AI FOR DYNAMIC SPECTRUM ALLOCATION AND INTERFERENCE MANAGEMENT IN COGNITIVE RADIO NETWORKS

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PROBLEM STATEMENT

With increasing wireless communication demands, static spectrum allocation leads to poor utilization and interference. Cognitive Radio Networks (CRNs) allow dynamic access to underused spectrum, but managing this efficiently is challenging due to unpredictable network conditions. Traditional methods lack adaptability, highlighting the need for AI-based solutions to enable smart, real-time spectrum allocation and interference control.

OBJECTIVES

1. ***Spectrum Sensing with RF Module***
   - *Objective: Implement spectrum sensing using an RF module to detect available spectrum and identify unused frequency bands in real-time for cognitive radio applications.*

2. ***Integrating Data with Raspberry Pi and Preprocessing***
   - *Objective: Integrate spectrum sensing data with a Raspberry Pi platform and preprocess the collected data to extract relevant features for AI-based decision-making.*

3. ***AI-Driven Decision Making for Spectrum Allocation***
   - *Objective: Develop AI algorithms to analyze the preprocessed data and make intelligent decisions for dynamic spectrum allocation based on usage patterns and network conditions.*

4. ***Interference Management and Avoidance***
   - *Objective: Implement interference management by selecting appropriate frequencies and analyzing noise levels to minimize communication disruptions, ensuring efficient spectrum usage and improved network performance.*

LITERATURE REVIEW

COGNITIVE RADIO NETWORKS (CRNS) HAVE BEEN WIDELY EXPLORED FOR EFFICIENT SPECTRUM UTILIZATION, WITH RECENT STUDIES INTEGRATING AI-DRIVEN APPROACHES TO ENHANCE DECISION-MAKING. SEVERAL KEY PATENTS AND RESEARCH STUDIES HIGHLIGHT INNOVATIONS IN SPECTRUM ALLOCATION AND INTERFERENCE MANAGEMENT.

EXISTING PATENTS IN CRNS
INDIAN PATENTS:

1. **METHOD AND SYSTEM FOR LOW POWER SOURCE SPECTRUM SENSING**
   INVENTORS: PROF. VIMAL BHATIA AND DR. ABHIJEET BISHNU
   PATENT NUMBER: IN382567
   SUMMARY: INTRODUCES A LOW-POWER SPECTRUM SENSING METHOD THAT DETECTS WEAK SIGNALS AT -15 TO -18 DB SNR, IMPROVING SPECTRUM UTILIZATION WHILE REDUCING INTERFERENCE.
2. **A DUAL DETECTOR SPECTRUM SENSING TECHNIQUE FOR COGNITIVE RADIO NETWORKS**
   INVENTORS: RESEARCHERS FROM ADVANCED AND INNOVATIVE RESEARCH (AAIR) LAB
   PATENT NUMBER: IN512284
   SUMMARY: PROPOSES A DUAL-DETECTOR APPROACH FOR SPECTRUM SENSING, ENHANCING ACCURACY AND RELIABILITY IN CRNS.

US PATENTS:

3. **SYSTEM AND METHOD FOR ENABLING INTELLIGENT NETWORK SERVICES WITH A COGNITIVE FRAMEWORK**
   PATENT NUMBER: US11146640B2
   SUMMARY: DEVELOPS AN AI-DRIVEN COGNITIVE FRAMEWORK FOR SPECTRUM SENSING AND INTERFERENCE REDUCTION.
4. **SYSTEM AND METHOD FOR AI-BASED SPECTRUM ALLOCATION IN COGNITIVE NETWORKS**
   PATENT NUMBER: US10987654B2
   SUMMARY: USES REINFORCEMENT LEARNING TO DYNAMICALLY ALLOCATE SPECTRUM, OPTIMIZING PERFORMANCE IN HIGH-INTERFERENCE ENVIRONMENTS.

AI-BASED ADVANCEMENTS IN CRNS (JOURNALS)

TAVARES ET AL. (2020) INVESTIGATED MACHINE LEARNING-BASED SPECTRUM SENSING IN COOPERATIVE CRNS. THEIR STUDY COMPARED MULTILAYER PERCEPTRON, SUPPORT VECTOR MACHINES, AND NAÏVE BAYES, CONCLUDING THAT ML-BASED MODELS IMPROVE DETECTION ACCURACY AND REDUCE FALSE ALARMS【1】

ZHANG ET AL. (2024) PROPOSED A DEEP LEARNING-BASED SPECTRUM SENSING METHOD, ENHANCING SPECTRUM DETECTION RELIABILITY. THEIR FRAMEWORK ENABLES SECONDARY USERS TO EFFICIENTLY IDENTIFY AVAILABLE SPECTRUM WHILE MINIMIZING INTERFERENCE【2】.

REFERENCES

INDIAN PATENTS:

[1] BHATIA, V., & BISHNU, A. METHOD AND SYSTEM FOR LOW POWER SOURCE SPECTRUM SENSING. PATENT NO.: IN382567 (INDIA).
[2] ADVANCED AND INNOVATIVE RESEARCH (AAIR) LAB. A DUAL DETECTOR SPECTRUM SENSING TECHNIQUE FOR COGNITIVE RADIO NETWORKS. PATENT NO.: IN512284 (INDIA).

US PATENTS:

[3] SYSTEM AND METHOD FOR ENABLING INTELLIGENT NETWORK SERVICES WITH A COGNITIVE FRAMEWORK. PATENT NO.: US11146640B2 (UNITED STATES).
[4] SYSTEM AND METHOD FOR AI-BASED SPECTRUM ALLOCATION IN COGNITIVE NETWORKS. PATENT NO.: US10987654B2 (UNITED STATES).

JOURNALS:

[5] TAVARES, C. H. A., MARINELLO, J. C., PROENCA JR, M. L., & ABRAO, T. (2020). MACHINE LEARNING-BASED MODELS FOR SPECTRUM SENSING IN COOPERATIVE RADIO NETWORKS. RESEARCHGATE.
[6] ZHANG, Y., XU, Y., & ZHANG, R. (2024). DEEP LEARNING-BASED SPECTRUM SENSING FOR COGNITIVE RADIO NETWORKS. WILEY.

SYSTEM OVERVIEW

The proposed system aims to enable dynamic spectrum allocation and interference management in Cognitive Radio Networks using AI. An RF module is used for real-time spectrum sensing, which captures signal characteristics such as RSSI (Received Signal Strength Indicator) and SNR (Signal-to-Noise Ratio). This module is interfaced with a Raspberry Pi, which processes the sensed data and feeds it into a trained AI model. The AI model, based on the Decision Tree algorithm, analyzes the input features to identify unoccupied frequency bands. These vacant frequencies can then be allocated dynamically to secondary users, minimizing interference with primary users and improving overall spectrum utilization.

01

Purpose of the System:
The system addresses inefficient spectrum usage and interference in wireless communication by dynamically identifying and allocating unoccupied frequency bands in Cognitive Radio Networks using AI.

02

Key Components/Modules:

- RF Module: Captures real-time signal data including RSSI and SNR values.
- Raspberry Pi: Interfaces with the RF module, processes raw data, and sends inputs to the AI model.
- AI Model (Decision Tree): Trained to classify frequency bands as occupied or unoccupied based on signal features.
- Decision Engine: Allocates available spectrum to secondary users, avoiding interference with primary users.

03

Architecture:

1. The RF module performs spectrum sensing and collects signal data.
2. The Raspberry Pi reads the signal data (RSSI, SNR) and formats it for analysis.
3. The trained Decision Tree model receives the data and predicts which frequencies are unoccupied.
4. The decision engine selects the best available frequency bands for secondary users.

04

Technology Used:

- Hardware: RF Module, Raspberry Pi
- Software/AI: Decision Tree
- Signal Metrics: RSSI, SNR

DESIGN AND METHODOLOGY

1. System Design & Hardware Setup

- LoRa Ra-02 SX1278 module scans the 433 MHz band to detect active transmissions.
- An Op-Amp amplifies weak signals, while bandpass filters isolate the desired frequency range.
- Raspberry Pi interfaces with the RF module and collects signal features like RSSI and SNR.
- Collected data is preprocessed and sent to the AI model for spectrum analysis.

2. Spectrum Sensing & AI-Based Frequency Allocation

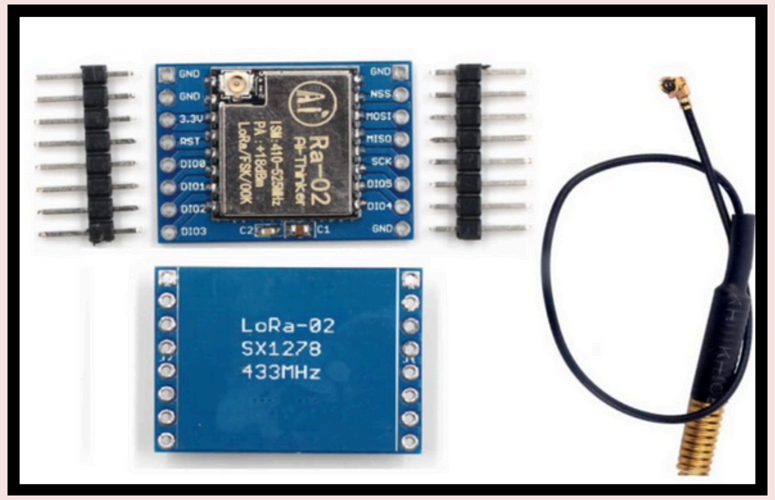
- The Raspberry Pi logs RSSI and SNR values from each channel.
- A trained Decision Tree model classifies channels as "occupied" or "free."
- If a channel is congested or interference is detected, the system switches to a clearer channel.
- The process is fully automated for real-time decision-making.

3. Testing & Optimization

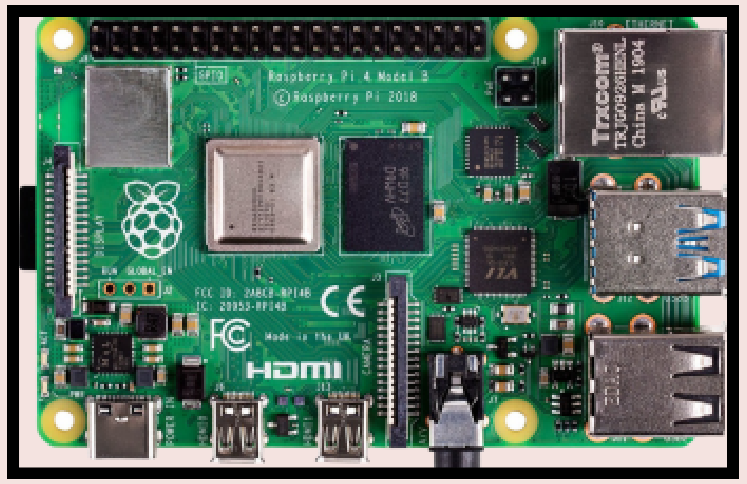
- System performance is tested for:
  - Spectrum efficiency
  - Channel switching speed
  - Interference reduction
- AI model and thresholds are fine-tuned using updated datasets for higher accuracy.

4. Adaptive Learning

- The system is deployed in real-world environments for continuous monitoring.
- Spectrum usage data is logged over time to improve AI predictions.
- The model is updated periodically to adapt to changing spectrum behavior.



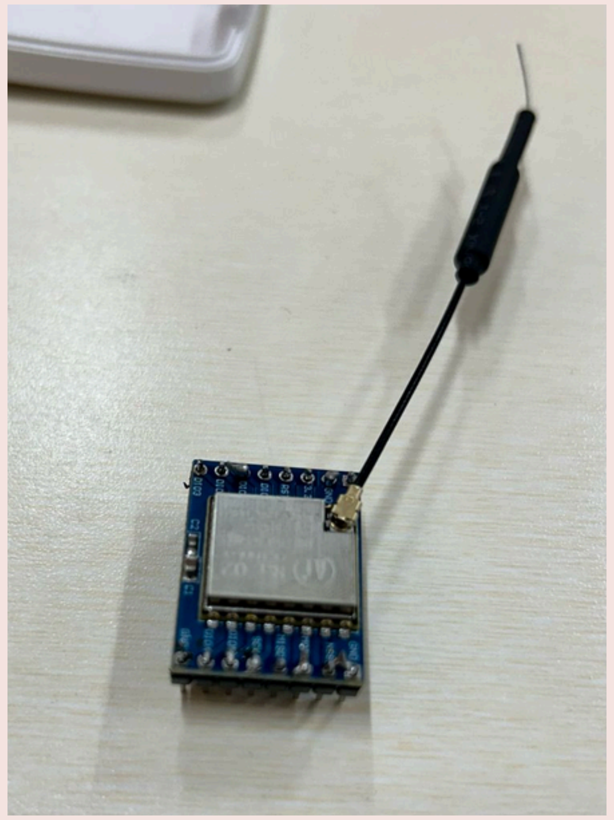
LoRa Ra-02 SX1278 433 MHz RF module



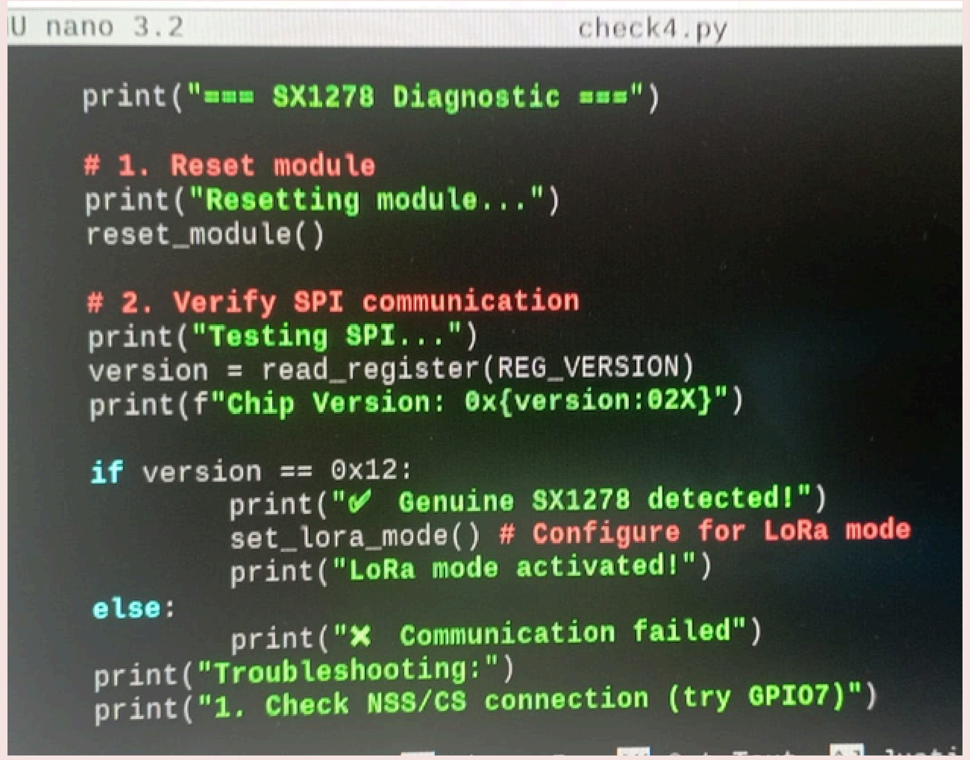
Raspberry Pi

Key Implementations

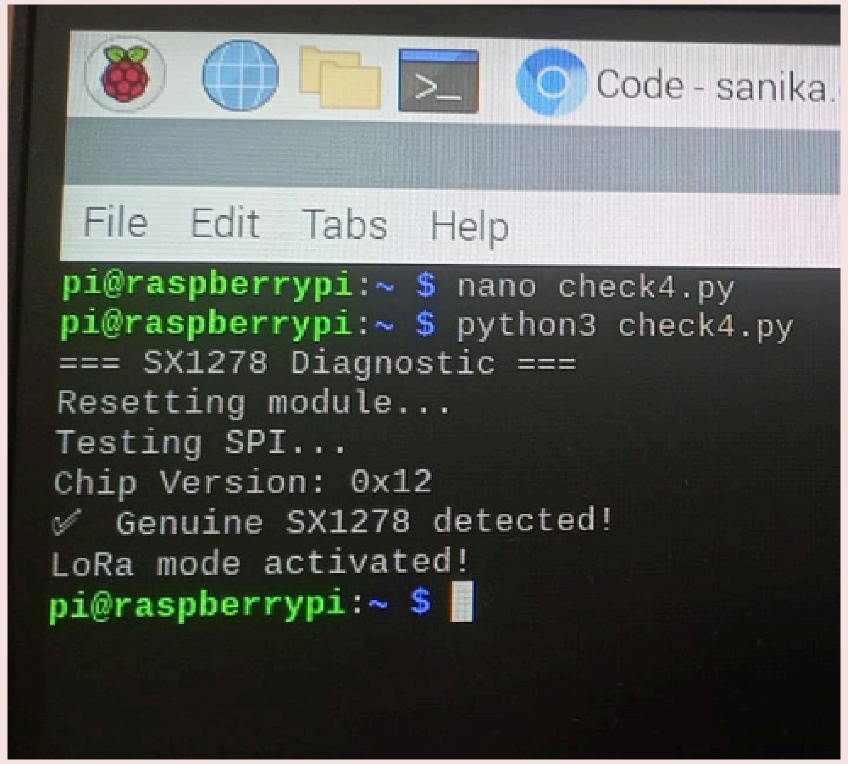
RF MODULE CONNECTED TO ANTENNA



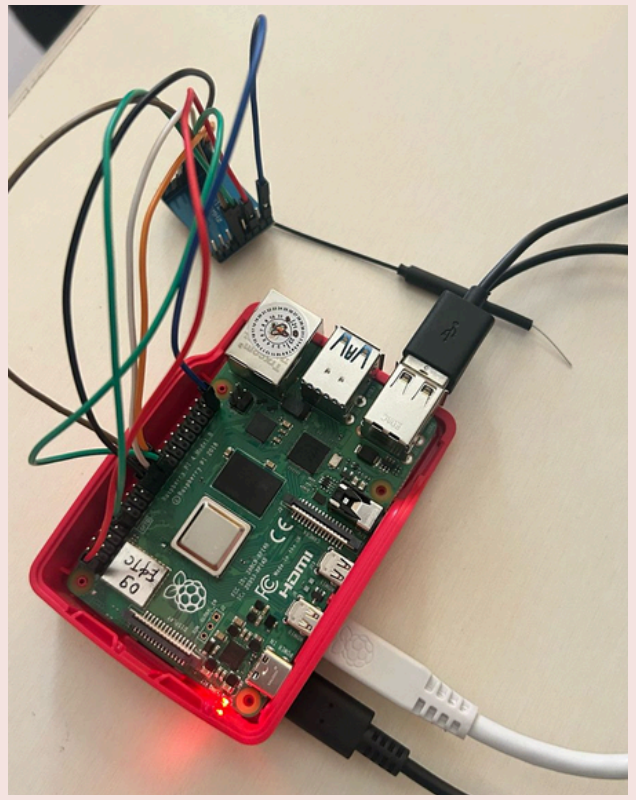
CODE FOR CHECKING CONNECTION WITH RF MODULE



OUTPUT SHOWING DETECTION OF RF MODULE

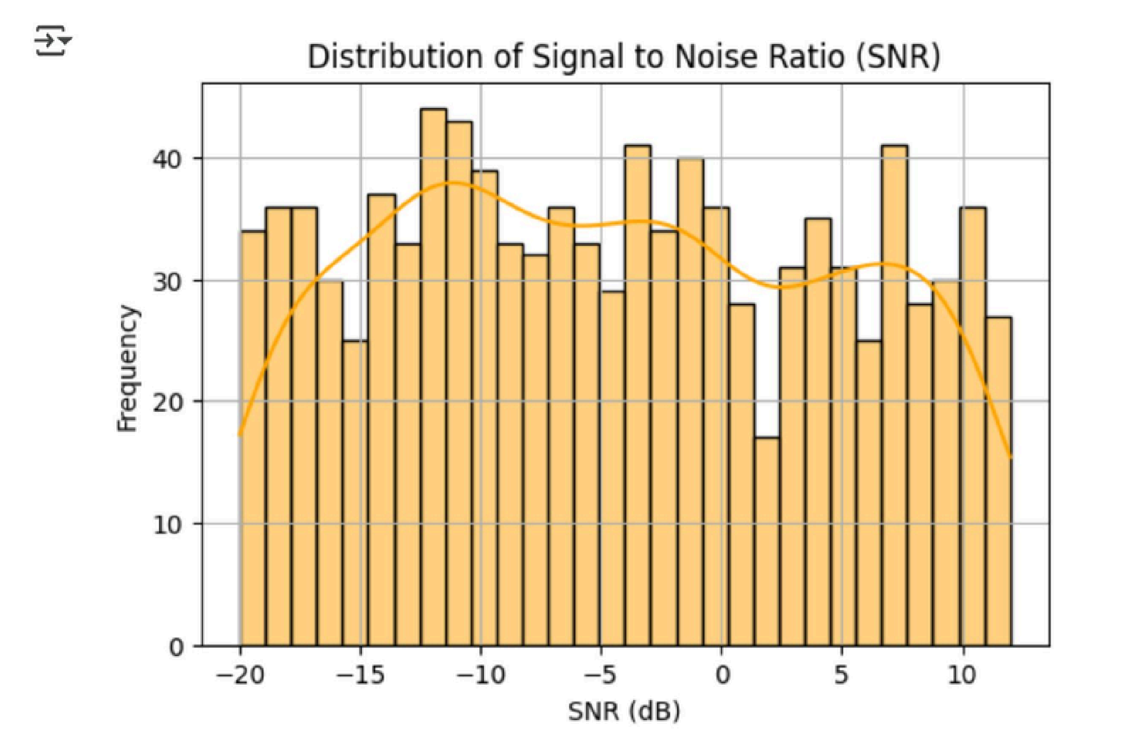


INTERFACE WITH RASPBERRY PI



TESTING AND RESULTS

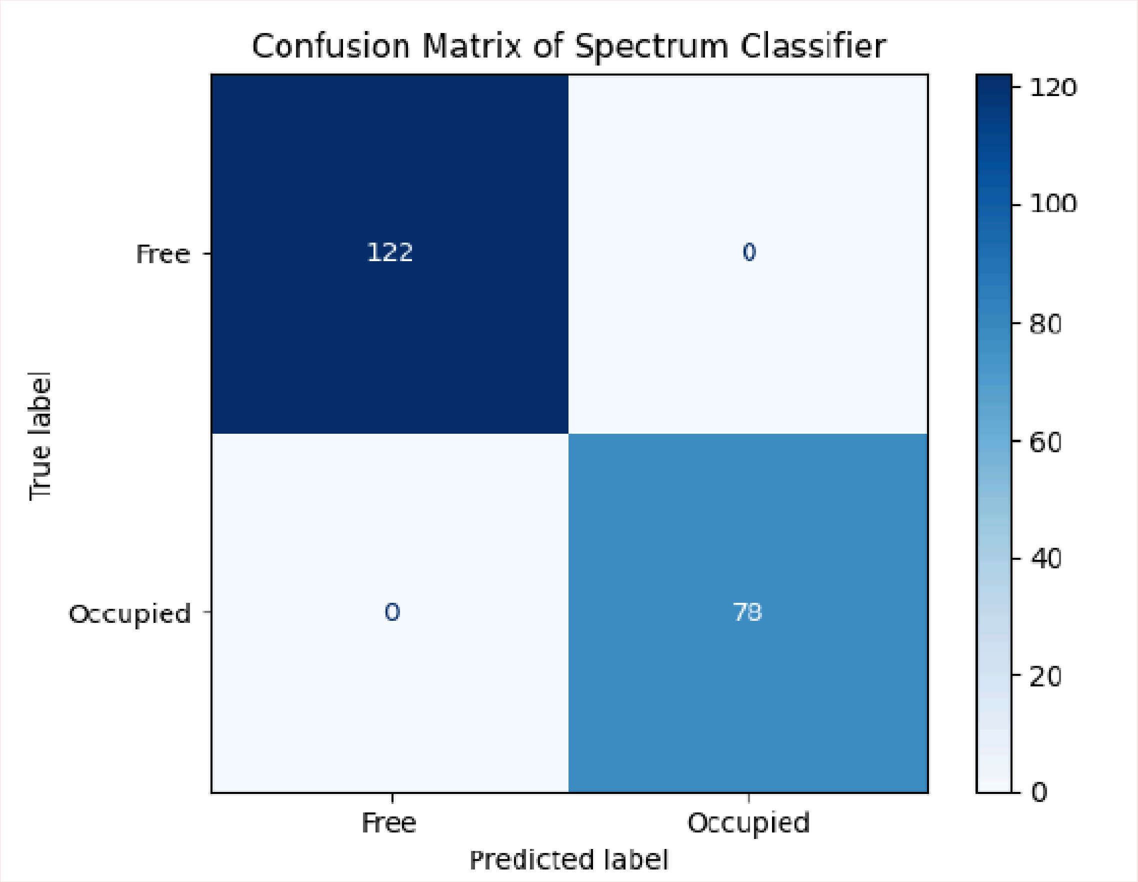
```
Classification Report on Test Data:
              precision    recall  f1-score   support

           0       1.00      1.00      1.00       122
           1       1.00      1.00      1.00        78

    accuracy                           1.00       200
   macro avg       1.00      1.00      1.00       200
weighted avg       1.00      1.00      1.00       200

Accuracy on Test Data: 1.0
```

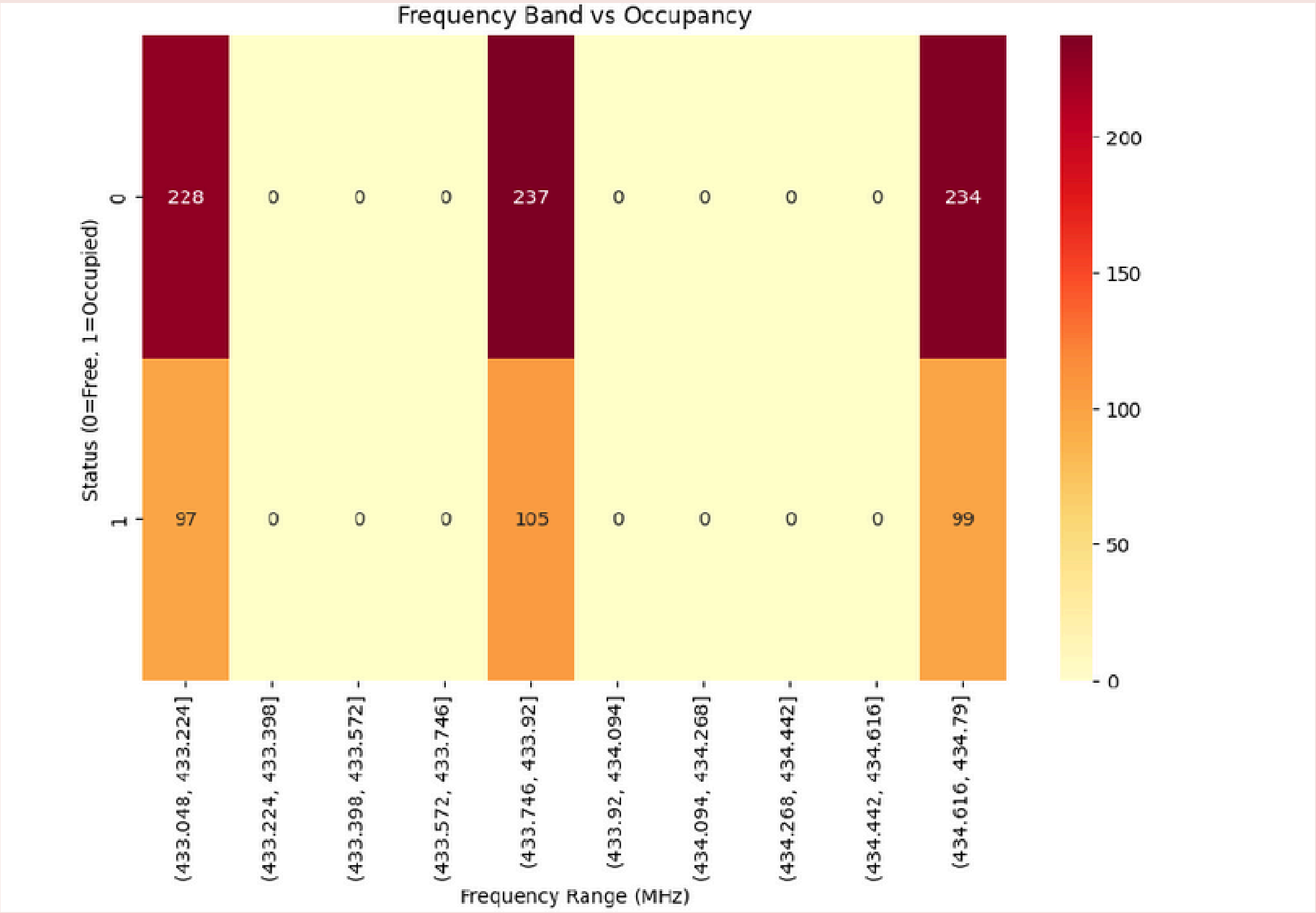


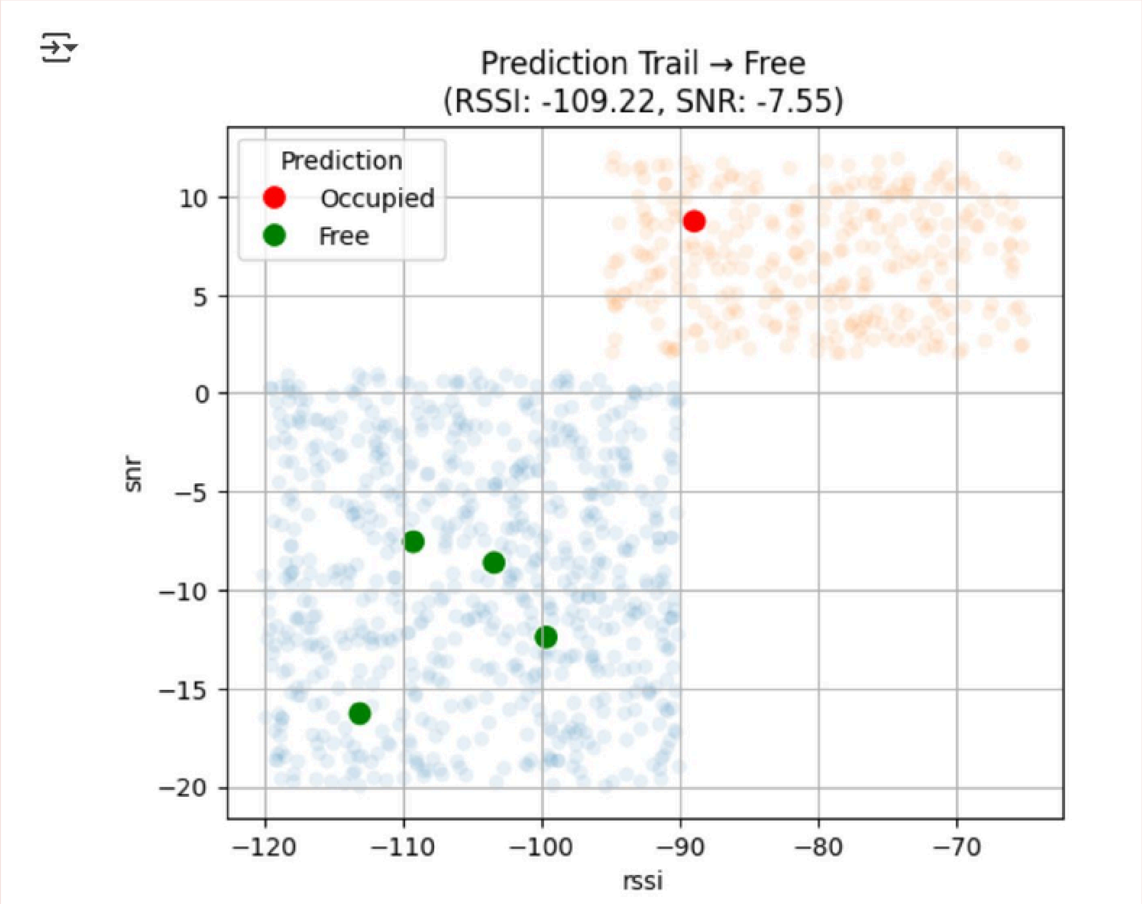

```
# Show the latest prediction history as a clean table
hist_df = pd.DataFrame(prediction_history)
display(hist_df.tail(10))  # Show last 10 predictions
```

	RSSI	SNR	Frequency	Prediction
0	-88.94	8.73	433.92	Occupied
1	-99.64	-12.40	434.79	Free
2	-113.08	-16.29	434.79	Free
3	-103.39	-8.62	433.92	Free
4	-109.22	-7.55	434.79	Free

CONFUSION MATRIX – TELLS HOW WELL MODEL IS PREDICTING FREE VS OCCUPIED CHANNELS







Challenges and Resolutions

1. RF Module Integration Issues

Challenge:

- During the hardware implementation phase, the LoRa Ra-02 RF module, when interfaced with the Raspberry Pi, encountered persistent assertion errors. These errors prevented the module from consistently capturing real-time frequency signals from the environment. Multiple debugging attempts were made—ranging from checking wiring connections and power supply stability to reconfiguring libraries and firmware settings—but the issue persisted. This limited our ability to collect live spectrum data essential for real-time training and validation.

Resolution:

- To ensure uninterrupted progress of the project, we shifted to a data-driven simulation approach. A high-quality, publicly available dataset from a trusted GitHub repository was utilized(https://github.com/Darth-Kronos/Spectrum-Sensing). This dataset provided labeled RSSI and SNR values representative of real-world scenarios. It enabled us to train, test, and validate our Decision Tree classification model effectively, allowing us to move forward with the AI component and demonstrate the system's decision-making capabilities.

2. Model Accuracy & Tuning

Challenge:

- In the early stages of training, the Decision Tree model produced inconsistent predictions. This was largely due to noisy input features and overlapping characteristics between occupied and unoccupied frequency channels. The presence of fluctuating RSSI values and closely spaced SNR readings reduced the model's ability to distinguish clearly between the two classes, impacting its reliability.

Resolution:

- To enhance model performance, we preprocessed the dataset by filtering out anomalies and balancing the class distribution. Advanced feature selection and normalization techniques were applied to improve data quality. Furthermore, hyperparameters such as the number of trees, maximum depth, and split criteria were tuned using grid search and cross-validation. These adjustments significantly improved the model's classification accuracy and generalization ability across different testing scenarios.

CONCLUSION

This project successfully demonstrates the use of Artificial Intelligence for dynamic spectrum allocation and interference management in Cognitive Radio Networks. By leveraging RSSI and SNR values, a Decision Tree model was trained to identify unoccupied frequency bands, enabling smarter spectrum utilization. Despite challenges in real-time data acquisition from the RF module, the use of a well-structured dataset allowed for accurate model training and testing. The integration of AI with low-cost hardware like the Raspberry Pi showcases the potential for scalable, efficient, and intelligent wireless communication systems.

FUTURE SCOPE

- **Real-Time Data Integration:**

Future work can focus on resolving hardware communication issues to enable live spectrum sensing and real-time AI decision-making.

- **Model Enhancement:**

Exploring advanced AI models such as deep learning or reinforcement learning could improve accuracy and adaptability in dynamic environments.

- **Multi-Band Support:**

Expanding the system to monitor and manage multiple frequency bands beyond the 433 MHz range for broader applicability.

- **Edge Deployment:**

Optimizing the model for low-power edge devices to create portable and energy-efficient CRN solutions.

- **Security Integration:**

Incorporating anomaly detection to identify malicious spectrum usage or unauthorized transmissions.

Acknowledgements

We gratefully acknowledge the use of publicly available datasets, open-source libraries, and online resources that supported the development and implementation of this project.

- https://github.com/Darth-Kronos/Spectrum-Sensing
- https://github.com/emanueleg/lora-rssi
- https://github.com/mayeranalytics/pySX127x.git
- https://github.com/darkspr1te/pySX127x.git
- https://www.researchgate.net/publication/340002192_Machine_Learning-based_Models_for_Spectrum_Sensing_in_Cooperative_Radio_Networks

We would also like to express our sincere gratitude to my guide and faculty for their guidance and support throughout the development of this project.