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A Comprehensive Study on Spectrum Sharing Between Cellular Networks and Wi-Fi Networks

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Abstract. This report provides a systematic analysis of spectrum sharing between cellular networks and Wi-Fi systems. With exponential growth in wireless data traffic and emerging technologies like 5G and Wi-Fi 6, efficient utilization of unlicensed frequency bands has become a critical challenge. The paper examines technical barriers, existing coexistence mechanisms, performance evaluation methodologies, and future research directions. Fundamental differences between cellular time-division multiplexing mechanisms and Wi-Fi's competitive protocols create significant obstacles for achieving harmonious spectrum sharing. Through detailed analysis of collaborative strategies, AI-driven technologies, and physical layer innovations, the report highlights both existing advancements and unresolved challenges. Finally, it discusses emerging trends, including 6G spectrum utilization, smart metasurfaces, semantic communication, and green networks, providing a roadmap for future research and standardization efforts.

Keywords: Cellular networks, Wi-Fi, Network spectrum, Sharing

1. Introduction

With the continuous growth of wireless bandwidth demands, traditional licensed frequency bands have become severely congested. Consequently, the coexistence of cellular networks and Wi-Fi in unlicensed bands (e.g., 5 GHz and 6 GHz) has garnered significant attention from both industry and academia. This approach promises to enhance spectrum utilization efficiency, reduce infrastructure costs, and lower energy consumption. However, coexisting with these heterogeneous networks faces challenges due to fundamental differences in design principles. Cellular networks like LTE and 5G employ centralized scheduling mechanisms for medium-range access, ensuring high reliability and low latency. In contrast, Wi-Fi utilizes a distributed Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. While this approach efficiently handles asynchronous burst traffic, it remains vulnerable to persistent interference. Such performance disparities result in severe degradation of Wi-Fi performance in shared environments—with throughput potentially plummeting by 80% under certain conditions. This report comprehensively examines technical barriers, cutting-edge solutions, performance metrics, and future prospects for achieving efficient and equitable spectrum sharing between these two mainstream wireless technologies. This paper adopts a multi-method approach (literature review, performance simulation, case studies) to explore solutions for equitable spectrum sharing and enhance cellular-Wi-Fi coexistence efficiency.

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2. Technical challenges

2.1. MAC layer protocol incompatibility

The core of coexistence issues lies in differences in media access control (MAC) policies. Long Term Evolution (LTE) and New Radio (NR) technologies employ time-division multiple access (TDMA) mechanisms, where base stations allocate transmission slots to user equipment, establishing a continuous and predictable transmission pattern. In contrast, Wi-Fi relies on Carrier Sense Multiple Access (CSMA/CA), where nodes listen for channel availability before transmission and perform random backoff if the channel is busy. The continuous transmission from LTE/5G networks interferes with Wi-Fi's Channel Confirmation (CCA) process, causing frequent access delays for Wi-Fi nodes. In high-density deployment scenarios like urban areas or crowded public spaces, this compatibility issue reduces Wi-Fi throughput by 40%-70% and increases latency by 3-5 times. Table 1 summarizes the development process of WiFi.

Table 1. WiFi standard development process [1]

Edition	Protocol	Publish time	Working frequency band (GHz)	Bandwidth used (MHz)	Theoretical rate (Mbps)	Modulation technique
founder WiFi	802.11	1997	2.4	20	1-2	DSSS/FHSS
WiFi 1	802.11b	1999	2.4	20	1-11	DSSS
WiFi 2	802.11a	1999	5	20	6-54	OFDM
WiFi 3	802.11g	2003	2.4	20	6-54	OFDM
WiFi4	802.11n	2009	2.4/5	20/40	72-600	MIMO/OFDM
WiFi 5	802.11ac	2014	5	20/40/80/160	433-6933	MU-MIMO/OFDM
WiFi6	802.11ax	2019	2.4/5/6	20/40/80/160	574-9608	MU-MIMO/OFDMA
WiFi 7	802.11be	2024	2.4/5/6	320	1376-46120	MU-MIMO/OFDMA

2.2. Fairness definition and measurement

The academic community has not reached a consensus on a unified standard to measure the fairness of heterogeneous sharing networks. Traditional indicators include three aspects. Time fairness means the equal allocation of channel time, space equity means equal opportunity per unit area. Utility fairness means equal satisfaction based on service requirements.

A novel concept called "opportunity fairness" has recently emerged, which takes into account the inherent asymmetry in MAC protocols. Its goal is to design allocation rules that are asymmetric in time or space but ultimately fair in terms of transmission opportunities, ensuring that neither system gets starved.

2.3. Increased hidden end-stage problems

In heterogeneous networks, differences in transmission power, sensitivity, and protocol design may prevent LTE base stations from detecting signals from Wi-Fi access points. This mutual detection

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failure exacerbates hidden terminal issues, resulting in significantly increased packet collisions. Studies show that collision rates in such environments exceed those of homogeneous Wi-Fi networks by over 50%, particularly evident in high-density deployment scenarios like stadiums or apartment complexes.

2.4. Different QoS requirements

Cellular networks and Wi-Fi systems typically handle different types of traffic with vastly varying quality-of-service (QoS) requirements. Cellular networks are increasingly adopting Ultra-Reliable Low Latency Communications (URLLC) services, demanding latency below 1 millisecond and packet success rates exceeding 99.9% [2]. In contrast, Wi-Fi primarily supports high-throughput, best-effort traffic like video streaming, which is less sensitive to latency but requires substantial bandwidth. The technical challenge lies in dynamically allocating resources within shared and unpredictable spectrum environments to meet these fundamentally different demands.

2.5. Security and privacy vulnerabilities

Distributed coordination mechanisms typically require nodes to exchange operational data (such as spectrum occupancy status and user requirements), which may lead to sensitive information leaks, including user locations, traffic patterns, and network topology. Malicious actors could exploit forged spectrum usage data to launch denial-of-service attacks. Although blockchain technology has been proposed through smart contracts to enhance transparency and security, its practical deployment remains constrained by high computational costs and latency issues – challenges that require further optimization.

3. Coordinatio classification and comparison of existing solutions

3.1. n-based spectrum sharing

3.1.1. Three strategies

In coordinated spectrum sharing schemes, the core objective is to achieve efficient coexistence between cellular networks and Wi-Fi through effective resource allocation and interference management. These solutions typically rely on predefined rules or dynamic adjustment mechanisms to ensure both technologies can meet their respective performance requirements while sharing spectrum resources. For instance, designing reasonable time slot allocation strategies allows Licensed Assisted Access (LAA) and Wi-Fi devices to transmit at staggered times, thereby reducing collision probabilities. Additionally, spatial multiplexing techniques combined with advanced methods like beamforming can further enhance spectrum utilization efficiency. To address compatibility issues arising from protocol differences, researchers have proposed various cross-layer optimization algorithms that enable comprehensive optimization from the physical layer to the MAC layer, thereby achieving better overall performance. Below are three coordinated spectrum sharing methods:

The Central Spectrum Coordinator (SC) collects global network information (e.g., traffic load, user distribution) and optimizes resource allocation. By integrating deep learning technology into the SC, it can predict traffic patterns and improve spectrum utilization by over 35%.

This solution employs a game theory model that treats cellular networks and Wi-Fi networks as independent participants. Through non-cooperative or cooperative games, a Nash equilibrium can be

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achieved. The novel evolutionary game framework enables adaptive strategy adjustments, with its convergence speed improving by 40% compared to traditional methods. The 3GPP Licensed Assisted Access (LAA) standard requires the use of a listen-before-talk (LBT) mechanism, which simulates Wi-Fi's Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Properly configured LBT mechanisms can keep Wi-Fi performance degradation within 15%.

3.1.2. Cellular network

The LBT-based cellular networks encompass the LAA protocol from the 4G era and the NR-U protocol for 5G. These networks employ a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism at the MAC layer, similar to WiFi's approach. In network modeling, they can be abstracted as WiFi networks with distinct access parameters, simplifying the modeling process [3]. A stochastic geometry analysis method was applied to evaluate performance metrics, including energy detection thresholds and mode switching probabilities in WiFi-LAA/NR-U coexistence networks, identifying optimal thresholds that maintain high transmission capacity and coverage. The study further analyzed throughput performance relationships between WiFi/LAA coexistence networks and network user density through stochastic geometry, revealing that user density impacts both networks differently. The study revealed that slot synchronization operations after backoff in LAA significantly impact network performance, with system improvement achievable through the Reservation Signal mechanism. Although establishing more complex Markov chain models enables performance analysis of non-saturated coexisting networks using different priorities, no explicit solution has been derived, leaving room for further network optimization. Beyond technical design considerations, practical implementation faces several key challenges.

3.2. Intelligent sharing solutions driven by artificial intelligence

In single-agent DRL, base stations learn optimal spectrum access strategies through environmental interactions, achieving a 25% LTE throughput boost without explicit coordination with Wi-Fi. Multi-agent DRL models multiple base stations as collaborative agents that share experiences to accelerate learning, ensuring minimum Wi-Fi throughput while increasing total system capacity by 40%. By integrating advanced machine learning and deep learning technologies, these solutions dynamically adapt to complex wireless environments for more efficient resource utilization. For instance, reinforcement learning algorithms not only optimize base station spectrum access strategies in single-agent scenarios but also enhance collaboration in multi-agent environments, significantly improving overall system performance. This distributed learning mechanism avoids the high complexity and communication overhead of traditional centralized approaches while ensuring fairness across different network environments.

Federated Learning (FL) enables multiple operators to collaboratively train global models without sharing raw local data, effectively safeguarding user privacy. Integrating FL with blockchain technology further enhances system security and auditability. Transfer learning reduces the required training sample size by 60% by transferring knowledge from one network environment to another. The introduction of FL significantly strengthens privacy protection capabilities [4]. Multiple network operators can jointly train global models without disclosing local data, enabling intelligent spectrum management. This approach is particularly suitable for scenarios involving sensitive user information, such as dedicated networks in healthcare or financial sectors. When combined with

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blockchain technology, FL not only improves data security but also enhances system transparency and auditability, providing reliable technical support for regulatory authorities.

To further enhance the practical value of AI-driven solutions, researchers are exploring ways to integrate these technologies with physical layer innovations. For instance, by jointly optimizing spectrum sensing and beamforming techniques, both spectral efficiency and signal coverage can be improved simultaneously.

3.3. Physical layer technology innovation

MIMO and Beamforming Technologies: Advanced multi-antenna systems enable spatial signal steering to reduce cross-system interference. The interference alignment scheme doubles spectral efficiency in dense environments. Three-dimensional beamforming proves particularly effective in vertical installations like high-rise buildings, effectively reducing inter-floor interference by over 15 decibels.

Capture effect utilization: Modern transceivers can decode strong signals correctly even in collision scenarios. A new two-dimensional Markov model provides a more accurate performance evaluation for LAA and Wi-Fi coexistence, reducing the prediction error from 30% to 5%.Figure 1 presents the newly proposed two-dimensional Markov chain model developed for physical layer innovation, effectively and clearly depicting state transitions of coexisting LAA and Wi-Fi networks in collision scenarios.

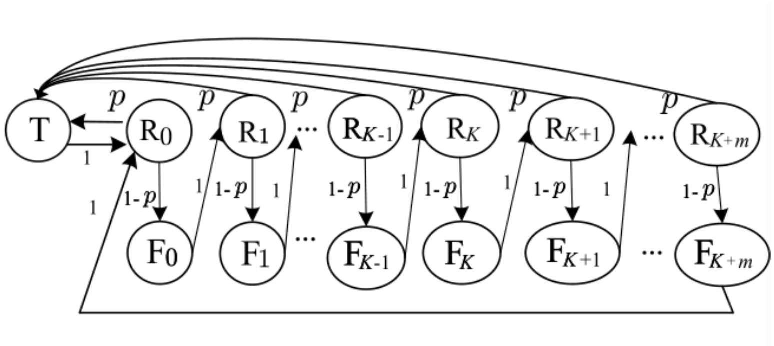

Figure 1. Markov chain

Full-duplex technology enables simultaneous signal transmission and reception on the same frequency band, theoretically doubling spectral efficiency. While self-interference cancellation technology achieves up to 80 dB signal suppression in laboratory environments, practical implementation still faces challenges. When applied to LAA small base stations, full-duplex technology has demonstrated a 40% capacity improvement, though its impact on Wi-Fi remains to be further investigated.

As a new entrant in the unlicensed frequency band, the fairness of cellular networks and WiFi networks is a concern of the industry. This paper focuses on this and proposes fairness constraints such as throughput fairness, proportionality fairness, access fairness, and 3GPP fairness. In the research on fair optimization of coexistence between cellular and WiFi networks, existing research work is divided into simulation-based [5]. There are four kinds: verification, based on a theoretical model, game theory, and artificial intelligence.

In physical layer innovation, researchers are tackling coexistence challenges between cellular networks and Wi-Fi by enhancing signal processing, modulation techniques, and spectrum efficiency. A standout solution is Adaptive Modulation and Coding (AMC), which dynamically

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adjusts transmission parameters based on channel conditions to boost throughput while minimizing interference [6]. Another crucial innovation is carrier aggregation technology, which enables simultaneous data transmission across multiple discrete frequency bands to enhance overall bandwidth efficiency [7]. For cellular networks, this technology achieves higher data rates without requiring additional spectrum resources while reserving more available frequency bands for Wi-Fi. However, implementation challenges such as cross-band synchronization and power control must be addressed to prevent new interference sources. The advancement of Multiple-Input Multiple-Output (MIMO) technology has also brought breakthroughs at the physical layer. Large-scale MIMO systems deploy numerous antenna elements to serve multiple users at the same time-frequency resources while providing spatial multiplexing gains.

4. Performance appraisal

4.1. The trade-off between throughput and fairness

System throughput measures the overall efficiency of shared resource allocation schemes, while fairness ensures balanced resource distribution. Compared to static allocation methods, intelligent algorithms consistently achieve higher throughput. Fairness is typically quantified by the Gini coefficient, with advanced solutions maintaining this index above 0.9 without significantly compromising throughput [8]. The throughput-fairness Pareto frontier established in recent research provides crucial guidance for system designers to balance these competing objectives.

4.2. Delay and reliability indicators

Compared to average latency, percentile-based latency metrics (e.g., 95th percentile) provide a more accurate reflection of user experience. A rigorous low-bit-rate mechanism can keep Wi-Fi 95th percentile latency within 20 milliseconds. For mission-critical services, the packet reception rate (PRR) target must exceed 99.9%. However, in high-traffic scenarios, existing shared solutions typically achieve only 95%-98% coverage. By implementing an optimal dynamic allocation algorithm, the service quality failure rate (i.e., service outage probability) can be reduced to below 1% [9].

4.3. Innovative evaluation methods

Digital twin technology: Creates a high-fidelity virtual copy of the physical network for large-scale testing, narrowing the gap between simulation and reality to an error margin of less than 5%.

Standardized test framework: ETSI and IEEE have released coexistence test specifications for LAA and Wi-Fi to ensure comparable and repeatable results [10].

Long-term evolution analysis: evaluates the robustness of shared solutions under dynamic conditions such as user mobility and traffic model changes. The deep learning-based solution improves long-term performance stability by 30% compared to traditional rule-based algorithms.

5. Future research directions

Future 6G systems are expected to utilize frequencies above 100 GHz (terahertz band). The propagation characteristics at these frequencies (e.g., high path loss, sensitivity to obstacles) will create new challenges and opportunities for spectrum sharing, requiring entirely new interference management and coordination protocols.

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RIS can dynamically control the wireless environment through programmable reflected electromagnetic waves. Theoretical studies show that the signal-to-noise ratio (SINR) can be increased by up to 20 dB, providing a revolutionary solution for interference control in shared spectrum.

The future of the same frequency band for both communications and radar-like sensing requires the development of a new shared framework that efficiently accommodates both uses without compromising either.

Generative AI can create highly realistic and diverse traffic scenarios for training, significantly improving the generalization ability of resource allocation models.

In computing power networks, joint optimization of computing task scheduling and spectrum allocation can reduce end-to-end delay by 30%.

As for semantic communication, the focus shifts from transmitting bits to conveying meaningful information. Resource allocation can be based on the semantic importance of content, which has the potential to revolutionize traditional efficiency metrics.

Current spectrum management regulations primarily rely on static allocation models, while future frameworks must support dynamic and flexible access mechanisms [11]. Research on blockchain-driven dynamic spectrum access systems and cross-carrier incentive mechanisms is crucial. Moreover, shared spectrum environments have created new attack surfaces, urgently requiring innovative authentication and security protocols to prevent vulnerability exploitation.

Green communication has become an increasingly vital area of focus in the evolution of spectrum sharing systems, as the growing demand for wireless connectivity continues to exert significant pressure on energy resources and environmental sustainability. Energy efficiency, in this context, is not merely a technical consideration but a core design objective that underpins the long-term viability of future communication networks.

6. Conclusions

Spectrum sharing between cellular networks and Wi-Fi systems is a critical strategy to address the global bandwidth crisis. With the widespread adoption of 5G technology and the rapid development of sixth-generation communication systems, licensed spectrum resources have become increasingly scarce. By designing access mechanisms for spectrum sharing, integrating cellular networks into unlicensed frequency bands has emerged as a vital approach to enhancing network performance. This paper tackles the challenges in current cellular-WiFi coexistence networks, including complex system interactions and insufficient quantitative analysis of fairness optimization. We establish theoretical models and optimize performance for duty-cycle-based NR-U/WiFi coexistence networks, providing access technology selection strategies for various network scenarios. Although significant progress has been made in coordination protocols, machine learning algorithms, and physical layer technologies, achieving perfect synergy still faces multiple challenges—particularly in fairness assurance, security, and ultra-strict quality of service (QoS) guarantees. The future of spectrum sharing lies in developing smarter, adaptive, and environmentally sustainable solutions. To fully realize the potential of shared spectrum resources for next-generation wireless networks, interdisciplinary collaboration across communication theory, artificial intelligence, and policy design must be prioritized.

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