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Design and Optimization of Data Acquisition System Using Wireless Underground Sensor Networks

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Abstract

Wireless Underground Sensor Networks (WUSNs) offer promising solutions for applications such as pipeline monitoring, agriculture, and border patrol, but they face significant challenges due to signal attenuation in underground environments. This paper presents the design, optimization, and experimental validation of a WUSN-based data acquisition system specifically designed to detect water leakage in underground pipelines. The challenges of reliable underground communication are addressed by investigating system performance in the 450 MHz and 900 MHz frequency bands using Software Defined Radio (SDR) technology and Quadrature Phase Shift Keying (QPSK) modulation. An experimental testbed was developed featuring a buried subsurface sensor module communicating with a surface data acquisition module. Results demonstrate successful data transmission at depths up to 1.5 meters, analyzing the trade-offs between operating frequency, modulation scheme, burial depth, signal-to-noise ratio (SNR), and data rate. QPSK modulation at 900 MHz provided a favorable balance of data rate and reliability for the tested conditions.

Keywords

Wireless Underground Sensor Networks (WUSN),
Data Acquisition System (DAQ), Software Defined Radio (SDR),
Pipeline Monitoring, QPSK, Underground Communication, GNU Radio

1. Introduction

Wireless Sensor Network (WSN) technology has expanded beyond terrestrial applications into underground environments, leading to the development of Wireless Underground Sensor Networks (WUSNs) [1]. WUSNs enable critical applications such as intelligent agriculture, infrastructure monitoring (pipelines, power grids) [2], environmental monitoring (landslides, earthquakes), border patrol, and mine safety [3].

The primary challenge distinguishing WUSNs from WSNs is the communication channel. Electromagnetic (EM) waves experience severe attenuation when propagating through soil, rock, water, and other subsurface media, drastically reducing communication range and reliability. Factors like soil moisture, composition, temperature, operating frequency, and burial depth significantly impact EM wave propagation [4]. Existing wireless systems (e.g., Wi-Fi, Cellular) perform poorly underground.

Reliable communication between buried sensor nodes and surface stations is crucial [5]. While lower frequencies suffer less attenuation, they require larger antennas, complicating deployment. Higher frequencies allow for smaller antennas but face increased path loss. Furthermore, energy constraints are critical, as buried nodes often rely on limited battery power.

This research focuses on designing and optimizing a WUSN data acquisition system (DAQ) for monitoring underground pipelines to detect water leakage. The feasibility of using relatively high frequencies, 450 MHz and 900 MHz, combined with Software Defined Radio (SDR) for flexibility and Quadrature Phase Shift Keying (QPSK) modulation for robust data transmission is investigated. The objectives are:

1) To develop a WUSN testbed simulating pipeline monitoring.

2) To investigate EM wave channel properties in soil within the 450 MHz – 900 MHz band [6].

3) To implement and evaluate QPSK modulation using SDR (GNU Radio and HackRF One) [7] [8].

4) To analyze the impact of frequency, modulation, burial depth, and antenna design on system performance (SNR, data rate).

This paper is structured as follows: Section 2 reviews related work. Section 3 details the proposed system architecture and components. Section 4 describes the experimental setup and design parameters. Section 5 presents and discusses the results. Section 6 concludes the paper and suggests future work.

2. Background

The concept of WUSNs has gained traction since its introduction, with applications ranging from mine safety and oil reservoir monitoring to pipeline leakage detection. Early work often focused on magnetic induction (MI) or very low frequencies, which require large antennas and yield low data rates.

2.1. Frequency Selection and Channel Modeling

The underground channel is complex, with path loss heavily dependent on frequency and soil properties (moisture, texture, density). Research suggests the 300

MHz - 400 MHz band might offer a balance between path loss and antenna size. However, simulations and some empirical studies indicate potential for communication up to 1 GHz. Studies have shown a limited range (0.5 m) at 2.4 GHz using terrestrial nodes. The soil moisture content significantly affects antenna performance, potentially shifting the operating bandwidth and increasing return loss, especially at higher frequencies. The Friis equation needs modification for underground environments, incorporating additional path loss terms related to the soil's dielectric properties and attenuation constant. Models like Peplinski's [9] are used to estimate soil dielectric properties based on frequency, water content, and soil composition. Path loss generally increases with both distance and frequency.

2.2. Antenna Design

Antenna selection for WUSNs is challenging due to size constraints, variable soil conditions, and the need for directionality. Lower frequencies necessitate physically larger antennas. Directionality is also a concern; omnidirectional antennas may have nulls that limit vertical communication, while directional antennas are larger and require precise alignment. The burial itself alters antenna characteristics. Research explores the optimization of antenna design considering the impact of soil [10].

2.3. Modulation and Power

Power consumption is critical for battery-operated buried nodes. While some systems use mobile charging, many applications require low-power operation. Amplitude-based modulation schemes (like ASK) are generally unsuitable due to signal attenuation underground. Frequency-based schemes (FSK) can be affected by noise and channel variations. Phase-based modulation (PSK), particularly QPSK, is considered more robust as phase is less affected by the medium compared to amplitude or frequency. QPSK offers better spectral efficiency than BPSK by transmitting two bits per symbol.

This work builds upon these findings by implementing and evaluating a flexible SDR-based system using QPSK in the 450/900 MHz range, with a focus on optimizing communication for pipeline monitoring while considering practical antenna constraints.

3. Proposed System Architecture

The proposed WUSN system is designed for detecting underground pipeline leaks. It consists of two main subsystems: a Subsurface Subsystem buried near the pipeline and a Surface Subsystem for data reception and analysis.

3.1. Subsurface Subsystem

The subsurface unit is designed to be buried at depths ranging from 1 to 5 meters. Its block diagram is shown in Figure 1.

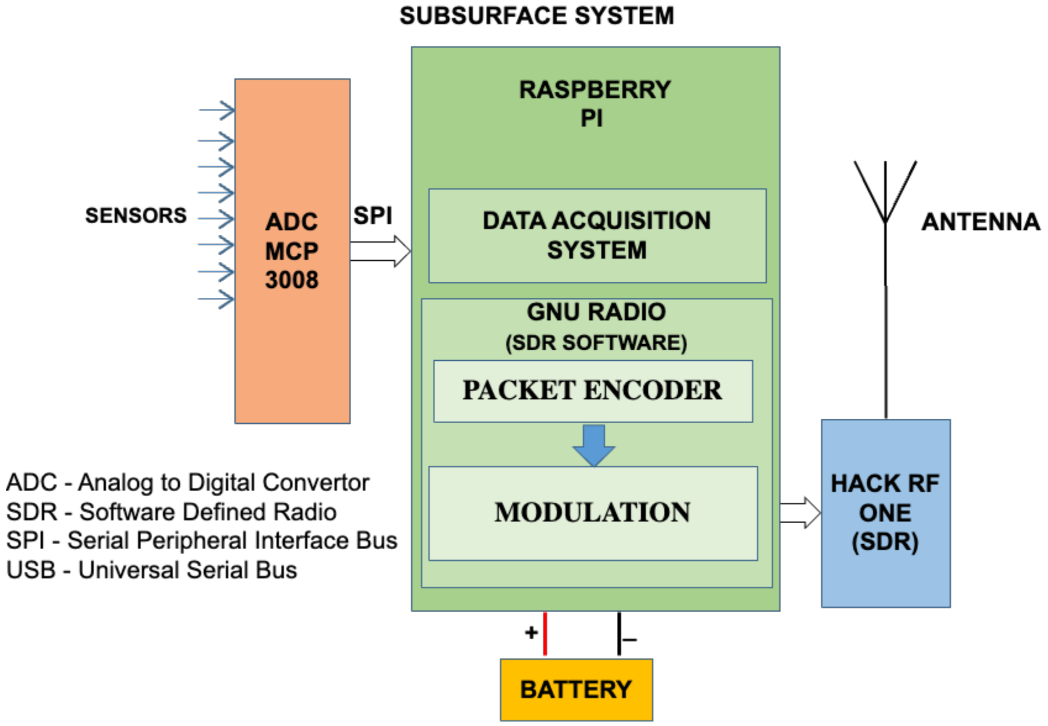

Figure 1. Subsurface system block diagram.

1) SENSORS: Analog sensors relevant to water leakage detection, including temperature, humidity, and soil moisture sensors, are utilized. Sensor outputs are typically voltage signals (0 V – 5 V).

2) Analog-to-Digital Converter (ADC): An MCP3008 10-bit ADC converts the analog sensor readings into a digital format [11]. It interfaces with the processing unit via the Serial Peripheral Interface (SPI) protocol.

3) Processing Unit: A Raspberry Pi 3 Model B serves as the central processing unit. It runs a Python script to acquire data from the ADC, log timestamps, and store the data in a .csv file format.

4) SDR and Transmission: GNU Radio software, running on the Raspberry Pi, processes the .csv data. It encodes the data into packets and performs QPSK modulation. The modulated digital signal is sent via USB to a HackRF One SDR transceiver. The HackRF One converts the digital signal to RF and transmits it through an antenna.

5) Antenna: Due to size constraints, low-gain isotropic antennas are used for transmission.

6) Power: The entire subsurface unit is powered by a portable battery pack (e.g., 20,000 mAh). Power consumption is optimized by utilizing the low-power Raspberry Pi and selecting efficient modulation and antenna configurations.

3.2. Surface Subsystem

The surface unit is positioned above ground, ideally directly above the buried unit. Its block diagram is shown in Figure 2.

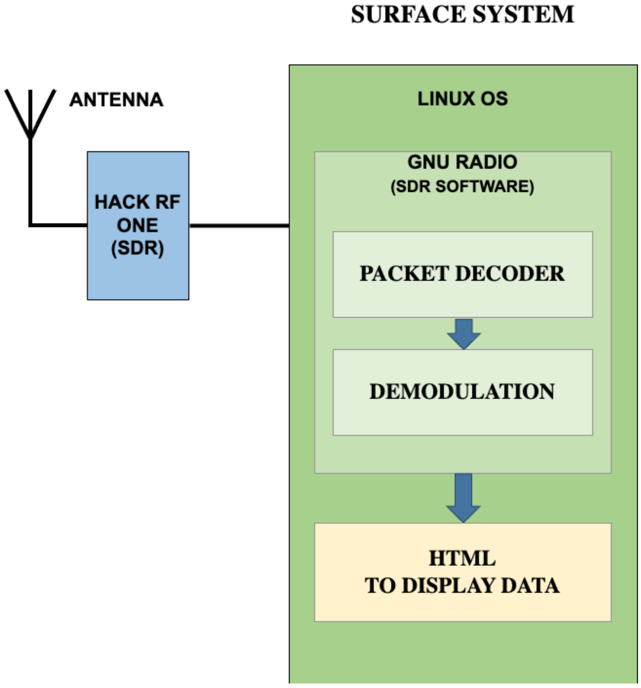

Figure 2. Surface subsystem block diagram.

1) Antenna: A high-gain directional antenna (Yagi-Uda or Parabolic) is used to capture the potentially weak signal transmitted through the soil.

2) SDR Receiver: The received RF signal is fed into another HackRF One SDR, which down-converts and digitizes the signal.

3) Processing and Display: The digitized signal is sent via USB to a computer running GNU Radio. GNU Radio demodulates the QPSK signal [12], decodes the packets, and reconstructs the original sensor data into a .csv file. A simple Python-based local web server can then display the received sensor data on an HTML page for real-time monitoring.

3.3. Software Defined Radio (SDR) Implementation

GNU Radio, an open-source software toolkit, provides the signal processing framework. It utilizes pre-built or custom processing blocks (coded in C++) that are linked together using Python flowgraphs. For transmission, the flowgraph includes blocks for reading the .csv file, packet encoding, QPSK modulation, and interfacing with the HackRF One (using an OSMOCOM sink). For reception, the flowgraph uses an OSMOCOM source to get data from the HackRF One, followed by QPSK demodulation, packet decoding, and writing to a file sink. The HackRF One serves as a flexible RF front-end, handling both RF transmission and reception, as well as analog-to-digital and digital-to-analog conversion.

4. Experimental Setup and Design

To evaluate the proposed WUSN system, an experimental testbed was constructed as shown in Figure 3.

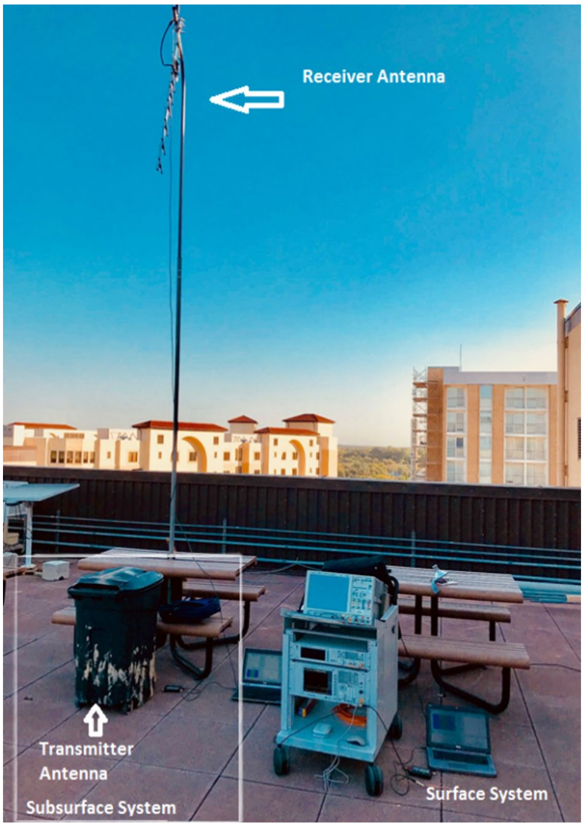

Figure 3. Experimental setup of proposed system.

4.1. Environment Setup

The subsurface subsystem was placed inside a container filled with a mixture simulating typical underground conditions: 50% soil, 30% sand, 10% clay, 5% stones, and 5% garden soil, as shown in Figure 4. For testing variable depths, the container holding the transmitter setup was buried at depths of 0.5m, 1.0m, and 1.5m below the surface.

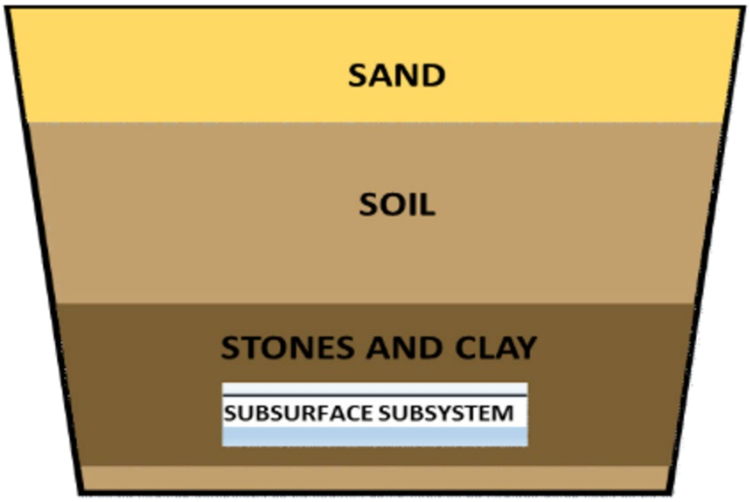

Figure 4. Soil, Clay, and sand arrangement in container.

4.2. Hardware Configuration

1) Subsurface: Raspberry Pi 3, MCP3008 ADC, Temperature/Humidity/Moisture Sensors, HackRF One, Battery Pack.

2) Surface: Laptop/Computer, HackRF One, High-Gain Antenna.

4.3. Antenna Selection and Specifications

Based on frequency and role, different antennas were used, balancing performance and size constraints.

1) 450 MHz:

Transmitter (Subsurface): Dipole antenna (2.15 dBi gain, 20.5 cm length).

Receiver (Surface): Yagi-Uda directional antenna (11.2 dB gain, eight elements, 120 cm length).

2) 900 MHz:

Transmitter (Subsurface): Ceiling-mount omnidirectional antenna (2.5 dBi gain, approx. 17 cm diameter).

Receiver (Surface): Grid parabolic directional antenna (15 dB gain, 60 cm × 90 cm size).

Key specifications are summarized in Table 1. Directional antennas were used at the surface receiver to maximize signal capture from the known transmitter location below. Low-gain, smaller antennas were used for the buried transmitter.

Table 1. Antenna parameters.

Parameters	Underground Antenna	Surface Antenna
Antenna Type	Isotropic Dipole	Directional Yagi-Parabolic
Gain	2.15/2.5 dBi	11.2/15 dB
Antenna Length	150 mm	~1000 mm
Frequency	400 MHz - 1 GHz	
Receiver Sensitivity	−93 dB	

4.4. Communication Parameters

Frequencies: 450 MHz and 900 MHz.

Modulation: Primarily QPSK, with BPSK and 8-PSK tested for comparison. QPSK was chosen for its balance of robustness and spectral efficiency [13].

SDR Settings: GNU Radio and HackRF One were used. The sample rate was set to 2 Msps. Bandwidth was fixed at 800 kHz for transmission tests. Receiver gains (RF, IF, BB) were adjusted for optimal reception. The transmitter RF gain was kept low (0 dBi - 2.15 dBi) to simulate power constraints.

Data Protocol: Sensor data was formatted into .csv files, then packetized, modulated, transmitted, received, demodulated, and decoded back into .csv files.

4.5. Performance Metrics

The system's performance was evaluated based on:

1) Signal characteristics: FFT plots, constellation diagrams, waterfall diagrams.

2) Signal-to-Noise Ratio (SNR): Measured using GNU Radio probes.

3) Data Rate: Calculated by transmitting a known file for a fixed duration (10 seconds) and measuring the amount of data successfully received.

Experiments were conducted with varying burial depths (0.5 m, 1 m, 1.5 m), operating frequencies (450 MHz, 900 MHz), and modulation schemes (BPSK, QPSK, 8-PSK). Each test was repeated multiple times, and average values were reported.

5. Results and Discussion

The experimental setup successfully demonstrated communication between the buried subsurface module and the surface module. Sensor data was acquired, transmitted wirelessly through the simulated soil medium, and received and displayed at the surface.

5.1. Signal Analysis

1) Spectrum: FFT plots confirmed transmission centered around the target frequencies (450 MHz/900 MHz) with the expected bandwidth (8pprox.. 800 kHz). The received signal power was significantly lower than the transmitted power (e.g., −45 dB received vs. −25 dB transmitted at 450 MHz), indicating substantial path loss through the medium. Waterfall diagrams visually confirmed the presence of the signal and its bandwidth over time at both the transmitter and receiver ends, as shown in Figure 5 and Figure 6 [14].

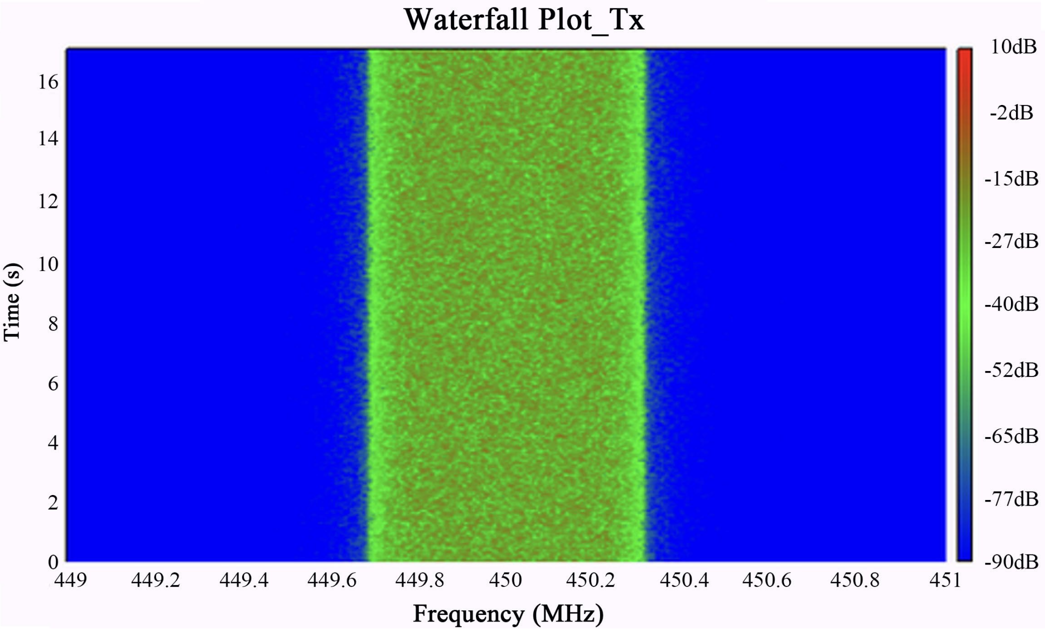

Figure 5. Waterfall diagram of the transmitted signal at 450 MHz.

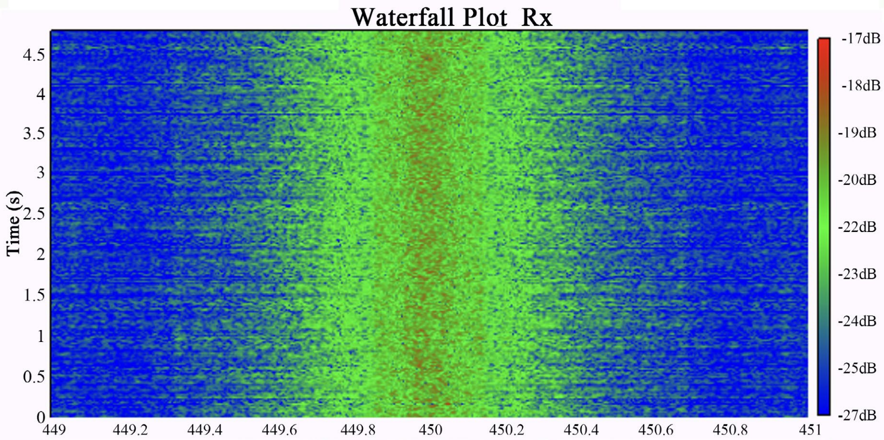

Figure 6. Waterfall diagram of the received signal at 450 MHz.

2) Constellation: Constellation plots were used to assess the quality of the QPSK modulation. At the transmitter, clear constellation points were observed, as shown in Figure 7. The received constellation showed more dispersion due to channel noise and distortion, but remained distinct enough for successful demodulation at the depths tested, as shown in Figure 8.

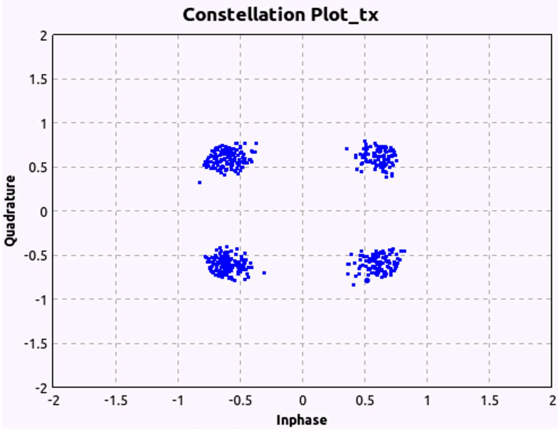

Figure 7. Constellation plot of the transmitted signal at 900 MHz.

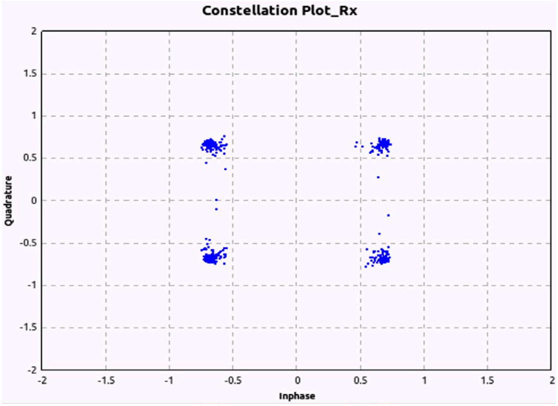

Figure 8. Constellation plot of the received signal at 900 MHz.

3) Time Domain: Signal scope plots of the modulated waveform at the transmitter and the attenuated/noisy version at the receiver are shown in Figure 9 and Figure 10.

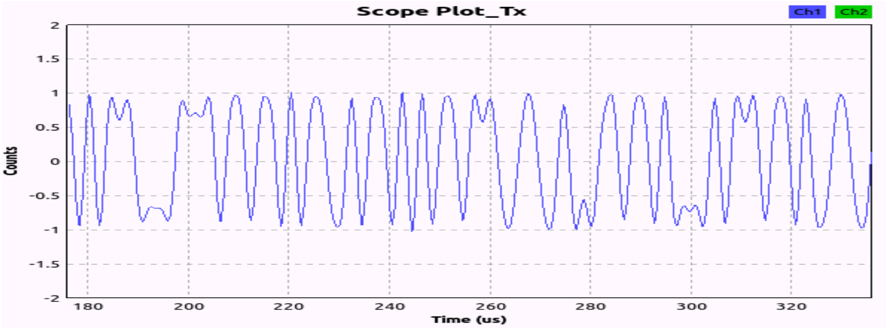

Figure 9. Signal scope of the transmitted signal a 900 MHz.

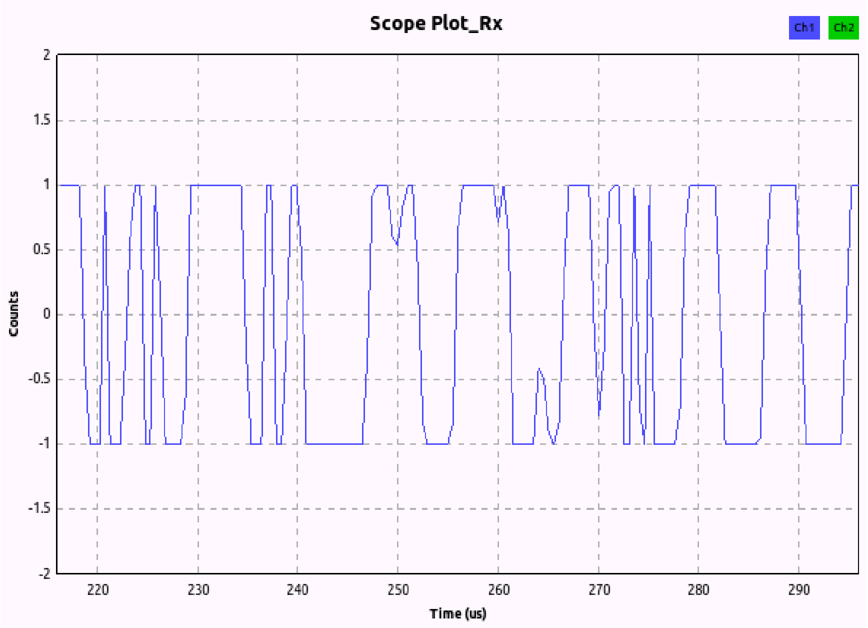

Figure 10. Signal scope of the received signal at 900 MHz.

5.2. Data Transmission Performance

Table 2 summarizes the key performance results for different configurations.

1) Effect of Depth: As expected, increasing the burial depth consistently decreased the average SNR and, consequently, the achievable data rate for all configurations. This aligns with channel models showing increased path loss with distance.

2) Effect of Frequency: Comparing 450 MHz and 900 MHz at the same depth and modulation (QPSK, 1.5 m depth), 900 MHz surprisingly yielded a higher data rate (1.953 Mbps) than 450 MHz (1.253 Mbps) despite similar SNR values (around 24.2 dB). While higher frequencies generally experience more path loss, the specific antenna gains (15 dBi parabolic at 900 MHz vs 11.2 dBi Yagi at 450 MHz for the receiver) and potentially different multipath/channel characteristics at these frequencies in the test environment might explain this outcome. At shallower depths (0.5 m), 900 MHz also provided higher data rates.

3) Effect of Modulation: Increasing modulation complexity (BPSK → QPSK → 8-PSK) generally increased the raw data rate, as more bits are encoded per symbol. For instance, at 900 MHz and a depth of 1.5 m, data rates were 1.245 Mbps (BPSK), 1.953 Mbps (QPSK), and 2.895 Mbps (8-PSK). However, higher-order modulations, such as 8-PSK, are typically more susceptible to noise (lower SNR tolerance), potentially leading to higher bit error rates, although error rates were not explicitly measured in this case. QPSK offered a good compromise, providing double the data rate of BPSK with reasonable robustness, as indicated by the stable SNR values of around 24 dB - 28 dB across depths.

Table 2. Data transmission analysis.

Modulation Scheme	TX gain (dB)	RX gain (dB)	Center Frequency (MHz)	Bandwidth (MHz)	Depth Distance TX to Rx	Average SNR	Average Tx Time	Average Data Received in 10 Seconds (Mbits)	Average Data Rate of transmission (Mbps)
BPSK	0	30	450	0.8	1.5	24.534	10	6.45	0.645
QPSK	0	30	450	0.8	1.5	24.265	10	12.53	1.253
8 PSK	0	30	450	0.8	1.5	24.452	10	21.95	2.195
BPSK	0	30	900	0.8	1.5	24.534	10	12.45	1.245
QPSK	0	30	900	0.8	1.5	24.265	10	19.53	1.953
8 PSK	0	30	900	0.8	1.5	24.452	10	28.95	2.895
BPSK	0	30	450	0.8	1	26.776	10	6.59	0.659
QPSK	0	30	450	0.8	1	26.522	10	11.96	1.196
8 PSK	0	30	450	0.8	1	26.254	10	19.94	1.994
BPSK	0	30	900	0.8	1	26.244	10	13.35	1.335
QPSK	0	30	900	0.8	1	26.244	10	19.86	1.986
8 PSK	0	30	900	0.8	1	26.344	10	29.56	2.956
BPSK	0	30	450	0.8	0.5	27.853	10	9.33	0.933
QPSK	0	30	450	0.8	0.5	27.742	10	10.96	1.096
8 PSK	0	30	450	0.8	0.5	27.722	10	29.96	2.996
BPSK	0	30	900	0.8	0.5	27.692	10	13.86	1.386
QPSK	0	30	900	0.8	0.5	28.124	10	25.01	2.501
8 PSK	0	30	900	0.8	0.5	27.985	10	31.45	3.145

5.3. System Functionality

The system successfully logged sensor data, transmitted it using the SDR pipeline, received and demodulated the signal, and displayed the results. The end-to-end data flow demonstrated the feasibility of the WUSN DAQ system for the target application. The achieved data rates (e.g., greater than 1 Mbps with QPSK) are sufficient for transmitting typical sensor readings in pipeline monitoring.

6. Conclusion and Future Work Results

This paper presented the design, implementation, and evaluation of an SDR-based WUSN data acquisition system for underground pipeline monitoring. The system utilizes a Raspberry Pi, HackRF One, and GNU Radio software to implement flexible communication, with a focus on QPSK modulation in the 450 MHz and 900 MHz bands.

Experimental results demonstrate the successful transmission of wireless data from a buried sensor node to a surface station through a simulated soil environment at depths of up to 1.5 meters. The trade-offs involving burial depth, operating frequency, modulation scheme, SNR, and data rate were analyzed. Increasing depth reduced SNR and data rates, as expected. QPSK modulation provided a robust and efficient method for data transmission compared to BPSK and potentially more error-prone 8-PSK. In this setup, 900 MHz operation with appropriate high-gain directional antennas at the receiver yielded higher data rates than 450 MHz, suggesting that with careful antenna selection, the challenges of higher frequencies can be mitigated for moderate depths. The system successfully proves the concept of using WUSNs with SDR for real-time underground monitoring.

Future work could focus on several areas:

1) **Power Optimization:** Replace the general-purpose HackRF One and Raspberry Pi in the buried node with a custom, low-power hardware radio and microcontroller design based on the findings (e.g., optimized for QPSK at 900 MHz). This would significantly extend battery life.

2) **Energy Harvesting:** Investigate the integration of energy harvesting techniques (e.g., utilizing thermal gradients, vibrations, or flow transducers) to power the subsurface node, potentially enabling perpetual operation.

3) **Alternative Propagation:** Explore alternative communication methods, such as Magnetic Induction (MI), which may offer different trade-offs, particularly for penetrating challenging media or achieving higher frequencies and bandwidths.

4) **Extended Depth Testing:** Conduct further experiments at greater burial depths (beyond 1.5 m) to determine the practical limits of the 450/900 MHz frequencies with optimized hardware.

5) **Network Aspects:** Extend the work from a point-to-point link to a multi-node network, investigating routing protocols suitable for WUSN energy and channel constraints.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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