UNIVERSITY OF NOTRE DAME

NEXASENSEE

EE40190 Senior Design I

High-Level Design

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Introduction

Environmental monitoring is a cornerstone of ensuring safety, efficiency, and comfort across various sensitive and controlled settings, including hospitals, research laboratories, factories, greenhouses, and prison systems. These environments require accurate monitoring and control of critical conditions such as temperature, humidity, pressure, gas concentrations, light intensity, and sound levels. Traditional systems using copper-based wiring or radio wave transmission have long been reliable and effective solutions. However, as technology evolves, there is growing interest in exploring alternative methods that complement existing systems to address specific needs and challenges in highly sensitive environments. Free-space optical communications represent one such innovative approach, offering unique advantages such as immunity to electromagnetic interference. This proposal outlines the development of an environmental monitoring system utilizing this emerging technology to enhance monitoring capabilities in environments where minimizing interference and ensuring data security are of utmost importance.

Problem Statement and Proposed Solution

Problem Description

The motivation for the problem selected arose from the challenges associated with electromagnetic pollution in highly sensitive environments such as intensive care units (ICUs). In these settings, radio electromagnetic interference (EMI) can disrupt critical medical equipment, posing risks to patient safety and complicating the operation of monitoring systems [1]. While traditional systems have been optimized over decades, the increasing density of electronic devices and wireless communications exacerbates concerns about radio EMI in environments like hospitals, where precision and reliability are paramount. Addressing these challenges requires a complementary approach to existing solutions, focusing on areas where electromagnetic interference could have the most critical impact.

One notable issue is that current monitoring systems may inadvertently contribute to electromagnetic congestion, particularly in ICUs filled with life-support machines and other sensitive electronics. The proposed system seeks to investigate how free-space optical communications could serve as a supplementary technology to alleviate some of these concerns. By reducing reliance on electromagnetic waves in critical applications, this approach has the potential to improve the reliability and safety of monitoring systems in highly controlled environments without the need for extensive rewiring or replacing existing infrastructure. By focusing on the unique advantages of optical communication, this project aims to complement and enhance the capabilities of established monitoring systems rather than replace them, paving the way for innovative solutions to address the growing challenges of radio electromagnetic interference in sensitive environments.

Proposed Solution

To address the challenges of radio wave electromagnetic interference and the limitations of traditional methods for communicating between monitoring devices in sensitive environments, we propose an environmental monitoring system using free-space optical communications. The system will be designed to measure and report critical environmental parameters, including temperature, humidity, pressure, gas concentrations, light intensity, and sound levels while ensuring reliability, precision, and immunity to radio electromagnetic interference. The system will consist of several key functional components, each leveraging advanced optical technologies to meet the project objectives. Our project will focus on developing a prototype system to demonstrate the feasibility of using free-space optics to achieve wireless connectivity between sensors for environmental monitoring in hospitals. The primary objective, beyond accurately measuring environmental parameters such as temperature, humidity, pressure, gas concentrations, light intensity, and sound levels, is to control and gather data from these sensors without relying on electromagnetic waves. By leveraging optical technologies, the system will ensure immunity to electromagnetic interference, addressing critical concerns in sensitive environments like hospitals. While the prototype will not be implemented in a clinical setting, it will validate the potential for this technology to deliver safe, precise, and reliable monitoring in real-world applications.

Solution Components

Sensing and Transmission Subsystem: At the core of the system is a custom-designed PCB that integrates components to handle sensing, signal generation, and optical data transmission. The optical transmitter will use high-efficiency LEDs to modulate and transmit environmental data as optical signals. Collimating optics such as lenses or parabolic mirrors may be included to ensure precise signal direction and minimize losses. The PCB will support battery power. Indicators such as power and status LEDs will provide feedback, while basic memory systems will log and timestamp sensor data for troubleshooting and reliability.

Receiving Hub: The receiving hub will decode the optical signals transmitted by the sensors and interface with the data console. A photodetector will capture the modulated optical signals, and an I2C protocol will efficiently transfer decoded data to the console.

Data Console and User Interface: A personal computer will serve as the central data console, providing a platform for signal processing and visualization. USB-C connections will enable ease of integration and scalability. The software will demodulate the optical signals into meaningful environmental data using techniques such as Fourier transforms or digital filtering. A user-friendly graphical interface will display sensor data in real-time, allowing users to monitor environmental conditions and analyze trends.

Software and Signal Processing: Advanced error-detection algorithms will ensure reliable data transmission. Real-time readouts will be provided through an intuitive graphical user interface (GUI), with features to visualize environmental parameters and alert users to anomalies.

System Requirements

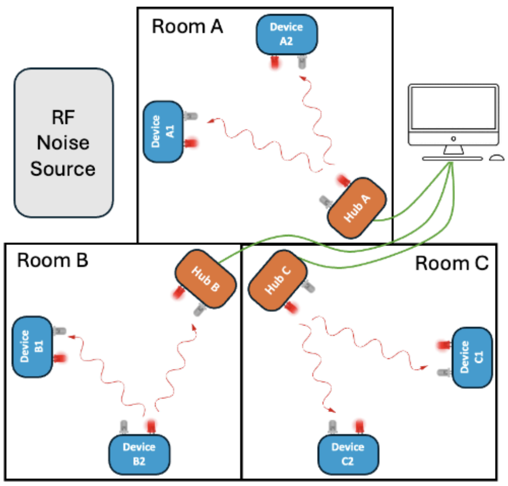

Figure 1. Example of Physical System Setup

Overall System

Our primary system requirements are 1) accurately capturing metrics about the room environment, 2) optically transmitting these metrics to a receiver on the alternate side of the room, 3) viewing and recording environmental metrics on a central console equipped with a GUI, and 4) manipulating monitoring parameters (e.g., which metrics to monitor and duration) via the central console.

Installation and Power

- The system must be easy to install with minimal setup requirements. Modular components will be necessary. No rewiring of the room or wiring of a device should be necessary; so the transmitting sensor devices must be battery-powered.
- The transmitting sensor devices and receiving hubs will have a removable adhesive backing, so that the devices can be easily attached to and removed from the wall.
- The transmitting sensor devices will be powered by a Lithium-Ion battery, ensuring a runtime of at least 2 weeks under typical operation. The receiver module will be powered via a USB connection to the central console.
- A battery status indicator will be available on the central console to alert users when charging is required.
- The battery must support recharging via USB-C, with an estimated charging time under 5 hours.
- To extend the life of the transmitting sensor devices battery on a single charge, low-power considerations such as metric transmission only when a significant change noted will be implemented.

  - Based on the standards of our applied settings, such as factories, ICUs, and labs, a significant change is defined [2]. This threshold would be easily manipulatable on the backend should a different significant value be required.

Mechanical

- As the transmitter and receiver will be affixed on walls towards the ceiling of a room for clear optical transmission, the weight of each module should not exceed 1.5 lb.
- The transmitter and receiver module should fit within their respective enclosures, not exceeding 4 x 4 x 3 inches in size for portability.

Sensing

The system will utilize integrated sensors to measure:

- Temperature, humidity, air quality, and air pressure.
- Light intensity.
- Sound levels.

The default sampling rate will be set to once every 5 seconds. The default transmission rate will be set by the predefined significant change thresholds.

Optical Transmission

- The system must support a minimum transmission range of 15 feet, the standard width for ICU individual patient modules.
- Each transmitter module will support up to 4 sensors, with the receiver to decode data from a single transmitter at a time.
- At least two transmitting sensor devices will need to be supported in one room. This will be to mitigate any blockage in line of sight for optical transmission.

User Interfaces

- The GUI on the central console will display current environmental metrics in real-time (e.g., the metric measured at the last significant change) and alerts for battery status. There will also be alerts on this central console for values that reach a concerningly low/high value.
- Users will be able to select which environmental factors they would like to monitor and save data points to a .xlsx or .csv file based on a pre-set recording time.

Safety

- The optical power of the transmitter must be limited to prevent damage to people’s eyes.
- Battery protection circuits must exist within the design to prevent overcharging, over-discharging, and other potential battery-related issues.

System Block Diagram

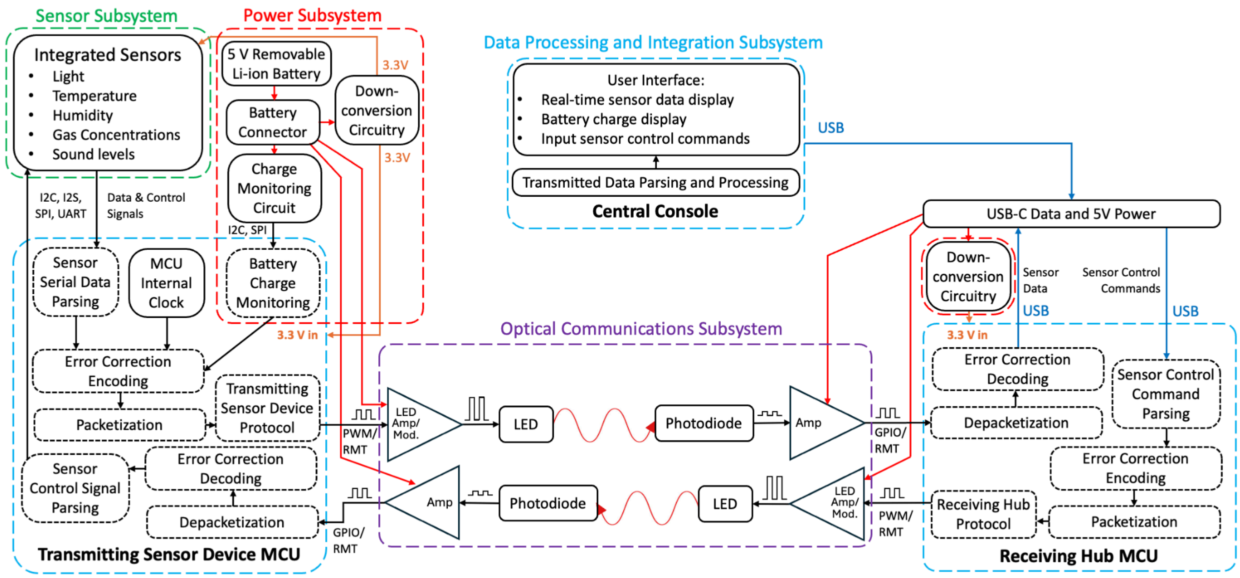

Figure 2. Full System Block Diagram

Overall System:

The following section specifies lower-level requirements for the different major subsystems of this project and provides a block diagram to visually represent the overall system architecture and the interfaces between subsystems. This project's major subsystems are:

1. Sensor subsystem
2. Optical communication subsystem
3. Power subsystem
4. Data Processing and Integration Subsystem

Sensor Subsystem Description and Interface Requirements

The sensor subsystem is responsible for collecting real-time environmental monitoring data, specifically light, temperature, humidity, gas, and sound levels. Data collected from individual sensors will be processed to extract desired parameters and time-stamped before transmission, to be performed by a central microcontroller. Central microcontroller software will manage to collect data from multiple sensors simultaneously.

To satisfy data sampling rate requirements (continuous sampling or interrupt-based sampling), standard serial communication interfaces including SPI, I2C, and I2S have transmission speeds of at least 100 kbits/s and are therefore satisfactory for this subsystem.

Optical Communication Subsystem Description and Interface Requirements

The optical communication subsystem will be responsible for reliable optical transmission and reception of data and control signals between the transmitting sensor devices and the receiving hub devices.

High-speed electrical signals to modulate the LED intensity can be outputted by I/O microcontrollers using pulse width modulation pins (PWM). Lower-level peripherals, such as ESP32's remote control transceiver (RMT) peripheral will output and read out faster signals if needed. To ensure the received photodiode signal can be distinguished from noise, electrical amplification of the output microcontroller logic signals and received photodiode signals will be implemented. The amplified photodiode signals can be read out by high-speed digital GPIO pins. Power to electrical amplification circuitry is provided by the power subsystem.

To ensure reliable optical transmission, the central microcontrollers from the data processing and integration subsystem will also be used to encode and decode error-correcting codes. If needed, multiple receiving hub devices will also be implemented to introduce redundancy.

Communication protocols are required to manage multiple devices transmitting and receiving on the same optical link: With all communications occurring on the same wavelength, each device will have an assigned address, to either be transmitted in a packet preamble or hard-coded for a specific time bin. Communication protocols will also be implemented on the central microcontrollers from the data processing and integration subsystem.

Power Subsystem Description and Interface Requirements

The power subsystem will provide stable power to all components. For the transmitting sensor devices, the internal power source will be a removable lithium-ion battery with downconversion circuitry for lower voltage devices. There must also be battery power monitoring circuitry controlled by the microcontrollers of the sensor subsystem. The receiving hub devices will be powered by its USB-C connection to the main console.

Data Processing and Integration Subsystem Description and Interface Requirements

The data processing and integration subsystem will be responsible for processing sensor data, implementing error-correcting codes, and managing communication protocols for the optical communication subsystem. This subsystem will also be responsible for gathering and storing data transmitted over the optical communication link and for providing a user interface for real-time display of environmental parameters and control of individual sensors. In each room, receiving hub devices receive environmental monitoring data from the sensor subsystem via the optical communications subsystem and transmit that data via a high-speed link (USB) to a central console. The receiving hub device also transmits control signals received from the central console to the sensor subsystem. The central console processes the transmitted data and provides the user interface.

Future Enhancement Requirements

To further improve the system's performance and expand its capabilities, the following enhancements are proposed:

1. **Increasing Ease of Installation - IP Tunneling**: implementing IP turning through a building internet network will eliminate the need for long ethernet cables between the receiving hub devices and the central console.

2. **Real-Time Camera Integration:**Real-time video is another common feature of monitoring systems. However, the transmission of video data requires a high-speed and reliable communication link.
3. **High-Speed Performance:**Enhancement of link speed via advanced signal processing (adaptive error correcting codes) and data modulation techniques (QPSK, PAM, QAM) could accommodate the transmission rate required for higher data sampling rates and real-time video.

High-Level Design Decisions

The following section outlines the high-level design decisions for the system, broken down into its major subsystems and interfaces. Each subsystem is described in terms of its function, the components used, and the rationale behind their selection, ensuring the design aligns with the system requirements.

Sensor Subsystem

The sensor subsystem is responsible for monitoring environmental conditions (light, temperature, humidity, gas, and sound levels). This data is critical for the system's overall objective of environmental monitoring. Major components include:

- **SPH0645LM4H-B MEMS Microphone:** Chosen for its small form factor, digital I2S interface, and ability to capture sound levels effectively.
- **BH1750 Light Sensor:** Selected for its precision in measuring illuminance in lux and its simple I2C interface, which reduces wiring complexity.
- **BME680 Environmental Sensor:** Provides temperature, humidity, pressure, and gas (VOCs) readings in a single package, optimizing space and minimizing power consumption.

Design considerations include:

- **Communication:** Sensors are interfaced via I2C (BH1750 and BME680) and I2S (SPH0645LM4H-B) to the microcontroller.
- **Power:** All sensors operate at 3.3V, supplied by the ESP32 through the USB power source. Decoupling capacitors (0.1 µF) are placed close to each sensor for power stability.
- **Accuracy:** The sensors meet the required accuracy and precision levels for the system's use case.

Optical Communication Subsystem

This subsystem is responsible for transmitting sensor data optically using modulated infrared signals. Major components include:

- **TSAL6200 Infrared LED:** Transmits modulated signals representing the sensor data.
- **BPW34 Photodiode:** Receives and converts the transmitted optical signals back to electrical signals at the receiver.
- **Resistors and Op-Amp:** Ensure proper current limiting for the LED and signal amplification for the photodiode.

Design considerations include:

- **Alignment:** Proper placement of the IR LED and photodiode ensures reliable communication over the intended distance.

- **Modulation:** The ESP32 generates the modulation signal required to encode the sensor data for optical transmission.
- **Power:** The LED is driven directly by a GPIO pin with a series resistor for current limiting.

Power Subsystem

Provides stable power to all components, ensuring proper operation without the need for complex power regulation circuitry. Major components include:

- **USB Power Source:** The receiver module is powered via a USB connection to the central console, providing a stable 5V supply.
- **Lithium-Ion Battery (Transmitting Sensor Devices):** Supplies power to the transmitting sensor devices, ensuring a runtime of at least 2 weeks under typical operation. A battery management circuit will be used for charging, protection, and monitoring of the Lithium-Ion battery.
- **Decoupling Capacitors:** Placed across the power lines to filter noise and ensure stable operation of sensitive components like the sensors and optical communication devices.
- **Schottky Diode:** Protects against reverse polarity or accidental shorts, particularly in the battery-powered transmitting sensor devices.

Design considerations include:

- The use of USB eliminates the need for additional power circuitry.
- Current requirements of the sensors and optical components are within the supply limits of the ESP32's 3.3V rail.

Data Processing and Integration Subsystem

Processes the collected sensor data, prepares it for optical transmission, and enables communication with external devices. Major components include:

- **ESP32 Development Board:** Handles all data acquisition, processing, and communication.

Design considerations include:

- Data aggregation is performed on the ESP32 to ensure efficient use of bandwidth during optical transmission.
- Supports expansion for future updates, such as additional sensors or alternative communication methods.

Overall System Considerations

- **Clocking:** Clock signals for the I2S microphone and other timed devices are generated internally by the ESP32.

- **Interface Consistency:** All sensors and communication components are chosen to work seamlessly with the ESP32, reducing development complexity.
- **Scalability:** The system design allows for the addition of new sensors or modules without significant hardware changes.

Known Unknowns/Open Questions

- Is it $50 per physical individual board or a pack of 5 of the same board?
- Choosing USB-C or Ethernet to connect the central console to the receiving hub device
- Defining the threshold for significant changes in environment metrics.
- Optimizing the communication of two transmitter modules with the receiving hub device
    - Minimum data rates for the optical communication link has yet to be determined. The chosen data rate must balance power consumption and data accuracy.
    - Will more advanced modulation schemes be needed to increase the data rate or link reliability?
- Difficulty of performing optical alignment of the transmitter LEDs to the receiver
- Can the prototype demonstrate the full functionality of the system in a controlled environment?
- How well will the sensing, communication, and power subsystems work together?
- Will the chosen battery meet the runtime requirements under all operating conditions?
- How will changes in temperature or humidity affect sensor accuracy? Will a fan be needed in the enclosure design?
- How susceptible is the optical transmission to ambient light interference, and what mitigation techniques (e.g., filters) are necessary?
- How precise does the alignment have to be for consistent communication?
- Which variant of the ESP32 should be used for this project?
    - ESP32-C3 - has single-core, ideal for low power consumption
    - ESP32-S3 - has Vector Processing Unit for heavy AI and DSP applications

Major Component Costs

Table 1 below outlines the key components of the environmental monitoring system, including sensors, peripherals, and additional hardware, with associated costs for procurement. The total cost of $226.59 reflects the full estimated budget for building the system and presenting functionality as specified.

This Bill of Materials ensures the integration of sensing, data processing, and optical transmission, enabling the system to meet its environmental monitoring and communication goals efficiently. Further adjustments may be necessary depending on changes in design or component availability.

Table 1. Major Component Cost Breakdown

Component	Part	Quantity	Unit Cost	Total Cost
Microcontroller	ESP32-S3 Development Board	1	$10.00	$10.00
SPH0645LM4H-B Microphone	SPH0645LM4H-B Microphone	1	$1.95	$1.95
	0.1 µF Ceramic Capacitor	1	$0.10	$0.10
BH1750 Light Sensor	BH1750FVI Sensor	1	$1.83	$1.83
	10 kΩ Resistor	2	$0.05	$0.10
	0.1 µF Ceramic Capacitor	1	$0.10	$0.10
BME680 Sensor	BME680 Environmental Sensor	1	$11.46	$11.46

	10 kΩ Resistor	2	$0.05	$0.10
	0.1 µF Ceramic Capacitor	1	$0.10	$0.10
Optical Communication	TSAL6200 Infrared LED	1	$1.00	$1.00
	BPW34 Photodiode	1	$1.00	$1.00
	Resistors (100 Ω, 330 Ω)	2	$0.05	$0.10
	Op-Amp (Signal Amplification)	2	$0.50	$1.00
Power Supply	USB Cable and Adapter	1 Set	$5.00	$5.00
	Schottky Diode (1N5819)	1	$0.10	$0.10
PCB Design	Custom PCB Design	2	***$50.00**	***$100.00**
Enclosure	3D-Printed Enclosure	1	Free	0
FedEx Printing	Poster Display	1	$50.00	$50.00
Miscellaneous Components	Wires, connectors, LEDs, etc.	1 Set	$10.00	$10.00

Battery Management	MCP73831 Li-Ion Charge Management Controller	1	$0.76	$0.76
Voltage Divider Resistors	100 kΩ and 10 kΩ Resistors	2	$0.05	$0.10
Schottky Diode	1N5819	1	$0.10	$0.10
Capacitors	10 µF Bulk Capacitor and 0.1 µF Ceramic Capacitor	2	$0.15	$0.30
Battery	Lithium-Ion Battery	1	$7	$7
	Total Cost			**$202.20**

Conclusion

The proposed environmental monitoring system using free-space optical communication provides a practical solution to the challenges of radio electromagnetic interference in sensitive environments. By combining advanced sensing technologies, optical transmission, and streamlined data processing, the system enables accurate and dependable monitoring of environmental parameters such as temperature, humidity, air quality, and sound levels.

This prototype demonstrates the potential of optical communication to enhance environmental monitoring without requiring modifications to existing infrastructure. Future enhancements, including real-time video capabilities and improved signal processing techniques, offer opportunities to build on this foundation and broaden the system's capabilities.

References

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[2] Guidelines for intensive care unit design. Critical Care Medicine 23(3):p 582-588, March 1995.