the receiver detects packets through preamble synchronization and demodulates the recovered signals. An optimization algorithm, such as Particle Swarm Optimization (PSO) or Genetic Algorithm (GA), is used to identify the preamble length that minimizes energy consumption while maintaining acceptable packet delivery ratio (PDR) and bit error rate (BER).

KEYWORDS: Cave environmental monitoring, LoRa, WSN and sensors.

I. INTRODUCTION

Underground cave environments present major communication challenges due to signal attenuation, multipath fading, and high noise levels. The proposed system uses LoRa (Long Range) wireless communication to ensure reliable data transmission over long distances. Virtual sensors for temperature, humidity, and gas levels are simulated in MATLAB to generate realistic environmental data. The system achieves improved reliability and energy efficiency, making it suitable for long-term underground environmental monitoring[1].

Wireless communication plays a vital role in remote monitoring applications such as mines, caves, and tunnels. Underground environments suffer from severe signal loss, noise interference, and limited accessibility. Reliable and energy-efficient data transmission is essential for continuous monitoring of temperature, humidity, and gas levels[2].

LoRa (Long Range) technology is a suitable choice due to its long-range, low-power, and robust communication features. The project focuses on using LoRa modulation with a long preamble to enhance packet detection and synchronization in challenging underground conditions. MATLAB simulation is used to model sensor data generation, channel behavior, transmission, and reception processes[3].

1.1 A. Ray Chowdhury, et al.(2025) , The paper presents a novel LoRa-based IIoT system for monitoring the underground coal mine environment. Maximum coverage distance is achieved with a minimum number of repeaters[5].

II. BLOCK DIAGRAM

The block diagram has been given in Fig 2.1

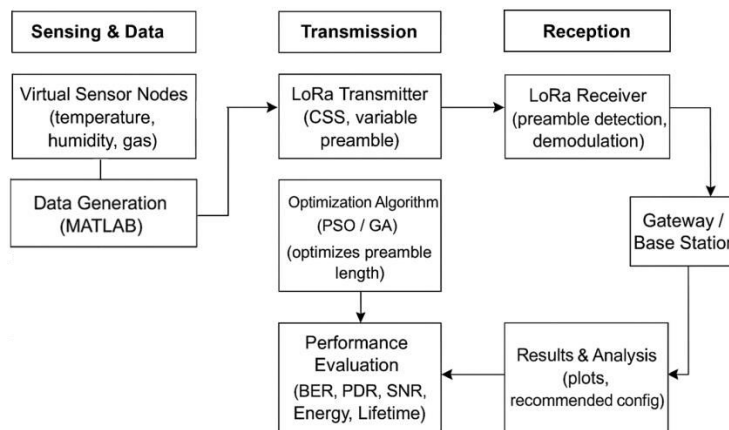


Fig 2.1: Block Diagram

The block diagram of the proposed energy-optimized monitoring system illustrates the overall workflow from data generation to performance evaluation. The system begins with virtual sensor nodes, which represent the sensing components used in a real underground monitoring setup. These sensors measure environmental parameters such as temperature, humidity, and gas concentration, which are critical for assessing cave conditions. In this project, these sensor readings are simulated in MATLAB using random or controlled data generation functions to mimic realistic environmental variations. This simulation stage serves as the foundation for testing and validating the wireless transmission system under controlled conditions without the need for physical sensors.

The generated sensor data is then fed into the LoRa transmitter module, where the data is encoded and modulated using the Chirp Spread Spectrum (CSS) technique. At the receiving end, the LoRa receiver module detects the incoming signal and performs preamble-based synchronization to identify the start of each data packet. Once synchronization is achieved, the receiver demodulates the chirp-modulated signal to extract the original sensor data.

The optimization algorithm block is a critical component that enhances the system's energy efficiency. Algorithms such as Particle Swarm Optimization (PSO) or Genetic Algorithm (GA) are implemented to determine the optimal preamble length that minimizes energy consumption while maintaining reliable communication.

III. PROPOSED METHODOLOGY

These method use LoRa-based wireless communication to ensure reliable data transfer in underground cave environments. Virtual sensors in MATLAB generate environmental data such as temperature, humidity, and gas concentration. The LoRa transmitter modulates the sensed data using Chirp Spread Spectrum (CSS) and includes a variable preamble length for synchronization .

An underground channel model is developed in MATLAB to simulate signal attenuation, multipath fading, and noise condition. The LoRa receiver detects and demodulates the transmitted signal to recover the original data accurately. An optimization algorithm (such as PSO or GA) is implemented to determine the optimal preamble length for minimizing energy consumption.

The system's performance is evaluated using key metrics such as Bit Error Rate (BER), Packet Delivery Ratio (PDR), Energy per Transmission, and Network Lifetime. The proposed approach provides a balance between reliability and energy efficiency, making it suitable for continuous underground monitoring applications.

An optimization algorithm—such as Particle Swarm Optimization (PSO) or Genetic Algorithm (GA)—is integrated into the system to identify the optimal preamble length that minimizes energy consumption without compromising packet delivery ratio (PDR) or bit error rate (BER). The algorithm operates by evaluating the trade-off between synchronization success and energy efficiency across different preamble lengths.

The proposed system’s performance is assessed using various metrics, including BER versus SNR, PDR, energy per transmission, and overall network lifetime.

IV. RESULT AND DISCUSSION

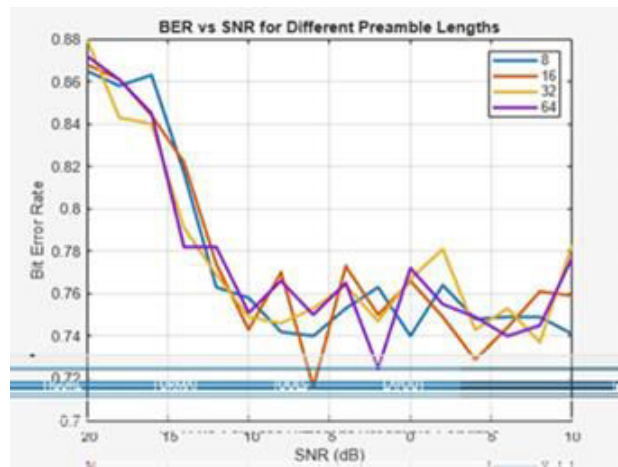


Figure 4.1. BER Vs SNR Different Preamble Lengths

The Bit Error Rate (BER) vs Signal-to-Noise Ratio (SNR) analysis for different preamble lengths provides insight into the reliability and robustness of the LoRa communication system in noisy underground environments. As the SNR increases, the BER decreases, indicating improved signal quality and fewer transmission errors.

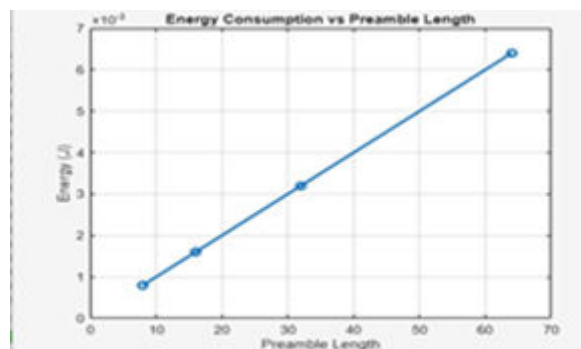


Figure 4.2. Energy Consumption Vs Preamble Length

The Energy Consumption vs Preamble Length analysis illustrates how the duration of the preamble affects the overall power usage of the LoRa communication system. As the preamble length increases, the energy consumption also rises because the transmitter remains active for a longer period during the synchronization phase.

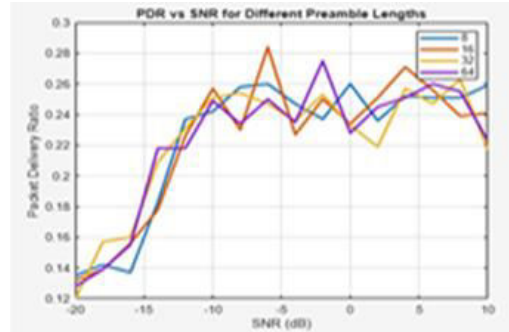


Figure 4.3. PDR Vs SNR for Different Preamble Lengths

The Packet Delivery Ratio (PDR) vs Signal-to-Noise Ratio (SNR) for different preamble lengths highlights the impact of signal quality and synchronization duration on data transmission reliability. As the SNR increases, the PDR also improves, indicating more successful packet receptions due to stronger and clearer signals.

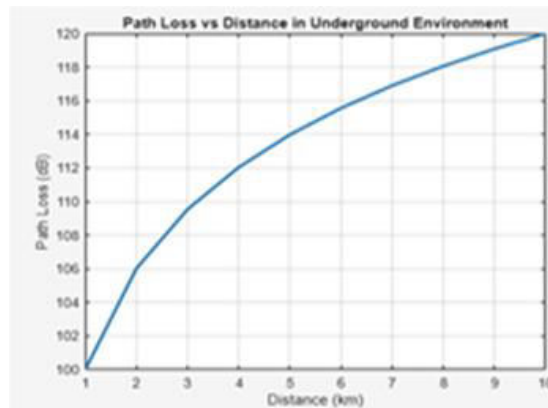


Figure 4.4. Path Loss Vs Distance in underground Environment

The Path Loss vs Distance analysis in an underground environment demonstrates how signal strength weakens as the distance between the transmitter and receiver increases. Due to the confined space, high humidity, rock composition, and irregular tunnel geometry, electromagnetic waves experience significant attenuation, leading to a nonlinear increase in path loss with distance. At shorter distances, the signal remains relatively stable, but as distance grows, reflections, diffraction, and absorption by underground materials cause severe degradation.

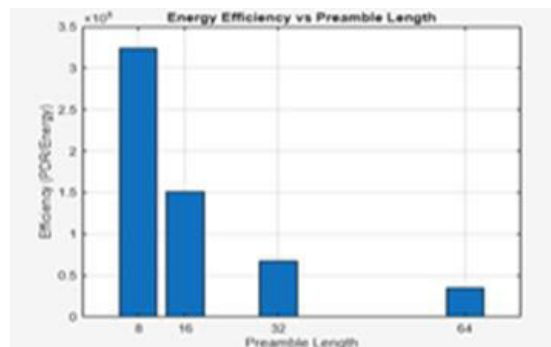


Figure 4.5. Energy Efficiency Vs Preamble Length

The Energy Efficiency vs Preamble Length analysis reveals how synchronization duration influences the power utilization of a LoRa-based communication system. Energy efficiency is defined as the amount of data successfully transmitted per unit of energy consumed. When the preamble length is short, energy efficiency tends to be higher because the transmission time and energy usage are reduced.

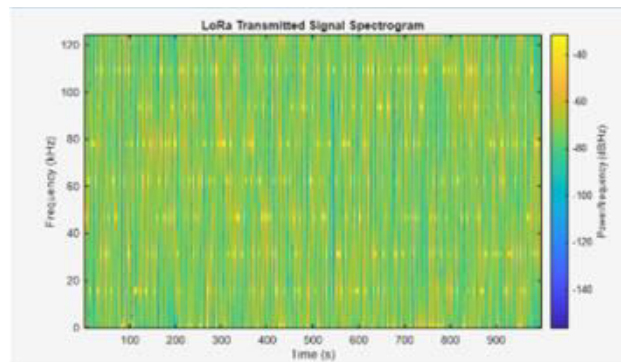


Figure 4.6. LoRa transmitted Signal Spectrogram

The LoRa transmitted signal spectrogram provides a time–frequency representation of how the signal’s spectral components vary during transmission. In a LoRa system, the signal is generated using Chirp Spread Spectrum (CSS) modulation, where the frequency of the carrier continuously increases or decreases over time, forming up-chirps and down-chirps.

V. CONCLUSION

The proposed energy-optimized monitoring system using LoRa technology provides an effective and sustainable solution for environmental data transmission in underground cave environments. By integrating LoRa’s Chirp Spread Spectrum modulation with an adaptive preamble optimization approach, the system successfully addresses challenges such as high signal attenuation, multipath interference, and limited energy resources. The MATLAB-based simulations demonstrate that optimizing the preamble length significantly improves synchronization accuracy, enhances packet delivery ratio (PDR), and reduces overall energy consumption. Furthermore, the application of optimization algorithms like PSO and GA ensures that the system operates efficiently under varying channel conditions. The results validate that the proposed model not only extends network lifetime but also enhances communication reliability, making it highly suitable for long-term underground monitoring and similar applications in other harsh or remote environments.

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