Group 1

RF Device Detection, Identification, and Secure Data Transmission using a Free-Space Optical Communication System

Team Members

Zachary Flores
Computer Engineering

Bill Noel
Computer Engineering

Sarah Thibaut
Photonic Science Engineering

Zackary Zuniga
Electrical Engineering & Photonic Science Engineering

Motivation and Background

Electronic Warfare is central to modern conflict.

- The US Army would benefit from a capability that can detect RF devices and display actionable data.

- Electronic Warfare is complex, however focused around RF transmission and reception.

- Knowledge about these transmission is critical.

Source: Joint Air Power Competence Centre (JAPCC), “Electronic Warfare – The Forgotten Discipline?,” JAPCC Journal, Autumn/Winter 2010

Motivation and Background

RF sensing of devices such as drones has become critical in RF Sensitive Zones

- Current sensors detect RF, but still produce emissions when relaying data!

- Traditional RF sensors aim to detect objects purely based on RF data, proven difficult, near impossible.

- A combined RF-plus-imagery approach could turn raw spectrum activity into contextual, decision-ready information for operators.

Goals

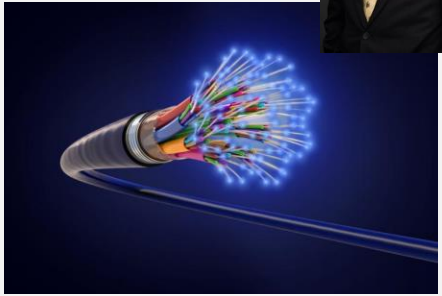
- **Collect RF data:** During system operation, the RF front-end shall detect activity in both the UHF band (e.g., 462–467 MHz) and the 2.4 GHz Wi-Fi band within 2 seconds of any transmission whose power is at least 15 dB above the local noise floor.

- **Collect Image Data from Optical System:** Integrate a camera module that captures images after RF signal detection, synchronized for real-time analysis, without a delay of $\leq 2s$.

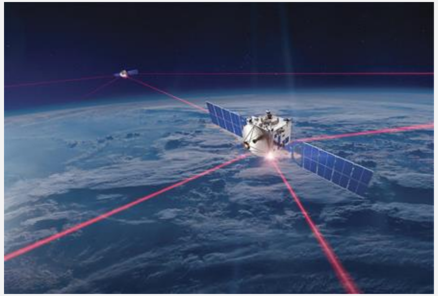
- **Display Information via Secure Optical Communication:** Transmit key RF and image data, such as devie type to a remote terminal using a free space optical communication link within $\leq 2s$.

Why Free Space Optical Communication?

Free Space Optical Communication (FSOC) does not emitt RF!



- FSOC takes advantage of the visible part of the Electromagnetic Spectrum rather than Radio



- Metal wires or fiber optics accomplish the same tasks, but ineffective across difficult terrain (mountains, forest, rivers)

- FSOC requires Line of Sight, but given the correct conditions, can overcome difficult terrain.

Objectives

- **Immediate Image Capture of Confirmed Devices:** Automatically capture and timestamp an image of the scene $\leq 2s$ after each confirmed RF detection and store it together with the RF metadata so it can be used for near real-time visual analysis of the emitting device.

- **Identify Individual RF-Transmitting Devices:** Apply digital signal processing to detect and characterize RF transmissions, and use machine-learning–based computer vision to assist in identifying the type of device observed in the captured image with a minimum 80% identification accuracy.

- **Display Identified Devices on the Web Application:** Develop a lightweight web interface that displays recently detected device classifications alongside their frequency and timestamp, dynamically updating as new detections occur within 2s.

Key Testing Specifications

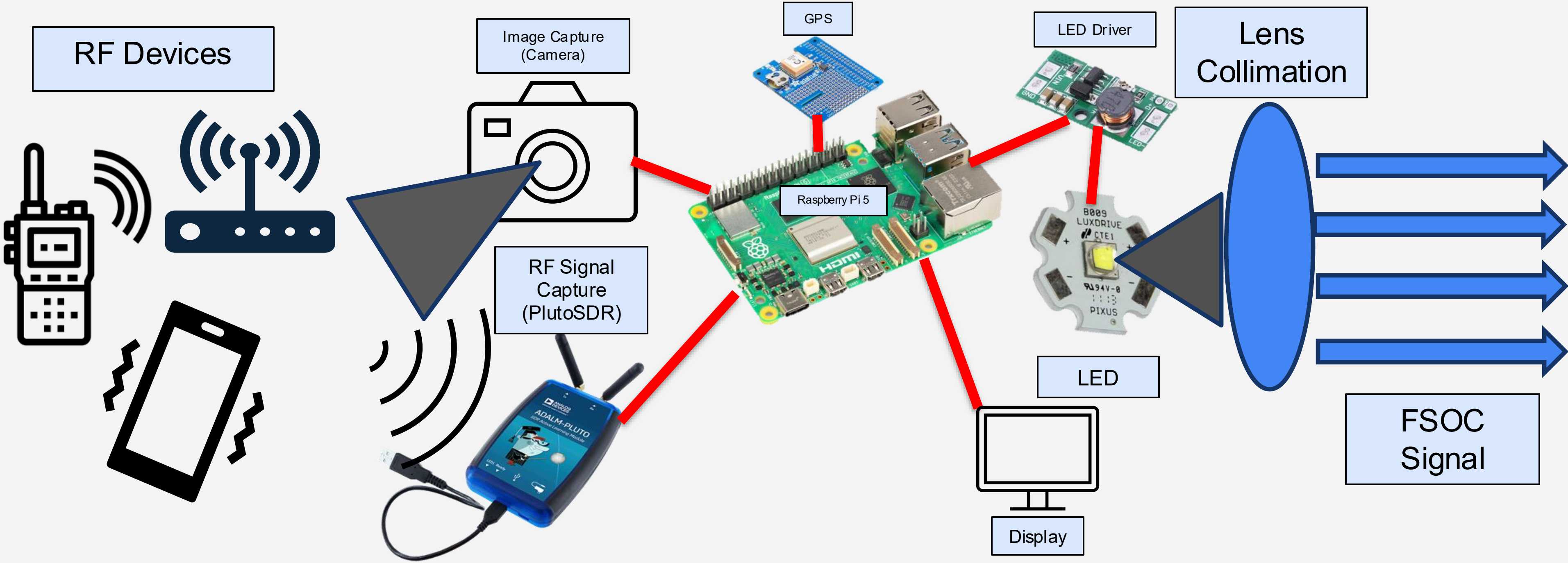
Component	Parameter	Specification
Tx/Rx System	End-to-End Latency	$\leq 15s$
Photodiode	Received Optical Power	$\geq -35\text{dBm at }15\text{m}$
Object Identification/RF Detection	Classification Accuracy	$\geq 80\%$

Specifications cont.

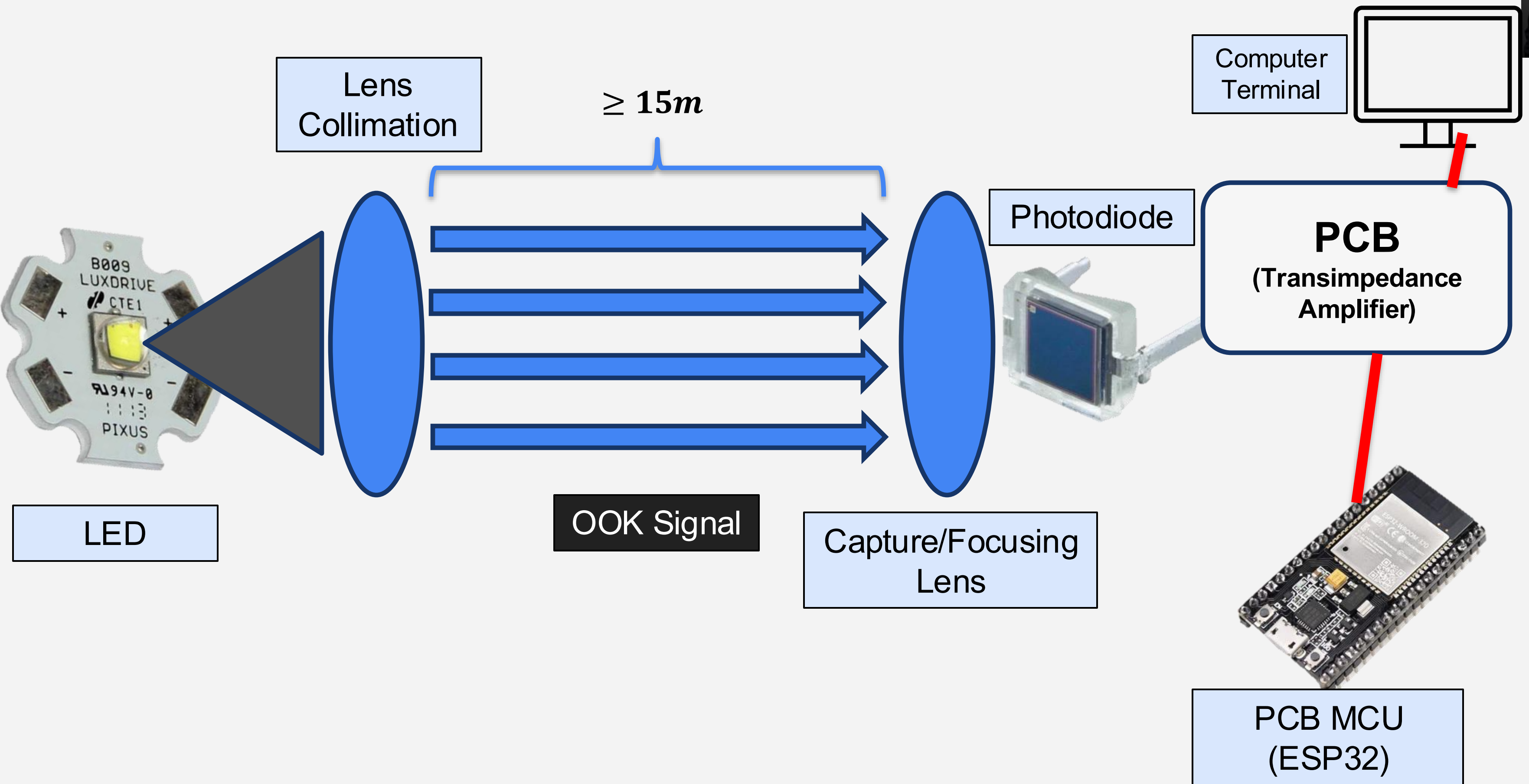
Component	Parameter	Specification
Object Detection Model	Accuracy	≥85%
Object Detection Model	Latency	<450 ms
Battery	Battery Life	≥24hrs
GPS	Accuracy	<20m
RF Antenna/SDR	Signal Detection	≥99%

Product Visualization

Overall Design: Transmitter

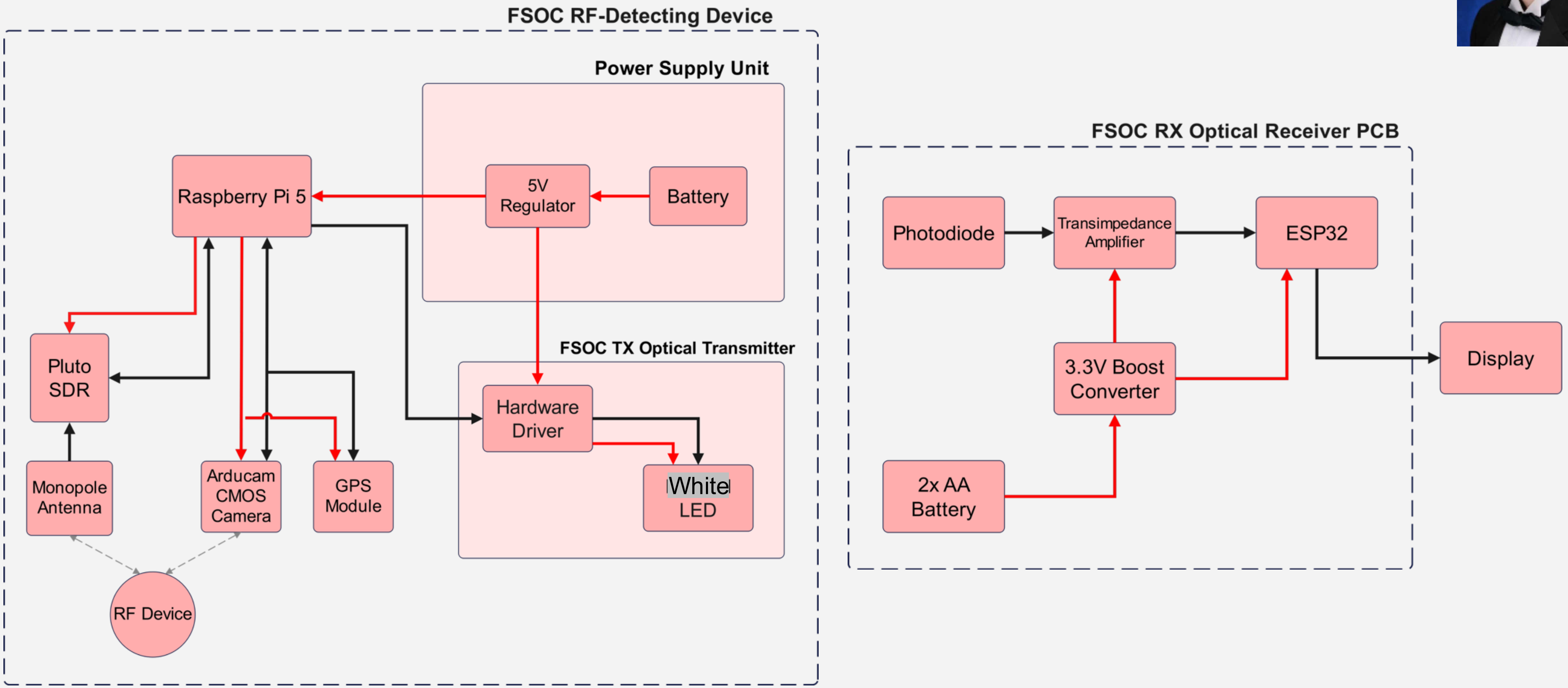


Overall Design: Receiver



Hardware

Hardware Design Block Diagrams



Hardware Component: Raspberry Pi 5

Key Specifications:

- Quad ARM Cortex-A76
- 8 GB LPDDR4X
- 2x USB 2.0, 2x USB 3.0
- Gigabit Ethernet
- 40x GPIO
- 2x micro-HDMI
- USB-C

a. High Connectivity
b. Large memory capacity
c. Software flexibility

Hardware Component: Software Defined Radio

Purpose:

To collect and process Radio Frequency signals

Desired Requirements:

- Frequency Range of 400MHz – 2.5GHz
- ADC of 8bit or higher
- Has available significant documentation
- Low-Cost Solution

RTL-SDR

HackRF One

LimeSDR Mini

bladeRF 2.0

ADALM-Pluto SDR

SDR Comparison Chart

Requirement	Frequency	Cost	Integration
RTL-SDR	500 kHz – 1.75 GHz	\$20 – \$50	Widely supported, plenty of documentation.
HackRF One	1 MHz – 6 GHz	\$300 – \$400	Widely supported, plenty of documentation.
LimeSDR Mini	10 MHz – 3.5 GHz	\$500 – \$550	Not widely supported, limited documentation.
bladeRF 2.0 micro	47 MHz – 6 GHz	\$540 – \$860	Somewhat supported; documentation from manufacturers, however limited community documentation.
ADALM-Pluto	325 MHz – 3.8 GHz (70 MHz – 6 GHz with augmentation)	~\$230	Excellent documentation; great open-source community resources.

Hardware Component: ADALM-PlutoSDR

Purpose:

To collect and process Radio Frequency signals

- Large Radio Frequency Range in base model – can be augmented
- 20MHz Bandwidth
- 12-bit ADC Critical for detecting weak signals
- Compatible with MATLAB, GNU Radio, SDR#

Feature	Specifics
Frequency Range	325MHz-3.8GHz
ADC Bit	12-bit
Compatibility	Raspberry Pi 5

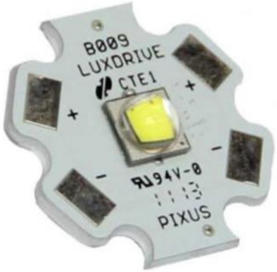
Hardware Component: Light Source

Purpose:

To emit light and transmit a message via free space optical communications

Desired Requirements:

- Low Cost & Widely Used in Military Application



Light Emitting Diode

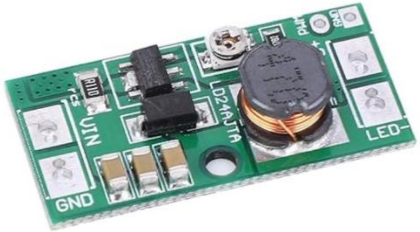
Laser Diode

Hardware Component: LED (White)

Purpose:

To emit light and transmit a message via free space optical communications

Feature	Specifics
Peak Wavelength	432nm
Weight	0.1 lbs
Viewing Angle	125°
Output Power	2 W



Jeanoko LD24AJTALED Driver Board

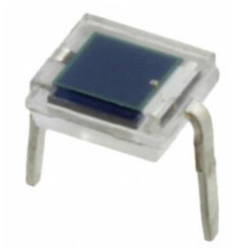
Cree Xlamp XM-L2 High Power LED

Hardware Component: Photodiode

Purpose:

To receive light and translate a message via free space optical communications

Feature	Specifics
Wavelength Range	430-1100nm
Angle of half sensitivity	$\phi = \pm 65°$
Rise Time	100 ns
Active Area	7.5 mm^2



BPW34S - Silicon PIN Photodiode

Hardware Component: Arducam 12MP Camera Module 3

Specifications:
- ➢ 4608x2592 "5K" resolution at 10 fps, 1280×720 at 30 fps
- ➢ 3.5 x 3 x 1.3 inches
- ➢ 1.6 ounces

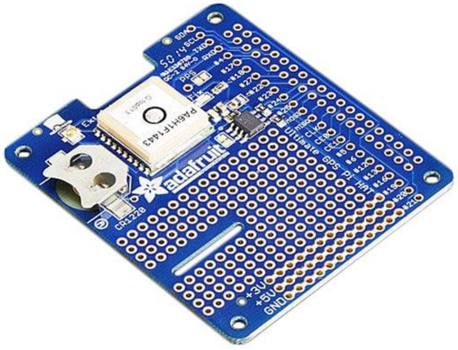
Selection Criteria:
- High enough resolution
- Lens with a fixed focus
- UVC Compatible
- Libraries
- Compact

We installed the camera in the RP5's CAM0 or CAM1 port, displayed to the right. One end of the camera ribbon is connected to the camera module, and the other is securely latched into one of the CAM ports.

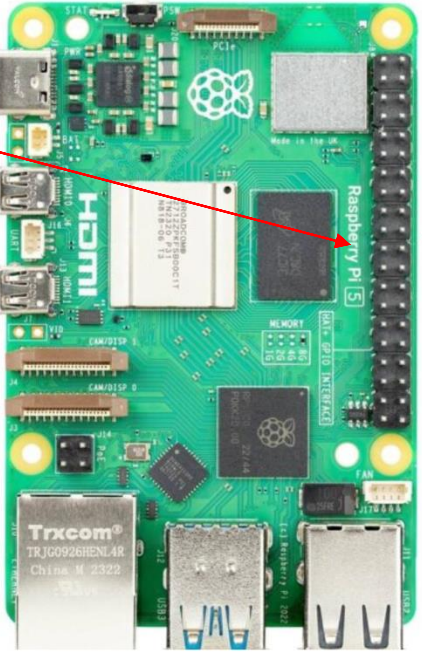
Geolocation Comparison Chart

GPS MODULE	DIMENSIONS	PLUG AND PLAY W/ LINUX?	POWER CONSUMPTION	COST
ADAFRUIT ULTIMATE GPS	25.5 x 35 x 6.5 mm^3	No	20 mA, 5 V	$29.95
GLOBALSAT BU-353S4	59 x 47 x 21 mm^3	Yes	60 mA, 5 V	$47.99
BEITIAN BN-880	28 x 28 x 10 mm^3	No	50 mA, 5 V	$33.98
WWZMDIB VK-172 USB GPS DONGLE	Small USB device	Yes	Unknown current, 5 V	$9.99

Hardware Component: Adafruit Ultimate GPS Hat



The GPS hat was soldered to the top of the GPIO header pins (shown on the right). We then open the Pi's terminal and downloaded the necessary libraries. Finally, we were able to scan for satellites in the area and establish a preliminary geolocation. We can now determine the location of our device without an internet connection.



Battery Comparison Chart

BATTERY TYPE	ENERGY DENSITY	FIELD USE	SOLAR RECHARGING
LITHIUM-ION	~150–250 Wh/kg	These are used in military or outdoor applications – often with protective circuitry and shock-resistant enclosures.	Charging needs to be carefully controlled. Can't be held at 100% charge for long periods, especially in heat.
LITHIUM-POLYMER	~150–250 Wh/kg	Soft pouch is vulnerable to puncture or swelling; can catch fire if overcharged or shorted.	For solar use, Li-Po can be used, but it may prove beneficial to slightly undercharge to prolong lifespan.
LIFEPO$_4$	90–120 Wh/kg	Chemically stable, they can be overcharged to some degree and can handle higher temperatures.	The charge profile matches well with typical solar setups, and it's more forgiving of being held at full charge.
NIMH	~60–120 Wh/kg	Very rugged and safe.	They can be recharged by solar simply but are considerably larger and heavier.
LEAD-ACID	~30–50 Wh/kg	Handles cold weather well.	Can be float charged indefinitely.

Hardware Component: Power Supply

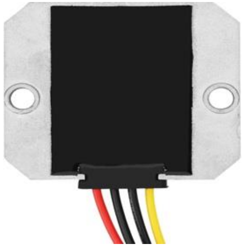
Purpose:

To supply power across the optical transmitter system

- Supplies 12.8V at 100A for an hour = strong battery life for prototype
- Easily meets power requirements:
  - 12V/2A to PYNQ
  - 5V/5A to Raspberry Pi 5
  - 5V/1A for LED
  - 5V/1A for PlutoSDR

Feature	Specifics
Longevity	100Ah
Weight	20lbs
Compatibility	Rechargeable

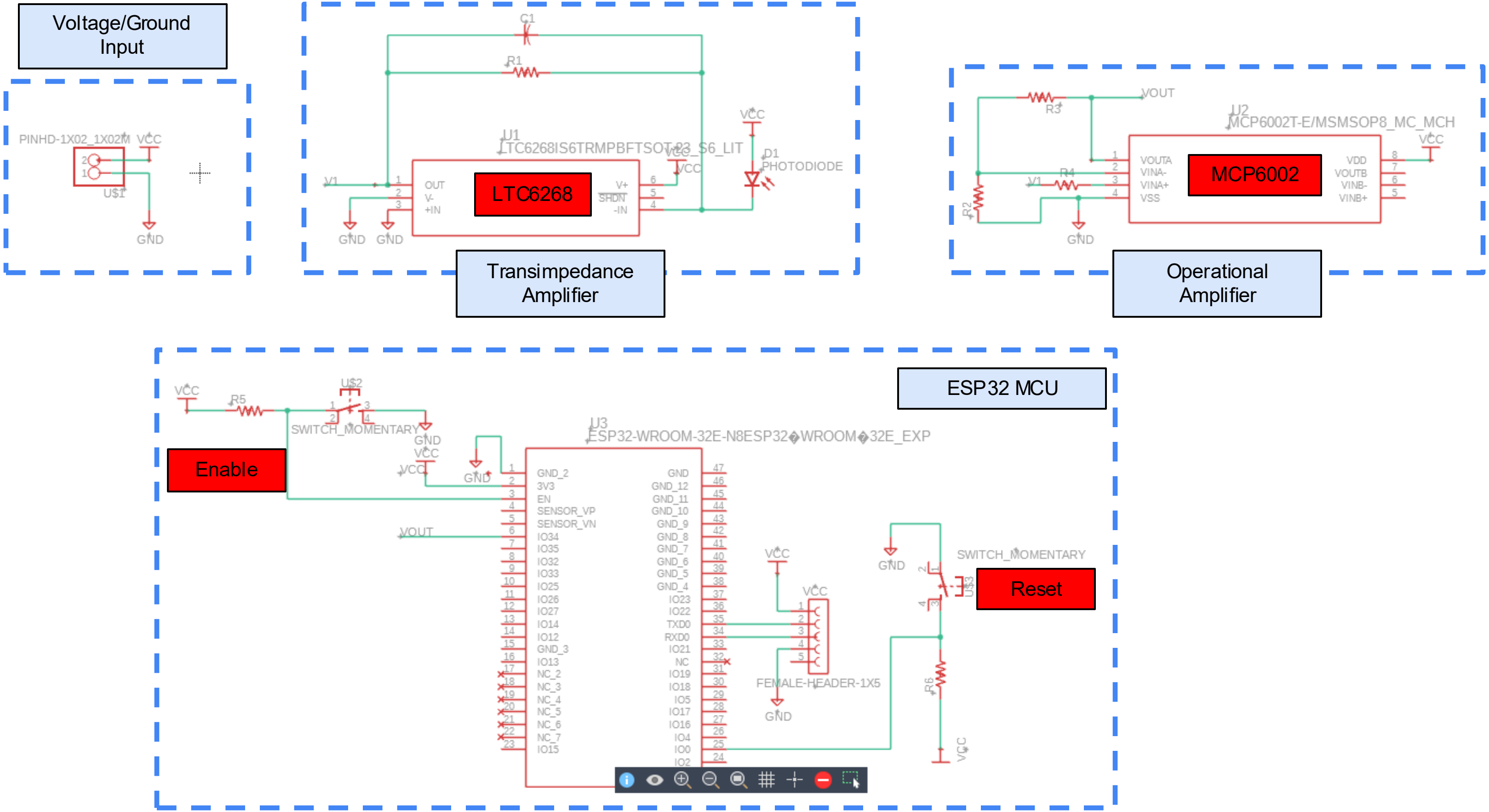
Power Queen 12.8V 100Ah LiFePO4 Battery



12V/24V to 5V Voltage Buck Regulator

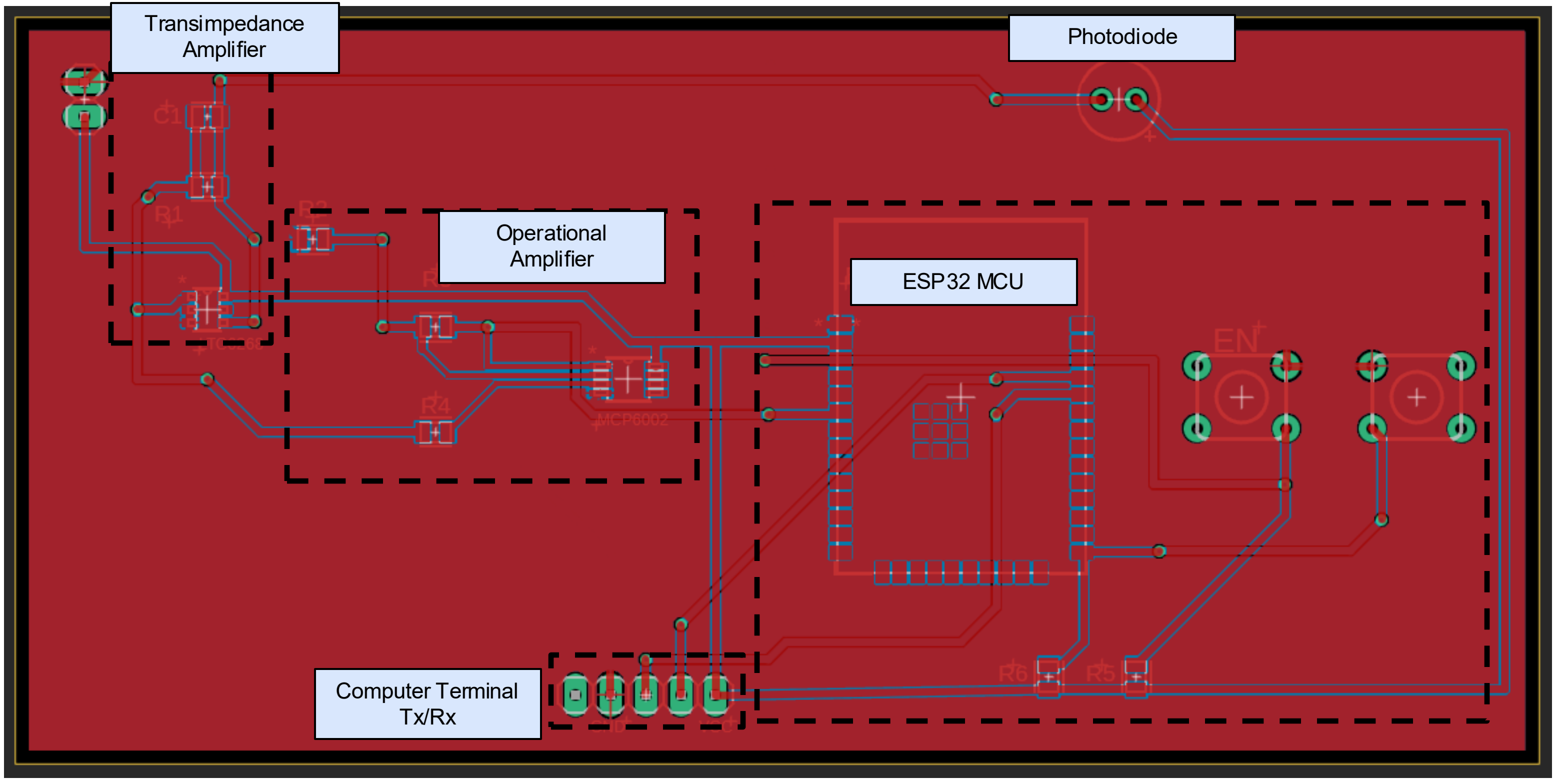
PCB Design

PCB Design



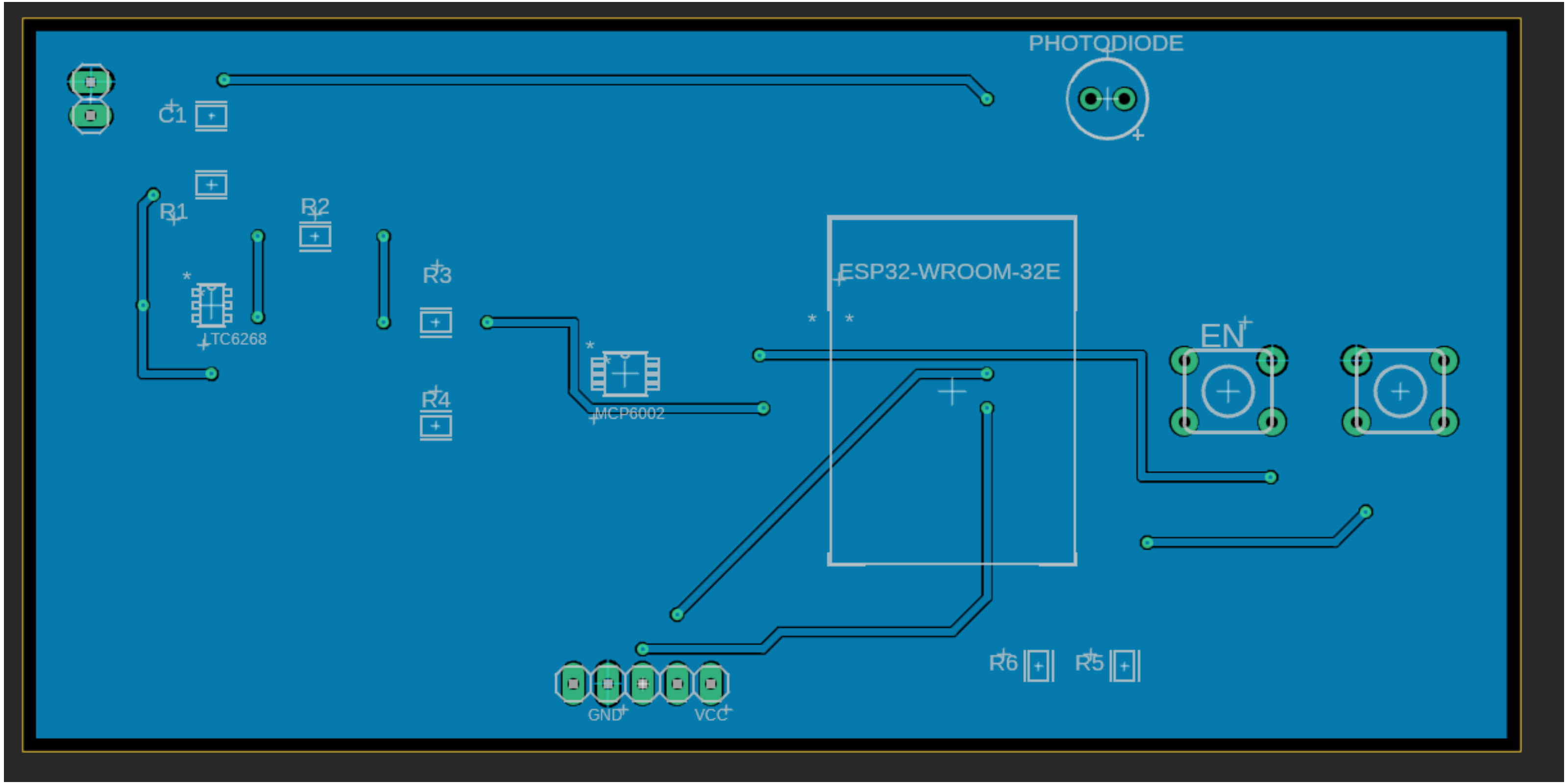
Voltage/Ground Input
PINHD-1X02_1X02M
VCC
U$1
GND
Transimpedance Amplifier
C1
R1
U1
LTC6268IS6TRMPBFTSOT-23_S6_LIT
LTC6268
OUT
V-
+IN
V+
SHDN
-IN
V1
VCC
D1
PHOTODIODE
GND
Operational Amplifier
VOUT
R3
U2
MCP6002T-E/MSMSOP8_MC_MCH
MCP6002
VOUTA
VINA-
VINA+
VSS
VDD
VOUTB
VINB-
VINB+
R4
R2
ESP32 MCU
R5
U$2
SWITCH_MOMENTARY
Enable
U3
ESP32-WROOM-32E-N8ESP32�WROOM�32E_EXP
GND_2
3V3
EN
SENSOR_VP
SENSOR_VN
IO34
IO35
IO32
IO33
IO25
IO26
IO27
IO14
IO12
GND_3
IO13
NC_2
NC_3
NC_4
NC_5
NC_6
NC_7
IO15
GND
GND_12
GND_11
GND_10
GND_9
GND_8
GND_7
GND_6
GND_5
GND_4
IO23
IO22
TXD0
RXD0
IO21
NC
IO19
IO18
IO5
IO17
IO16
IO4
IO0
IO2
FEMALE-HEADER-1X5
U$3
R6
Reset

PCB Design



Transimpedance Amplifier
Photodiode
Operational Amplifier
ESP32 MCU
Computer Terminal Tx/Rx
C1
R1
R4
MCP6002
EN
R6
R5

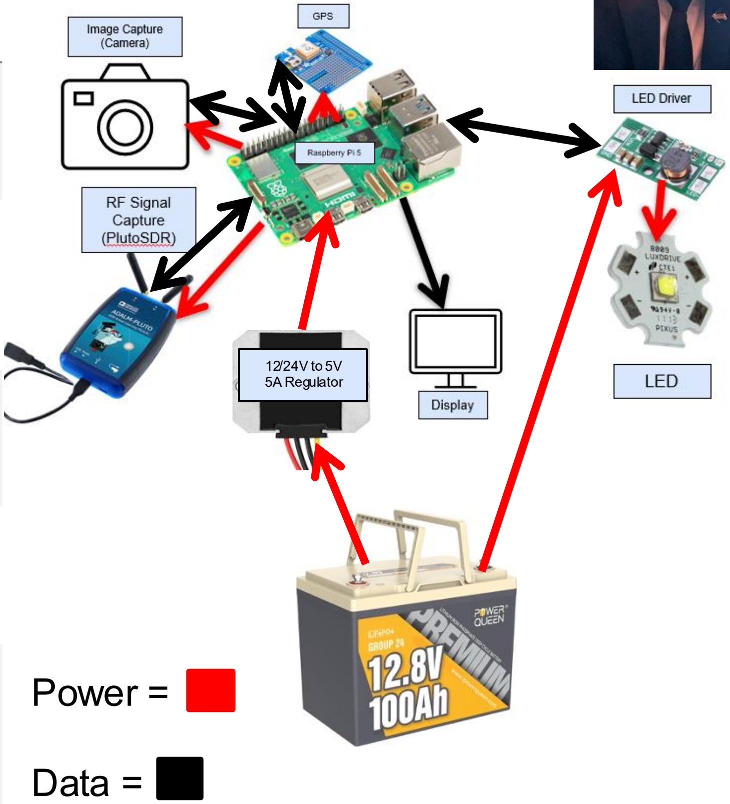
PCB Design – Optical Receiver



Power Distribution

Power Distribution Table: Transmitter

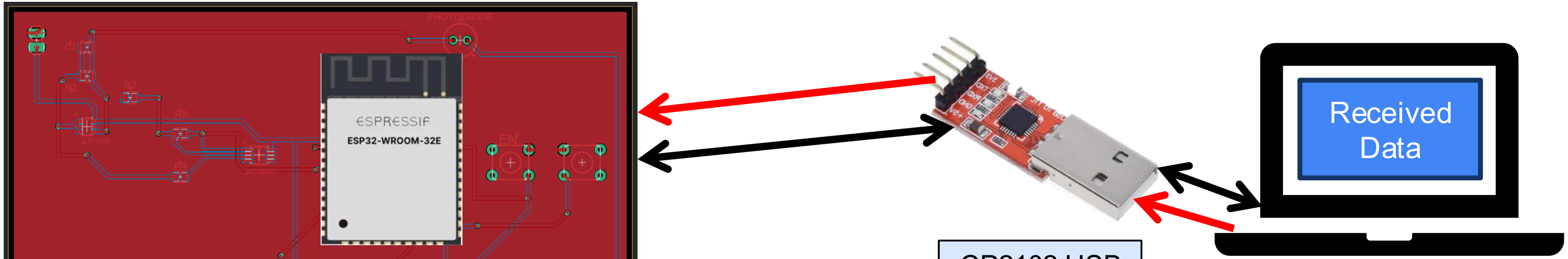
Component	Supply Voltage (V)	Typical / Max Current	Approx. Power (W)	Notes
ADALM-Pluto SDR	5	0.40 A	2.00	Powered via USB; ~400 mA in normal operation.
Raspberry Pi 5	5	3.00 A (design max)	15.00	Includes headroom for CPU load and attached peripherals.
White LED	3.2 (forward)	20 mA	0.064	Driven by LED driver at ~20 mA for Li-Fi transmission.
LED Driver Board	5	0.10 A (est.)	0.50	Includes driver losses and LED load reflected to 5 V rail.
12 MP Arducam Camera	3.3	0.35 A (max)	1.15	Based on max 1.16 W specification for the camera module.



Power Distribution: Receiver

ESP32 Power Requirements:

3.3V, 0.5A



CP2102 USB to TTL

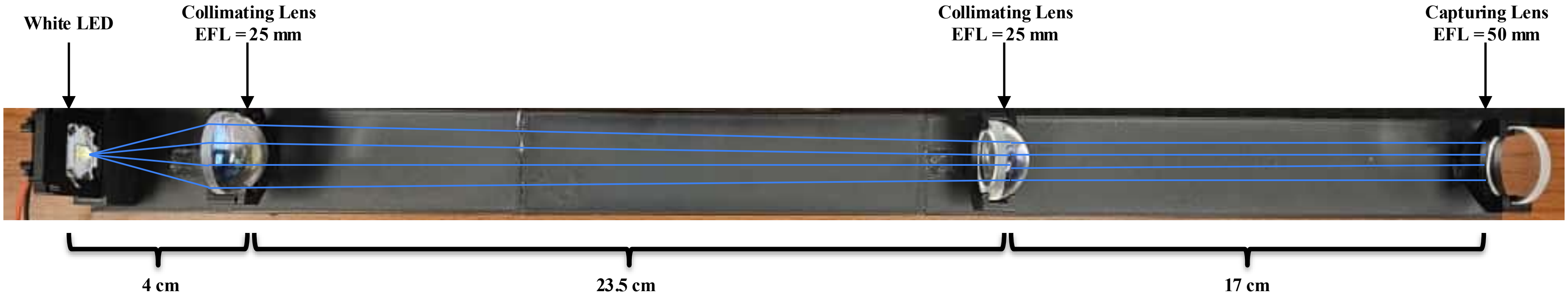
Computer Terminal

Power =

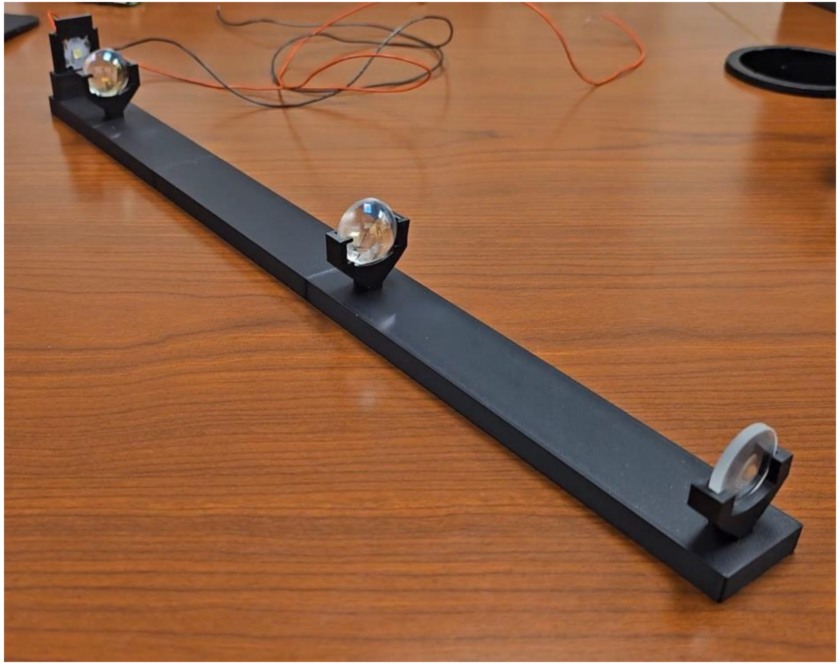
Data =

Optical

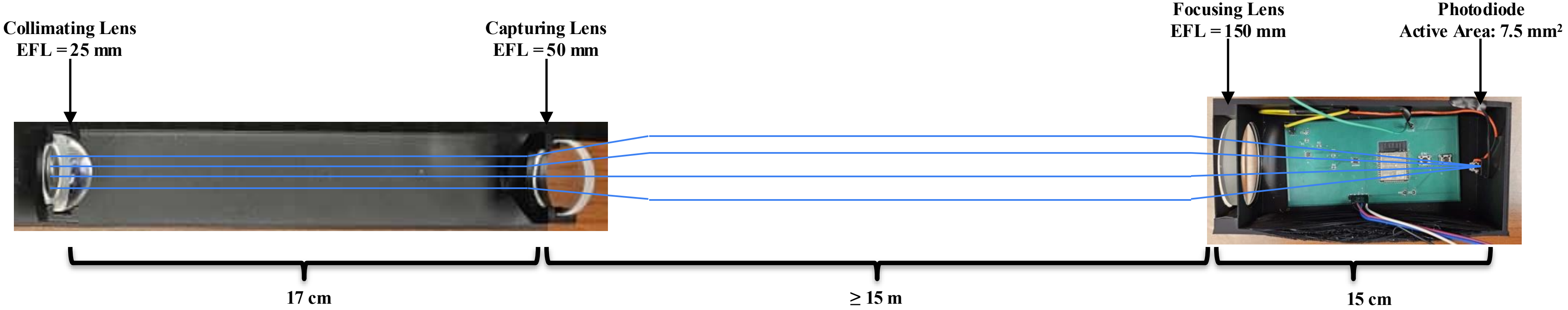
Optical Setup



Optical Setup



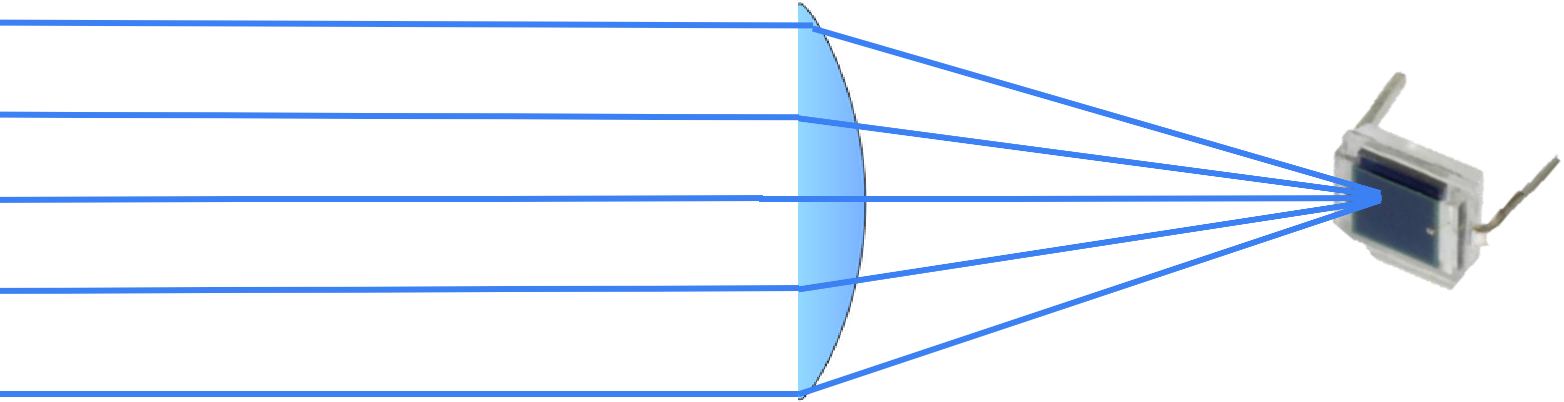
Optical Setup



Optical Setup: Optimizing the Reciever

Purpose:

To increase the number of photons captured.



Plano-Convex Lens
EFL=150mm

Optical Setup: Optimizing the Receiver

Housing: Transmitter

Housing: Receiver

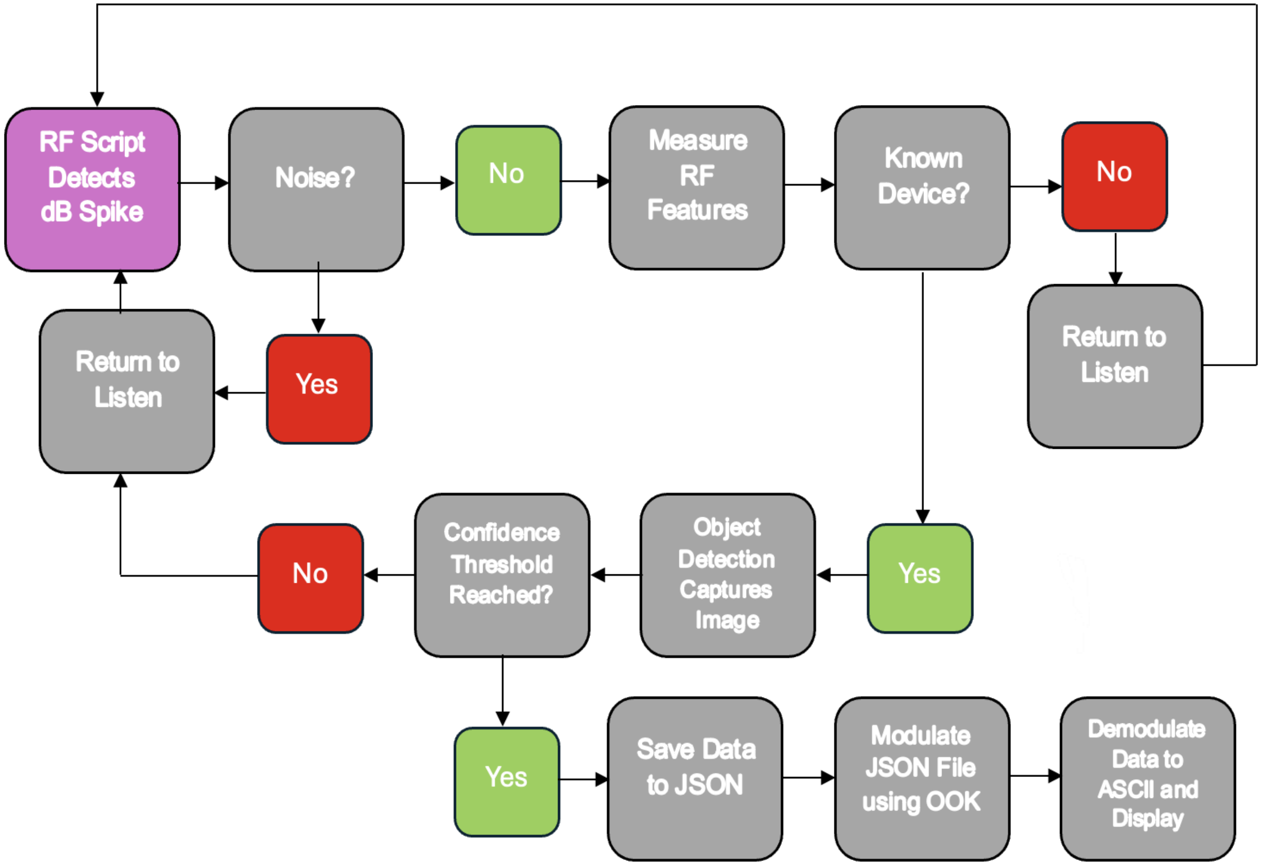
Front View

Top View

Side View

Software

Software Logic Flowchart



Software Component: SDR

Purpose:

To obtain and visualize RF Spectrum.

SDR# Software Defined Radio

Compatible with ADALM-Pluto SDR

- Enables visualization RF data
- Can be used to record Spectrum
- Can be used to replay signals

Primarily used in our testing and evaluation to verify data recorded – not critical for final design

Feature	Specifics
Recording/Replay	IQ/WAV Files
User Interface	Waterfall/Spectrogram
Compatibility	ADALM-SDR, RTL-SDR, HackRF, etc.

Software Component: Object Detection Model

Model Architecture Requirements:

- Fast enough to meet latency specifications (Prioritize FPS)
- Strong at cross-domain generalization for deployment in new environments
- Must not exceed the Raspberry Pi 5's resources

	YOLOv12	Faster R-CNN	RF-DETR
Common with many catered resources	Yes	Yes	Yes
Architecture	CNN-based	CNN-based	Transformer
Must be paired with classifier head	No	Yes	No
Suited to edge devices like the Pi 5	Yes	No	Yes
Attention mechanisms	Yes	Yes	Yes
Chosen			✓

Software Component: Detection Software

Object Tracking ✓

- Tracks individual objects across multiple images
- Can improve accuracy
- Dependent on high FPS for best results

Image Segmentation

- Provides more detailed information about object dimensions
- Performs better with localization as a core goal rather than classification

Software Component: RF-DETR

RF-DETR:
Roboflow Detection Transformer

Uses the DINOv2 Backbone:
- Improved Feature Generalization
- Better Performance on Low Image Sizes
- Learns in Fewer Epochs

Uses EMA and Transformer Architecture:
- Designed for Cross-Domain Generalization

Software Component: SOFT Object Tracking

SOFT:
Simple Online and Fast Tracking

- Simple, easily adaptable to RF-DETR model outputs
- Prioritized for speed so:
- More Frames = Higher Accuracy

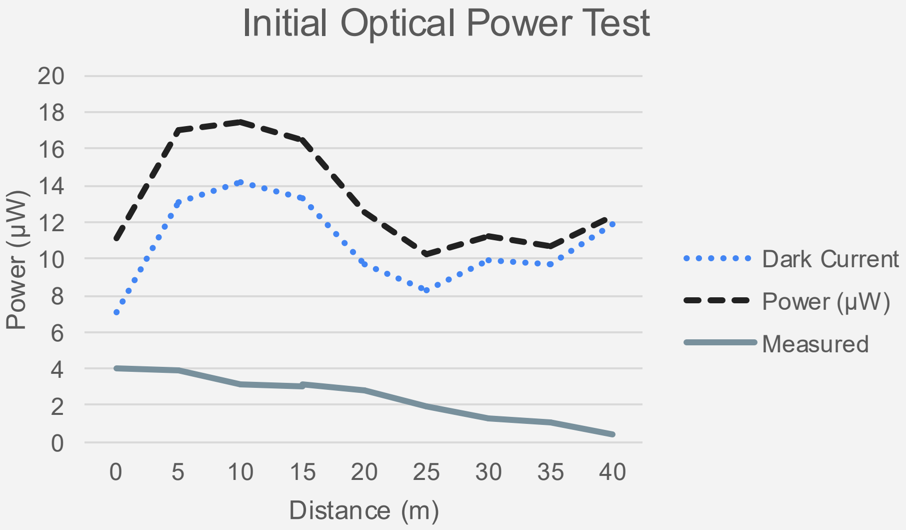
Software Comparison Chart

NEED	SELECTION	ALTERNATIVE 1	ALTERNATIVE 2	ALTERNATIVE 3
A HIGH-LEVEL LANGUAGE ON THE RASPBERRY PI TO ORCHESTRATE RF DETECTION, RUN DSP ON PLUTO SDR DATA, INTERFACE WITH THE CAMERA AND ONNX MODEL, AND GENERATE JSON METADATA IN ONE COHESIVE CODEBASE.	**Python3:** Balances speed of development and strong scientific libraries, maximizing tradeoff between development efficiency and latency.	**C/C++:** Fast, tight control over timing and memory, but fewer libraries and fewer libraries for development.	**Rust:** Memory safe and high performance, but smaller ecosystem for SDR and vision work production.	**Node.js:** Great for web APIs, but weak in scientific / signal processing compared to Python's NumPy/SciPy stack.
LIGHTWEIGHT WEB FRAMEWORK TO DISPLAY THE SYSTEM'S RECENT DETECTION AND IMAGE THROUGH A SIMPLE DASHBOARD DIRECTLY FROM THE PI.	**Flask:** Lightweight and Python-native, making it perfectly sized for the scale of its need.	**Django:** Full framework, but time and space heavy for a local UI design.	**FastAPI:** Very modern with high-performance async APIs, but introduces unnecessary time complexities for a localized build.	Express.js: Popular, lightweight, tons of middleware. However, Node.js is required, leading to more moving parts (two languages, two ecosystems).
A STRAIGHTFORWARD WAY TO CONTROL THE RASPBERRY PI'S GPIO PINS FOR LI-FI LED MODULATION AND OTHER DIGITAL SIGNALS.	**gpiozero:** Simplistic, clean object-oriented interface, reducing errors, and is capable to meeting timing needs for OOK.	**RPi.GPIO:** Widely used and allows direct control of pins, but it is easier to misconfigure pins.	**pigpio:** Very powerful, supports precise timing and remote control. However, it does require running a daemon and more advanced setup; overkill for simple LED on/off FSOC rates.	**WiringPi / C-level libraries:** High performance, with the benefit of being close to the hardware. However, it requires C code, which leads to a more complex build and debug.
A FIRMWARE FRAMEWORK TO IMPLEMENT TIMING-SENSITIVE LI-FI DEMODULATION ON THE ESP32, INCLUDING ADC SAMPLING, OVERSAMPLING, THRESHOLDING, AND BIT/BYTE RECONSTRUCTION.	**Arduino Core for ESP32:** Offers the best balance between performance and simplicity, ensuring reliable bit timing and sampling with C/C++ without more complicated APIs.	**ESP-IDF:** Powerful, and offers professional-grade control over the ESP32. However, there is a steeper learning curve and introduces risk of overcomplication of project setup.	**MicroPython:** Easy and Interactive, uses Python. The tradeoff is that it is notably slower in sampling and bit timing.	**PlatformIO:** Great multi-platform build system, integrates with Arduino well. However, it is an extra tooling to learn; still requires a choice between Arduino vs ESP-IDF underneath.

Prototyping

Prototyping and Testing: FSOC Test

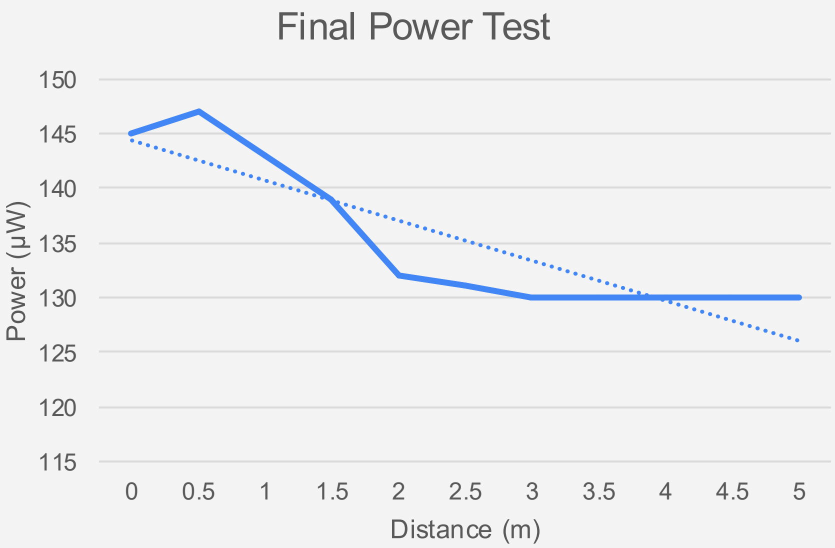
- For the initial testing, in inconsistent lighting environment, and uncollimated light.



Distance (m)	Dark Current	Power (μW)	Measured
0	7.07	11.09	4.02
5	13.09	16.98	3.89
10	14.21	17.39	3.18
15	13.33	16.48	3.15
20	9.68	12.49	2.81
25	8.31	10.25	1.94
30	9.92	11.25	1.33
35	9.64	10.69	1.05
40	11.85	12.26	0.41

Prototyping and Testing: FSOC Test

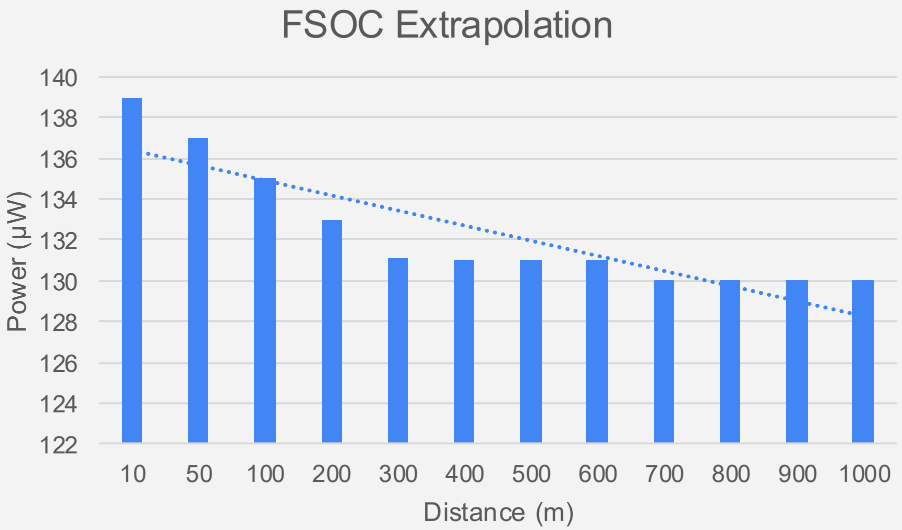
- For the final testing, in consistent lighting environment, and with collimated light.



Distance (m)	Power (µW)
0	145
0.5	147
1	143
1.5	139
2	132
2.5	131
3	130
3.5	130
4	130
4.5	130
5	130

Prototyping and Testing: FSOC Extrapolation

- For extrapolation up to 1km, from the data we were able to record, using line of best fit, and assuming perfect environment/conditions, gives us the following:



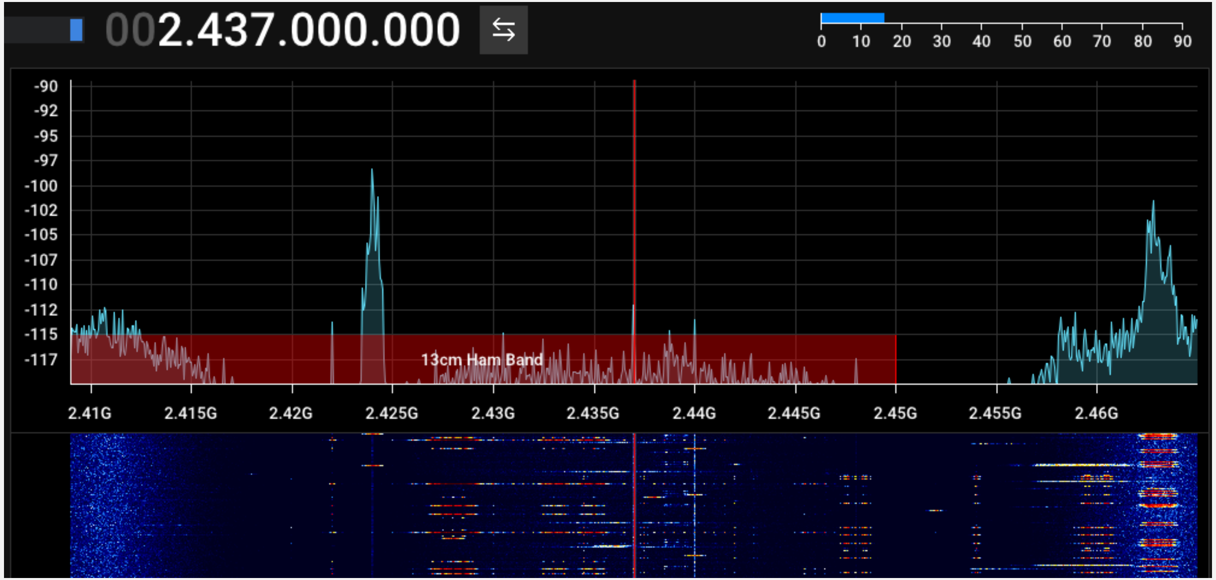
The power quickly converges to ~130 µW and stays essentially constant out to 1 km.

Prototyping and Testing: PlutoSDR-to-Raspberry Pi 5 Data Collection

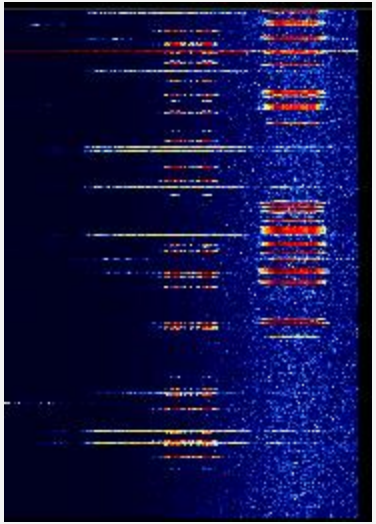
Wi-Fi 2.4 GHz Range

56 MHz Bandwidth centered on Channel 6

Includes Center Frequencies of Channels 1 through 11

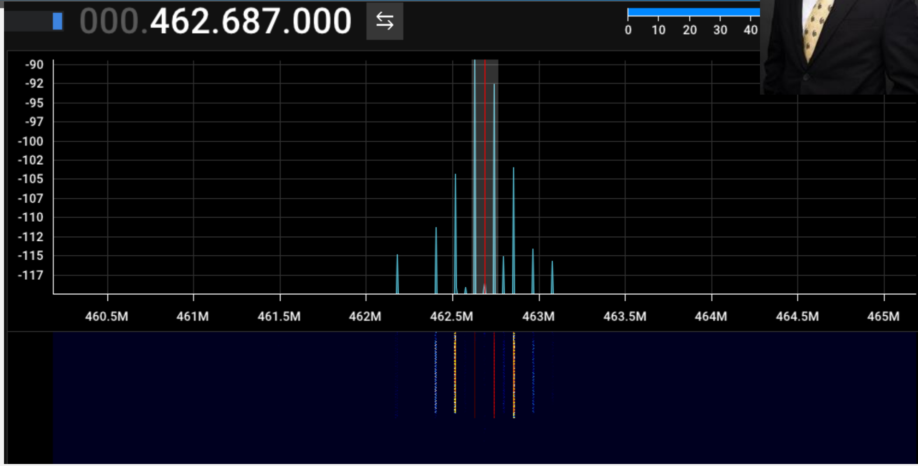


Drone Signal Isolated, on Channel 11



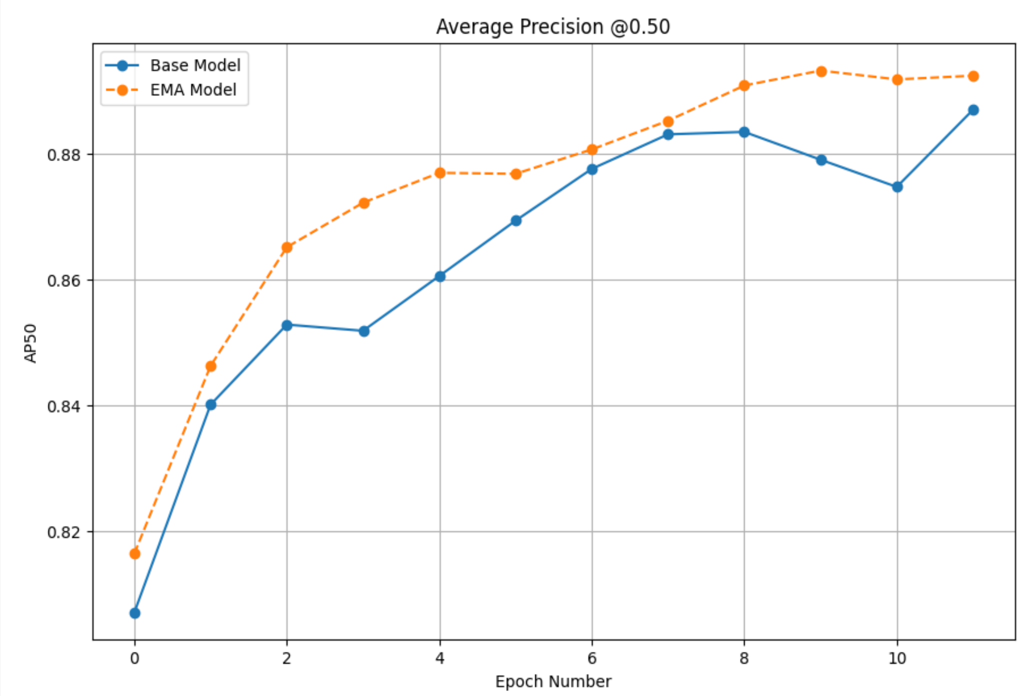
Prototyping and Testing: PlutoSDR-to-Raspberry Pi 5 Data Collection

Walkie-Talkie FRS Signal
- Distance: 5 Feet



Walkie-Talkie FRS Signal
- Distance: 30 Feet
- Walls and Obstacles Present

Prototyping and Testing: Object Detection



AP50 visualization with Res = 438x438 px

Res=384	AP50	Precision	Recall
All	89.2%	92.2%	82.0%
Drone	87.9%	94.7%	-
Cell Phone	84.2%	82.0%	-
Router	95.6%	100%	-

Res=640	AP50	Precision	Recall
All	92.9%	91.2%	89.0%
Drone	93.8%	96.2%	-
Cell Phone	87.9%	77.7%	-
Router	96.9%	99.7%	-

Administrative Content

Budget

- Our project is currently being sponsored by Chief Warrant Officer 5 Richard Godfrey, an Electromagnetic Warfare (EW) Officer for the US Army.

Bill of Materials

QTY	PART NUMBER / NAME	DESCRIPTION	UNIT COST (USD)	TOTAL COST (USD)
1	ADALM-Pluto	RF Development Tools SDR Active Learning Platform	$565.59	$565.59
1	Raspberry Pi 5 (8GB)	Single-board computer	$82.00	$82.00
1	HiLetgo CP2102 USB–TTL	USB 2.0 to TTL serial adapter	$7.39	$7.39
1	Arducam USB Camera Module 3	IMX708 12MP UVC Camera	$47.00	$47.00
1	BPW34S	Silicon PIN Photodiode	$1.32	$1.32
1	LD24AJTA	Adjustable LED Driver Board	$6.20	$6.20
1	Cree XLamp XM-L2	Cool-white high power LED	$10.58	$10.58
1	ESP-WROOM-32	ESP32 Wi-Fi/BLE module	$3.33	$3.33
1	Type-C Female Serial Basic Breakout	USB Type-C breakout board	$1.40	$1.40
1	MCP6002	Dual op-amp	$0.44	$0.44
1	LTC6268	Low-noise op-amp	$0.60	$0.60
1	USB-C Cable	Power/data cable	$3.93	$3.93
1	Power Queen 12V 100Ah LiFePO4	Main system battery	$197.89	$197.89
1	12–24V to 5V 5A Regulator	DC-DC buck converter	$10.99	$10.99
2	LA1252	N-BK7 Plano-Convex Lens	$31.53	$63.06
1	LA1255	N-BK7 Plano-Convex Lens	$28.72	$28.72
1	LA1433	N-BK7 Plano-Convex Lens, Ø1", f = 150 mm	$24.32	$24.32

Work Distribution

Work	Zach F.	Bill	Sarah	Zack. Z
SDR Data Collection		x		x
Data Parsing		x		
ML Algorithm Implementation	x			
Peripheral Installation	x	x		x
UI Design and Implementation		x		
Image Capture	x	x		
FSOC Tx Optics			x	x
FSOC Rx Optics			x	x
Tx Power Supply				x
Rx Power Supply				x
Rx TIA				x
Housing				x
Tx Modulation		x		x
Rx Demodulation		x		x

Issue: Extenuating Situations

- One of the major challenges we ran into with our project was the delay with ordering and receiving parts to build the prototype itself. Though we were able to eventually get the parts approved with government sponsor, we could not get everything shipped on time.

- The solution for this was ordering some new parts out of pocket and redesigning the project with different individual parts, including the modified LED, driver for LED, lenses and photodiode for the FSOC.

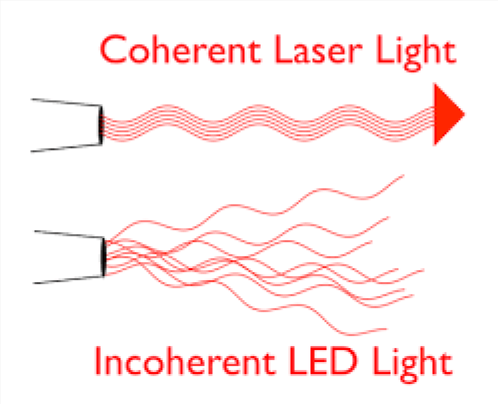
Issues: Hardware/Software

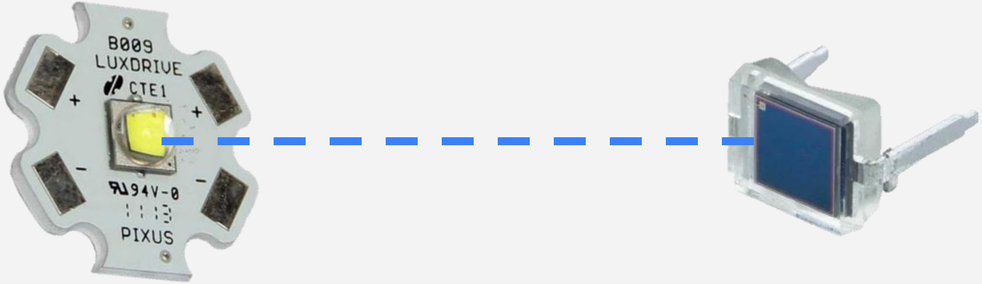
- Locking in meaningful RF parameters proved tricky. Small changes in gain, offset, and bandwidth would either speed up detection but explode our false alarms, or calm the false alarms but make real signals disappear unless they were very strong and close. The noise floor also moved around with time and environment, so values that worked in one test session didn't always hold in another, forcing a lot of iteration to balance speed of detection against reliability of readings.

- Integration proved to be challenging in this project as well. Namely, integrating the object detection model into our main logic pipeline as it required restructuring directories and wiring in new input and output parameters. This meant carefully defining what data the model consumed and how its results were passed back into our pipeline.

Issues: Optics

- Optical Collimation of Incoherent Light source proved to be extremely difficult
- Establishing Line of Sight also proved to be difficult

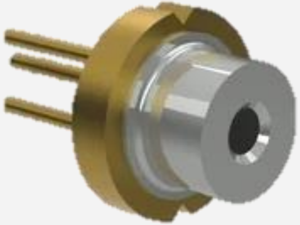




Future Improvements

- For improvements of the project that could be made in the future include:

- More LEDs
- Multiple receivers
- Better antennas for optimized ranges
- Auto-Line of Sight Connector
- Laser Diode



Questions?