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Review

Coexistence in Wireless Networks: Challenges and Opportunities

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Abstract: The potential consequences of interference on communication networks are one of the main challenges in the nature and efficiency of wireless communication links. The interruption is seen as additional noise to the device, which can have a major impact on the efficiency of the connection. The rapid expansion of broadband wireless networks and the increasing congestion of the radio frequency spectrum due to shared usage by terrestrial and satellite networks have heightened concerns about potential interference. To optimize spectrum utilization, multiple terrestrial and satellite networks often coexist within the same frequency bands allocated for satellite communications services. Spectrum interference in wireless networks is a topic of much interest in the current scenario as it can present a lot of challenges. This article provides a critical review of the coexistence and spectrum sharing in wireless networks. Along with this, mitigation techniques to avoid interference have also been discussed in detail. The article aims to give a detailed discussion on the challenges and opportunities in this field by reviewing significant recent works in this field.

Keywords: coexistence; interference; spectrum sharing; wireless networks; 5G

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1. Introduction

The network densification and spectrum bands available to many technologies are projected to meet the rising capacity demands in new wireless technologies [1]. As a result, the degree of interference will rise, as will the complexity of inter-technology interactions, which will require spectrum sharing methods to handle [2]. It is imperative to devise innovative spectrum sharing methodologies that enable various technologies to access the spectrum efficiently, thereby optimizing its overall utilization. Developing such systems is a complex endeavor, hindered not only by technological challenges but also by legal and economic limitations [3]. The millimeter-wave (mm Wave) frequency range proves suitable for future wireless networks focused on short-range, high-speed communication due to its broader spectrum and higher frequencies, compared to current frequency bands [4]. As a relatively new technology, mm Wave systems should be designed to seamlessly interoperate with existing services and complement other technologies to improve overall network performance. Consequently, the challenges associated with coexistence have emerged as a pivotal issue in the realm of next-generation wireless communications [5].

As the demand for seamless mobile connectivity continues to grow, the IMT-2020 (5G) system, hereafter referred to as 5G, is emerging as a pivotal technology for ensuring comprehensive global broadband coverage in the future [6]. 5G has important features such as delivering low-latency, high-speed connectivity, uniform service with high traffic volume, support for countless connected devices, and exceptional mobility across various scenarios. To address the escalating demand for high data rate services, fifth-generation (5G) technology is being developed to enhance network performance and introduce new capabilities such as high-speed data transmission, ultra-low latency, and massive connectivity [7].

To enhance spectrum efficiency and effectively support high data rates, one viable approach is to identify additional available spectrum resources. Nevertheless, improving spectrum efficiency poses a formidable challenge, particularly in sub-3 GHz bands, where the spectrum is congested, fragmented, and inefficiently utilized across heterogeneous wireless networks, resulting in interference issues. The 3400–3600 MHz frequency band offers a wider contiguous bandwidth compared to lower frequency bands and has superior propagation characteristics relative to higher frequency bands. Consequently, it has emerged as a pivotal frequency band for the commercial deployment of 5G systems [8].

2. Related Survey

The coexistence of satellite and terrestrial communication within the millimeter wave (mm Wave) spectrum presents unique challenges and opportunities, warranting dedicated investigation. While satellite systems operate in various frequency bands, such as the S-band and Ka-band, the mm Wave spectrum is particularly relevant due to its critical role in next-generation broadband communication, including 5G and beyond. The high spectrum availability in mm Wave frequencies makes it attractive for both satellite and terrestrial applications, necessitating effective spectrum sharing strategies to mitigate interference and enhance coexistence. This section reviews key studies that explore coexistence challenges in mm Wave bands, along with their proposed mitigation techniques, while highlighting their limitations and interconnections.

Several surveys have systematically analyzed interference scenarios and spectrum sharing strategies in mm Wave communication. One such study [9] investigated the design space for spectrum sharing across different system layers, emphasizing the impact of inter-technology coexistence. While this study provides a structured overview of interference challenges, it lacks a detailed evaluation of the real-world implementation constraints. Another survey [10] explored the synergy between radar and communication systems, discussing waveform design, signal modeling, and processing techniques. This work contributes to the understanding of spectrum coexistence, yet it primarily focuses on theoretical modeling rather than practical deployment challenges. The study in [11] briefly examines the advancements in satellite communication, providing insights into present and future applications. However, it lacks an in-depth discussion of coexistence issues specific to mm Wave frequencies, making it a complementary reference rather than a core analysis of spectrum sharing.

Further research has delved into frequency reuse strategies within both satellite and mobile cellular systems. Ref. [12] comprehensively examines coexistence challenges in broadband mm Wave communication, covering interactions with fixed services, non-orthogonal multiple access (NOMA), and microwave systems. Additionally, an extensive study [13] investigated radar systems operating in the 5 GHz band, discussing spectrum regulations and sharing principles. Although this research provides a foundational understanding of spectrum sharing strategies, its focus on the 5 GHz band makes its findings less directly applicable to mm Wave coexistence. Finally, another survey [14] examined heterogeneous wireless networks operating in TV white spaces, offering a comparative analysis of different coexistence techniques. While its insights on spectrum sharing mechanisms are valuable, the study does not specifically address the coexistence of mm Wave satellite and terrestrial systems.

However, recent advancements have significantly expanded on these topics, addressing new coexistence challenges. For instance, the emergence of mm Wave-based networking and sensing applications, such as mNetS [15] and CoSense [16], demonstrates novel approaches to integrating networking with sensing for applications in health diagnostics and traffic monitoring. These systems optimize coexistence by leveraging idle periods and deep learning models to enhance sensing resolution, without significantly affecting network throughput. This directly aligns with the objectives of our work, which seeks to optimize resource utilization in congested mm Wave environments by exploiting temporal and spatial variations in traffic.

To address spectrum congestion, bidirectional data offloading techniques have been proposed to optimize spectrum and power allocation in coexisting 5G and Wi-Fi networks at 60 GHz [17]. This approach, which maximizes the sum rate through resource allocation, reflects the growing trend towards dynamic spectrum management, a key consideration in our investigation. Concerns about interference between terrestrial networks and satellite services in shared frequency bands have been extensively analyzed. Studies on co-channel interference and out-of-band emissions provide critical guidelines for protecting satellite services while optimizing terrestrial network deployment [18]. Furthermore, intelligent resource allocation strategies have been explored to manage interference in hybrid satellite–terrestrial networks, ensuring efficient coexistence in congested environments [19]. These studies highlight the importance of adaptive interference management, which is a central theme in our research.

With the growing interest in expanding spectrum access, particularly in the 12 GHz band, recent research emphasizes the need for adaptive spectrum sharing policies to enable the integration of 5G terrestrial services while mitigating interference with incumbent systems [20]. This focus on dynamic spectrum access aligns with our investigation into flexible resource allocation strategies. Furthermore, advancements in reconfigurable hardware, such as the reconfigurable substrate integrated waveguide (SIW) filtenna operating in the 5G mm Wave band [21], offer promising solutions for reducing adjacent channel interference and enabling passive spectrum coexistence. Similarly, joint multi-dimensional resource allocation algorithms based on block coordinate descent have been proposed to optimize uplink throughput in 5G/Wi-Fi coexisting mm Wave networks [22], addressing the growing demand for high throughput in hotspots. These recent developments illustrate the importance of adaptive techniques in managing interference and optimizing resource allocation, which are the core elements of our research. By incorporating these findings, this review extends prior research and addresses the evolving landscape of coexistence challenges in wireless networks, highlighting the need for dynamic and intelligent resource management strategies to ensure efficient and harmonious spectrum utilization.

3. Types of Wireless Communication

Wireless communication networks transmit data through electromagnetic waves instead of using physical cables. Wireless communication networks have emerged as a dominant force, supplanting wired connections in many applications [23,24]. Leveraging radio waves for data transmission, these networks offer unparalleled flexibility and mobility, enabling communication between devices without physical cables. This technology has fostered significant advancements in areas like mobile computing, internet access, and home automation, fundamentally altering how we connect and share information in the modern world [25]. Figure 1 shows the different types of wireless communication systems.

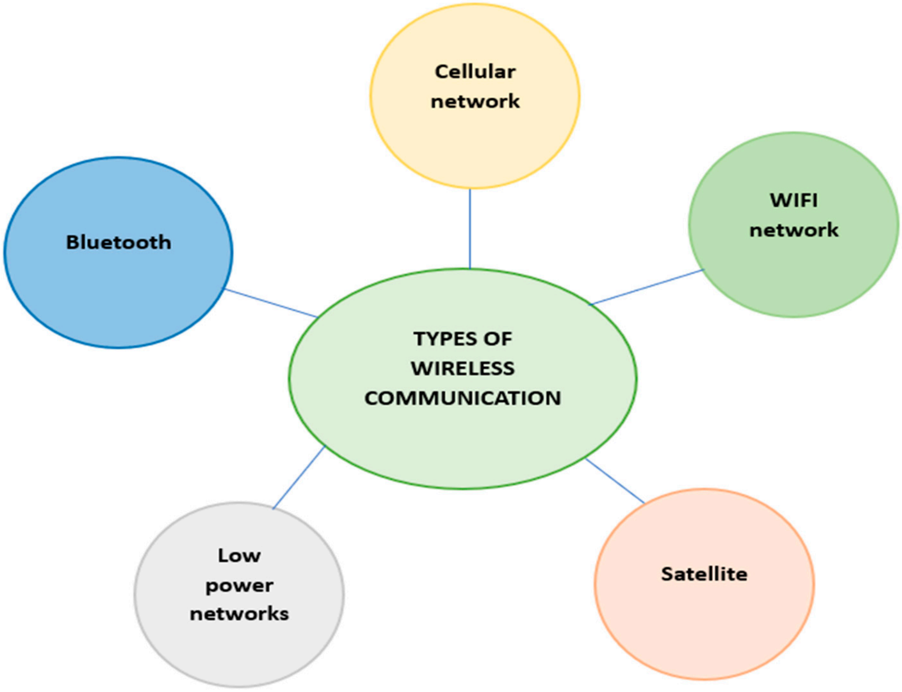

Figure 1. Types of wireless networks.

3.1. Cellular Networks

A cellular network is a form of wireless communication system that divides the coverage area into cells supplied by base stations or cell towers in order to deliver voice and data services to mobile devices over a large geographic area [26–28]. These networks have undergone several waves of development through time, with each generation offering advances in data speed, coverage, and capabilities [29]. The partitioning of the coverage area into discrete geographic areas known as cells is where the word "cellular" originates from [30].

Despite their diverse technological implementations, various wireless systems share a common network architecture comprising three primary components as follows: the mobile device, the radio access network (RAN), and the core network, as illustrated in Figure 2.

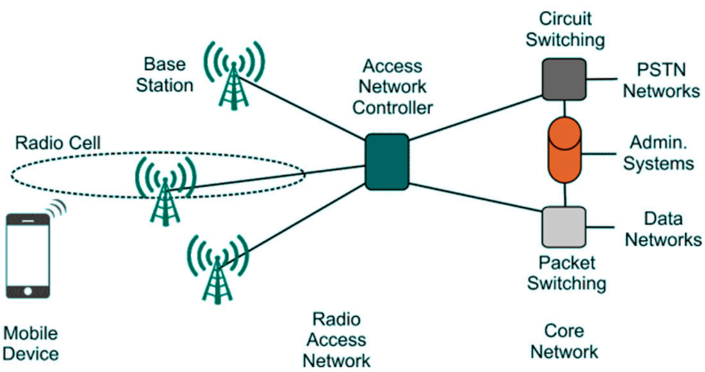

Figure 2. General architecture for cellular networks [31].

3.2. Wi-Fi Networks

Wi-Fi networks, often referred to as Wireless Fidelity networks, are a type of wireless local area network (LAN) technology that enables devices to connect to the internet and communicate with one another wirelessly inside a constrained space [32–34]. Wi-Fi networks are secured through protocols such as WPA, WPA2, and WPA3, ensuring data encryption and connection safety. Wi-Fi is frequently used to wirelessly connect devices like smartphones, computers, tablets, and smart home appliances to the internet in homes, offices, public spaces, and various other locations, as shown in Figure 3 [35,36]. Recent advancements, such as mesh networks for eliminating dead zones, highlight the pivotal role of Wi-Fi in enabling modern communication and supporting the growth of smart technologies.

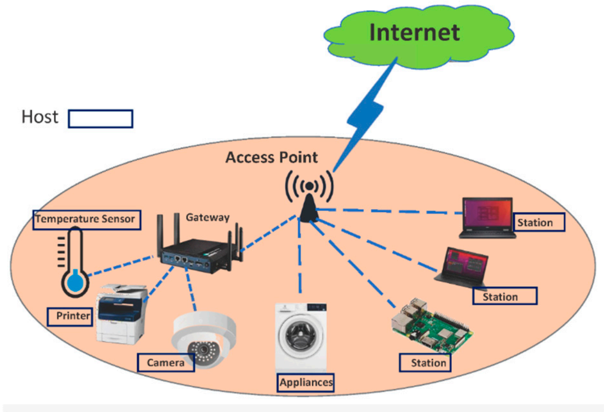

Figure 3. Example of a LAN for an IOT system [37].

Bluetooth and Bluetooth Low Energy (BLE): Bluetooth is a short-range wireless technology that enables devices to connect and exchange data over short distances, typically up to 100 m [38]. It was initially created for voice communication and information exchange between electronic devices like PCs, headsets, and cellphones. Bluetooth has developed over time to offer a number of profiles and services, such as audio streaming, file sharing, and device pairing [39]. A Bluetooth extension known as Bluetooth Low Energy was created for applications that only need sporadic data exchanges, optimized for minimal battery consumption [40]. Fitness trackers, smartwatches, and other IoT gadgets that frequently run on batteries are excellent candidates for BLE [41]. Like conventional Bluetooth, it uses the 2.4 GHz radio spectrum to operate [42]. Recent advancements, such as Bluetooth 5.0 and beyond, have enhanced BLE's range, speed, and support for mesh networking, further solidifying its role in modern wireless ecosystems. Both Bluetooth and BLE play complementary roles, enabling seamless connectivity across diverse applications.

3.3. Zigbee and Other Low-Power Wireless Networks

Zigbee networks are a kind of low-power wireless communication system designed for controlling and transferring data over short distances [43,44]. Zigbee networks are characterized by their mesh topology, which enables devices to communicate directly or relay data through intermediate nodes, improving range and reliability. It supports up to 65,000 nodes, making it highly scalable for large networks. Zigbee is frequently used in situations where devices need to interact wirelessly while using the least amount of power, which makes it suitable for use in sensor networks, home automation, and industrial control [45]. Some other examples of similar low-power networks are Z-Wave and Thread [46,47].

Other low-power wireless networks, such as Z-Wave, Long Range Wide Area Network (LoRaWAN), and Thread, complement Zigbee by targeting similar use cases with unique strengths. Z-Wave operates in the sub-1 GHz band, reducing interference and extending the range, making it popular in smart home devices. LoRaWAN is designed for long-range, low-power communication, often used in industrial IoT and smart city applications. Thread, like Zigbee, leverages IEEE 802.15.4 but focuses on IPv6-based communication for seamless internet integration. These networks prioritize low power consumption to extend the battery life of the connected devices, making them essential for IoT deployments. Each protocol caters to specific requirements, from Zigbee's robust mesh networking to LoRaWAN's extensive coverage, ensuring flexibility in low-power wireless communication across diverse environments. Together, they enable scalable, energy-efficient solutions for smart technologies.

3.4. Satellite Communication Systems

Satellite communication systems are advanced technologies that enable the transmission of data, voice, and video signals over long distances by utilizing satellites in the Earth's orbit. These systems play a crucial role in connecting remote and inaccessible areas where terrestrial communication infrastructure is limited or unavailable. Satellite communications operate through a network of ground stations, user terminals, and orbiting satellites, using radio frequencies in various bands, such as the C-band, Ku-band, Ka-band, and L-band, to provide global coverage [48]. Particularly in regions with sparse or nonexistent terrestrial communication infrastructure, these systems are essential for enabling global connectivity [49]. Wide-area coverage is made possible through satellite communication, which is utilized for many purposes such as navigation, internet access, military communication, television transmission, and more [50]. Depending on the use and coverage region, communication satellites are deployed in a variety of orbits, including medium Earth Orbit (MEO), geostationary Orbit (GEO), and low Earth Orbit (LEO) [51], as shown in Figure 4.

Satellite communication systems are widely used in various domains, including broadcasting, global positioning systems (GPS), disaster management, remote sensing, and military operations [52]. The emergence of high-throughput satellites (HTS) and satellite constellations like SpaceX's Starlink and OneWeb has revolutionized the industry, enabling high-speed internet access even in the most remote locations. These systems are pivotal in bridging the digital divide and supporting the global communication infrastructure.

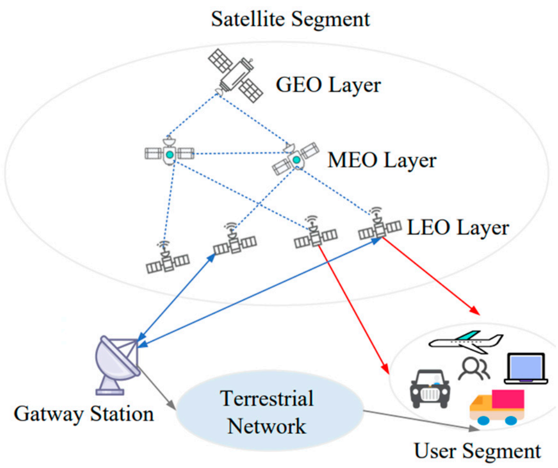

Figure 4. Multi-layer satellite networks [53].

4. Spectrum Sharing and Coexistence

The mm Wave band, boasting higher frequencies and a wider spectrum than traditional frequency bands, proves to be an ideal candidate for future wireless networks, emphasizing high-speed, short-range communication [54]. As an emerging technology, millimeter wave is expected to be interoperable with existing systems and capable of collaborating with other technologies to enhance overall network performance. Consequently, addressing coexistence challenges has become a crucial aspect of next-generation wireless communications [55].

The coexistence of wireless networks is essential for effective communication between various technologies, such as satellite systems, 5G, and mm Wave. For each of these, specific strategies are needed to reduce interference and maximize spectrum utilization. Because of their narrow propagation ranges and great sensitivity to interference, millimeter-wave coexistence in 5G presents difficulties. While Dynamic Spectrum Sharing (DSS), as demonstrated by Verizon's implementation, allows for smooth cohabitation across mm Wave and sub-6 GHz bands, beamforming and massive MIMO reduce signal overlap. Dynamic spectrum access strategies have been shown to improve dependability in real-world urban microcell experiments [56].

Spectrum sharing techniques like Carrier Aggregation (CA), which enable LTE and 5G to function on different carriers while maximizing throughput, are necessary for 5G and LTE coexistence. Operators such as NTT Docomo have implemented network slicing, which reduces interference by allowing independent service operation within shared networks. Spectrum sharing issues arise when satellites and terrestrial networks interact. Multi-operator studies have shown that Reverse Spectrum Allocation dynamically reallocates frequencies in order to reduce interference [57]. Furthermore, AI-based power control reduces interference in terrestrial 5G networks by regulating satellite uplink transmissions.

Figure 5 illustrates the coexistence of the following three major communication systems: radar communication, terrestrial communication, and satellite communication. The central "Coexistence" node signifies the interplay and spectrum sharing between these technologies. The arrows indicate bidirectional interactions, showing how each system influences and depends on others.

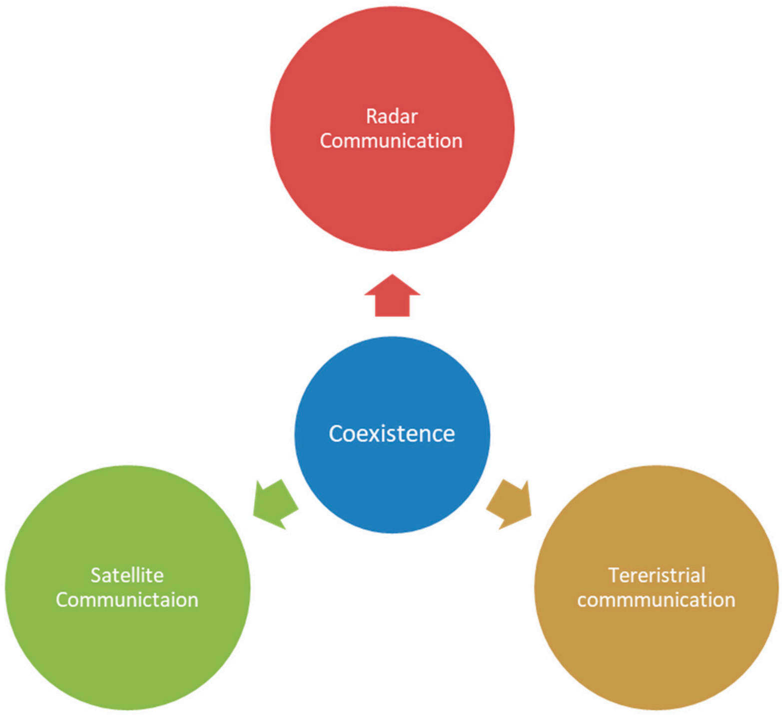

Figure 5. Coexistence of communication networks.

4.1. Coexistence in Radar Networks

Spectrum sharing between radar and communication systems has emerged as a critical research area. The growing prominence of radar technology, with applications ranging from autonomous vehicles to Internet of Things (IoT) devices, has intensified the need for efficient spectrum utilization [58]. However, as the proliferation of radars continues, ensuring their ability to coexist and function without mutual interference is becoming increasingly vital. This challenge is referred to as coexistence in radar networks.

Convolutional Neural Network (CNN)-based techniques for interference reduction and denoising in [59] produce promising performance outcomes for radar processing. Nevertheless, these models usually require more memory to operate because they have millions of parameters that are kept in hundreds of megabytes of memory [60–62]. Previously, studied examined quantization methods for CNN-based radar signal denoising and interference reduction. These studied investigated the potential of various CNN architectures and sizes for quantization by employing piecewise constant activation functions and quantized weights. This approach aims to reduce memory consumption during both model storage and inference. Figure 6 represents a deep learning-based interference mitigation model designed to process and reduce noise in communication signals. The input layer receives raw signals, which pass through multiple convolutional and feature extraction layers that identify interference patterns. These layers apply filtering, normalization, and activation functions to suppress interference while preserving the original signal. The final output layer produces a refined signal with minimized interference, enhancing communication reliability.

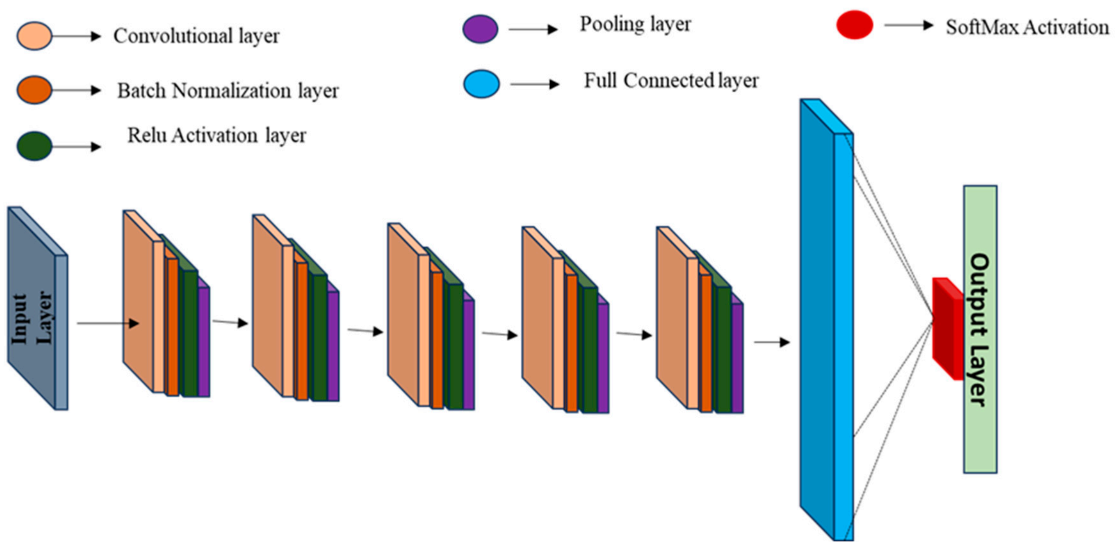

Figure 6. CNN architecture for denoising.

In order to maximize the available bandwidth and accomplish both radar detection and communication, Ref. [63] offers a novel transmission approach. With a receiver system that enables channel estimation for radar without compromising the communication data rate, the technique combines orthogonal frequency-division multiplexing (OFDM) for communication and frequency-modulated continuous wave (FMCW) for radar. The results demonstrate that the system provides good sensing accuracy under low SNR circumstances and communication performance that is only slightly lower than a perfect CSI scenario. More specifically, the uplink of a large MIMO communication system coexisting with a radar system within the same frequency band was investigated in [64]. Radar-generated clutter at the MIMO receiver is considered in the system's model. Several linear receiver architectures, ranging from simple channel-matched beamforming to advanced zero-forcing and linear minimum mean square error techniques, have been proposed to mitigate the effects of channel congestion. These studies demonstrate that clutter significantly impacts cellular communication system performance and highlight the critical role of large-scale antenna arrays at the base station in enhancing data detection and system robustness.

A hybrid radar communication approach is depicted in [65], inserting data into chirp sub-carriers using Fractional Fourier Transform (FrFT) multiplexing with varying time-frequency rates. The goal of the optimization techniques are to improve the Bit Error Rate (BER) and bandwidth occupancy. When compared to a conventional Linear Frequency Modulated (LFM) pulse of comparable duration and bandwidth, the FrFT waveform preserves the radar characteristics while providing better performance, such as a lower BER and strong resistance to channel distortions. A solution for coexisting downlink communication and MIMO radar systems is provided in [66]. By employing a constructive MUI and exchanging multi-user interference power for reduced transmit power, the method strikes a compromise between power efficiency and performance. A gradient projection method is used to address the power reduction problem while considering the effect of BS interference on MIMO radar systems. Additionally, the technique employs a strong power minimization strategy to deal with faulty channel information. The outcomes demonstrate that the suggested strategy preserves performance–complexity balance while saving energy costs.

4.2. Coexistence in Satellite Communication

The rapid rise of internet applications and services has intensified the demand for high-speed, versatile, and reliable communication networks with minimal latency. Consequently, satellite communications have entered a critical phase of development [60]. Satellites can significantly contribute to meeting this demand, either as standalone systems or as integrated satellite–terrestrial networks, leveraging their unique capabilities and technological advancements [67]. Figure 7 illustrates the interference in satellite and terrestrial communication networks, where multiple signals overlap, causing disruptions. The satellite transmits signals to ground stations, but interference sources, such as overlapping frequency bands or environmental factors, introduce noise. Wireless communication devices and base stations also contribute to interference, affecting signal clarity and reception. The distorted signals can degrade communication quality, leading to data loss, increased latency, or connectivity issues.

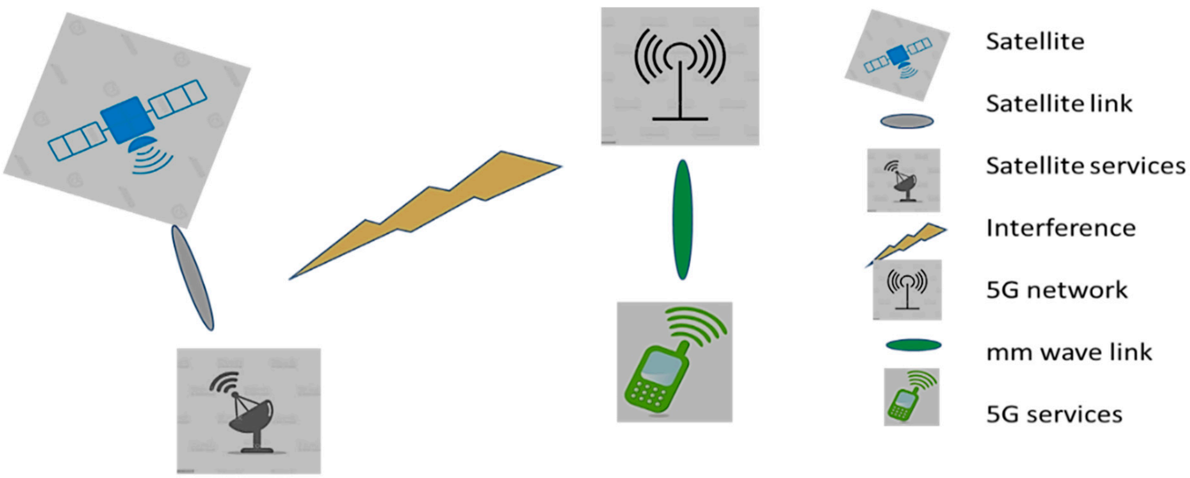

Figure 7. Coexistence of the 5G signal and satellite services.

Facilitating communication across great distances and in isolated areas, satellite communication is an essential part of contemporary communication systems [68]. However, the coexistence of satellite communication systems has become an important issue because of the growing number of satellite systems and the limited amount of orbital space that is accessible [69]. 5G cellular systems operating below 6 GHz are provided in [70]. The study analyzes the potential impact of out-of-band emissions, receiver saturation, and active antenna systems on both the uplink and downlink performance. The outcomes will inform the assessment of how future 5G deployments may affect C-band satellite Earth station receivers and the related stakeholders. It suggests and tests possible ways that enable both systems to coexist more easily, such as turning off essential emitters or reducing the power of their transmission.

Muhammad and Anwar [71] developed a methodology to assess the compatibility of existing satellite networks and emerging 5G services within the millimeter-wave spectrum, aligned with the IMT-2020 framework. This study modeled signal propagation and analyzed interference between fixed satellite services (FSS) operating in the same band and adjacent-channel passive Earth exploration satellite services (EESS). The results indicate that FSS satellites may experience up to 7.9 dB of increased interference, while most EESS sensors fail to meet safety standards. To ensure coexistence, additional spectrum allocation or interference mitigation measures are necessary. This approach can also be applied to assess interference from non-terrestrial platforms such as airships, balloons, and UAVs. A smart antenna system employing the Recursive Least Squares (RLS) algorithm for adaptive beamforming is proposed in [72] to facilitate coexistence between FSS and 5G networks. The RLS algorithm is utilized to generate a null beam directed toward FSS Earth stations, thereby mitigating interference. The simulation results demonstrate that this approach significantly reduces the required separation distance between 5G base stations and FSS Earth stations, enabling effective coexistence with minimal interference.

Ensuring the coexistence of satellite communication systems is a complex challenge that necessitates a multi-disciplinary approach. This involves several key strategies, such as interference mitigation, spectrum management, and advanced signal processing techniques. Interference mitigation focuses on reducing the potential disruptions caused by overlapping signals, while spectrum management involves carefully allocating frequency bands to avoid conflicts. Advanced signal processing techniques are employed to enhance the clarity and reliability of the communication. With ongoing research and development, these strategies can be refined to ensure that multiple satellite communication systems can operate efficiently and reliably within the same orbital space.

4.3. Coexistence in Terrestrial Communication

The deployment of the fifth generation of mobile radio communication by 2020 was projected to face several challenges, including a rise in service demand with low latency, in order to service billions of end customers known as satellite mobile users [73]. Terrestrial communication systems will most likely meet a thick network of countless small cells at any time and anywhere. As a result, services from terrestrial systems are unavailable to some of the world's most remote locations [74]. Moreover, effective interference control is necessary to share the spectrum between satellite systems and terrestrial equipment because of the limited supply of spectral resources.

Two channel assignment algorithms for maximizing multicast coverage in terrestrial networks are analyzed in [75]. The study investigates the interactions and coexistence of different channel assignment systems operating within the same area and spectrum. Multiple base stations within a common service area are considered, and network performance is evaluated based on the coverage area and the signal-to-interference-plus-noise ratio (SINR). It has been demonstrated that combining different schemes can be beneficial, since blended systems can benefit from the best aspects of each plan. A coexistence test scenario was established across multiple channels with randomly positioned terrestrial base stations to simplify the analysis. Figure 8 represents a base station (BS) coverage and coexistence model, illustrating the overlapping service areas of multiple base stations. Each colored region represents the coverage area of a different BS (BS1, BS2, BS3, BS5, etc.), highlighting how multiple base stations coexist within an 8 km radius. Larger coverage areas, such as BS 5. . .BS i, indicate extended network service regions, while smaller zones represent localized base stations that provide targeted connectivity. The overlapping areas suggest potential interference zones, where multiple BS signals interact, requiring efficient frequency management and interference mitigation techniques to maintain seamless communication.

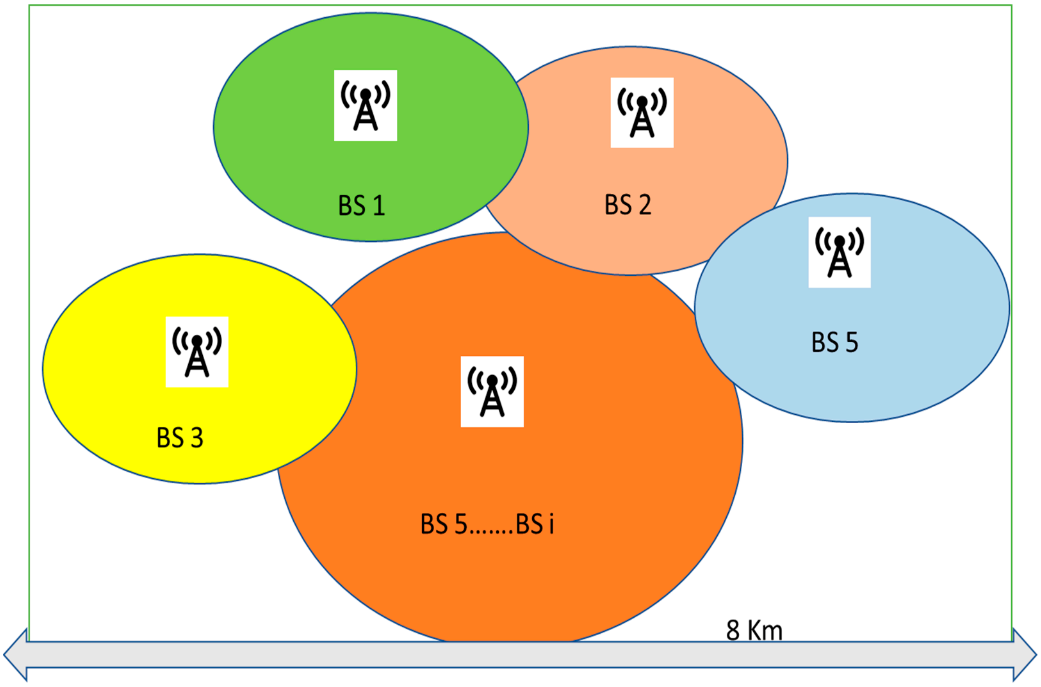

Figure 8. Base station coverage and coexistence.

A framework for intelligent spectrum management based on artificial intelligence and software-defined networks (SDN) is presented in [76]. An integrated satellite and terrestrial network (ISTN) with interoperability and the capacity to reprogram is created by combining heterogeneous satellite and terrestrial networks using SDN. AI is also used to set up networks for optimal resource distribution and forecast environmental conditions. The framework, in short, suggests a novel method for utilizing and combining the spectrum of terrestrial and satellite networks. The influence of interference between satellite and terrestrial systems sharing a spectrum is examined in [77]. A realistic coexistence model was developed to derive a closed-form expression for the satellite link outage probability in the presence of terrestrial interference. Both terrestrial and satellite links are modeled with Nakagami fading, while the satellite link additionally considers shadowing Rician fading. Numerical simulations demonstrate that unmanaged terrestrial interference substantially degrades the satellite link outage performance. The formulas acquired are useful for forecasting and mitigating harmful interference while creating coexistence strategies for terrestrial and satellite systems.

This study focuses on designing robust beamforming for satellite-based IoT systems coexisting with terrestrial networks. It addresses the challenges posed by phase errors in channel estimation and formulates an optimization problem to maximize system performance under outage and power constraints. A two-level iterative algorithm is proposed to efficiently solve this complex problem [78].

To evaluate coexisting radar, satellite, and terrestrial communication systems, researchers used simulations, testbeds, and field trials to assess key metrics. INR measures interference relative to noise, while SINR evaluates communication quality. BER quantifies transmission errors, and throughput assesses data transfer rates. Latency measures delays from interference, spectral efficiency evaluates spectrum utilization, and PDR determines packet delivery reliability. Table 1 gives an overview of coexistence with the references for all coexistence scenarios.

Table 1. Overview of coexistence with the References.

Coexistence	References
Coexistence of 5G system and fixed satellite service	[8,71,72,79–85]
Coexistence of radar and communication systems	[59,63–66,86–90]
Coexistence of terrestrial and satellite services	[75–78,91]

5. Interference and Mitigation Techniques

Interference is a common issue that occurs in various wireless communication systems. It can cause signal distortion or complete signal loss, leading to poor quality of service or even a complete breakdown of the system [92–95]. However, various interference mitigation techniques are available to address these issues and ensure a reliable and stable communication system [96].

One of the most common interference mitigation techniques is frequency hopping. This technique rapidly switches communication channels to deter interference [97]. Spread spectrum techniques distribute signals across a wider frequency band to minimize the impact of interfering signals. Power control mitigates interference by adjusting transmission power to optimize signal strength without causing disturbances [98]. This technique is particularly effective in cellular communication systems, where multiple devices may transmit simultaneously.

Another effective interference mitigation technique is beamforming [99]. This technique involves the use of multiple antennas to create a focused signal in a particular direction, minimizing interference from other directions. Beamforming is particularly useful in outdoor communication systems, where signals may be disrupted by natural obstacles or competing signals. The effect of discrete modulations on three-user interference channel interference mitigation is examined in [100]. The study offers effective and straightforward capacity approximations. It implies that for more generic channels, the Ozarow–Wyner bound needs to be improved, since the current bound might be pessimistic in the event of poor alignment or when an inefficient number of levels (N) is used. Although the findings are primarily theoretical, they point to real-world uses for interference alignment by considering discrete interference as noise once discretely modulated signals have been aligned.

The usefulness of relaying in mitigating interference in a communication context with limited interference was examined in [101]. The study optimizes quantization noise covariance to characterize rate scaling with relay link capacity. It links this scaling to the deterministic relay channel by analyzing the spatial DoF gains from MIMO relaying under noise correlation. The study examines a BICM OFDM system using a prediction-error filter (PEF) to minimize the time-domain disturbance [102]. This approach effectively handles interference without weakening distant tones. Simulations show that, without narrowband interference, the system with PEF performs efficiently and matches similar systems [103].

In [104], two spectrum sharing approaches, orthogonal and non-orthogonal, were investigated for integrated satellite-mobile and autonomous terrestrial-mobile systems. An interference management scheme for co-located base stations and indoor small cells was developed, optimizing the number of blank subframes within a pattern period. System-level performance metrics, including the capacity, spectral efficiency, and energy efficiency, were derived. A novel hybrid approach combining Maximum Likelihood Estimation and wavelet-based self-cancelation is proposed to enhance BER performance in OFDM systems [105]. Significant improvements in the bit error rate were observed when comparing 64-QAM and differential offsets with the traditional rapid Fourier transform methods.

A reliable method for mitigating interference between IMT-advanced and FSS in the 3400–4200 and 4500–4800 MHz bands is suggested in [106], employing null steering MU–MIMO SDMA. In order to produce spatial nulls towards FSS Earth stations, the current precoding matrix is altered. Through simulation, a numerical method for determining the interference power at FSS stations from IMT-Advanced base stations is derived and put into practice, greatly speeding up the solution process. The method's efficiency was evaluated across varying separation distances and FSS Earth station orientations under both co-channel and adjacent channel sharing scenarios.

Deep Q-learning-dependent transmission power control, which dynamically modifies a system's transmission power depending on current interference, is one of the newer methods for mitigating interference in dynamic environments [107]. This strategy has been especially successful in High Altitude Platform Stations (HAPS), where intelligent power adaptation is necessary for spectrum sharing with terrestrial and non-terrestrial networks (NTNs). This technique balances interference levels and increases system throughput by optimizing power allocation through the use of reinforcement learning. Message Passing (MP)-based distributed Multi-User Detection (MUD) is a recent development that improves decoding efficiency and reduces interference in satellite communication networks [108]. In situations requiring Inter-Satellite Links (ISLs), where effective detection algorithms are needed to handle signal distortions and multi-user interference, this technique is very pertinent. MP-based MUD improves detection accuracy while lessening the computational load on individual satellite nodes by utilizing distributed processing.

Static frequency division is the strategy used in traditional spectrum allocation techniques, which frequently leads to inefficient use and increased interference. By dynamically reassigning frequency bands between Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN) in response to current interference circumstances and spectrum demand, Reverse Spectrum Allocation solves this problem [57]. This method improves overall coexistence efficiency, reduces spectral congestion, and permits smooth spectrum sharing.

The bar graph with the interference reduction is shown in Figure 9. CNN-based denoising offers the highest interference reduction (95%) but demands high computational resources, making it ideal for radar and wireless systems. Techniques like beamforming and null steering provide strong performance (90–92%) for high-precision applications, while adaptive power control (75%) suits low-complexity scenarios like cellular networks.

Coexistence in the communication network was analyzed and studied, and the research advantages and limitations are tabulated in Table 2.

Table 2. Comparison of the coexistence and interference mitigation techniques.

Proposed Technique/Algorithm	Advantages	Limitations	References
Deep interference mitigation and denoise real-world FMCW radar signals	CNN was used	To evaluate and optimize based on real data	[9]
Co-channel coexistence analysis between 5G IOT system and fixed satellite service at 40 GHz	Parameters considered are height of station, distance, and antenna patterns	Specific to high frequency of 40 GHz	[18]
Interference mitigation using adaptive beamforming with the RLS algorithm	Minimum distance to mitigate the interference	Only the distance parameter is considered	[72]

Table 2. *Cont.*

Proposed Technique/Algorithm	Advantages	Limitations	References
Spread spectrum	Distributes signals across a wider frequency band to minimize interference impact	May require additional bandwidth and resources	[84]
Beamforming	Creates a focused signal in a specific direction using multiple antennas	Requires advanced hardware and spatial processing capabilities	[85]
Frequency hopping	Mitigates interference by rapidly switching frequencies	Susceptible to frequency hopping jammers	[100]
Interference mitigation via relaying	A relay channel with correlation is used	Requires a large number of antennas, assumes optimal quantization noise covariance, may not be practical.	[101]
BICM OFDM system	Minimize interference using a bit-interleaved coded system	Effective in the absence of narrowband interference	[103]
Spectrum sharing	Explore spectrum sharing techniques for multiple systems	May require complex interference management schemes	[104]
Hybrid techniques	Combine Maximum Likelihood Estimation and self-cancellation	Results are dependent on modulation and data rates	[105]
Null steering MU-MIMO SDMA	Employs null steering MU-MIMO SDMA for interference mitigation	Requires knowledge of victim FSS ES direction angles	[106]
Highly selective filter for suppressing interference of 5G signals at C-band satellite receiver	Filters are used to provide less loss	Parameters are not considered	[109]

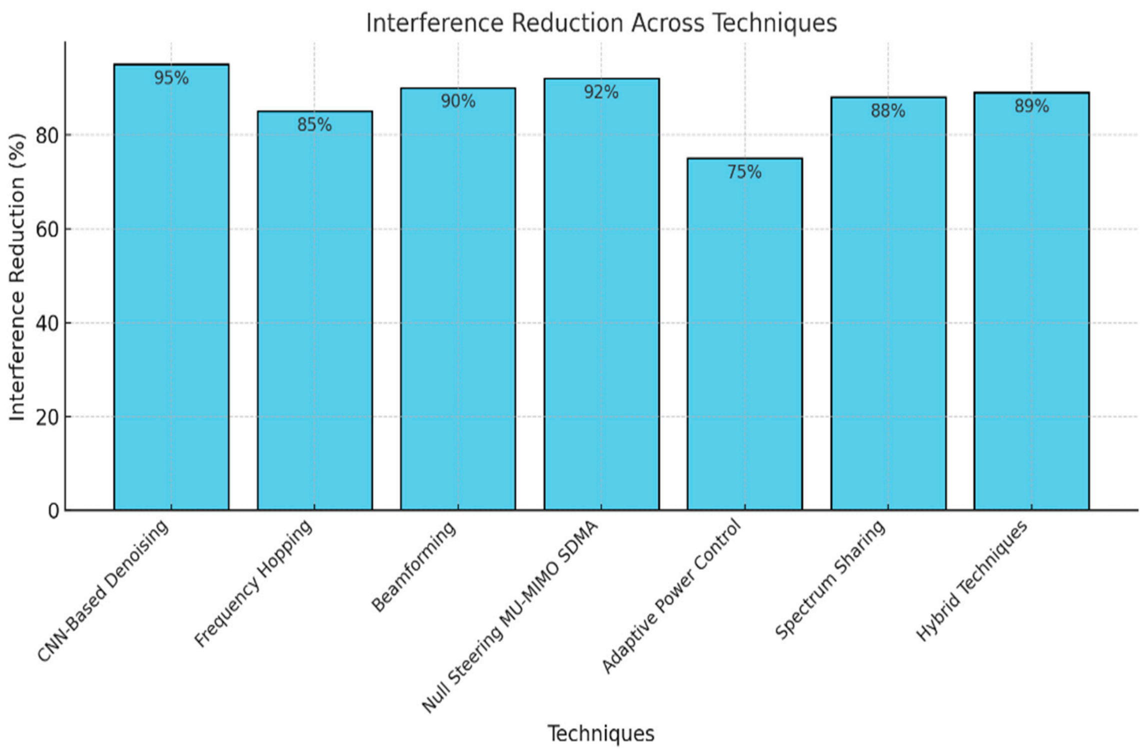

Figure 9. Bar graph with interference reduction.

6. Challenges, Opportunities, and Limitations of Coexistence

Wireless communication technology has become increasingly integrated into our daily lives. The proliferation of devices capable of wireless connectivity has led to a surge in the demand for network capacity [110]. The coexistence of multiple wireless communication systems poses significant challenges in ensuring reliable and efficient network operation. Diverse technologies, protocols, and spectrum sharing requirements create complex interactions that can degrade system performance [111]. Below are some of the key challenges of coexistence in wireless communication.

- Interference: Interference remains a primary challenge in wireless communication coexistence [112]. Multiple wireless systems operating within the same frequency band can cause mutual interference, leading to signal degradation and elevated error rates. This can result in poor quality of service, reduced range, and decreased data rates. Interference can occur due to overlapping frequency bands, insufficient separation between systems, and power imbalances [113].
- Network congestion: As the number of wireless communication systems increases, they compete for limited resources such as bandwidth and transmission power, leading to network congestion [114]. This can result in reduced performance, increased latency, and lower throughput. Network congestion can occur due to insufficient capacity, high demand, and inefficient resource allocation.
- Security: With multiple wireless communication systems operating in the same space, there is an increased risk of unauthorized access and security breaches. This can result in data theft, malicious attacks, and network downtime [115]. Security challenges can occur due to weak encryption, insufficient authentication, and vulnerabilities in the wireless communication systems.
- Coexistence standards: The coexistence of multiple wireless communication systems requires the development of coexistence standards to ensure that different systems can effectively operate together. However, the development of these standards can be complex, time-consuming, and costly. This can result in delays in the implementation of new wireless communication systems and reduced innovation [116].
- Compatibility: Diverse wireless systems employing disparate protocols and technologies often exhibit incompatibility challenges [117]. This can result in reduced interoperability and increased complexity in the management of wireless communication systems [118].
- Frequency resource management: The growing number of wireless communication technologies has intensified the competition for available spectrum resources. Efficient frequency management is required to mitigate spectrum scarcity, but issues such as spectrum fragmentation, inefficient allocation, and regulatory constraints pose significant challenges.
- Energy consumption management: The demand for high-speed, always-on connectivity has led to concerns about energy efficiency in wireless networks. Managing energy consumption, especially in battery-powered devices and infrastructure, is critical; however, existing systems often lack optimized power control mechanisms, resulting in excessive energy use.
- Adaptation to dynamic environments: Wireless networks operate in highly dynamic conditions where factors such as interference levels, user mobility, and environmental changes constantly fluctuate. The inability of current systems to adapt efficiently to these variations leads to network inefficiencies and degraded service quality.

Wireless communication is an essential aspect of modern society, with many devices and technologies relying on it [119]. However, a primary challenge in wireless communication is the coexistence problem, where multiple wireless systems sharing the same frequency band experience interference, resulting in degraded performance [120]. To avoid coexistence and ensure efficient and reliable wireless communication, several opportunities exist, including the following:

- Spectrum allocation: One of the primary ways to avoid coexistence is to allocate specific frequency bands to different wireless systems. This approach ensures that each wireless system operates in its own frequency band, thereby reducing the likelihood of interference [121]. Governments and regulatory bodies often play a significant role in spectrum allocation, and they allocate frequency bands based on factors such as the type of wireless application, geographical location, and licensing requirements [122].
- Frequency agility: Another opportunity to avoid coexistence is frequency agility, where wireless systems are designed to switch between multiple frequency bands [123]. This approach allows wireless systems to avoid congested frequency bands and operate in less crowded areas, thereby reducing the likelihood of interference. Frequency agility is commonly used in wireless networks such as Wi-Fi, where multiple frequency bands are available for use [124].
- Power control: Wireless systems can employ power control to mitigate interference. This involves dynamically adjusting the transmission power of the devices to avoid disrupting nearby wireless networks [125]. For instance, in cellular networks, base stations regulate their power output based on the mobile device's distance and signal strength, thereby reducing the potential for interference with neighboring cellular systems [126].
- Antenna design: Antenna design plays a critical role in avoiding coexistence. Antennas can be designed to focus their energy on specific directions, thereby reducing the likelihood of interference with nearby wireless systems. Additionally, antenna diversity techniques such as MIMO (Multiple Input Multiple Output) can be used to improve the reliability of wireless communication by using multiple antennas to transmit and receive signals [127]
- Protocol design: Protocol design is also an essential aspect of avoiding coexistence. Wireless protocols can be designed to detect and avoid interference, such as using collision avoidance techniques to avoid packet collisions in Wi-Fi networks [128]. In addition, protocols can be designed to prioritize critical data and ensure that it is transmitted without interference [129].

7. Conclusions and Future Recommendations

Coexistence in wireless communication is generally advantageous; however, certain scenarios demand targeted strategies to mitigate interference and maintain reliable performance. Key techniques such as dedicated frequency bands, spatial separation, time division, power control, and interference avoidance are crucial in managing coexistence challenges. Furthermore, optimizing spectrum allocation, enhancing frequency agility, implementing adaptive power control, advancing antenna technologies, and refining protocol frameworks present valuable opportunities to improve wireless system performance in congested frequency environments. Future research should prioritize the development of intelligent coexistence mechanisms that harness artificial intelligence and machine learning for dynamic spectrum management and adaptive interference mitigation. Investigating reconfigurable intelligent surfaces and cutting-edge antenna technologies will further strengthen signal directionality and optimize coexistence approaches. Moreover, establishing unified coexistence standards will be essential to ensure seamless integration across emerging wireless technologies, including 6G and beyond. By addressing these challenges and advancing coexistence strategies, wireless systems can achieve greater efficiency, enhanced service quality, and lead to more sustainable spectrum utilization in increasingly dense and complex communication networks.

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List of Abbreviations

5G	5th—generation
NOMA	Non-orthogonal multiple access
RAN	Radio access network
LAN	Local area network
BLE	Bluetooth low energy
LoRaWAN	Long range wide area network
MIMO	Multiple input multiple output
mm	Millimeter
GEO	Geostationary orbit
MEO	Medium Earth orbit
LEO	low Earth orbit
FrFT	Fractional Fourier transform
IoT	Internet of things
CNN	Convolutional neural network
FMCW	Frequency modulated continuous wave
OFDM	Orthogonal frequency-division multiplexing
LFM	Linear frequency modulated
EESS	Earth exploration satellite service
RLS	Recursive least square
FSS	Fixed satellite services

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