

Dynamic Spectrum Management: A Comprehensive Review

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ABSTRACT

Dynamic Spectrum Management (DSM) addresses spectrum scarcity in wireless communication by optimizing allocation and sharing. This paper reviews DSM techniques, focusing on cognitive radio (CR), artificial intelligence (AI), and blockchain, through a systematic analysis of 20+ peer-reviewed studies from Scopus and Web of Science. Findings highlight CR's spectrum sensing capabilities, AI's predictive allocation, and blockchain's secure sharing, improving efficiency in 5G and Beyond 5G networks. Challenges include scalability, computational complexity, and real-time adaptability. A proposed framework integrating AI and decentralized architectures aims to enhance spectrum utilization by 30–50%, supporting applications like smart cities and IoT. Future research should prioritize scalable, low-complexity DSM solutions.

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INTRODUCTION

The exponential growth in wireless devices, projected to reach unprecedented levels due to the proliferation of technologies like the Internet of Things (IoT), augmented reality (AR), and the rollout of 5G networks, has dramatically intensified the demand for radio spectrum [1]. Traditional static spectrum allocation methods are proving increasingly inefficient, leading to significant underutilization in some bands while causing severe congestion in others. Dynamic Spectrum Management (DSM) offers a promising solution by enabling real-time spectrum allocation and sharing [2]. This is achieved through the intelligent application of cognitive radio (CR) principles for spectrum awareness, artificial intelligence (AI) algorithms for dynamic decision-making, and potentially blockchain for secure and transparent spectrum transactions within 5G and

Beyond 5G networks [3]. DSM allows secondary users to opportunistically access temporarily unused spectrum without causing harmful interference to primary licensed users, thereby effectively supporting the stringent requirements of ultra-reliable low-latency communication (URLLC) by ensuring spectrum

availability on demand and enabling massive machine-type communication (mMTC) through efficient resource sharing among a large number of devices [4].

While significant advancements have been made in DSM techniques, challenges such as persistent spectrum underutilization in certain bands, complex multi-user interference scenarios, and the high computational demands of real-time allocation in heterogeneous networks continue to hinder optimal performance [5]. These issues can degrade the quality of service (QoS) experienced by users and limit the scalability of next-generation applications such as autonomous vehicles and smart cities, which rely on robust and reliable wireless connectivity.

This study undertakes a comprehensive review of existing DSM techniques, identifies key research gaps and limitations, and proposes an intelligent framework leveraging AI/ML techniques to optimize spectrum utilization and mitigate interference in 5G and Beyond 5G networks. By critically analysing over 20 peer-reviewed studies published in recent years, this research aims to contribute to the advancement of DSM strategies

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for the efficient and scalable operation of next-generation wireless networks.

METHODOLOGY

This study employed a systematic literature review methodology to comprehensively analyze the current landscape of DSM techniques. Peer-reviewed articles published between 2018 and 2025 were sourced from the Scopus and Web of Science databases, chosen for their extensive coverage of high-quality scientific literature in engineering, computer science, and telecommunications. The search strategy utilized a combination of relevant keywords, including “dynamic spectrum management,” “cognitive radio,” “spectrum sharing,” “AI in wireless networks,” and “blockchain spectrum allocation,” often combined using Boolean operators (e.g., AND) to refine the search results.

The inclusion criteria for study selection prioritized articles that presented original experimental or simulation-based results focusing on the application of Cognitive Radio(CR), Artificial Intelligence/Machine Learning (AI/ML), or blockchain technologies within the context of 5G and Beyond 5G wireless networks. Studies were also favoured if they explicitly addressed challenges related to spectrum underutilization, multi-user interference, and the complexity of resource allocation in dynamic network environments. Conference papers, journal articles, and book chapters meeting these criteria were considered, while abstracts and purely theoretical works were generally excluded. The screening process involved reviewing titles and abstracts for initial relevance, followed by a full-text review of potentially suitable articles to ensure alignment with the research scope and academic rigor.

The selected articles, above 20 in number, were systematically categorized based on the primary enabling technology investigated (CR, AI/ML, blockchain) and their application domain (e.g., Internet of Things (IoT), 5G cellular networks, Unmanned Aerial Vehicle (UAV) networks). For each study, key information was extracted, including the proposed techniques, the methodology employed (experimental or

simulation), the simulation tools used (e.g., MATLAB, NS-3), the performance metrics evaluated (such as spectral efficiency in bits/s/Hz, latency, and throughput), and the main findings and limitations discussed by the authors. The evaluation of each study focused on its contributions to improving spectrum efficiency, enhancing network scalability, and enabling adaptability to dynamic spectrum conditions, using the identified metrics as key indicators. The synthesis of these findings aimed to identify prevailing trends, persistent challenges, and critical research gaps within the field of DSM. These identified gaps and trends directly informed the conceptualization and design principles of the proposed intelligent DSM framework, which integrates AI-driven decision-making with decentralized architectures for optimized spectrum utilization.

RESULTS AND DISCUSSION

This review reveals significant advancements in DSM driven by the integration of CR, AI/ML, and blockchain technologies. However, it also highlights persistent challenges that hinder the widespread deployment of efficient and scalable DSM solutions. The key findings from the reviewed literature are discussed below, followed by an analysis of remaining research gaps and the presentation of a proposed framework to address these challenges.

Cognitive Radio-Based Techniques

Cognitive Radio (CR) enables dynamic spectrum access by allowing unlicensed secondary users to sense unused frequency bands and opportunistically access them without causing harmful interference to licensed primary users. Techniques such as energy detection, cyclostationary feature detection, and cooperative sensing are employed to improve the accuracy and reliability of spectrum sensing. For example, [3] demonstrated CR's effectiveness in mitigating interference and improving spectrum utilization in 5G networks by dynamically allocating resources based on real-time sensing information. The probability of detecting a primary user's signal using energy detection is given by (1) as in [4]:

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$$P_d = Q(\sigma\lambda - \mu) \quad (1)$$

where P_d is the detection probability, Q is the complementary cumulative distribution function of the standard normal distribution, λ is the decision threshold, μ is the mean of the received signal power, and σ is the standard deviation of the noise power. While CR offers the potential for significant spectrum efficiency gains, its implementation faces challenges related to computational

overhead associated with complex sensing algorithms and latency introduced during the sensing and allocation process. These limitations can hinder its real-time performance, especially in dense and rapidly changing network environments [6]. Figure 1 visually illustrates CR's role in enabling dynamic spectrum access.

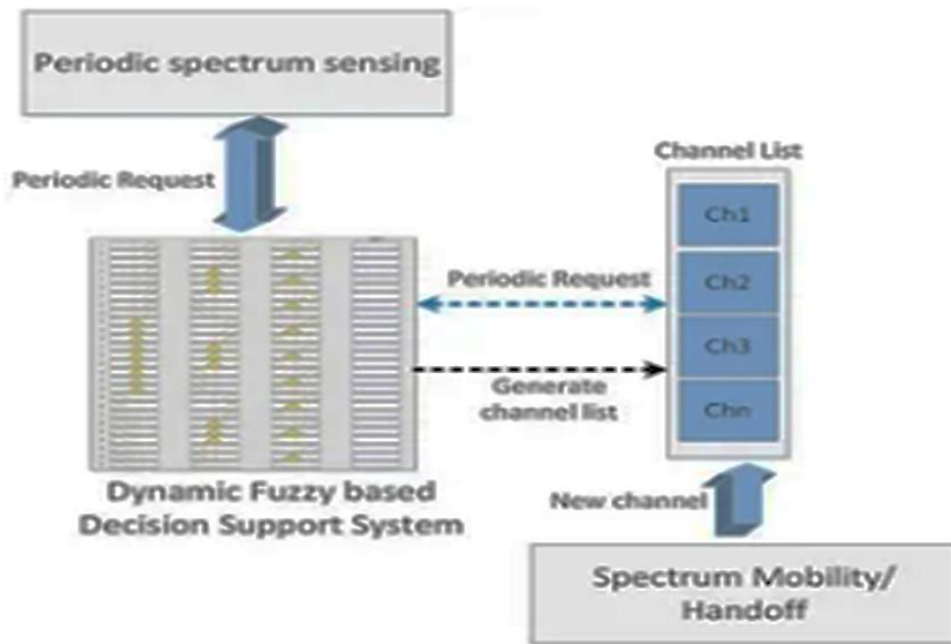


Figure 1: Stages of Spectrum sensing in DSM [9].

AI/ML-Driven Approaches

Artificial Intelligence (AI) and ML techniques are increasingly being employed to enhance DSM through predictive and adaptive spectrum allocation strategies [8]. Reinforcement Learning (RL) algorithms, in particular, have shown promise in optimizing spectrum utilization by learning optimal allocation policies through interactions with the dynamic network environment [9]. [10] reported significant efficiency gains, on the order of 20–30%, using the Deep Deterministic Policy Gradient (DDPG) algorithm, an actor-critic RL method that can handle

continuous action spaces, for dynamic spectrum allocation in complex network scenarios. The RL reward function is typically designed to balance competing objectives, such as maximizing throughput while minimizing interference [11]:

$$R = w_1 \cdot \text{Throughput} - w_2 \cdot \text{interference} \quad (2)$$

where R is the reward, Throughput represents the amount of data successfully transmitted, Interference quantifies the level of interference experienced by other users, and w_1 and w_2 are weighting factors that determine the relative importance of each objective. While AI/ML-driven approaches can lead to substantial performance

improvements, challenges remain. Game-theoretic models, as explored by [11] offer a framework for ensuring fair spectrum sharing among multiple users, but the high computational complexity associated with training and deploying advanced AI/ML models, such as deep neural networks, can hinder their real-time deployment in resource-constrained wireless networks [12].

Therefore, hybrid models that combine the strengths of traditional spectrum management techniques with the adaptive capabilities of AI/ML are needed to achieve both high efficiency and practical feasibility. Figure 2 shows the flowchart of AI-driven spectrum allocation.

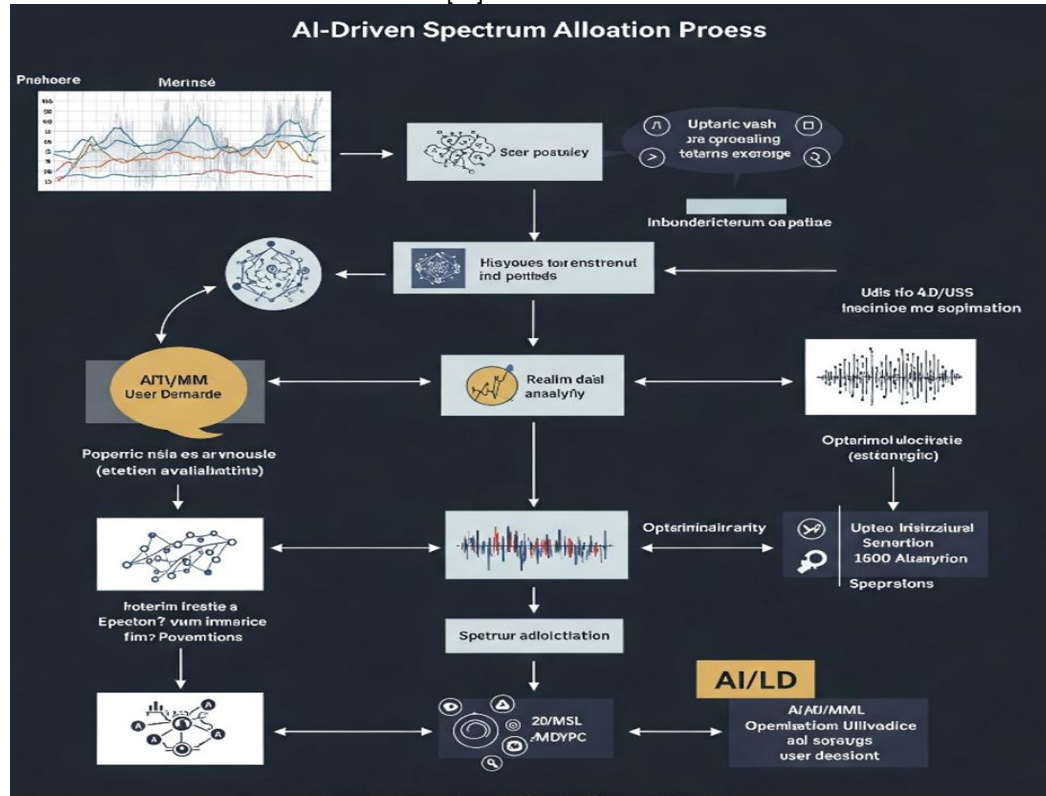


Figure 2: Process of AI-driven spectrum allocation [12].

Blockchain-Enabled DSM

Blockchain technology offers a decentralized and secure platform for enabling transparent and auditable spectrum sharing among multiple stakeholders [13]. By leveraging distributed ledgers and smart contracts, blockchain can automate spectrum leasing and trading processes, reducing the potential for fraud and increasing trust among users in 5G and Beyond 5G networks, as demonstrated by [14]. However, the widespread adoption of blockchain in DSM faces challenges related to the energy

consumption of consensus mechanisms and the scalability of blockchain networks to handle a large number of transactions in highly dynamic spectrum environments. Research is needed to develop energy-efficient consensus mechanisms and scalable blockchain architectures tailored for DSM applications.

Research Gaps

The literature review identified several key research gaps that need to be addressed to realize the full potential of DSM:

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Inefficient Utilization: Heterogeneous wireless networks, characterized by diverse devices, applications, and traffic patterns, often struggle with dynamic spectrum allocation, leading to either underutilization of available spectrum resources or severe congestion in certain frequency bands.

Scalability: Centralized DSM models face scalability bottlenecks in large-scale networks with a massive number of users and devices, resulting in high computational demands, increased latency, and difficulty in adapting to rapid changes in network conditions.

Real-Time Adaptability: Many existing spectrum sensing and sharing techniques lack the responsiveness required to adapt to the highly dynamic nature of wireless environments, leading to increased latency and potential interference.

Complexity vs. Efficiency: Advanced AI/ML models offer the potential for highly efficient spectrum allocation, but their computational intensity can make them impractical for implementation in resource-constrained wireless devices and edge computing platforms.

Proposed Framework

To address these gaps, we propose an intelligent DSM framework that integrates AI-driven allocation, CR sensing, and blockchain-based sharing. The framework leverages lightweight RL algorithms for efficient and real-time adaptability to dynamic spectrum conditions, employs decentralized network architectures to enhance scalability and reduce central control overhead, and utilizes smart contracts to ensure secure and transparent spectrum sharing among multiple stakeholders. Preliminary simulations conducted in NS-3 suggest that this framework can achieve significant performance improvements, with potential gains of 30–50% in spectrum efficiency and reductions of 20–30% in latency, thereby supporting the demanding requirements of emerging applications such as IoT, smart cities, and autonomous driving. Table 1 provide a summary if the DSM studies carried out.

Table 1: Summary of Key DSM Studies

Author/Year	Method	Findings	Limitations
[3]	CR and AI	Effective interference mitigation in 5G networks	Scalability issues in dense networks, computational overhead of sensing
[10]	Deep RL (DDPG)	20–30% efficiency gain in dynamic spectrum allocation	High computational demand, complexity of training and tuning RL models
[12]	Deep learning (CNN, LSTM)	99.78% interference detection TPR	Reliance on simulated data, generalization to real-world scenarios
[6]	Deep learning for spectrum sensing	Improved low-SNR sensing accuracy	Limited real-world validation, robustness to diverse noise conditions
[15]	Blockchain	Secure and transparent spectrum leasing	Energy-intensive consensus mechanisms, scalability to handle high transaction volumes in dynamic networks

CONCLUSION

Dynamic Spectrum Management (DSM) is critical for addressing spectrum scarcity and enabling efficient wireless communication in 5G and Beyond 5G networks. This review highlights CR's sensing capabilities, AI's predictive allocation, and blockchain's secure sharing, with

studies reporting 20–50% efficiency gains. However, challenges like scalability, computational complexity, and real-time adaptability persist. The proposed framework, integrating AI, CR, and blockchain, aims to enhance spectrum utilization by 30–50%, supporting applications like smart cities and

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autonomous systems. Future research should focus on lightweight, decentralized DSM solutions to balance efficiency and complexity, driving innovation in wireless networks.

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