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Adaptive Hybrid Access Scheme for 5G URLLC using Machine Learning and Fountain Codes

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Abstract—Ultra-reliable low-latency communication (URLLC) is a pivotal aspect of 5G mobile networks, necessitating robust mechanisms for secure and dependable data transfer. With the rise of applications requiring strict performance standards, especially in industrial automation and healthcare, it is crucial to adopt sophisticated methods like machine learning and novel coding techniques to effectively tackle these challenges (Indoonundon & Fowdur, 2021). Machine learning integration aids in optimizing resource distribution and channel allocation, allowing networks to quickly adapt to changing conditions and user needs, thus boosting performance and reliability in URLLC contexts (Niknam et al., 2019). This flexibility is especially vital due to the swift increase in data traffic and the intricacy of contemporary wireless environments, prompting a transition from conventional model-driven methods to data-driven strategies that utilize the extensive data within the network (Niknam et al., 2019). Such a shift promotes more knowledgeable decision-making that can adapt to real-time situations, enhancing the system's capability to sustain low latency and high dependability for essential applications (Savazzi et al., 2020; Chen et al., 2018). Present studies are delving into the use of sophisticated channel coding patterns and error control techniques, which are crucial for addressing the distinct challenges presented by URLLC application demands, ensuring effective transmission within the strict latency and reliability parameters (Indoonundon & Fowdur, 2021). Additionally, the exploration of innovative methods like fountain codes offers the promise of dependable transmission without the necessity for retransmission, thus resolving the core issues of URLLC in scenarios requiring utmost reliability and minimal latency

Keywords-Ultra-reliable low-latency communication (URLLC),Machine Learning,Resource Optimization,Channel Coding,Error Control Techniques

I. Introduction

Current fifth generation (5G) mobile networks face an increasingly diversified range of demand drivers, including virtual reality, industrial automation, smart grid, e-health, multimedia, tactile Internet, the Internet of Things, and the Internet of Vehicles. The pressure to fulfill these diverse requirements necessitates innovative solutions that can support a multitude of applications with varying needs in terms of latency, reliability, and capacity (Chen et al., 2018). To address these diverse challenges, the implementation of ultra-reliable low-latency communication is fundamental, particularly for mission-critical uses where the costs of failure are substantial, such as in telesurgery and real-time data transmission for industrial systems (Yaacoub et al., 2021).

The provision of reliable low-latency communication is a central pillar of the 5G standards, as established by the International Telecommunication Union. Alongside the evolution of enhanced mobile broadband and massive machine-type communications, URLLC represents one of the key service classes that 5G networks must be equipped to handle (Yaacoub et al., 2021) (Indoonundon & Fowdur, 2021). As URLLC encompasses stringent requirements for end-to-end latency and reliability, it is crucial to ensure that dedicated network resources are allocated to maintain service continuity, especially for mission-critical operations that cannot tolerate delays or disruptions (Yaacoub et al., 2021). In order to meet these stringent requirements effectively, a combination of advanced technologies such as machine learning, resource management, and innovative coding strategies must be leveraged, allowing for dynamic adaptation to network conditions and the precise allocation of resources to URLLC applications, thereby optimizing overall performance and reliability (Ahmadi et al., 2021)(Yaacoub et al., 2021).

Adaptive Channel Assignment for Hybrid Spectrum Access in Sub-6 GHz Networks

The growing demand for mobile data in the 5G era has driven the need for efficient utilization of available spectrum. Consequently, adapting channel assignment strategies in hybrid spectrum networks is critical to enhancing both performance and user experience while addressing interference challenges

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inherent in shared access scenarios (Strużak & Tjelta, 2014). Adaptive channel assignment mechanisms can leverage advanced algorithms and resource optimization techniques to dynamically allocate spectrum based on real-time traffic demands and interference conditions, thereby ensuring robust performance across heterogeneous use cases and user requirements in next-generation wireless networks (Zhong et al., 2022). Moreover, the integration of artificial intelligence in resource management can further streamline these adaptive processes, enabling proactive methodologies that optimize spectrum utilization while maintaining quality of service amid varying network conditions (Elsayed & Erol - Kantarci, 2019). With the increasing complexity of network demands and the diverse range of applications expected in 5G and beyond, the implementation of AI-driven spectrum management techniques has become essential for meeting these challenges effectively (Li et al., 2020).

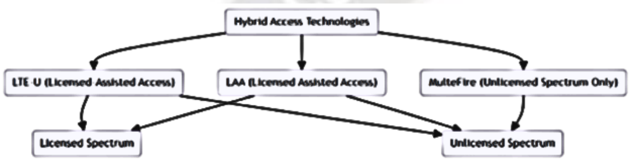

FIGURE 1. Three hybrid access technologies for LTE licensed and unlicensed spectrum (LTE-U, LAA, and MulteFire).

Additionally, the introduction of intelligent algorithms that can predict traffic patterns and resource needs is essential for achieving the desired efficiency in spectrum management, as traditional optimization methods may fall short in accommodating the dynamic nature of wireless communications (Li et al., 2020). Furthermore, these intelligent algorithms can help facilitate a more nuanced understanding of user behavior and network conditions, fostering an environment where resources are allocated not just reactively but also strategically, ultimately promoting enhanced service quality across various applications and scenarios in future wireless ecosystems (Salh et al., 2021) (Li et al., 2020) (Nouruzi et al., 2022) (Elsayed & Erol - Kantarci, 2019). This strategic approach is particularly necessary to accommodate the diverse and heterogeneous traffic emerging from various applications, such as Internet of Things devices and real-time communications, which impose stringent quality of service requirements that traditional methods alone cannot satisfy (Elsayed & Erol - Kantarci, 2019). In this context, the evolving landscape of 5G and beyond necessitates the development of intelligent resource management solutions that go beyond conventional practices, underscoring the importance of integrating advanced technologies like AI to drive efficient spectrum utilization and robust network performance (Elsayed & Erol - Kantarci, 2019) (Benzaıd & Taleb, 2022) (Li et al., 2020) (Nouruzi et al., 2022). Moreover, the reliance on AI for network management is not only about enhancing operational efficiency; it also addresses the inherent challenges of increased complexity and diverse service requirements emerging in future wireless networks (Elsayed & Erol - Kantarci, 2019). This shift towards AI-driven methodologies reflects a broader trend in wireless networking, where intelligent systems are increasingly instrumental in managing the complexities and demands of contemporary and future communication technologies (Li et al., 2020). The deployment of such intelligent systems is expected to redefine how spectrum resources are allocated, allowing for a more adaptive and responsive framework that can keep pace with user needs and network conditions, ultimately realizing the full potential of advanced wireless communication systems (Elsayed & Erol - Kantarci, 2019). The integration of AI-driven techniques also offers a promising avenue for addressing dynamic network environments, as intelligent algorithms can facilitate real-time adaptations in response to fluctuating traffic patterns and interference levels, which are critical for maintaining high reliability and user experience in the evolving landscape of wireless communications (Benzaıd & Taleb, 2022)(Elsayed & Erol - Kantarci, 2019)(Li et al., 2020)(Nouruzi et al., 2022). In light of these advancements, it becomes imperative to explore novel approaches for intelligent spectrum management that not only prioritize performance but also enhance security in the face of evolving cyber threats and vulnerabilities associated with increased connectivity and diversified services expected in 5G and beyond networks (Li et al., 2020) (Xue et al., 2023) (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022). This necessitates a comprehensive examination of AI's role in spectrum management, particularly how it can enhance both performance and security through adaptive and autonomous strategies designed to meet the unique demands posed by a wide array of connected devices and services (Benzaıd & Taleb, 2022). To achieve this, it is essential to identify effective security measures that can keep pace with the evolving threat landscape, particularly as the integration of AI into spectrum management introduces new complexities and vulnerabilities that must be addressed proactively (Benzaıd & Taleb, 2022). Furthermore, the synergy between AI-enabled spectrum management and adaptive security measures can significantly enhance the network's resilience against emerging cyber threats, thereby ensuring a secure and efficient operational environment for future communication infrastructures (Benzaıd & Taleb, 2022) (Li et al., 2020). Moreover, the application of AI techniques, such as deep learning and reinforcement learning, can facilitate automated responses to security incidents, enabling real-time adjustments to spectrum allocation strategies that protect against potential vulnerabilities without sacrificing performance (Li et al., 2020).

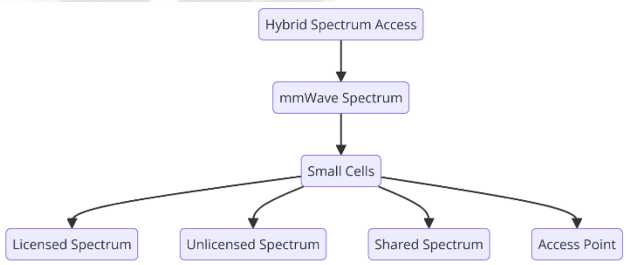

FIGURE 2. Hybrid spectrum access in mmWave small cells

In this regard, the research community is increasingly focusing on developing frameworks that leverage machine learning for both optimizing resource allocation and enhancing security, which together form a holistic approach to next-generation network management and resilience (Li et al., 2020). This

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comprehensive approach underscores the necessity of integrating AI techniques not only for performance optimization but also for evolving security needs, as traditional methods struggle to address the complexities introduced by advanced networking environments and the diverse technological landscape in 5G and beyond networks, ultimately paving the way for a more secure and efficient wireless ecosystem that can adapt to the dynamic demands of the future. (Benzaıd & Taleb, 2022) (Xue et al., 2023) (Li et al., 2020) (Nouruzi et al., 2022) This convergence of AI-driven spectrum management and security solutions not only enhances the operational capabilities of future networks but also propels the development of innovative applications that rely heavily on seamless connectivity and robust performance, reiterating the need for a paradigm shift in how wireless environments are designed, deployed, and maintained in the years to come. (Nouruzi et al., 2022) (Xue et al., 2023) (Li et al., 2020) (Benzaıd & Taleb, 2022) In summary, the integration of AI into spectrum management not only facilitates improved resource allocation and traffic management but also enables adaptive security measures that can address the multifaceted challenges posed by emerging technologies and user demands, ultimately leading to a more resilient and efficient wireless network infrastructure that can better support the diverse applications and services envisioned for 5G and beyond (Li et al., 2020) (Xue et al., 2023) (Benzaıd & Taleb, 2022) (Nouruzi et al., 2022). The challenges associated with managing spectrum in such complex environments necessitate an approach that not only incorporates AI and machine learning techniques but also examines their impact on network dynamics and user experience, ensuring that the resulting solutions are both effective and sustainable in the rapidly evolving telecommunications landscape. (Li et al., 2020) (Benzaıd & Taleb, 2022) (Nouruzi et al., 2022) (Xue et al., 2023) This focus on developing intelligent, AI-driven strategies for spectrum management and security is crucial, particularly as the proliferation of connected devices and services introduces new vulnerabilities that traditional approaches fail to mitigate, thereby highlighting the urgent need for a paradigm shift towards more adaptive and robust wireless network designs. (Nouruzi et al., 2022) (Li et al., 2020) (Benzaıd & Taleb, 2022) (Xue et al., 2023) This emphasis on AI-driven methodologies emphasizes the necessity for proactive measures in managing the security landscape while concurrently addressing the operational challenges posed by a diverse array of applications and services in the advancing telecommunications realm, thereby laying the groundwork for a resilient infrastructure capable of adapting to the dynamic requirements of the future. (Benzaıd & Taleb, 2022) (Wang et al., 2022) (Nouruzi et al., 2022) (Li et al., 2020) As these AI-integrated frameworks are developed, it becomes increasingly important to ensure that they not only optimize performance but also incorporate robust security protocols to mitigate the threats emerging from the complexity of new technologies and interconnected devices, facilitating a seamless transition to next-generation wireless networks that are both efficient and secure. In this context, the integration of intelligence in resource allocation strategies can significantly enhance the network's ability to adapt to changing traffic conditions while simultaneously addressing the security challenges inherent in such environments, thereby ensuring a more robust and resilient framework for next-generation wireless networks (Li et al., 2020) (Benzaıd & Taleb, 2022) (Nouruzi et al., 2022) (Xue et al., 2023). This multifaceted approach not only aligns with the growing demand for enhanced connectivity and performance but also addresses the pressing need for resilient security measures that can evolve alongside the innovation of network technologies and user requirements, highlighting the critical role of adaptive AI solutions in the ongoing development of 5G and beyond. (Li et al., 2020) (Xue et al., 2023) (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022) This holistic strategy promotes the concept of a secure and intelligent network environment, where AI not only facilitates optimized spectrum management but also fortifies the system against emerging cyber threats, ensuring reliable and efficient communication services in increasingly complex network topologies (Li et al., 2020). To achieve this, it is essential to identify effective security measures that can keep pace with the evolving threat landscape, particularly as the integration of AI into spectrum management introduces new complexities and vulnerabilities that must be addressed proactively. In this regard, ongoing research must focus on the development of adaptive frameworks capable of incorporating real-time data analysis and predictive algorithms to anticipate potential security breaches while ensuring the optimal allocation of spectrum resources, thus leading to stronger defenses against the rapidly evolving landscape of cyber threats in the context of next-generation wireless networks. This necessity for adaptive frameworks drives the evolution of security measures alongside spectrum management strategies, as future networks must not only be resilient to existing vulnerabilities but also proactive in anticipating and mitigating new threats that emerge from the convergence of diverse technologies and applications, underlining the pivotal role of AI-powered solutions in shaping the future of secure and efficient wireless networking. In light of these considerations, it becomes increasingly clear that leveraging AI-driven techniques in spectrum management is not merely a technological enhancement but a fundamental requirement to address the complexities inherent in next-generation wireless communication systems, ensuring that adaptive security measures are integrated at every level of the network architecture to enable a truly robust and resilient infrastructure capable of supporting the diverse services and applications of the future. (Wang et al., 2022) (Li et al., 2020) (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022) Furthermore, the implementation of AI within these frameworks lays the foundation for dynamic adaptation to user behaviors and network conditions, thereby facilitating a more intelligent management of spectrum resources that is essential for meeting the ever-increasing demands for connectivity and performance in the context of evolving telecommunication technologies. This adaptability is critical in driving performance improvements and enhancing user experience, as it allows networks to respond in real-time to fluctuations in demand and security threats, thereby creating a more agile and responsive telecommunications environment that can support the diverse and demanding applications expected in 5G and beyond. (Benzaıd & Taleb, 2022) (Li et al., 2020) (Xue et al., 2023) (Nouruzi et al., 2022) To effectively address these multifaceted challenges, a comprehensive strategy that integrates advanced AI techniques

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for proactive spectrum management and security is essential, ensuring that networks not only optimize the allocation of resources but also maintain resilience against cyber threats that are becoming increasingly sophisticated and prevalent (Nouruzi et al., 2022) (Xue et al., 2023) (Benzaıd & Taleb, 2022) (Li et al., 2020).

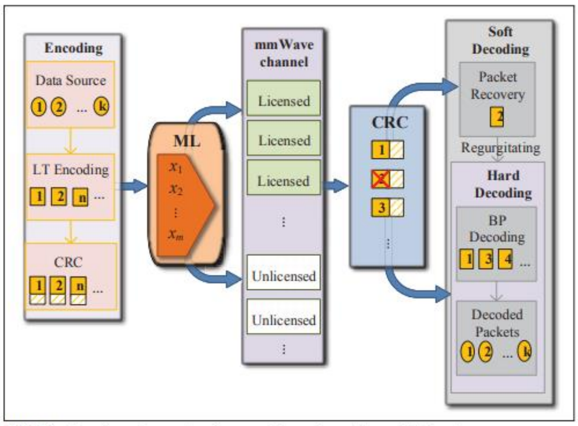

FIGURE 3. Adaptive channel assignment based on ML and LT code.

In particular, the application of advanced AI techniques, such as deep learning and reinforcement learning, can facilitate smarter resource allocation and enhance overall network performance, thereby paving the way for robust and adaptable management solutions tailored to the dynamic landscape of future telecommunications systems (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022) (Li et al., 2020) (Xue et al., 2023). Moreover, by harnessing the potential of AI for real-time data analytics, these systems can identify patterns and anomalies that signify threats or inefficiencies in spectrum utilization, thus empowering operators to make informed decisions that enhance both performance and security across various network layers. This integration of AI into spectrum management not only enhances the capacity and efficiency of the networks but also significantly strengthens the security posture against emerging threats that are characteristic of complex multi-user environments. This comprehensive approach acknowledges the need for a seamless integration of performance optimization and security resilience, ultimately enabling networks to evolve and adapt to future challenges in the telecommunications landscape while safeguarding user data and network integrity against sophisticated cyber threats which are on the rise in the context of next-generation wireless communication systems. (Nouruzi et al., 2022) (Li et al., 2020) (Benzaıd & Taleb, 2022) (Lin et al., 2021) In this context, the incorporation of intelligent spectrum management techniques can play a significant role in addressing these challenges, as they enable dynamic adjustments that ensure high reliability and quality-of-experience while concurrently mitigating potential cybersecurity risks that arise from increased interconnectivity and reliance on shared spectrum resources. Therefore, the development of AI-driven spectrum management solutions is not simply about enhancing throughput or efficiency; it also encompasses the essential task of fortifying systems against security vulnerabilities, ultimately striving to create a resilient framework that can adapt to the multifaceted demands of upcoming wireless technologies and applications (Nouruzi et al., 2022) (Li et al., 2020) (Benzaıd & Taleb, 2022) (Xue et al., 2023). This holistic view underscores the necessity of integrating AI to advance both operational capabilities and security measures, ultimately leading to the establishment of a robust infrastructure that can adeptly navigate the complexities of next-generation wireless networks and meet the diverse needs of users. Moreover, as the deployment of next-generation networks progresses, the fusion of AI techniques with adaptive channel assignment strategies becomes increasingly critical, enabling the optimization of spectrum utilization while ensuring robust protection against evolving cyber threats and improving user experiences across various applications and services (Li et al., 2020) (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022) (Xue et al., 2023). This convergence of AI and adaptive channel assignment strategies not only prioritizes efficient spectrum usage but also establishes a proactive stance against potential vulnerabilities, reinforcing the notion that intelligent resource management is fundamental for the resilience and performance of future wireless networks, thereby paving the way for a more secure and adaptive telecommunication ecosystem. (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022) (Li et al., 2020) (Xue et al., 2023) This focus on integrating intelligent spectrum management underscores the necessity for advancements in autonomous network capabilities, thereby ensuring that the infrastructure can not only adapt to changing user demands but also preemptively address potential security threats through learned behaviors and predictive analytics (Li et al., 2020) (Nouruzi et al., 2022).

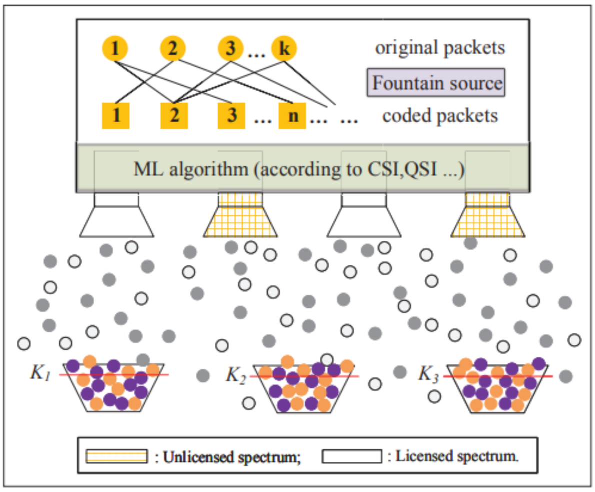

FIGURE 4. Fountain coding/decoding schematics.

Additionally, as wireless communication landscapes evolve, the reliance on traditional manual methods for spectrum management may become increasingly insufficient, requiring more adaptive and intelligent solutions that leverage the potential of AI to facilitate real-time adjustments and risk assessments, culminating in a network environment that is both performant and resilient (Benzaıd & Taleb, 2022) (Li et al., 2020) (Nouruzi et al., 2022). In this regard, embracing AI-driven techniques for spectrum management is crucial, as they empower networks to operate autonomously and efficiently, responding to the complexities of modern communication demands while maintaining a strong security posture against increasingly sophisticated cyber threats (Li et al., 2020). This necessity calls for a paradigm shift in how we approach network

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management, prioritizing an integrated model that not only streamlines performance but also significantly enhances security measures, thus ensuring that next-generation networks can effectively support the anticipated surge in connectivity and application diversity (Benzaıd & Taleb, 2022) (Xue et al., 2023) (Li et al., 2020) (Nouruzi et al., 2022). This shift towards an AI-enabled spectrum management paradigm reflects the growing recognition that the future of wireless communication hinges on not just operational efficiency, but also on robust security frameworks capable of adapting to emerging threats and network dynamics, thereby ensuring that the infrastructure remains resilient in the face of ever-changing demands and cyber risks. (Li et al., 2020) (Benzaıd & Taleb, 2022) (Xue et al., 2023) (Nouruzi et al., 2022)

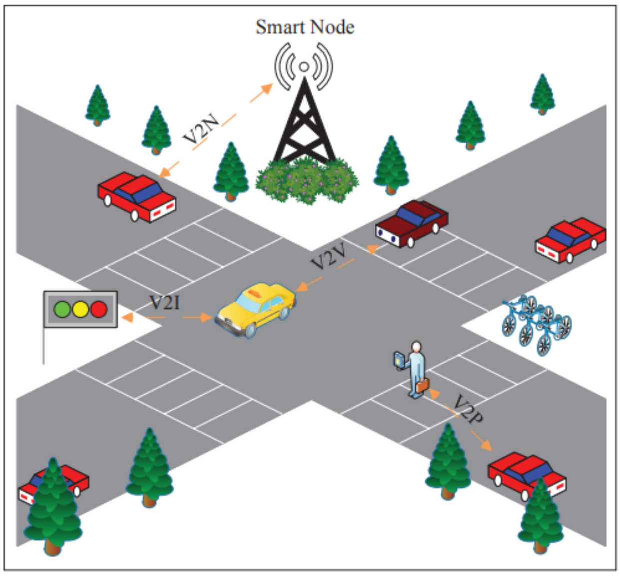

FIGURE 5. Typical deployment scenario of V2X.

This evolving landscape emphasizes the intersection of performance and security, where intelligent systems must be developed to not only manage resources but also foresee and counteract potential vulnerabilities, establishing a foundation for safe and effective communication as we move towards fully interconnected environments characterized by diverse applications, increased traffic, and heightened security concerns. (Li et al., 2020) (Benzaıd & Taleb, 2022) (Nouruzi et al., 2022) (Xue et al., 2023) Consequently, adopting AI-driven solutions for adaptive channel assignment emerges as a critical enabler for achieving both operational excellence and heightened security, allowing networks to dynamically manage spectrum allocation while simultaneously identifying and mitigating potential threats through advanced predictive analytics and decision-making processes (Li et al., 2020) (Nouruzi et al., 2022) (Benzaıd & Taleb, 2022). Furthermore, the integration of AI techniques into adaptive channel assignment can facilitate the development of smart algorithms that analyze network behaviors, enabling proactive measures to enhance both efficiency and security, which is essential as we transition into more intricate wireless ecosystems marked by varied application demands and heightened cyber risks. In this regard, it is essential to explore innovative approaches that leverage AI's capabilities to enhance spectrum management strategies, as these technologies will be pivotal in navigating the complexities of future wireless environments and protecting against evolving cyber threats (Li et al., 2020). To achieve these objectives, a concerted effort must be directed toward research that focuses on the design and implementation of AI-driven spectrum management solutions that not only improve channel assignment efficiency but also incorporate adaptive learning mechanisms to anticipate and respond to changing network conditions and security challenges. (Benzaıd & Taleb, 2022) (Nouruzi et al., 2022) (Xue et al., 2023) (Li et al., 2020) In addition, interdisciplinary collaborations among researchers, network operators, and cybersecurity experts are crucial for developing comprehensive frameworks that integrate AI technologies into spectrum management, ensuring that both performance enhancement and security fortification are prioritized in the design of next-generation wireless networks . In light of these considerations, the integration of artificial intelligence into spectrum management strategies is not merely advantageous but essential, as it offers the potential to revolutionize how networks adapt to user requirements while simultaneously safeguarding against the increasingly complex landscape of cybersecurity threats, thereby ensuring the resilience and reliability of future wireless communication ecosystems. By fostering an ecosystem where AI techniques can continuously learn and evolve, we can create networks that are not only responsive to traffic demands but are also fortified against potential vulnerabilities, ultimately ensuring sustainable growth and security (Xue et al., 2023). The continuous evolution of AI technologies enables the development of systems capable of self-optimization and adaptive learning, which are critical in dynamically adjusting channel assignments and managing spectrums effectively, thereby addressing both the performance and security needs inherent to tomorrow's interconnected environments (Li et al., 2020) (Gacanin, 2018). Moreover, the deployment of AI-driven solutions can significantly enhance the ability to detect anomalies and potential threats within the network, allowing for timely interventions that maintain service integrity and security. This proactive stance not only bolsters the network's defenses but also enhances overall user experience by minimizing service disruptions and optimizing resource utilization, which is vital as the demand for seamless connectivity continues to escalate across various sectors and applications (Li et al., 2020). As such, the alignment of AI-driven spectrum management with adaptive channel assignment strategies not only facilitates more effective resource allocation but also strengthens the network's ability to proactively counteract potential cyber threats, thereby creating a resilient framework that can seamlessly adapt to both traffic demands and security challenges. Additionally, integrating machine learning models that can analyze traffic patterns and predict peak usage times can further optimize spectrum allocation, ensuring that channels are utilized efficiently while minimizing interference among coexisting technologies, which is crucial for maintaining operational efficacy in an increasingly congested spectral landscape. By leveraging AI's capacity for rapid adaptation and decision-making, networks can dynamically adjust their channel assignments in response to changing conditions, such as sudden surges in user activity or the emergence of new wireless technologies, thereby maintaining optimal performance and service quality.

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