DESIGN AND DEVELOPMENT OF FULL-DUPLEX WIRELESS TRANSCEIVERS SYSTEM USING 433MHz CIRCUIT MODULES

Matthew B. Olajide, Oluwaseyi E. Giwa, Joy B. Ogunsakin, Oluwatosin A. Aina, David S. Kuponiyi

[124] Department of Electrical/Electronic Engineering, Olabisi Onabanjo University, Nigeria.
[3]Department of Electrical and Electronics Engineering, University of Ilorin.
[5]Department of Electrical Electronics Engineering, Gateway (ICT) Polytechnic Saapade, Nigeria
olajide.mathew@oouagoiwoye.edu.ng, giwaoluwaseyi475@gmail.com, ogunsakin.jb@unilorin.edu.ng, tosinaina2@gmail.com, david.kuponiyi@gaposa.edu.ng

Received: February 14, 2025, Accepted: April 28, 2025

Abstract: The growing demand for reliable and cost-effective wireless communication systems for applications such as remote monitoring, control systems, and Internet of Things (IoT) networks highlights the challenges posed by existing technologies, including latency, limited range, and high-power consumption. This study focuses on the design and development of a full-duplex wireless transceiver system operating at 433 MHz, utilizing commercially available RF circuit modules. The objective is to enable simultaneous bidirectional data transmission, thereby enhancing communication efficiency while minimizing latency. The transceiver system was constructed using 433 MHz RF transmitter and receiver modules, microcontrollers for signal processing, and optimized antennas to ensure stable communication. The design incorporates features aimed at achieving low power consumption, compact circuitry, and advanced noise suppression. Experimental evaluations were conducted to assess performance and communication range. The system demonstrated reliable bidirectional communication within a 100-meter range. Its low power consumption and effective noise suppression ensured efficient operation with minimal interference, making it suitable for short-range applications. The full-duplex transceiver system offers a cost-effective and efficient solution for short-range wireless communication, with potential applications in IoT networks, remote monitoring, and control systems. It provides a solid foundation for further advancements in wireless technology.

Keywords: - frequency modulation, data transfer rate, power efficiency, signal quality, transceiver range, wireless transceiver.

Introduction

Radio Frequency (RF) communication is a widely used technology for wireless data transmission and reception. In this paper, the 433MHz frequency band is a popular choice for various applications such as remote controls, home automation systems, and low-power wireless sensor networks (Baker *et al*., 2024; Mousavi *et al*., 2022; Orfanos *et al*., 2023). This paper provides an in-depth understanding of how 433MHz RF transmitters and receivers operate, covering their fundamental principles, components, and key considerations. Wireless communication systems have become integral to modern technology, enabling seamless data exchange across various applications (Kuponiyi *et al*., 2023). Full-duplex communication, which allows simultaneous transmission and reception of signals, offers significant advantages in improving data throughput and reducing latency, (Wang *et al.,* 2022). This project focuses on the design and development of a full-duplex wireless transceiver system using 433 MHz RF circuit modules.

The 433 MHz frequency band is widely used due to its license-free operation, long-range capabilities, and low power consumption, making it ideal for short-range wireless communication (Koul *et al*., 2024; Kumar *et al*., 2024; Stiller *et al*., 2023). By leveraging readily available RF modules, this study aims to create a cost-effective and reliable communication system suitable for applications such as remote monitoring, IoT networks, and industrial automation (Omolola & Adelakun, 2024; Javaid *et al*., 2021; Olajide *et al*., 2024; Tang *et al*., 2020). The design incorporates modular components, efficient signal processing techniques, and noise suppression mechanisms to enhance performance. The developed system is evaluated for its reliability, range, and data transfer capabilities, demonstrating its potential for real-world deployment. This system can be used in areas where there is no mobile communications and during natural disasters.

Materials and Method

The entire Wireless transceivers system operating at frequency range of 433 MHz are widely used in short-range communication systems, including IoT devices, home automation, and remote controls (Adelakun *et al*., 2024; Al-Rawi, 2019). RF communication involves the transmission and reception of electromagnetic waves through the air or free space (Abrasi, 2021). These waves propagate at the speed of light and carry information encoded in their amplitude, frequency, or phase. The 433MHz frequency band is part of the Ultra High Frequency (UHF) range, which lies between 300MHz and 3GHz. The 433 MHz frequency band falls under the Industrial, Scientific, and Medical (ISM) spectrum, making it license-free in many countries (Abdulghafor *et al*, 2021; Ma *et al*., 2024). Key Components in Modeling:

i. Power supply section
ii. Transmitter Design - Includes modulation schemes such as Amplitude Shift Keying (ASK) and Frequency Shift Keying (FSK) for efficient data transmission.
iii. Receiver Design - Focuses on demodulation techniques, noise filtering, and signal amplification to ensure reliable data reception.
iv. Antenna Design - Optimized for compact size and high efficiency at 433 MHz, using monopole or helical designs.
v. Channel Modeling - Considers path loss, shadowing, and multipath fading to simulate real-world propagation environments.

The methodology that we proposed will work on 433MHz channel and will work wirelessly with the help of speakers for transmitting and receiving the audio signals. We use a

433MHz transmitter are receiver at both ends for transferring data. Condenser mic is used for providing the input signal and speaker to produce the output. The power for the circuit is given by 9V battery and voltage regulators are used to regulate the voltage.

The relationship between wavelength (λ) and frequency (f) is given by the equation:

$$\lambda = c / f \quad (1)$$

Where:

- λ = the wavelength (in meters)
- c = the speed of light (approximately 3 × 10^8 m/s)
- f = the frequency (in Hertz)

At 433MHz, the corresponding wavelength is approximately 0.69 meters.

Higher carrier frequency allows small and antenna, but increases the DC power drastically (Punitha et al., 2019). Apparently increasing the carrier frequency increases the path loss and hence more transmitter power is required. Mathematically, the path loss can be calculated as

$$L_{path} = 10\, Log\, \frac{(4\pi)^2}{\lambda^n} + L_{atten} \quad (2)$$

Where

d is the distance of two nodes,

λ is wave length and

L_{atten} is the attenuation in the path.

Although increased path loss forces the low power WSN designers toward lower carrier frequencies, the network reliability and interference and jamming immunity is an important motivation for higher carrier frequencies (Winkler *et al.*, 2004). Another important issue is the energy-per-bit value. Energy-per-bit is measure of comparing the energy efficiency of low power transceivers and is calculated as:

$$E_b = T_b \times P_{DC} \quad (3)$$

Where

P_{DC} is the average DC power and

T_b is time duration of single bit.

This equation implies that for a given DC power, increasing data rate decreases the energy-per-bit, and this means more energy efficient transceiver.

After determining the transmitter radiation power and range, the receiver sensitivity can be calculated using Friis wave propagation equation. It must be noted that accurate calculation of the path loss, especially for indoor applications is very complicated and Friis equation calculated the path loss for a point-to-point communication. However this equation can be used as a primary design guideline in WSN applications (Mou, 2017). Friis equation calculates the ratio of received power to transmitted power:

$$\frac{P_r}{P_t} = \left\{\frac{\lambda}{4\pi d}\right\}^2 G_r G_t \quad (4)$$

Where:

Pr and Pt = received and transmitted powers, respectively,

λ = wave length and d is the nodes distance.

Gr and Gt = the receiver and transmitter antennas gain, respectively.

Power supply circuit analysis

To ensure a stable dc voltage at low mains voltages. A 12V step down transformer of 220/12V, 100mA was used. Full wave rectifier-Four diodes D1-D4 (IN5407) were used to convert the AC voltage available at the secondary of the transformer to DC. These diodes were chosen because of its current capacity since the switching circuit are drawn from the power circuit. Figure 1 present circuit diagram of DC power supply.

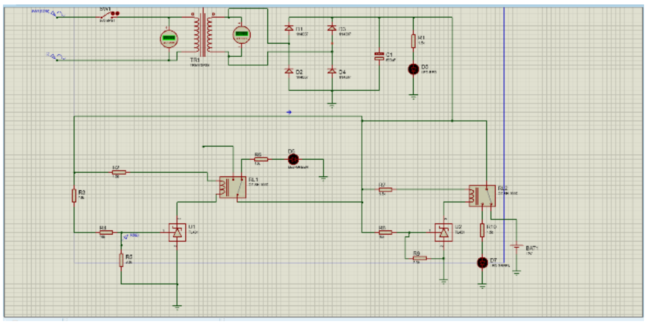


Figure 1: Circuit diagram of a DC power supply

For the transformer,

$$V_s/V_p = N_s/N_p \quad (5)$$

Since Ns/ Np =1 /20

Vs / 240v =1 / 20

So Vs =240 /20 =12v

In practice, the primary voltage varies but is not expected to be less than 180v. Electrolytic and ceramic capacitor were used separately to filter the ripples present and remove or smoothening the ripples which might remain after filtering respectively. The values of the capacitors used with a 50Hz supply may range from 100µF-3000 µF depending on the load current and the degree of filtering and smoothening required. In selecting capacitors, the ripple voltage required is 10% of the peak value. The selection of the capacitor is based on the following calculations:

For a charged capacitor Q = CV=It (6)

I=CV/t

Thus, C = It/ V ripple

But t =T= 1/f (7)

For a full wave rectifier, the frequency of the rectified DC output is 2×the supply frequency 2×50 = 100Hz

T = 1/100 = 0.01s

V ripples (peak) = Vmax - Vdc (8)

Vdc =0.6366 Vmax

V max =1.414 Vrms

V rms =12 -Vd

Vd = total diode drop =0.6×4 =2.4

V_{rms} = 12 - 2.4 = 9.6V

Vmax =1.414 × 9.6 = 13.576V

Vdc =Vave=0.6366 × 13.576 =8.635V

Vripple = Vmax - Vdc =13.576 -8.635 =4.941V

Therefore, V ripple = (pk-pk) =2×4.941V =8.982V

10% ripple =10/100 × 8.982 = 0.8982V

But C= I t/V ripple = 0.35×0.01s/0.8982 =3.9milliF

C=3900µF

C =3900µF was the preferred value.

For the smoothening capacitor, V ripple =10% of 0.8982 =0.089V

Therefore, C = 0.35 ×0.01/0.089 = 0.03896 mF

C=390 µF

The working voltage of a filter capacitor must always be more than 1.414 times the expected secondary voltage of the step-down transformer which equals 12V.For this application, a 500µF/50V was used for C1.

Voltage regulator (LM 7805): Voltage regulator was required to stabilize the output to the desired voltage level (5V). A voltage regulator takes an unregulated at its input and provides a regulated one at its output. They are available as either fixed or adjustable regulators. The design requires +5v supply.

433 MHz RF Transmitter:

RF transmission very strong and more reliable than IR transmission. RF communication uses a selected frequency and not like IR signals which have noises from other IR emitting sources. The 433MHz wireless module is cheap and easy to use. These modules are often used only in pairs and only simplex communication is feasible. This module could cover a minimum of three meters and with proper antenna an influence supplies it can reach up to 100 meters but is not proved practically. But practically we can hardly get about 97.5 to 98.2 meters in a normal condition. Figure 2a present the transmitter module while Figure 2b present the structure of the transmitter.

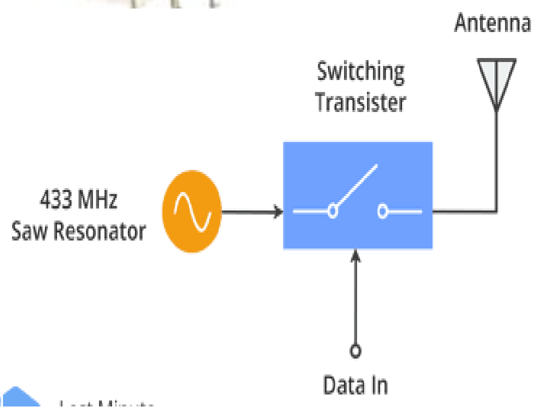


Figure 2a: 433 MHz RF Transmitter Figure 2b: 433 MHz RF Transmitter structure

A 433MHz RF transmitter is a device that converts digital or analog data into a modulated RF signal at the specified frequency. The transmitter consists of several key components:

Encoder

The encoder is responsible for converting the input data (e.g., binary digits) into a format suitable for transmission. Common encoding schemes used in 433MHz systems include Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and On-Off Keying (OOK).

Modulator

The modulator takes the encoded data and modulates it onto a carrier signal at the desired frequency (433MHz). The modulation process involves varying one or more characteristics of the carrier signal, such as amplitude, frequency, or phase, according to the input data.

Oscillator and Frequency Synthesizer

The oscillator generates the carrier signal at the desired frequency (433MHz). In more advanced systems, a frequency synthesizer may be used to generate precise and stable frequencies.

Power Amplifier

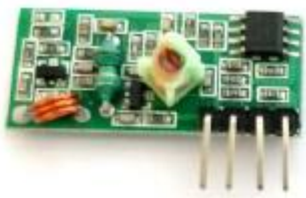
The power amplifier amplifies the modulated signal to a sufficient power level for transmission through the antenna.

Antenna

The antenna is a crucial component that converts the electrical signals from the transmitter into electromagnetic waves that can propagate through the air. Typical antennas used in 433MHz systems include whip antennas, loop antennas, and printed circuit board (PCB) antennas.

MHz RF Receiver

The main function of the RF receiver module is to receives the modulated RF signal, and demodulate it. There are two sorts of RF receiver modules. Super regenerative modules are usually low cost and low power designs employing a series of amplifiers to extract modulated data from a carrier. Super regenerative modules are generally imprecise as their frequency of operation varies considerably with temperature and power supply voltage. Super heterodyne receivers are advantageous over super regenerative and that they offer increased accuracy and stability over voltage and temperature.



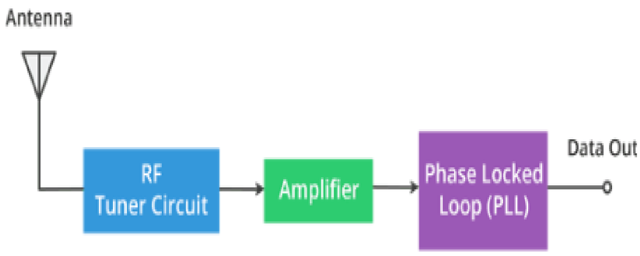


Figure 3a: 433 MHz RF Receiver Figure 3b: 433 MHz RF Receiver structure

MCP60:

MCP602 is a low-power operational amplifiers. These op amps utilize a complicated CMOS technology that gives low bias current, high speed operation, high open-loop gain and rail-to-rail output swing. This product offering operates with one supply voltage which will be as low as 2.7V, while drawing 230µA (typ.) of quiescent current per amplifier, these are ideal for single-supply operation (Guna *et al*., 2021).

Condenser Mic

RF condenser microphones use a relatively low RF voltage, generated by a low-noise oscillator. The signal from the oscillator may either be amplitude modulated by the capacitance changes produced by the sound waves moving the capsule diaphragm, or the capsule could also be a part of a resonator that modulates the frequency of the oscillator signal. Demodulation yields a low-noise audio signal with a really low source impedance. The absence of a high bias voltage permits the utilization of a diaphragm with looser tension, which can be wont to achieve wider frequency response thanks to higher compliance (Guna *et al*., 2021).

Frequency response: 50Hz – 18 kHz
S/N rate: >105dB
Output level: 200mV ± 5mV
Receiver battery voltage: 5.0v
From frequency range: given
f_L = 350MHz , and f_u = 433MHz
Sampling frequency, $f_S = 2(f_u - f_L)$
f_S = 2 (433 - 350) = 166MHz
Therefore, 200MHz for sampling frequency is harmonic for both 350MHz and 433MHz

Sampling period, $t_s = 1 / f_s$
$t_s = 1 / (166 \times 10^6) = 6.02 \times 10^{-9} = 0.00602\mu s$
Given the maximum frequency of voice signal to be 18 KHz
W = 18 kHz
Nyquist rate = 2W = 2 x 18 kHz = 36 kHz
Minimum frequency response (sampling frequency) = 2W = 36 kHz
Maximum sampling period (frequency response), $t_s = 1 / f_s = 1 / (36 \times 10^3) = 0.278\mu s$

Amplitude Shift Keying (ASK)
As mentioned previously, these modules applied a technique known as ASK, to transmit digital data over the radio. In amplitude shift keying, the amplitude of the carrier wave (433 MHz signal in our case) is modified in response to an incoming data signal. It's a lot like the Amplitude Modulation technique used in AM radio. Because it only has two levels, it is sometimes referred to as Binary Amplitude Shift Keying (Islam & Jin, 2019).

The advantage of Amplitude Shift keying is that it is very simple to implement. The decoder circuitry is quite simple to design. Furthermore, ASK requires less bandwidth than other modulation techniques such as FSK (Frequency Shift Keying). This is one of the reasons why it is cost effective

The Tone Control and Mixer Stage
An electronic device known as an audio mixer is used to combine (or mix), route, and alter the volume, timbre, and dynamic of audio signals. The combined output signal with pre-amp control is created by adding the changed signal (voltage or digital sample). The mixer in radio is a circuit that combines these signals in a process called "Heterodyning". A major requirement is to minimize feedback (Lin & Jarrahi, 2020).
The transmitter is housed and attached directly to a conventional handle or ear-hung microphone, thereby making much standard microphone wireless. "Compression" is the stage of the process that takes place in the transmitter and lowers or compresses the dynamic range of the audio stream (Mao *et al*., 2019).

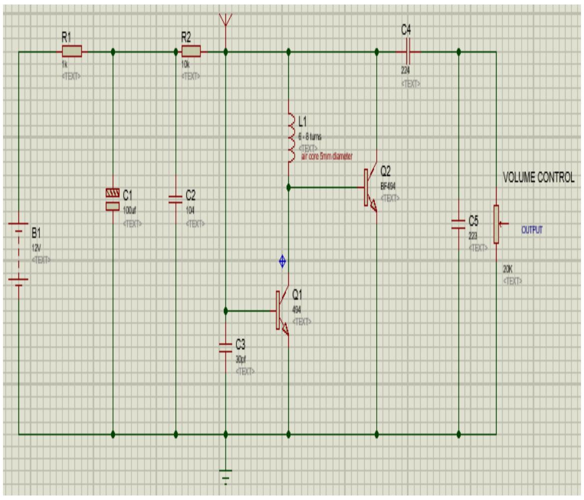


Figure 4: Diagram of volume control

The 'front end' is the initial portion of receiver circuitry, its purpose is to offer a first step of radio frequency filtering to prevent undesired radio frequency from interfering with succeeding stages.

Simulation

The proposed system circuit diagram has been successfully simulated in the software Proteus 8 Professional Software. The system uses a RF 433 MHz transmitter and receiver along with an audio source for input and a speaker for output. The simulation model of the proposed system is shown in the figures 5, 6, 7, 8, 9 and 10.

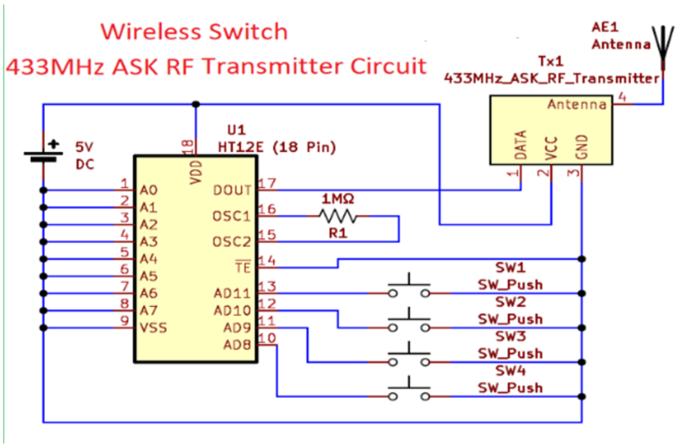


Figure 5: Transmitter Circuit diagram

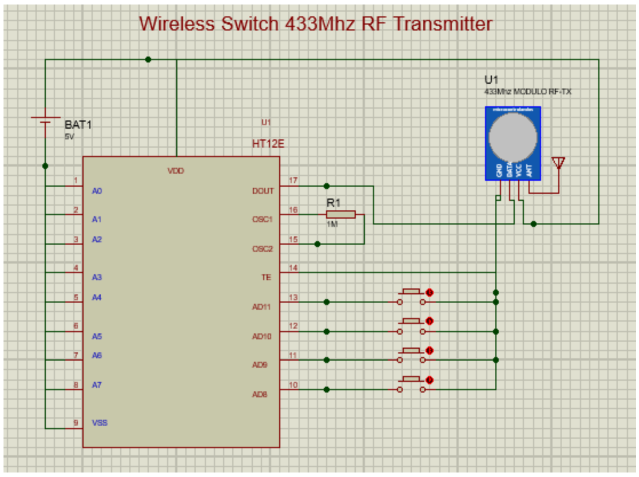


Figure 6: Simulation Transmitter Circuit

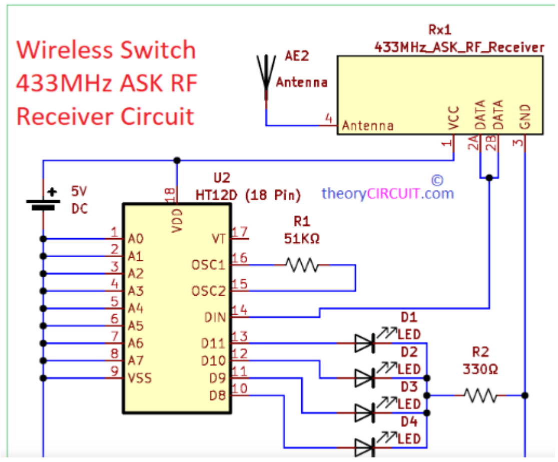


Figure 7: Receiver Circuit diagram

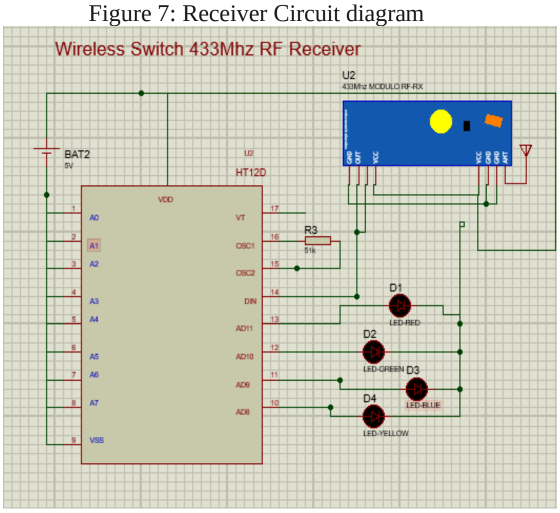


Figure 8: Simulation Receiver Circuit

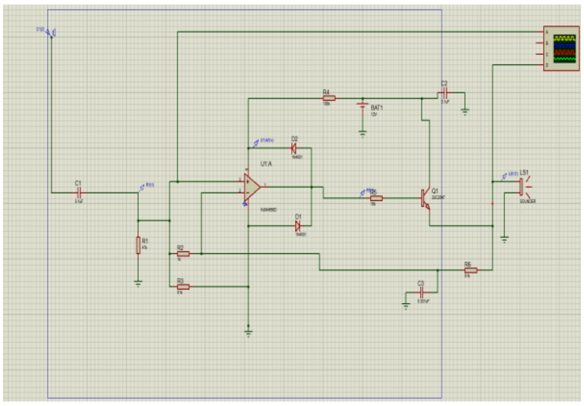


Figure 9: Simulated output (a) and input circuit

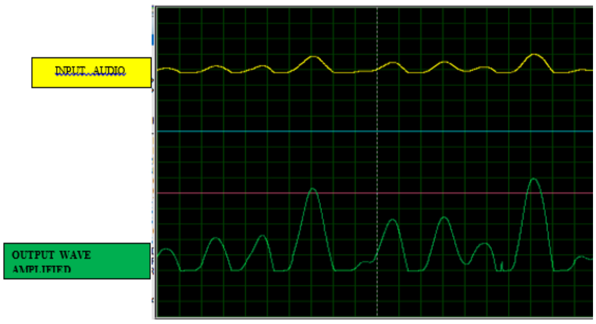


Figure 10: Simulated result of input and output Oscillator waveform

Proposed Model

Figure 11 and 12 present the working model of our proposed method. It works on 433MHz channel wirelessly. 433MHz transmitter and receiver are used at both ends for transferring data. Condenser mic is used for providing the input signal and speaker to produce the output. The power for the circuit was design and developed to give 12V, and voltage regulators are used to regulate the voltage. Various passive elements like resistor, capacitor and inductors are used as required. Sliding switch is used to switch on and off the device.

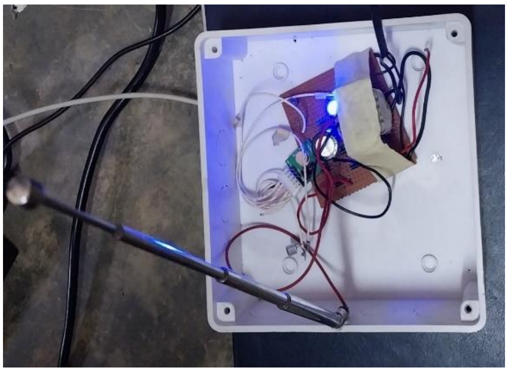


Figure 11: Constructed Transceiver (Transmitter section)

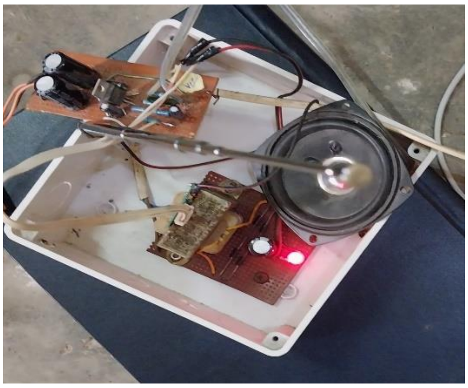


Figure 12: Constructed Transceiver (Receiver section)

Test and Observation

During the evaluation performance of the system, interference from other radio equipment and ambient noise was observed. This is one of the disadvantages of ASK.

However, as long as you transmit data at a relatively slow rate, it can work reliably in most environments. It was also observed that during the testing of this project that the antenna impedance of 75 ohms matched the circuit impedance. Also on maximum power, the power transistor heats up at power amplifier stage; to solve this issue a heat sink is needed for the transistor, worth mentioning is the observation that touching of the inductor coil caused the frequency to drift by a reasonable amount. The output at the receiving end becomes faded as the distance increases and vanishes totally at more than 100 metres radius.

Conclusion

The study successfully utilizes a 433 MHz transmitter to transmit audio signals and a 433 MHz receiver to receive them, achieving a range of approximately 97.5 to 98.2 meters, which closely aligns with the design specifications. The model was simulated to ensure efficient operation under various conditions. This product is strategically designed for commercialization, targeting users in remote locations, particularly during natural disasters, in industrial environments, or for athletes trekking in mountainous regions. Additionally, academic departments, such as the Geology Department of an institution, can leverage it for seamless communication during field programs, such as "Geology of Nigeria." The system provides a cost-effective alternative to expensive mobile devices, especially in remote areas where mobile networks are unavailable. The design prioritizes user convenience and reliability, effectively addressing the key challenges encountered in environments that require robust and efficient communication solutions.

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