NEXASENSEE

EE40190 Senior Design II

Design Review 1

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System Block Diagram

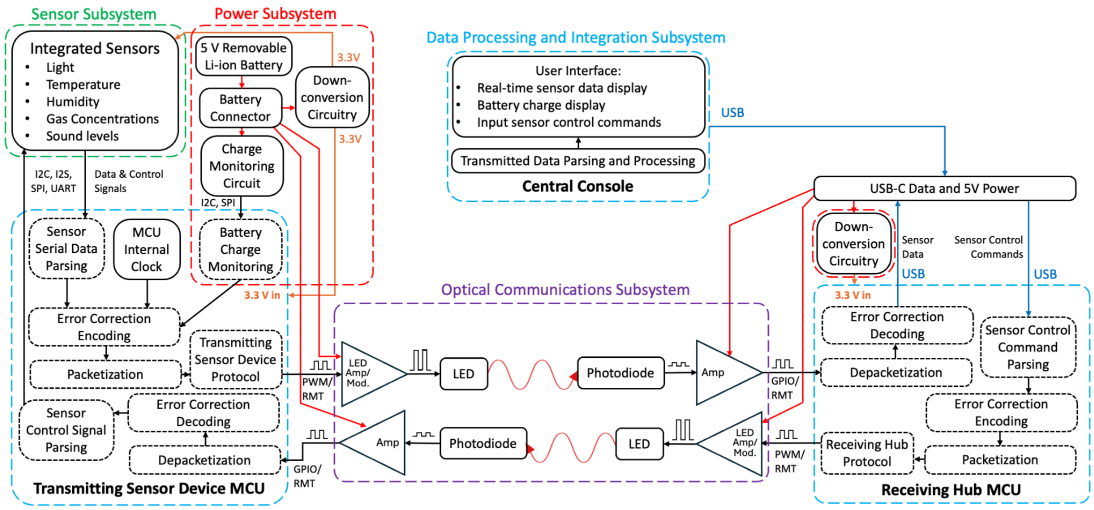

Figure 1. Full System Block Diagram

Sensor Subsystem

BME Sensor Schematic Description

1. Overview

The BME sensor circuit is designed to measure temperature, humidity, pressure, and gas concentrations while interfacing with a microcontroller via I2C communication. The design ensures power stability, proper signal integrity, and testability by incorporating essential passive components.

2. Components & Their Functions

a. BME680 Sensor (U1)

- **Function:** Measures environmental parameters (temperature, humidity, pressure).
- **Communication:** Supports I2C and SPI, but this schematic is designed for I2C mode.
- **Power:** Operates at 3.3V, sourced from the system's power rail.

b. Capacitors for Power Stability

- **C1 (0.1µF) & C2 (0.1µF)**
  - **Purpose:** Decoupling capacitors placed close to the VDDIO pin of the sensor.
  - **Function:**
    - Helps filter noise from the power supply.
    - Ensures smooth voltage delivery, preventing fluctuations that might affect sensor readings.

c. Pull-Up Resistors for I2C Communication

- **R1 (4.7kΩ) & R2 (4.7kΩ)**
  - **Purpose: Pull-up resistors for the I2C lines (SCL & SDA).**
  - **Function:**
    - Ensures that the SDA (data) and SCL (clock) lines remain at logical high when idle.
    - Enables proper I2C communication between the BME sensor and the microcontroller.
    - Value (4.7kΩ) is chosen to balance signal integrity and power consumption.

d. Connector for Testing (J1)

- **4-pin Connector (J1)**
  - **Purpose:** Allows for external testing and debugging.
  - **Pins Included:**
    - SCL_BME & SDA_BME → I2C data and clock lines for sensor communication.
    - 3.3V → Power supply input for the sensor.

■ GND → Ground reference.

○ **Function:**

■ Enables external connections for debugging.

■ Allows for easy integration with test equipment (logic analyzers, oscilloscopes).

3. Summary

This schematic provides a stable and reliable sensor interface by incorporating power filtering capacitors, pull-up resistors for I2C, and a dedicated test header for debugging. The design follows best practices for minimizing noise, ensuring signal integrity, and enabling efficient sensor operation.

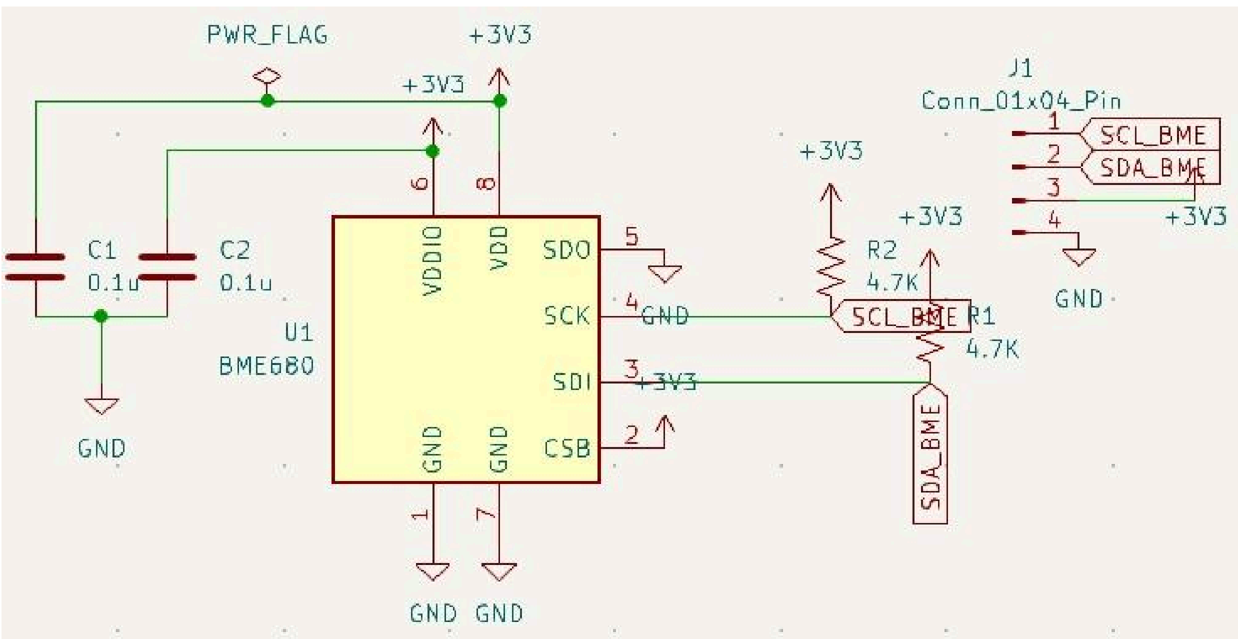

Figure 2. BME Sensor Schematic

BH1750 Light Sensor Schematic Description

1. Overview

This schematic integrates the BH1750 ambient light sensor, which measures light intensity and communicates via I2C. The design includes voltage level shifting to interface the 3.3V sensor with a 5V system, ensuring safe and stable operation. Passive components are used for signal integrity, noise filtering, and pull-ups.

2. Components & Their Functions

a. BH1750 Light Sensor (U3)

- **Function:** Measures ambient light intensity and outputs data over I2C (SCL & SDA).
- **Power:** Operates at 3.3V with a direct power connection to the +3.3V rail.
- **Address Pin (ADDR_BH):** Configurable via an external resistor (R6) to change the I2C address.

b. Capacitor for Power Stability

- **C4 (0.1µF)**
  - **Purpose:** Decoupling capacitor placed near the BH1750 power pin (VCC).
  - **Function:**
    - Filters out high-frequency noise from the power supply.
    - Ensures stable voltage regulation for the sensor.

c. Pull-Up Resistors for I2C Communication

- **R8 (4.7kΩ) & R9 (4.7kΩ)**
  - **Purpose:** Pull-up resistors for the SDA and SCL lines.
  - **Function:**
    - Keeps I2C lines high when idle.
    - Ensures proper logic level detection for stable communication.

d. Level Shifting Circuit (Q1, R7, R8, D1)

To safely interface the 3.3V I2C sensor with a 5V system, a bidirectional level shifter is included:

- **Q1 (2N7002 - N-channel MOSFET)**
  - **Purpose:** Acts as a bidirectional level shifter for the SDA line.
  - **Function:**
    - The MOSFET pulls SDA_BH to 3.3V while allowing safe 5V signals to interface.
    - Ensures compatibility between different voltage logic levels.
- **R7 (4.7kΩ - Pull-up to 5V)**
  - **Purpose:** Provides a pull-up for the 5V side of the SDA line.

- **Function:** Ensures the I2C bus remains at the correct logic level when no device is pulling it low.

- **D1 (1N5819 - Schottky Diode)**
  - **Purpose:** Protects SCL_BH from voltage spikes and ensures signal integrity.
  - **Function:**
    - Provides clamping protection to prevent overvoltage.
    - Maintains signal integrity between 3.3V and 5V devices.

e. Connector for External Testing & Debugging (J3)

- **5-Pin Connector (J3)**
  - **Pins Included:**
    - SCL_OUT & SDA_OUT: I2C communication lines for external devices.
    - ADDR: I2C address configuration.
    - +5V: External power for testing.
    - GND: Common ground reference.
  - **Function:**
    - Enables external connections for debugging.
    - Allows interfacing with different microcontrollers or test equipment.

3. Summary

This schematic integrates the BH1750 ambient light sensor with a level-shifting circuit for safe operation in mixed 3.3V/5V environments. Passive components such as pull-up resistors, capacitors, and protection diodes ensure stable communication, noise reduction, and debugging capability. The J3 connector provides a simple interface for testing and expansion.

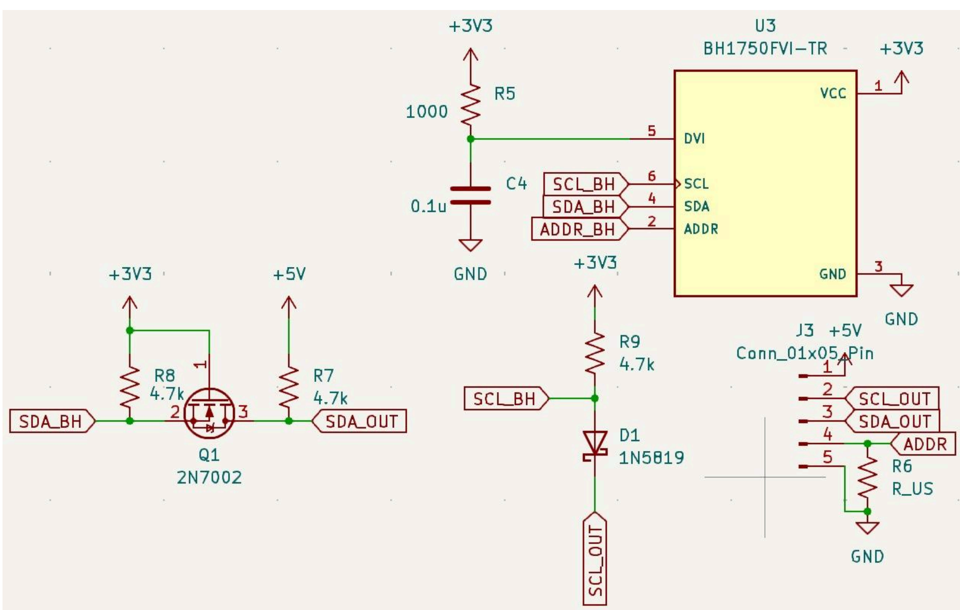

Figure 3. BH1750 Light Sensor Schematic

I²S Microphone Schematic Description

1. Overview

This schematic integrates an I²S MEMS microphone, designed to capture digital audio signals and transmit them via the I²S protocol. The microphone interfaces with a microcontroller or processor using the Bit Clock (BCLK), Word Select (WS), and Data (DATA) lines. The design ensures proper power stability, signal integrity, and testability by incorporating essential passive components.

2. Components & Their Functions

a. I²S Microphone (IC1)

- **Function:** Captures audio signals and outputs them in I²S format.
- **Power:** Operates at VDD (typically 3.3V).
- **Communication:** Uses three key I²S signals:
  - **BCLK:** Synchronizes the audio data transfer.
  - **WS:** Determines whether data corresponds to the Left or Right audio channel.
  - **DATA:** Outputs digital audio data in sync with the clock signals.
- **Channel Selection:**
  - **SELECT:** Configures whether the microphone outputs Left or Right channel audio.
  - Pulled **LOW (GND)** → Left Channel
  - Pulled **HIGH (VDD)** → Right Channel

b. Decoupling Capacitor for Power Stability

- **C4 (22µF)**
  - **Purpose:** Decoupling capacitor placed near the microphone's VDD pin.
  - **Function:**
    - Filters out noise from the power supply.
    - Ensures stable voltage to the microphone.

c. Signal Resistors for Stability

- **R1 (6Ω on DATA line)**
  - **Purpose:** Series resistor to reduce reflections and noise in the digital signal.
  - **Function:**
    - Helps prevent signal degradation.
    - Ensures clean data transmission to the microcontroller.
- **R2 (Pull-down Resistor on SELECT pin)**
  - **Purpose:** Ensures a default channel selection for the microphone.
  - **Function:**
    - Prevents floating SELECT pin, ensuring a stable Left/Right channel configuration.

d. Connector for Testing & Integration (JP2)

- **6-Pin Connector (JP2)**
  - **Pins Included:**
    - BCLK (Bit Clock) → Synchronization signal for I²S communication.
    - DATA → Digital audio output signal.
    - WS (Word Select) → Determines Left/Right channel transmission.
    - SELECT → Configurable pin to assign Left/Right channel.
    - VDD → Power supply input (typically 3.3V).
    - GND → Ground reference.
  - **Function:**
    - Allows for external debugging and connection to a microcontroller.
    - Provides a clean interface for firmware development and testing.

4. Summary

This schematic enables digital audio capture using an I²S MEMS microphone with a properly configured power supply, I²S communication lines, and a debugging interface. Passive components such as resistors and capacitors ensure signal integrity, power stability, and flexible configuration. The JP2 connector facilitates easy integration and testing with a microcontroller.

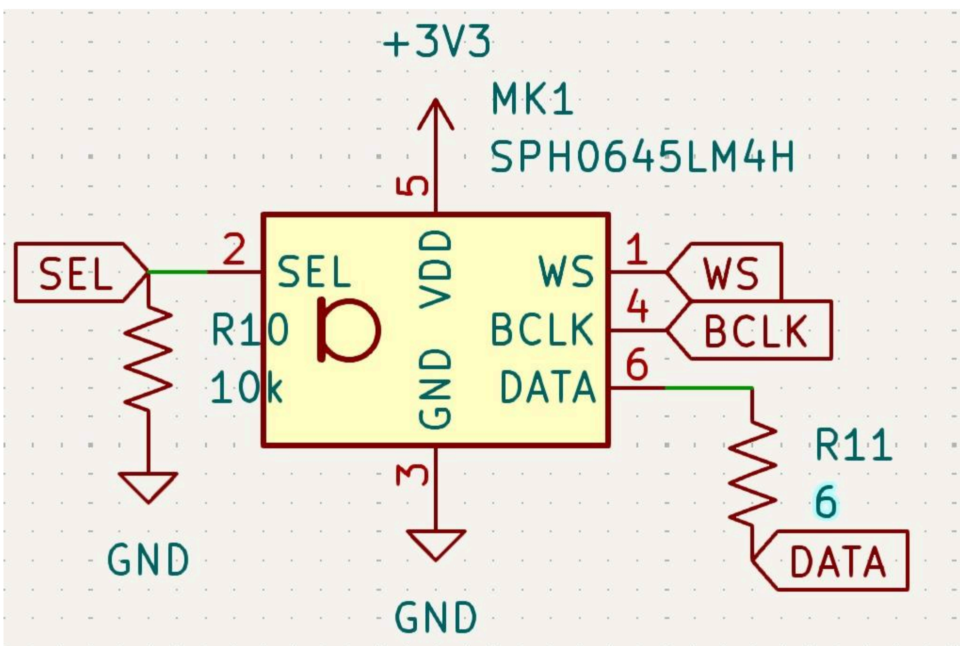

Figure 4. I²S Microphone Schematic

Optical Communications Subsystem

Overview

As stated in the High Level Design, the optical communication system must satisfy the following requirements:

1. Successful transmission and reception of information.
2. Speed of communication: 100 kbps.
3. Range of transmission: 10 ft. ~ 3 m.

Additionally, the optical communication system should aim for lower power consumption to relax the battery requirements.

Another way to state (1) is that the encoded information must be recoverable from the received signal, which requires the signal to overcome noise/interference. Therefore, the circuitry should be designed to reduce noise/interference, both optical (reduced via filters and wavelength selection) and electrical (reduced with low-noise electrical components and design).

Signal Format and Circuitry Bandwidth

To satisfy the speed requirement, we consider 2 optical signal formats:

1. Standard on-off keying (OOK) at 100 kbps

In this format, each symbol is a pulse of length $\frac{1}{100\ kbps}$ = 10 μs. The corresponding sinc function frequency response has nulls at multiples of 100 kHz. To create fast transitions and prevent inter-symbol interference, a standard rule of thumb is to design the corresponding circuitry to include 5 nulls (i.e. design for a bandwidth of 500 kHz).

2. IrDA: UART based protocol at 115.2 kbps

In this format, the symbol length is $\frac{1}{115.2\ kbps}$ = 8.7 μs; however the actual bit =1 pulse is $\frac{3}{16} \times 8.7\ \mu s$ = 1.63 μs long (see Figure 5). The separation between pulses allows for increased robustness to inter-symbol interference and a relaxed requirement for the number of nulls of the pulse's frequency response required for a distinguishable signal. A standard rule of thumb is to include 2 nulls (i.e. design for a bandwidth of $2 \times \frac{1}{1.63\ \mu s}$ = 1.22 MHz).

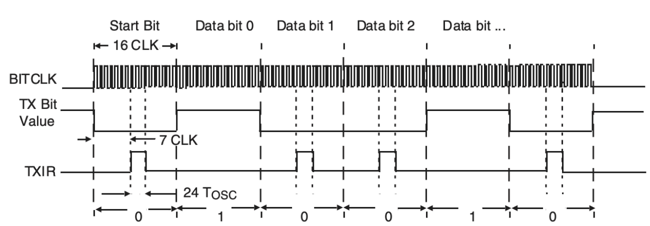

Figure 5. IrDA signal format

Given the lower inter-symbol interference and availability of the ESP32 library UART-IrDA, we **design our optical communication system for IrDA (circuitry bandwidth = 1.22 MHz)**.

Optical Components

To avoid visible light noise, we choose infrared optical components. For 1 device to transmit to multiple receivers in a room, we choose an LED with a relatively wide angle of half-intensity. Following the requirements, the optical components must be able to generate 1.63 µs pulses, so the rise and fall times must be significantly shorter. For conversion of fast optical signals to an electrical signal, photodiodes (PDs) are often used. Additionally, the LED transmit power and PD sensitivity must be sufficient to transmit over 3 m.

An LED and PD with these qualities are the TSAL6200 and the BPW34. The relevant properties are:

LED: TSAL6200	**Photodiode: BPW34**
• Wavelength: 940 nm • Intensity: 600 mW/Sr @ 1A • Rise/fall time = 15 ns • IV characteristic on datasheet	Rise/fall time = 100 ns Radiant area = 7.5 mm2 I vs Ee characteristic on datasheet Capacitance: 25 pF @ V_B = 3 V, 25 pF @ V_B = 0 V

Considering the PD's radiant area, the LED intensity at a driving current of 1A, PD's current vs. intensity characteristic, and transmission distance of 3 m, the expected current is 0.33 µA. While small, this current can be amplified to be readable by the ESP32.

While the BPW34 has peak sensitivity at infrared wavelengths, it is also sensitive to visible light. We will use an infrared longpass filter to isolate the response to infrared radiation (see Figure 6).

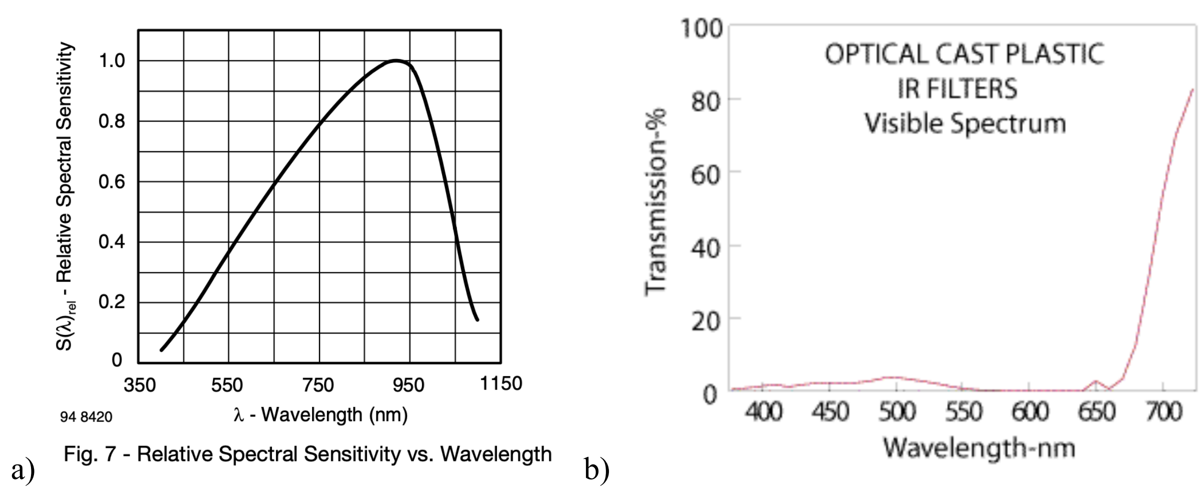

Figure 6. a) BPW34 spectral sensitivity and b) IR filter spectral response (from datasheets)

Optical Subsystem Electrical Design

Transmitter

To convert 3.3V digital signals from the MCU GPIO to 300mA pulses on the LED, we use an NMOS as a high-speed, high current switch. We have chosen the DMG2302UK-7 because it sufficiently fast (Rise/fall time: < 5ns << 1.63 µs), it works up to 2.4 A (> 1 A), its threshold V_{GS} = 0.6 V is lower than and its maximum input voltage $V_{GS,max}$ = 20 V is higher than the MCU logic voltage (3.3V), and it has a small on-resistance $R_{DS,on}$ = 120 mΩ @ V_{GS} = 2.5 V. The schematic is shown below:

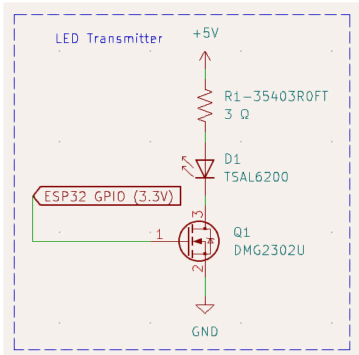

Figure 7. Optical Transmitter Schematic

The transistor is off for a majority of the time. While transmitting, the signal is only high for 3/16 of the bit =1 symbol length, so the signal is high only 3/32 of the time during transmission. If the transmitter is only transmitting ⅓ of the time; the equivalent continuous current is $1\,A \times 3/32 \times 1/3 =$ 31.25 mA.

Receiver

The receiver must convert 0.33 µA signals from the photodiode to 3.3 V digital signals readable by an ESP32 GPIO pin. A transimpedance amplifier (TIA) can serve as an initial amplification stage, and a comparator can convert the small TIA output voltage into a 3.3 V digital signal. To reiterate, the bandwidth requirement is 1.22 MHz and low noise electrical components and power supplies should be used.

A comparator that satisfies these requirements is the TLV3501. The TLV3501 has a maximum toggle frequency of 80 MHz (>> 1.22 MHz), outputs 5V (which can be stepped down to 3.3 V with a voltage divider), and has a minimum input voltage of 0.3 V (which determines the TIA gain required). Additionally, the comparator requires 5 V power and has a quiescent current of 3 mA.

An op-amp that is designed for high gain, high BW, low noise amplification is the OPA657. The OPA 657 has a high gain-bandwidth product (GBP) = 1.6 GHz. To reach 0.3 V output for the comparator from an input of 0.33 µA, the feedback resistance R_F = 1 MΩ. The bandwidth is calculated as:

$$f_{-3dB} = \sqrt{GBP / (2\pi R_F C_D)}\ \text{Hz}$$

For R_F = 1 MΩ and a diode capacitance of 25 pF, f_{3dB} = 3.2 MHz > 1.22 MHz.
The OPA657 has a quiescent current of 16 mA and requires a supply voltage of +/- 5V, which requires a dedicated power supply. The power dissipated by the feedback resistor is negligible because the PD current is extremely low, and the output current of the TIA is negligible because the input impedance of the comparator is on the order of 10^{12} Ω.

In order to account for variation in received power due to installation, a manual potentiometer (3296W-1-103RLF) is included at the inverting input of the comparator to adjust the comparator threshold voltage. The receiver circuitry is shown in Figure 7.

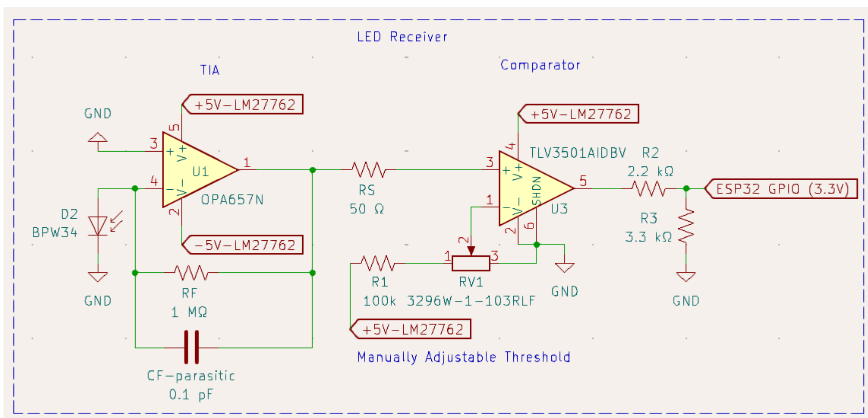

Figure 7. Optical Receiver Schematic

The voltage divider at the output of the comparator dissipates approximately 1 mA of current.

To provide stable +/- 5 V from 5 V, with a current requirement of 16 mA + 3.2 mA + 1 mA = 20.2 mA, the LM27762 (390 uA quiescent current) is used (maximum output current = 250 mA >> 20.2 mA). Decoupling capacitors are included for stable supply voltage. The schematic is shown below:

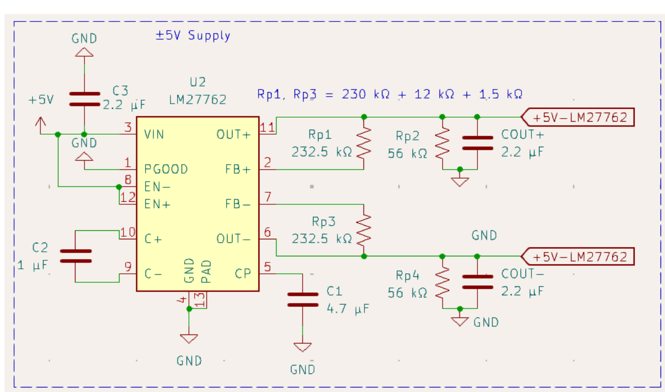

Figure 8. +/- 5V power supply

Power Subsystem:

The power subsystem is responsible for providing stable and reliable power to all system components and ensures proper operation of the sensor subsystem, microcontrollers and communication models. The power distribution varies across the transmitting and receiving hubs, but both rely on a 5V removable lithium-ion battery and power over Ethernet (PoE) for sustained operation.

Major Components and Functions

Lithium-Ion Battery (5V, Removable): The primary power source for the transmitting sensor device. We will employ Power over Ethernet (PoE) for our receiver hub.

Down-Conversion (5V to 3.3V Buck Converter): Steps down the 5V battery to 3.3V for low-power components like the ESP32 and sensors. We selected a Buck Convertor over an LDO to decrease the energy dissipated to heat. Connections include Common System Ground, Input Voltage (V_{in}), and Output Voltage (V_{out}) to the MCU and sensors.

Battery Charge Monitoring: Monitors our real-time battery voltage, current, and charge level. This information will be sent to our central console for consistent user awareness.

1. **Major Components and Selection Justification:**

1.1. Transmitting Hub Power System

- *ESP32-S3-WROOM-1U (MCU)*
  - Power: 3.3V via buck converter
  - Why: low power consumption, compatibility with 3.3V logic, dual-core, has specialized vector processing hardware for DSP tasks.
    - Compared to alternatives like the STM32 series, which may require additional external components for Wifi/bluetooth, the ESP32 integrates these features directly, reducing complexity and power consumption.
    - Additionally, its low-power sleep modes help extend battery life, which is the preference in an energy sensitive application
- *MAX17055 - Fuel Gauge IC*
  - Power: directly connected to the battery (2.3V - 4.9V range)
  - Why : provides real-time battery monitoring for low-power alerts and charge optimization
    - MAX17055 was selected due to its high accuracy in battery state of charge estimation compared to traditional based monitoring circuits. It offers advanced ModelGauge m5 technology, enabling

precise charge estimation without requiring a sense resistor, reducing power loss and simplifying PCB layout.
    - Compared to INA219, it primarily monitors current and voltage without coulomb counting.
- *5V Lithium-Ion Battery (removable)*
  - Why: high energy density, rechargeability, and a reliable power source for all transmitting components
    - Unlike coin cell batteries, which lack necessary current output or NiMH packs, which suffer from higher self-discharge rates.
  - Life estimate: Designed for up to one month of operation based on system load calculations
- *Buck Converter (Step-Down Regulator, 5V to 3.3V)*
  - Why: More efficient over LDOs, with 85-90% efficiency and minimizes heat dissipation
    - LDOs such as the AMS1117 would result in excessive power loss as heat, especially when stepping down from 5v to 3.3V at high current levels. A switching regulator ensures minimal power waste, prolonging battery life while remaining stable output voltage
- *Decoupling Capacitors* $(10\mu F + 0.1\mu F)$
  - Why: stabilized power supply, reduces noise and ensure smooth voltage regulation
    - These values were selected based on best practices for MCUs and high speed communication modules
- *TSAL6200 (LED) and Associated Circuitry for Optical Transmission*
  - Power: 5V
  - Why: High speed optical transmission

1.2. Receiving Hub Power System

- *ESP32-WROOM-S3-1U (MCU)*
  - Power: 3.3V (via Power over Ethernet - PoE)
  - Why: Connected to photodiode signal processing circuit and ethernet module. The same benefits as in the transmitting hub apply here, with the added advantage of Ethernet connectivity for high-speed, low-latency data transmission
- *BPW34 (Photodiode) and associated circuitry*
  - Power: reverse biased at ~ 5V
  - Why: highly sensitive for infrared communication
- *W5500 Ethernet Module (SPI Interface)*
  - Power: 3.3V from PoE
  - Why: Facilitates wired data transmission to the central processing unit

- Ethernet provides a more reliable and interface resistant data link compared to wireless alternatives such as WiFI. It ensures low latency and high data integrity, making it well suited for critical data transmission between the receiving hub and the processing unit.

2. **Detailed Power Scheme**

2.1. Power Flow

- Transmission Hub:
    - Battery (5V) → Buck Converter (3.3v) → ESP32 → Sensors
    - Battery(5V) → LED
    - Battery fuel Gauge (MAX17055) monitors battery health and communicates via I2c
- Receiving Hub
    - PoE → Step-down Regulator (3.3V) → ESP32, Ethernet Module
    - PoE → LM27762 → TIA, comparator

3. **Voltage Regulation and Power Connections**

- 5V Rail: Feeds buck converter and PoE input
- 3.3V Rail: Powers MCUs, sensors, and communication components
- Common ground scheme: ensures no voltage mismatches
- Decoupling and noise reduction considerations
    - Capacitors: $10\mu F$ and $0.1\mu F$ near all major ICs for voltage stability
    - Ferrite Beads: used on power lines to filter electromagnetic interference

4. **Interfaces Between Subsystems**

- ***I2C:*** Sensors and battery monitor communicate with the ESP32 MCU
- ***SPI/RMII:*** Ethernet module interface for data transmission
- ***GPIO***: Optical LED control and photodiode signal reception

5. **Unusual Requirements and Board Layout Considerations**

- ***Buck converter selection:*** requires 500mA - 1A output capacity
    - The ESP32 MCU, sensors and communication modules collectively draw a peak current of about 600mA, requiring a buck converter that can reliably supply at least 1A to ensure overhead for unexpected surges
    - A lower capacity buck converter could cause voltage drops or instability when components operate at peak loads. So a 85-90% efficiency is necessary to reduce heat dissipation prolonging battery life
- ***Board Layout:*** Wide power traces, common ground plane for noise reduction
    - A common ground ensures a consistent reference voltage across all components, reducing ground loops and interference in sensitive signals (especially for analog sensors and high frequency communication lines)
- ***Infrared LED placement:*** requires precise alignment with the photodiode for effective transmission

- Optical communication is line-of-sight dependent, so misalignment between infrared LED (transmitter) and photodiode (receiver) could result in signal loss or weak data transmission
- Board design must accommodate adjustable mounting positions to fine-tune alignment during testing

6. **Plan for Demonstrating Working Subsystems (Design Review 2)**
   - Sensor data collection on breakout boards. Relevant measurements will be displayed on the serial monitor periodically.
   - Power management demonstration: show battery monitoring via fuel gauge IC
   - Optical transmission testing: LED transmission and photodiode reception validation for short distance (> 3m).
   - Data Transmission via Ethernet: Verify connectivity between receiving hub and processing system

Power Requirements Summary			
Component	**Voltage (V)**	**Current (Active, mA)**	**Current (Sleep, µA)**
ESP32-S3-WROOM-1U **Microcontroller**	3.3V	80 - 500	<1 (?)
BME680 Sensor **(Temp, Humidity, Pressure, Gas)**	1.71V to 3.6V	0.09 - 12	0.15
BH1750 **Sensor (Light)**	2.4V to 3.6V	0.12 - 0.18	0.01
I^2S **SPH0645LM4H Microphone (Audio)**	1.62V to 3.6V	600 µA	10
TSAL6200 **Infrared LED and associated circuitry**	5 V	31.25 mA	N/A, LED either on or off
BPW34 **Photodiode and associated circuitry**	5 V	20.2 mA	N/A, always on
MAX 17055 **(Fuel Gauge IC)**	2.3V to 4.9V	18 - 30 µA	7 - 12
Buck Converter Efficiency	~ 85-90%	N/A	N/A

Total: 132 mA.
Given that the board is required to run for 2 weeks:
132 mA x 336 hours/2 weeks = 44352 mAh/2 weeks.

This is an extremely large battery capacity (not available). Further testing is needed to determine sleep schemes to extend battery life.

Data Processing and Integration Subsystem

Error Correction

The error correction uses structured redundancy to detect and correct for errors. The specific technique required depends on the nature of the error.

Random Error

Random bit errors are caused by noise/interference near the bit frequency (high frequency). Traditional block codes, such as BCH, LDPC, Polar codes, Hamming codes, generate error correcting bits sequences for individual data blocks and are relatively simple to decode. Convolutional codes spread error over multiple bits (convolution) and can encode data continuously (bit by bit), but are more complex to decode. (Viterbi/maximum likelihood).

Burst Error -

Burst errors are caused by interference near the packet frequency. The standard burst error correcting technique is Reed-Solomon codes, which performs polynomial fitting of modularized data and uses the fit to generate redundancy. Lost or corrupted symbols (typically bytes or packets) are recovered using polynomial interpolation, assuming that intact packets are perfect.

Combination of Random and Burst Error:

A combination of Reed-Solomon and convolutional codes are commonly used to correct for a combination of random and burst errors. Random errors are corrected bit-by-bit with convolutional codes, then burst errors are corrected with Reed-Solomon.

Regardless of the nature of the error, heavy digital signal processing is needed for encoding and decoding, which motivates the **ESP32-S3,** which has specialized hardware for vector processing, as the choice for MCU. Additionally, the ESP32-S3 dual-core architecture can be used to handle communications and sensor data simultaneously..

Hub connection to Central Console

To connect to the central processor, ethernet will be used. The W5500 is an Ethernet adapter chip that connects to the ESP32 via SPI, and can communicate at much higher frequencies (80 MHz) than the optical communication system.