

A Comprehensive Review of 5G Wireless Communication: Spectrum Diversity with Technological Innovations and Current Challenges

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Abstract: This paper provides a comprehensive overview of the fifth-generation (5G) wireless technology, focusing on its technological advancements, including diverse spectrum standards and critical challenges. It reviews the different frequency bands used in 5G, from sub-6 GHz to millimeter waves, and discusses their impact on network performance. Key challenges such as high deployment costs, complex spectrum management, and security vulnerabilities are explored. The paper also examines existing literature on 5G, highlighting research on network architecture, massive MIMO, and edge computing. By integrating these elements, the paper aims to offer a thorough understanding of 5G's current state and future prospects.

Keywords: *Wireless communication, 5G, IEEE, frequency*

1. Introduction

The fifth-generation (5G) wireless technology represents a transformative leap in global connectivity, promising unprecedented advancements in speed, latency, and network efficiency. Designed to surpass the capabilities of its predecessors, 5G is poised to revolutionize various sectors by delivering enhanced mobile broadband, ultra-reliable low latency, and massive connectivity. This survey explores the technological innovations that underpin 5G, including advancements in radio access networks, massive MIMO (Multiple Input Multiple Output), and beamforming techniques. It also delves into the evolution of network architecture with the introduction of service-based architecture and cloud-native principles. Furthermore, the paper examines the pivotal role of edge computing in reducing latency and improving performance, as well as the integration of 5G with emerging technologies like augmented reality (AR), virtual reality (VR), and autonomous vehicles. By investigating these technological advancements, this survey aims to provide a comprehensive understanding of how 5G is shaping the future of wireless communication and its potential impact on various industries. Despite its transformative potential, 5G technology faces several significant challenges. One major issue is the high cost associated with deploying 5G infrastructure, including the installation of small cells and the upgrade of existing network elements. This financial burden can hinder widespread adoption, especially in regions with limited resources. Additionally, the need for new spectrum bands, such as millimeter waves, introduces complexities related

to spectrum management and interference. Security remains a critical concern, as the expanded attack surface in 5G networks presents increased vulnerabilities to cyber threats. Furthermore, there are ongoing debates regarding the potential health impacts of increased electromagnetic exposure and public resistance to new infrastructure. Addressing these issues is crucial for realizing the full benefits of 5G and ensuring its successful integration into global communication networks.

2. Challenges in Wireless 5G communication

Some major challenges faced in 5G technology from 2020 onward:

1. Spectrum Allocation and Management:

- **Spectrum Scarcity:** Limited availability of high-frequency spectrum and the need for effective allocation.
- **Interference Management:** Challenges in managing interference, especially with the introduction of new frequency bands like millimeter waves.

2. Infrastructure Deployment:

- **High Costs:** Significant investment required for deploying 5G infrastructure, including small cells and upgraded backhaul networks.
- **Regulatory Hurdles:** Complex regulatory processes and local regulations affecting the deployment of 5G infrastructure.

3. Technical Complexity:

- **Integration with Legacy Systems:** Difficulties in integrating 5G technology with existing 4G and earlier network infrastructure.

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- **Network Slicing:** Complexities in implementing and managing network slicing to ensure different use cases have the appropriate network resources.
4. **Security and Privacy:**
 - **Increased Attack Surface:** Expanded attack vectors due to the increased number of connected devices and more complex network architecture.
 - **Data Privacy Concerns:** Ensuring the privacy and security of user data in a highly interconnected environment.
 5. **Latency and Reliability:**
 - **Real-World Performance:** Challenges in achieving the promised ultra-low latency and high reliability in practical deployments.
 - **Quality of Service (QoS):** Maintaining consistent QoS across diverse applications and user environments.
 6. **Health Concerns:**
 - **Public Perception:** Concerns and debates over potential health effects of increased exposure to electromagnetic fields from 5G infrastructure.
 7. **Economic and Market Factors:**
 - **Return on Investment:** Uncertainties regarding the

financial return on investment for 5G deployment and adoption.

- **Market Fragmentation:** Variability in 5G adoption and deployment across different regions and markets.

3. Standards used in 5G communication network

The 5G spectrum is characterized by its use of three distinct frequency ranges, each governed by specific IEEE standards to address various performance and coverage needs. These ranges are categorized into low-band, mid-band, and high-band frequencies. Low-band frequencies, often referred to as Sub-1 GHz, offer extensive coverage and better penetration through obstacles but with lower data rates. Mid-band frequencies, such as those in the 1-6 GHz range, provide a balanced approach, offering higher speeds and moderate coverage. High-band frequencies, or millimeter waves (24 GHz and above), deliver the highest data rates and capacity but with limited range and penetration. These frequency ranges are standardized under IEEE 802.11 and other related standards to optimize 5G network performance across different applications and deployment scenarios.

The different frequency range comes under 5G spectrum is represented with three known IEEE standards are as follows:

Table 1: Different IEEE based 5G spectrum

Specification	802.11an	802.11ac	802.11ad	802.11af
Frequency Bands	2.4 GHz, 4.9 GHz, 5 GHz	5 GHz	60 GHz	0.47–0.71 GHz
Modulation Techniques	OFDM	OFDM	OFDM, Single Carrier, Low-Power	OFDM
Channel Bandwidth	20, 40 MHz	20, 40, 80 MHz (160 MHz optional)	2 GHz	5, 10, 20, 40 MHz
Maximum Data Rate (Single Stream)	Up to 150 Mbps (1x1, 40 MHz)	Up to 433 Mbps (1x1, 80 MHz),	Up to 4.6 Gbps	Up to 54 Mbps
Up to 867 Mbps (1x1, 160 MHz)				
Maximum Data Rate (Multiple Streams)	Up to 600 Mbps (4x4, 40 MHz)	Up to 1.73 Gbps (4x4, 80 MHz),	Up to 7 Gbps	
Up to 3.47 Gbps (4x4, 160 MHz)				
Spectral Efficiency	15 bps/Hz (4x4, 40 MHz)	21.665 bps/Hz (4x4, 80 MHz)	1 bps/Hz (2 GHz)	Not Available
Effective Isotropic Radiated Power (EIRP)	22-36 dBm	22-29 dBm	1-10 dBm	16-20 dBm
Indoor Range	12-70 meters	12-35 meters	60 meters	<100 meters
Outdoor Range			100 meters	<5 km

Penetration Through Walls	Yes	Yes	Yes	Yes
Non-Line-of-Sight Operation	Yes	Yes	Yes	Yes
Global Availability	Yes	Yes (Limited in China)	Yes	Yes

The IEEE 802.11 standards define various specifications for wireless communication, each tailored to different frequency bands and performance requirements. The 802.11an standard operates in the 2.4 GHz, 4.9 GHz, and 5 GHz bands, utilizing OFDM modulation with channel bandwidths of 20 and 40 MHz, achieving maximum data rates of up to 150 Mbps for a single stream and 600 Mbps for multiple streams. In contrast, 802.11ac, which is confined to the 5 GHz band, supports higher data rates up to 867 Mbps per stream and 1.73 Gbps across multiple streams, with optional channel bandwidths of up to 160 MHz. The 802.11ad standard, operating at 60 GHz, provides significantly higher data rates of up to 4.6 Gbps for single streams and 7 Gbps for multiple streams, though its range is more limited. Meanwhile, 802.11af, utilizing frequencies from 0.47 to 0.71 GHz, offers a maximum data rate of 54 Mbps, with a longer outdoor range of up to 5 km. All these standards support penetration through walls and non-line-of-sight operation, but their global availability and effective isotropic radiated power (EIRP) vary, influencing their deployment and use cases across different regions.

4. Literature Review

In [Zaidan et al. (2020)], the authors provide an in-depth analysis of the architecture and emerging technologies in 5G networks. They discuss advancements such as millimeter waves, massive MIMO, and network slicing, which are crucial for understanding the foundation and capabilities of 5G networks.

Ali, Haq, and colleagues (2021) offer a comprehensive survey on 5G technology, network architecture, and emerging applications. Their review highlights the technological innovations and potential uses of 5G, providing valuable insights into how this technology is shaping the future of connectivity (Ali et al., 2021).

Zhang, Liu, and their team (2021) focus on the security challenges and solutions in 5G networks. Their survey addresses the security threats inherent in 5G systems and discusses various strategies to mitigate these risks (Zhang et al., 2021).

Ali, Ali, and others (2020) explore the concept of network slicing in 5G, detailing the technologies and applications involved. They also examine the challenges associated with implementing network slicing and its implications for network management (Ali et al., 2020).

Xu, Li, and their colleagues (2020) identify and analyze the major challenges and opportunities presented by 5G technology. Their comprehensive review covers various aspects of 5G and provides a thorough understanding of the current landscape and future prospects (Xu et al., 2020).

Alomar, AlShamari, and their team (2021) review the key enabling technologies of 5G and discuss potential future directions. Their survey focuses on the technological advancements that make 5G possible and the areas where further research is needed ([Alomar et al., 2021]).

Kumar, Kumar, and others (2021) provide insights into recent developments in 5G, highlighting ongoing challenges and suggesting future research areas. Their review offers a snapshot of the current state of 5G technology and its evolving nature (Kumar et al., 2021).

Sharma, Verma, and their team (2021) examine the evolution of wireless networks from 5G to future generations. Their survey includes key advancements and trends, providing a perspective on how wireless technology is expected to develop (Sharma et al., 2021).

Zhang, Wang, and colleagues (2020) review the integration of edge computing with 5G networks. They discuss how edge computing enhances the performance and application of 5G systems, highlighting its role in reducing latency and improving efficiency (Zhang et al., 2020).

Liu, Zhang, and their team (2021) survey various network architectures and techniques used in 5G wireless communication systems. Their review covers the different approaches and technologies that underpin 5G networks (Liu et al., 2021).

Table 1 shows various existing works in wireless 5G communication networks.

Table 1: Comparative analysis of various existing works

Reference	Focus	Key Topics Covered	Findings
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Ali et al. (2020)	Network Slicing	Technologies, applications, challenges of network slicing	In-depth analysis of network slicing; challenges and solutions
Ali et al. (2021)	5G Technology and Applications	Technology, network architecture, emerging applications	Comprehensive review of 5G technology and its applications
Alomar et al. (2021)	Enabling Technologies and Future Directions	Key technologies, future research directions	Reviews crucial enabling technologies and future directions for 5G
Kumar et al. (2021)	Recent Developments, Challenges, Future Directions	Developments, challenges, future research areas	Provides insights into current developments and future research
Liu et al. (2021)	Network Architectures and Techniques	Network architectures, techniques used in 5G systems	Surveys various architectures and techniques used in 5G
Sharma et al. (2021)	Evolution of Wireless Networks	Evolution from 5G to future generations	Examines advancements and trends in wireless networks beyond 5G
Xu et al. (2020)	Challenges and Opportunities in 5G	Challenges, opportunities associated with 5G	Identifies key challenges and opportunities in 5G technology
Zaidan et al. (2020)	Architecture and Emerging Technologies	5G network architecture, millimeter waves, massive MIMO	Discusses 5G architecture and technologies like millimeter waves and MIMO
Zhang et al. (2020)	Edge Computing in 5G	Integration of edge computing with 5G	Reviews impact of edge computing on 5G performance and applications
Zhang et al. (2021)	5G Network Security Challenges and Solutions	Security challenges, solutions in 5G networks	Reviews security threats and potential solutions in 5G networks

The most of the research objectives identified from table 2 are to explore the advancements in 5G technology, focusing on network slicing, enabling technologies, and architectural innovations, while also identifying and addressing the key challenges, such as security, spectrum management, and integration with emerging technologies. This research aims to provide insights into the future directions of 5G and its impact on global connectivity and communication networks.

5. Conclusion

In conclusion, the evolution of IEEE 802.11 standards—spanning 802.11an, 802.11ac, 802.11ad, and 802.11af—highlights the diverse challenges and opportunities within wireless communication. Each standard addresses unique frequency bands and modulation techniques, presenting different trade-offs between data rates, coverage, and spectral efficiency. The role of spectrum allocation is critical, as it influences the performance and deployment of these technologies. For instance, while 802.11ad

achieves remarkable data rates in the 60 GHz band, its limited range poses significant deployment challenges, particularly in non-line-of-sight scenarios. Conversely, 802.11af's use of lower frequencies allows for extended range but at the cost of reduced data rates. Existing literature has extensively explored these standards, examining their applicability across various environments and use cases. Studies have focused on optimizing spectral efficiency, managing interference, and addressing the limitations of each frequency band. However, challenges such as the high deployment costs of advanced standards like 802.11ad and the need for global spectrum harmonization remain unresolved. As wireless communication continues to advance, understanding the role of spectrum and addressing these challenges will be key to maximizing the potential of these technologies and ensuring their successful integration into next-generation networks.

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