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Techniques employed in distributed cognitive radio networks: a survey on routing intelligence

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Abstract
In order to meet the growing needs for wireless communication in dynamic and diverse circumstances, Cognitive Radio Networks (CRNs) have evolved as a transformational model. The important area of intelligent routing in CRNs is examined in this review, along with the potential, problems, and developments that have shaped this emerging discipline. A close study is done on spectrum-aware routing, machine learning-based methods, game theory-inspired strategies, and bio-inspired processes to show how they help solve problems like changing spectrum access, security issues, and the need to efficiently distribute resources. The ever-changing nature of radio settings presents both possibilities and difficulties for innovation in the fields of signal processing, machine learning, and protocol design. The main conclusions of the study highlight how important intelligent routing is to changing how CRNs operate in the future. In the face of dynamic situations, it offers improved resilience, adaptation, and spectrum efficiency. Security innovations, human-centered strategies via intelligent interfaces, and fusion with cutting-edge technology like blockchain and machine learning all reveal novel perspectives on CRNs. With far-reaching ramifications, intelligent routing is positioned as a keystone for reimagining the potential of wireless communication. Future navigation offers a paradigm shift as cutting-edge technology and intelligent routing algorithms combine, opening up previously unimaginable possibilities in the constantly changing field of wireless communication. This study acts as a compass, pointing practitioners and academics in the direction of intelligent routing's revolutionary potential in the development of CRNs.

Keywords Cognitive Radio Networks (CRNs) · Routing · Machine learning · Scalability · Security · Energy efficiency

1 Introduction

Due to the widespread use of mobile devices, Internet of Things (IoT) devices, and wireless networks, wireless communication technologies have grown at an unprecedented rate, creating an unprecedented demand for spectrum resources. A valuable resource that has to be properly managed in order to meet the varied communication requirements of different

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Extended author information available on the last page of the article services and applications is spectrum, the limited range of frequencies utilized for wireless communication [1]. However, it has been shown that the conventional method of fixed spectrum allocation in which certain frequency bands are allocated to specific users or services is ineffective and has increased to the scarcity of spectrum.

The spectrum is fixed and does not take into consideration changes in demand over time or across different geographic regions. It is based on static assumptions about the consumption patterns of various services [2, 3]. It indicates that although certain frequency bands encounter congestion and interference, others may remain to be underused in particular locations or at particular times. Due to this inefficient use of spectrum, wireless networks are unable to fulfil the increasing needs of bandwidth-intensive applications like computer casinos, streaming video, and real-time communication. This leads in subpar performance and resource waste.

A potential approach to resolving the critical matters of spectrum scarcity and inefficiency in modern wireless communication networks is the deployment of Cognitive Radio Networks (CRNs). The demand for spectrum resources is growing faster than the supply due to the widespread use of wireless devices and applications [4, 5]. The conventional method of fixed spectrum allocation, which assigns certain frequency bands to some customers or services for exclusive usage, exacerbates this mismatch. Huge areas of the spectrum are thus underutilized or unused at specific times and places, which leads in inefficiencies and resource waste.

By proposing intelligent radios that can sense their surroundings on their own, assess spectrum utilization, and modify their transmission parameters based on that information, Mitola and Maguire's 1999 concept of cognitive radio completely changed the field. With cognitive radios, operating parameters may be dynamically adjusted depending on the real-time conditions of the radio frequency (RF) environment, in contrast to conventional radios that broadcast at constant power levels and on predefined frequencies [6]. Due to their adaptive behaviour, cognitive radios can identify and capitalize of spectrum access possibilities even in congested or underutilized frequency bands.

In CRNs, secondary users equipped with cognitive radios opportunistically access spectrum bands that are unoccupied or lightly used by primary users, which are often referred to as spectrum white spaces. By dynamically accessing these unused spectrum resources, CRNs can significantly improve spectrum utilization efficiency and alleviate congestion in crowded frequency bands [7, 8]. Moreover, CRNs are designed to operate in a cooperative manner, where secondary users collaborate with primary users to minimize interference and ensure coexistence, thereby fostering a more efficient and harmonious spectrum sharing environment.

In order to efficiently manage spectrum resources and provide dependable communication, CRNs moving from static to dynamic spectrum access require intelligent routing methods. Due to the dynamic nature of spectrum availability and the need for real-time adaptability to changing network conditions, traditional routing protocols which are designed for static systems with predictable connectivity patterns might not be appropriate for CRNs [9, 10]. To determine the best routing decisions, intelligent routing mechanisms in CRNs must consider a variety of factors, including network topology, interference limitations, spectrum availability, and Quality of Service (QoS) requirements.

CRNs may dynamically route traffic via available spectrum channels due to these intelligent routing techniques, avoiding congested bands and providing the least of interruption to primary users [11]. By the use of efficient algorithms and cognitive abilities, CRNs are able to maximize spectrum resource consumption while maintaining continuous communication and user equity.

But traditional wireless networks, CRNs have a flexible structure that allows them to operate both with and without a fixed network infrastructure. Within CRNs, there are two main network configurations: decentralized or dispersed networks, where SUs communicates via multi-hop connections without depending on a fixed infrastructure, and centralized networks, which are enabled by a Single-User (SU) Base Station (BS) [21]. In distributed CRNs where SUs connects with one another via a decentralized system this research focuses on the circumstance were accessing the SU base station often involves multi-hop communication. Dispersed CRNs are useful in a variety of situations, including emergency response operations, rural broadband distribution, and disaster relief activities. The distributed CRNs' decentralized structure provides benefits in these kinds of situations, including scalability, robustness, and adaptability. But dependable routing algorithms are required for efficient communication in dispersed CRNs in order to create pathways between source and destination SUs, especially in multi-hop communication scenarios [22, 23]. Compared to typical wireless networks, routing in CRNs presents significant difficulties because of the structured manner Primary Users use spectrum and the variety of channel configurations that SUs may choose among. The integration of CRNs with Wireless Sensor Networks is shown in Fig. 1. It demonstrates decentralized sensor nodes with cognitive radio capabilities that allow for intelligent decision-making and dynamic spectrum access. The visualization emphasizes cooperative protocols and collaborative spectrum sensing, illustrating how distributed CRNs may improve network resilience and spectrum efficiency in dynamic conditions.

Due to their incapacity to adapt to dynamic channel conditions and dynamic spectrum availability, traditional routing algorithms developed for static wireless networks are not directly applicable to CRNs. In CRNs, spectrum-aware routing is essential to assure optimal spectrum resource use while avoiding interference with primary users. Consequently, in order to create an effective communication pathway, routing algorithms in CRNs need to take spectrum availability into considerations and modify as essential [24, 25]. A distributed CRN scenario with both PUs and SUs is provided to illustrate the importance of spectrum-aware routing. In this case, efficient routing is essential for enabling PUs and SUs

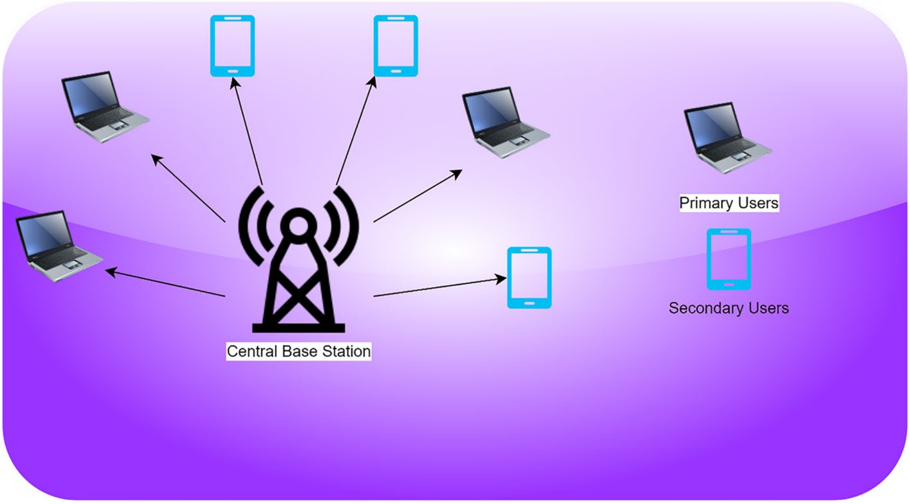

Fig. 1 Distributed CRNs of Wireless Sensor Networks

to communicate without interference, ensuring the best possible spectrum use and network management. Also, A comprehensive summary of several applications for CRNs can be provided in Table 1. It focuses towards how essential CRNs are in a variety of industries, such as disaster relief, healthcare, transportation, military and defense, and telecommunications. This comprehensive review demonstrates how adaptable CRNs are and how they may be used to address a diversity of requirements and issues in many industries.

1.1 Objectives of the survey

This survey's main goal is to provide people a comprehensive knowledge of the multiple routing strategies used in distributed CRNs. The survey specifically aims to:

- Examine the fundamental concepts and characteristics of CRNs.
- Investigate the importance of routing intelligence in CRNs and the challenges associated with routing in dynamic spectrum environments.
- Review the existing literature on routing techniques in CRNs, including spectrum-aware routing, cognitive decision-making, game theory-based routing, machine learning approaches, and hybrid routing techniques.
- Analyze the performance metrics and evaluation criteria used to assess the effectiveness of routing techniques in CRNs.
- Provide insights into the strengths, weaknesses, and applicability of different routing techniques through a detailed analysis of case studies and real-world deployments.
- Identify open research challenges and future directions for advancing routing intelligence in CRNs.

In order to provide the foundation for future study in this field and to provide a strong knowledge of the issue, this article aims to provide a comprehensive analysis of the different routing techniques used in CRNs. The focus of this research is to improve routing strategies that are specifically designed to meet the needs of CRNs by studying multiple routing methods and their application in CRNs.

2 Fundamentals of Cognitive Radio Networks

The concept of cognitive radio serves as the foundation for CRNs, a novel approach to wireless communication. Cognitive radio is essentially the term for intelligent radios that are able to detect their environment on their own, assess spectrum utilization, and adapt their broadcast conditions in order to maximize spectrum use while residing peacefully alongside primary users [26]. Utilizing software-defined radios (SDRs) and complex algorithms, CRNs enable radios to think like humans. It implies that they can dynamically adjust their working parameters in response to specific observation of the radio frequency (RF) environment.

Key characteristics of CRNs include:

- **Dynamic Spectrum Access**: CRNs, also called as spectrum white spaces, enable secondary users with opportunistic access to unused spectrum bands by primary users. CRNs reduce congestion in congested frequency bands and improve the efficiency of spectrum utilization by dynamically accessing unused spectrum resources [27].

Table 1 Various application of Cognitive Radio Networks

Application	Limitations	Advantages
Wireless Broadband Access [12]	● Efficient spectrum utilization. ● Enhanced coverage and connectivity. ● Dynamic spectrum access.	● Interference from primary users. ● Spectrum sensing complexity. ● Regulatory constraints.
Public Safety Communications [13]	● Spectrum flexibility for emergency communication. ● Reliable communication in disaster scenarios.	● Interference in critical situations. ● Complexity in network management.
Smart Grid Communication [14]	● Spectrum agility for utility monitoring and control. ● Improved reliability and resilience.	● Interference in critical power distribution. ● Security and privacy concerns.
Military Communications [15]	● Spectrum availability in dynamic battlefield environments. ● Enhanced communication security. ● Rapid deployment and reconfiguration.	● Susceptibility to jamming attacks. ● Complexity in interoperability. ● Regulatory restrictions in certain regions.
Wireless Sensor Networks [16]	● Efficient spectrum utilization for sensor data transmission. ● Enhanced network lifetime through dynamic spectrum access.	● Interference from primary users. ● Energy consumption and resource constraints.
Satellite Communications [17]	● Spectrum agility for satellite link optimization. ● Improved spectrum efficiency in satellite bands.	● Interference from terrestrial sources. ● Complexity in spectrum coordination.
Internet of Things (IoT) [18]	● Spectrum flexibility for IoT device connectivity. ● Enhanced IoT network scalability.	● Interference in crowded spectrum bands. ● Complexity in device synchronization.
Urban Wireless Networks [19]	● Improved spectrum utilization in densely populated areas. ● Enhanced mobility management.	● Interference from neighboring networks. ● Spectrum fragmentation.
Aeronautical Communications [20]	● Dynamic spectrum sharing for seamless connectivity. ● Spectrum availability for in-flight connectivity.	● Regulatory constraints in urban environments. ● Interference from ground-based sources.

- **Spectrum Sensing**: Cognitive radios are able to identify and detect suitable spectrum bands by the use of spectrum sensing techniques. Cognitive radios allow secondary users to take use of underutilized spectrum resources for communication by continually scanning the radio frequency environment for spectrum possibilities [28].
- **Spectrum Management**: In CRNs, efficient spectrum management is essential to ensuring the efficient use of available spectrum resources. CRNs may maximize spectrum use while reducing conflicts and interference by utilizing strategies such spectrum aggregation, spectrum handoff, and interference management [29].
- **Spectrum Sharing**: Primary and secondary users may coexist in the same frequency bands with the assistance of spectrum sharing methods. By use of cooperative spectrum sharing protocols and adaptable spectrum access techniques, CRNs ensure efficient and inclusive spectrum usage while reducing interruptions to primary users [30].
- **Cognitive Capabilities**: Cognitive abilities that enable for thoughtful decision-making and dynamic spectrum conditions adaptation are built into CRNs. By improving spectrum usage efficiency and reducing interference to primary users, cognitive radios are able to self-adjust their transmission parameters in real-time based on observations of the radio frequency environment [31].
- **Cooperative Communication**: In order to improve the dependability and effectiveness of data transfer, CRNs often adopt cooperative communication methods. The performance of the network as a whole may be improved by secondary users collaborating to relay data packets, increase coverage, and reduce fading effects [32].
- **Interference Mitigation**: In order to reduce interference for primary users and improve the QoS for secondary users, CRNs strategic planning interference mitigation techniques. Secondary users are ensured to operate in a manner that complies with transmissions from primary users via the use of strategies like power management, interference cancellation, and spectrum etiquette protocols [33].
- **Spectrum Policy and Regulation Compliance**: To ensure legal and ethical spectrum utilization, CRNs adhere by regulatory requirements and spectrum policy [34]. The integrity of the wireless communication ecosystem and the development of stakeholder trust depend on compliance to spectrum laws, licensing deals, and spectrum access regulations.
- **Security and Privacy**: Robust security and privacy systems are in place by CRNs to protect sensitive data and communication channels from malevolent intrusions and gain unauthorized access [35]. Secure communication in CRNs is ensured by access control, authentication, and encryption methods that protect data privacy and network integrity.
- **Scalability and Resilience**: In order to support a high number of users and adjust to changing network circumstances, CRNs are built to be durable and scalable. Scalability and robustness of CRNs are improved by distributed routing algorithms, fault tolerance techniques, and dynamic resource allocation methods, which allow them to function well in a variety of circumstances [36].
- **Energy Efficiency**: In CRNs, energy economy is particularly important for battery-powered devices and situations with limited resources. Sleep modes, power management techniques, and energy-efficient transmission protocols all contribute to reducing energy use and extending cognitive radio battery life, which improves network sustainability and dependability [37].

The primary attributes of CRNs include, but are not limited to, adaptive spectrum access, spectrum sensing, spectrum management, sharing, cognitive capacities, cooperative communication, interference reduction, adherence to spectrum regulations, security and privacy, scalability and resilience, and energy efficiency. When combined, these features allow CRNs to improve network performance, maximize spectrum use, and provide dependable, efficient wireless communication in a variety of dynamic, heterogeneous conditions.

2.1 Spectrum sensing and access techniques

CRNs depend on spectrum sensing, which is a core component that allows them to find and detect empty spectrum bands for strategic access. CRNs use a range of spectrum sensing methods, such as the following:

- **Energy Detection**: Energy detection is the process of determining the occupancy of a specific frequency band by measuring the energy level within it. Cognitive radios detect spectrum opportunities by comparing the received energy level to a fixed value [38].
- **Cyclostationary Feature Detection**: In order to distinguish between occupied and unoccupied spectrum bands, cyclostationary feature detection uses the cyclostationary properties of radio frequency transmissions [39]. In order to determine cyclostationary patterns indicated of primary user activity, cognitive radios analyze statistical characteristics of the received signals.
- **Cooperative Sensing**: To increase spectrum sensing accuracy and dependability, various cognitive radios work together in cooperative sensing [40]. Therefore, cognitive radios exchange sensory data and decide how much spectrum to consume.
- **Machine Learning-Based Spectrum Sensing**: Support vector machines (SVM), neural networks, and deep learning algorithms are examples of machine learning techniques that are increasingly being used in CRNs for spectrum sensing [41]. Using existing sensing data and signal characteristics, these techniques train classifiers to detect specific spectrum opportunities and distinguish between primary user signals and noise.
- **Compressive Sensing**: A new approach to signal processing termed compressive sensing makes it possible to recover sparse signals from drastically reduced samples [42]. Compressive sensing methods may be used in CRNs to efficiently sample the RF spectrum and reconstruct signals of interest, which reduces energy consumption and overhead while maintaining sensing accuracy.
- **Spectrum Database-Assisted Sensing**: Spectrum databases record data on the availability and occupancy of spectrum within a particular region, providing cognitive radios valuable insights for spectrum sensing [43]. In order to improve the accuracy and efficiency of spectrum sensing, cognitive radios can query spectrum databases to acquire real-time information on spectrum availability. This capability supports local sensing data.
- **Hybrid Sensing Techniques**: Multiple spectrum sensing approaches are combined in hybrid sensing techniques to take advantage of their complementary strengths and reduce their individual limitations [44]. Cognitive radios are able to accomplish robust and dependable spectrum sensing in a variety of situations and environmental conditions by combining energy detection, cyclostationary feature detection, and other sensing techniques.
- **Dynamic Sensing Frameworks**: Cognitive radios with dynamic sensing frameworks can adapt its sensing parameters and techniques to the network's requirements and the

ever-changing environment [45]. Cognitive radios can adjust to changes in spectrum occupancy and enhance the accuracy and efficiency of their sensing by dynamically adjusting sensing parameters including bandwidth, sensing threshold, and sensing duration.

2.2 Challenges and opportunities

2.2.1 Challenges for CRNs

CRNs have a number of drawbacks despite their considerable benefits in terms of flexibility and spectrum efficiency, such as:

- **Spectrum Sensing Reliability**: Accurately identifying available spectrum bands depends on the precision of spectrum sensing. But noise, fading, and shadowing can all decrease spectrum sensing's accuracy, resulting in false positives or wasted possibilities [46].
- **Spectrum Handoff**: The process of switching between multiple spectrum bands as users move throughout a network is known as spectrum handoff [47]. As users shift between multiple spectrum bands, effective spectrum handoff methods are crucial to maintaining connectivity and ensuring the smooth communication.
- **Interference Management**: The performance of CRNs may be degraded by interference from primary users and surrounding users. In order to reduce interference and ensure dependable communication in CRNs, effective interference management strategies are needed [48].
- **Spectrum Mobility**: Spectrum mobility is the capacity of CRNs to dynamically adjust to variations in user needs and available spectrum as users relocate around the network [49]. In order to assure smooth communication and continuous connection when users move between various geographical locations or network services, effective spectrum mobility management is important.
- **Regulatory Compliance**: Regulatory agencies have established licensing requirements and a variety of spectrum rules that CRNs must abide by. In order to prevent infractions and ensure the legal functioning of CRNs, regulatory compliance includes adherence by spectrum use regulations, licensing agreements, and interference avoidance techniques [50].
- **Coexistence with Legacy Systems**: It is essential that CRNs live in harmony with existing users and traditional wireless systems that use the same frequency bands [51]. Careful coordination, spectrum sharing protocols, and interference mitigation methods are necessary to ensure compatibility and minimum interference with older systems while preserving the integrity of modern communication services.
- **Spectrum Heterogeneity**: CRNs function in situations with heterogeneous spectrum, which are defined by a variety of frequency ranges, modulation techniques, and propagation properties. Optimizing communication protocols, modulation methods, and resource allocation strategies to compensate for variable spectrum characteristics and increase efficiencies over a range of frequency bands is known as managing spectrum heterogeneity [52].
- **Resource Allocation and Optimization**: To maximize the effectiveness and usefulness of CRNs, resource allocation must be accomplished. Dynamic resource allocation techniques improve network efficiency and maximize resource utilization by allocating

resources according to user demand, channel conditions, and QoS requirements [53]. Case studies of these techniques include spectrum auctioning, bandwidth allocation, and power control.
- **Cognitive Radio Security**: Cognitive radio security includes measures against malicious attacks, security risks, and unauthorized access to CRNs. Misleading data from spectrum sensing, identifying rogue users, difficulties with authorization and authentication, and privacy concerns are the some of the security challenges that CRNs address. Secure and reliable communication is ensured and security vulnerabilities are prevented for CRNs via the use of intrusion detection systems, encryption protocols, and strong security mechanisms [54].

2.2.2 Opportunities for CRNs

CRNs provide a variety of possibilities for innovation and growth in wireless communication in spite of these obstacles:

- **Enhanced Spectrum Efficiency**: CRNs may dramatically increase spectrum usage efficiency by dynamically accessing underutilized spectrum resources, allowing for more effective use of the existing spectrum [55].
- **Flexibility and Adaptability**: CRNs' cognitive abilities provide them the flexibility and agility to adapt to changing communication needs since they can immediately adjust to shifting network circumstances and spectrum availability [56].
- **Coexistence with Legacy Systems**: With CRNs, secondary users and primary users can coexist while having the least amount of interference and most effective spectrum sharing. The incorporation of cognitive radio technology into existing wireless networks is made much easier by this capability [57].
- **Spectrum Sharing and Access**: Innovative spectrum sharing and access models that encourage user cooperation and maximize spectrum use are made possible by CRNs. Dynamic spectrum access methods, such spectrum leasing, trading, and pooling, allow for the effective use of available spectrum and promote a thriving wireless application and service ecosystem [58].
- **Cognitive Networking**: Cognitive networking concepts that take use of cognitive skills to improve user experience, improve network performance, and accommodate a range of communication needs may be developed due to CRNs. Cognitive networking techniques enable networks to dynamically adapt to changing environmental conditions and user demands, increased efficiency and dependability. Examples of these techniques include cognitive routing, cognitive MAC protocols, and cognitive network management [59].
- **Spectrum Innovation**: The creation of innovative methods for spectrum sensing, spectrum sharing, and interference reduction is encouraged by CRNs, which also stimulate innovation in spectrum management protocols, technologies, and methodologies. To enable more effective and adaptable spectrum usage in future wireless systems, research in spectrum innovation includes dynamic spectrum access, spectrum sensing fusion, spectrum database technologies, and spectrum regulatory frameworks [60].
- **Green Communications**: By reducing the ecological impact of wireless networks, reducing carbon emissions, and reducing energy usage, CRNs enable the growth of ecologically friendly communication solutions [61]. CRNs can operate in a more environmentally sustainable way because to energy-efficient transmission protocols, sleep

modes, and cognitive power management techniques, which promotes green communications and sustainable targets.

- **Cross-Domain Integration**: Cross-domain integration and convergence of wireless communication technologies are enabled by CRNs, enabling heterogeneous networks and devices to cooperate and interoperate smoothly. The combination of CRNs with emerging technologies like 5G networks, smart grid systems, and IoT presents novel possibilities for innovative applications and services that include a wide range of sectors including healthcare, transportation, and smart cities [62].
- **Spectrum Policy and Regulation Reform**: In order to promote more effective and equitable use of spectrum resources, boost competition and innovation in the wireless industry, and handle new issues including congestion and scarcity of spectrum, CRNs support improvements to spectrum restrictions and policy [63]. In order to encourage investment in cognitive radio technology and advance spectrum commons methods for the benefit of the public, advocacy activities concentrate on spectrum sharing frameworks, spectrum licensing models, and regulatory incentives.

To summaries, CRNs enable intelligent spectrum management, efficient spectrum sharing, and dynamic spectrum access, hence transforming wireless communication. Although they have to deal with issues like interference control and dependable spectrum sensing, CRNs provide a lot of potential to improve spectrum flexibility, efficiency, and coexistence with older systems. Researchers and practitioners may fully realize the promise of cognitive radio technologies for next wireless communication systems by tackling these obstacles and turning advantage of the advantages provided by CRNs.

The problems and possibilities associated with CRNs are shown in Fig. 2, which provides a brief synopsis of the big challenges and possible trends for the area. In the meanwhile, Tables 2 and 3 provide a thorough analysis of the number of studies that has already been done in the field by synthesizing the literature review results for opportunities and

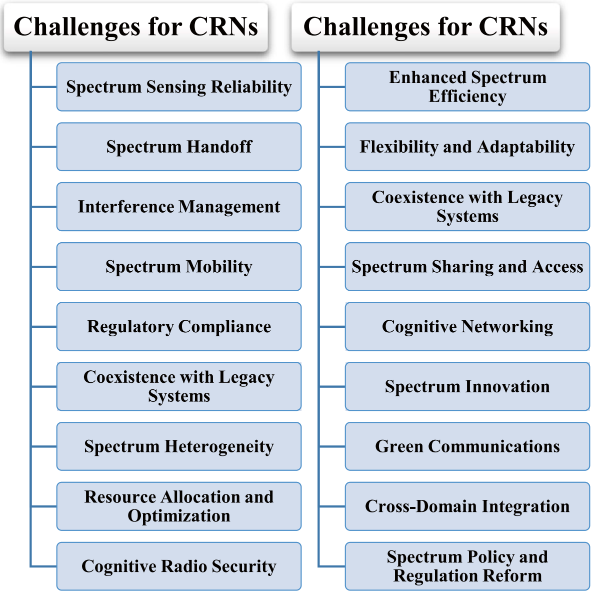

Fig. 2 Challenges and Opportunities of CRNs

Table 2 Literature Review for Challenges and Solutions in Cognitive Radio Networks

Authors	Objective	Limitations	Proposed Solutions
[64]	To identify key challenges in CRNs and propose solutions to address them.	Limited focus on specific spectrum sensing techniques.	Introduce a novel cooperative spectrum sensing algorithm to improve sensing reliability and accuracy.
[65]	To analyze the impact of interference in CRNs and propose interference mitigation strategies.	Lack of real-world experimentation to validate proposed solutions.	Propose a game theory-based approach for interference management and validate through simulation and testbed experiments.
[66]	To investigate the scalability issues in routing protocols for large-scale CRNs.	Lack of consideration for dynamic network topologies and mobility patterns.	Introduce a hierarchical routing architecture and adaptive routing algorithms to improve scalability in large CRNs.
[67]	To address security concerns in CRNs and propose mechanisms to enhance network security.	Limited discussion on practical implementation challenges.	Propose a lightweight authentication and encryption scheme for CRNs and evaluate its performance through simulation and experimentation.
[68]	To explore the challenges related to spectrum handoff in CRNs.	Lack of consideration for multi-hop scenarios.	Introduce a spectrum handoff optimization algorithm based on machine learning.
[69]	To investigate the impact of mobility on routing protocols in CRNs.	Limited analysis of QoS implications.	Propose a mobility-aware routing protocol and evaluate its performance through simulations.
[70]	To analyze the energy efficiency of routing protocols in CRNs.	Limited scope in evaluating heterogeneous networks.	Introduce an energy-aware routing algorithm considering both node and link characteristics.
[71]	To address the challenges of spectrum sharing in CRNs.	Lack of discussion on regulatory considerations.	Propose a cooperative spectrum sharing framework and validate through analytical modeling.
[72]	To investigate the impact of channel fading on routing performance in CRNs.	Limited discussion on dynamic channel conditions.	Propose a routing protocol resilient to channel fading using reinforcement learning techniques.

Table 3 Literature Review for Opportunities and Solutions in CRNs

Authors	Objective	Limitations	Proposed Solutions
[73]	To explore the potential opportunities of dynamic spectrum access in CRNs.	Limited discussion on practical implementation challenges.	Propose a framework for efficient spectrum sharing and dynamic spectrum access protocols.
[74]	To investigate the role of machine learning in enhancing CRN performance.	Lack of analysis on scalability in large-scale networks.	Propose a novel machine learning-based spectrum sensing approach and evaluate its performance.
[75]	To analyze the opportunities for enhancing security in CRNs.	Limited consideration for cross-layer security solutions.	Propose a comprehensive security framework integrating encryption, authentication, and intrusion detection mechanisms.
[76]	To explore the potential of bio-inspired techniques in CRN optimization.	Lack of empirical validation of proposed bio-inspired algorithms.	Propose a bio-inspired routing algorithm inspired by ant colony optimization and evaluate through simulations.
[77]	To investigate the benefits of cooperative communication in CRNs.	Limited discussion on overhead associated with cooperative strategies.	Propose a cooperative routing protocol and evaluate its performance through analytical modeling and simulations.
[78]	To explore the potential of cognitive decision-making in CRNs.	Lack of discussion on real-world implementation challenges.	Propose a cognitive routing protocol based on decision-making algorithms and validate through simulations.
[79]	To investigate the role of game theory in optimizing spectrum allocation in CRNs.	Limited analysis of the impact of heterogeneous user behavior.	Propose a game theory-based spectrum allocation framework and evaluate its performance through theoretical analysis.
[80]	To explore the opportunities for energy harvesting in CRNs.	Limited consideration for practical energy harvesting techniques.	Propose an energy harvesting-based routing protocol and evaluate its feasibility through simulations and testbed experiments.
[76]	To analyze the potential of cross-layer optimization in CRNs.	Lack of discussion on the trade-offs between cross-layer optimization and protocol complexity.	Propose a cross-layer optimization framework integrating routing, MAC, and physical layer parameters.
[81]	To investigate the benefits of mobility-aware routing in CRNs.	Limited analysis of mobility patterns and their impact on routing performance.	Propose a mobility-aware routing algorithm considering both node mobility and channel conditions, and validate through simulations.

solutions and obstacles in CRNs, respectively. Each author provides an overview of the study's objective, potential drawbacks, and proposed solutions to maximize advantage of the opportunities which have been recognized. Furthermore, Table 4 provides an overview of the possible benefits and technical developments that may be used to CRNs, providing information on the field's future possibilities and developments. When combined, these visuals and tables provide insightful information on the state of CRNs, pointing out both the challenges and opportunities for advancement and innovation in the field.

2.3 Key components

The essential components of CRNs comprise:

1) **Dynamic Spectrum Access (DSA)**: Dynamic spectrum access pertains to the capacity of cognitive radios to autonomously and dynamically select suitable frequency bands for transmission in accordance with the real-time availability of spectrum [82]. DSA facilitates the opportunistic access of cognitive radios to unoccupied or underutilised spectrum bands, thus maximising the usage of the spectrum and enhancing the overall efficiency of the network.
2) **Intelligent Decision-Making**: Cognitive radios adapt their behaviour to enhance performance while avoiding interference with primary users [83]. These radios make decisions based on information sensed. Intelligent decision-making includes the manipulation of spectrum data, assessment of environmental circumstances, and dynamic adaptation of transmission parameters in order to optimise spectrum utilisation.
3) **Network Infrastructure**: The network infrastructure comprises elements like as access points, base stations, and other network components that provide data interchange and enable communication among cognitive radios [84]. This infrastructure facilitates communication between cognitive radios and other network elements in an efficient way, providing as the backbone of the CRNs.
4) **Spectrum Mobility Management**: By enabling smooth transitions and handovers across various frequency bands, spectrum mobility management ensures uninterrupted connectivity for cognitive radios as they transverse various radio environments [85]. Allocation and reconfiguration of frequency resources in a dynamic method contribute to performance optimization and continuous connectivity.
5) **Cognitive Network Management**: The cognitive network management system is responsible for supervising the CRNs' overall effectiveness. The system incorporates various functionalities, including resource allocation, network monitoring, and policy enforcement, in order to guarantee optimum performance and compliance with regulatory limitations [86]. Effective cognitive network management is critical for preserving the efficiency and integrity of the entire network.
6) **Regulatory Compliance**: Spectrum utilisation is regulated by regulatory regulations and practices that CRNs must adhere too. By utilising compliance mechanisms such as spectrum etiquette protocols and geolocation databases, cognitive radios are able to function in compliance with regulatory frameworks and prevent any disruption to licenced users. Regulatory compliance ensures that the CRNs function legally and ethically [87].
7) **Cognitive Radio Testbeds**: The validation of cognitive radio principles in real-world scenarios needs experimental platforms and testbeds as essential components. Before adopting CRNs, these systems act as testbeds for industry and scholars to assess their

Table 4 Potential Benefits and Technological Advancements in CRNs

Opportunities	Potential Benefits	Technological Advancements
Advancements in Machine Learning	Improved spectrum sensing accuracy, optimized decision-making, and adaptability to dynamic conditions.	Machine learning algorithms, pattern recognition, and historical data analysis.
Signal Processing Innovations	Enhanced reliability in spectrum sensing, better extraction of meaningful information from the radio frequency spectrum.	Cooperative sensing, advanced signal processing algorithms, noise management.
Protocol Design for Enhanced Adaptability	More efficient spectrum utilization, improved overall network performance.	Adaptive modulation schemes, machine learning feedback, spectrum prediction models.
Dynamic Spectrum Access (DSA) Enhancements	More efficient and reliable spectrum access, improved coordination among cognitive radios.	Innovations in spectrum databases, geolocation databases, spectrum sharing policies.
Cooperative Strategies for Spectrum Sharing	Improved decision-making processes, enhanced spectrum sharing among cognitive radios and with primary users.	Cooperative spectrum sensing, sharing protocols, collaboration among neighboring radios.
Regulatory Frameworks and Standards	Fair and equitable spectrum usage, guidelines for the deployment of CRNs.	Robust regulatory frameworks, collaboration among industry stakeholders, standards.
Cognitive Radio Security and Privacy	Enhanced security against unauthorized access, increased trust in the operation of CRNs.	Novel security mechanisms, authentication, encryption, secure spectrum sensing.
Energy-Efficient Cognitive Radio Designs	Sustainable operation, reduced environmental impact, extended operational lifetime in resource-constrained scenarios.	Low-power hardware, energy-aware algorithms, sleep-wake cycling strategies.

performance and sustainability [88]. Algorithms, protocols, and the entire structure of a system are improved by testing in realistic environments.

8) **User Interfaces and Human-in-the-Loop Interaction**: The increasing complexity of CRNs requires the growing relevance of user interfaces in enabling human-in-the-loop interaction [89]. These interfaces enable the development of preferences, transmission of feedback, and formulation of high-level decisions by users or network administrators, hence encouraging a collaborative culture between humans and cognitive systems. CRNs' efficiency and user adoption are enhanced by their user interfaces.

The components mentioned in Table 5 are the fundamental aspects of CRNs, enabling them to operate with intelligence and adaptability in wireless surroundings that are dynamic and heterogeneous. The cognitive engine is especially responsible for coordinating the decision-making processes that allow cognitive radios to achieve performance optimization via the use of real-time environmental information.

3 Routing in Cognitive Radio Networks

In CRNs, routing is essential for enabling dependable and effective communication since it decides the routes that data packets travel to go from source to destination nodes. CRNs function in dynamic and diverse spectrum environments, in contrast to traditional wired or wireless networks, where spectrum availability, channel conditions, and network topology may change unexpectedly [90, 91]. Therefore, adaptive mechanisms that can adjust to these changing circumstances and maximize spectrum use are needed for routing in CRNs. These mechanisms also need to guarantee minimum disturbance to primary users and dependable communication for secondary users. A comprehensive review of the literature on routing in CRNs is shown in Table 6, along with the objectives, limitations, and solutions proposed by different WSNs authors.

3.1 Importance of routing intelligence

In CRNs, routing intelligence is important because it allows nodes to make decisions in changing spectrum environments, resulting in efficient and dependable communication.

Table 5 Key Components of CRNs

Component	Network Reliability	Security Features	Interoperability	Scalability
Dynamic Spectrum Access (DSA)	✓	✓	✓	✓
Intelligent Decision-Making	✓	✓	✓	✓
Network Infrastructure	✓	✗	✗	✗
Spectrum Mobility Management	✓	✓	✓	✓
Cognitive Network Management	✓	✓	✓	✓
Regulatory Compliance	✓	✓	✓	✓
Cognitive Radio Testbeds	✓	✗	✗	✗
User Interfaces and Human-in-the-Loop Interaction	✓	✓	✓	✓

Table 6 Literature Review of Routing in Cognitive Radio Networks

Authors	Objective	Limitations	Proposed Solutions
[92]	Create a routing mechanism that considers spectrum use to maximize spectrum usage in CRNs.	Underutilization results from previous techniques' limited spectrum awareness.	Create a cognitive routing system that selects a dynamic route based on spectrum sensing.
[93]	Traffic should be prioritized according to the needs of individual applications to improve QoS support.	As traditional protocols don't provide QoS, a variety of applications have performance problems.	Develop a routing protocol that considers the needs of the application for enhanced network performance.
[94]	Use secure routing protocol for CRNs to allay privacy and security worries.	Traditional protocol flaws leave networks open to security risks and privacy violations.	Incorporate safe routing methods, authentication, and encryption into your suggested secure routing protocol.
[95]	Utilize an energy-efficient routing protocol to increase CRN energy efficiency.	Conventional procedures result in wasteful energy use and shorter battery life for devices.	Provide a routing system that plans sleep modes, optimizes paths, and reduces transmission distances.
[96]	Fault tolerance and distributed routing techniques may improve scalability and resilience.	Traditional protocols have limited durability and scalability, which limits network adaptation.	Provide a routing protocol with distributed algorithms, dynamic resource allocation, and fault tolerance.
[97]	In CRNs, promote cooperative communication by using cooperative routing protocol.	Conventional protocols hinder collaborative communication, which lowers network performance as a whole.	To promote node collaboration for higher throughput and reliability, provide a cooperative routing protocol.
[98]	Interference-aware routing in CRNs may reduce interference effects and improve spectral efficiency.	In classical protocols, network performance is deteriorated by interference from main and secondary users.	Provide a routing system that selects the optimum path and boosts spectral efficiency by accounting for interference limitations.
[99]	Use a mobility-aware routing protocol to address mobility issues in CRNs and provide smooth connection and handoffs.	Traditional protocols have interruptions and connection problems due to node mobility in CRNs.	To guarantee a seamless connection and increased efficiency, provide a routing system that is aware of node mobility and modifies handoff sequences and routing paths appropriately.
[100]	When using a game theory-based routing system in CRNs, you can guarantee equitable and effective spectrum sharing.	Static allocation techniques in old protocols lead to a lack of efficiency and fairness in spectrum sharing.	To guarantee fair and efficient use of the spectrum, propose a game theory-based routing system that considers both the availability of spectrum and the utility functions of users.
[101]	Use a traffic-aware routing protocol that takes traffic patterns into account to maximize routing pathways and reduce delays in CRNs.	Static routing choices in traditional routing systems might result in less-than-ideal pathways and delays.	Create a traffic-aware routing protocol to reduce latency and improve overall performance by dynamically modifying routing channels in response to traffic patterns.

The following important factors demonstrate how important routing intelligence is in CRNs:

- **Spectrum-Aware Routing**: Nodes in CRNs can generate well-informed decisions depending on the quality and availability of the spectrum due to routing intelligence. When determining transmission channels, spectrum-aware routing systems take into account the amount of spectrum occupancy and interference [102]. This reduces disturbance to primary users and optimizes throughput for secondary users.
- **Dynamic Adaptation**: Routing methods for CRNs must be able to dynamically adapt to shifting network circumstances, including variations in the amount of spectrum resources, node mobility, and interference [103]. Nodes with intelligent routing mechanisms may dynamically update transmission variables and reconfigure routing pathways to preserve optimum performance in ever-changing environments.
- **QoS Support**: In CRNs, as numerous applications may have differing requirements in terms of latency, dependability, and throughput, routing intelligence plays an important role in providing QoS guarantees [104]. Using QoS parameters to prioritized traffic, intelligent routing algorithms select pathways that optimize spectrum use while fulfilling the needs of the application.
- **Interference Mitigation**: Reducing interference to primary users and nearby secondary users is one way that efficient routing intelligence reduces interference in CRNs [105]. Intelligent routing protocols may improve the overall performance and reliability of CRNs by taking interference limits into account while selecting a path.
- **Energy Efficiency**: By optimizing the routing pathways and transmission parameters to reduce energy consumption, routing intelligence may make a substantial contribution to energy efficiency in CRNs. In order to save energy and preserve communication reliability, intelligent routing protocols may choose pathways with reduced energy consumption, improve transmission power levels, and take into consideration the energy restrictions of nodes [106, 107]. CRNs may improve network sustainability, lower total energy consumption, and increase the battery life of mobile devices by taking energy-efficient routing algorithms into consideration.
- **Scalability and Resilience**: In large-scale networks with a high degree of node mobility and dynamic topology changes, routing intelligence plays an important role in ensuring the scalability and robustness of CRNs. By facilitating effective route maintenance, discovery, and adaptation, intelligent routing methods enable CRNs to grow to support a high number of nodes and efficiently respond to network dynamics. By the use of fault tolerance techniques, dynamic resource allocation methods, and distributed routing algorithms, CRNs may improve scalability and resilience to network failures, congestion, and disturbances [108, 109].
- **Cross-Layer Optimization**: By combining routing decisions with other layers of the protocol stack, especially as the physical layer, application layer, and medium access control (MAC), routing intelligence allows cross-layer optimization in CRNs. Intelligent routing protocols may increase resource utilization, improve end-to-end communication quality, and optimize overall network performance by taking into account interactions and dependencies across various protocol levels. With cross-layer optimization, CRNs may perform conventional layered techniques by using all of synergies across various protocol stack layers [110].
- **Spectrum Mobility Management**: By enabling smooth handover and transition between multiple spectrum bands as users move within the network, routing data enables with spectrum mobility management in CRNs. Depending on the availability of

spectrum resources and user mobility patterns, intelligent routing protocols may modify routing pathways and spectrum distribution. CRNs may guarantee continuous communication and sustain connection while users move between multiple frequency bands and network settings by organizing spectrum handoff processes and optimizing spectrum allocation [111].

- **Security and Privacy**: By integrating secure routing methods, authentication, and encryption techniques into routing protocols, routing intelligence plays an important role in resolving security and privacy problems in CRNs. To protect against malicious attacks, unauthorized access, and information leakage, intelligent routing protocols may encrypt routing messages, impose access control regulations, and authenticate communication partners [112]. CRNs may improve network security, protect user privacy, and reduce security concerns associated with cognitive radio technology by including security and privacy elements into routing decisions.

Intelligent routing in CRNs in Table 7 is more essential than only path selection. QoS optimization, resource usage, regulatory compliance, flexibility, security resilience, cooperation, efficiency, and capabilities are just a few of the characteristics that are explored with each component. It has a variety of functions that provide flexibility, effectiveness, and security. Intelligent routing will be essential to solving the complex problems and achieving the maximum capabilities of dynamic and opportunistic spectrum access as CRNs improve more.

3.2 Traditional routing protocols vs. cognitive routing

Due to their lack of spectrum awareness and ability to adapt to dynamic spectrum conditions, traditional routing protocols like distance-vector and link-state routing are not well suited for CRNs. In contrast to these traditional protocols, CRNs' cognitive routing protocols utilize spectrum awareness and cognitive ability to make intelligent routing decisions. Cognitive routing systems dynamically adjust routing pathways depending on real-time spectrum circumstances, maximizing performance and reliability by considering variables including spectrum availability, utilization, and interference levels [113, 114]. These protocols provide major benefits over conventional routing protocols in CRNs by ensuring effective spectrum usage, mitigating interference, and prioritizing traffic based on QoS parameters.

3.3 Requirements and challenges in routing for CRNs

The main difficulties and problems with CRNs are briefly described in Fig. 3. In order to facilitate a rapid grasp of the major challenges such spectrum scarcity, interference management, security issues, and dynamic spectrum access, it offers a succinct visual representation of the challenges encountered in CRNs. To achieve consistent and dependable communication, CRNs must overcome developmental issues and routing issues in comparison to the regular before mentioned:

- **Spectrum Mobility Management**: Routing systems that can efficiently manage spectrum mobility as users move across the network are essential for CRNs. In order to preserve connection and maximize spectrum utilization, this involves an involved in the control and transition across various frequency bands. In order to assure continuous

Table 7 Routing Intelligence in Cognitive Radio Networks

Aspect	Adaptability	Security Resilience	Collaboration	Efficiency	Learning Capability	QoS Optimization	Resource Utilization	Regulation Compliance
Spectrum-Aware Routing	✓	✓	✗	✗	✗	✓	✓	✗
Dynamic Adaptation	✓	✓	✗	✗	✗	✗	✓	✗
QoS Support	✓	✓	✗	✗	✗	✓	✗	✗
Interference Mitigation	✓	✓	✗	✗	✗	✗	✓	✗
Energy Efficiency	✓	✓	✗	✓	✗	✗	✓	✗
Scalability and Resilience	✓	✓	✗	✗	✗	✗	✓	✗
Cross-Layer Optimization	✓	✓	✗	✗	✗	✗	✓	✗
Spectrum Mobility Management	✓	✗	✗	✗	✗	✗	✓	✗
Security and Privacy	✗	✓	✗	✗	✗	✗	✗	✓

Fig. 3 Challenges and Issues in CRNs

communication when users move between various spectrum bands and network environments, routing protocols need to adaptively distribute spectrum resources to manage spectrum handoff procedures [115, 116].

- **Energy Efficiency**: In CRNs, routing protocols are essential for maximizing energy efficiency and extending the battery life of mobile devices. Energy-efficient routing techniques, such trying to reduce on transmission distances, finding the best routing pathways, and setting up sleep modes for inactive nodes, should be used by these protocols. Routing protocols have the potential to improve the sustainability and endurance of CRNs by lowering energy consumption and preserving battery power, especially in situations with limited resources [117].
- **Spectrum Awareness**: In CRNs, routing protocols need to be spectrum-aware, able to detect and adapt dynamically to variations in the quality and availability of the spectrum. Nodes may choose routes that reduce interference to primary users and maximize spectrum use for secondary users by using spectrum-aware routing [118].
- **Dynamic Adaptation**: For CRNs, routing protocols need to be able to adjust dynamically to variations in spectrum conditions, traffic patterns, and network architecture. This requires for sophisticated route identification, maintenance, and optimization systems that can adapt quickly to environmental changes [119].
- **Interference Mitigation**: Interference from neighboring secondary users and primary users is a problem for CRNs. In the presence of spectrum-sharing restrictions, routing protocols must include interference mitigation strategies to reduce interference and ensure dependable communication [120].
- **QoS Support**: In CRNs, routing protocols have to provide QoS requirements for various services and applications. This involves routing traffic in a priority approach, ensuring that latency and reliability standards are maintained, and allocating resources optimally to meet application-specific QoS criteria [121].

- **Security and Privacy**: Secure routing protocols, such as encryption, authentication, and secure routing methods, are essential components of CRN routing protocols that protect against malicious attacks and unauthorized access to network resources [122].

Intelligent routing protocols have the ability to improve communication performance, reliability, and efficiency in CRNs by tackling these objectives and obstacles. This may let future wireless networks realize the full benefits of dynamic spectrum access.

4 Classification of routing techniques

Routing strategies play a significant role in CRNs since they provide efficient and reliable communication through the process of directing data packets across the network [123, 124]. The above routing techniques may be classified into different categories based on the underlying ideas and methodology that control them. Descriptions of each classification include the following:

4.1 Spectrum-aware routing

Spectrum-aware routing is an essential component of CRNs that ensures dependable communication while maximizing spectrum consumption [125]. These methodologies depend on the capacity of cognitive radios to detect the surrounding spectrum and modify their routing decisions accordingly. Detailed expansion follows:

1) **Dynamic Spectrum Availability**: Spectrum-aware routing algorithms accept that spectrum capacity in CRNs is dynamic. In contrast to conventional networks that distribute spectrum bands statically, CRNs provide opportunistic access to bands of spectrum that are not in use by primary users [126]. In order to detect accessible spectrum bands, also as white spaces, routing protocols must continuously monitor the spectrum environment due to its geographical and historical volatility of spectrum availability.
2) **Interference Minimization**: Maximizing spectrum utilisation for secondary users while minimising interference to primary users is one of the principal goals of spectrum-aware routing. Dynamic route adjustments are implemented by these routing methods in order to prevent interference to primary users and avoid occupied frequencies, factoring interference levels and spectrum occupancy [127]. This promotes spectrum coexistence by ensuring that secondary users operate within regulatory constraints and do not cause adverse interference to authorized users.
3) **Spectrum Sensing and Adaptation**: Spectrum-aware routing protocols use spectrum sensing functionalities in order to identify accessible spectrum bands and analyse their suitability for the transmission of data. Cognitive radios use cooperative sensing, energy detection, and cyclostationary feature detection to regularly review the spectrum area [128]. Routing choices are determined using sensed spectrum details in order to select paths that pass across vacant or overused spectrum bands, hence improving the efficiency of spectrum utilisation.
4) **Dynamic Path Adjustment**: Spectrum conditions in CRNs are susceptible to significant variation due to environmental factors, fluctuating user activity, and the movement of nodes. In order to accommodate these fluctuations, spectrum-aware routing protocols dynamically update routing pathways in response to actual spectrum conditions [129].

In the occurrence that a previously accessible spectrum band becomes occupied or encounters increased interference, the routing protocol proceeds to reroute traffic via alternative routes that acquire more available spectrum. The above existing network consistent communication and maximises the utilisation of the spectrum.

5) **Efficient Spectrum Utilization**: The objective of spectrum-aware routing algorithms is to maximise the usage of available spectrum resources via intelligent deployment. These methods improve the efficiency and dependability of communication for secondary users while reducing the disturbance to primary users by choosing routing pathways that pass-through interference-free or hardly congested spectrum bands [130]. By optimising the consumption of spectrum, CRNs are able to increase their overall capacity and performance, hence facilitating the support of a greater quantity of users and applications.

In CRNs, dynamic spectrum access and effective spectrum utilization are made possible in significant part by spectrum-aware routing. The full potential of CRNs in addressing the issues of spectrum scarcity and inefficiency in wireless networks is actually realized by taking into consideration spectrum availability, reducing interference, and dynamically adapting routing paths [131]. These techniques ensure reliable communication while maximizing the utilization of available spectrum resources.

4.2 Cognitive decision-making in routing

In CRNs, where nodes with cognitive capabilities method was designed routing decisions, cognitive decision-making in routing constitutes a paradigm shift [132, 133]. A comprehensive description of cognitive decision-making in routing is described below:

1) **Integration of Cognitive Capabilities**: Cognitive abilities such as learning, reasoning, and adaptability are integrated into the routing process utilizing cognitive decision-making techniques. Nodes in CRNs may analyze complex data, gain insights, and to choose optimal routing pathways by simulating human-like cognitive processes [134]. Nodes can anticipate network behaviour, adapt to changing environmental conditions, and dynamically optimize routing strategies due to their cognitive abilities.
2) **Autonomous Routing Decisions**: Nodes that collaborate in cognitive decision-making are allowed to use their own routes depending on their capacity for cognitive processing. Nodes use cognitive algorithms and decision-making frameworks to analyze the spectrum environment, forecast network conditions, select routing pathways rather than depending on centralized control or predetermined routing Table [135]. Because of their autonomy, nodes are able to adjust their routing pathways in real time to the changing conditions of the network.
3) **Analysis of Spectrum Data**: In order to make intelligent routing decisions, cognitive routing protocols utilize spectrum data that is obtained by spectrum sensing techniques. Nodes are always the spectrum for available bands, identify if they are essential for data transmission, and monitor the spectrum environment [136]. Nodes may ensure effective spectrum utilization and reliable communication by analyzing spectrum data to identify the best routing paths that move between spectrum bands with the minimal possible of interference and maximum throughput.
4) **Prediction of Network Behavior**: Nodes can forecast network activity utilizing cognitive decision-making techniques by using past data, noticed trends, and outside inputs. Nodes are able to proactively adjust routing patterns in order to prevent congestion,

reduce interference, and maximize resource efficiency by learning from previous experiences and projecting future occurrences [137]. Predictive routing techniques improve CRNs' flexibility and reactivity, allowing them to continue high-performance communication in turbulent and uncertain circumstances.

5) **Dynamic Optimization of Routing Paths**: Using observations and future predictions in real time, cognitive routing systems dynamically optimize routing paths. Nodes monitor changes in network circumstances, continuously assess how well the routing pathways are performing, and make necessary adjustments to the routing decisions [138]. Nodes can react in spectrum availability, traffic patterns, and interference levels by dynamically adjusting their routing pathways, which ensures effective and reliable communication in CRNs.

Therefore, by enabling nodes to create strategic, adaptive, and autonomous routing decisions, cognitive decision-making techniques revolutionize routing in CRNs. These strategies unlock the full potential of CRNs for future wireless networks by incorporating cognitive capabilities into the routing process, improving communication's flexibility, efficiency, and reliability.

4.3 Game theory-based routing

Game theory-based routing is an advanced approach in CRNs whereby routing choices are made by taking into account the strategic interactions between network nodes [139, 140]. Through the use of game theory ideas, Fig. 4 shows how network nodes strategically cooperate to maximize routing techniques. This representation shows how game theory-based routing protocols operate in CRNs and how they may guide strategic

Fig. 4 Game Theory-Based Routing of CRNs

choices to enhance network efficiency and performance. Below is a detailed explanation of game theory-based routing:

1) **Non-cooperative Games**: Cognitive radios compete for availability to the spectrum resources in non-cooperative games, acting independently from each other. Individual utilities are improved by routing decisions which consider interference, signal quality, and data rate into consideration. A decentralised strategy is shown in the way each radio operates in its own self-interest without directly communicating with others [141]. In circumstances where radios have conflicting objectives and must operate independently to improve spectrum utilisation, non-cooperative games are effective.
2) **Modeling Strategic Interactions**: Routing techniques based on game theory approach network nodes as rational individuals who deliberately select their routing strategies in order to maximize their utility. These methods simulate node-to-node interactions as games in which node-to-node strategic routing route selection is dependent on node capabilities, objectives, and predicted node behaviour [142]. Game theory-based routing protocols strive to optimize throughput, reduce latency, or minimize interference by improving routing techniques by considering the strategic behaviour of nodes.
3) **Formulation of Routing Games**: Game theory-based routing formulates routing decisions as games in which nodes represent players and routing pathways indicate strategies. Nodes consider their preferences, resource availability, and the expected outcomes of other nodes while choosing their routing pathways. Depending on the degree of coordination and rivalry among nodes, routing games may feature a variety of game types, including non-cooperative, cooperative, and mixed-strategy games [143]. These strategies allow nodes to make strategic routing decisions that maximize their utility while taking other nodes' behaviour into account by structuring routing decisions as games.
4) **Cooperative Games**: Cognitive radios collaborate with each other in cooperative game theory to improve network performance as a whole. Radios communicate to decide on combined routing that is advantageous to the whole group and communicate information. When cooperation may result in improved efficiency, reduced interference, and better spectrum utilisation, cooperative games are advantageous [144]. By enabling radios to work together to accomplish shared objectives, this approach promotes a more peaceful and efficient network environment.
5) **Stackelberg Games**: Stackelberg games simulate interactions between superiors and subordinates in CRNs. Followers' routing decisions are influenced by a leader, who is also represented as a primary user or an authority. The supporters follow the leader's strategic routing decisions, as chosen by the leader [145]. A balance between decentralised decision-making and centralised control is facilitated by this hierarchical structure. Stackelberg games are suitable for situations when a leading entity is needed to impact cognitive radio behaviour and ensure that it matches with larger network objectives.
6) **Optimization of Routing Strategies**: Routing protocols that are based on game theory aim to maximize routing techniques in order to accomplish ultimate objectives while taking into account nodes' strategic interactions. Nodes carefully consider variables including network structure, interference levels, and spectrum availability while choosing routing pathways that optimize their utility function. Stackelberg equilibrium, evolutionary game theory, and Nash equilibrium are types of game theory-based optimization methods that are used to develop stable routing systems in which no node has an incentive to unilaterally diverge from its chosen path [146].

7) **Adaptation to Dynamic Environments**: Routing strategies based on game theory perform well in the dynamic and unpredictable conditions shown in CRNs. Nodes regularly modify their routing strategies in response to changes in user behaviour, spectrum availability, and network conditions. Game theory-based routing algorithms ensure resilient and efficient communication in CRNs even in the presence of adversarial behaviours and uncertainty by dynamically modifying routing strategies based on game theory provide reliable and effective solutions by considering the strategic relationships between nodes [147, 148]. With the use of these strategies, nodes can maximize their utility via logical routing decisions that preserve the stability and equity of the whole network. Game theory-based routing methods improve the overall effectiveness, consistency, and fairness of communication in CRNs, which improves wireless network performance by making a distinction between node cooperation and competition.

In conclusion, game theory-based routing methods provide an effective foundation for maximizing routing strategies in CRNs by considering nodes' strategic interactions with each other. The aforementioned techniques facilitate the development of efficient, resilient, and adaptable routing protocols that optimize network node utility and guarantee dependable communication in fluctuating and unpredictable settings. Routing decisions are formulated as games, and routing strategies are refined accordingly.

4.4 Machine learning approaches

CRNs depend heavily on machine learning techniques for routing, which enable nodes to make intelligent and flexible routing decisions based on data-driven insights [149, 150]. The use of machine learning algorithms to analyses network data and draw lessons from the past is shown in Fig. 5 as an optimization of routing choices. The potential of machine learning techniques in CRNs to adaptively optimize routing patterns, improve network efficiency, and make intelligent decisions in response to dynamic spectrum circumstances is summed up in this image. The machine learning techniques used in CRN routing are elaborated upon in depth below:

1) **Supervised Learning**: Training routing algorithms using labelled datasets—where the optimal routes are predetermined analysis of historical supervised learning. By extrapolating from this training set, the routing algorithm obtains the ability to forecast the best routes in novel situations. When historical data is available, supervised learning may be utilised to inform routing choices and is successful [151]. It is appropriate for situations with well stated routing goals and historical trends since it provides an organised method for learning optimum routing pathways.
2) **Learning from Data**: In order to identify patterns and trends in the network environment, machine learning techniques in CRN routing make use of feedback mechanisms, historical data, and network observations. Through the analysis of historical routing decisions, network performance indicators, and contextual factors, machine learning algorithms extract significant knowledge that can inform future routing decisions [152]. These algorithms enable nodes to make reasonable decisions based on acquired knowledge by learning to spot patterns in the data and develop correlations between various routing parameters.
3) **Prediction of Network Behavior**: CRN routing machine learning techniques use observed patterns and previous data to forecast network performance and behaviour.

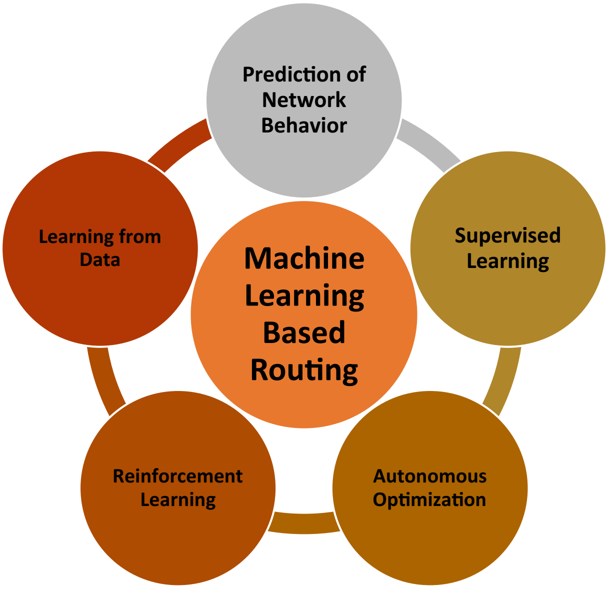

Fig. 5 Machine Learning-Based Routing of CRNs

These algorithms assess network circumstances in the future, foresee possible interference or congestion, and proactively adjust routing choices to minimize any problems and determine past trends and patterns [153]. By allowing nodes to optimize routing pathways in ahead, predictive routing algorithms improve network performance and efficiency as well as the basic communication dependability of CRNs.

4) **Autonomous Optimization**: Routing protocols that are based on machine learning allow routing variables and strategies to be automatically optimized based on observed data and recently acquired knowledge. To optimize network performance and efficiency, these protocols automatically modify routing parameters such route selection, transmission power, and spectrum allocation [154]. Machine learning-based routing protocols may optimize routing patterns in real-time, adapt to changing network conditions, and enhance overall network performance without the need for human intervention since they are constantly learning from observations and responses from the network.
5) **Reinforcement Learning**: Cognitive radio agents use trial-and-error interactions with their surroundings to select the optimal routing strategies via reinforcement learning. Based on the success or failure of their routing decisions, agents get feedback in the form of incentives or penalties [155]. As time passes, the agents modify their routing plans to bring network conditions and accessible spectrum into consideration. Reinforcement learning allows cognitive radios to modify their routing behaviour according to their own to accomplish long-term objectives, which considers them suitable for dynamic and unstable network configuration.

To sum up, by utilizing data-driven insights, predictive abilities, and autonomous optimization, machine learning techniques provide a powerful tool for routing decision optimization in CRNs. These methods improve network performance, efficiency, and reliability in dynamic and unpredictable CRN situations by allowing nodes to adjust to changing network conditions, forecast network information, and optimize routing techniques in real-time.

4.5 Hybrid routing techniques

Hybrid routing approaches are an adaptable and multifaceted method for routing in CRNs [156, 157]. They achieve this by integrating several routing algorithms in order to enhance performance and flexibility. In order to maximize routing choices and improve network performance, Fig. 6 illustrates the integration of many routing methodologies, including machine learning techniques, game theory-based routing, cognitive decision-making, and spectrum-aware routing. Figure 6 highlights the adaptability of hybrid routing strategies in CRNs, demonstrating their capacity to successfully handle a variety of network issues and needs by using the advantages of many routing paradigms. The following is a comprehensive analysis of hybrid routing techniques:

1) **Integration of Multiple Approaches**: Hybrid routing techniques combine a variety of routing methodologies into a place effective, including spectrum-aware routing, cognitive decision-making, game theory-based routing, and machine learning. Hybrid routing protocols maximize on the benefits of different methodologies by integrating various routing mechanisms and algorithms, while minimizing the limitations of each [158]. The integration enables the implementation of a dynamic and all-encompassing routing critical aspects of efficiently managing the variable and diverse features of CRNs.
2) **Synergistic Effects**: Hybrid routing strategies strive to attain synergistic outcomes by the use of the combined features provided by various routing methodologies. An example about how spectrum-aware routing could provide important insights into interference

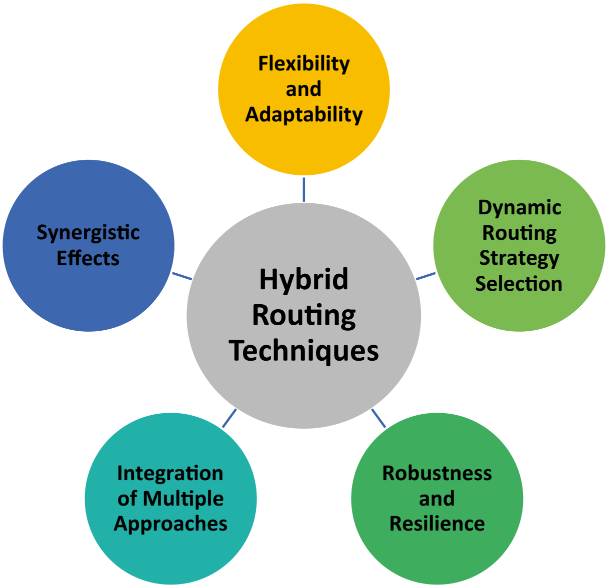

Fig. 6 Hybrid Routing Techniques of CRNs

levels and spectrum availability is via the deployment of cognitive decision-making, that can enhance the flexibility and effectiveness of routing decisions [159]. Hybrid routing protocols have the capability to optimize routing patterns in order to enhance spectrum usage, minimize interference, and provide dependable communication in CRNs thru combination of these methodologies.

3) **Dynamic Routing Strategy Selection**: Hybrid routing protocols possess the capability to transfer dynamically between various routing algorithms in response to application priorities, network conditions, and user demands. For example, when exposed to severe levels of interference, the protocol may provide priority to routing techniques based on game theory in order to reduce interference and improve throughput. On the other, in conditions where spectrum availability is dynamic, the protocol can emphasize spectrum-aware routing, which involves modifying route topologies in keeping with spectrum quality and availability [160]. The capacity of hybrid routing protocols to dynamically adapt routing methods enables them to effectively respond to evolving network conditions and continuously enhance performance.
4) **Flexibility and Adaptability**: Hybrid routing methods have the capacity to adjust and handle a wide range of CRN situations and requirements. These methods have the ability to modify routing strategies in accordance with particular network circumstances, user preferences, and application requirements by integrating several routing algorithms [161]. Moreover, hybrid routing protocols have the capacity to progress by integrating new methodologies or modifying parameters in response to developing technologies and scientific developments. This ensures that continuous optimization and performance improvement in CRNs are achieved.
5) **Robustness and Resilience**: Hybrid routing protocols enhance the resilience and robustness of CRNs via the use of fallback and redundancy methods. When one routing technique has errors or inadequate performance, the protocol represents the ability to effortlessly shift to different approaches in order to preserve connectivity and dependability [162]. The ability of CRNs to endure failures and meet challenges enhances its overall resilience, guaranteeing continuous communication despite the presence of difficult situations.

By merging several routing approaches and maximizing on their unique strengths to enhance performance, flexibility, and resilience, hybrid routing techniques provide a flexible and efficient method for routing in CRNs. Hybrid routing protocols have the capability to improve communication dependability, flexibility, and efficiency over a wide range of CRN circumstances by dynamically selecting routing techniques in accordance with network dynamics and application requirements.

4.6 Bio-inspired routing

Biometric routing solutions have surfaced as inventive strategies to tackle the intrinsic limitations of CRNs, gaining inspiration from the complicated and streamlined processes of biological systems [163, 164]. By using natural concepts, these methods enhance routing decisions, hence boosting the intelligence, flexibility, and overall efficiency of these dynamic wireless communication networks. The discussion of bio-inspired routing in CRNs is covered in Fig. 7.

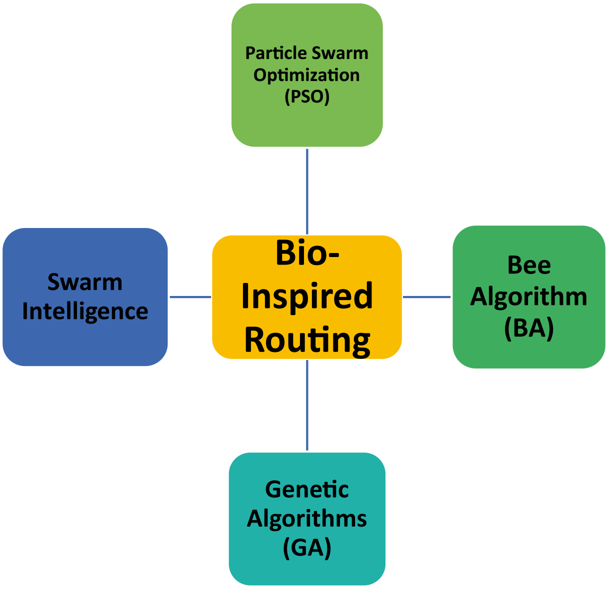

Fig. 7 Bio-Inspired Routing of CRNs

1) **Genetic Algorithms (GA)**: Genetic Algorithms (GA) improve routing solutions in dynamic network conditions by taking inspiration from the concepts of natural selection and evolution. In order to simulate the process of genetic evolution, GA uses “genes” to encode potential routing solutions within a population. Simulate the processes of genetic variation and natural selection by introducing these solutions to selection, crossover, and mutation operations. Within the area of cognitive radio routing, GAs continuously improves routing solutions by adapting them to the dynamic conditions of the network [165, 166]. Similar to the survival of most adaptable in biological evolution, favoured routes are those that demonstrate greater efficiency or adaptability to changes in the spectrum. GA enhances the intelligence of CRNs by enabling the self-adaptation of routing techniques throughout the span of evolution.
2) **Swarm Intelligence**: Swarm Intelligence is inspired by the decentralised and self-organizing features of biological swarms, including those found in fish, birds, and bees. Swarm Intelligence conceptualises a network within the area of CRNs whereby cognitive radios combine to enhance routing decisions by using local interactions. Each cognitive radio functions as an autonomous organization, responding to its immediate surroundings and changing its routing decisions in relation to the data sent among swarm’s components [167, 168]. The use of this decentralised methodology empowers the network to promptly adapt to fluctuations in interference, spectrum conditions, and network topology. Swarm intelligence improves efficiency and flexibility by enabling the network to adapt collectively to proposed change via decentralised decision-making.
3) **Particle Swarm Optimization (PSO)**: Particle Swarm Optimization (PSO) is a methodology that is inspired by the synergistic functions of fish schools and flocks of birds. PSO portrays cognitive radios as particles within a multidimensional search space, where each particle represents a potential routing solution, as applicable to CRNs [169, 170]. As they explore the search space, these particles dynamically modify their positions

in relation to their individual experiences and the swarm's collective knowledge. PSO facilitates the investigation and convergence of cognitive radios to optimum pathways in response to fluctuating spectrum circumstances, with respect to routing choices. PSO is adaptable due to the decentralized framework; as the swarm continuously improves its routing techniques, it automatically adjusts to the changing network condition.

4) **Bee Algorithm (BA)**: A bio-inspired method to routing in CRNs is introduced by Bee Algorithm (BA), which features characters from the foraging behaviour of honeybees. Bees within a honeybee colony communicate information on food sources by complicated synchronized movements. Cognitive radios communicate information on spectrum conditions and routing decisions in CRNs employing BA. The network continuously improves its routing methods by means of various interactions, with a particular emphasis on pathways that lead in more advantageous usage of spectrum [171, 172]. BA enhances the flexibility of CRNs even by enabling of collaboration and communication between radios, empowering them to improve routing decisions collectively.

The integration of these bio-inspired routing strategies into CRNs enhances their intelligence, efficiency, and flexibility in the presence of the different challenges provided by dynamic spectrum access and nuanced network dynamics [173]. By modelling behavioural patterns, these methodologies provide novel approaches to improve routing decisions within environment characterised by uncertainty and unpredictability. In conclusion, PSO, BA, GA, and Swarm Intelligence provide CRNs with a framework inspired by nature, providing them to implement more intelligent and adaptable routing based on natural principles [174, 175]. The current routing systems show potential in optimizing connectivity, effectively managing spectrum resources, and improving the overall performance of CRNs in wireless conditions distinguished by unpredictability and predictability.

Strengthening of reliable and efficient routing solutions for future wireless communication networks, each classification of routing techniques in CRNs has different advantages and addresses different challenges [176]. Practitioners and researchers can uncover the complete potential of dynamic spectrum access for next-generation wireless networks by understanding and investigating these strategies, hence accelerating the state-of-the-art in CRN routing ahead.

5 Performance evaluation of CRNs

Various metrics and criteria are used to evaluate the efficacy and suitability of routing methods in CRNs in order to determine their performance. Commonly used for the evaluation of routing protocols in CRNs are the following evaluation metrics, comparison criteria, and evaluation metrics:

5.1 Evaluation metrics

In order to evaluate the efficacy, efficiency, and performance of routing strategies in CRNs, evaluation metrics are crucial components. These metrics provide researchers and practitioners precise measurements that let them compare various routing protocols in Table 8, identify their advantages and disadvantages, and determine that how adapted these are for individual application scenarios. The assessment results are shown as High, Medium, or Low based on how each technique should perform according to the appropriate metric. When evaluating routing algorithms in the context of CRNs, a variety of evaluation metrics are used. An overview of several important evaluations is provided below:

1) **Throughput**: the amount of data successfully transmitted over the network within a given time frame.
2) **End-to-End Delay**: The time taken for a packet to travel from the source node to the destination node.
3) **Packet Delivery Ratio**: The ratio of successfully delivered packets to the total number of packets transmitted.
4) **Routing overhead**: the amount of control overhead generated by routing protocols for managing routing information.
5) **Network Scalability**: The ability of the routing protocol to maintain performance as the network size increases.
6) **Energy efficiency**: the energy consumption required for routing operations in the network.
7) **Fairness**: the equitable distribution of network resources among different users or flows.

Based on evaluation metrics, Fig. 8 compares the effectiveness of many routing techniques in CRNs. It provides a visual representation of how different routing systems perform in relation to important criteria including security, QoS provisioning, interference reduction, spectrum consumption, and adaptation to changing conditions.

A comprehensive analysis of the various routing techniques used in CRNs is given in Table 8. Also provide an overview of the efficacy and performance of various routing techniques, it also provides information on their drawbacks and suitability for use in CRN contexts. This evaluation will help gain the knowledge about the deployment and use of routing strategies in CRNs by providing information about the relative performance of these approaches.

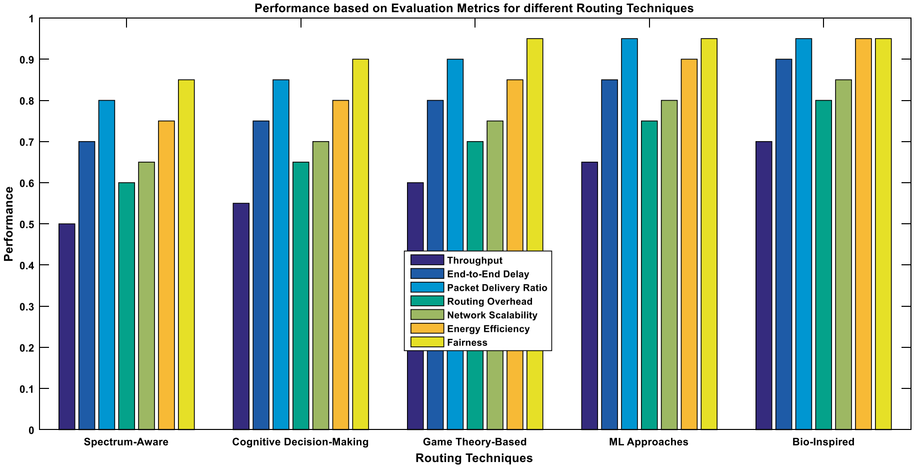

Fig. 8 Performance based on Evaluation Metrics for Different Routing Techniques

Table 8 Evaluation of Routing Techniques in CRNs

Routing Technique	Throughput	End-to-End Delay	Packet Delivery Ratio	Routing Overhead	Network Scalability	Energy Efficiency	Fairness
Spectrum-Aware Routing	High	Low	High	Low	High	Medium	High
Cognitive Decision-Making	High	Low	High	Low	High	Medium	High
Game Theory-Based Routing	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Machine Learning Approaches	High	Low	High	Low	High	Medium	High
Bio-Inspired Routing	Medium	Low	Medium	Medium	Medium	High	Medium

5.2 Performance metrics for routing in CRNs

Based on important performance indicators often used in CRNs in Table 9, each routing method is evaluated. Compared to the expected performance of each approach in the corresponding metric, the assessment values are shown as High, Medium, or Low. These are relative values which could vary depending on some network adapters as well as outside factors.

1) **Spectrum Utilization**: The routing protocol's effectiveness in using spectrum, based on actual variables like spectrum fragmentation and spectrum handoff frequency.
2) **Interference Mitigation**: The routing protocol's capacity to reduce interference for both primary users and neighbouring secondary users.
3) **Adaptability to Dynamic Spectrum Conditions**: The routing protocol's capacity to dynamically modify routing pathways in response to variations in channel conditions and spectrum availability.
4) **QoS Provisioning**: The routing protocol's capacity to satisfy QoS demands for various applications, including throughput, latency, and dependability.
5) **Robustness to Node Failures**: The routing protocol's strength to tolerate node failures and network splits while preserving communication.
6) **Security**: The efficacy of the routing protocol in safeguarding data security and integrity and thwarting assaults like spoofing, jamming, or eavesdropping.

A visual representation of performance metrics for the various routing strategies used in CRNs can be seen in Fig. 9. Sponsors can compare and evaluate the efficacy of each routing strategy thanks to its visualisation of important metrics such as spectrum usage, interference mitigation, adaptability to dynamic spectrum conditions, QoS provisioning, robustness to node failures, and security. This figure helps to choose best routing strategy for CRN deployments by providing a comprehensive knowledge of the performance characteristics of different routing approaches.

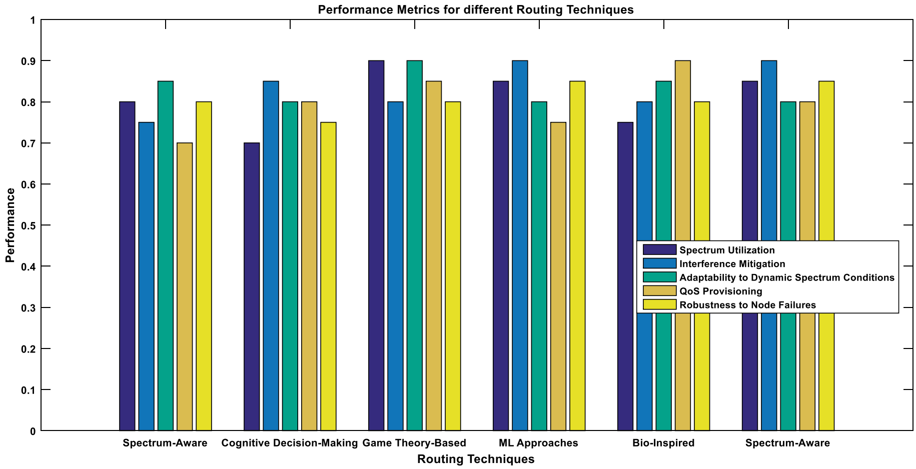

Fig. 9 Performance Metrics for Different Routing Techniques

Table 9 CRN Routing Techniques Evaluation

Routing Technique	Spectrum Utilization	Interference Mitigation	Adaptability to Dynamic Spectrum Conditions	QoS Provisioning	Robustness to Node Failures	Security
Spectrum-Aware Routing	High	High	High	Medium	Medium	Medium
Cognitive Decision-Making	High	High	High	High	High	High
Game Theory-Based Routing	Medium	Medium	Medium	Medium	Medium	Medium
Machine Learning Approaches	High	Medium	High	Medium	Medium	Medium
Bio-Inspired Routing	Medium	Medium	High	Medium	High	Medium

5.3 Comparison criteria

The comparative criteria-based analysis of routing algorithms in CRNs is shown in Table 10. Every routing method is evaluated based on its compatibility, scalability, overhead, complexity, flexibility, and deployment issues. Based on each technique's predicted performance for each condition, the assessment results are shown as High, Medium, or Low. These are relative values that might change based on certain network adapters as well as outside factors.

1) **Scalability**: The routing protocol's capacity to sustain performance as the size of the network or the number of users rises.
2) **Overhead**: the amount of controller traffic that the routing protocol generates in order to transfer routing information and maintain routing tables.
3) **Complexity**: the implementation of the routing protocol's memory and computational requirements.
4) **Flexibility**: the routing protocol's flexibility in accommodating varying network topologies, traffic patterns, and allocate resources.
5) **Compatibility**: the routing protocol's interoperability with the protocols, standards, and network infrastructure already in existence

6) **Deployment Considerations**: practical aspects including routing protocol configuration, maintenance, and deployment efficiency in actual CRN deployments.

The comparative criteria used to analyse different routing strategies in CRNs are shown in Fig. 10. The visual representation of various factors, including scalability, overhead, complexity, flexibility, compatibility, and deployment issues, facilitates the evaluation and comparison of the attributes of different routing approaches by stakeholders. In order to help with decision-making and the selection of the best routing method for CRN deployments, this illustration gives a systematic summary of the major evaluation criteria for routing techniques. Through the use of these metrics and criteria, researchers and practitioners may evaluate routing protocols and understand about their advantages, disadvantages, and appropriateness for different CRN applications

Table 10 CRN Routing Techniques Comparison Matrix

Routing Technique	Scalability	Overhead	Complexity	Flexibility	Compatibility	Deployment Considerations
Spectrum-Aware Routing	High	Low	Medium	High	High	Medium
Cognitive Decision-Making	High	Low	High	High	High	Medium
Game Theory-Based Routing	Medium	Medium	Medium	Medium	Medium	Medium
Machine Learning Approaches	High	Low	High	High	Medium	Medium
Bio-Inspired Routing	Medium	Medium	Medium	High	Medium	High

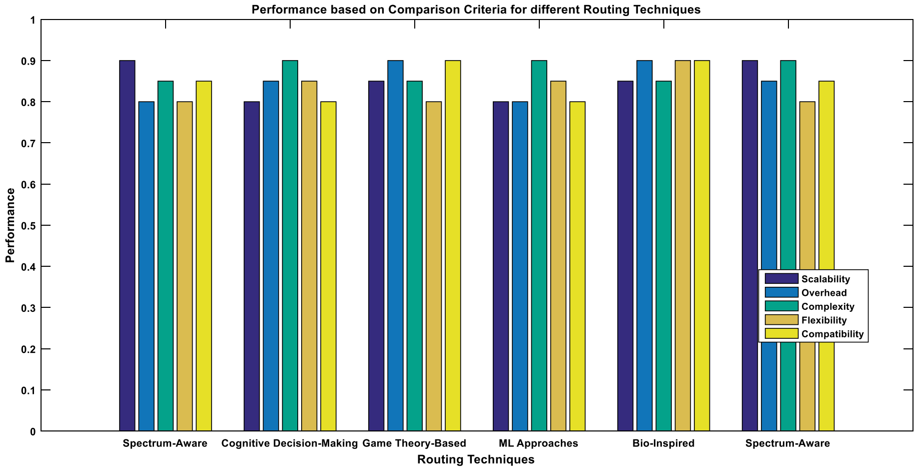

Fig. 10 Comparison Criteria for Different Routing Techniques

and deployment conditions. The selection of the best routing strategies to successfully address the needs and challenges of CRNs is facilitated by this review procedure.

5.4 Case studies

Case studies based on real-world scenarios are very essential for enhancing basic knowledge of how routing approaches operate in surroundings that are both diverse and dynamic. Evaluations that are particular to the environment are provided by these studies. These evaluations accept a variety of characteristics, including network architecture, user mobility, and spectrum availability. This article delves into three interesting scenario examples that provide information on the practical application and performance of selected routing algorithms in CRNs. These case studies are presented in this article.

5.4.1 Smart grid communication infrastructure

Scenario In order to provide real-time power distribution network monitoring, control, and administration, smart grids need a good communication infrastructure. CRNs are a potential way to improve smart grid communication efficiency and dependability.

Evaluation The deployment of CRNs in smart grid scenarios is studied in this case study, with an emphasis on routing strategy optimization for monitoring and power distribution applications. The research assesses how well routing algorithms work inside the smart grid infrastructure to provide defect detection, load balancing, and timely data transmission. The objective of the research is to find routing methods that increase the responsiveness and robustness of smart grid communication systems by evaluating the performance of routing protocols under various demand scenarios and grid circumstances.

5.4.2 Healthcare IoT and telemedicine

Scenario In order to provide remote patient monitoring, medical data transmission, and teleconsultation, healthcare IoT applications and telemedicine services depend on smooth and secure communication networks. In healthcare settings, CRNs provide an opportunity to improve communication and data transfer.

Evaluation The integration of CRNs in IoT and telemedicine applications for healthcare is studied in this case study, which highlights the significance of dependable and low-latency communication for patient care and medical data management. In healthcare situations, routing algorithms are assessed based on their capacity to prioritise important healthcare data, protect patient privacy and confidentiality, and adjust to changing network conditions. In order to obtain routing solutions that improve healthcare delivery and accessibility, the research evaluates the effect of routing algorithms on the calibre of telemedicine services and patient outcomes.

5.4.3 Environmental monitoring and conservation

Scenario Sensor networks are used by environmental monitoring systems to collect data on habitat conditions, biodiversity, and environmental characteristics. To assist with environmental monitoring and conservation initiatives, CRNs provide a versatile and energy-efficient communication platform.

Evaluation The use of CRNs in environmental monitoring and conservation applications is examined in this case study, with an emphasis on routing strategy optimization for data collection, analysis, and distribution. In distant and ecologically sensitive places, the research assesses how well routing algorithms perform in terms of balancing energy usage, increasing network lifespan, and guaranteeing data integrity. The study seeks to develop routing techniques that assist conservation and sustainable environmental management by evaluating the usefulness of routing protocols in supporting ecological monitoring, habitat protection, and biodiversity research.

5.4.4 Smart city infrastructure and services

Scenario Smart city projects use technology to improve public involvement, infrastructural efficiency, and urban services. Applications for smart cities, such traffic control, environmental monitoring, and smart lighting, may greatly benefit from the support of CRNs.

Evaluation The implementation of CRNs in smart city services and infrastructure is studied in this case study, with an emphasis on routing strategy optimization for a range of urban applications. The research aims to analyze how well routing algorithms function in fulfilling the communication needs of environmental sensing platforms, intelligent transportation networks, and smart lighting systems. The project intends to discover routing solutions that promotes the growth of resilient and sustainable smart cities by evaluating the effects of routing protocols on resource optimization, citizen welfare, and urban service delivery.

5.4.5 Educational campus networking

Scenario Effective interpersonal networks are essential for academic activity, campus-wide internet access, and administrative functions on educational campuses. In educational contexts, CRNs provide a novel way to improve connection and maximise network resources.

Evaluation The introduction of CRNs in school environments is studied in this case study, with particular attention given to the optimization of routing strategies for online learning environments, faculty and student communication, and campus-wide Wi-Fi connectivity. The research assesses how well routing algorithms perform in controlling network congestion, ensuring fair access to resources, and upholding data security and privacy in educational settings. The research intends to develop routing solutions that improve educational experience and promote digital learning efforts by evaluating the effects of routing protocols on user experience, network reliability, and administrative efficiency.

5.4.6 Smart home automation and IoT

Scenario IoT devices are integrated by smart home automation systems to automate domestic chores, increase energy efficiency, and enhance user convenience. In order to connect smart home devices and enable intelligent automation features, CRNs provide a dynamic communication architecture.

Evaluation The integration of CRNs in IoT and smart home automation systems is examined in this case study, with an emphasis on optimising routing strategies for data interchange, device connection, and remote-control features. The research assesses how well routing algorithms work in terms of reducing latency, increasing throughput, and ensuring smooth communication between central control systems and smart home appliances. The objective of the study is to identify routing solutions that improve the functionality and effectiveness of smart home automation systems by evaluating the effects of routing protocols on energy consumption, user experience, and system dependability.

5.4.7 Agricultural Monitoring and Precision Farming

Scenario IoT sensors and data analytics are used in precision farming methods to monitor crop conditions, increase crop production, and optimise agricultural operations. For the purpose of implementing agricultural monitoring systems in isolated and rural locations, CRNs provide a scalable and flexible communication platform.

Evaluation The deployment of CRNs in precision farming and agricultural monitoring applications is studied in this case study, with an emphasis on routing strategy optimization for data collection, analysis, and decision support. In agricultural sensor networks, the research assesses how well routing algorithms perform in terms of lowering energy consumption, optimising data accuracy, and ensuring dependable connection. The study aims to identify routing solutions that promote sustainable and efficient agricultural operations by evaluating the effects of routing protocols on resource utilisation, productivity on farms, and crop management methods.

The performance metrics for several case studies in CRNs are shown in Fig. 11. Every case study focuses on a particular application domain where CRNs are used to address particular needs and communication challenges. The performance metrics shown in the graph provide light on how well CRN solutions work in diverse situations. Throughput, packet delivery ratio, later part delay, routing overhead, network scalability, energy efficiency, and fairness are some of these metrics. Decision makers can review the efficiency and suitability of CRN solutions in a range of real-world applications by examining these metrics across a variety of case studies, including smart grid communication infrastructure, healthcare IoT and telemedicine, environmental monitoring, smart city infrastructure, educational campus networking, smart home automation, and agricultural monitoring. The Fig. 11 provides a thorough overview of the performance of CRNs in various use cases, assisting in the formulation of well-informed decisions and directing the design of CRN solutions that are optimised for particular application domains.

6 Future directions

In the field of CRNs, each of the research issues presented in Table 11 provides a potential area for some more research and application for the field. The purpose of these future directions is to address new obstacles, make use of emerging technologies, and realize the full potential of CRNs for wireless communication systems of the next generation. We delve into the potential future directions that may impact the landscape of routing in CRNs here. These possibilities may be future directions.

The research issues that are being addressed above shed new light on the various challenges and opportunities that are associated with CRNs. These challenges and opportunities vary from spectrum management and security to applications in a variety of fields, including smart cities, public safety, and rural connectivity. Bringing these potential future

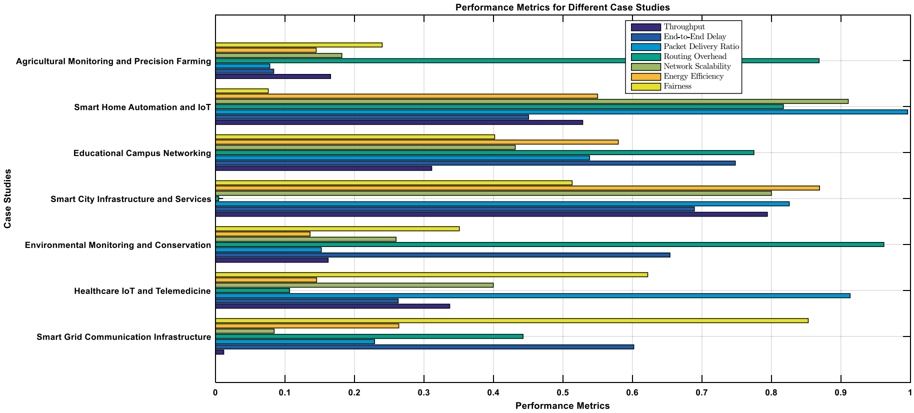

Fig. 11 Performance Metrics for Different Case Studies

Table 11 Emerging Research Areas in Cognitive Radio Networks

Research Issue	Description
Spectrum-Aware Machine Learning	Investigation of machine learning methods for spectrum sensing, resource allocation, and decision-making in CRNs.
Dynamic Spectrum Sharing	Studying strategies for dynamic spectrum sharing to improve spectrum use and support a variety of users.
Cognitive Network Optimization	Creation of optimization methods to improve CRNs' energy efficiency, scalability, and network performance.
Secure and Resilient Routing	Studying strong and secure routing strategies to counter security risks and guarantee continuous communication in CRNs.
Cooperative Spectrum Sensing	Progress in cooperative spectrum sensing methods to reduce sensing mistakes and increase sensing dependability.
Multi-Objective Routing	Investigating methods for multi-objective routing in order to balance competing goals like fairness and throughput.
Edge Computing Integration	Enhance CRN capabilities for real-time data processing and analytics with the integration of edge computing concepts.
Standardization and Interoperability	Initiatives to standardize common interfaces and protocols to enable interoperability among CRN implementations.
Cognitive Radio for IoT Edge Computing	Connectivity and spectrum efficiency are increased by integrating cognitive radio capabilities into IoT edge computing settings.
Spectrum Management Policies	Study of structures and regulations to support trading, sharing, and dynamic spectrum access.
Cognitive Radio for Vehicular Networks	Implementation of CRNs in automobile contexts to facilitate communication between vehicles and intelligent transportation systems.
Bio-Inspired CRNs	Construction of effective and flexible cognitive radio network designs by the use of bioinspired algorithms and concepts.
Cognitive Radio for 6G Networks	Expectations on the use of cognitive radio in upcoming 6G networks, such as intelligent routing and better spectrum management.
Cognitive Radio for IoT Edge Computing	Connectivity and spectrum efficiency are increased by integrating cognitive radio capabilities into IoT edge computing settings.
Spectrum Management Policies	Study of structures and regulations to support trading, sharing, and dynamic spectrum access.
Machine Learning-Driven Spectrum Management	Machine learning algorithms are used to optimize spectrum management activities, including allocation and handoff.
Energy-Efficient Routing	Study of routing methods intended to reduce energy use and increase CRN node battery life.
Dynamic Channel Bonding	Investigating methods for dynamically bonding channels to combine fragmented spectrum bands and improve data transfer speeds.

Table 11 (continued)

Research Issue	Description
Security in Dynamic Environments	Investigation into adaptable security systems that may dynamically change to counteract evolving threats and network circumstances.
Federated Learning for CRNs	Federated learning frameworks are used to facilitate cooperative model training between dispersed CRN nodes.
Spectrum Marketplaces	The creation of decentralized spectrum markets to facilitate effective spectrum trade and distribution across CRN users.
Cognitive Radio Resource Management	Create resource management algorithms that maximize the distribution of communication, storage, and processing resources inside CRNs.
Predictive Network Analytics	Predictive analytics approaches are integrated to avoid network congestion, improve routing choices, and forecast network behaviour.
Spectrum Blockchain	Investigates blockchain-based methods for transaction logging, access control, and spectrum management that are transparent and safe.
Cross-Layer Optimization	Examining methods for cross-layer optimization to improve physical layer characteristics, routing choices, and application performance in CRNs all at once.
Cognitive Radio for IoT	Modification of cognitive radio concepts and methodologies to facilitate integration with IoT networks and devices.
Reinforcement Learning for CRNs	By using algorithms for reinforcement learning, CRN nodes may learn on their own and modify their behaviour in response to environmental input.
Edge Intelligence in CRNs	Implementation of edge intelligence technologies in CRNs to facilitate localized data processing, analytics, and decision-making.
Privacy-Preserving Techniques	Investigation into privacy-preserving techniques to safeguard user information, identities, and communication styles in CRNs.
Cognitive Radio Testbeds	Creation of realistic testbeds and simulation platforms to facilitate the practical assessment and verification of CRN algorithms and protocols.
Cognitive Satellite Networks	Cognitive radio concepts are extended to satellite communication networks to enhance connectivity and spectrum efficiency.
Self-Organizing Networks	Investigating self-organizing network topologies and protocols to allow for the independent setup, administration, and optimization of CRNs.
Cognitive Radio for 5G and beyond	5G and next-generation wireless networks will use cognitive radio capabilities to improve scalability, efficiency, and flexibility.
Quantum-Inspired CRNs	Examining quantum-inspired computing methods to address optimization and decision-making issues in CRNs.
Environmental Sensing Networks	The use of CRNs in environmental monitoring applications, including tracking animals, pollution detection, and disaster relief.

Table 11 (continued)

Research Issue	Description
Context-Aware Routing	Creation of routing algorithms that take into account network structure, user mobility, and contextual data like location.
Spectrum Mobility Management	Examination of spectrum mobility management methods, such as spectrum handoff schemes and dynamic spectrum access.
Intelligent Spectrum Sensing	Investigation of cutting-edge spectrum sensing methods based on AI and signal processing technologies.
Cognitive Radio Resource Allocation	Creation of resource allocation systems that maximize the CRNs' use of bandwidth, power, and spectrum resources.
Heterogeneous CRN Integration	Combining various CRNs, such as multi-tier networks and cognitive radio sensor networks, into one cohesive system.
Cognitive Radar Systems	Cognitive radio ideas used to radar systems for better radar performance and adaptive spectrum utilization.
Dynamic Spectrum Allocation	Studying techniques for dynamic spectrum allocation in order to allocate spectrum resources in real time according to demand.
Secure Multi-User Spectrum Access	Examining safe multi-user access strategies to guarantee equitable and safe spectrum distribution among heterogeneous users in CRNs.
Cognitive Radio for Public Safety	Implementation of CRNs in public safety domains, including emergency communication and catastrophe response.
Autonomous Spectrum Management	Creation of autonomous spectrum management frameworks to allow CRNs to self-optimize, self-organize, and self-repair.
Cognitive Radio for Rural Connectivity	Smart radio technology modified to solve underprivileged and rural regions' connection issues.
Spectrum-Aware Traffic Engineering	Traffic engineering procedures are optimized with network circumstances, traffic patterns, and spectrum availability taken into account.
Cognitive Radio for Smart Cities	Using CRNs to facilitate the use of smart city applications, such as intelligent utilities and transportation.
Green CRNs	Research is being done on energy-efficient cognitive radio protocols and strategies to lessen wireless networks' carbon impact.
Cross-Domain CRNs	Research on CRNs in many domains: space, undersea, aerial, and terrestrial networks.

research directions into consideration has the potential to stimulate innovation process as feasible to design wireless communication networks that are more intelligent, adaptable, and inefficient.

7 Conclusion

In summary, this survey has meticulously examined the landscape of intelligent routing in CRNs, unravelling the intricate dynamics of adaptive communication environments. The important outcomes underscore the pivotal role of intelligent routing in overcoming challenges posed by dynamic spectrum access, security concerns, and the imperative for resource efficiency. Spectrum-aware, machine learning-based, game theory-inspired, and bio-inspired routing strategies have emerged as crucial components in addressing these challenges. While the dynamic nature of the radio environment introduces complexities, it also unveils opportunities for innovation in machine learning, signal processing, and protocol design. The implications of intelligent routing are poised to reshape the future of CRNs. As networks evolve, intelligent routing promises enhanced spectrum efficiency through optimized spectrum utilization and reduced interference. Its adaptability contributes to the resilience of networks in dynamic environments, ensuring robust communication even in challenging conditions. Furthermore, advancements in security, such as secure cooperative spectrum sensing and privacy-preserving techniques, fortify the foundations of trustworthy communication frameworks. The human-centric approach, facilitated by interfaces enabling user engagement and high-level decision-making, opens new dimensions in cognitive networks. Integrating intelligent routing with emerging technologies like machine learning, blockchain, and edge computing paves the way for seamless integration with 6G and beyond. In the years ahead, ongoing research and development are expected to catalyse transformative changes, propelling CRNs toward increased efficiency, adaptability, and resilience. In essence, intelligent routing stands as a cornerstone in the advancement of CRNs, ushering in an era where wireless communication capabilities are redefined. As we navigate the future, the fusion of intelligent routing strategies with cutting-edge technologies promises a paradigm shift, unlocking new possibilities and potential applications in the realm of wireless communication.

Author contributions All authors played key roles in shaping the content of this paper. Rahul Priyadarshi, Ravi Ranjan Kumar, and Zhang Ying collaborated in conceiving and designing the experiments. Rahul Priyadarshi and Ravi Ranjan Kumar carried out the experiments, and Zhang Ying contributed to the data analysis. The collaborative effort of Rahul Priyadarshi, Ravi Ranjan Kumar, and Zhang Ying is reflected in the joint writing of the paper.

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