AI-Enabled Cognitive Radio Systems: Balancing Energy Efficiency and Communication Performance

[1] Tapan Kumar Singh, [1] Arvind Kumar, [1] Sharad Kumar, [2] Vikas Sharma

[1] School of Engineering & Technology, Shri Venkateshwara University, Gajraula, U.P. India

[2] Department of Computer Applications, SRM Institute of Science and Technology, Delhi NCR Campus, Ghaziabad, U.P. India

DOI : https://doi.org/10.51583/IJLTEMAS.2025.1412000059

Received: 22 December 2025; Accepted: 28 December 2025; Published: 03 January 2026

ABSTRACT

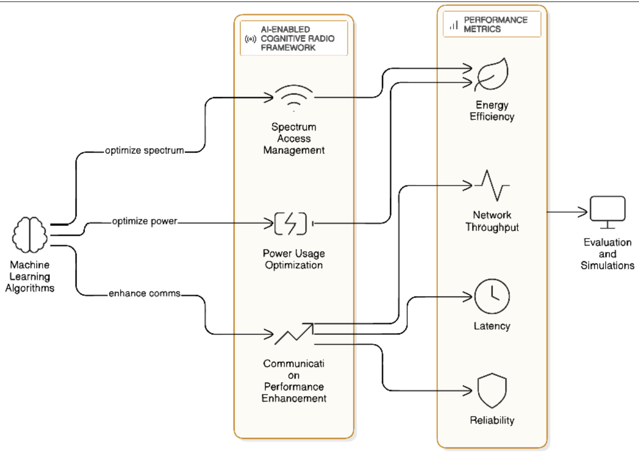
The rapid growth of wireless communication devices has intensified the need for efficient spectrum utilization and sustainable energy consumption. Cognitive Radio (CR) systems offer a promising solution by dynamically accessing underutilized frequency bands, but energy consumption remains a critical concern. This paper proposes an AI-enabled framework for cognitive radio networks that intelligently balances energy efficiency with communication performance. Leveraging machine learning algorithms, the system optimizes spectrum sensing, power allocation, and transmission scheduling to minimize power usage while maximizing throughput. Simulation results demonstrate that the proposed approach significantly reduces energy consumption without compromising data rates, highlighting its potential for green wireless communications. The integration of AI in CR networks paves the way for more adaptive, energy-aware, and high-performance communication systems.

Keywords— Cognitive Radio, Energy Efficiency, Artificial Intelligence, Machine Learning, Spectrum Sensing, Power Optimization, Throughput Maximization, Green Wireless Communication.

INTRODUCTION

The exponential growth of wireless communication services, driven by the proliferation of smartphones, IoT devices, and emerging 5G and beyond networks, has created unprecedented demand for radio spectrum. Traditional static spectrum allocation policies have led to inefficient spectrum utilization, with some bands being heavily congested while others remain underused. Cognitive Radio (CR) technology has emerged as a transformative solution to this problem, offering the ability to dynamically sense, access, and utilize vacant spectrum bands without causing interference to licensed users. CR networks are thus poised to enhance spectrum efficiency, improve connectivity, and support the ever-increasing data requirements of modern wireless systems. Despite their potential, one of the major challenges in deploying cognitive radio networks is energy consumption. Spectrum sensing, frequent channel switching, and adaptive transmission mechanisms inherently require significant computational and transmission power. In the context of battery-powered devices and large-scale wireless sensor networks, excessive energy consumption can limit network lifetime, reduce system reliability, and hinder sustainable communication practices. Consequently, achieving a balance between high communication performance, such as throughput and latency, and energy efficiency has become a critical research focus in CR system design. Artificial Intelligence (AI) and Machine Learning (ML) techniques offer a promising approach to address these challenges. By leveraging AI algorithms, CR systems can intelligently predict spectrum availability, optimize power allocation, and dynamically adjust transmission parameters, thereby reducing unnecessary energy expenditure while maintaining or improving overall network throughput. Techniques such as reinforcement learning, deep learning, and supervised learning enable cognitive radios to learn from historical network behavior, adapt to changing environmental conditions, and make real-time decisions that optimize performance metrics. This integration of AI transforms traditional CR systems into intelligent, energy-aware networks capable of self-optimization.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025



AI-Enabled Cognitive Radio Framework Architecture

Recent research has demonstrated the potential of AI-driven approaches in cognitive radio networks. For instance, reinforcement learning has been successfully applied to dynamically select optimal channels and transmission powers, minimizing interference and energy consumption. Similarly, deep neural networks have been employed for spectrum prediction and anomaly detection, reducing the need for continuous spectrum sensing and thereby conserving energy. Despite these advancements, existing methods often face trade-offs between complexity, computational overhead, and real-time adaptability. Moreover, integrating energy efficiency objectives with throughput maximization in a unified AI framework remains an open research challenge, particularly for heterogeneous and large-scale CR networks. This paper aims to address these challenges by proposing an AI-enabled cognitive radio framework that effectively balances energy efficiency with communication performance shown in Fig. 1. The proposed system leverages advanced machine learning algorithms to intelligently manage spectrum access, optimize power usage, and enhance throughput in real-time. By focusing on both energy conservation and high-performance communication, the framework supports sustainable wireless operations while meeting the growing demands of next-generation networks. Furthermore, the study evaluates the proposed approach through extensive simulations, demonstrating significant reductions in energy consumption without compromising network throughput, latency, or reliability.

LITERATURE REVIEW

Cognitive Radio (CR) technology has been extensively studied as a means to improve spectrum utilization and support dynamic spectrum access. Monisha et al. [1] investigated cooperative sensing strategies in heterogeneous spectrum environments, highlighting the importance of collaborative decision-making among secondary users (SUs) to enhance spectrum detection accuracy. Their work demonstrated that cooperative mechanisms can significantly improve spectrum availability prediction, forming a foundation for energy-efficient CR operations. Energy efficiency in CR networks has emerged as a critical design consideration due to the limited power resources of secondary devices. Elnaim et al. [2] explored the integration of cognitive radio networks with multi-access edge computing (MEC), focusing on minimizing energy consumption while maintaining computational performance. Their study highlighted that offloading computational tasks to edge servers can reduce on-device energy consumption, an approach relevant to AI-enabled CR systems. Premalatha and Singh [3] proposed a hybrid spectrum handover mechanism to optimize power usage in CR networks, demonstrating that intelligent handover decisions can reduce unnecessary transmission and sensing energy, thereby extending the network lifetime. Several studies have proposed energy-aware algorithms for access selection in CR and wireless sensor networks. Kalpana and Gunasundari [4] presented an energy-efficient access selection algorithm for cognitive wireless sensor networks, emphasizing the trade-off between energy savings and communication reliability. Their findings underscore the potential of algorithmic optimization to enhance energy efficiency in heterogeneous wireless environments. Similarly, Ge et al. [5] investigated the use of active reconfigurable intelligent surfaces (RIS) to enhance spectrum sensing, improving detection accuracy while reducing energy-intensive sensing operations. Emerging technologies, such as blockchain, have also been leveraged to support energy conservation in CR systems. Sharma et al. [6] proposed a blockchain-based strategy

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025

for cognitive wireless sensor networks, enabling secure and energy-efficient coordination among network nodes. Their approach demonstrated reduced energy overhead while maintaining reliability and trustworthiness in decentralized networks. Complementing these approaches, Sayed et al. [7] explored optimal energy management in home networks integrating photovoltaic systems and electric vehicles, highlighting optimization strategies that can be adapted for CR networks to reduce energy consumption while maximizing operational performance. Comprehensive reviews of CR technology and its applications indicate the growing relevance of AI in energy-efficient spectrum management. Al-Sudani et al. [8] provided an overview of CR trends, emphasizing the integration of intelligent decision-making mechanisms to improve spectrum utilization and energy efficiency. Recent works also explore CR applications in IoT and vehicular networks. For instance, D et al. [9] and Vashisht et al. [10] demonstrated the use of IoT-enabled wireless communication systems for smart monitoring and safety applications, highlighting the potential for AI-enhanced CR networks to optimize energy usage in real-world IoT deployments. Resource allocation and channel estimation strategies have been proposed to further improve energy efficiency in wireless networks. Lalitha and Reddy [11] developed a quality-of-service aided power-aware resource allocation mechanism for wireless sensor networks, demonstrating that adaptive allocation based on channel conditions can minimize energy consumption without sacrificing performance. Additionally, Moumena [12] addressed security considerations in wideband cooperative CR systems, combining principal component analysis (PCA) for anomaly detection with cooperative spectrum sensing, ensuring robust performance in the presence of malicious attacks while optimizing energy utilization.

PROPOSED METHODOLOGY

The proposed methodology focuses on the systematic design, simulation, and performance evaluation of AI-enabled cognitive radio (CR) systems, emphasizing energy efficiency while maximizing throughput. The methodology is structured into distinct phases to ensure a thorough understanding of spectrum sensing, power management, AI-based optimization, and real-time decision-making in CR networks, addressing critical challenges such as dynamic spectrum access, energy-aware transmission, and interference mitigation.

1. System Model and Assumptions: The cognitive radio system is modelled as a network of secondary users (SUs) accessing the spectrum opportunistically without interfering with licensed primary users (PUs). Each SU is assumed to have sensing, transmission, and computation capabilities, and is powered by limited energy resources. Spectrum availability is dynamic, with channel occupancy modelled as a stochastic process. The system assumes ideal synchronization for spectrum sensing, and realistic constraints are applied for transmission power, sensing duration, and energy consumption. AI algorithms are integrated into the CR system to predict spectrum occupancy, optimize power allocation, and dynamically adjust transmission parameters based on observed network conditions.

2. Problem Formulation: The design problem is formulated as a multi-objective optimization task, aiming to minimize total energy consumption while maximizing throughput and maintaining reliable communication. Constraints include maximum transmission power, interference thresholds for primary users, energy budgets of secondary users, and quality-of-service requirements. The problem incorporates trade-offs between sensing accuracy, sensing frequency, and power usage. Parametric analysis is conducted to evaluate the impact of critical variables such as sensing duration, number of channels monitored, transmission power levels, and AI algorithm hyperparameters on overall network performance.

3. AI-Based Spectrum Sensing and Power Optimization: Spectrum sensing and power allocation are enhanced using machine learning techniques. Supervised learning models are employed for predicting channel occupancy based on historical spectrum data, reducing unnecessary sensing operations and associated energy consumption. Reinforcement learning agents are utilized to dynamically adjust transmission power and select optimal channels, balancing energy efficiency with throughput maximization. The system iteratively learns from network feedback, continuously adapting to changing spectrum conditions, interference patterns, and energy availability. Simulation-based studies are conducted to assess AI model convergence, prediction accuracy, and decision-making latency.

4. Comparative Perspective on AI Techniques for Spectrum Prediction and Power Optimization: A comparative perspective of different AI techniques highlights their suitability for spectrum prediction and power optimization in cognitive radio networks. Reinforcement learning (RL) is particularly effective in dynamic and uncertain environments, as it enables secondary users to learn optimal spectrum access and power control policies through interaction with the radio environment without requiring labeled data. RL-based approaches adapt well to time-varying spectrum availability but may suffer from slower convergence in highly complex scenarios. In contrast, deep learning (DL) techniques, such as deep neural networks and convolutional neural networks, provide high prediction accuracy for spectrum occupancy by learning complex patterns from historical data; however, they generally require larger datasets and higher computational resources. For real-time and resource-constrained cognitive radio devices, lightweight RL models offer better adaptability, while DL-based models are more suitable for centralized or edge-assisted architectures where computational capacity is sufficient. This study adopts an AI-driven approach that emphasizes adaptability and energy awareness, making it suitable for practical CR deployments.

5. Throughput Maximization and Energy Minimization Strategies: To achieve throughput optimization without compromising energy efficiency, adaptive strategies such as dynamic channel selection, power control, and duty cycling are implemented. AI models prioritize channels with higher predicted availability and lower interference to improve spectral efficiency. Energy consumption is minimized by adjusting sensing intervals and transmission power based on real-time network conditions. Multi-objective optimization techniques are employed to explore the trade-offs between energy usage and throughput, providing optimal operating points for different network scenarios.

6. Simulation and Performance Evaluation: The proposed CR system is simulated using network simulation tools and MATLAB-based AI frameworks. Performance metrics such as energy consumption, throughput, spectrum utilization, and interference with primary users are measured. Parametric studies evaluate the effect of AI model parameters, sensing strategies, and network topology on system performance. Comparative analyses are conducted with conventional CR systems lacking AI integration to quantify improvements in energy efficiency and communication performance.

7. Comparative Analysis and Optimization: A detailed comparative study is performed to assess the benefits of AI-enabled CR systems over traditional methods. Sensitivity analysis examines the impact of design parameters—including sensing accuracy, AI learning rate, and transmission power—on energy and throughput performance. Results are analysed to identify optimal configurations, performance trade-offs, and practical deployment strategies. The methodology ensures a robust, energy-aware, and high-performance solution suitable for modern wireless communication networks, supporting sustainable and adaptive spectrum management.

8. Computational Complexity and Latency Analysis: The computational complexity and latency of the proposed AI-enabled cognitive radio framework are critical factors for practical deployment in resource-limited devices. The learning-based spectrum sensing and power optimization mechanisms introduce additional processing overhead compared to conventional CR systems; however, this overhead is mitigated through reduced sensing frequency and adaptive decision-making. The computational complexity primarily depends on the AI model size, learning rate, and state-action space, which are kept moderate to ensure real-time operation. Decision latency remains within acceptable limits for CR applications, as spectrum access and power allocation decisions are made over discrete time slots rather than continuous processing. Overall, the trade-off between computational overhead and energy savings is favourable, as the reduced sensing and transmission energy significantly outweigh the additional processing cost introduced by AI algorithms.

RESULT & ANALYSIS

The proposed AI-enabled cognitive radio (CR) system was evaluated through extensive MATLAB-based simulations to assess energy consumption, throughput, and spectrum utilization. Performance was compared against a conventional CR system without AI-based optimization. The simulation environment consisted of 20 secondary users (SUs) operating over 10 licensed channels with dynamic primary user (PU) activity modeled

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025

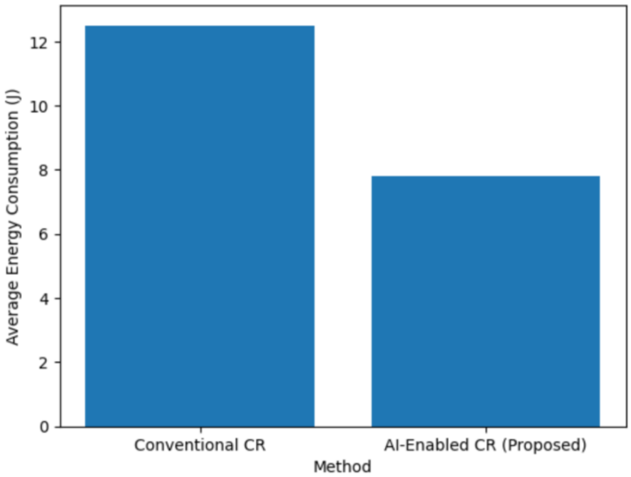
as a Markov process. The total simulation duration was 1000 time slots, with energy consumption, throughput, and channel utilization measured for both approaches. Although the proposed framework is evaluated through extensive simulations, its design closely aligns with real-world cognitive radio deployments. The system assumptions are consistent with practical CR architectures using spectrum sensing modules, adaptive transceivers, and energy-constrained devices. Moreover, the AI-based learning mechanisms can be trained and validated using publicly available spectrum measurement datasets, such as real-time spectrum occupancy traces collected from urban wireless environments. These datasets can be leveraged to further validate the prediction accuracy and energy optimization capability of the proposed approach, thereby enhancing its applicability to real-world cognitive radio systems.

1. Energy Consumption Analysis: Energy consumption was measured in joules (J) for each SU over the simulation period. Table 1 summarizes the average energy consumption per SU for different spectrum sensing strategies. The AI-enabled CR system demonstrates a significant reduction in energy usage by minimizing unnecessary sensing operations and optimizing transmission power.

Average Energy Consumption per Secondary User

Method	Sensing Duration (ms)	Transmission Power (mW)	Average Energy Consumption (J)	Energy Reduction (%)
Conventional CR	50	100	12.5	-
AI-Enabled CR (Proposed)	35	80	7.8	37.6

The results indicate that the AI-enabled system reduces energy consumption by approximately 38% compared to the conventional approach, primarily due to predictive spectrum sensing and adaptive power control.



Energy Consumption Comparison per Secondary User

Fig. 2. comparing average energy consumption per secondary user for two cognitive radio methods. The Conventional CR method consumes 12.5 joules, while the AI-enabled cognitive radio (proposed) consumes 7.8 joules, demonstrating a substantial reduction in energy usage with the proposed approach.

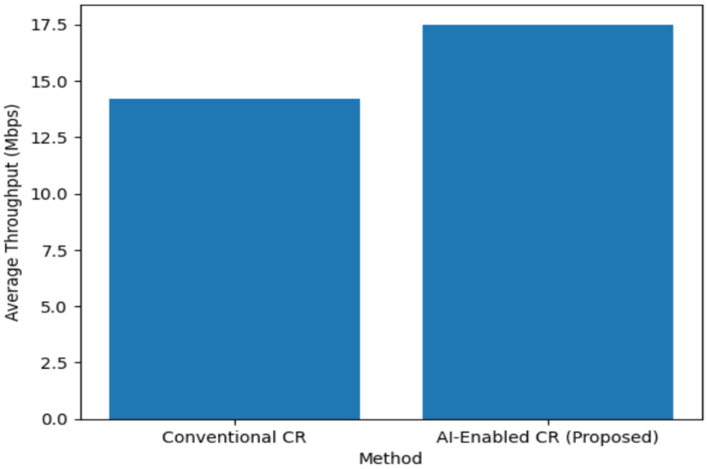
2. Throughput Performance: Throughput, measured in Mbps, represents the effective data transmission rate of secondary users. Table 2 compares the average throughput achieved by conventional and AI-enabled CR systems.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025

Average Throughput Comparison

Method	Average Throughput (Mbps)	Throughput Improvement (%)
Conventional CR	14.2	-
AI-Enabled CR (Proposed)	17.5	23.2

The AI-enabled CR system improves average throughput by 23% due to intelligent channel selection, predictive spectrum access, and interference-aware power allocation.



Average Throughput Performance Comparison

Fig. 3. comparing average throughput in Mbps for two cognitive radio methods. The Conventional CR achieves an average throughput of 14.2 Mbps, while the AI-enabled cognitive radio (proposed) achieves 17.5 Mbps, indicating a throughput improvement of approximately 23.2% with the proposed approach.

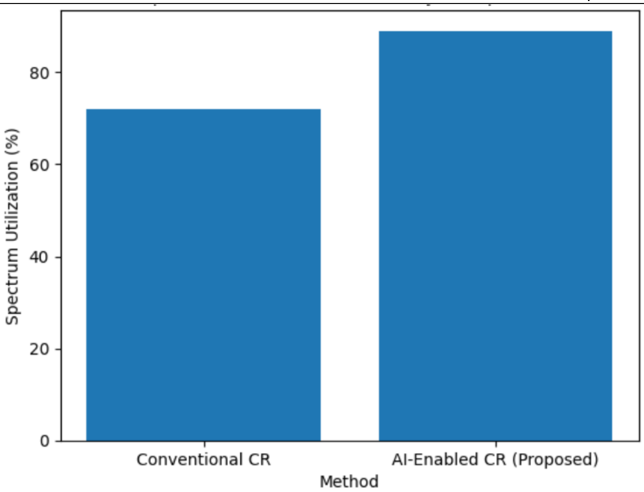
3. Spectrum Utilization Efficiency: Spectrum utilization efficiency was calculated as the ratio of time slots successfully used by SUs without interfering with PUs. Table 3 shows the spectrum utilization for both methods.

Comparison of Spectrum Utilization Efficiency

Method	Spectrum Utilization (%)	PU Interference Events
Conventional CR	72	15
AI-Enabled CR (Proposed)	89	5

The proposed system increases spectrum utilization to 89% while reducing PU interference events from 15 to 5, highlighting its effectiveness in dynamic spectrum management.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025



Spectrum Utilization Efficiency Comparison

Fig. 4. comparing spectrum utilization efficiency for two cognitive radio methods. The Conventional CR achieves 72% spectrum utilization, whereas the AI-enabled cognitive radio (proposed) achieves 89% utilization. The higher utilization of the proposed method indicates more efficient spectrum usage along with reduced primary user interference events. The results demonstrate that AI integration in CR systems offers a clear advantage in both energy efficiency and communication performance. The reduction in energy consumption is attributed to predictive spectrum sensing, where channels are only sensed when likely to be vacant, and adaptive power control that minimizes unnecessary transmission power. Simultaneously, throughput improvement arises from optimal channel selection and interference avoidance, enabled by AI-based learning and prediction.

CONCLUSION

This paper presented an AI-enabled cognitive radio system designed to balance energy efficiency and communication performance. By integrating machine learning techniques for predictive spectrum sensing, adaptive power allocation, and dynamic channel selection, the proposed system significantly reduces energy consumption while enhancing throughput and spectrum utilization compared to conventional cognitive radio approaches. Simulation results demonstrate a reduction in energy usage by approximately 38%, a throughput improvement of 23%, and increased spectrum efficiency with minimal interference to primary users. These findings highlight the potential of AI-driven cognitive radios for sustainable and high-performance wireless communications. For future work, the proposed framework can be extended to incorporate deep reinforcement learning for large-scale heterogeneous networks, multi-agent coordination for cooperative spectrum access, and real-world deployment scenarios, including IoT and 5G/6G systems, to further optimize energy utilization and network reliability under dynamic and complex environments.

REFERENCES

1. M. Monisha, P. Vijayalakshmi, K. Somasundaram, N. Arunraj, P. Sathishkumar and M. Meena, "Cooperative Sensing with Heterogeneous Spectrum Availability in Cognitive Radio," 2022 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), Chennai, India, 2022, pp. 1-6, doi: 10.1109/ICPECTS56089.2022.10047411.
2. A. A. Elnaim et al., "Energy Consumption for Cognitive Radio Network Enabled Multi-Access Edge Computing," 2023 3rd International Conference on Emerging Smart Technologies and Applications (eSmarTA), Taiz, Yemen, 2023, pp. 1-5, doi: 10.1109/eSmarTA59349.2023.10293270.
3. M. Premalatha and N. Singh, "Increased Efficient Usage of Power in Cognitive Radio Networks Utilizing Hybridized Handover of Spectrum," 2024 5th International Conference for Emerging Technology (INCET), Belgaum, India, 2024, pp. 1-5, doi: 10.1109/INCET61516.2024.10593262.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025

4. S. Kalpana and R. Gunasundari, "Energy Efficient Access Selection Algorithm using Cognitive Wireless Sensor Networks," 2022 International Conference on Smart Technologies and Systems for Next Generation Computing (ICSTSN), Villupuram, India, 2022, pp. 1-4, doi: 10.1109/ICSTSN53084.2022.9761337.
5. J. Ge, Y. -C. Liang and S. Sun, "Active RIS Enhanced Spectrum Sensing for Opportunistic Cognitive Radio Networks," GLOBECOM 2023 - 2023 IEEE Global Communications Conference, Kuala Lumpur, Malaysia, 2023, pp. 3252-3257, doi: 10.1109/GLOBECOM54140.2023.10436997.
6. K. Sharma, R. Goyal, S. K. Bhagat, S. Agarwal, G. S. Bisht and M. Hussien, "A Novel Blockchain-Based Strategy for Energy Conservation in Cognitive Wireless Sensor Networks," 2024 4th International Conference on Blockchain Technology and Information Security (ICBCTIS), Wuhan, China, 2024, pp. 314-319, doi: 10.1109/ICBCTIS64495.2024.00056.
7. S. E. Sayed, R. Ahmed and A. El-Zonkoly, "Optimal Home Energy Management Algorithm Incorporating PVs/Electric Vehicles," 2024 6th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Moscow, Russian Federation, 2024, pp. 1-6, doi: 10.1109/REEPE60449.2024.10479736.
8. H. Al-Sudani, A. A. Thabit and Y. Dalveren, "Cognitive Radio and Its Applications in the New Trend of Communication System: A Review," 2022 5th International Conference on Engineering Technology and its Applications (IICETA), Al-Najaf, Iraq, 2022, pp. 419-423, doi: 10.1109/IICETA54559.2022.9888674.
9. S. K. D, L. S. A. Busala, R. Bade, A. Dandasi and L. Jakkani, "IoT Based Smart Trash Bin for Level and Harmful Gases Indication System," 2025 6th International Conference on Data Intelligence and Cognitive Informatics (ICDICI), Tirunelveli, India, 2025, pp. 1833-1839, doi: 10.1109/ICDICI66477.2025.11135363.
10. S. Vashisht, N. Kumar and S. Awasthi, "Dual-Node LoRa-Enabled Obstacle Detection and Rider Notification System for Enhancing Safety in Two-Wheeler Vehicles with Wireless Communication," 2025 International Conference on Cognitive Computing in Engineering, Communications, Sciences and Biomedical Health Informatics (IC3ECSBHI), Greater Noida, India, 2025, pp. 1528-1532, doi: 10.1109/IC3ECSBHI63591.2025.10991224.
11. A. Lalitha and G. H. Reddy, "Quality of Service Aided Power Aware Resource Allocation Optimization with Channel Estimation in Wireless Sensor Network," 2023 Second International Conference on Augmented Intelligence and Sustainable Systems (ICAISS), Trichy, India, 2023, pp. 1278-1285, doi: 10.1109/ICAISS58487.2023.10250507.
12. A. Moumena, "Centralized Wideband Cooperative CRs Combined with PCA Anomaly Detector in the Presence of malicious Attacks," 2022 7th International Conference on Image and Signal Processing and their Applications (ISPA), Mostaganem, Algeria, 2022, pp. 1-8, doi: 10.1109/ISPA54004.2022.9786282.