1 System Overview

This project explores the use of sunlight (via ambient light backscattering (ALB)) as a medium for low-power communication between sensor nodes. The communication system operates by tracking, modulating and reflecting sunlight using a liquid crystal display (LCD), directing the modulated beam towards a receiving node, and capturing the signal with a photodiode. The received optical signal is then demodulated into digital data. A high level system diagram can be seen in Figure 1.

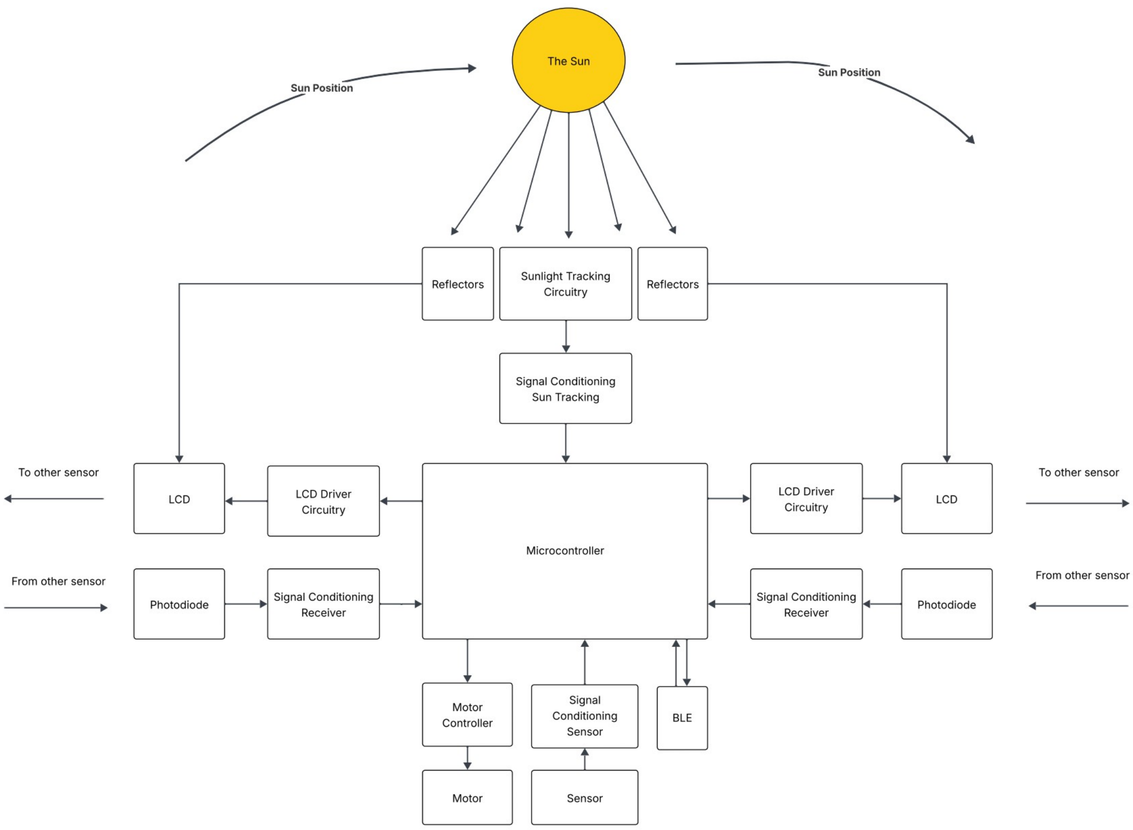

Figure 1: High level system diagram of a single node.

The goal of this system is to demonstrate point-to-point communication by modulating ambient light, without relying on active light sources. This approach supports the broader objective of enabling remote sensing networks that consume minimal power and can operate in outdoor environments using only harvested sunlight.

The system can be divided into two interdependent subsystems: sunlight tracking and optical communication. The sunlight tracking side is responsible for ensuring that the harvester is continuously aligned with the sun's position by utilising a combination of light-sensing algorithms and motor control to maximise the strength of the ambient light signal. The communication side focuses on transmitting and receiving data using sunlight as the medium - this includes modulation and demodulation techniques, controlling the LCD for modulation, and the photodiode receiver circuit for detecting the incoming signal.

This report focuses on the technical aspects of the communication side, outlining the key design principles, the proposed modulation scheme as well as a description of the planned experimental setup, including any challenges anticipated during implementation.

2 Modulation Scheme

The communication method for this system involves modulating ambient sunlight using an LCD. The purpose of the LCD is to selectively block or pass light, enabling information to be encoded onto the light beam which is to be directed towards a receiving photodiode. In choosing an appropriate modulation technique, both the characteristics of the LCD as well as variable light intensity and general noise associated with visible light based communication have been considered.

2.1 Modulation Technique Selection

Initially On-Off Keying (OOK) was considered because of it's simplicity, as well as it's application in several existing ALB technologies. OOK is a form of Amplitude Shift-Keying (AKS) where binary 0's and 1's are represented by the absence or presence of light respectively. However, OOK is susceptible to ambient light fluctuations and noise, especially outdoors, which can make it difficult for the receiver to reliably distinguish between the 'on' and 'off' states.

To address these concerns, Frequency Shift-Keying (FSK) is proposed as a more robust alternative. By using specifically Binary-FSK (BFSK), two distinct modulation frequencies represent binary 0's and 1's, and because the receiver detects changes in frequency as opposed to amplitude, BFSK is less sensitive to noise and is hence a more reliable scheme for modulating the reflected light signal. It's also worth noting that FSK based modulation eliminates the common issue of flickering, because the two carrier signals can be set well above the frequency that the human eye can detect.

2.2 LCD Modulation Implementation

When using an LCD to modulate light for communication purposes, some key metrics to consider are the response time (i.e. how quickly the display responds to a supply voltage) as well as the rise and fall time of the shutter. Because the LCD being used is taken from a pair of 3D glasses, there is no datasheet on it's electrical or optical characteristics is available. Hence the rise and fall times, and the response time will have to be calculated experimentally, as discussed below.

The MSP430 microcontroller will be used to control the LCD by toggling a GPIO pin at two predefined frequencies corresponding to 0 and 1. The maximum output of a GPIO pin on the MSP430 is around 3V, and while it is acceptable to apply this voltage to the pins of the shutter, lower voltages result in slower response times and hence lower achievable modulation frequencies. To ensure that the LCD performs as best as possible, a MOSFET will be used at the output of the GPIO to drive the signal to 5V hence improving response and rise and fall times. In order to calculate the rise and fall times, the LCD will be placed between a non modulating light source and the photodiode receiver circuit. A simple square wave will be generated from the microcontroller at a known frequency, and the results will be measured by the photodiode. From this experiment both the response time and the rise and fall times can be calculated.

Taking the results of this experiment into consideration, two carrier frequencies can be selected for the FSK modulation scheme. It's also worth noting that another limitation of LCD's are the slow switching speeds. This is because it takes time for the display to turn from transparent to solid, and vice versa, and hence the maximum modulation speed is typically rather low (i.e. below 200 Hz). To counter this, the commonly used method is to use periods that are shorter than the entire rise and fall times, preventing the modulated signal from reaching a steady-state plateau. Optimal switching periods can be found through further experimentation as well as trial and error.

2.3 Encoding Strategy

A robust encoding scheme is essential to ensure reliable point-to-point communication, and support the systems low power requirements. The proposed transmission protocol is designed keeping the following considerations in mind:

- Allow for asynchronous, power efficient communication between nodes.
- Reduce the impact of noise or interference on packet integrity.
- Simplify decoding at the receiver side.

Each message will begin with a preamble, followed by the payload and likely error checking fields. All bits will be transmitted via fixed duration bursts of FSK modulated signals, with two distinct carrier frequencies representing binary 0's and 1's

2.3.1 Wake-Up Signal and Low Power Operation

To minimise power consumption in remote sensing applications, all nodes will operate in a low power standby mode by default. A specific "wake-up" message will be sent, and once detected by the receiver, the microcontroller fully wakes up and is now ready to receive the message. This idea is inspired by infrared based standby systems and means that the receiver does not need to waste energy waking up periodically to see if there's any data to receive. This is inline with the extremely low power requirement of the project.

2.3.2 Error Protection

It's very important in digital communication to include some basic data redundancy to improve reliability and reduce transmission errors. A common approach is to use bit repetition, where each logical bit is transmitted multiple times (i.e. sending 111 to represent a logical 1 and 000 to represent a 0). This way if one of the bits gets corrupted during transmission, it can be inferred what the bit was meant to be (i.e. 101 or 011 can be assumed to be 1). This approach provides single bit correction. Of course a limitation of this method is that it requires longer transmission times, which will increase the power consumption per tranmission by however many repetitions per bit. This is a major consideration given the extremely low power requirement.

Alternatively, a parity bit can be added at the end of the payload to detect errors. While this is effective for single bit errors within a data word, if too many bits are corrupted then it may not catch the error at all (as the parity might still match the original parity scheme. Until experimental transmission results in different environments have been obtained, both approaches will be considered.

3 Receiver Design

The receiver subsystem is responsible for detecting and decoding the incoming modulated sunlight signal into a digital bit stream. The receiver circuit consists of the following:

1. Photodiode - to convert light intensity into current.
2. Analog Band-pass Filter - to isolate the FSK carrier frequencies and reduce noise.
3. Transimpedance Amplifier (TIA) - to convert and amplify the current from the photodiode into a measurable voltage.
4. Analog-to-Digital Converter (ADC) - to sample the analog signal and convert it into a digital signal for further processing and decoding.

A receiver subsystem diagram can be seen in Figure 2

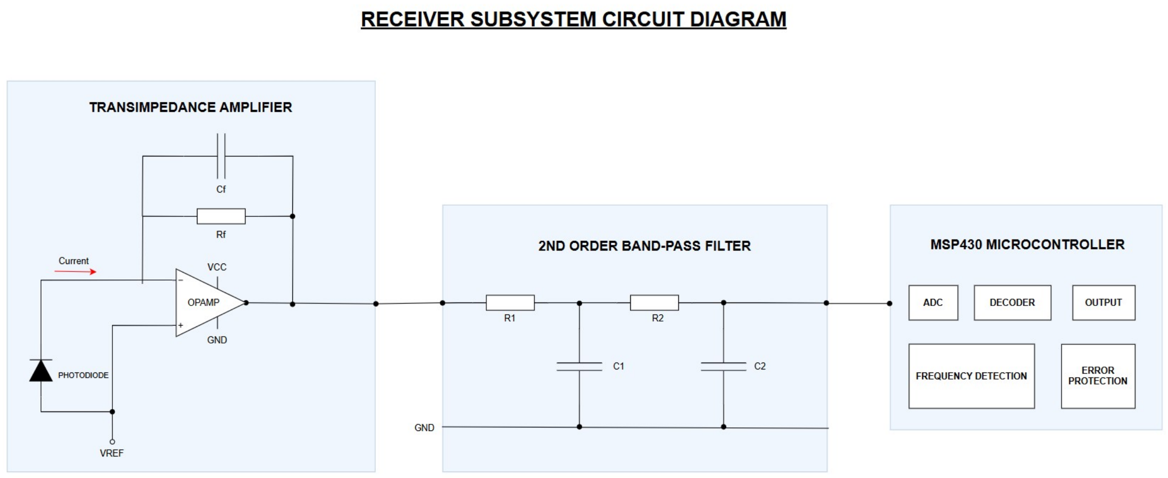

Figure 2: Receiver subsystem diagram.

3.1 Photodiode Selection

The BPW34 was deemed suitable for the receiver due to its high sensitivity, fast response time and low dark current value. The photodiode will be operated in reverse bias mode.

3.2 Analog Band-pass Filter

To improve the signal to noise ratio (SNR), an analog band-pass filter is placed in the signal path between the photodiode and TIA. The filter will be centred around the midpoint of the two chosen FSK carrier frequencies, such that both frequencies are amplified, while attenuating high and low frequency noise. This stage will be especially useful for laboratory testing, as ambient fluorescent lights typical of the environment tend to modulate at 120 Hz.

3.3 Transimpedance Amplifier

The filtered current from the photodiode is fed into the TIA, which converts the photocurrent into a voltage, which can then be digitized by the ADC. The most basic implementation includes a low-noise op-amp with a feedback resistor and capacitor. This topology will be used and the resistor and capacitor values will be selected based on initial testing with the photodiode.

3.4 Analog-to-Digital Conversion

The output of the TIA is connected to an ADC pin on the MSP430 microcontroller. Sampling will occcur at a fixed rate to capture the incoming waveform, and these samples will be processed in firmware to identify the dominant modulation frequency in each bit window, and hence reconstruct the transmitted bit stream.

In terms of frequency detection, there are a few different options to be considered:

- Zero-crossing frequency estimation
- Fast fourier transform
- The Goertzel algorithm

These methods will be evaluated during implementation based on processing limitations of the MSP430 as well as energy and signal clarity considerations.

4 Planned Experimental Setup

To validate the feasibility and performance of the system, a controlled lab based test environment will be used for initial experimentation. This allows for controlled testing of the overall system's power consumption, achievable range, and reliability under varying lighting conditions.

4.1 Non-modulating Torch Setup

In order to obtain repeatable results, the intensity and position of the light beam must be consistent in relation to the receiver circuit. This immediately rules out the sun as a test source, as there is no reliable manner in which the same intensity and position can be achieved. Instead, a non-modulating torch will be used, allowing us to be fully in control of the testing conditions.

The transmitter setup will consist of the LCD panel placed in the beam path of the torch, and modulated using the MSP430 microcontroller using the FSK modulation scheme described in section 2.1.

The receiver consists of a photodiode, amplification circuit and comparator circuit, and will be positioned 1.5 metres away from the torch beam.

The main goal of this setup is to test the system's basic functionality, and ensure that modulated light can be reliably detected and demodulated over short distances in a controlled indoor environment. Following successful lab testing, the experimental setup will transition to a sunlight based environment. These tests will be done over greater distances, and system performance will be evaluated in the intended operating environment to validate feasibility.

4.2 Performance Metrics

The following performance parameters will be evaluated through repeated tests:

- Power Consumption:
  Both the transmitter and receiver sides will be evaluated for average current draw in both standby and active states.
- Communication Range:
  Tests will be conducted at increasing distances (starting from 1.5 metres) to evaluate an approximate working range. Alignment sensitivity will also be assessed at each distance.
- Variable Lighting:
  Tests will be run under varying ambient light levels to simulate changing conditions (direct sunlight, overcast etc.):
  - Dark room (with no ambient lighting) - This is purely to ensure the communication works as intended.
  - Standard lab lighting - This is more realistic to application operating conditions where the sun will be present as an ambient source as well as directed towards the receiver with a reflector.
  - Bright indoor sunlight (if available) - An extension of standard lab lighting by using sunlight as ambient light.
- Message Accuracy:
  Initially, the output of the receiver circuitry will be connected directly to an oscilloscope to verify if the message sent is being received correctly. The oscilloscope output can then be compared to the decoded message to ensure that decoding is working as intended (although this stage will likely occur independently to general system testing).