ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

A Remote Microwave Environmental Monitoring System: Automation and Power Management

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Team #2

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1 Introduction

1.1 Objective and Background

1.1.1 Goals

Monitoring environmental microwaves is crucial for detecting electromagnetic interference, assessing potential health impacts, and understanding background radiation levels in various environments [1], [2]. Current methods involve manual deployment of monitors at different locations, which is time-consuming, labor-intensive, and resource-demanding [3]. Our project aims to solve this problem by developing an automated remote microwave environmental monitoring system that efficiently collects comprehensive data while minimizing human intervention and power consumption.

1.1.2 Functions

The remote microwave environmental monitoring system will automatically collect environmental microwave data through strategically deployed vector network analyzers (VNAs) [4] connected to the internet. The system will intelligently transition between active monitoring and low-power states based on environmental triggers, control a rotating platform for 360-degree multi-angle data collection, and efficiently manage power to all components including the VNA, pan-tilt mechanism, lifting vehicle, and cameras.

1.1.3 Benefits

Our system will benefit researchers, environmental agencies, and telecommunications companies by providing consistent, accurate, and comprehensive microwave data collection without requiring constant manual oversight. It will reduce operational costs and human resources needed for environmental monitoring while ensuring continuous data collection over extended periods. The system's power management capabilities will allow for deployment in remote locations with limited power access, expanding the potential monitoring coverage.

1.1.4 Features

Unlike existing environmental monitoring systems that require manual setup and regular maintenance, our solution offers unique automated features including smart wake-up mechanisms based on environmental triggers, energy-efficient standby modes, and an automated rotating platform for comprehensive 360-degree data collection. The integrated power management system specifically designed for microwave monitoring equipment differentiates our solution from general-purpose environmental monitors that lack specialized power optimization for VNAs and related equipment.

1.2 High-Level Requirements List

- The system must successfully collect and transmit environmental microwave data with a minimum sampling rate of once per hour during active monitoring periods, maintaining measurement accuracy within ±2dB of a lab-calibrated reference VNA.
- The automatic monitoring system must transition between active monitoring and low-power standby modes based on programmable environmental triggers (such as time schedules, detected activity, or remote commands) with a maximum transition time of 30 seconds.
- The pan-tilt mechanism must provide automated 360-degree rotation capabilities with a minimum of 8 measurement positions (45° increments) and complete a full rotation cycle within 5 minutes to ensure comprehensive spatial data collection.
- The power management module must reduce overall system power consumption by at least 20% compared to continuous operation, while maintaining reliable power delivery to all components including the VNA, pan-tilt mechanism, lifting vehicle, and cameras.

2 Design and Requirements

2.1 Diagrams

2.1.1 Block Diagram

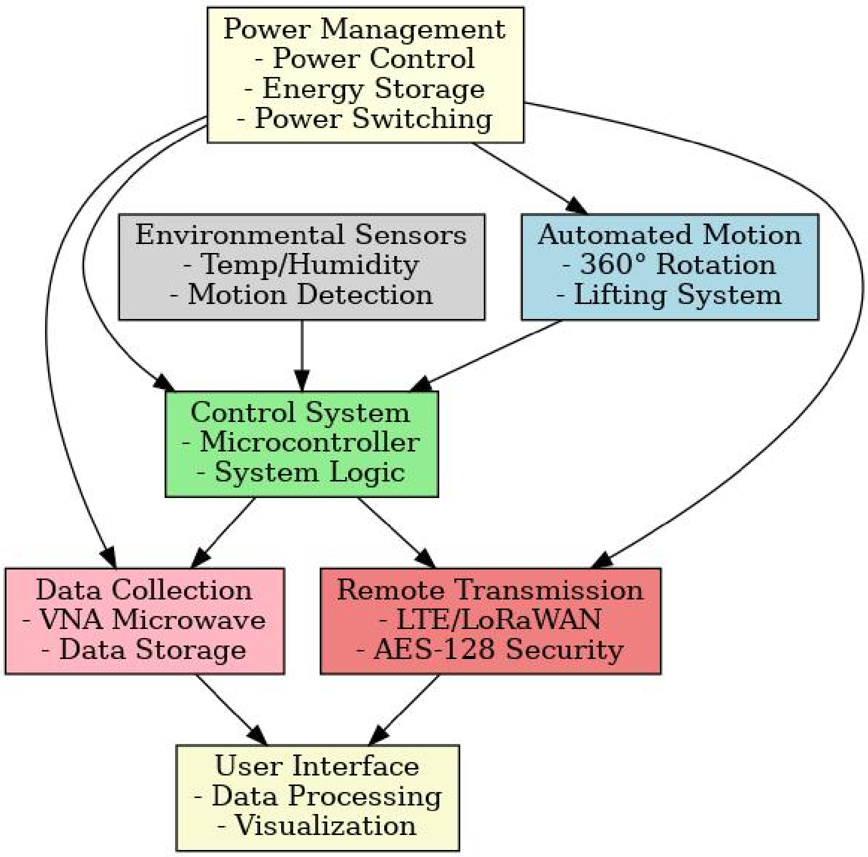

Figure 1: Block diagram of the Remote Microwave Environmental Monitoring System

This block diagram illustrates the core functional components of the remote microwave environment monitoring system, which well demonstrates the various functions of this design. The power management module ensures stable energy distribution while optimizing power consumption through intelligent low-power mode. The automatic motion system consists of a 360° rotating platform and a lifting mechanism, which can achieve comprehensive multi-angle data acquisition. Meanwhile, environmental sensors such as temperature, humidity, and motion detectors provide critical inputs to determine optimal monitoring conditions and trigger system activation.

At the center of the system, the control system we designed can process sensor inputs, manage system transitions, and coordinate the operations of all subsystems. Meanwhile, the data acquisition module utilizes a Vector Network Analyzer (VNA) to capture high-precision microwave data, which is then stored locally to ensure reliability. The remote transmission system securely transmits collected data through LTE/LoRaWAN [5], using

AES-128 encryption to ensure data integrity. Finally, the user interface provides real-time visualization and post analysis capabilities, enabling researchers and environmental agencies to remotely monitor and analyze data. The system is designed for remote autonomous operation, minimizing human intervention while maintaining continuous and accurate environmental monitoring.

2.2 Descriptions & Requirements of Physical & Block Diagrams

2.2.1 System Overview

Our remote microwave environmental monitoring system integrates four primary subsystems that work together to achieve autonomous operation and power efficiency. The Automated Monitoring System handles physical movement and positioning, the Power Management System optimizes energy usage, the Control System coordinates operations, and the Data Collection and Transmission System acquires and transmits microwave measurements. This design allows for comprehensive environmental monitoring without requiring constant human intervention while maintaining energy efficiency for extended deployment periods.

2.2.2 Automated Monitoring System

The Automated Monitoring System facilitates comprehensive microwave data collection through controlled physical movement of the monitoring equipment. The system incorporates a pan-tilt mechanism that provides 360-degree rotation with positioning accuracy of ±2 degrees, allowing for directional measurements across multiple angles. This mechanism must complete a full rotation within 5 minutes while maintaining stable positioning throughout the measurement process. Supporting this rotation system is a lifting vehicle designed to handle a minimum payload of 15 kg, accommodating the VNA and associated equipment while allowing for height adjustments to capture data at different elevations. Environmental sensors operating within a temperature range of -20°C to +50°C and humidity tolerance up to 95% non-condensing monitor ambient conditions, while motion detection sensors with a 10-meter range provide inputs for system activation when relevant activity is detected in the monitoring area.

2.2.3 Power Management System

The Power Management System serves as the energy control center, significantly reducing power consumption during periods of inactivity while ensuring reliable operation during active monitoring. The system's power distribution module routes appropriately regulated power to different components with voltage variations maintained within ±5% during normal operation. This precise power control enables the system to reduce consumption by at least 20% when in standby mode compared to active monitoring, with transitions between power states completing within 30 seconds. The integrated energy storage provides a minimum of 1 hour backup operation at full monitoring capacity, allowing for uninterrupted data collection during temporary external power fluctuations.

The entire power management architecture includes comprehensive protection circuits for over-current, over-voltage, and thermal conditions, with automatic shutdown capabilities that prevent damage to sensitive components during adverse electrical or environmental conditions.

2.2.4 Control System

The Control System functions as the central intelligence of the monitoring platform, coordinating all operations and making decisions based on environmental conditions and programmed parameters. At its core, a microcontroller operating at a minimum clock speed of 80 MHz with at least 256 KB RAM processes inputs from environmental sensors and manages system transitions with a wake-up trigger latency of no more than 100 ms. The system supports at least 3 configurable wake-up conditions, including time-based schedules, environmental sensor triggers, and remote activation commands. All state transitions are logged with timestamps and triggering conditions, creating a comprehensive operational history that can be analyzed to optimize system performance. Watchdog functionality provides system resilience by automatically resetting operations if the main control loop becomes unresponsive for more than 2 minutes, ensuring the monitoring system remains operational even when unexpected software issues occur.

2.2.5 Data Collection and Transmission System

The Data Collection and Transmission System handles the core functionality of acquiring accurate microwave measurements and securely transmitting this data to remote servers for analysis. The Vector Network Analyzer interface supports sampling rates of at least once per minute during active monitoring while maintaining measurement accuracy within ±2dB of a lab-calibrated reference VNA. Collected data is stored locally in a minimum 16 GB storage capacity capable of retaining at least 7 days of continuous monitoring information, creating a buffer that prevents data loss during temporary communication outages. The wireless communication module employs long-range protocols such as LTE or LoRaWAN with a minimum range of 5 km in open terrain, enabling remote deployment while maintaining reliable connectivity. All data transmissions utilize 128-bit AES encryption with error checking and automatic retransmission capabilities, ensuring both the security and integrity of the environmental monitoring data throughout the transmission process.

2.2.6 Integration and System Interfaces

The effectiveness of our monitoring system depends on seamless communication between subsystems through well-defined interfaces. The Control System connects to the Automated Monitoring System through digital control signals using I2C and SPI protocols for motor positioning and sensor data acquisition. Power state management occurs through dedicated control lines between the Control System and Power Management System, with PWM capability enabling variable power control based on operational requirements. High-speed data transfer between the Control System and Data

Collection System utilizes USB 3.0 or equivalent interfaces with a minimum 5 Gbps bandwidth, supporting the substantial data throughput required for VNA measurements. The Power Management System provides regulated power to all subsystems through dedicated power lines with isolated grounds for sensitive measurement equipment, preventing cross-interference. All digital interfaces maintain a bit error rate below 10^{-9} under normal operating conditions, with inter-system communication protocols implementing error detection through minimum 16-bit CRC. System-wide synchronization maintains a maximum clock drift of less than 10 ppm between subsystems, and all external connectors meet IP65 or higher environmental protection standards to ensure reliability in varied deployment conditions. Signal integrity is preserved through proper shielding that provides at least 40 dB attenuation for frequencies between 1 GHz and 10 GHz, critical for accurate microwave measurements in the presence of potential electromagnetic interference.

2.3 Contribution to Overall Functionality

The integrated design of our remote microwave environmental monitoring system creates a solution greater than the sum of its parts. The Automated Monitoring System eliminates the need for manual repositioning by providing consistent multi-angle measurements through programmable movement patterns, significantly reducing the human intervention required for comprehensive spatial data collection. The Power Management System directly addresses deployment limitations by extending operational life through intelligent energy usage control, enabling installations in locations with restricted power availability that would otherwise be impractical for continuous monitoring. By handling autonomous decision-making about when and how to collect data, the Control System replaces human operators in routine monitoring scenarios while maintaining the ability to respond to environmental triggers and scheduled requirements. The Data Collection and Transmission System ensures that the primary purpose of environmental monitoring is fulfilled with high-quality, secure data capture and transmission, providing researchers and stakeholders with reliable information for analysis without requiring on-site data retrieval. This integration of capabilities creates a fully autonomous solution that overcomes the limitations of conventional manual monitoring methods while maintaining data quality and comprehensive coverage.

3 Ethics and Safety

3.1 Ethics

Environmental microwave monitoring involves several important ethical considerations that our team has carefully evaluated throughout the design process. Our project adheres to professional standards while addressing specific ethical concerns related to data collection, privacy, environmental impact, and research integrity.

3.1.1 Privacy and Data Security

Our remote monitoring system collects microwave environmental data that is primarily focused on electromagnetic radiation patterns rather than personal information. However, we recognize that any remote sensing technology carries potential privacy implications. To address these concerns, we have implemented several safeguards:

First, our system employs 128-bit AES encryption for all data transmission, ensuring that collected environmental data remains secure from unauthorized access. This encryption standard provides robust protection while maintaining the integrity of scientific measurements. Additionally, we have designed our data collection protocols to specifically avoid capturing any personally identifiable information, focusing exclusively on electromagnetic radiation patterns relevant to environmental assessment.

The system also incorporates access controls that limit data retrieval to authorized personnel through multi-factor authentication. Our data management protocols include regular security assessments and updates to maintain protection against emerging vulnerabilities. These measures align with the IEEE Code of Ethics [6] principle of respecting the privacy of individuals while pursuing scientific knowledge that benefits society.

3.1.2 Environmental Stewardship

While our project aims to monitor environmental conditions, we are mindful of our own environmental impact. The physical deployment of our monitoring equipment involves placing electronic devices in natural settings, which presents ethical responsibilities regarding habitat disruption and resource consumption.

To minimize our environmental footprint, we have designed the system with several sustainable features. The power management system significantly reduces energy consumption, extending battery life and decreasing the frequency of maintenance visits that could disturb natural habitats. We have selected components with minimal hazardous materials and established end-of-life recycling protocols for all electronic components.

For deployments in sensitive ecosystems, we follow environmental assessment protocols to ensure our monitoring activities do not adversely affect local wildlife or plant life. The physical footprint of our equipment has been minimized through thoughtful design integration, and installation procedures have been developed to avoid permanent alterations to deployment locations.

3.1.3 Scientific Integrity and Transparency

Our commitment to ethical research practices extends to ensuring scientific integrity in how we collect, analyze, and present environmental microwave data. The system is designed to provide accurate, reliable measurements that can be independently validated, supporting the IEEE principle of making decisions "consistent with the safety, health, and welfare of the public." [6]

We will implement calibration procedures that ensure measurement accuracy within ±2dB of lab-calibrated reference equipment, and our data collection methodology includes comprehensive metadata that documents all measurement conditions and system parameters. This transparency enables other researchers to evaluate the validity of our findings and potentially reproduce our methods.

Furthermore, we commit to openly acknowledging the limitations of our technology, including potential measurement uncertainties and environmental factors that might influence data quality. This honest assessment helps prevent misinterpretation of monitoring results and supports responsible decision-making based on our collected data.

3.1.4 Compliance with Professional Ethics Guidelines

Beyond these specific considerations, our team is committed to upholding the broader principles outlined in the IEEE Code of Ethics [6] and ACM Code of Ethics [7]. These include:

- Maintaining and improving our technical competence through ongoing education about environmental monitoring technologies
- Seeking, accepting, and offering honest criticism of our technical work to identify and correct potential errors
- Treating all persons fairly regardless of factors such as race, religion, gender, disability, age, or national origin in our collaborative development process
- Avoiding real or perceived conflicts of interest in our research and development activities

These principles guide not only our technical design choices but also how we interact with stakeholders, colleagues, and the broader scientific community throughout the development and deployment of our environmental monitoring system.

3.2 Safety

The safety of users, maintenance personnel, and the general public is a paramount concern in our remote microwave environmental monitoring system design. We have conducted a thorough safety analysis to identify potential hazards and implemented appropriate mitigation strategies.

3.2.1 Electrical Safety

As an electronic monitoring system operating in potentially harsh environmental conditions, electrical safety is a primary concern. Our design incorporates multiple layers of protection:

The power distribution system includes overcurrent protection, ground fault detection, and automatic shutdown capabilities wehn detecting abnormal conditions. All electrical components are enclosed in weatherproof housings, preventing water ingress that could lead to short circuits or electrical failures. For maintenance operations, clearly marked disconnect switches allow safe power isolation, and all high-voltage components include warning labels and physical barriers to prevent accidental contact.

These protections ensure that both routine maintenance and unexpected environmental events (such as flooding or lightning) do not create electrical hazards for personnel or wildlife in the vicinity of the monitoring equipment.

3.2.2 Mechanical Safety

The physical components of our system, particularly the pan-tilt mechanism and lifting vehicle, present potential mechanical hazards that we have addressed through careful design:

All moving parts incorporate torque-limiting features that prevent the mechanism from applying harmful force if obstructed. Motion detection sensors create safety zones around the equipment, automatically pausing movement when human presence is detected. The rotation and elevation mechanisms include mechanical stops that prevent over-travel, and emergency stop capabilities can be activated both locally and remotely.

3.2.3 Safety Testing and Compliance

Our testing protocol includes simulated fault conditions to verify that protection mechanisms function correctly under worst-case scenarios. Documentation includes detailed safety procedures for installation, maintenance, and decommissioning phases to ensure consistent safety practices throughout the system lifecycle.

Through these multifaceted safety considerations, we ensure that our environmental monitoring system achieves its scientific objectives while maintaining the highest standards for human and environmental safety. This approach aligns with the IEEE Code of Ethics commitment to ”hold paramount the safety, health, and welfare of the public” [6] in all our engineering decisions.

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