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Dynamic Spectrum Allocation in Cognitive Radio Networks Using Deep Learning

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***Abstract** The increasing bandwidth and the underutilization of available frequency resources have made it a challenging situation for effective spectrum management in wireless communication. This project focuses on optimizing spectrum allocation in Cognitive Radio (CR) networks using the Genetic Algorithm(GA) and marking its performance against various machine learning algorithms including Decision trees, Random Forest, and Logistic Regression to evaluate their effectiveness in predicting optimal channels and adapting to dynamic network conditions. Comparative analyses are conducted to evaluate the performance of various algorithms and the results suggest that GA provides a robust solution compared with many of the machine learning algorithms This study also lays a strong foundation for integrating optimization techniques to enhance efficiency, adaptability, and overall performance.*

I. INTRODUCTION

The demand for efficient spectrum management has become a critical challenge due to the rapid evolution of wireless communication technologies. Despite the increasing demand for bandwidth, the traditional static spectrum allocation methods have often led to underutilization of available frequency resources. This ineffectiveness has driven the adoption of Cognitive Radio (CR) technology, which allocates the spectrum by allowing secondary users to access the unused channels without disturbing the primary users. This leads to optimizing the usage of the spectrum, reducing the interference, and maximizing the network capacity.

The main aim of this project is to overcome the spectrum allocation problem in CR networks by comparing the performance of Genetic Algorithm (GA), and Machine Learning algorithms, including Logistic Regression, Decision Tree, Random Forest, and K-Nearest Neighbors. GA, inspired by the principles of natural selection, by exploring a wide solution space and finding global optima. In contrast, ML algorithms are tested for predictive accuracy and adaptability to dynamic network conditions, which will give insights into the potential of ML to achieve localized decision-making.

The findings demonstrate that GA is more effective for multi-objective optimization in CR networks, consistently outperforming ML algorithms in achieving balanced and efficient spectrum allocation. With this, we aim to develop a robust framework for dynamic spectrum allocation, which offers solutions that can adapt to network demands and improve CR network efficiency. These findings also contribute to the development of next-generation wireless communication systems, such as 6G and IoT, which will also decrease the challenges of spectrum scarcity and increase the connectivity demands.

II. PROBLEM STATEMENT

The growing demand for wireless communication services has led to spectrum scarcity and inefficient utilization of available frequency resources. Traditional static spectrum allocation methods fail to address the dynamic nature of modern communication networks, resulting in underutilization and increased interference. Cognitive Radio (CR) networks offer a solution by enabling dynamic spectrum access, where secondary users can intelligently access unused channels. However, effective spectrum allocation in CR networks involves multi-objective optimization, balancing conflicting goals like maximizing throughput, minimizing interference, and ensuring fairness among users. This project aims to compare the performance of Genetic Algorithms (GA) and machine learning (ML) algorithms, including Logistic Regression, Decision Tree, Random Forest, and K-Nearest Neighbors (KNN), in solving the spectrum allocation problem. The challenge lies in determining which approach provides the most efficient and adaptable solution for real-time spectrum management in dynamic network environments.

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III. LITERATURE REVIEW

- The increasing need for wireless communication makes it essential to allocate spectrum in Cognitive Radio (CR) networks efficiently. With the help of CR technology, secondary users can access unused spectrum bands without interfering with primary users. The complexity of spectrum allocation arises from the need to optimize multiple, conflicting objectives such as maximizing throughput, minimizing interference, and ensuring fairness. Various optimization strategies, such as Genetic Algorithms (GA) and Machine Learning (ML) algorithms, have been explored in order to address these issues.
- Genetic Algorithms (GA) have been widely used in CR networks for multi-objective optimization due to its capacity to handle complicated, NP-hard problems. GA successfully balances throughput, interference, and fairness in dynamic CR networks,[1]. The evolutionary nature of GA enables it to explore a large solution space, making it well-suited for dynamic spectrum allocation. [12]. GA is adaptable in handling varying network conditions, making it a reliable method for optimizing spectrum and power allocation in CR systems.
- Machine Learning (ML) algorithms, such as Random Forest, Decision Trees, and K-Nearest Neighbors (KNN), have also been applied to predict optimal spectrum usage. [2] Random Forest outperformed other models in terms of prediction accuracy, providing a robust method for real-time spectrum allocation. effectiveness of Support Vector Machines (SVM) in predicting available spectrum based on historical data[3].
- Spectrum Sensing is crucial for identifying available channels in CR networks. Various spectrum sensing techniques, such as energy detection and matched filtering, help secondary users detect unused spectrum without interfering with primary users. Accurate spectrum sensing ensures efficient and interference-free access to the spectrum, enabling secondary users to make informed decisions[4].
- The ability to move between spectrum bands as they become accessible is known as spectrum mobility. This is essential for maintaining continuous communication in environments where spectrum availability fluctuates. [5] Hybrid models combining GA and ML have been proposed to leverage the strengths of both approaches. The combination of GA-ML models allows for better adaptability and faster convergence, making it suitable for dynamic spectrum allocation in real-time environments. [6].
- Comparative studies show that while GA excels in optimizing multiple objectives and exploring large solution spaces, ML models are faster and more efficient for prediction-based tasks[7]. GA provides higher-quality solutions for complex, multi-objective problems, while ML algorithms like Random Forest and KNN offer real-time efficiency.

IV. METHODOLOGY

The methodology of this project involves a systematic approach to optimizing spectrum allocation in Cognitive Radio (CR) networks

1. **Genetic Algorithm (GA):** The genetic algorithm is applied to optimize the spectrum allocation by evolving a population of candidate solutions using selection, crossover, and mutation. This includes the following steps:

- <u>Initialization</u> : Generate an initial population of solutions where each individual represents a potential spectrum allocation.
- <u>Fitness Evaluation</u>: Measures the fitness function for each individual regarding the effectiveness of the assigned spectrum based on different objectives including throughput, fairness, and interference.
- <u>Crossover and Mutation:</u> Apply crossover and mutation to introduce diversity and explore the solution space.
- <u>Termination</u> : Repeat the process for a predefined number of generations or until convergence is reached.

2. Machine Learning Algorithms: Various machine learning algorithms are tested to predict and optimize spectrum allocation, including:

- Logistic Regression : A simple model to use for binary classification to predict whether a channel is suitable or not.

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- Decision Tree: A tree-based model where the data gets split according to features, hence making it possible to make decisions about channel allocation.
- Random Forest: A bagging method that combines the results of multiple trees to make predictions, improving accuracy and reducing overfitting.
- K-Nearest Neighbors (KNN): A non-parametric method that predicts the spectrum allocation based on the nearest neighbors in the feature space. These algorithms are trained on the preprocessed data to predict optimal channels for users, based on historical patterns and features in the Channel Matrix.
- Performance Metrics: The models are evaluated based on their ability to maximize throughput, minimize interference, and ensure fairness. Key metrics include convergence speed, solution\textbf{ }quality, and adaptability to real-time network conditions.
- Cross-Validation: A cross-validation approach is used to evaluate the performance of both GA and ML models on the training and validation datasets, ensuring that the models generalize well to unseen data.

Modules

For the implementation of spectrum allocation in Cognitive Radio (CR) networks, the following modules were used:

- NumPy: Used for handling large datasets, performing matrix operations, and numerical computations. It supports efficient array manipula-tion and mathematical operations, making it essential for managing the Channel and Reward Matrices in the project.
- Pandas: Utilized for data manipulation and analysis. It simplifies tasks such as reading datasets, cleaning data, and performing operations like normalization, imputation, and dimensionality reduction on the Channel and Reward matrices.
- Matplotlib: Used for creating visualizations and plots to display results and performance metrics. It is essential for visualizing the spectrum allocation results, comparing the performance of different algorithms, and illustrating convergence trends.
- Scikit-learn: A key library for machine learning algorithms, including Decision Trees, Random Forest, Logistic Regression, and K-Nearest Neighbors (KNN). It also provides tools for data splitting (training, testing, validation), cross-validation, and model evaluation.
- DEAP (Distributed Evolutionary Algorithms in Python): This library is specifically designed for implementing evolutionary algorithms such as Genetic Algorithms (GA). DEAP facilitates the creation of genetic algorithms for optimization tasks, including spectrum allocation, by providing tools for defining individuals, fitness functions, selection, crossover, and mutation processes.

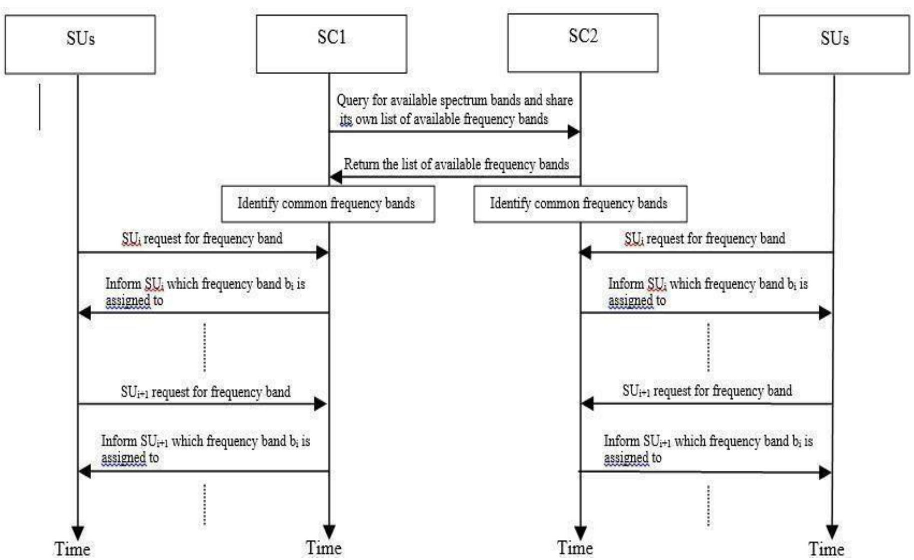

Fig.4.1. Architecture .

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V. EXPERIMENT RESULTS

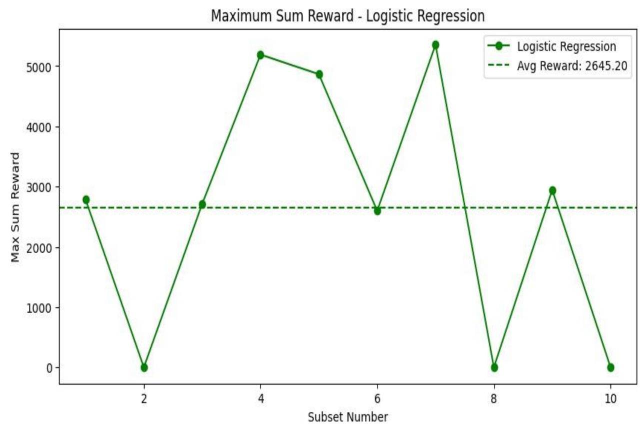


Fig.5.1

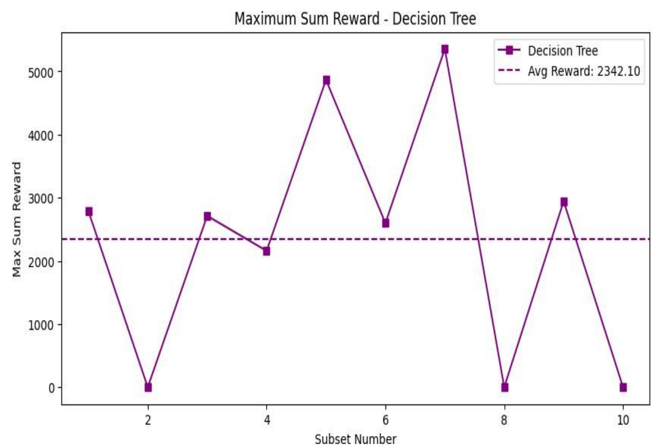
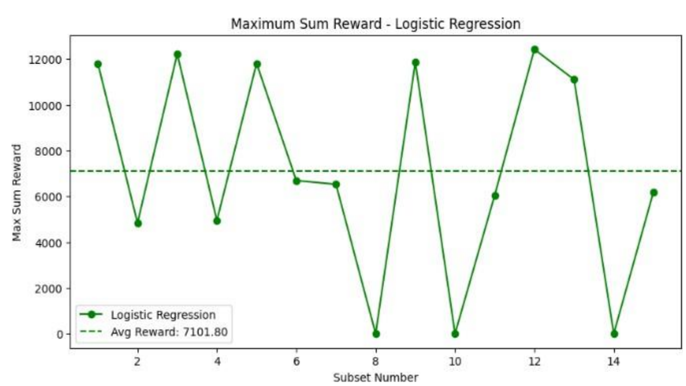


Fig.5.2



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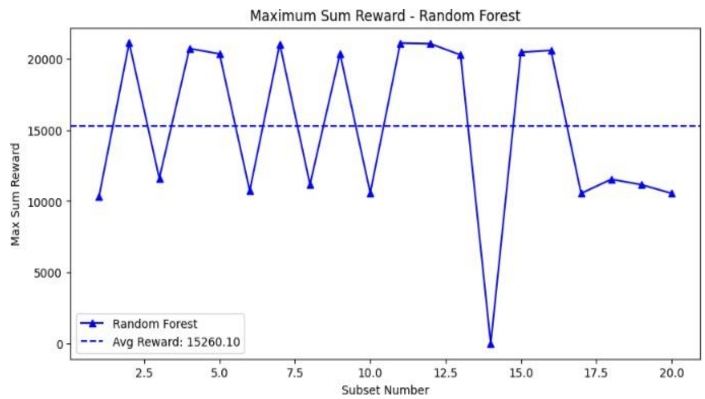


Fig.5.4

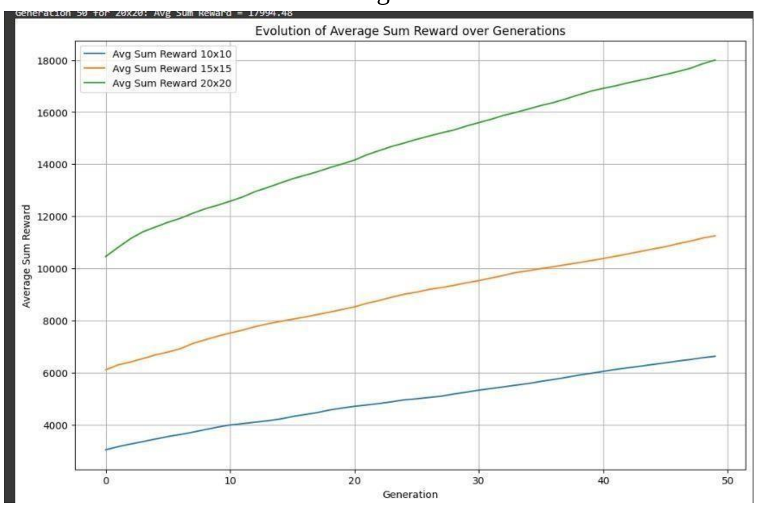


Fig.5.5

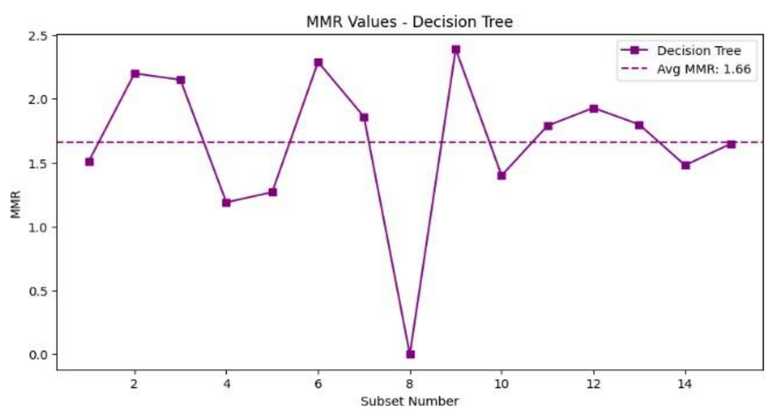
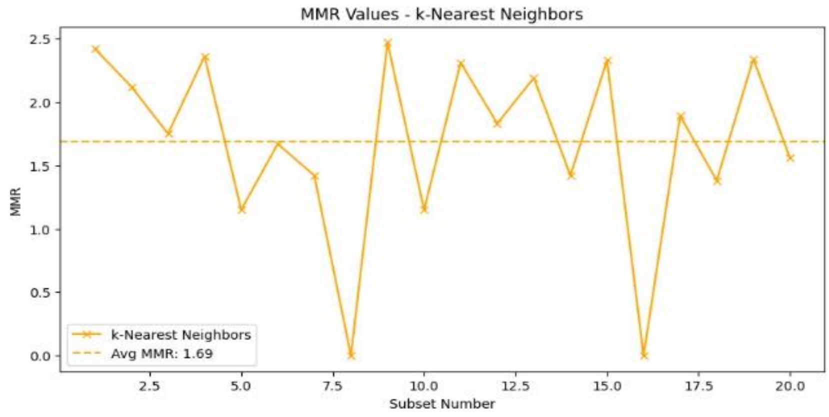


Fig.5.6



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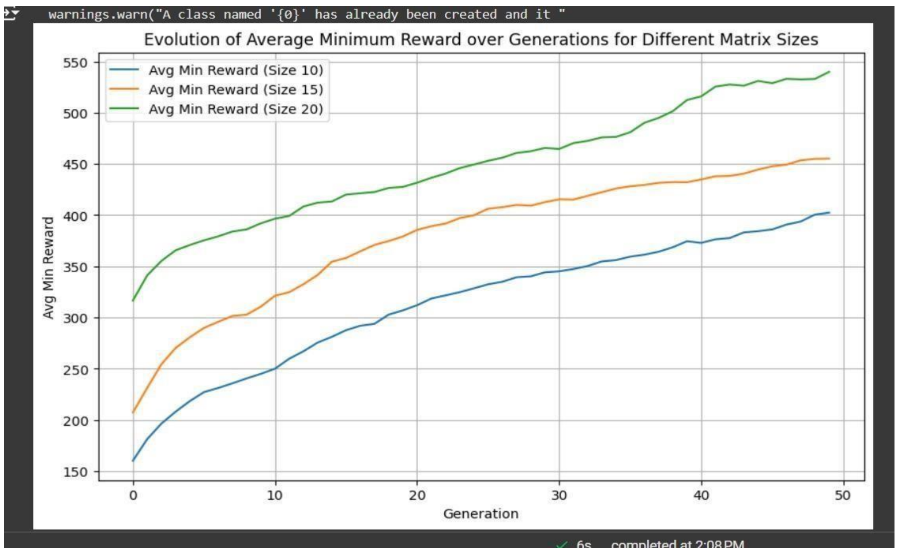

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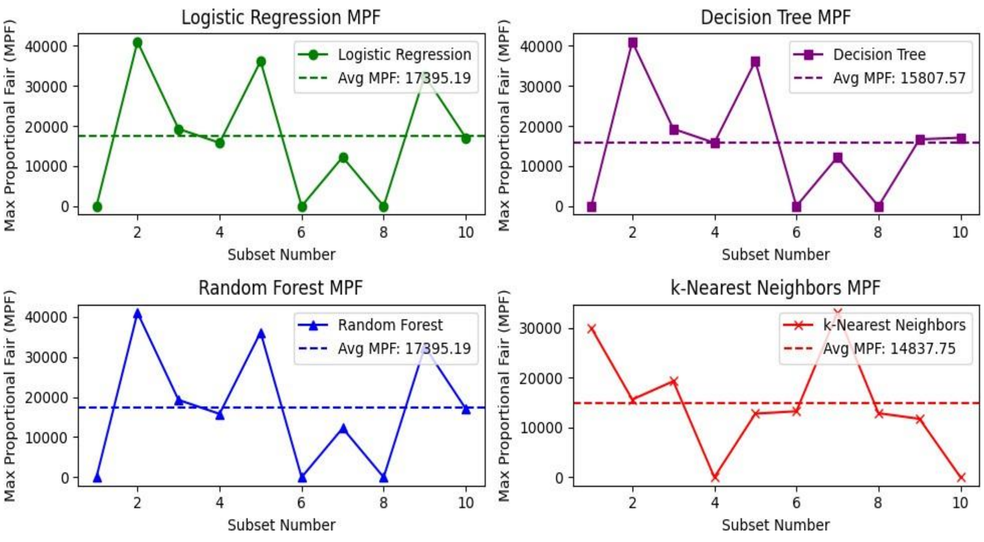

Fig.5.9

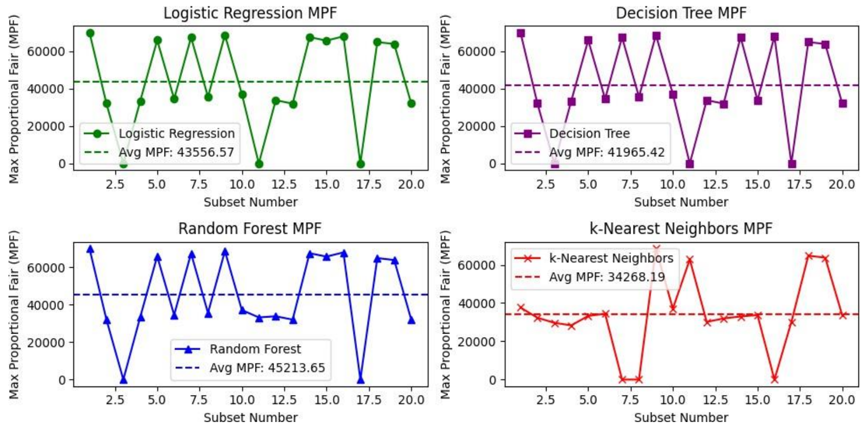

Fig.5.10

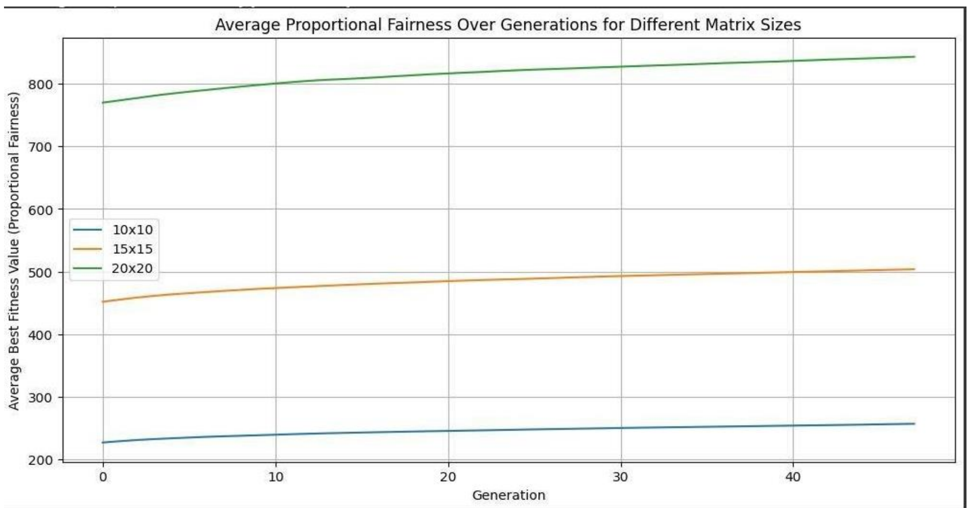

Fig.5.11

VI. CONCLUSION

This project addressed the challenge of optimizing spectrum allocation in Cognitive Radio (CR) networks by comparing the performance of Genetic Algorithms (GA) and Machine Learning (ML) models, such as Logistic Regression, Decision Tree, Random Forest, and K-Nearest Neighbors (KNN). By leveraging utility functions—Max-Sum-Reward (MSR), Max-Min-Reward (MMR), and Max-Proportional-Fair (MPF)—we evaluated the ability of these methods to maximize spectrum utilization, ensure fairness, and maintain proportionality. The results demonstrate that GA performs better in multi-objective optimization. Its adaptability to dynamic environments and ability to explore large solution spaces make it an ideal choice for real-time spectrum management in CR networks. ML algorithms, particularly KNN and Random Forest, showed strong performance in fairness-oriented tasks (MMR). However, their reliance on historical data and limited adaptability to changing conditions make them less effective for dynamic optimization tasks. In conclusion, GA performs better and is the recommended approach for optimizing spectrum allocation in CR networks, especially in environments requiring real-time adaptability and comprehensive multi-objective optimization. This project lays the foundation for integrating these methods into next-generation wireless systems, such as 6G and IoT, to address the growing demand for efficient and intelligent spectrum utilization.

VII. FUTURE ENHANCEMENT

- **Integration with Emerging Technologies:** Expand the model to support 5G and future wireless communication technologies to meet the increasing demand for spectrum efficiency.
- **Advanced Machine Learning Techniques:** Incorporate techniques such as transfer learning and ensemble methods to improve adaptability and performance in varied network conditions.
- **IoT Applications:** Adapt the system for Internet of Things (IoT) environments, optimizing spectrum management for smart cities and industrial automation scenarios.
- **Real-Time Data Analytics:** Implement real-time analytics and feedback loops to enable proactive spectrum allocation adjustments in response to dynamic network changes.
- **Security Measures:** Explore and develop robust security protocols to protect against vulnerabilities in decentralized spectrum management, ensuring reliable operation across

VIII. ACKNOWLEDGEMENT

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