International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

Design and Implementation of a Low-Cost 2.4 GHz RF Activity Monitoring System using ESP32 and nRF24L01

Krishnakumar R
Undergraduate Student, Department of ECE
Muslim Association College of Engineering
Venjaramoodu, Thiruvananthapuram, Kerala, India

Aadhil Rehman P A
Undergraduate Student , Department of ECE
Muslim Association College of Engineering
Venjaramoodu, Thiruvananthapuram, Kerala, India

Rahman A
Undergraduate Student, Department of ECE
Muslim Association College of Engineering
Venjaramoodu, Thiruvananthapuram, Kerala, India

Niranjan S Vinod
Undergraduate Student, Department of ECE
Muslim Association College of Engineering
Venjaramoodu, Thiruvananthapuram, Kerala, India

Jissmi K
Associate Professor, Department of ECE
Muslim Association College of Engineering
Venjaramoodu, Thiruvananthapuram, Kerala, India

Abstract - The rapid proliferation of wireless communication devices has resulted in increasing radio-frequency (RF) ac-tivity within the 2.4 GHz Industrial, Scientific, and Medi-cal (ISM) band. Wireless technologies such as Wi-Fi, Blue-tooth, ZigBee, and numerous Internet of Things (IoT) de-vices coexist within this frequency region, creating a need for simple and economical methods of observing RF ac-tivity. Conventional spectrum analyzers provide accurate frequency-domain measurements but are often expensive for educational and low-cost embedded applications. This pa-per presents the design and implementation of a compact 2.4 GHz RF activity monitoring system using an ESP32 mi-crocontroller and an nRF24L01 transceiver. The proposed system sequentially monitors RF channels supported by the transceiver and utilizes its Received Power Detector (RPD) functionality to identify the presence of RF energy above the internal detection threshold. The ESP32 controls the scan-ning operation, processes the channel activity information, and displays the observed results on an SSD1306 OLED dis-play. An LM2596-based power regulation stage and local de-coupling components are employed to support stable opera-tion of the RF module. Experimental operation demonstrates the ability of the developed prototype to observe variations in RF activity and provide standalone real-time visualization. The proposed system offers an economical platform for ba-sic spectrum awareness, educational experiments, and intro-ductory investigation of wireless activity in the 2.4 GHz ISM band.

Keywords - ESP32, nRF24L01, RF Activity Monitoring, 2.4 GHz ISM Band, Received Power Detector, Spectrum Awareness, Embedded Systems.

I. INTRODUCTION

The 2.4 GHz Industrial, Scientific, and Medical (ISM) band is one of the most extensively utilized frequency regions for short-range wireless communication. Technologies including IEEE 802.11 Wi-Fi, Bluetooth, IEEE 802.15.4-based communication systems, and several proprietary wireless protocols operate within or overlap this frequency range. The rapid growth of wireless and Internet of Things (IoT) devices has consequently increased the density of radio-frequency transmissions within this band.

When several wireless systems operate within the same frequency region, simultaneous transmissions and overlapping channels can result in increased RF activity and potential interference. Observing the distribution of RF activity across frequency channels can therefore provide useful information for wireless communication experiments, interference studies, and basic spectrum awareness.

Professional spectrum analyzers are widely employed for detailed frequency-domain analysis. These instruments provide accurate measurements of signal frequency and received power and may offer advanced functions such as resolution-bandwidth control, signal analysis, and interference characterization. However, their cost can make them unsuitable for simple educational experiments and low-budget embedded applications.

Software Defined Radio (SDR) provides another flexible approach to RF spectrum monitoring. SDR platforms can capture portions of the radio spectrum and use digital signal processing techniques for visualization and analysis. Although SDR systems provide considerably greater functionality, they may require additional hardware, a host computer, and specialized software.

For applications requiring only basic information regarding the presence or absence of RF activity, a simpler embedded solution can be useful. Certain low-cost RF transceiver modules contain receiver-side energy detection mechanisms that can be utilized to obtain basic information about RF activity across their supported channels.

This work presents a low-cost 2.4 GHz RF activity monitoring system using an ESP32 microcontroller and an nRF24L01 RF transceiver. The system sequentially configures the transceiver to different RF channels and utilizes its Received Power Detector (RPD) to determine whether RF energy exceeding the internal detection threshold has been observed.

The proposed system is intended as an RF activity monitoring platform rather than a replacement for a calibrated spectrum analyzer. It does not provide accurate received-power measurements or identify the modulation and communication protocol of a detected transmission. Instead, the objective is to develop a compact and economical embedded platform capable of providing basic visualization of RF activity within the operating range of the nRF24L01.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

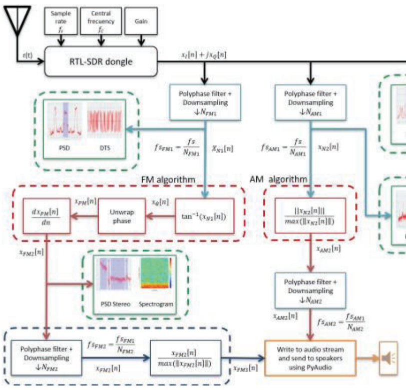

Figure 1: Existing approach for RF spectrum monitoring.

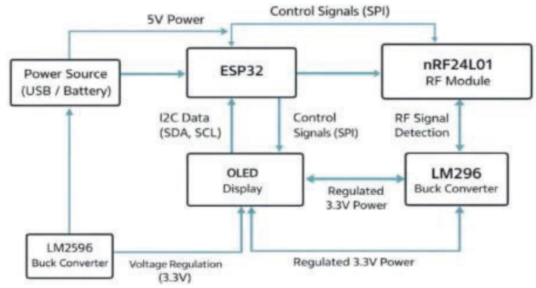

Figure 2: Block diagram of the proposed 2.4 GHz RF activity monitoring system.

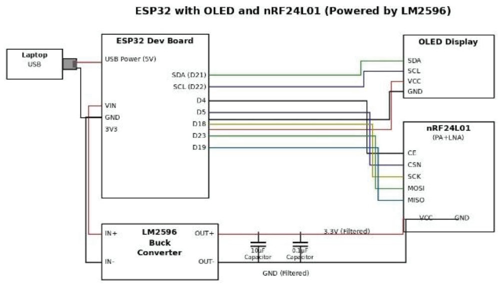

Figure 3: Circuit diagram of the proposed RF activity monitoring system.

II. EXISTING SYSTEM

RF spectrum monitoring is conventionally performed using professional spectrum analyzers. These instruments are capable of displaying received signal power as a function of frequency and provide high measurement accuracy, wide frequency coverage, and advanced RF analysis capabilities.

Professional spectrum analyzers are widely employed in communication laboratories, RF system development, electromagnetic compatibility testing, and interference investigation. Despite their measurement capabilities, such instruments can represent a significant investment when an application requires only basic RF activity observation.

Software Defined Radio systems represent a more flexible and comparatively economical alternative. SDR receivers digitize received RF signals and perform subsequent signal processing using software. Techniques such as the Fast Fourier Transform can be used to obtain frequency-domain representations of captured signals.

Depending on the hardware and software platform, SDR systems may support spectrum visualization, signal demodulation, and protocol analysis. However, SDR-based monitoring generally involves greater system complexity than a simple embedded RF detector and may depend on external computing resources.

Therefore, an opportunity exists for a compact embedded system designed specifically for basic RF activity awareness where calibrated measurement and signal demodulation are not required.

III. PROPOSED SYSTEM

The proposed system is a compact embedded platform designed to monitor RF activity within the 2.4 GHz operating region supported by the nRF24L01 transceiver. The major components consist of an ESP32 microcontroller, an nRF24L01 RF transceiver module, an SSD1306 OLED display, an LM2596-based power regulation stage, and appropriate power-supply decoupling components.

The ESP32 acts as the central controller and coordinates RF scanning and visualization operations. The nRF24L01 functions as the RF sensing element and communicates with the ESP32 through the Serial Peripheral Interface (SPI).

The ESP32 sequentially configures the nRF24L01 to different RF channels. For each selected channel, the receiver observes the RF environment and its Received Power Detector status is acquired. The RPD provides an indication when received RF energy above its internally defined threshold has been detected.

The acquired channel information is processed by the ESP32 and displayed using the SSD1306 OLED module. Communication between the OLED and ESP32 is performed through the I²C interface using the SDA and SCL signal lines.

A dedicated regulated power path is provided for the RF module. The LM2596-based regulation stage supplies the required voltage, while local decoupling capacitors help reduce supply disturbances near the RF transceiver.

IV. DESIGN AND WORKING

A. Circuit Diagram

The hardware interconnection of the proposed RF activity monitoring system is shown in Fig. 3. The ESP32 serves as the central processing and control unit.

The nRF24L01 is interfaced with the ESP32 through SPI communication using the SCK, MOSI, MISO, CSN, and CE signal connections. This interface enables the controller to configure the RF channel and control receiver operation.

The SSD1306 OLED display is connected through the I²C interface using the SDA and SCL lines. The display provides visual output for channel and RF activity information.

Power-supply stability is important for reliable RF module operation. The regulated supply is therefore supported by local decoupling capacitors near the nRF24L01. A common ground reference is maintained among the ESP32, RF transceiver, OLED, and power-supply circuitry.

B. Working Principle

When the system is powered on, the ESP32 initializes the communication interfaces and peripheral devices. The nRF24L01 is configured for receiver operation, while the OLED is initial-

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

ized to display scanning and activity information.

The scanning process begins from the initial configured RF channel. The ESP32 programs the nRF24L01 to the selected channel and enables receiver operation. After the required observation interval, the RPD status is acquired.

The RPD does not provide a continuously varying numerical received-power value. Instead, it indicates whether RF energy above its internal detection threshold was observed during the measurement interval. The ESP32 records this information and advances to the next channel.

This operation is repeated across the configured scanning range. The collected information is processed and presented on the OLED display. Continuous repetition of the scanning process allows variations in nearby RF activity to be observed over time.

C. Algorithm

The operational sequence of the proposed RF activity monitoring system is described below.

1. Initialize the ESP32 microcontroller, nRF24L01 RF transceiver, and SSD1306 OLED display.
2. Configure the SPI interface for communication between the ESP32 and nRF24L01 and initialize the I²C interface for communication with the OLED display.
3. Configure the nRF24L01 for receiver operation and set the RF channel index to the initial channel.
4. Configure the RF transceiver to the selected channel and allow the receiver to observe the channel for the required measurement interval.
5. Read the Received Power Detector status from the nRF24L01.
6. Determine whether RF energy above the internal detection threshold has been observed.
7. Display the corresponding RF activity information on the OLED display.
8. Increment the RF channel index and configure the nRF24L01 to the next channel.
9. Repeat the RF activity detection process until the maximum configured channel is reached.
10. After completing the channel range, reset the channel index to the initial channel.
11. Repeat the complete scanning process continuously to provide real-time RF activity monitoring.

D. Flowchart

The operational flow of the proposed RF activity monitoring system is illustrated in Fig. 4. The process begins with initialization of the ESP32, nRF24L01, and OLED display. The RF channel is then initialized and the transceiver is configured to monitor the selected channel.

The Received Power Detector status is acquired to determine whether RF energy above the detector threshold has been observed. Based on the detection status, the corresponding activity information is displayed. The channel index is then incremented and the scanning process continues.

Once the maximum configured channel is reached, the channel index is reset to the initial value and a new scanning cycle begins. This continuous operation allows the system to repeatedly observe variations in RF activity within the supported frequency range.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed RF activity monitoring system was implemented using the ESP32 microcontroller, nRF24L01 RF transceiver,

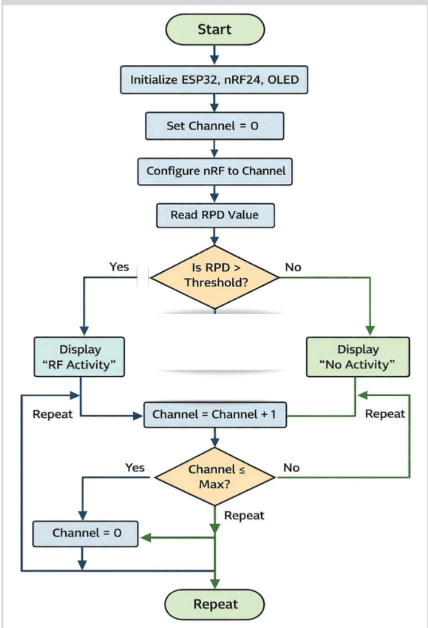

Figure 4: Flowchart of the RF channel scanning and activity detection process.

SSD1306 OLED display, LM2596 power regulation stage, and associated passive components.

The prototype was assembled and tested in an indoor environment containing commonly used wireless devices operating in the 2.4 GHz ISM band.

During operation, the ESP32 controlled the nRF24L01 and sequentially scanned the configured RF channels. The OLED display provided real-time information regarding the scanning process and observed RF activity.

Variations in detected activity were observed during repeated channel scanning. The implementation therefore demonstrated the basic feasibility of using a low-cost RF transceiver and microcontroller to obtain an indication of RF activity without requiring an external computer during normal operation.

An important limitation of the developed system is that the observed output represents threshold-based RF activity rather than a calibrated measurement of received signal power. The RPD function of the nRF24L01 indicates whether the received RF energy exceeds its internal threshold and therefore cannot directly determine the exact received power of the observed signal.

Furthermore, detection of RF activity does not identify the wireless protocol responsible for the transmission. Signals from Wi-Fi, Bluetooth, IEEE 802.15.4-based devices, proprietary RF systems, or other sufficiently strong sources operating within the relevant frequency region may contribute to the observed activity.

Consequently, the proposed system should be considered a low-cost RF activity monitoring platform rather than a full-featured or calibrated spectrum analyzer. Professional spectrum analyzers remain necessary when accurate power measurement, high frequency resolution, modulation analysis, or detailed signal characterization is required.

Despite these limitations, the developed prototype demonstrates the intended concept of low-cost and standalone RF activity monitoring. The compact hardware architecture and

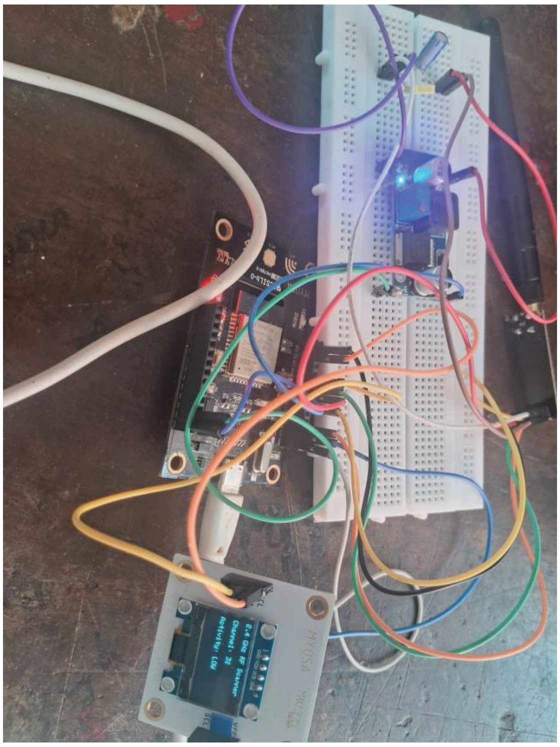

Figure 5: Hardware implementation and experimental operation of the proposed system.

local OLED visualization make the system suitable for educational demonstrations and basic experiments involving RF activity and wireless coexistence in the 2.4 GHz ISM band.

VI. ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to everyone who supported and guided them throughout the successful completion of this project.

The authors extend their sincere thanks to the project guide for the valuable guidance, continuous encouragement, and technical support provided during the development of this work.

The authors also express their appreciation to the Head of the Department, project coordinator, and faculty members of the Department of Electronics and Communication Engineering, Muslim Association College of Engineering, for providing the necessary facilities, academic support, and encouragement throughout the project.

VII. CONCLUSION

A low-cost 2.4 GHz RF activity monitoring system using an ESP32 microcontroller and nRF24L01 transceiver has been designed and implemented. The system sequentially monitors RF channels and utilizes the Received Power Detector functionality of the nRF24L01 to identify RF energy exceeding its internal detection threshold.

The ESP32 performs channel control, acquisition of activity information, and real-time visualization through an OLED display. The use of regulated power delivery and local decoupling supports reliable operation of the RF module.

Experimental operation demonstrated continuous channel scanning and standalone visualization of observed RF activity. Although the system does not provide calibrated received-power measurements or protocol identification, it provides an economical platform for basic RF spectrum awareness, educational demonstrations, and preliminary wireless activity investigation.

The developed prototype demonstrates that readily available embedded hardware can be utilized to observe basic RF activity without requiring expensive laboratory-grade instrumentation.

Future improvements may include the use of RF receiver hardware capable of quantitative RSSI measurement, long-term channel-activity logging, improved graphical spectrum visualization, and techniques for identifying or classifying different sources of RF activity.

VIII. REFERENCES

[1] E. Santos-Luna, A. Prieto-Guerrero, R. Aguilar-Gonzalez, V. Ramos, M. Lopez-Benitez, and M. Cardenas-Juarez, “A Spectrum Analyzer Based on a Low-Cost Hardware-Software Integration,” in *Proc. 2019 IEEE 10th Annual Information Technology, Electron-ics and Mobile Communication Conference (IEMCON)*, 2019, doi: 10.1109/IEMCON.2019.8936239.

[2] E. G. Sierra and G. A. Ramirez Arroyave, “Low Cost SDR Spectrum Analyzer and Analog Radio Receiver Using GNU Radio, Raspberry Pi2 and SDR-RTL Don-gle,” in *Proc. 2015 7th IEEE Latin-American Con-ference on Communications (LATINCOM)*, 2015, doi: 10.1109/LATINCOM.2015.7430125.

[3] D. Ball, N. Naik, and P. Jenkins, “Lightweight and Cost-Effective Spectrum Analyser Based on Software Defined Radio and Raspberry Pi,” in *Proc. 11th UKSim-AMSS European Modelling Symposium on Com-puter Modelling and Simulation*, pp. 260–266, doi: 10.1109/EMS.2017.51.

[4] A. Arcia-Moret, E. Pietrosemoli, and M. Zennaro, “Whisppi: White Space Monitoring with Raspberry Pi,” in *Proc. Global Information Infrastructure Symposium*, 2013.

[5] T. Zhang, A. Patro, N. Leng, and S. Banerjee, “A Wireless Spectrum Analyzer in Your Pocket,” in *Proc. 16th International Workshop on Mobile Comput-ing Systems and Applications*, 2015, pp. 69–74, doi: 10.1145/2699343.2699353.

[6] A. Saeed, K. A. Harras, E. W. Zegura, and M. H. Am-mar, “Local and Low-Cost White Space Detection,” in *Proc. 37th IEEE International Conference on Distributed Computing Systems (ICDCS)*, 2017, pp. 503–516, doi: 10.1109/ICDCS.2017.292.

[7] R. Helbet, P. Bechet, V. Monda, S. Miclaus, and I. Bouleanu, “Low-Cost Sensor Based on SDR Platforms for TETRA Signals Monitoring,” *Sensors*, vol. 21, no. 9, Art. no. 3160, 2021, doi: 10.3390/s21093160.

[8] P.-W. Wu, L. Huang, D. Ramirez, Y.-H. Xiao, and H. C. So, “One-Bit Spectrum Sensing for Cognitive Radio,” *IEEE Transactions on Signal Processing*, vol. 72, pp. 549–564, 2024, doi: 10.1109/TSP.2023.3343569.

[9] Nordic Semiconductor, “nRF24L01+ Single Chip 2.4 GHz Transceiver Product Specification.”

[10] Espressif Systems, “ESP32 Series Datasheet.”

[11] Solomon Systech, “SSD1306 128 x 64 Dot Matrix OLED/PLED Segment/Common Driver with Controller.”

[12] Texas Instruments, “LM2596 SIMPLE SWITCHER Power Converter Datasheet.”