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***Design and Implementation of an IoT-Based
Universal Control Unit for Smart Home Wireless
Appliances***

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Dedication

*To my dear brother living abroad,
To the heart that, despite the distance, has always remained close to me with his
support and kindness,
To the one who has always been my pillar of strength and whose words have been a
source of motivation in every step I take,
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always been a great driving force behind my success.*

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because of your presence.*

Abstract:

The rapid growth of the Internet of Things (IoT) has significantly transformed smart home technologies by enabling remote monitoring and control of household appliances. However, the diversity of wireless communication protocols used by different devices creates interoperability challenges and complicates home automation systems. This project presents the design and implementation of an IoT-based universal control unit capable of controlling wireless home appliances using both Infrared (IR) and Radio Frequency (RF) communication technologies. The proposed system is built around the ESP32-S3 microcontroller and integrates IR transmitters/receivers, RF communication modules, Wi-Fi connectivity, and GSM communication through the SIM800L module. The system is capable of learning, storing, and replaying IR and RF commands while providing remote access through IoT technologies. Hardware design was developed using EasyEDA and implemented on a custom PCB. Experimental tests demonstrated the effectiveness of the proposed solution in controlling various smart home appliances through a unified platform. The developed system provides a flexible, low-cost, and scalable solution for integrating heterogeneous wireless devices within smart home environments.

Keywords: Smart Home, Internet of Things (IoT), ESP32-S3, Infrared (IR), Radio Frequency (RF), Universal Control Unit, SIM800L, Home Automation.

Résumé:

La croissance rapide de l'Internet des Objets (IoT) a considérablement transformé les technologies des maisons intelligentes en permettant la surveillance et le contrôle à distance des appareils domestiques. Cependant, la diversité des protocoles de communication sans fil utilisés par différents équipements crée des problèmes d'interopérabilité et complique les systèmes domotiques. Ce projet présente la conception et la réalisation d'une unité de contrôle universelle basée sur l'IoT capable de contrôler des appareils domestiques sans fil à l'aide des technologies de communication Infrarouge (IR) et Radiofréquence (RF). Le système proposé est basé sur le microcontrôleur ESP32-S3 et intègre des modules émetteurs/récepteurs IR, des modules RF, une connectivité Wi-Fi ainsi qu'une communication GSM via le module SIM800L. Le système est capable d'apprendre, de stocker et de reproduire des commandes IR et RF tout en offrant un accès à distance grâce aux technologies IoT. La conception matérielle a été réalisée avec EasyEDA et implémentée sur un circuit imprimé personnalisé. Les tests expérimentaux ont démontré l'efficacité de la solution proposée pour contrôler différents appareils domestiques à travers une plateforme unifiée. Le système développé constitue une solution flexible, économique et évolutive pour l'intégration d'appareils sans fil hétérogènes dans les environnements de maison intelligente.

Mots-clés: Maison intelligente, Internet des Objets, ESP32-S3, Infrarouge, Radiofréquence, Unité de contrôle universelle, SIM800L, Domotique.

المخلص:

أدى التطور السريع لتقنيات إنترنت الأشياء (IoT) إلى إحداث نقلة نوعية في أنظمة المنازل الذكية من خلال توفير إمكانيات المراقبة والتحكم عن بعد في الأجهزة المنزلية. إلا أن تنوع بروتوكولات الاتصال اللاسلكية المستخدمة في هذه الأجهزة يسبب مشكلات في التوافق والتكامل بينها. تهدف هذه المذكرة إلى تصميم وإنجاز وحدة تحكم عالمية قائمة على إنترنت الأشياء للتحكم في الأجهزة المنزلية اللاسلكية باستعمال تقنيتي الأشعة تحت الحمراء (IR) والترددات الراديوية (RF). يعتمد النظام المقترح على المتحكم ESP32-S3 ويضم وحدات إرسال واستقبال IR و RF بالإضافة إلى الاتصال عبر Wi-Fi ووحدة GSM من نوع SIM800L. يتميز النظام بقدرته على تعلم أوامر التحكم وتخزينها وإعادة إرسالها، مع إمكانية التحكم عن بعد عبر تقنيات إنترنت الأشياء. تم تصميم الدارة الإلكترونية باستخدام برنامج EasyEDA وإنجاز لوحة PCB خاصة بالنظام. أظهرت الاختبارات العملية نجاح النظام في التحكم بمختلف الأجهزة المنزلية من خلال منصة موحدة، مما يوفر حلاً مرناً ومنخفض التكلفة وقابلاً للتطوير لدمج الأجهزة اللاسلكية المختلفة داخل بيئات المنازل الذكية.

الكلمات المفتاحية: المنزل الذكي، إنترنت الأشياء، ESP32-S3، الأشعة تحت الحمراء، الترددات الراديوية، وحدة تحكم عالمية، SIM800L، الأتمتة المنزلية.

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List of Abbreviations

IoT: Internet of things
IR: Infrared
RF: Radio Frequency
AI: Artificial intelligence
GSM: Global System for Mobile
TVs: Televisions
SHS: Smart home systems
EMR: Electromagnetic Radiation
NIR: Near Infrared
MIR: Mid Infrared
FIR: Far Infrared
DVD: Digital Video Disc
LOS: Line-of-Sight
LED: Light Emitting Diode
IM/DD: Intensity Modulation / Direct Detection
RZI: Zera Inverted mode
PPM: Pulse position modulation
IrDA: Infrared Data Association
AGC: Automatic Gain Control
HF: High Frequency
VHF: Very High Frequency
UHF: Ultra High Frequency
SHF: Super High Frequency
PCS: Personal Communication Services
3G: Third Generation
GPS: Global Positioning System
LEO: Low Earth Orbit

GEO: Geostationary Earth Orbit

LF: low frequency

MF: Medium Frequency

HF: High Frequency

RAM: Random Access Memor

SRAM: Static Random Access Memor

SSID: Service Set Identifier

PWM: Pulse Width Modulation

ASK: Amplitude Shift Keying

MCU: Microcontroller Unit

HTML: Hyper Text Markup Language

LDO: Low Dropout Regulator

ESD: Electrostatic Discharge

TVS: Transient Voltage Suppressor

DC: Direct Current

HTTP: Hyper Text Transfer Protocol

List of Acronyms

- f*** : Frequency (Hz)
f_c: Carrier Frequency (Hz)
λ: Wavelength (m)
d: Distance between Transmitter and Receiver (m)
P_t: Transmitted Power (W)
P_r: Received Power (W)
G_t: Transmitting Antenna Gain (dBi)
G_r: Receiving Antenna Gain (dBi)
V: Voltage (V)
I: Current (A)
R: Resistance (Ω)
P: Electrical Power (W)
C: Capacitance (F)
L: Inductance (H)
MHz: Megahertz (10^6 Hz)
GHz: Gigahertz (10^9 Hz)
nm: Nanometer (10^{-9} m)
μm: Micrometer (10^{-6} m)

General Intdroduction

General Introduction

The emergence of IoT technology has led to revolutionary shifts in different fields, and the domestic setting is certainly not an exception to this. Smart homes, which used to seem like a futuristic fantasy before, have become a tangible possibility due to the incorporation of IoT technologies. Such houses comprise a network of interconnected gadgets that interact with one another to facilitate task automation and optimize living conditions for their inhabitants. From mere automation devices, smart homes have grown into sophisticated AI environments designed to adapt to user needs and habits. The use of IoT gadgets such as thermostats, lights, appliances, and home security systems enables homeowners to manage their living space from a distance. This innovation not only improves the quality of life but contributes to sustainable practices by maximizing energy.

This dissertation consists of four main chapters, summarized as follows:

The first chapter deals with some of the basic concepts associated with wireless control within smart home systems such as infrared (IR) and radio frequency (RF). It begins with the general idea about smart homes along with the evolution of this concept and explains why there is now an increasing demand for a standardized system to control smart home devices because of their heterogeneous communication protocols. In addition to the introduction, there is the general description of the basics of IR communications, which include a definition, physical properties, methods for sending and receiving signals via this protocol, and examples of its use in consumer electronics and home appliances. In turn, the basics of RF communications include the spectrum, physical characteristics of signal propagation in indoor environment, and the key approaches to transmitting, modulating, and coding messages in smart homes.

The second chapter will provide an overview of the technologies involved in the development of the universal control unit, namely embedded, IoT, and communication technologies. Firstly, it will elaborate on the role of embedded systems in controlling the smart home, mentioning the usage of the Arduino platform to prototype, learn commands, decode, and test the system, as well as the shift from the software prototype towards hardware implementation. Then, it will introduce the ESP32-S3 as an intelligent control module to be employed in this system. The chapter will cover its architecture, Wi-Fi and Bluetooth connectivity, as well as its appropriateness in connecting IR and RF subsystems. Moreover, the technological peculiarities of the IR and RF modules, such as circuitry of transmitters and

receivers, timing, and antenna design will be elaborated. Apart from that, the technology of IoT communication through Wi-Fi and GSM (SIM800L) will be described. Lastly, the web platform and database layer used to store commands and synchronize the system will be introduced.

Chapter Three, Hardware Design of the Universal IR/RF IoT Control Unit, highlights the hardware implementation of the suggested system. This chapter explains the system architecture as well as the operations of the control unit in IR mode, RF mode, and IoT mode. In addition, it elaborates the IR module and RF module design, the design of the main control circuitry using ESP32-S3 microcontroller and the SIM800L for remote communication, and also discusses the PCB design using EasyEDA .

Chapter four is titled Software Development, IR/RF Commands Processing, and Experimental Tests and involves software development and evaluation of the proposed system design. It discusses how the system can be prototyped with Arduino technology and firmware designed for commands processing and IoT control. The chapter also includes experimental tests performed to evaluate the system's efficiency.

Through this research, both the theoretical and practical work relating to the development of the proposed system has successfully been done, thus making it possible to develop a universal infrared radio frequency Internet of Things smart home control unit. The created system allows controlling various devices that can be found in homes using infrared technology, radio frequency technology, and the Internet of Things technology. Thus, the proposed system shows that it is possible to combine different wireless technologies in one embedded system, making it the basis for future research work.

Chapter I:
Wireless Smart Home Control
Using IR and RF

I.1 Introduction

The development of wireless communication technologies has greatly revolutionized the concept of smart homes allowing users to remotely operate household appliances. There are different types of wireless communication used in home automation systems; however, Infrared (IR) and Radio Frequency (RF) communication technologies have gained wide popularity because of their simplicity, cost-effectiveness, reliability, and broad use in consumer electronics.

While Infrared communication technology is widely applied to control short-range line-of-sight consumer electronics like TVs, air conditioners, and multimedia systems, the latter technology is more preferable due to its ability to ensure longer communication range and better performance in obstacle-penetration. These technologies allow creating universal control systems that can manage smart devices on the basis of a single platform.

This chapter introduces theoretical background needed to comprehend the proposed approach to the design of a home automation system. This chapter gives an overview of smart home systems, principles of operation of infrared communication, radio frequency communication technologies, wireless communication propagation and transmission/reception techniques.

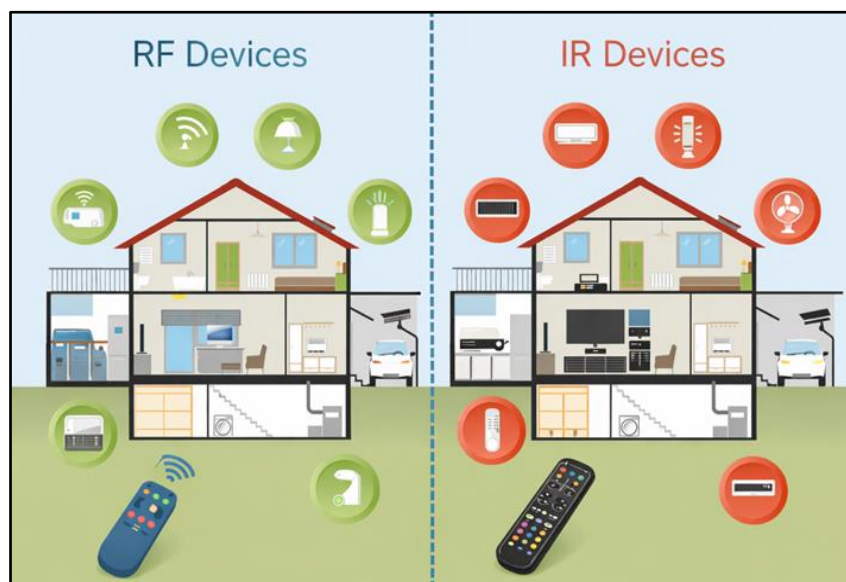


Figure I.1: RF and IR Technologies in Home Automation

I.2 Smart home systems and the need for universal control

The SHS has had unprecedented successes in the last decade and researchers are always trying to improve on its previous works. With the help of IoT, it is easier than ever to establish communication between home appliances and users. In recent years, an IoT based SHS has been the most popular choice. All devices are connected to the Internet so you can control all the equipment in the house at the same time. IoT enables users to monitor and control many things of their house from any place in the world [1].



Figure I.2: Smart Home System Overview

I.2.1 Evolution of smart homes

A "smart home" is a home that has a lot of connected devices and systems that can be controlled and automated to make life easier, more comfortable, more energy efficient, and safer. The idea of smart homes goes back to the early 1980s, when the phrase "home automation" started to catch on. At the time, the idea was new: homes that could be controlled by pushing a button or from a distance using computers. But these first smart homes were nothing like the smooth experiences we have now. People thought they were "gimmicky," and they were often complicated and expensive. Today, smart homes have come a long way and are now a big part of modern life [2].

I.2.2 Heterogeneity of household communication protocols

Smart home systems use communication protocols to let different devices talk to each other and work well together in the home. These protocols make sure that sensors, appliances, and control units can all connect to each other reliably, which makes automation and interaction possible. KNX-RF, EnOcean, Zigbee, Z-Wave, and Thread are some of the most common protocols used in smart home applications. Each has its own set of features, such as range, power use, and network architecture [3].

I.2.3 Need for a unified wireless control unit

Smart home environments are marked by the presence of various communication technologies, resulting in challenges related to heterogeneity and interoperability [4][5]. Different devices often use different protocols, like WiFi, Zigbee, RF, and IR, which makes the system more complicated and makes it harder to connect devices [4]. Unified control frameworks have been suggested to combine different technologies into one platform so that smart home devices can be managed from one place in a more efficient way [6]. Also, wireless control modules can be central units that let users control several devices from one place, which makes the system easier to use and works better overall [7].

I.3 Fundamentals of infrared communication (IR)

The infrared portion of the electromagnetic spectrum occupies the frequency range of (300 GHz - 430 THz), which corresponds to wavelengths of about 980 nm. Light waves can be transmitted as well as received in this frequency range, thus allowing for data transmission through these light waves via communication between two mobile devices or from a mobile device to one that is fixed.

Point-to-point communication: There should be no barriers between the transmitter and receiver infrared devices so that they can see each other clearly.

Diffuse communication: The transmitter and receiver IR devices should be close together, but they don't have to be in the same line of sight. Most commercial IR products work well when they are within 15 degrees of each other [8].

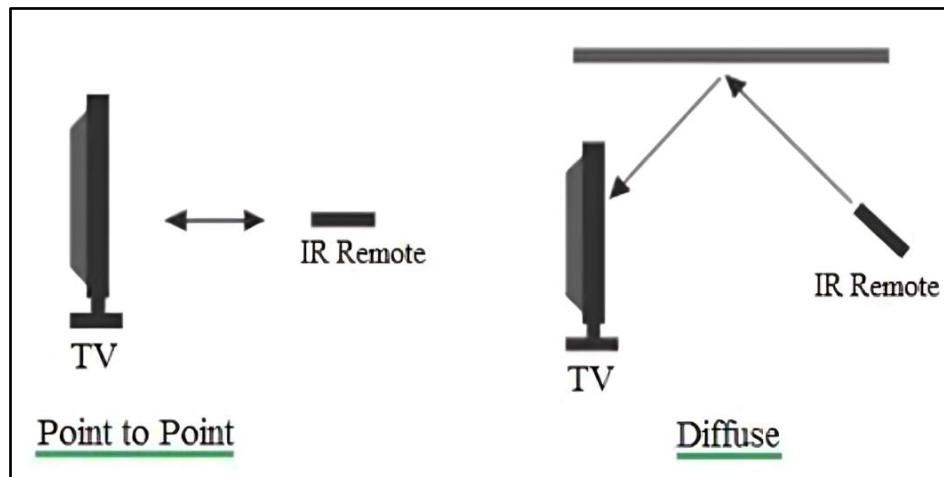


Figure I.3: Infrared Communication Network

I.3.1 Definition of infrared radiation

Infrared is one type of EMR consisting of electromagnetic waves having longer than visible light wavelengths with all of the same characteristics of EMR. Wavelengths of IR radiation extend beyond (from the longest wavelength to the shortest) the approximate value at the red edge of the visible spectrum (700 nm) to the point where microwaves start on the electromagnetic spectrum (1 mm). So the IR frequency range is going from about 430 THz to 300 GHz [9].

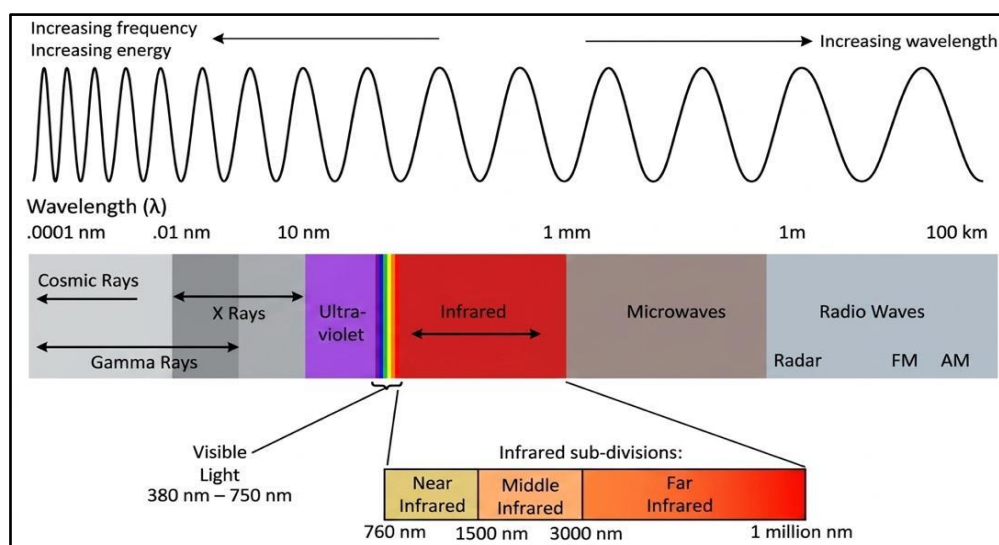


Figure I.4: A representation of the electromagnetic spectrum including the infrared light

I.3.2 Position of IR in the electromagnetic spectrum

The electromagnetic spectrum has infrared (IR) radiation between microwaves and the visible spectrum of our eyes. The starting point for IR radiation is around 700 nanometres, (hereafter referred to as “nm”) or 0.7 micrometres, (also called “ μm ”).

The endpoint for IR radiation is approximately 1 mm, where IR merges with microwaves.

In terms of order within the electromagnetic spectrum, the following categories are applicable for infrared radiation labelled sequentially based on length from shortest to longest by their respective wavelengths:

- Visible Light: 400 nm - 700 nm
- Infrared Radiation: 700 nm - 1 mm
- Microwave Radiation: Greater than 1 mm in length [10].

Thus, infrared radiation fills the area between visible light (from the red end of the spectrum) and microwaves.

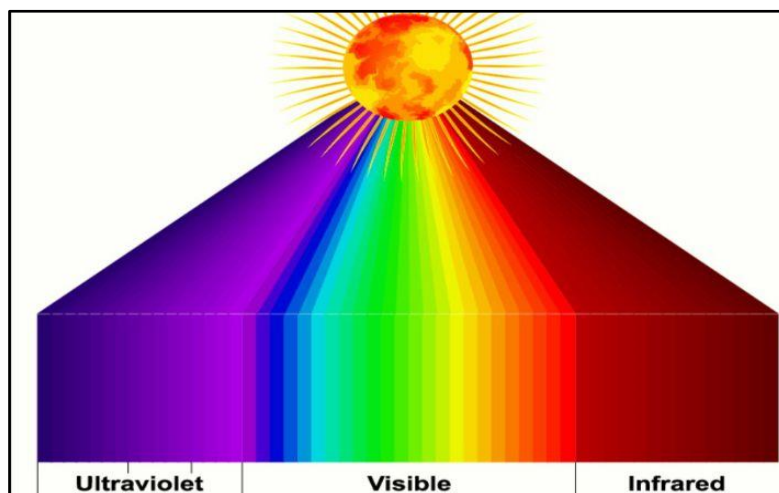


Figure I.5: Electromagnetic Spectrum

I.3.3 Near IR, mid IR, and far IR

The infrared spectrum is a key part of the electromagnetic spectrum. It sits between visible light and microwaves. Infrared wavelengths fall into three main categories: near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR). Each of these regions has distinct features and uses. Knowing these divisions, along with terms like MWIR (mid-wave IR) and

LWIR (long-wave IR), is important for industries that depend on spectroscopy, thermal imaging, and optical sensing. In this guide, we will explain infrared wavelengths, compare the regions, and look at their applications [11].

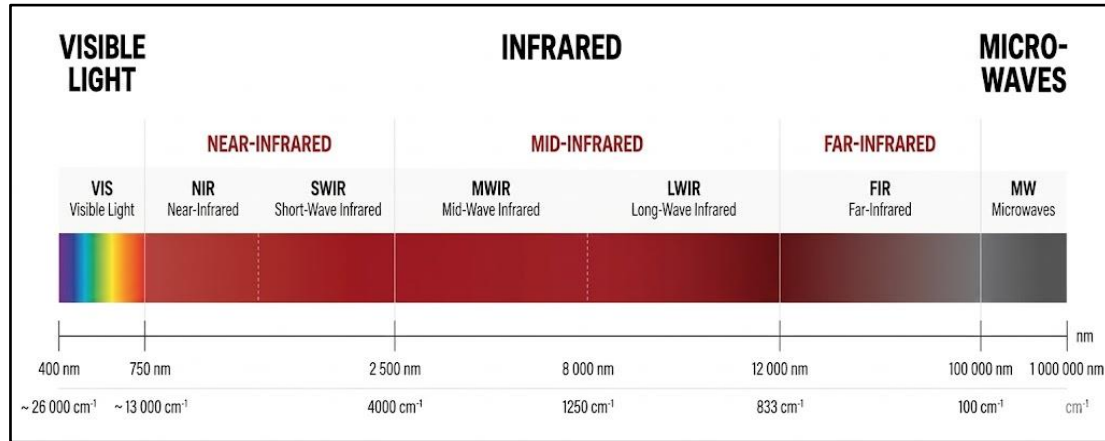


Figure I.6: Electromagnetic Spectrum (Infrared Region)

Infrared light spans wavelengths between 0.7 μm to 100 μm , divided into the following regions:

Region	Wavelength Range	Frequency Range	Key Applications
Near-Infrared (NIR)	0.7 – 2.5 μm	120 – 430 THz	Spectroscopy, fiber optics, material analysis
Mid-Infrared (MIR)	2.5 – 12 μm	25 – 120 THz	Gas sensing, molecular spectroscopy, coatings
Far-Infrared (FIR)	12 – 100 μm	3 – 25 THz	Thermal imaging, astronomy, environmental analysis

Table I.1: Classification of Infrared Regions and Their Applications

I.3.4 IR in consumer electronics and home appliances

IR (infrared) communication is a popular and low-cost way to wirelessly control consumer electronic products like televisions, air conditioners, DVD players, projectors and other home theaters. An IR remote sends modulated light signals to an IR receiver, allowing the IR receiver to decode the command and change the state of the appliance (on/off, volume, channel or fan speed) [12].

To provide central remote control capability of multiple appliances, such as lights, fans, or sockets using a single remote (IR) control unit or a smartphone device (IR transmitter), modern smart-home solutions utilize IR technology combined with a microcontroller, such as an Arduino. Many remote (IR) controls used in consumer IR systems work under the conditions of line-of-sight and are limited to short distances (approximately 10 meters). Their low power consumption and ability to avoid minimal interference, makes IR consumer systems a very popular method for integrating legacy IR appliances into advanced smart home automation systems [13].

I.4 Physical and technical characteristics of IR communication

Infrared (IR) communications utilize invisible infrared light (typically between 750 nm and 1 mm in wavelength) to wirelessly transmit data over short distances. There are various applications for IR communications; for instance, they are regularly used for line of sight communication (e.g. remote controls). IR communication is considered inexpensive, secure, low-power communication method to transfer data from point A to point B [13-17].

Here are the key physical and technical characteristics of infrared communication:

Physical Characteristics:

- **Spectrum Usage:** Infrared communication operates at or near 850 - 950 nm within the near-infrared (or infrared) band, i.e. just below the visible red portion of the light spectrum [18].
- **Line-of-Sight (LOS):** Communication via infrared signals generally requires a direct line between the transmitter and receiver but there are reflective based infrared systems that can bounce off of walls or ceilings [19].
- **Physical Containment:** Infrared signals cannot penetrate through walls or opaque surfaces; therefore, maintaining a high degree of security within a single room;

preventing a potential communications interference from devices located in other rooms [20].

- **Components:** Infrared transmitters generally use either LEDs or lasers to create infrared light, while receivers will typically be photodiodes (pin type photodiodes) or phototransistors [21].
- **Range:** Infrared communications are normally short range (1-2 meters for normal use) but some infrared data communications have a greater distance.

Characteristic of Technology:

- **Modulation Technique:** IM/DD is the method of communication via an intensity modulation with direct detection of light. Thus, the light intensity can vary to carry the information being sent [22].
- **Data Rates:** Slow data transfer rates (908.6 kb/s) are possible, while the highest rate observed in any particular application is greater than 1 Gb/s (i.e., up to 4 Mb/s), and, therefore, there are typically higher rates than this data transfer rate.
- **Operating Modes:**

Directed: Requires proper alignment to be used (like remote controls).

Diffuse: Provides a light reflection or scattering so that it can be used in a space without defined lines of vision; therefore, there is much more flexibility and ease of use for operating an item within a room if using a diffuse mode [23].

- **Data Encoding (IrDA Standards):** The types of data Encoding result in: in idR, Robert Zera Inverted mode (RZI) and IDR or Pulse position modulation (PPM) for fast IR (FIR) are the standards used by IrDA [24].
- **Noise and Interference:** IR devices can experience interference, mainly from strong ambient/light sources, including sunlight and fluorescent bulbs [25].

I.4.1 Wavelength and optical propagation

- **Wavelength:**

Infrared radiation is a part of the electromagnetic spectrum. It has a wavelength range of 750 nm to 1 mm and a frequency range of 400 THz to 300 GHz [26].

BAND	WAVELENGTH	APPLICATIONS
Far IR	14-50 μ m	Properties of molecules
Long-wave IR	8-14 μ m	Laser radar, forward-looking IR
Near IR	1-3 μ m	Personnel detection
Very-near IR	0.76-1 μ m	Imaging, laser ranging (industrial)

Table I.2: Infrared Spectrum Bands and Applications

- **optical propagation:**

Light moves along straight lines through a material that has a uniform density, also called a homogeneous medium. When the light reaches the boundary between two different kinds of materials, it will either reflect or refract based on the characteristics of those materials. The amount that the light direction changes (its angle) is determined by Snell's Law, and light intensity can also be reduced because of absorption and/or scattering within the medium as it travels through the medium to the point of being transmitted [27].

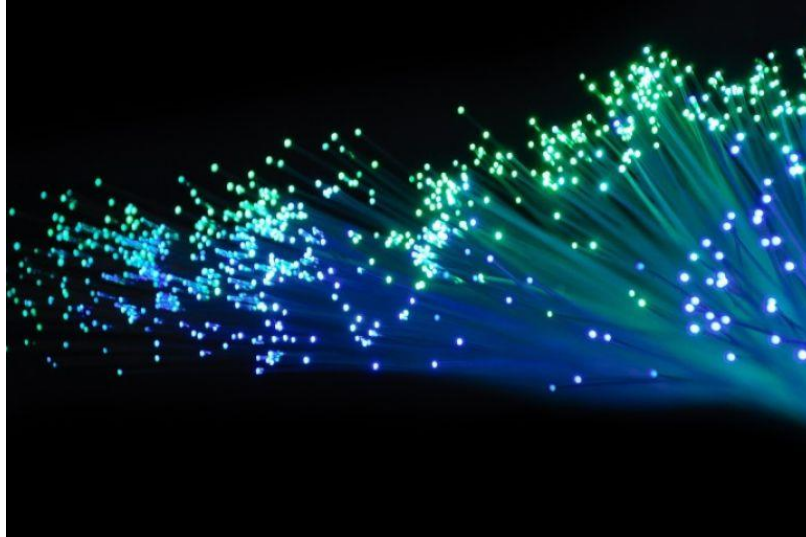


Figure I.7: optical propagation

I.4.2 Line-of-sight requirement

The Line of Sight constraint deals with the blockage of the signal from the transmitting to the receiving object by the ground (i.e., taking into account interference due to light time delays). In this case, the ground is treated as an ellipsoid that is stationary in respect to the central body fixed frame. The ellipsoid is used to represent the ground as 'locally flat' (i.e., no hills, no mountains, and no valleys) and serves as the most basic representation of the ground. More complex models of the ground require the use of Az-El masks as well as some form of terrain model; these effects are handled by different Access constraints [28].

I.4.3 Reflection and diffuse propagation inside rooms

The fundamental principles governing the reflections of sound will be true as long as the reflecting surface is infinite in size. In reality, however, all free edges of a given reflective surface or panel will cause the sound energy they reflect to scatter off the surface into all directions away from the edge. Therefore, whenever the sound wave strikes any other reflective surface (such as a wall) that is not infinite in size, that surface will also scatter the sound energy off into various different directions from the point of incidence to the surface. This scattering of sound after it has passed through an object is called diffraction; it occurs very frequently in room acoustics and is often referred to as sound scattering. Diffuse reflection has been defined by some as being the result of diffraction. Therefore, it is necessary to first define and describe diffraction before we can define and describe

diffuse reflection [29].

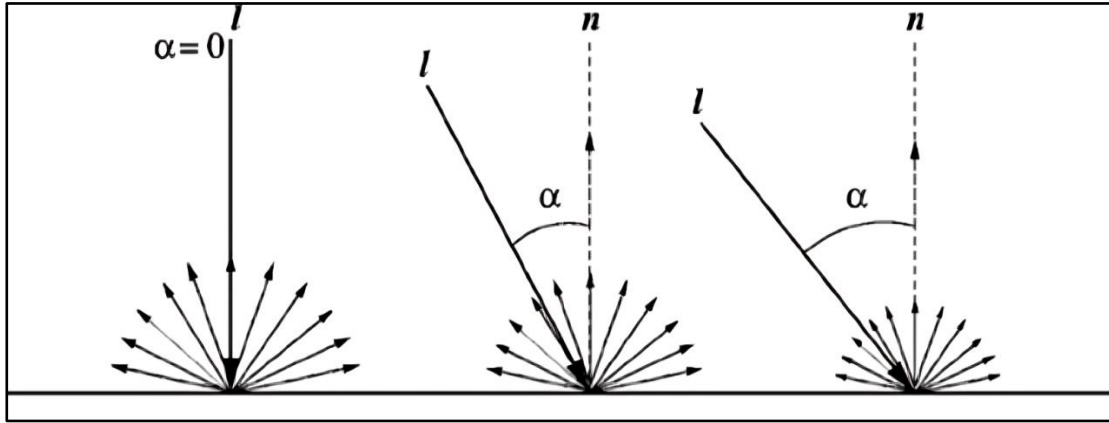


Figure I.8: Diffuse reflection

I.4.4 Effect of sunlight and ambient lighting

Visual performance and human performance are greatly affected by both sunlight and the ambient light in the indoor space. Evidence shows that there is an improvement in cognitive performance, alertness, and mood with increased exposure to natural daylight in comparison to low quantities or uneven distributions of artificial light, which often result in fatigue and decreased task performance [30].

The amount of ambient light in various environments differs significantly between indoor spaces and outdoor spaces; typical outdoor light levels can be 8 times greater than typical indoor levels (including on cloudy days). The differences in the amount of natural sunlight and ambient light produce a direct impact on circadian rhythm, sleep quality, and mental health. Consequently, it is critical to consider the lighting of an indoor space when designing human-centric lighting systems [31][32].

I.4.5 Range limitations and directional behavior

Natural (e.g., plants and animals, fungus) and engineered (e.g., telecommunications, transportation) systems exhibit both range limits as well as directional behaviors when they spread or communicate. For instance; in nature the geographic limits of a species' range are determined by not only the availability of resources but also the direction a species moves and how well search for food locally, which affect the degree to which the individual can disperse from source populations and remain viable beyond that range [33].

Similarly, technologically based (e.g., directional sensor networks); the range of a sensor's detection ability is limited by both the existence of a detection region or sector and

the number of possible operational orientations; thereby creating physical limitations in how many different types of targets or signal will be covered which will affect the information that is communicated when a signal or target is detected. Directional behavior can improve detection strength within a finite directional path but decreases the omni-directional path thereby increasing the amount of misalignment and obstruction errors within the system [34].

I.5 IR transmission and reception techniques

Electromagnetic Radiation from infrared range (430THz-300GHz) has a wavelength of $\sim 980\text{nm}$. Light wave propagation in this frequency range can be utilized to provide the transmission and reception of data to/from two portable devices or between a portable device & a fixed device in an infrared communication system [35].

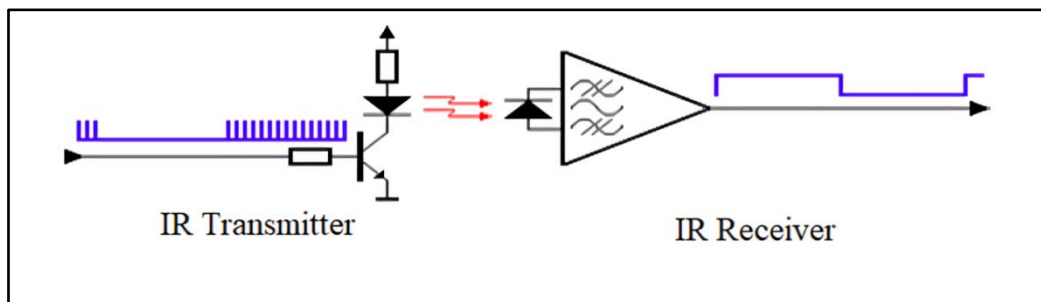


Figure I.9: IR Transmitter and Receiver

I.5.1 IR LED as optical transmitter

The IR LED is used to transmit infrared signals. The IR LED looks just like a regular LED, but instead it will transmit infrared signals. The IR LED is not visible to the human eye because IR rays are out of the visible spectrum of light.

IR LEDs will produce light output that is not visible to the human eye. IR LEDs can also be used as replacement LEDs for remote controls, night vision in camcorders, and as invisible beam sensors [36].

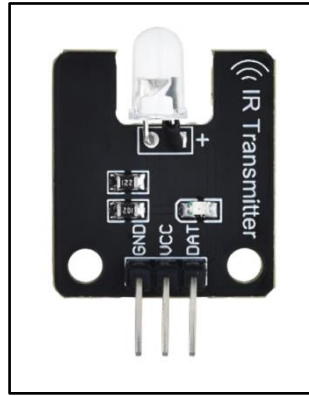


Figure I.10: IR LED as optical transmitter

I.5.2 IR receiver modules and demodulation

Modules for receiving IR signals are highly interconnected systems designed to detect signals sent by IR transmitters and produce useable electrical signals from them. They consist of a Photodiode, gain stage amplifier, automatic gain control circuitry and demodulation stage, which combines to convert signals over a modulated frequency (usually ~38 kHz) to avoid interference from outside light sources into correctly filtered, amplified and demodulated digital signals for use with microcontrollers and other digital circuit devices [37].

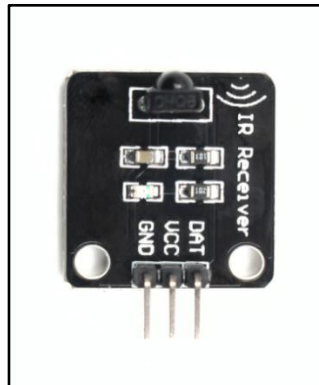


Figure I.11: IR receiver modules

I.5.3 Carrier frequencies in remote control systems

Using an infrared (IR) remote control system, data can be transmitted accurately by modulating the IR signal on to a 38 kHz (38,000 Hz) carrier frequency. By modulating the IR signal onto a carrier frequency, it reduces the likelihood of interference from ambient light

sources that emit IR energy, such as the sun or electric lights. Therefore, when the IR signal is modulated (on to the carrier frequency), it can be easily identified from the different background noise of the IR environment that exists when an IR signal is generated at the same time an IR device receives and demodulates the IR signal back into its useable digital format [38].

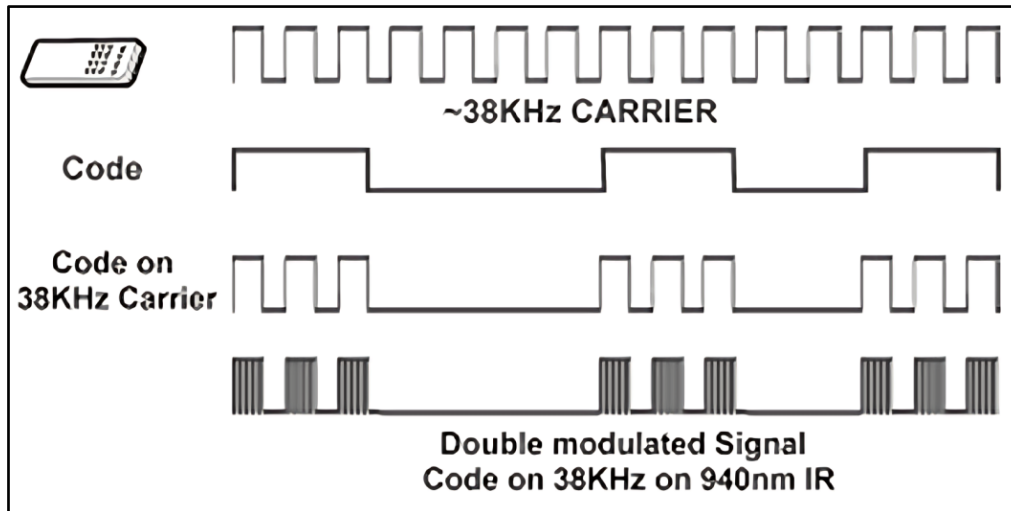


Figure I.12: Signal Modulation Using a 38 kHz Carrier Frequency in Infrared Remote Control Systems

I.5.4 Common IR coding schemes

The majority of infrared remote control systems utilize a standardized modulation protocol. A transmitter will send a square wave signal, with a frequency of either 38kHz or 40kHz, and is designed such that it operates at an average of 50% duty cycle for the duration of the transmission. A stream of bits will represent the digital data in a manner that pulses the square wave so that it can be transmitted from one or more infrared LED's. Typically, the infrared light produced will have a wavelength of 940 nm (plus or minus 100 nm). The details of the transmitter circuits will be covered in this section [39].

The receiver circuitry includes a photodiode that can detect light emitted at the same frequency as specified above, a pre-amplifier and a demodulator. The pre-amplifier includes a bandpass filter, which will have a 3db rollover at $\pm 3\text{kHz}$ from its center frequency. There is also an AGC in the receiver circuit to adjust the input signal for optimum levels for the demodulator. Most protocols utilize long preambles (or leading pulses), which create an AGC reference point prior to modulation. The output of the receiver is a bit stream that corresponds to the original gating signal that created/modulated the transmitted data. As almost all

protocols are active low, i.e., in the carrier level system, a low level (typically zero volts) is equal to a logical '1' and a high level (typically 5 volts) represents a logical '0', the overall operation of receiver circuits and modules will be discussed.

I.5.5 Learning and replaying IR commands

The ability to capture a command sent by infrared and then re-send that command on command using the same exact transmission frequency (IR frequency) has been utilized in applications such as programmable remotes and microcontroller based designs [37].

Learning:

- Use Infrared Photo Diode as the receiver of the incoming IR signal.
- Demodulate the incoming signal to retrieve the original data.
- Convert the Data into bitstreams.
- Store Data in Memory for Future Use.

Replaying:

- Data stored in memory has been retrieved.
- The same signal is retransmitted using an IR LED.
- Typically the data will be transmitted as a carrier frequency of roughly 38KHz.
- The original remote command will be accurately reproduced.

I.6 Applications of IR in smart homes

IR (infrared) technology is utilized extensively within the realm of smart homes as a method of control and integration for many types of devices/technologies that are found in homes today. IR has special importance with devices of television control and air conditioning control due to the transmission of IR signals from remotes or smart hubs to IR sensors on the devices to allow for adjustment of both the operational functions (e.g., power, volume, etc.) as well as the operational parameters (e.g., temperature, mode of operation, etc.) of the devices. In addition to consumer electronics, IR technology is commonly used throughout media systems (home theater systems and/or audio systems) to allow for control of multiple devices from a single interface. In addition to these applications, legacy device integration is completed by integrating an older style of device utilizing the traditional (non-smart) type of IR remote control into a new type (i.e., smart) type of system through use of an

IR blaster or universal controller. By using tools for automating older appliance types, end users can therefore take advantage of enhanced convenience and flexibility for their overall system [40].

I.6.1 Television control

remotely controlling your television set, for example via remote control, using an IR remote control sends infrared signals to the television set so that you can turn it on/off, change channels and adjust the volume. The TV receives the signals through its infrared receiver (IR) sensor [41].



Figure I.13: Television control

I.6.2 Air conditioner control

This means that you can control your air conditioner from anywhere, so you'd be able to adjust the temperature, fan speed, mode and the power on/off. The remote control sends IR commands through IR (infrared) signals to the AC unit to change the settings requested. The AC then receives these IR

commands and acts upon them via its built-in IR receiver [42].

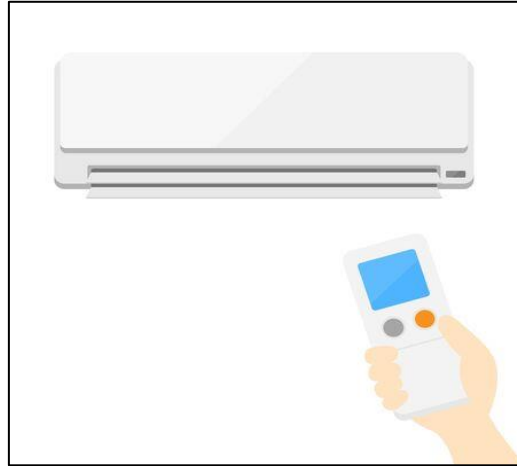


Figure I.14: Air conditioner control

I.6.3 Media systems

The controlling of DVD players, satellite boxes, sound systems, etc., is accomplished by sending infrared (IR) coded light signals from the remote control and the media device decodes the IR signal to perform the requested action [43].

I.6.4 Legacy device integration

This means being able to connect older IR appliances to newer smart home systems, without having to buy anything new. The IR blaster (a type of smart hub) sends or captures the original infrared codes from the older device so that you can control it via an app or automation system [44].

I.7 Fundamentals of radio frequency (RF) communication

Electromagnetic waves at frequencies between 300 and 3 kHz are termed Radio Frequency, and the modulation of audio and/or visual signals onto these high frequency waves allows for wireless communications to take place. Visualize something like placing a letter (the signal) onto an envelope (the carrier wave) and sending it via a Post Office (the electromagnetic wave); this is what makes broadcast radio and some other forms of wireless communication possible. An early example of this technology can be found in FM radio broadcasting where audio signals are modulated onto carrier frequencies within the range of 88-108 MHz [45].

I.7.1 Definition of RF communication

The term "RF" was originally meant to apply strictly to radio or radio frequency but now has come to mean all types of wireless or high frequency signals. The most obvious example of this is Amplitude Modulation radio, which falls between 535 kHz through 1605 kHz. Computer networks operate on a frequency range of approximately 2.4 GHz. Historically RF was typically thought of as being between 1 kHz and 1 GHz. If microwave frequencies are included in the definition of RF then their range expands to include 300 GHz. The two tables below show some of the names for the different frequency bands. The third table shows some of the uses of those frequency bands [46].

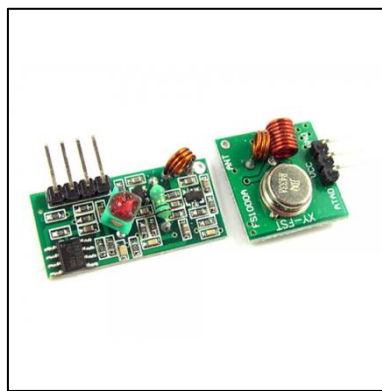


Figure I.15: RF Receiver and Transmitter

I.7.2 RF spectrum overview

Radio frequency spectrum is broken down into some different bands of frequencies exhibited on a log scale which can then be labelled as "l.f.", "m.f.", "h.f.", and so on (these are displayed in Figure I.7.2). The range of frequencies known as microwaves (generally, 1-30 GHz) has further been divided with each subset assigned its own alphabetical designation; for example, X Band covers the range from 8 to 12 GHz, but will also be found listed differently by various authorities causing some confusion between them. The range of frequencies from 30 to 100 GHz is referred to as the Millimetric Band. The International Telecommunications Union (ITU) has included allocations for radio frequencies up to 275 GHz; however, there's only minimal amounts of non-experimental use above 100 GHz at the present time [47].

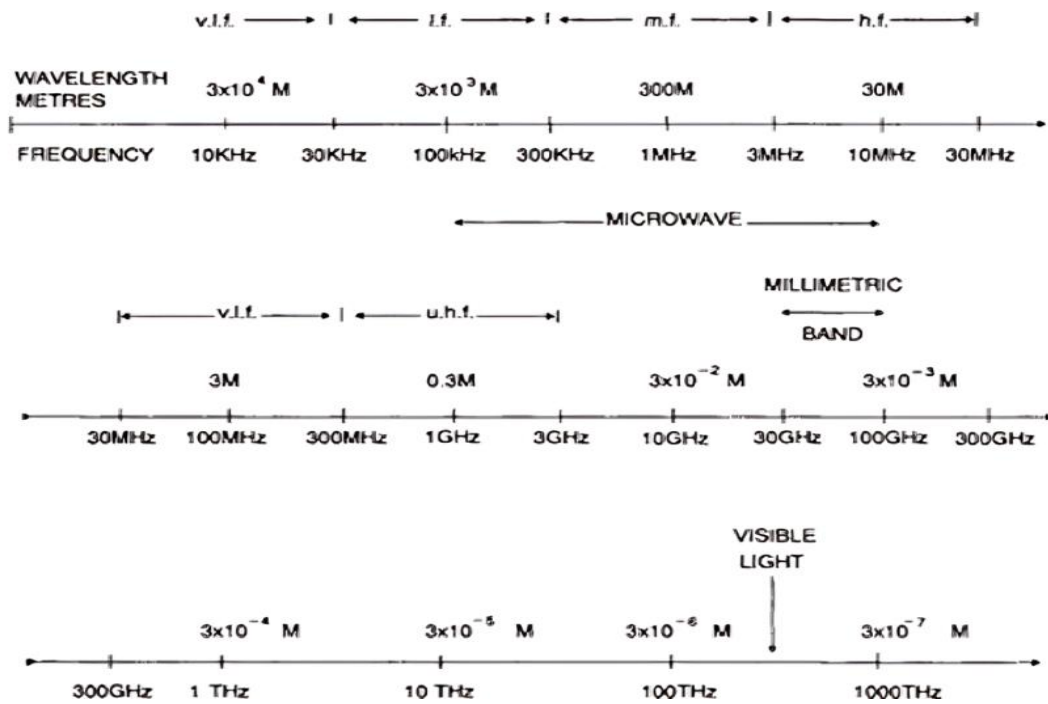


Figure I.16: Radio frequency bands and designation

I.7.3 Difference between low frequency, HF, VHF, UHF, SHF

- **High Frequency (HF):**

HF Sky wave is the predominant method of communication from the Earth to space; however, Ground wave is also acceptable for establishing two-way communications at short ranges (50 km). In short, one of HF's primary advantages is its capability of providing reliable BLOS (beyond line of sight) communications over short and long distances [48].

HF is primarily used in many different situations and it is a highly available frequency that is easily deployed and requires almost no infrastructure. Furthermore, depending on the method of use, the types of technologies available to utilize the HF frequencies can be very different. Some of the major applications of HF include international radio broadcasting, long-range communication for aircraft and ships and CB radios.

- **Very High Frequency (VHF):**

The reflection and diffraction of waves allow them to spread out further, allowing for distance to be travelled through buildings. FM radio (88-108 MHz) and broadcast television are two major uses of this phenomenon. Other examples include radio beacons for aviation and AM communication with aircraft.

- **Ultra High Frequency (UHF):**

Frequency Bands consist of two different types of communication methods, short and long range (LOS). In both cases, if the transmission signal travels to an object or the object blocks the signal then it will not reach the receiving (intended) end. Technologies such as GPS, microwaves, and Wireless PCS, 3G and Bluetooth are all types of Frequency Band communication methods that utilize the long and short LOS methods of communication regardless of distance, which can be respectively defined as a long-distance microwave device communicating via either 3 km or 10 in both short-haul microwave and/or GPS [49].

- **Super High Frequency (SHF):**

Absorption from the atmosphere (e.g. rain, clouds) limits the distance of propagation.

Satellite telecommunication services for telephony and television, LEO and GEO satellite systems and prospective future mobile telephone systems are examples of uses for these types of propagation [50].

Range Name	Abbreviation	Frequency Range
High Frequency	HF	3 MHz - 30 MHz
Very High Frequency	VHF	30 MHz - 300 MHz
Ultra High Frequency	UHF	300 MHz - 3 GHz
Super High Frequency	SHF	3 GHz - 30 GHz

Table I.3: RF Spectrum Ranges

I.7.4 Position of 315 MHz with in the RF spectrum

The radio frequency 315 MHz is in the UHF (Ultra High Frequency) portion of the spectrum above VHF and below the microwave band. It is used extensively for applications that require short-range wireless communications such as remote controls, keyless entry systems, and garage door openers, along with any other application that is considered low-power RF.

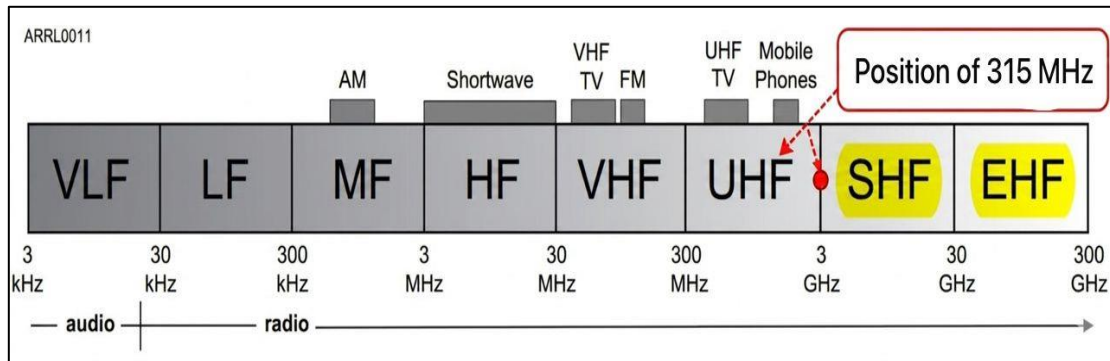


Figure I.17: Position of 315 MHz within the RF spectrum

I.7.5 Clarification of UHF and very-high-frequency concepts in home control

- **The UHF Frequency Range (300 MHz-3 GHz):** is commonly utilized for indoor, short-distance automated processes. The shorter wavelengths (1-10 cm) can go through walls, steel, and concrete without impediment.
- **The VHF Frequency Range (30-300 MHz):** is used for long-distance outdoor applications. Its wavelengths (10-100 m) travel a greater distance than UHF, but are easily blocked by obstacles [51].

I.8 Detailed RF band study for wireless control

Wireless control systems are typically using sub-GHz and UHF RF bands due to their optimal balance between range, penetration capability and lower power consumption. In general, sub-GHz RF bands (e.g., 315 MHz, 433 MHz, 868 MHz, and 915 MHz) provide some level of improved obstacle penetration and longer distances when compared to 2.4 GHz RF bands.

These benefits make the sub-GHz RF bands particularly desirable for remote controls, home automation, sensor networks and low-power IoT devices. However, due to variable spectrum regulations, varying levels of interference and data rate requirements of each application there can be no absolute definitive RF band that would be appropriate for all applications; therefore a specific RF band must be used for each application.

I.8.1 LF, MF, HF overview

As shown the low frequency range (Long Wave) for Transmissions are between 140.5 KHz to 283.5 kHz Longwaves in this frequency range are available at various locations around the world and fall under the category of Low Frequency (LF) Transmission. To note,

Navigational Beacons (Nav aids) operate on frequencies that are equal or less than 100 KHz therefore, also fall under LF.

Next in line is MF (Medium Wave) for the purposes of transmission; this covers 525 KHz to 1705 KHz. This portion of the spectrum can be the start of low frequency Shortwaves.

Next we have High Frequency (HF) covering between 3 to 30 MHz; this covers a wide range of frequency that includes Shortwave transmissions. The range of Shortwave Transmissions are substantial and accessible for broadcasting and amateur radio operators from across Continents [52].

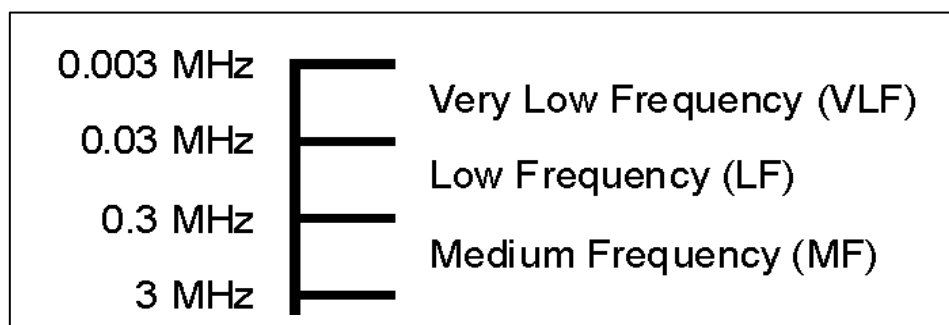


Figure I.18: The radio spectrum

I.8.2 VHF band characteristics

VHF (Very High Frequency) is the radio frequency range from 30 MHz to 300 MHz. It sits between the HF and UHF bands and is popular because it offers good signal qualities, including relatively long distances for transmission and low loss in the atmosphere.

You can find VHF in various applications like FM radio broadcasting, television transmission, land mobile communications (including emergency and military services), marine communication, amateur radio, and air navigation systems such as VOR, DME, and ILS [53].

I.8.3 UHF band characteristics

UHF (Ultra High Frequency) means a certain range of frequencies in the electromagnetic spectrum that extends from 300 MHz to 3 GHz. It is sometimes referred to as the decimeter waveband because its wavelengths vary from 10 cm to 1 m. UHF waves possess line-of-sight propagation and have shorter distances than VHF waves. Their penetration capacity through buildings is greater than that of VHF waves [53].

I.8.4 Why home remote systems often use sub-GHz RF

The home automation remote system and IoT devices use radio frequency signals below the GHz band (315 MHz, 433 MHz, 868 MHz, and 915 MHz) because they offer superior performance in three critical areas compared to 2.4 GHz systems (Wi-Fi and Bluetooth) in the following key aspects: greater range, enhanced obstacle penetration, and reduced power usage [54][55][56].

I.8.5 Comparison between 315 MHz, 433 MHz, 868 MHz, and 2.4 GHz for smart homes

Feature	315 / 433 MHz	868 MHz	2.4 GHz
Common Protocols	Proprietary, Garage doors	Z-Wave, LoRa	Wi-Fi, Bluetooth, Zigbee, Matter
Range	High (Long distance)	Medium-High	Low-Medium
Wall Penetration	Excellent	Very Good	Moderate
Data Rate	Very Low	Low	Very High
Interference Risk	Low	Low	High (Crowded)
Power Usage	Ultra-Low	Low	Moderate to High

Table I.4: Comparison between 315 MHz, 433 MHz, 868 MHz, and 2.4 GHz for Smart Home Applications

I.9 RF propagation in indoor environments

The environment around indoor RF propagation, like walls, floors, and other things in the way, has a big effect on it. These things cause reflection, diffraction, and scattering. These things make the channel more complicated than it is outside because they cause multipath propagation and a lot of signal loss. For smart homes and IoT applications to have reliable wireless communication systems, it is important to accurately model how signals move through buildings [54] [55].

I.9.1 Free-space propagation

Free-space propagation implies electromagnetic wave propagation without any reflections or obstacles. The electromagnetic waves commonly employed for wireless

communication have frequencies between 3 kHz and 3 THz. In an ideal situation, the electromagnetic wave would propagate equally in all directions from the transmitting antenna.

While there is no absorption in free space, the density of power falls exponentially with respect to the square of the distance from the transmitting antenna. This follows from the Friis transmission equation because the transmitted energy distributes over the surface area of the growing spherical wavefront. As a result, the received power is much less when the distance between the transmitter and receiver becomes large [54].

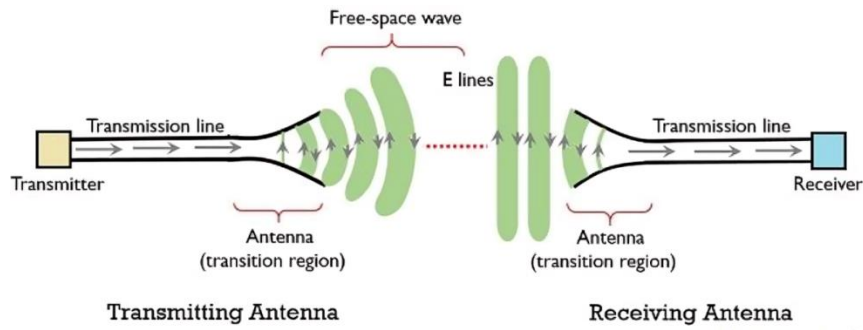


Figure I.19: Free-space propagation between transmitting and receiving antennas

$$Pr = PtGtGr\left(\frac{\lambda}{4\pi d}\right)^2$$

- **Pr:** Received power
- **Pt:** Transmitted power
- **Gt, Gr:** Antenna gains
- **λ :** Wavelength
- **d:** Distance between antennas

I.9.2 Attenuation through walls and obstacles

Attenuation in RF signals occurs due to passage through walls, doors, furniture, and other objects when the signals travel indoors. Attenuation depends on the material used in construction, thickness, and frequency. Materials such as reinforced concrete, metals, and bricks cause more attenuation compared to wood and glass. This attenuation is bound to impact the performance of wireless communication systems in

smart homes [55][56].



Figure I.20: RF attenuation caused by walls and indoor obstacles.

I.9.3 Reflection, diffraction, and multipath

Reflection is an effect where electromagnetic waves are bounced off due to large surface areas, such as the walls, ceiling, or metal objects. The bending of waves as they move around an obstacle or edge is called diffraction. In scattering, RF waves are scattered by either irregular surface areas or small objects. The three effects cause the generation of several propagation paths from the transmitter to the receiver, referred to as multipath propagation. Interference caused by multipath can be either constructive or destructive, resulting in fading of signals [54] [56].

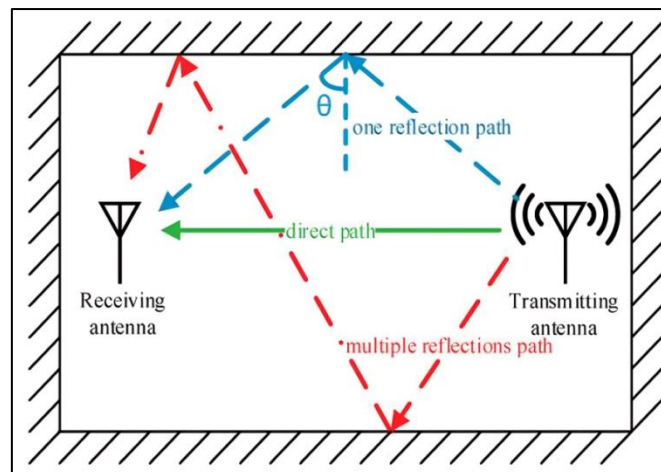


Figure I.21: Reflection, diffraction, and multipath propagation effects

I.9.4 Antenna orientation effects

Antenna orientation is one factor that influences wireless communication effectiveness. Alignment of the antennas used for transmitting and receiving is very vital since it determines how the signal strength is distributed. Antenna orientation may limit the area covered by the system and cause unnecessary loss during signal transmission. Vertical positioning of the antennas is the norm in most indoor wireless systems [57].

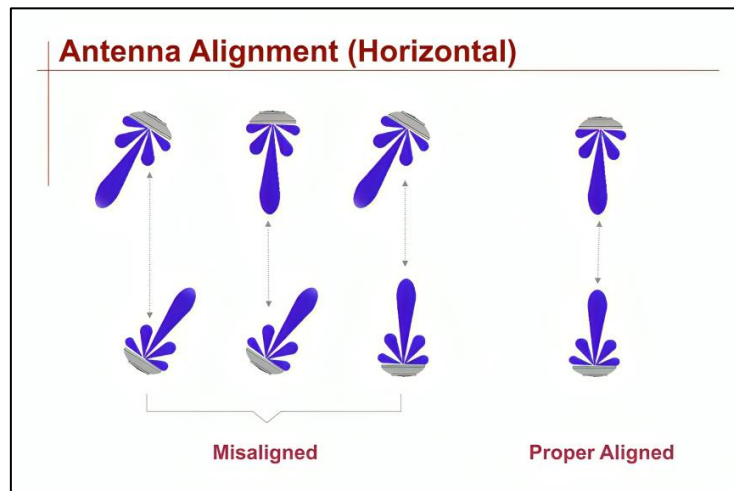


Figure I.22: Influence of antenna orientation on RF signal propagation

I.9.5 Interference sources in domestic environments

Domestic environments consist of many devices that have the potential to create electromagnetic interference and influence wireless communication systems. Some of these sources of interference include Wi-Fi routers, microwaves, Bluetooth devices, cordless phones, and switching power supplies which work on the same frequencies. This interference may cause signal distortion, increased packet loss, and unreliable communication systems. It is therefore essential to properly arrange devices and manage the frequencies [57][58].



Figure I.23: Common interference sources in indoor domestic environments.

I.10 Conclusion

The theoretical background for communication technologies used in smart homes, specifically the Infrared (IR) and Radio Frequency (RF) technologies, is discussed in this chapter. First, the history of smart home technologies, the necessity for a unified wireless approach to control devices, and the limitations of different communication protocols are discussed.

After that, the chapter continues with an introduction to the infrared communication technology and its physical properties, methods of sending and receiving messages, propagation properties, and typical uses in home electronic devices. Moreover, the fundamentals of RF communications, including spectrum types, frequency bands, and propagation properties, were considered in this chapter.

Indoor RF propagation issues, including attenuation, reflection, diffraction, multi-path propagation, antenna alignment, and sources of electromagnetic interference, were covered in this chapter as well. All theoretical knowledge acquired during the analysis conducted in this chapter will form the theoretical basis needed to implement the proposed hybrid IR/RF smart home control system.

CHAPTER II:
Embedded Systems and IoT
for Control Units

II.1 Introduction

The fast development of embedded technologies and Internet of Things has caused significant changes in smart home automation systems. These technologies help monitor, manage and operate household devices in a convenient way through the use of highly interconnected systems. Thus, modern smart home systems offer improved opportunities for comfort, increased energy efficiency, better security features, and remote access to the system.

The current chapter will describe the technical background and core technologies required to build the universal wireless control unit. First, the concept of embedded systems and their importance in building the smart home system will be considered. Then the chapter will provide information about using Arduino and ESP32-S3 platforms to build the system and validate the developed algorithms. Moreover, the chapter will focus on describing the features of the ESP32-S3 microcontroller, which is one of the key components of the designed system.

Moreover, the fundamentals of working with Infrared (IR) and Radio Frequency (RF) communications will be considered. This part will include details regarding the interface of these hardware and software aspects. Further, solutions for establishing IoT connectivity using Wi-Fi technology and remote access will be discussed. Finally, the power management aspects and different techniques of voltage regulation will be highlighted.

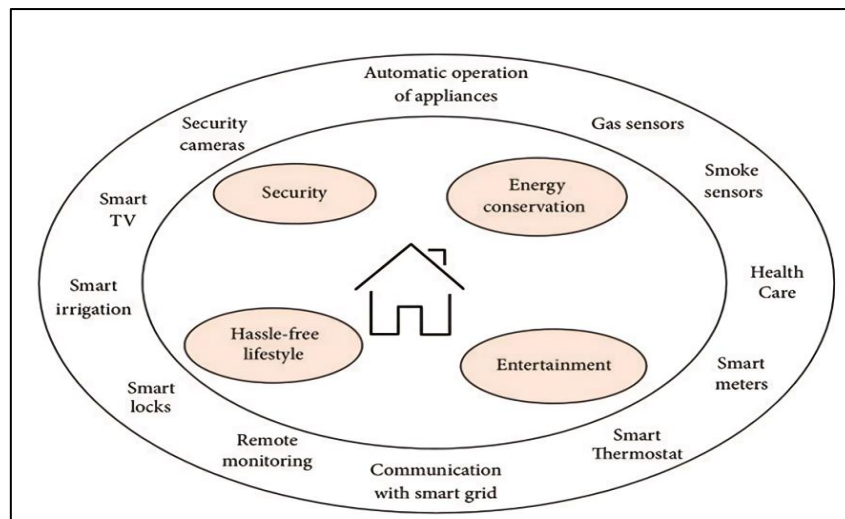


Figure II.1: system smart home block diagram Universal control system IoT diagram

II.2 Embedded systems in smart home control

The rise of intelligent home automation systems can be attributed to rapid technological advancements aimed at improving energy efficiency, comfort, and security in residential environments. These systems rely on embedded devices and Internet of Things (IoT) technologies to integrate and control various household components, enabling automation and remote management.

At the core of these systems are embedded devices, which provide the necessary processing and communication capabilities to interact with sensors, actuators, and controllers within the home. These devices collect and process data in real time, ensuring accurate monitoring and control of household functions.

IoT technologies further enhance these capabilities by enabling communication between devices and external systems through the internet. This allows users to remotely access and control their home systems using smartphones, tablets, or computers [1].

II.3 Arduino platform in prototyping and algorithm development

A development board stage was conducted to prototype and validate the functionality of the system prior to proceeding with the PCB design phase. Two development platforms were used: ESP32-S3 as the transmitting unit and Arduino Uno as the receiving unit [2].

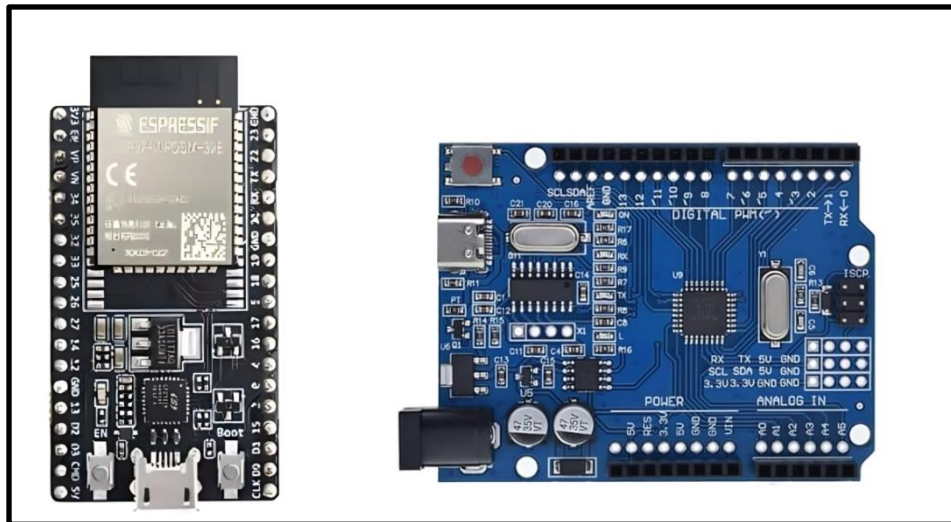


Figure II.2: Development boards used during system prototyping

All experiments were carried out on a breadboard to ensure flexibility and allow modifications during testing. This prototype stage allowed the validation of wiring integrity, communication stability, and algorithm performance before the final PCB implementation .

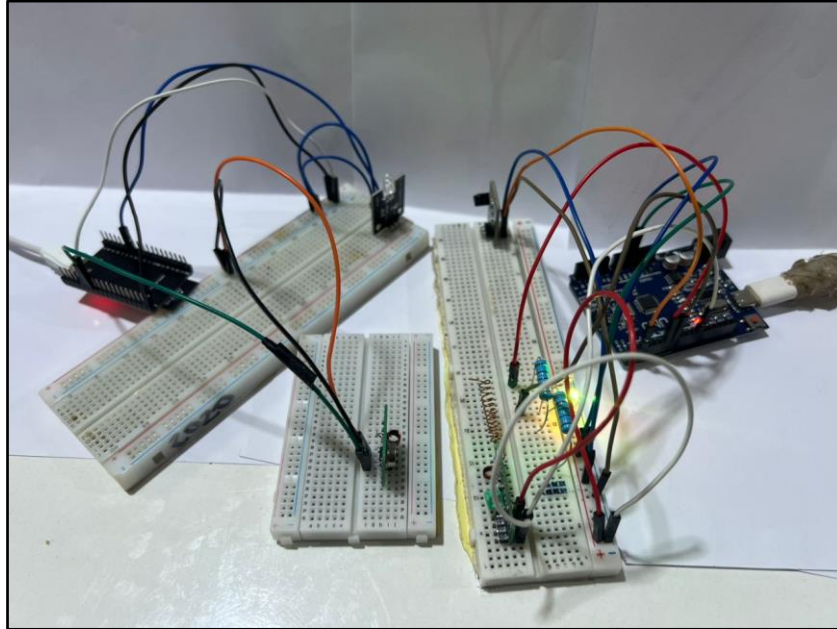


Figure II.3: Experimental setup of the IR and RF communication system

The system was tested using two wireless communication methods: Infrared (IR) and Radio Frequency (RF 315 MHz). The ESP32-S3 was programmed to generate control signals according to the selected communication mode, while the Arduino Uno was programmed to receive, decode, and display the incoming data via the Serial Monitor.

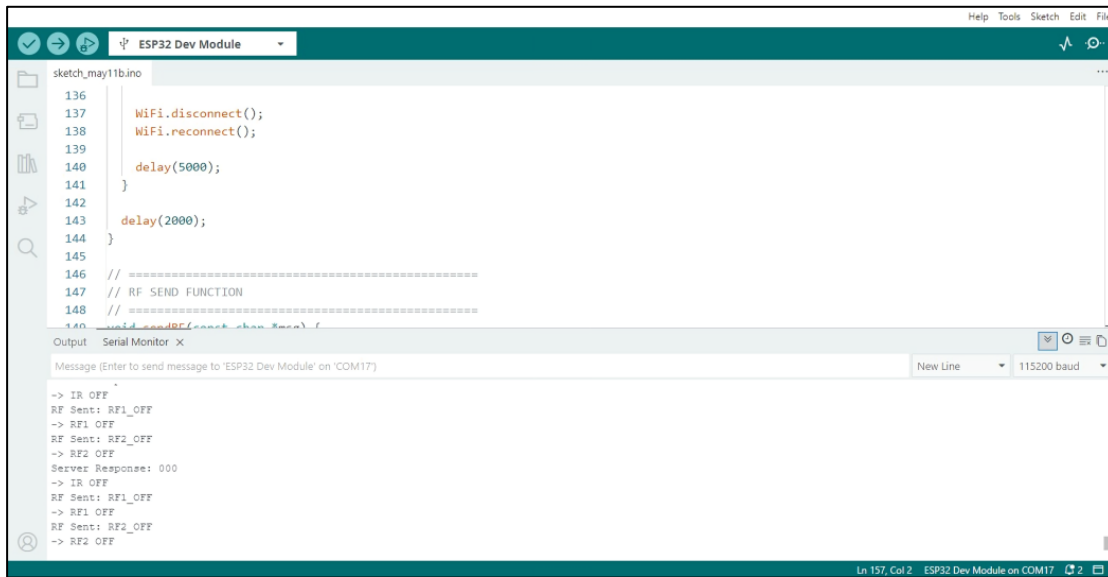


Figure II.4: Transmitted data displayed on the Serial Monitor

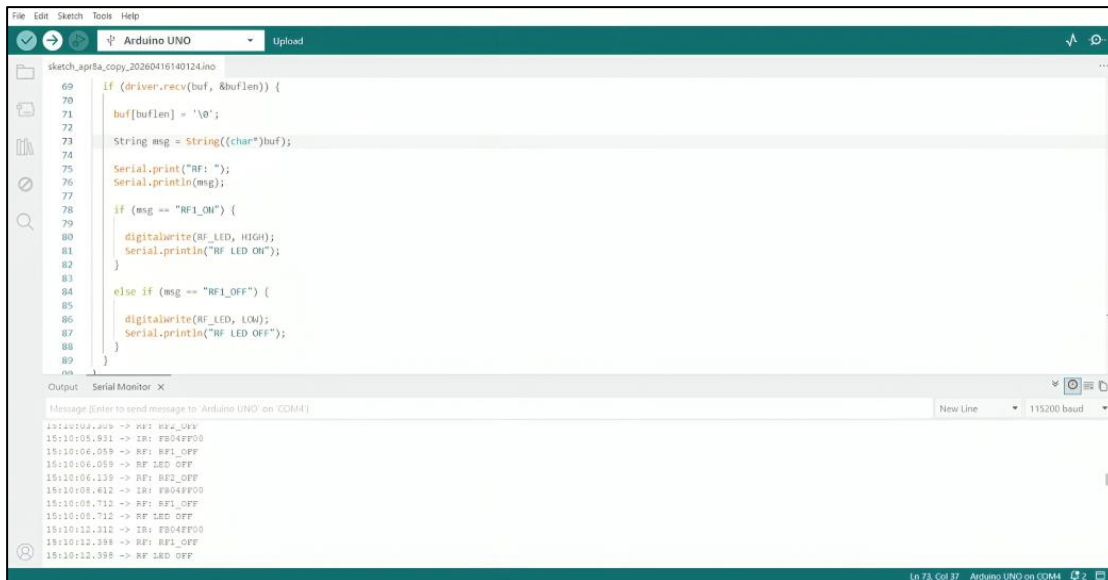


Figure II.5: Received data displayed on the Serial Monitor

The Arduino IDE was used to develop the source code for programming the system. The ESP32-S3 and Arduino Uno boards were connected to the computer via USB interfaces to compile and upload the programs onto the microcontrollers. After the uploading process was completed, several tests were carried out to verify signal transmission and reception, confirming that the system operated correctly as intended.

II.3.1 Advantages of Arduino in rapid prototyping

One of the most compelling features of Arduino for professional developers is its extensive hardware ecosystem. Each Arduino board, along with its derivatives, adheres to a standard hardware interface, enabling custom-designed electronics to be easily stacked atop the processor board to build out a functional embedded system prototype. These custom electronic boards, commonly referred to as shields, can integrate virtually any type of components, including motor drivers, sensors, actuators, LEDs, or anything else the application demands. Arduino's widespread adoption among hobbyists has significantly benefited professionals in the embedded systems field by fostering the development of an extensive array of readily available shields tailored for almost any conceivable application [3].

II.3.2 Command learning, decoding, and testing

The following paragraphs illustrate the implementation of the command learning, decoding, and testing in the created IoT solution using ESP32 in the implementation of the communication with the aid of both the IR and 315 MHz RF.

In the command learning stage, some specific control codes for different types of users' commands were defined. For IR signal implementation, the NEC protocol was applied to send commands through unique hexadecimal code representation. Within the scope of this implementation, the ON command was associated with the code 0xF708FF00, and the OFF command with the code 0xFB04FF00. The IRremote library was applied to generate the required control command codes.

In addition, for 315 MHz RF communication, the RadioHead ASK library was applied to send some textual control commands such as "RF1_ON" and "RF1_OFF" which act as command data packages in this scenario.

On the receiving side, the command decoding operation involves the application of the IR remote library to decode the received IR signal from the transmitting node. Specifically, the decoded raw hexadecimal code is compared with two predetermined codes of (0xF708FF00 and 0xFB04FF00) and depending on the results, the system performs a certain action. For RF, character string commands should be decoded[4] [5].

II.3.3 Transition from prototype to final PCB

The development of the proposed system started with an experimental prototype and finished with a dedicated Printed Circuit Board (PCB) design. During the prototyping phase, we tested each hardware module—like the ESP32-S3 microcontroller, RF transmitter and receiver modules, and IR transmitter and receiver devices—individually. This was to make sure everything worked correctly and communicated properly.

After we confirmed that the components performed as needed, we combined them onto a custom PCB layout. The final PCB, illustrated in Figure II.6, includes all communication interfaces and supporting circuitry on one board. It simplifies wiring, makes the system more reliable, and easier to maintain. Plus, it looks more professional, making it ideal for actual use in the real world. [6].

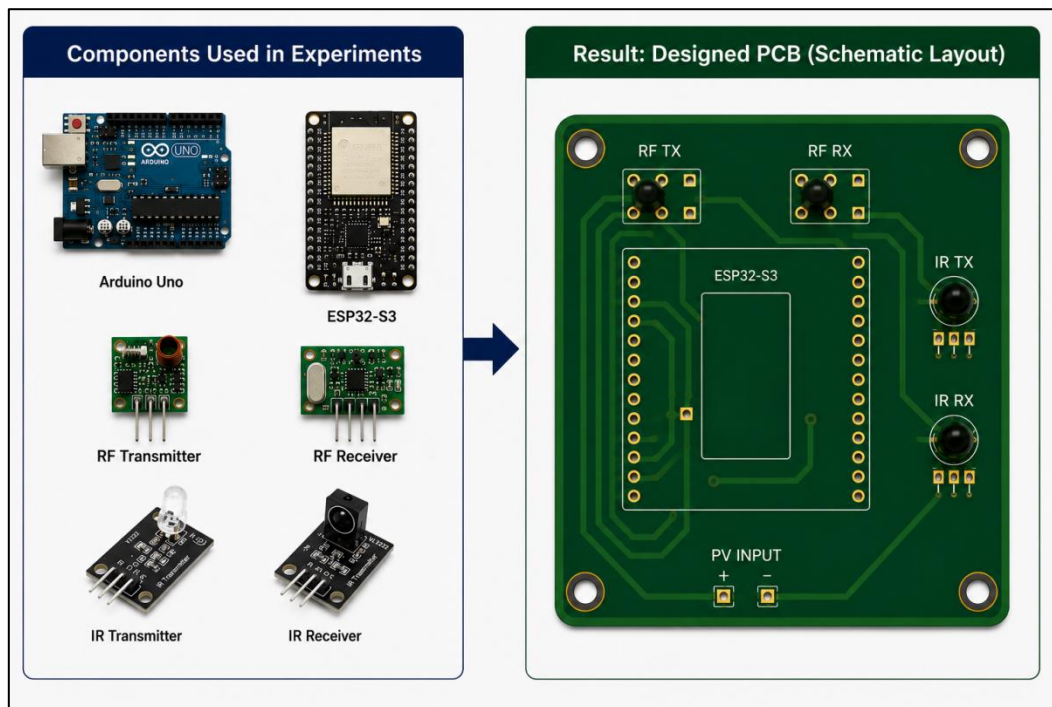


Figure II.6: Transition from Experimental Prototype Components to the Final PCB Design

II.4 ESP32-S3 as the final intelligent control unit

ESP32-S3 is used as the central intelligent control unit in this project due to its high processing capability, integrated wireless communication features, and flexibility in embedded control applications.

It operates as the main controller of the proposed smart wireless control system and manages both Infrared (IR) and Radio Frequency (RF) communications.

The ESP32-S3 is a low-power microcontroller-based System-on-Chip (SoC) equipped with a dual-core Xtensa LX7 processor, which makes it suitable for real-time control tasks while maintaining low energy consumption. This characteristic is particularly important for embedded and portable systems. In addition, it integrates 2.4 GHz Wi-Fi connectivity, which allows possible future expansion toward IoT-based control systems.

Furthermore, the ESP32-S3 provides a wide range of General Purpose Input/Output (GPIO) pins, enabling easy interfacing with external modules such as IR transmitters, IR receivers, RF transmitter and receiver modules, as well as other sensors and indicators .

Although the ESP32-S3 also supports Bluetooth Low Energy (BLE), this feature was not used in this project, since the communication system is based only on IR and RF technologies [7].



Figure II.7: ESP32-S3-WROOM-1-N8R8

Selected Inputs and Outputs:

Inputs:

- Push buttons for user commands
- RF receiver module (if used for testing/learning)
- IR receiver module (for signal verification)

Outputs:

- IR LED transmitter
- RF transmitter module
- Status LEDs (optional for debugging)

II.4.1 Architecture and main features

The ESP32's memory subsystem is thoughtfully designed to achieve a balance between performance and energy efficiency. It incorporates various types of memory, each tailored to meet specific functional needs. The chip integrates static random-access memory (SRAM) to handle program execution and data storage, which is further divided into instruction RAM and data RAM. This segmentation enhances access speeds and promotes the efficient execution of embedded applications. Beyond its internal SRAM, the ESP32 also supports external flash memory, used primarily for storing firmware and managing file systems. Additionally, it features dedicated real-time clock (RTC) memory, which preserves essential data even during deep sleep modes. This capability is especially valuable for low-power IoT applications [8].

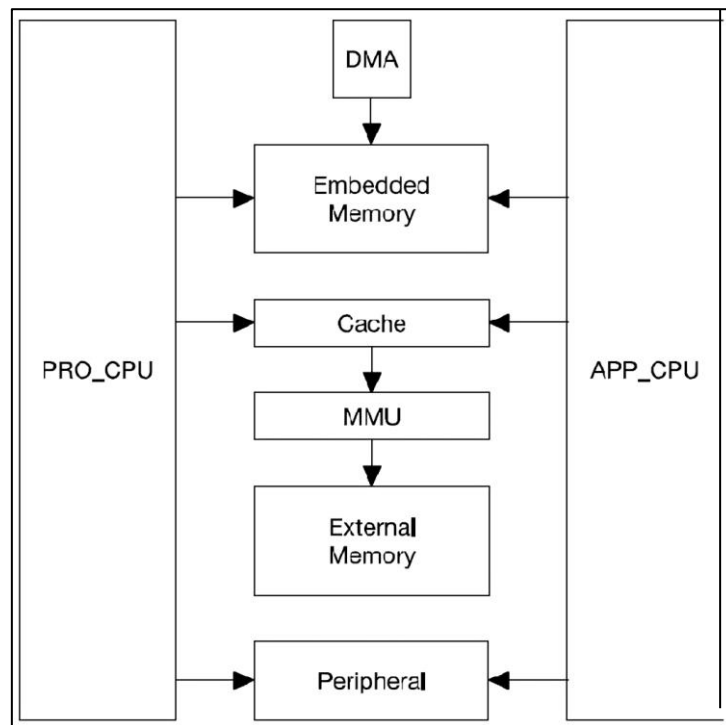


Figure II.8: System Architecture Diagram of ESP32

II.4.2 Wi-Fi connectivity

The ESP32 microcontroller features integrated Wi-Fi connectivity, allowing it to connect to a local network using the TCP/IP protocol.

enables wireless communication between the control unit and other devices in a smart home system, and allows users to remotely monitor and control different appliances. For security, access to the network is protected using SSID authentication and a password [9].

II.4.3 GPIO suitability for IR and RF interfacing

The base shield board for the ESP32 HARVESTER includes header pins that provide access to the GPIO pins as well as pins for 5 Volts, 3.3 Volts and ground. Each GPIO pin can read and/or generate digital signals indicating logic high or logic low states. These GPIO pins are suitable for interfacing directly with external devices such as an IR receiver and RF transmitter [10].

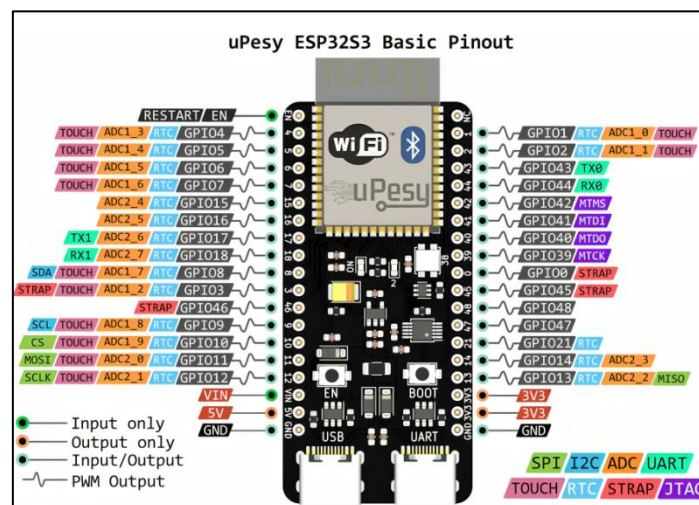


Figure II.9: ESP32-S3 GPIO Pinout Used for IR and RF Interfacing

The range of wavelengths used for the IR data transmission is optimal between 900 nm and 1300 nm. Commercially available IR LEDs operate around 940 to 950 nm so an IR LED that transmits at 940 nm is used as a transmitter. The simplest form of an IR transmitter consists of an IR LED and a resistor. The transmitted signal must be modulated at a 38 kHz frequency in order to be detected correctly by the receiver. When the signal is received, the output from the receiver will be inverted since the receiver is active low[11].

Wireless technologies are used extensively in many different industries. Wireless Radio Frequency (RF) Communication occurs at 315MHz which is low power consumption and suitable for use with embedded systems (enabling more efficient wireless data transfer). An RF module could be interfaced with the ESP32 via GPIO pins [12].

II.5 IR subsystem technologies

The Infrared (IR) subsystem is a short-range wireless communication technology that uses infrared light signals for data transmission. It is widely used in remote control applications due to its simplicity, low cost, and reliability.

In this project, the IR subsystem is implemented using an Infrared LED transmitter and an IR receiver connected to the main control unit ESP32-S3. This allows the microcontroller to send control commands by converting electrical signals into modulated infrared light.

Infrared communication is achieved using a carrier frequency of 38 kHz, which is used to modulate the transmitted signal and reduce interference from ambient light sources [13].

- **IR subsystem components**

The IR subsystem consists of two main components:

IR Transmitter:

The infrared LED is connected to a GPIO pin of the ESP32-S3 through a current-limiting resistor. A PWM signal is used to generate the 38 kHz modulation required for infrared transmission [13][17].

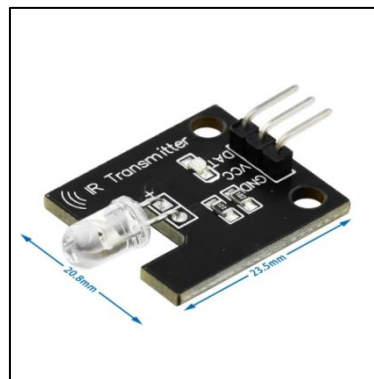


Figure II.10: IR Transmitter Module

IR Receiver:

The IR receiver module has three pins (VCC, GND, and OUT). It provides a digital output signal that is connected to an input GPIO pin of the ESP32-S3 for signal decoding and processing [16]

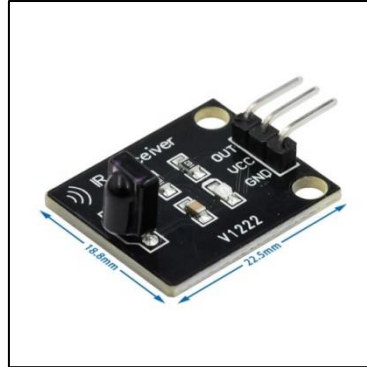


Figure II.11: IR Receiver Module

- **Power supply configurations**

Two different power supply configurations were tested to evaluate the performance of the IR subsystem:

5V configuration:

Provides stronger signal transmission and longer communication range when using standard IR modules.

3.3V configuration:

Directly compatible with ESP32-S3 GPIO logic levels. It offers lower power consumption but with a reduced transmission range compared to the 5V configuration

- **Hardware implementation**

The hardware implementation phase is the actual implementation of the designed system. In this phase, all the various electronic components and communication units were assembled and tested for effective system functioning. The hardware implementation phase involves both RF and IR wireless communication technologies whereby the signals sent are received by the ESP32-S3 microcontroller. Prior to the hardware implementation, there was some form of prototyping and testing in order to verify the overall effectiveness of the system.

II.5.1 IR transmitter driver circuits

IR emitters produce infrared (IR) light (electromagnetic radiation that has longer wavelengths than visible light). Applications of IR emitters typically include IR remote controls or optical communication. Most IR emitters consist of a light-emitting diode (LED) constructed from semiconductor material (such as gallium arsenide) emitting IR light when electric current passes through them.

IR emitters may be modeled as diodes, and their electrical characteristics (such as capacitance and inductance) affect both switching action and frequency response. These characteristics impact rise and fall times of signals (particularly at high frequencies). As a result, a driver circuit is needed to regulate current and to improve performance characteristics of the IR transmitter[14].

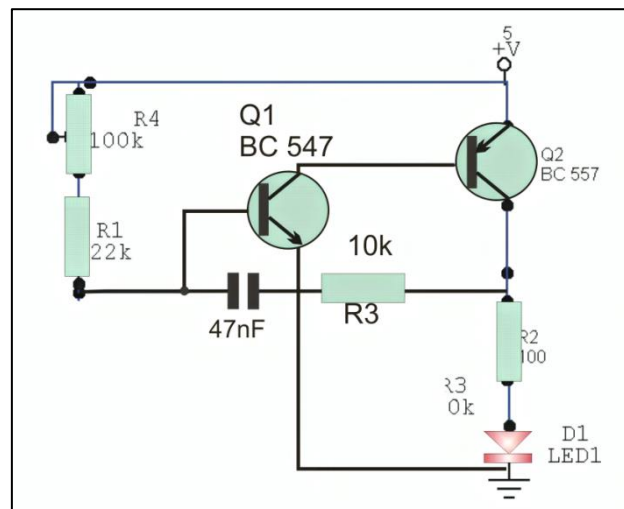


Figure II.12: IR transmitter circuit of the IR sensor

II.5.2 IR receiver interface circuits

An infrared remote is typically found in home theater systems, and they send signals via infrared light. In the case of a TV remote control, there are circuits that will detect when buttons are pressed. They create a signal, then amplify it and send it to an infrared LED. The infrared LED emits infrared light; this is what an infrared receiver on an electronic device detects.

For modern remote controls, modulation is performed on the output of the infrared LED. A modulator creates a series of pulses at 38 kHz. The modulation allows the remote's

infrared signal to be separated from other sources of infrared light. When a button press is detected, the infrared LED emits a pulse of infrared light that contains input information.

On the receiving end, a TSOP infrared receiver receives the infrared signal at a frequency of 38 kHz. The TSOP converts the infrared pulse into an electrical signal, which is then sent to the microcontroller to be decoded and executed [15].

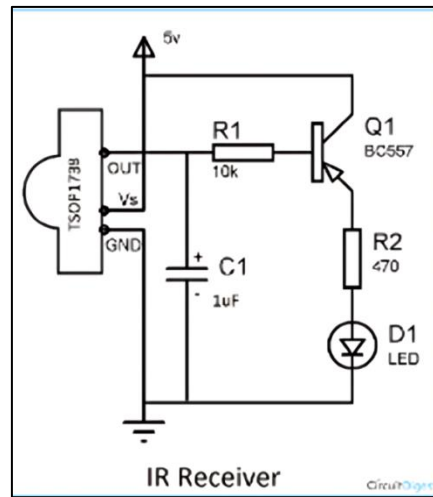


Figure II.13: Receiver circuit of the IR sensor

II.5.3 Timing precision and pulse generation

The ESP32-S3 generates pulse signals using Pulse Width Modulation (PWM). These pulses are precisely timed in order to produce a stable waveform suitable for infrared signal transmission and decoding [16].

Accurate timing is essential because the IR receiver relies on correctly shaped and well-timed pulses to interpret the transmitted data. Any deviation in timing may lead to communication errors or incorrect signal decoding between the transmitter and receiver.

During the pulse generation process, a sequence of high (ON) and low (OFF) states is produced. This ON/OFF switching forms the modulated infrared signal that represents the basis of the communication system.

Systems featuring early infrared (IR) remotes operated by simply turning an LED on and off to send control signals from the remote to the device being controlled. These systems experienced significant interference and range-related issues due to natural and artificial IR sources interfering with the ability to detect the IR signal.

Modern IR control systems utilize a modulated 38 kHz carrier. The command data is sent to the receiver by switching on and off the 38 kHz carrier signal of the IR LED, which creates varying length pulses. This method of control allows for a more reliable signal with less interference from other natural and artificial IR light sources.

The use of a modulated carrier frequency allows for accurate detection and decoding of the transmitted commands at the receiver, thereby providing a more reliable means of maintaining communications with IR devices.

II.5.4 IR libraries and protocol support

This section describes the software libraries and communication protocols used for the generation and decoding of Infrared (IR) signals in the system. IR communication does not rely only on hardware components; it also depends on software libraries that enable the interpretation and reproduction of specific signal formats.

In this project, the IR subsystem implemented on the ESP32-S3 uses software libraries to encode and decode IR signals compatible with common consumer electronics protocols [17].

IR communication protocols

Several standardized IR communication protocols are used in consumer electronics. The most common protocols include:

- The **NEC protocol**, which is widely used in television remote controls and consumer devices.
- The **Sony SIRC protocol**, used in Sony electronic systems.
- The **RC5 / RC6 protocols**, commonly used in multimedia and control systems.

Each protocol defines:

- The structure of data frames
- The timing of transmitted pulses
- The representation of binary data (logic 0 and 1)

Signal representation

Infrared communication is based on pulse patterns consisting of ON/OFF sequences:

- A logical “1” is represented by a specific timing sequence of pulses.
- A logical “0” is represented by a different timing sequence.

A complete IR command is formed by combining multiple pulses into a structured frame. Once received, the IR receiver decodes the pulse sequence and reconstructs the original transmitted command.

IR libraries

Software libraries simplify the implementation of IR communication by handling signal encoding and decoding automatically. These libraries typically provide functions for:

- Transmitting IR commands to external devices
- Receiving and decoding IR signals
- Managing protocol-specific timing and frame structure

Multiple protocol configurations were evaluated to verify the generation of infrared signals. The test was conducted with an Arduino UNO and the IRremote library along with many of the more popular IR protocols, including Samsung and NEC. The successful decoding of the transmitted signals by the IR receiver confirmed that the transmitted signals matched the expectations of timing and protocol structure.

The results support the assertion that the IRremote library can accurately handle standard infrared communication protocols by decoding received signals into structured commands. This confirms the IR communication system is reliable and should be compatible with most widely used IR standards.

II.6 RF subsystem technologies

RF subsystem technology is highly utilized in wireless communication systems in order for them to transmit and receive signals from each other without being connected through any wires or cables. This technology uses electromagnetic signals within certain frequencies and is mostly utilized in wireless controls systems, IoT applications, wireless sensing and home

automation. An RF system comprises a transmitter, a receiver, an antenna and signal processing circuits to ensure efficient performance of the system. [18].

II.6.1 RF 315 MHz transmitter module

Wireless transmission units are among the key components used in any wireless sensor node architecture after the microcontroller. Wireless transmission units play a vital role in transferring data between nodes; unlike other parts of a wireless sensor node, however, these devices have a large amount of power consumption based on the distance between two nodes, the environment in which you operate, and how large the amount of data transmitted will be, which will all impact the reliability and life of the entire system.

This thesis will look specifically at the 315MHz RF (ASK) transmitter module as an example of a low-cost and compact wireless communications device that can operate over relatively short distances (up to approximately 100m) based on the design of the antenna and the other conditions under which it is used.

The RF transmitter is used broadly across many different applications including but not limited to remote control systems, alarm systems, and other low data rate wireless communications. When compared to infrared communications, RF communications provide greater range; do not require line-of-sight; and are not as susceptible to interference from outside sources [19].

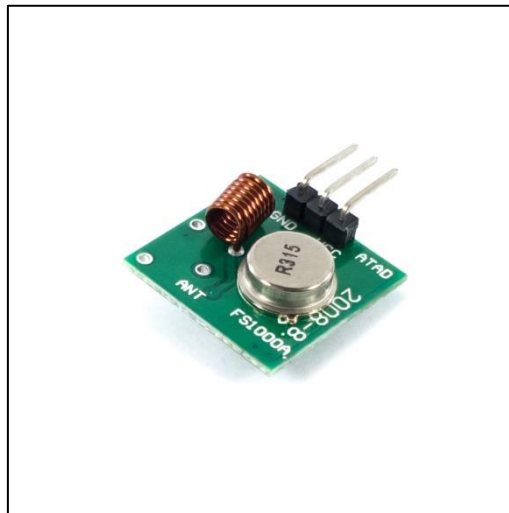


Figure II.14: RF 315 MHz transmitter module

II.6.2 RF 315 MHz receiver module

The RF receiver module is one component of a wireless communication system. It receives data signals from an RF transmitter using a microcontroller (MCU), which receives power through a supply source. The RF receiver module will continue to monitor the RF signals until the MCU processes the information received from the RF transmitter.

The RF receiver module only uses simplex communication and therefore does not send data to or from the RF transmitter; only receiving data transmitted by the RF transmitter. The received signals will be decoded by the appropriate software libraries (e.g., VirtualWire) that will decode the data to obtain the data that was transmitted.

To maintain reliable communication, the receiver will remain active and continue listening to receive packets of information from the RF transmitter. When information is received, it will be decoded and processed through the microcontroller[19].

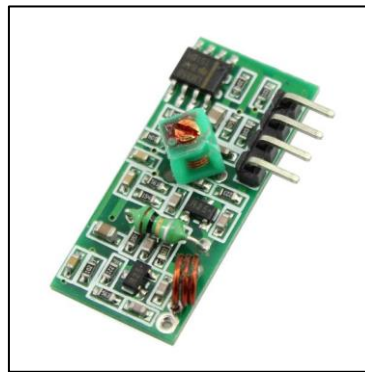


Figure II.15: RF 315 MHz receiver module

II.6.3 Antenna design considerations

The measurement is conducted in an indoor environment. RF power is generated at different frequencies and transmitted into the room using antennas. The receiver is placed at a certain distance from the transmitter and is composed of an antenna connected to a receiving circuit. The output is measured to evaluate the received signal.

It can be observed that the received power depends on the frequency and antenna characteristics, and that using multiple frequency bands can increase the total received power compared to a single frequency band [20].

For a 315 MHz RF system, proper antenna design such as antenna length and placement is essential to ensure efficient signal transmission and reliable communication.

II.7 IoT connectivity and remote operation

A description of the system created for testing the performance of the IEEE 802.11 b/g/n Wi-Fi protocol on the ESP32 indicates that the system will consist of multiple components, allowing them to be connected remotely through Wi-Fi or a mobile device, in order to perform remote measurements from anywhere in the world via wireless connections, and monitor the received data in real-time via the Wi-Fi or Bluetooth connection.

The testing system will comprise the following major components: An ESP32 microcontroller development board with integrated wireless (Wi-Fi) and Bluetooth communication capabilities; external antennas used to improve the signal quality throughout the tests; and a battery that will provide power to the ESP32 board during the tests, thus enabling portability.

The ESP32 microcontroller is an extremely powerful microcontroller that is frequently used for IoT applications due its wireless capabilities (Wi-Fi) and sufficient processing power to meet the requirements of a modern IoT system [21].

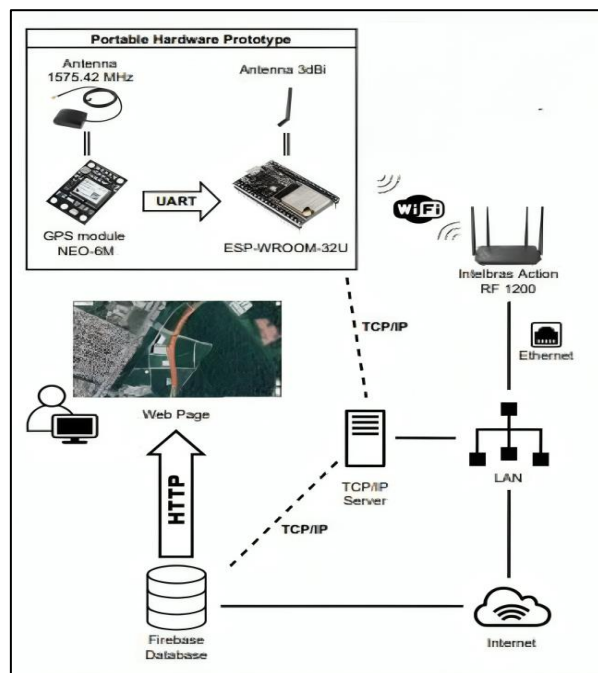


Figure II.16: Simplified block diagram of the developed system with portable hardware prototype and software employed

II.7.1 Smart home remote access concepts

When the relays are put together, it is because the IoT system has had a fault in failing to connect and stop controlling the load; this allows all loads still to be controlled by normal switches even though the IoT relay has been turned off. When the IoT system sends out a signal to the relay, the relay will then turn on, allowing it to effectively control the appliance connected to it through normal switches or through the IoT system's remote control over Wi-Fi and infrared (IR).

We will control the appliances that are being monitored and controlled by the IoT system through remote control through infra-red (IR) and Wi-Fi. Our design will allow any device that can connect to Wi-Fi and has a web browser (regardless of their operating system) to control the appliances being monitored/controlled by the IoT system without installing an application.

For Wi-Fi control, the system provides an Access Point (AP) that has a specific SSID to connect to. The user must first connect to the AP using the assigned password and then open a web browser to access a fixed link with an HTML web page that is used to control the appliances. The home Wi-Fi router can also allow for connection through the use of Wi-Fi to control appliances and access the internet.

The main controller of the system will be a microcontroller that acts as a central core for controlling all of the elements in the system. The microcontroller will also provide the ability to operate in either Access Point mode or Station mode to facilitate multiple modes of operation with the IoT system and to allow for control of appliances remotely [22].

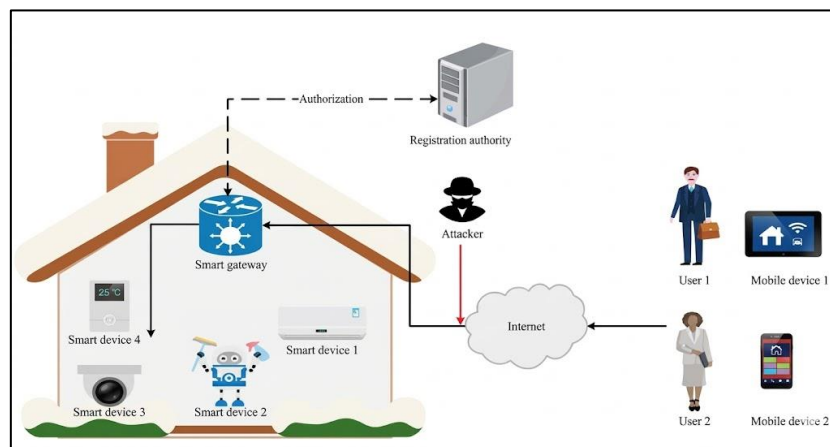


Figure II.17: Architecture of a secure smart home IoT remote access system based on a home registration approach

II.7.2 Server-based remote control

The IoT concept encourages utilizing internet capabilities to enable a device or appliance to remotely access real-time data with minimal human interaction. To accomplish this goal, IoT systems contain three fundamental components: an embedded microcontroller (processing unit) is connected via a communications module to the internet; the component collects data from the environment(s) and sends it to the microcontroller for processing. Once processed, the collected data is transmitted from the microcontroller to either a web server (using an IP address) or the receiving device. The receiving device (such as a smartphone) also connects wirelessly to the communications module.

Some examples of IoT-based systems include: surveillance systems, traffic monitoring, and healthcare systems. With IoT-based systems (such as these examples), users are able to control remote systems based on their ability to remotely access the data collected. Overall, IoT technology can help make our lives easier and more efficient by providing us with the ability to control various functions/operations remotely (via cellular service) [23].

II.7.3 Role of Wi-Fi in local and internet access

The ESP32, developed by Espressif Systems, is a low-cost and low-power system-on-chip and an advanced successor of the ESP8266. It integrates Wi-Fi as well as Bluetooth (Classic and Low Energy), making it suitable for Internet of Things (IoT) applications.

The chip includes dual-core 32-bit processors, built-in RF components, power management units, and communication interfaces, which enhance its performance in embedded systems. Its ultra-low power consumption and multiple operating modes make it ideal for mobile devices, wearables, and smart home applications.

The ESP32 supports IEEE 802.11 b/g/n Wi-Fi standards and can operate in Station, Access Point, or dual mode, providing flexible network configurations. It also includes power-saving features such as modem sleep to improve energy efficiency.

Overall, the ESP32 is widely used as a central controller in IoT systems due to its efficient wireless connectivity and high performance [24].

II.7.4 Role of GSM/SIM800L Module in Wide-Area Communication for IoT Systems

One of the most prominent advantages offered by the SIM800L GSM module is its capability of performing wide-area wireless communication of IoT-based devices independently from local Wi-Fi networks. By connecting the device through cellular networks, this module offers such kinds of services as SMS and GPRS.

The SIM800L GSM module can be used as a communication link for IoT monitoring systems allowing transmitting collected data or system logs from an embedded system to a remote database on the Internet in real time.

This feature allows providing immediate notifications or remote monitoring performed via SMS messages or web/mobile applications.

Furthermore, the use of this type of communication module is justified in cases when no Wi-Fi infrastructure is available or reliable due to the possibility of using a cellular network for establishing connectivity.

For enhancing the performance of IoT-based monitoring solutions, lightweight communication protocols such as MQTT can be implemented to increase the speed of data transmission and minimize the amount of bandwidth used for that purpose.

In summary, GSM modules, such as SIM800L, facilitate reliable wide-area communication for IoT-based devices.

II.7.5 Local control versus cloud control

As companies continue to digitize, there is an increased need for modern IoT based automation solutions that use a distributed architecture versus a conventional centralized model. This results in increased levels of flexibility, scalability, and interoperability.

Local Automation Clouds is one of the key concepts in this shift to an automated solutions, combining local controls with Internet based services to provide real-time communications and enable efficient system coordination.

The majority of modern automated solutions will have to supply technologies such as: both real-time performance, secure systems, scalability in terms of equipment, and low cost.

Therefore, the majority of all contemporary solutions will combine both local and cloud processing to increase performance and reliability.

Therefore, the integration of both local and cloud control is critical to developing next generation IoT/automation systems [26].

II.8 Power supply and regulation technologies

Power management in Internet of Things (IoT) systems is an important concern, especially since most IoT devices are small battery-powered devices and need to use as little energy as possible while running for an extended period of time. Therefore, IoT semiconductors are designed to be very energy-efficient.

Wireless Sensor Network (WSN) uses distributed sensing nodes to collect information and transmit this data to other systems with the use of battery power. The typical power management architecture for IoT includes many components, such as rectifiers/switching regulators/DC-DC converters/battery management units. All of these different blocks are connected to create a total system which uses a combination of processing those blocks to manage input power through regulation techniques to provide a safe/consistent volt (DC voltage) which is supplied to sensors/microprocessors. Additionally, the power management blocks are essential for optimizing the energy used by the system, thereby matching battery discharge performance with the run time of the system, and helping ensure that the total system works reliably during use[27].

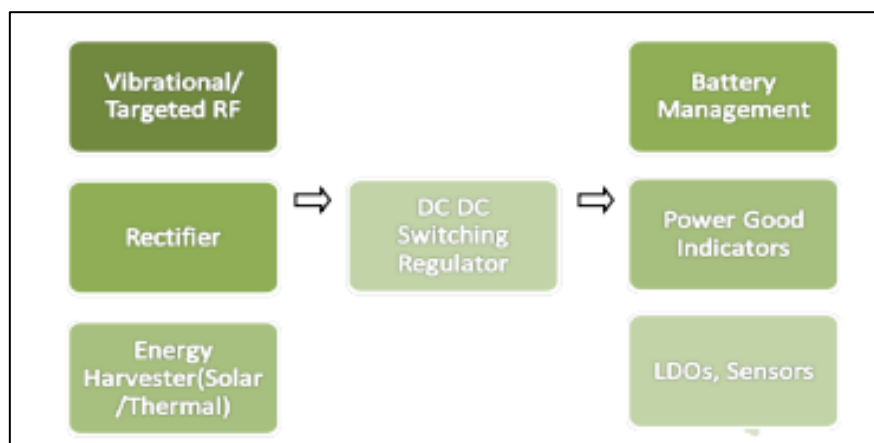


Figure II.18: Typical power management architecture of an IoT node

II.8.1 Buck converter

A step-down converter is a type of DC to DC converter known as a buck converter (or buck regulator). This type of converter allows you to take a higher input voltage and reduce it to a lower output voltage that has been regulated at the output.

Typically a buck converter is composed of three fundamental switching elements: a MOSFET, diode, and either an inductor or capacitor. Energy is accumulated in the inductor during the switching process then released to the load providing a regulated voltage output.

To regulate the output voltage from a buck converter, the duty cycle of the switching signal is varied producing efficient voltage regulation with minimal losses. Buck converters are frequently used to provide stable voltage levels to IoT devices and embedded systems so that components like microcontrollers (e.g., ESP32) receive stable voltage levels (5V and/or 3.3V) [28].

Advantages of a buck converter compared to linear voltage regulators include but are not limited to; higher efficiency, less heat generated, better performance in low power applications; and additional operation in switching mode rather than linear mode [29].

II.8.2 LDO regulation

The efficiency of a linear regulator is determined by its dropout voltage. For this reason, many linear regulators rely on low dropout (LDO) regulators to provide higher efficiencies than other methods.

While maximizing the efficiency of LDO regulators may result in better stability, LDO regulators can experience decreased phase margin as a result of both output impedance and load capacitance, which could create problems with the stability of these devices.

There are many options available for improving the stability of LDO regulators while still providing a low-power solution. Some of these options include alternative topologies for LDO regulators that improve transient response and noise performance without increasing circuit complexity or chip area significantly[28].

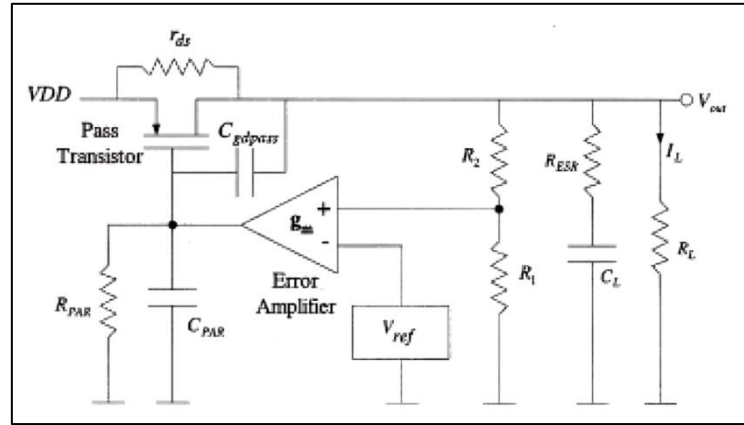


Figure II.19: Typical LDO voltage regulator

II.8.3 ESD protection

To protect electronic circuits from electric shocks, internal protection mechanisms have been designed to protect electronic circuits from electric shocks; however, in most cases, an external transient voltage suppressor (TVS) device will provide additional reliability against ESD events; this can often be combined with TVS devices that respond to ESD events and to protect against other transient events such as lightning.

Depending on the type of signal interface, different protection devices are used (including diodes, varistors, spark gaps, and other protective devices). PIN diodes are also frequently used for RF and power protection applications where use can be made of their ability to limit current and facilitate better ESD performance.

Characterisation in respect of ESD testing is typically carried out utilising standard testing, for example, TLP (Transmission Line Pulse), VFTLP, RF characterisation; however ESD events (i.e., lightning) will create a gradual loss of performance within an electronic circuit, even though standard testing methods define thresholds that indicate failure[31].

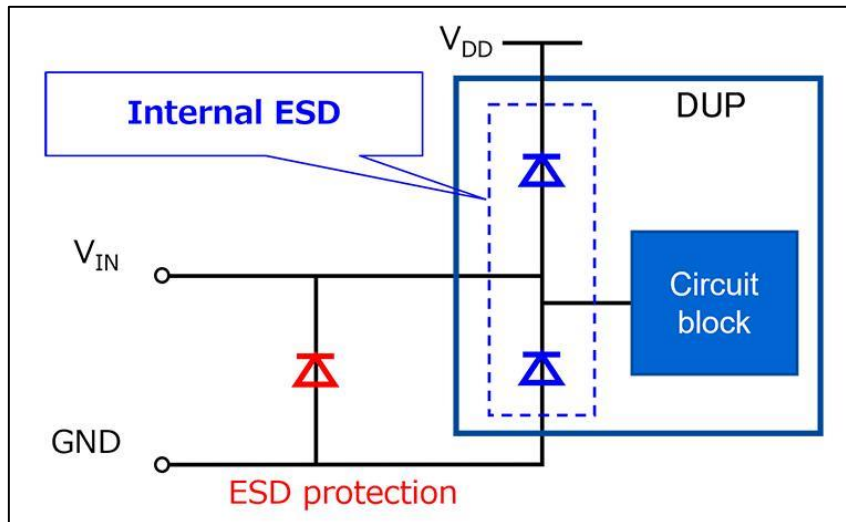


Figure II.20: Typical ESD protection circuit using TVS diode

II.8.4 Stability requirements for RF/GSM transmission

To reduce the level of noise coupling, one common method is the application of electromagnetic bandgap (EBG) structures. EBGs are simply repeating etched patterns of metal on the power or ground plane and have a predetermined frequency response. EBGs are successful for isolating noise and typically provide in excess of 30 dB of isolation.

Although EBGs can be very effective as a way to isolate noise from power and ground planes, they can also degrade the signal due to the presence of multiple split power planes, coupled with via transitions. As a result, several alternative design methods/approaches have been proposed that provide both digital and RF devices with power from a single power source while eliminating the ability for switching noise to couple to the RF signal path[32].

II.9 Reliability and energy optimization

The devices in the Internet of Things operate under limitations of power, memory capacity and network resources (bandwidth). They are normally querying for data and generating large volumes of generated data every day, which uses large amounts of energy. The majority of the energy consumed is during the sensing, transmitting of data from the sensor, and retransmission of data. Developing applications that utilize edge and fog computing will help reduce the amount of communication and improve overall energy efficiency.

Security threats to IoT systems cause battery drainage attacks, which are in turn related to the potential failure of a node or disconnection from the overall network; these battery

drainage attacks also deny typical function and operate energy-efficiently and ultimately affect the overall reliability of the IoT system.

Another reason is that due to the different protocols, standards, and platforms used in various IoT systems, there is a significant level of heterogeneity across all devices and networks, which presents numerous challenges regarding interoperability. To create a fully functional IoT system, it is important to ensure that devices, platforms, and applications are able to communicate with one another seamlessly in order to ensure reliable operations [33].

Achieving energy efficiency and interoperability is crucial to maintaining the reliability and sustainability of IoT networks.

II.10 Conclusion

In this chapter, the theoretical background, as well as technical information necessary for implementing the proposed universal wireless smart home control system, has been considered. The focus has been placed on understanding how embedded systems and technologies from IoT can be utilized for creating intelligent and controlled environment.

Two major platforms used in developing a wireless smart home control system have been described, including the Arduino board and ESP32-S3 microcontroller board. These boards enable fast prototyping of electronic projects and provide support for wireless communication and programming.

Principles of operation of both IR and RF technologies have been analyzed and explained, along with their respective hardware modules, protocols, and software libraries available in the process of building an electronic project.

Finally, this chapter also briefly considers various IoT connectivity solutions (including Wi-Fi connection), power management issues (including the use of buck converters, low-dropout regulators, and protection circuits), as well as issues related to reliability and energy efficiency.

All the theoretical concepts and technological principles considered above will serve as a basis for designing hardware and implementing PCB of the universal smart home control system.

Chapter III : Hardware Design of Unit

III.1 Introduction

In any electronic system design, the careful selection of components plays a critical role in ensuring functionality, efficiency, reliability, and cost-effectiveness. Choosing the appropriate electronic parts is not solely based on their electrical specifications, but also on a set of design oriented and practical considerations that impact the overall system performance and production viability.

The selection process typically considers several key factors, including:

- Efficiency in terms of electrical usage in order to reduce losses, particularly in the stage where voltage is regulated.
- Ability to conform to the voltage and current values needed in the circuit.
- Suitability in terms of cost and practicality.
- Availability in the market to facilitate easy acquisition and replacement.
- Space-efficient physical dimensions.
- Efficiency in stability and noise reduction to ensure the smooth functioning of delicate devices within the circuit.
- Conformity to integration requirements, especially for those circuits that incorporate microcontrollers.
- Provisions for built-in protection and reliability within a certain range of environmental conditions.

These criteria form the basis for selecting each component used in the design, from power regulators and microcontrollers to passive filtering elements. The following sections explain how these factors were applied in the context of the implemented circuit.

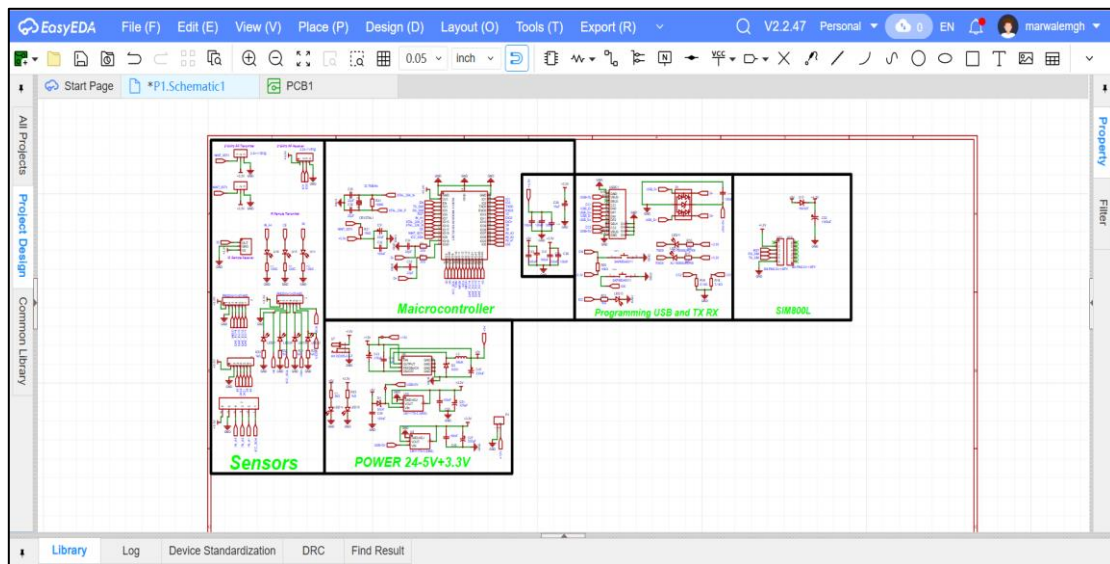


Figure III.1: Schematic Interface in EasyEDA Software

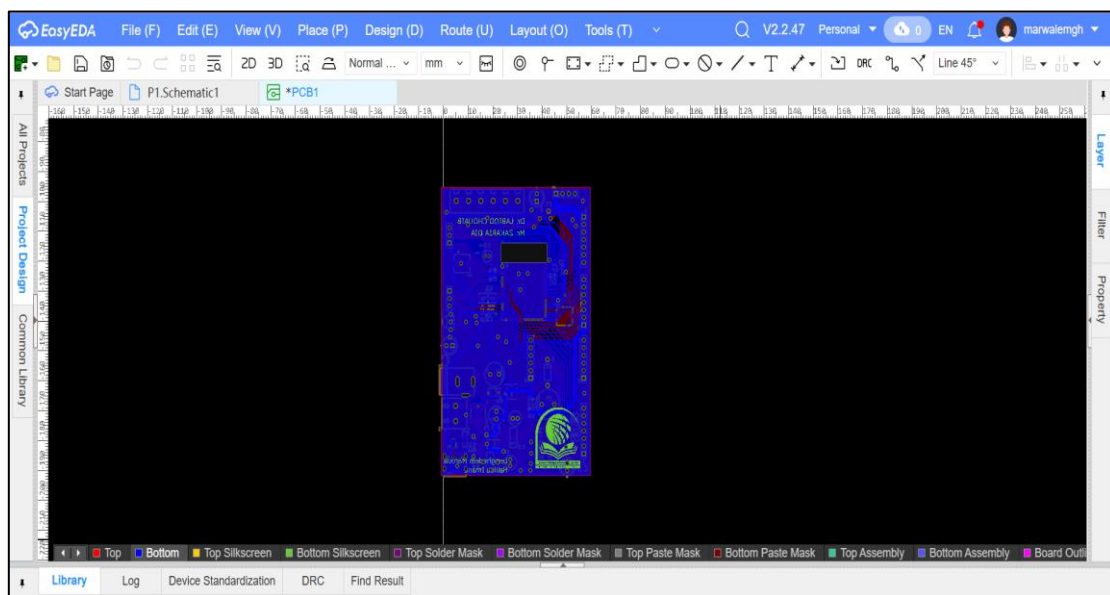


Figure III.2: Bottom Layer View of the PCB Layout in EasyEDA

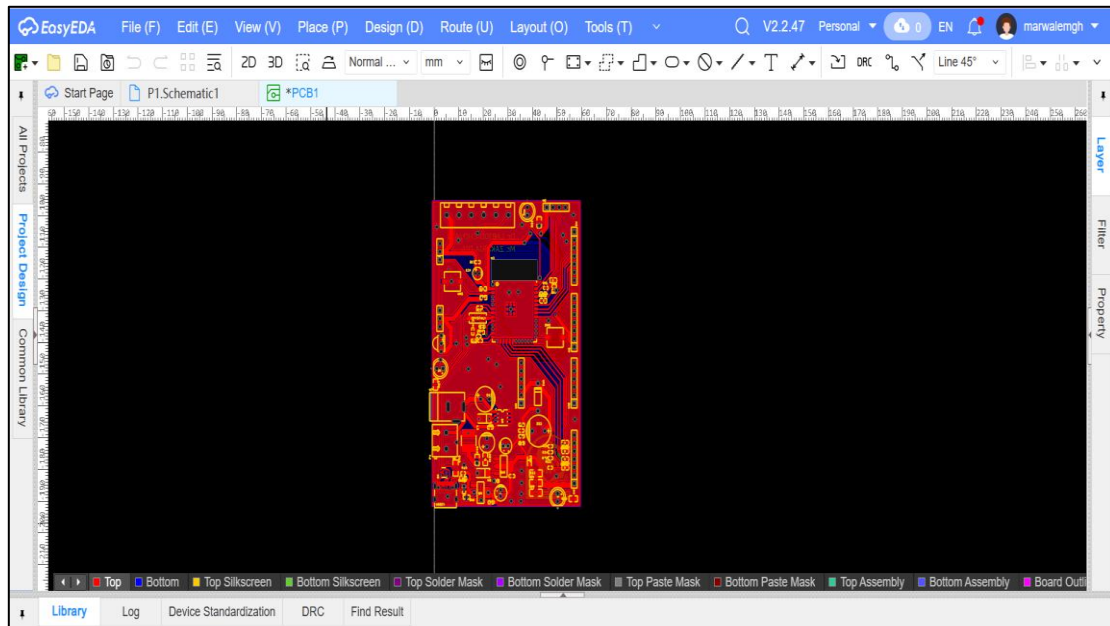


Figure III.3: Top Layer View of the PCB Layout in EasyEDA

III.2 Circuit Design Explanation

The following part discusses the designing of the suggested electronic circuit, along with the functions served by each component included in it. Besides, it includes a description of the interconnectivity among various components that make the entire process of operation effective and reliable.

III.2.1 Power Circuit Design Explanation

The circuit section works like a DC-DC buck converter. It needs the XL1509-5.0 voltage regulator to work. This converter changes a 12V source into a steady 5V output. The 5V output is good for powering both digital and analog subsystems. The operation is in switching mode. The design includes a 68μH inductor, an SS34 Schottky diode along with filtering capacitors. This combination sustains voltage stability plus reduces output ripple. The resulting design is small. It has thermal protection and good performance. This makes it appropriate for embedded and systems with limited power [92][93].

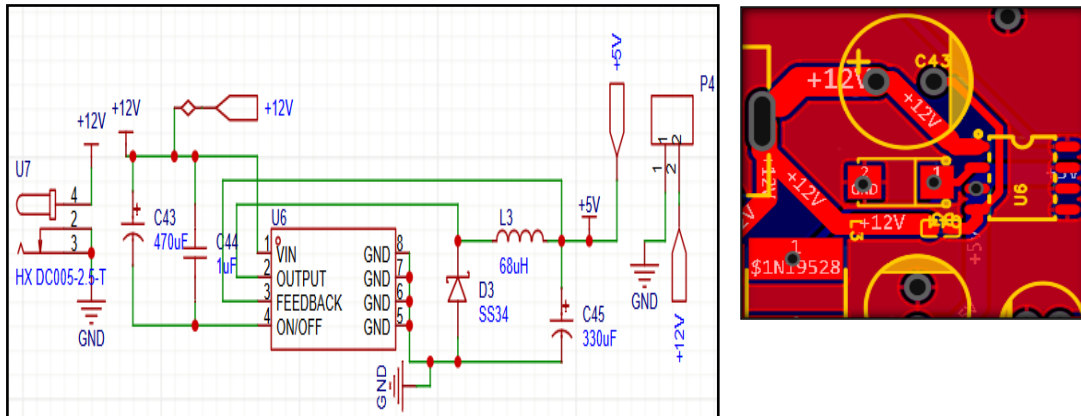


Figure III.4: circuit and PCB of DC-DC buck converter based on the XL1509-5.0

III.2.1.1 Why XL1509-5.0

High Efficiency

$$\eta = \frac{V_{out} \times I_{out}}{V_{in} \times I_{in}}, \quad \eta = \frac{5 \times 2}{12 \times 0.87}, \quad \eta = 0.957, \quad \eta \times 100 \approx 96\%$$

Where:

$$- V_{in} = 12V - V_{out} = 5V - I_{out} = 2A - I_{in} = 0.87A$$

- **Regulated 5V Output:** Provides a stable 5V without requiring manual adjustment.
- **Supports High Load Current:** Capable of supplying currents up to 2A.
- **Wide Input Voltage Range:** Operates with input voltages between 4.5V and 25V.
- **Overheat Protection:** Includes automatic shutdown in case of excessive temperature.
- **Simplified Design:** Requires a minimal number of external components.
- **Stable Output (Low Ripple):** Ensures a smooth voltage suitable for digital circuits.

III.2.2 Linear Regulation Stage 3.3V

The circuit section achieves linear voltage regulation through the LM1117-3.3 low dropout regulator (LDO). It takes a 5V input from USB plus changes it to a steady 3.3V output. The 3.3V output works with low-voltage digital components [92][93][94].

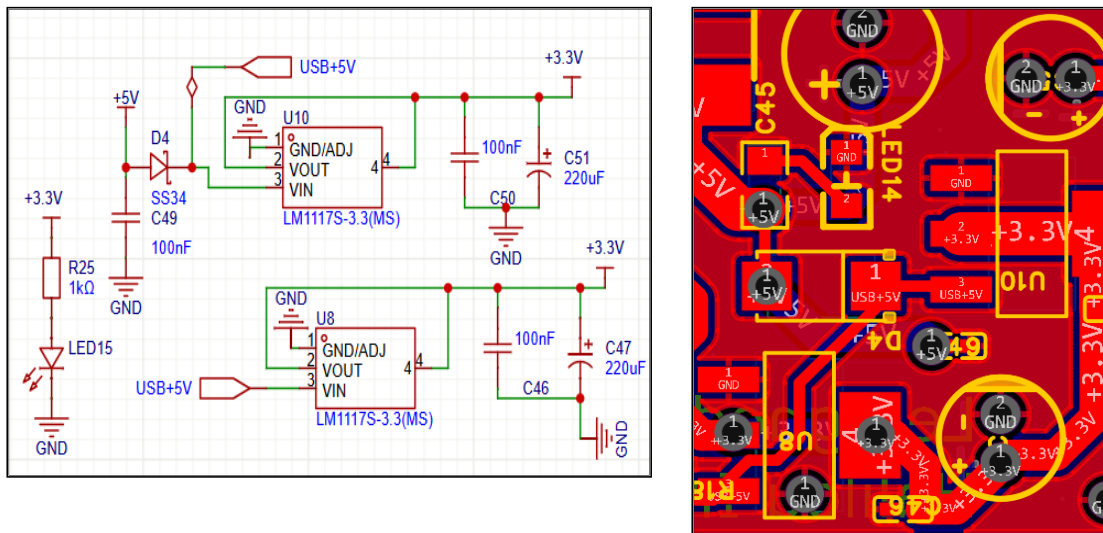


Figure III.5: Circuit and PCB of DC-DC buck converter based on the LM1117-3.3

II.2.2.1 Why LM1117-3.3

- **Simple Design:** The design is basic It has a fixed output plus requires few parts Low
- **Dropout:** It has a low dropout It operates with an input voltage near $\approx 4.5V$ Stable
- **Output:** It offers clean power to microcontrollers and sensors

- **Cost Effective:** The cost is low. It is commonly available besides inexpensive

Efficiency Note

$$\eta = \frac{V_{out} \times I_{out}}{V_{in} \times I_{in}}, \quad \eta = \frac{3.3 \times 0.8}{5 \times 1}, \quad \eta = 0.528, \quad \eta \times 100 \approx 53\%$$

Where:

$$- V_{in} = 5V - V_{out} = 3.3V - I_{out} = 0.8A - I_{in} = 1A [64]$$

(Not ideal for high-current loads, better for simplicity & low noise)



Figure III.6: LM1117-3.3

III.2.3 Microcontroller Unit Design Explanation

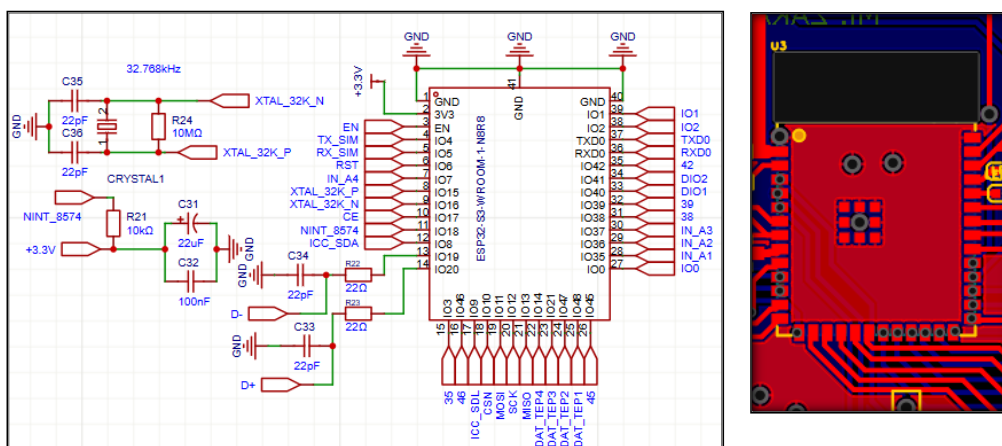


Figure III.7: Circuit and PCB of Microcontroller Unit (ESP32-S3-WROOM-1-N8R8)

The ESP32-S3-WROOM-1-N8R8 is a compact module that is powered by the ESP32-S3 processor manufactured by Espressif Systems. It is a powerful device featuring a dual core 32-bit Tensilica Xtensa LX7 CPU capable of operating at a maximum frequency of 240 MHz. The module supports Wi-Fi (802.11b/g/n) and Bluetooth Low Energy (BLE) communications. Additionally, this particular board contains 8 MB of Flash memory and 8 MB of PSRAM, providing additional functionality in terms of data management and processing [95][96].

- **Wi-Fi 802.11 b/g/n + Bluetooth LE:** Suitable for IoT communication and wireless connectivity
- **8MB PSRAM + 8MB Flash:** Large memory for complex and data-intensive applications
- **Rich Peripheral Set:** ADC, SPI, I2C, UART, PWM, USB OTG for flexible hardware interfacing.
- **Security Features:** Hardware encryption, secure boot, flash encryption
- **Ultra-Low Power Modes:** Ideal for battery-powered applications

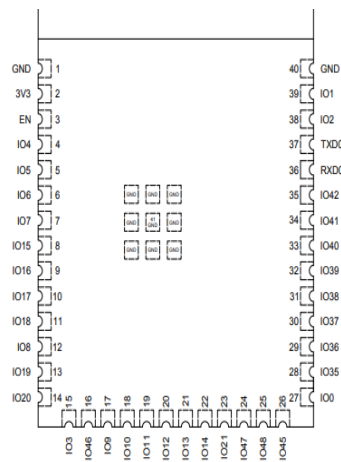


Figure 3-1. Pin Layout (Top View)

Figure III.8: Unit (ESP32-S3-WROOM-1-N8R8)

In this design, the ESP32-S3 uses a stable 3.3V power supply which is maintained by the LM1117-3.3 LDO. They also added in bypass capacitors near the power pins to stabilize the voltage and reduce noise, so that the microcontroller is able to function as it should [76].

III.2.4 USB Interface and ESD Protection

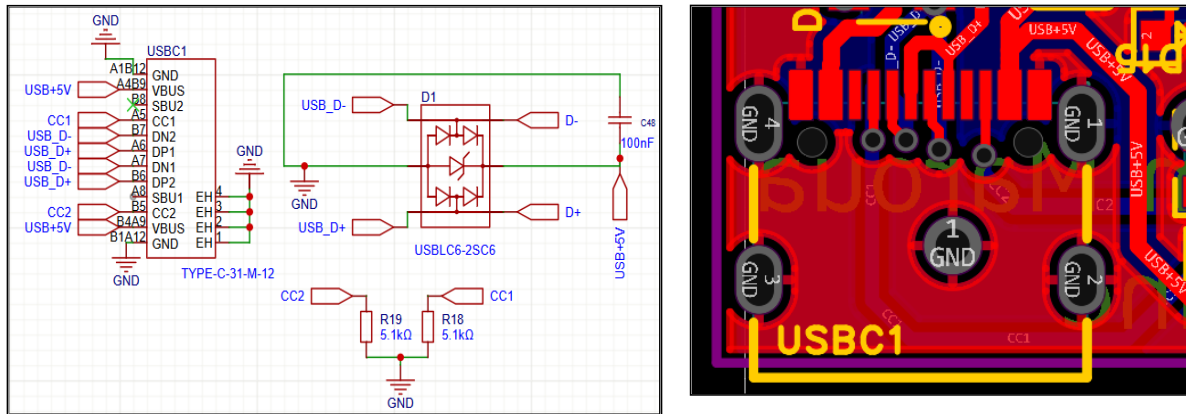


Figure III.9: Circuit and PCB of USB Interface and ESD Protection using (USBLC6-2SC6)

The USB connection in the circuit is designed to interface with the USB OTG functionality integrated in the ESP32-S3. In order to ensure smooth data flow and to protect the microcontroller from voltage spikes or static shock, two important components are added:

- **5.1 KΩ Pull-down Resistors**

There are two 5.1 kΩ resistors connected to the CC1 and CC2 lines. These resistors must be present for proper enumeration and signaling according to the USB 2.0 standard, particularly relating to full-speed device mode operability [97].

- **USBLC6-2SC6 (ESD Protection Diode Array)**

The device being offered is an array of low-capacitance TVS diodes, which is used to protect USB data lines from electrostatic discharge events and voltage spikes. The array works by clamping dangerous voltage transients, along with adhering to IEC 61000-4-2 specifications in regard to ESD immunity [98].

Together, these components improve the robustness and reliability of the USB interface, enabling safe and stable communication between the ESP32-S3 and host devices (e.g., PC or USB power source).

III.2.5 Infrared Control Subsystem

The function of Infrared Control Subsystem is to facilitate wireless communication between the transmitter and receiver through the infrared signal protocol. Its aim is to ensure

that the embedded system has a relatively simple, cost-effective, and power-saving communication protocol for short-distance data transfer.

III.2.5.1 IR Transmitter Module

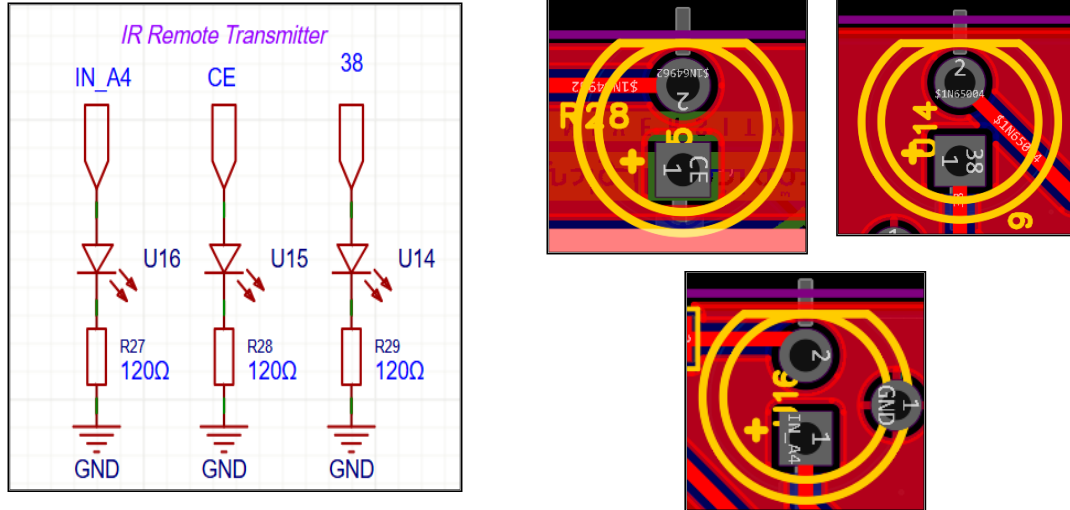


Figure III.10: Circuit and PCB of IR Transmitter(MHL512IR059CRT)

Like Figure III.10 shows, the infrared control subsystem integrates the MHL512IR059CRT IR transmitter directly on the PCB to provide reliable infrared signal transmission for remote-control and IR communication applications. The transmitter was selected due to its stable optical output, low power consumption, and compatibility with the TSOP38238 IR receiver module [99].

III.2.5.1.1 Why 120 Ω

To ensure safe operation of the IR LED **MHL512IR059CRT**, a current-limiting resistor must be used. The resistor value is calculated using Ohm's Law:

$$R = \frac{V_{dc} - V_f}{I}$$

Where:

- **R**: series resistor (Ω)
- **V_{dc}**: supply voltage (3.3V)
- **V_f**: forward voltage of IR LED

- **I**: forward current

From the datasheet of **MHL512IR059CRT**:

- **V_f** $\approx$ 1.2V (typical at 20 mA)
- **I** = 20mA=0.02A

Substitution:

$$R = \frac{3.3 - 1.2}{0.2}$$

$$R = \frac{2.1}{0.02} = 105 \Omega$$

After calculating the current-limiting resistor value using Ohm's Law, the standard resistor value selected is 120 Ω as a practical and safe choice.

III.2.5.2 IR Receiver Module

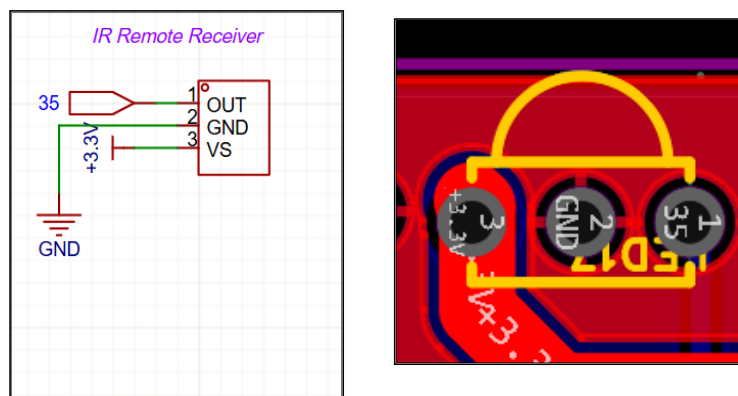


Figure III.11: Circuit and PCB of IR Receiver(TSOP38238)

Like Figure III.11 shows, the TSOP38238 infrared receiver is directly integrated into the PCB to provide reliable infrared signal reception for remote-control and IR communication applications. The receiver operates at a carrier frequency of 38 kHz and offers high immunity against ambient light and electrical interference, ensuring stable communication performance in embedded system applications [100].

- IR Receiver Module: **TSOP38238**.
- Carrier Frequency: 38 kHz, suitable for standard IR remote-control systems.
- Operating Voltage: 2.5V – 5.5V, compatible with various microcontroller platforms.

- Operating Temperature Range: -25°C to 85°C , ensuring stable operation under different environmental conditions.
- Range: Up to 10 m.
- **Noise Rejection:** High immunity against ambient light and electrical interference.
- **Data Rate:** Up to 2400 bps.

III.2.6 General Expansion Header Subsystem

The General Expansion Header Subsystem is used to interface with the basic microcontroller pins so that other components can be added whenever needed. It improves the versatility of the system as well.

III.2.6.1 SIM800L Interface Header

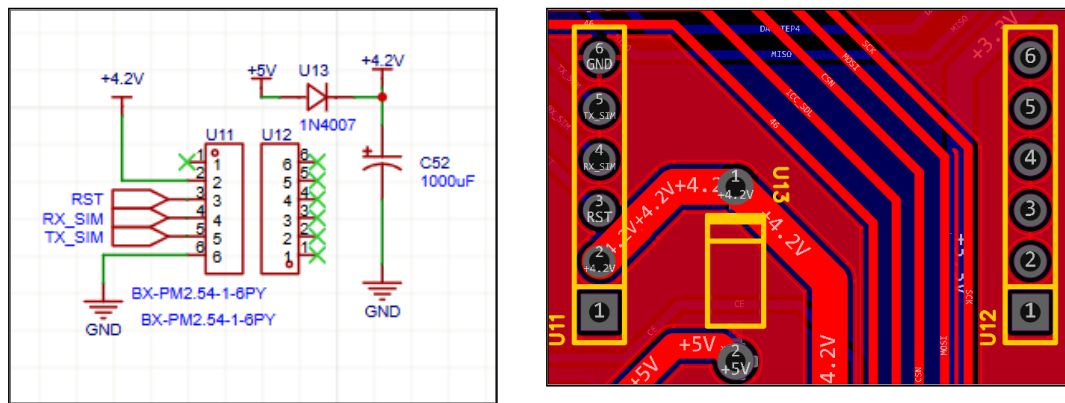


Figure III.12: Circuit and PCB of SIM800L Module Header Interface

The system connects to servers and mobile apps via the internet. While Wi-Fi is the main tech, a GSM module was added as a backup. This ensures access when Wi-Fi is down, improving reliability. It lets users monitor and control things via cell networks, even without Wi-Fi.

It has many advantages that led to its selection, including:

- Support for quad-band GSM/GPRS networks (850/900/1800/1900 MHz), **making it globally compatible.**
- Easy UART interface for serial communication with microcontrollers.

- Moderate power consumption, capable of transferring data at speeds up to 85.6 kbps via GPRS.
- Supports SMS, voice calls, and internet connectivity (TCP/IP protocol).
- Low cost and widely available, making it ideal for low-cost industrial applications.



Figure III.13: Real picture of SIM800L module

III.2.6.2 RF Module Interface Header

The RF communication module interface has been incorporated into the PCB via a header interface for accommodating RF module components that can be externally installed. This will provide flexibility and ensure that the RF module is easily mounted, removed, or replaced on the board in case of any adjustments required. It is clear from here that the RF module is not soldered permanently on the board but is an interface on the PCB.

III.2.6.1.1 RF Transmitter Module

Based on the analysis of Figure III.14, it is clear that the RF transmitter is not soldered directly onto the PCB but rather there is specific space for its installation on the board. Such an arrangement of the components makes it possible to connect the RF transmitter in a plug-and-play manner. Thus, it contributes greatly to the improvement of the hardware system design flexibility and helps to ensure reliable wireless signals transmission inside the system.

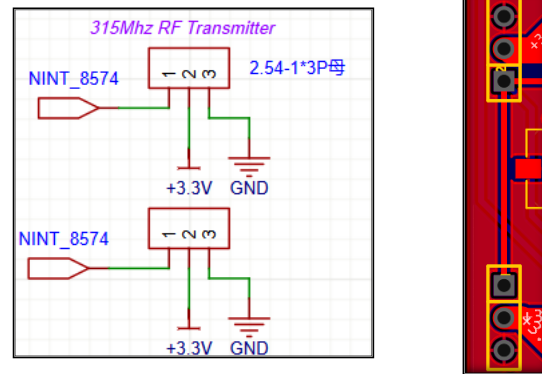


Figure III.14: Circuit and PCB of RF Transmitter Module

III.2.6.1.2 RF Receiver Module

As can be seen from Figure III.15, the RF receiver module does not have any direct soldering connections made on the PCB. Rather, the PCB is equipped with specific spaces reserved for accommodating the RF receiver module. This way, the RF receiver module is made installable within the system in a plug-and-play mode. This improves the efficiency and flexibility of the hardware installation process.

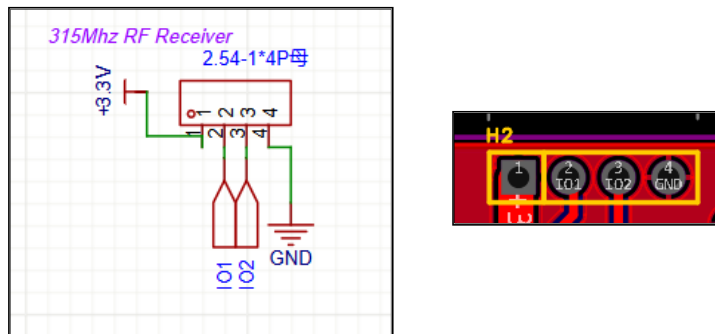


Figure III.15: Circuit and PCB of RF Receiver Module

- **RF Receiver Module:** 315 MHz RF receiver module suitable for wireless communication and remote control applications.
- **Operating Frequency:** 315 MHz, ensuring compatibility with standard low-power RF transmitters.
- **Operating Voltage:** 3.3V – 5V, allowing direct interfacing with most microcontroller platforms.
- **Operating Temperature Range:** -20°C to 70°C, ensuring reliable performance under typical environmental conditions.

- **Communication Range:** Up to 50–100 m (depending on obstacles and antenna quality).
- **Noise Immunity:** Moderate resistance to electromagnetic interference with improved stability when using proper antenna design.
- **Data Rate:** Typically up to 4 kbps, suitable for simple digital signal transmission and control commands [101].

To boost the RF module's 315 MHz transmission and reception range, we added a quarter-wave monopole antenna. The antenna length comes from the wavelength at the operating frequency.

The wavelength is given by:

$$\lambda = \frac{c}{f}$$

where:

- λ = wavelength (m)
- $c = 3 \times 10^8$ m/s (speed of light)
- $f = 315 \times 10^6$ Hz (operating frequency)

Substituting the values:

$$\lambda = \frac{3 \times 10^8}{315 \times 10^6}$$

$$\lambda = 0.952\text{m}$$

For a quarter-wave antenna:

$$L = \frac{\lambda}{4}$$

$$L = \frac{0.952}{4}$$

$$L = 0.238\text{m}$$

$$L = 23.8\text{cm}$$

Therefore, the recommended antenna length for the 315 MHz RF transmitter and receiver modules is approximately **23.8 cm**, which can be practically rounded to **24 cm**.



Figure III.16: Helical Antenna Integrated with the RF Receiver

III.2.7 Free GPIO Expansion Pins

III.2.7.1 Pin Headers Section

- Access Other headers are linked to unused GPIOs from the microcontroller.
- They also provide possibilities for future development, fault-finding, or adding personalized peripherals.

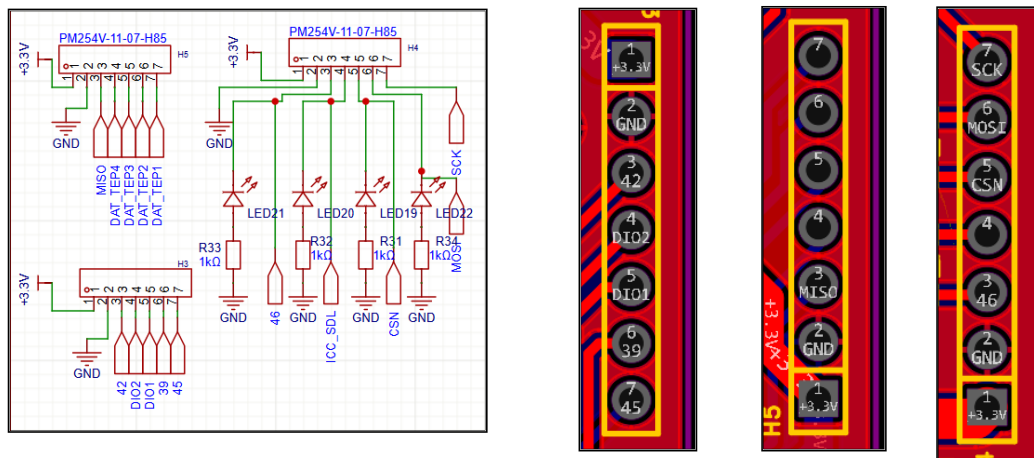


Figure III.17: Circuit and PCB of Pin Headers Section

III.2.7.2 Terminal Blocks Section

Moreover, there are also available free GPIO expansion pins that can be accessed using terminal block connectors, as illustrated in Figure III.18. The use of these terminal blocks allows for a more durable and solid connection, making them ideal for connections that will last for a long time, such as sensor and control systems.

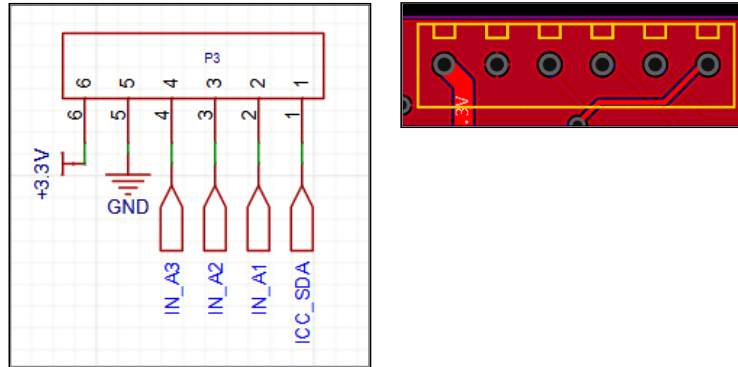


Figure III.18: Circuit and PCB of Terminal Blocks

III.3 PCB Board Dimensions

The final PCB layout was carefully designed to optimize component placement, minimize trace lengths, and ensure mechanical compatibility with the target enclosure. As shown in the Figure III.19, Figure below, the board has a total length of 60.5 mm and a width of 96.7 mm.

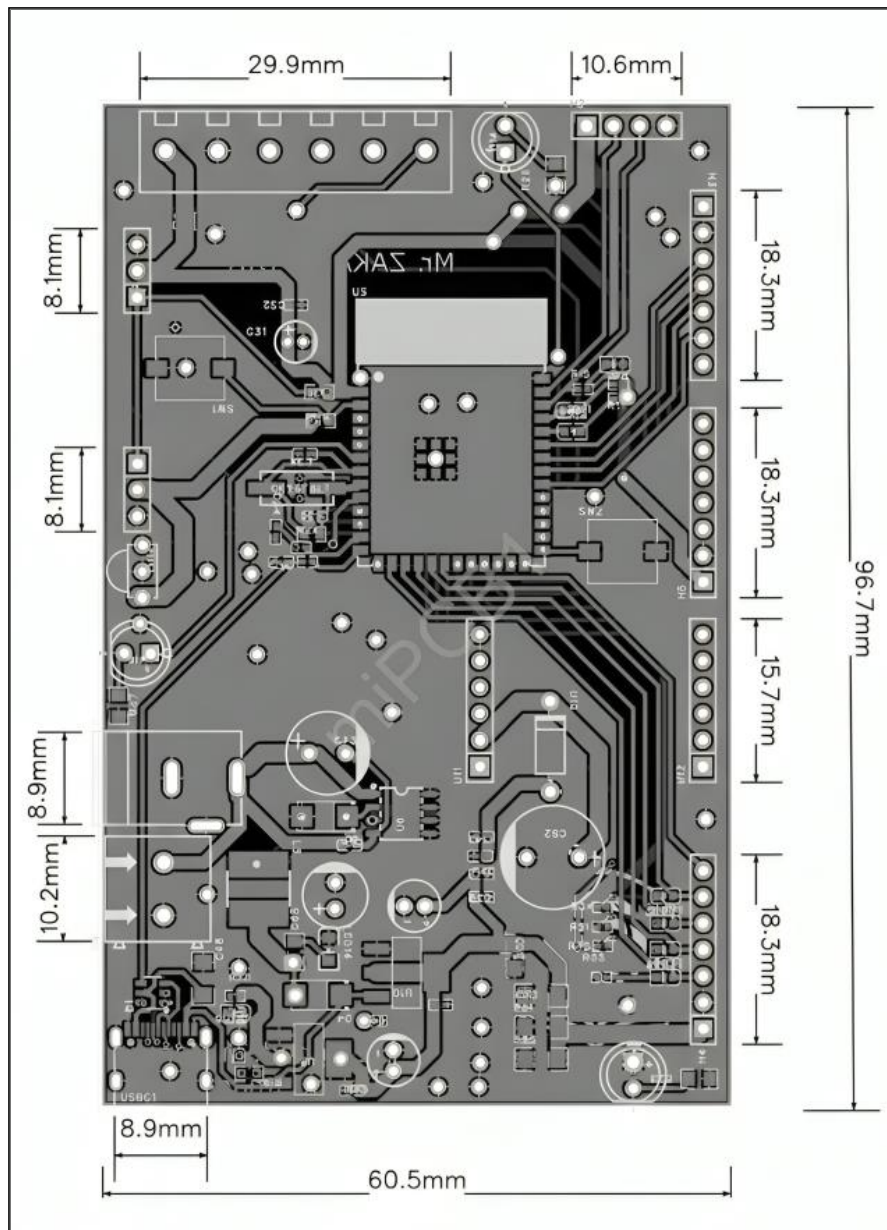


Figure III.19: General PCB Board Dimensions

III.4 3D PCB Visualization

To provide a clearer representation of the final hardware design, a three-dimensional (3D) view of the PCB board is presented in the following figure. The 3D visualization illustrates the overall arrangement of the electronic components, connectors, and module interfaces on the board. It also helps verify the mechanical structure and gives a realistic overview of the final assembled PCB before fabrication.

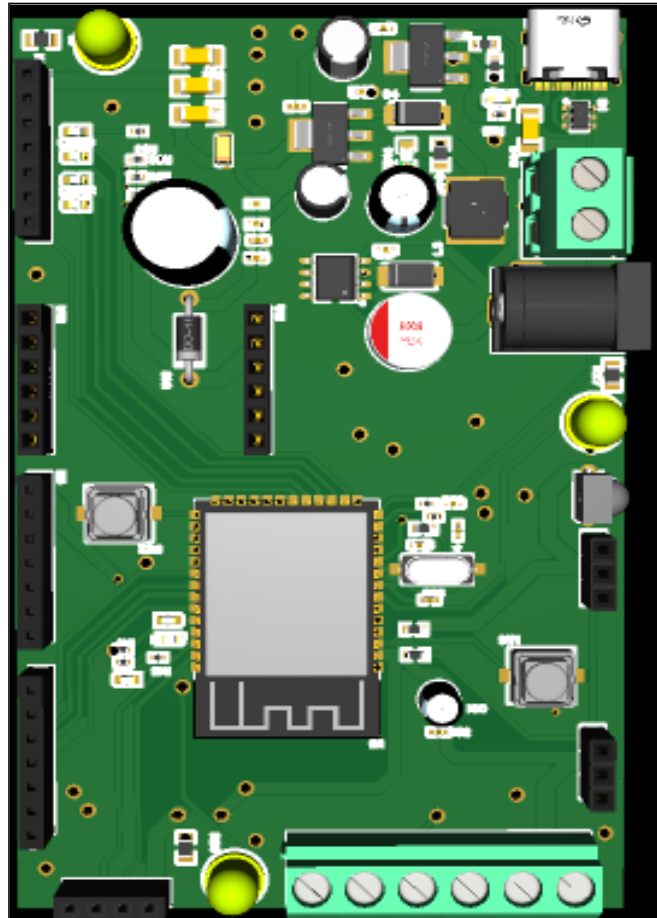


Figure III.20: 3D View of the Final PCB Board

III.5 PCB Pin Mapping

To make it easier to add external modules and simplify system implementation, we included connectors on our PCB for the ESP32 GPIO pins, power supply lines, and ground connections. The pin mapping diagram shows where each connector is and what it does, making it simple to interface with things like the IR transmitter and receiver, RF modules, GSM module, and relays – all part of our smart control system.

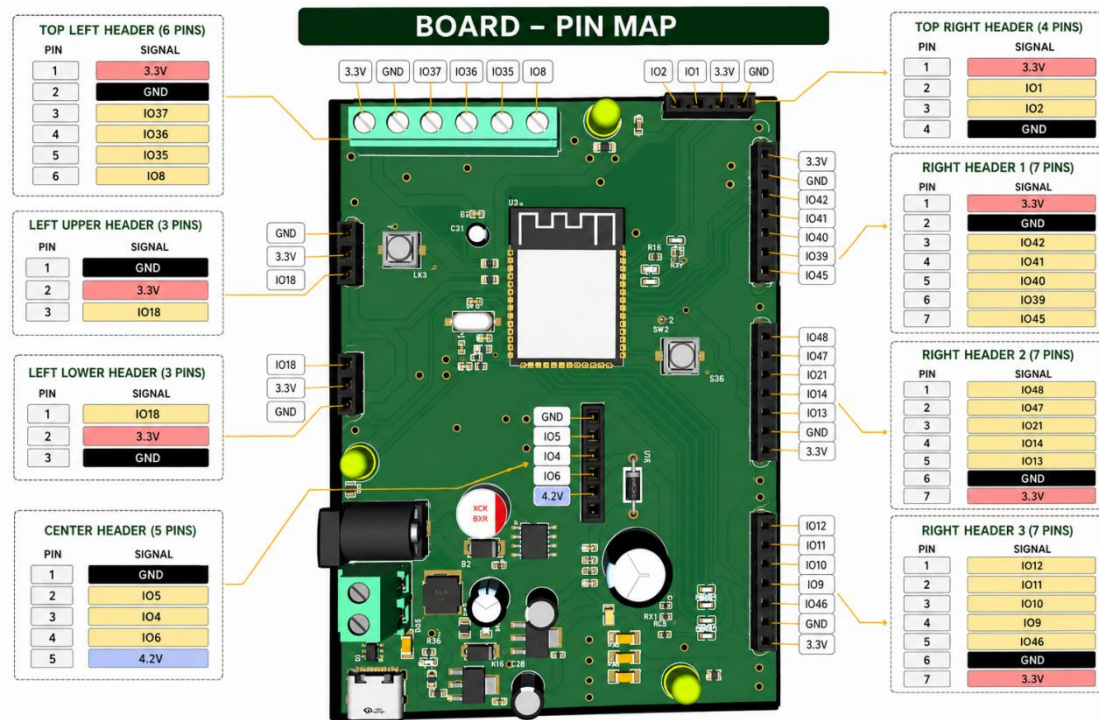


Figure IV.21: Pinout Diagram of the Developed PCB

III.6 PCB Board After manufacturing

This Figure shows the printed circuit board (PCB) of the smart system after the manufacturing process is completed. The board has been carefully designed to integrate all the essential electronic components.

A high-quality manufacturing process was chosen, using a 2-layer PCB to ensure electrical performance and stability.



Figure III.22: PCB Board After manufacturing

III.7 Conclusion

In this chapter, the development of the hardware platform for the proposed universal wireless control system was considered. Components choice was made on the basis of technical, economic, and reliability criteria to provide reliable work of the entire system.

All required components, including the power source, ESP32-S3 controller, infrared communication subsystem, RF communication interfaces, USB port, and expansion headers, were integrated into the PCB layout. Also, special circuitry was included to increase the stability of the system and reliability of the used hardware.

Finally, the results of this work are reflected in the obtained PCB layout and the produced PCB. These two show that all necessary subsystems have been successfully integrated into one single hardware platform capable of being utilized in smart homes.

Chapter IV:
Implementation of the system
and results

IV.1 Introduction

The results of the experiments conducted with the implementation and testing of the proposed intelligent home control system are considered in the current chapter. The main goal of this experiment was to ensure that all hardware and software modules are working properly and that the IR, RF, and Wi-Fi communication systems are efficiently used within the system.

Several experiments have been performed in order to estimate the performance of the prototype under various operating conditions. Some of the results include successful command transmission and reception, response of the relay interface, wireless communication, and efficiency of the remote control using the Internet of Things.

The purpose of this analysis is to prove that the proposed system is able to provide efficient and flexible wireless control of household appliances through different communication channels.

IV.2 Overall System Architecture

In this section, the overall architecture of the proposed smart home control system is presented. The system designed by us is expected to give the user the ability to control their home appliances wirelessly through local and remote means by applying IoT technology. This system involves hardware components that allow for the efficient functioning of the system through wireless connections.

These include the use of IR and RF technology in order to control household appliances, along with internet connectivity in order to allow for remote control. In the following subsections, the general architecture, the functional architecture of the proposed system, and the adopted operational principle will be discussed.

IV.2.1 General Overview of the Proposed System

The suggested system would be a Smart Home Control system, which allows its users to remotely operate their household appliances through a custom-made smartphone application. There are two types of household appliances in consideration, namely, those controlled by infrared signals (e.g., air conditioners, televisions, and set-top boxes) and those controlled by radio frequency (i.e., ceiling fans, lights, and garage doors). The central IoT control system receives the commands sent by the user's smartphone application via the internet and Wi-Fi networks, which will convert them into IR or RF signals for the operation of the appliance concerned.

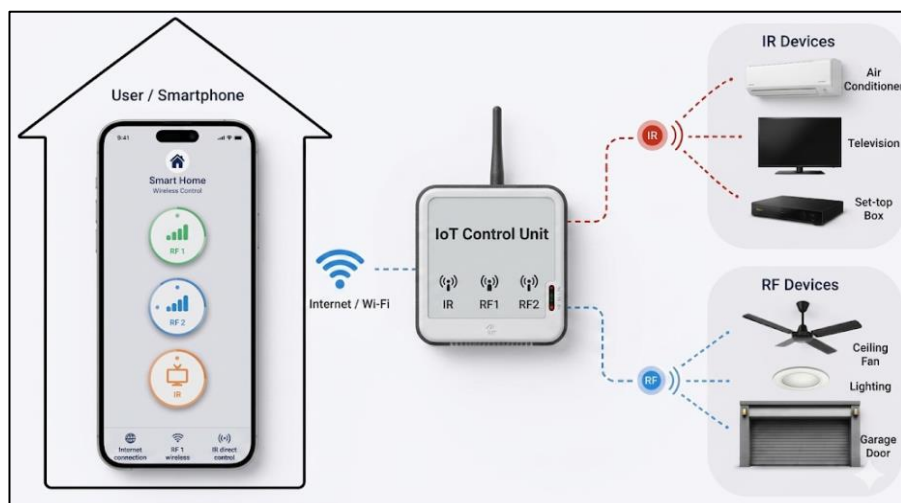


Figure IV.1: General overview of the proposed smart home control system

Users will only interface with the suggested system using the application on their smartphones. When sending a command, it will travel first to the cloud-based server then pass to the IoT control system via Wi-Fi network. Based on the selected button, the IoT control system will send an IR signal if the user wants to operate all IR devices at once, or an RF signal if he/she intends to operate just one RF device alone.

IV.2.2 Functional Architecture of the System

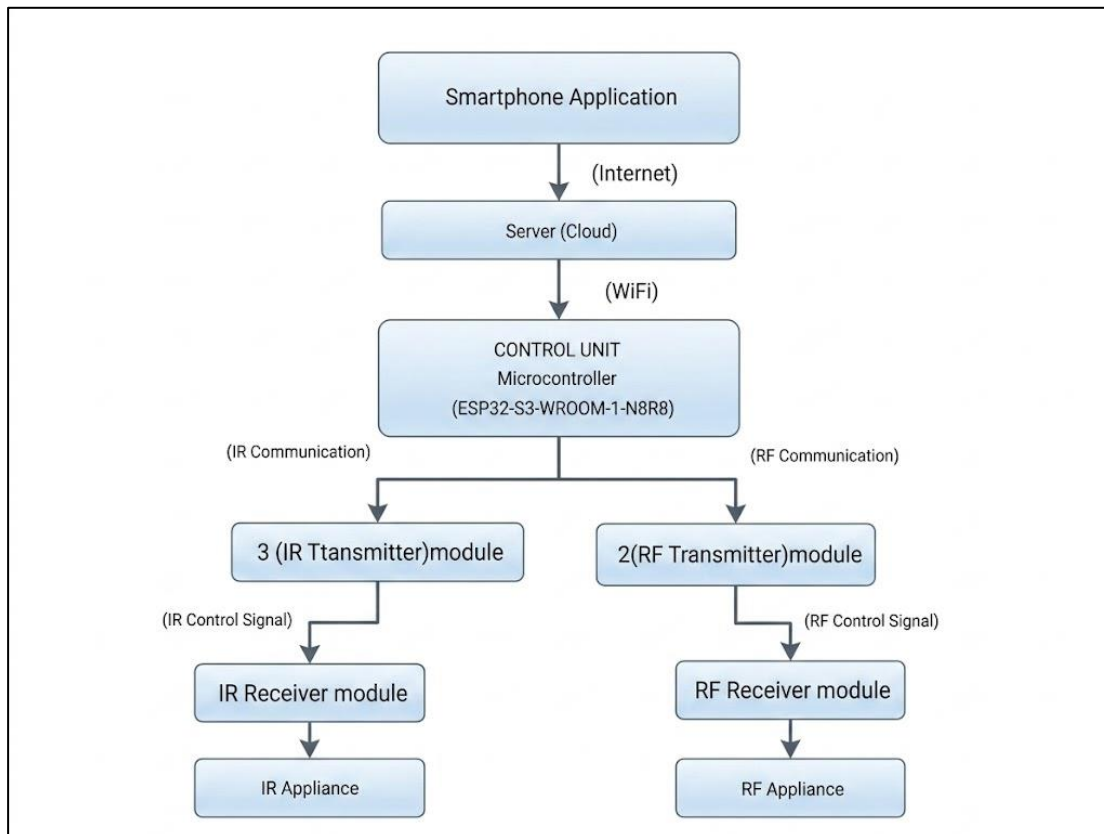


Figure IV.2: Functional Architecture of the System

As seen in Figure IV.2, the data flow in the proposed system takes place in a linear manner, starting from the user to the target appliance. The user triggers the command by clicking on the smartphone application interface. The command will be relayed through the internet connection to the cloud server that serves as the intermediary channel between the user and the home system. The server will pass the command to the central control unit using the Wi-Fi connection. Upon receiving the command, the control unit processes it to determine which kind of command to issue. In case the command is issued based on the IR button, the control unit triggers all the three IR transmitters, resulting in an infrared signal being transmitted to the air conditioner, television, and set-top box. In case the command comes

from the RF1 or RF2 button, the control unit will trigger the appropriate RF transmitter, causing the transmission of a digital signal at 315 MHz to the single RF receiver module.

IV.2.3 System Operating Principle

The basic operating principle of the suggested system involves transmitting the digital control signals through RF and IR communication systems. The operating principle of the system is based on performing the necessary actions in a definite sequence in order to provide reliable remote control of various electronic devices.

Step 1: Command Reception

The initial stage involves sending the corresponding command by means of the transmitter. At the stage of transmitting RF signals, the transmitted information is transmitted using the 3-bit digital code structure. During this stage, each command consists of a particular combination of bits. This signal is received by the RF receiver and sent further to the microcontroller.

Step 2: Signal Processing

Once the signal is received by the microcontroller, it is decoded into the 3-bit binary sequence, thus providing information regarding the operation to be performed. Each bit is considered as a certain logical state, where logic “HIGH” is binary “1” and logic “LOW” is binary “0”.

Step 3: IR or RF Signal Transmission

After processing the command, the output signal is produced by the system.

- In case of an infrared communication protocol for the target device, the command will be sent by the IR transmitter.
- In the case of RF communication protocol for the target device, the command will be sent by the RF transmitter.

The waveforms that are being transmitted consist of pulses that represent binary bits of information.

Step 4: Execution of Command by the Target Device

Finally, the target device receives the transmitted signals and decodes the binary bits representing the command. The device will perform a particular action in accordance with the 3-bit received command.

IV.3 Hardware Design and Implementation

This section presents the hardware implementation of the proposed smart home control system. The hardware design of this system involves embedding control, wireless communications, and Internet of Things to enable remote/local control of the appliances via IR/RF communication modes.

IV.3.1 System Components and Layout

The proposed system will comprise several hardware modules that would guarantee reliable wireless communications and intelligent control operations. The overall system layout is based on a microcontroller that is connected to several communication and control modules.

The basic hardware modules employed in this system consist of:

- ESP32 microcontroller board.
- IR communication module.
- RF wireless communication module.
- Wi-Fi communication interface.
- Power supply circuitry.
- Controlled household appliances.

The organization of the system setup was aimed at making the signal connections easier and ensuring effective communication among the various hardware modules.

IV.3.2 Central Control Unit Design

The central control unit embodies the heart of the processing system implemented in the device. The development of the controller utilizes the ESP32 microcontroller in view of its capabilities of built-in Wi-Fi and power saving, as well as the applicability to IoT projects.

Functions of the ESP32 include the following:

- Establishing wireless communication with the server.
- Receiving and processing control commands.
- Managing IR and RF transmission operations.
- Coordinating communication between all system modules.
- Executing appliance control instructions in real time.

The controller maintains system functioning and performs the computation necessary for effective communication and commands processing. In addition, the controller's wireless capability substantially simplifies the hardware setup.

IV.3.3 IR Communication Module

The IR communication module was designed to facilitate wireless control of infrared-controlled home appliances like television sets, air conditioners, and media equipment.

It works by sending encoded IR signals sent by the ESP32 towards the desired appliance, The appliance will then perform the required action after receiving the command.

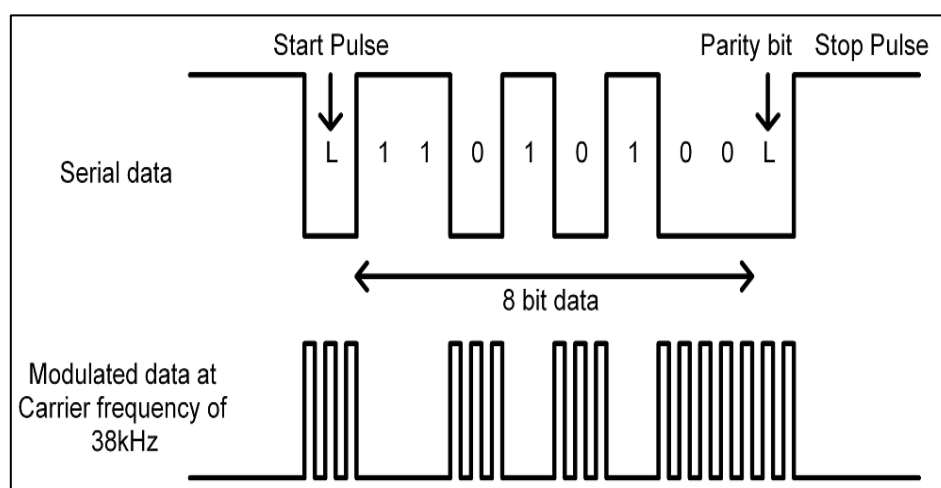


Figure IV.3: Modulation of Infrared Data Using a 38 kHz Carrier Frequency

Advantages of using the IR module include:

- Low implementation cost.
- Low power consumption.
- Fast response time.
- Compatibility with conventional consumer electronic devices.

Infrared signaling requires visibility between the sender and receiver and thus has a shorter range than RF communications.

IV.3.3.1 Analysis of IR Transmitted Signals

Measurements for the signals transmitted via IR communication were done using a digital oscilloscope in order to determine whether the communication channel is working properly. Waveforms from the oscilloscope correspond to the ON and OFF commands that have been transmitted via the IR LED from the ESP32-S3 board.

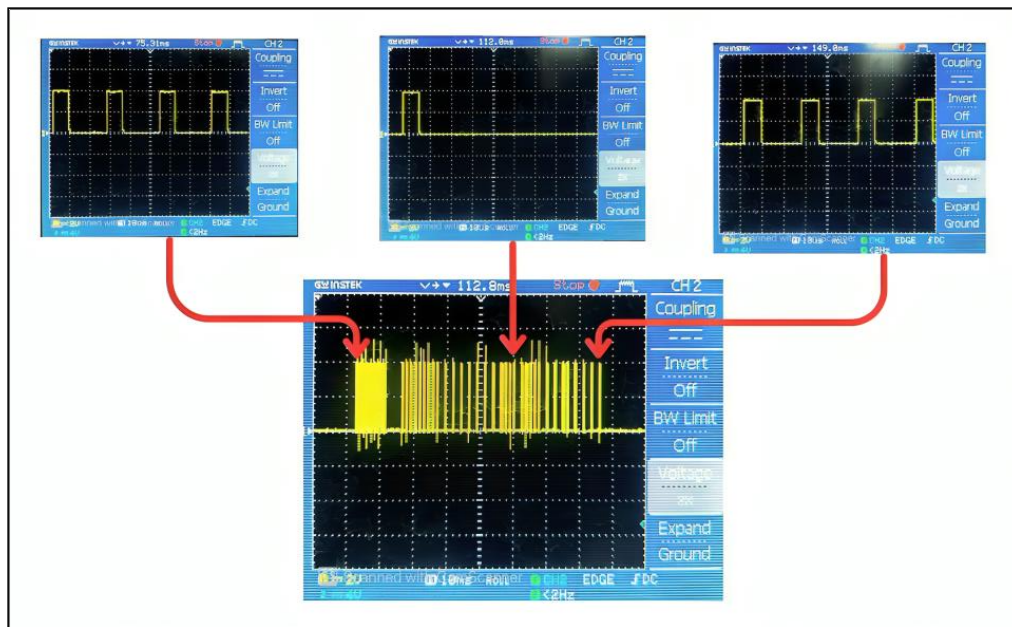


Figure IV4: IR Transmission Signal for ON Command (0xF708FF00)

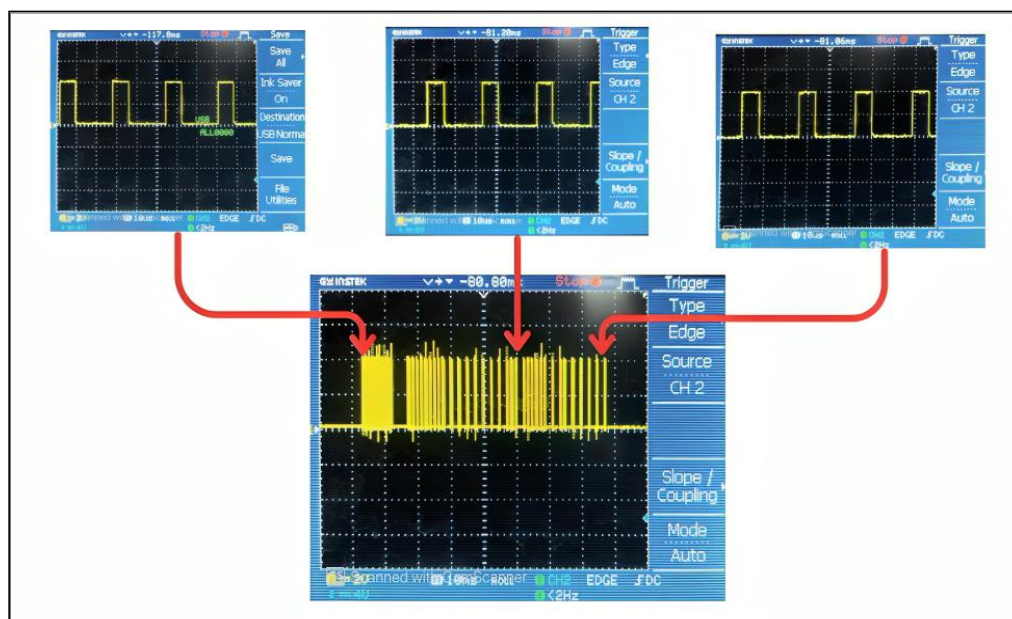
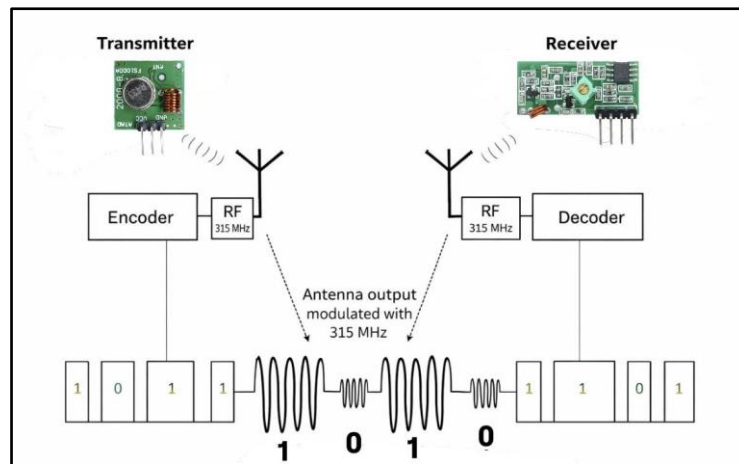


Figure IV5: IR Transmission Signal for OFF Command (0xFB04FF00)

IV.3.4 RF Communication Module

The RF communication module was implemented in the system for wireless control of appliances from a distance without aligning visually the communication devices.

RF technology enables the ESP32 microcontroller to send encoded commands wirelessly to remote devices via radio frequency. This mode of communication increases the flexibility of the system and can be used for controlling appliances from another room or behind walls.

**Figure IV.6:** RF Communication Architecture (315 MHz)

The use of the RF communication module in the system ensures some operational benefits:

- Extended communication range.
- Non-line-of-sight operation.
- Reliable wireless transmission.
- Improved smart home coverage.

Therefore, the implementation of RF technology significantly expands the usability and scalability of the smart home control system based on the IoT paradigm.

IV.3.4.1 Analysis of RF Transmitted Signals

Transmission of the RF signal was carried out with the aid of a digital oscilloscope for checking if the appropriate command signals were transmitted wirelessly. Waveforms captured are for both ON and OFF commands that are transmitted from the RF transmitter operating at 315MHz frequency band.

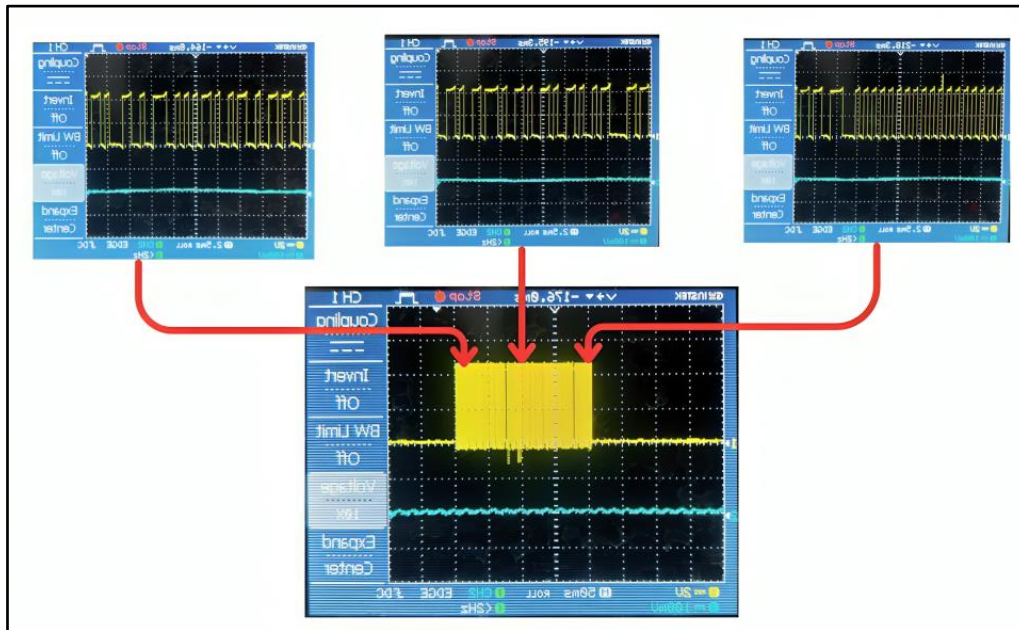


Figure IV.7: RF transmitted signal corresponding to command RF1_ON

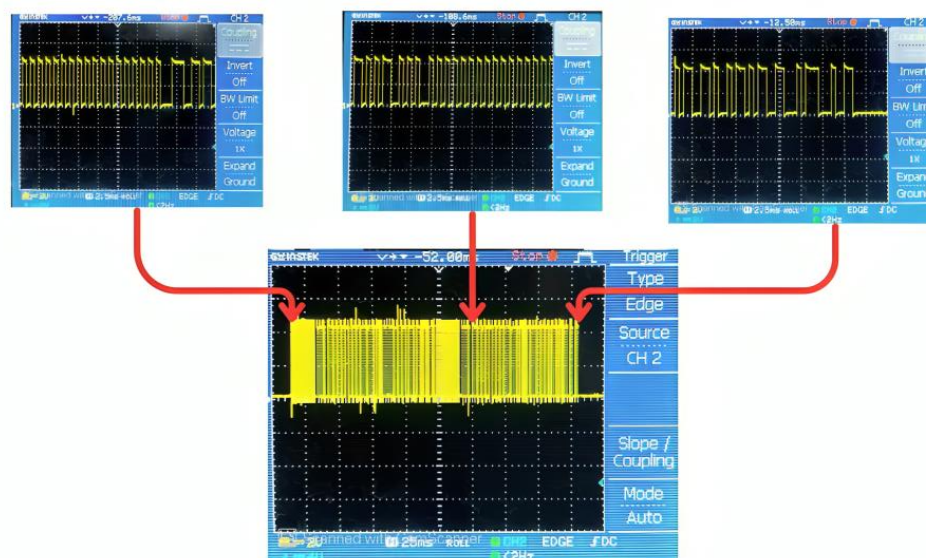


Figure IV.8: RF transmitted signal corresponding to command RF1_OFF

IV.3.5 Wi-Fi Communication and IoT Implementation

Communication with the internet in the described intelligent home solution is realized by means of Wi-Fi technology implemented in the ESP32 microcontroller. Having powered on the system, the ESP32 module connects to the local Wi-Fi network using an already specified SSID and password in the program code. As soon as the connection is established, the microcontroller gets the ability to communicate with the remote server through sending or receiving messages.

HTTP protocol is used for establishing the communication between the ESP32 and the server. Periodically, the microcontroller sends GET HTTP requests to the server and receives from it certain control commands. According to the received information, the ESP32 starts the working of either the IR or RF modules to provide control of home appliances from remote locations.

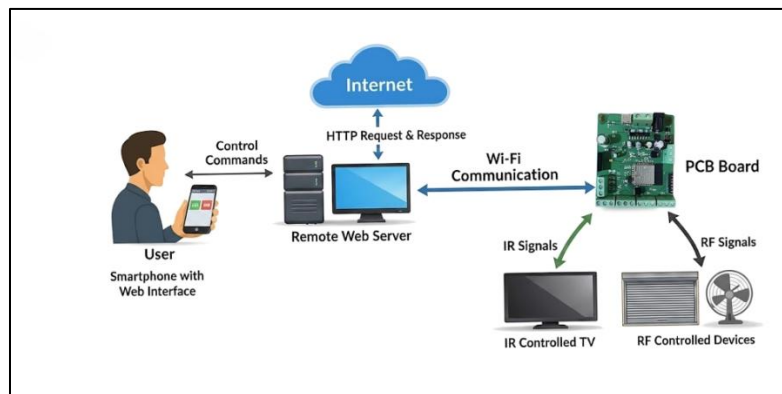


Figure IV.9: Wi-Fi Communication and IoT Integration of the Smart Home System

A web interface that works through the server side is also included into the design of the intelligent home system. The user can send commands to the server via smartphone or a computer to control various home devices remotely.

Therefore, it should be said that the use of Wi-Fi technology and the internet has a crucial role to play in implementing the described smart home solution in IV.3.6 Power Supply Circuit

IV.3.6 Relay Interface Module

The controlled device interface comprises relay-based switching interfaces attached to the wireless receiver units. In the discussed system, there were two relay-based interfaces

associated with the RF communication system (RF1 and RF2), while another relay interface was connected to the IR communication subsystem.

Each relay interface functions as an electrical switch whose operating state depends on the wireless command. As soon as the wireless command is decoded by either the RF or IR receiver, the relay interface is triggered through ESP32-S3, thereby controlling the connected loads.

Relay interfaces constitute the last control element in the discussed system and imitate typical domestic appliance such as lights and other electrical equipment. This arrangement provides practical testing of the remote wireless operation of appliances using either RF 315 MHz or infrared communication systems.

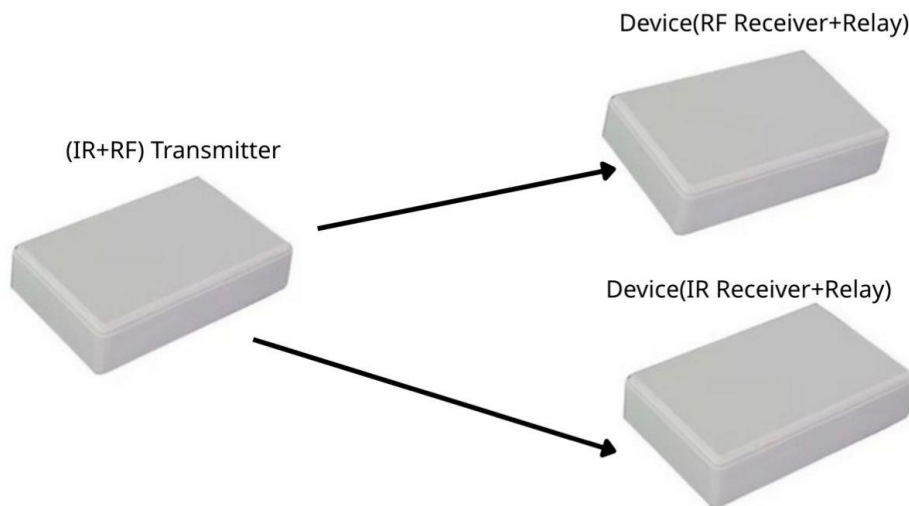


Figure IV.10: IR/RF Relay-Based Communication Interface Architecture

IV.4 Software Implementation

This part talks about the software for the system. It covers the development setup, tools, and parts needed for the mobile app to talk to the ESP32 microcontroller and various control modules. The software lets the system handle commands in real-time and keeps RF, IR, and relay controls working properly.

IV.4.1 Embedded Programming

For implementing the software functionality of the proposed system, the Arduino IDE was chosen. It provides a convenient development environment for working with embedded

devices, particularly ESP32 microcontrollers. The Arduino IDE also includes the Serial Monitor, a powerful tool for efficient programming, debugging, and testing.

The program is designed to ensure continuous work. Thus, upon initialization, the microcontroller will start all necessary modules of communication with the external devices and will wait for a wireless command from the transmitter. Once the system receives the command, it will decode the signal and perform an appropriate action like turning on or off the relay.

To develop the program that implements the functionality of the system, different libraries were utilized. On the transmitter side, the `<WiFi.h>`, `<HTTPClient.h>`, `<RH_ASK.h>`, `<SPI.h>`, and `<IRremote.h>` libraries were used to provide communication over networks and transmission of RF and IR signals. Similarly, on the receiver side, the `<RH_ASK.h>` and `<SPI.h>` libraries were used for the transmission of RF commands, whereas the `<IRremote.h>` library provided IR communication capabilities.

IV.4.2 Server-Based IoT Platform

It should be noted that the role of the IoT server as an intermediate entity in the proposed IR control and communication system is essential in providing data exchange between hardware elements and the software interface. In particular, the function of the server includes transferring real-time command data received via the interface, such as turning the light source ON and OFF, to the embedded control unit.

After processing a command in the server, it is transmitted to the ESP32 microcontroller. It is necessary to emphasize that this chip is responsible for interpreting incoming data, which results in activation of a corresponding command via the infrared transmission module.

The overall architecture of the wireless communication system under analysis involves using the centralized control approach. At that, the ESP32 microcontroller acts as a core processing element and controls an infrared transmitter as its output element.

Thus, a combination of hardware elements allows implementing efficient real-time control and ensuring stable communication with external devices. Furthermore, the system provides wireless communication capabilities by establishing connection through Wi-Fi.

In turn, Wi-Fi technology provides for a possibility of data exchange and interaction between the user interface and the embedded control unit.

IV.5 Final System Prototype

Figure IV.11 shows the finished smart home control system after putting together all the hardware and communication bits. The ESP32 microcontroller in the transmitter unit talks to the mobile app via Wi-Fi and the Internet. It sends control commands to the receiver using RF communication, then the IR transmitter module kicks in to direct infrared signals to the appliances.

Relay modules turn the connected devices on and off based on the mobile app commands. So, the final product works really well, combining IoT, RF, and IR tech into one slick remote control system.

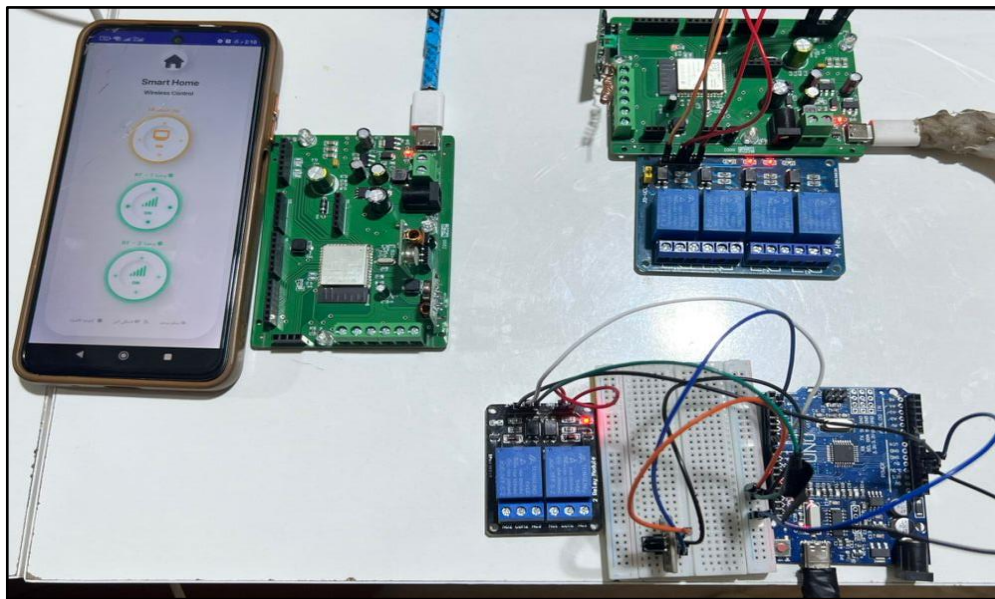


Figure IV.11: Final implemented prototype of the proposed smart home control system

IV.6 Conclusion

Experimental results shown below prove the successful development of the suggested smart home control system. During the experiment, the prototype proved to function reliably; specifically, the ESP32-S3 microcontroller, IR communication module, RF communication module, relay interface, and internet connection via Wi-Fi proved to work without any issues.

Tests conducted showed that control signals were sent and received properly via both infrared communication channel and RF communication channel. What is more, IoT-based control system made it possible to operate home appliance devices remotely using internet connection.

As can be seen from the results, the developed system works well and successfully fulfills the purposes for which it was made. It worked reliably during tests and reached the set goals. Besides, it is relatively inexpensive and adaptable and can be used in existing tasks and will meet clients' needs in the future.

General Conclusion

General Conclusion

The fast development of smart home technologies and IoT led to a significant increase in demand for efficient solutions that can allow users to control home appliances in one system. It is against this background that the main aim of this research was to create an IoT-based universal control unit capable of controlling not only Infrared (IR) but also Radio Frequency (RF) wireless devices using a single control system.

For this purpose, the work was started by analyzing literature on relevant issues, including information on smart homes, embedded systems, IoT technology, and wireless communications. A special focus was placed on studying the features of IR and RF communication technologies suitable for use in home automation. Further, the hardware and software structure of the system under consideration was designed based on the use of the ESP32-S3 microcontroller.

This system is able to provide integration between Wi-Fi connections, IR transmissions, RF communication at 315 MHz, and relay control interfaces. Due to the usage of a server IoT platform that was created, users will be able to use their smartphone to send remote commands, while ESP32-S3 will handle all incoming data and create required control IR or RF signals. Testing sessions were done via oscilloscope and have shown proper creation and sending of both kinds of control signals.

These results confirm the effectiveness of using IoT technology along with hybrid IR and RF communication in one control system. Proposed by me, the project provides an affordable, scalable, and highly flexible solution to smart home automation.

For future improvements, the proposed system may be improved through the addition of bidirectional communication, status feedback of devices, increased security measures, cloud storage capabilities, and support for other wireless technologies like BLE, Zigbee, or Matter. These advancements would enable greater compatibility, intelligence, and practicality of the suggested smart home control system.

In summary, the developed universal control device shows how the application of Internet of Things, infrared, and radio frequency technologies can effectively solve the challenges faced in smart home environments.

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