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Review

Interference Mitigation in B5G Network Architecture for MIMO and CDMA: State of the Art, Issues, and Future Research Directions

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Abstract: The emergence of Beyond 5G (B5G) networks introduces novel challenges related to interference management, particularly within the context of Multiple-Input, Multiple-Output (MIMO) and Code Division Multiple Access (CDMA) technologies. In this comprehensive review paper, we delve into the intricacies of interference mitigation techniques within the B5G framework, with a specific focus on MIMO and CDMA systems. Firstly, we provide a brief overview of MIMO and CDMA principles, emphasizing their significance in B5G networks. MIMO leverages spatial diversity by employing multiple antennas in both the transmitter and the receiver, thereby enhancing capacity and reliability. CDMA, on the other hand, enables multiple users to share the same frequency band by assigning unique codes to each user. Next, we categorize the various types of interference encountered in MIMO and CDMA systems. These include co-channel interference, adjacent-channel interference, and multiuser interference. Understanding these interference sources is crucial for designing effective mitigation strategies. Our exploration of interference mitigation techniques covers state-of-the-art approaches tailored for MIMO and CDMA scenarios. Lastly, we discuss future research directions in interference mitigation for B5G networks. This review paper provides valuable insights for researchers, practitioners, and network designers seeking to enhance the robustness and efficiency of B5G communication systems by effectively mitigating interference in MIMO and CDMA contexts.

Keywords: interference mitigation; beyond 5G (B5G); multiple-input multiple-output (MIMO); code division multiple access (CDMA)

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Citation: Yang, H.; Qamar, F.; Kazmi, S.H.A.; Jafri, S.T.A.; Ariffin, K.A.Z.; Nguyen, Q.N. Interference Mitigation in B5G Network Architecture for MIMO and CDMA: State of the Art, Issues, and Future Research Directions. *Information* **2024**, *15*, 771. https://doi.org/10.3390/info15120771

Academic Editor: Zhengchuan Chen

Received: 30 September 2024
Revised: 25 November 2024
Accepted: 27 November 2024
Published: 3 December 2024

1. Introduction

In this paper, several abbreviations are used frequently. Key abbreviations include; Internet of Things (IoT), Multiuser, Multiple-Input, Multiple-Output (MU-MIMO), Reconfigurable Intelligent Surface (RIS), channel state information (CSI), signal-to-interference-plus-noise ratio (SINR).

B5G refers to beyond the fifth generation of mobile communication technology, which is a further evolution of the previous generation, 4G [1]. It also refers to the next sixth-generation (6G) networks [2]. Its main features include providing higher data transfer speeds, lower communication latency, higher device connection density, and stronger network capacity [3]. The introduction of B5G is driven by the need for continuous iteration and innovation of communication technology [4]. The goal of this next wave of mobile communication technology is to transmit data at faster speeds, enhance user experience to higher levels, and achieve faster download and upload rates, especially for high-traffic applications like virtual reality, augmented reality, and high-definition video and for artificial intelligence (AI) and machine learning (ML) applications. At the same time, B5G focuses on reducing communication system delays and providing faster responses for real-time application scenarios, such as autonomous driving, telemedicine, and remote operations [5]. Its design to support the simultaneous connection of more devices makes it an ideal choice in the Internet of Things era, encouraging effective communication across a multitude of intelligent gadgets [6]. B5G increases network capacity and coverage to better meet high-density-population areas and extensive service needs [7]. Meanwhile, via the development of network slice technology, personalized services for different applications have been achieved [8]. Currently, the adaptable design of 5G supports a diverse range of application scenarios, including improved mobile broadband, extensive Internet of Things (IoT) capabilities, and low-latency communications [9]. This provides a robust foundation for the advancement of the future digital society. Although the introduction of 5G technology brings numerous innovations and benefits, it also poses a series of problems and challenges [10]. Firstly, in one study, the author introduces spectrum resource allocation as a significant issue, as the availability of spectrum resources in the high-frequency band is relatively limited, potentially leading to competition and spectrum scarcity [11]. Secondly, the substantial cost of establishing B5G infrastructure places significant financial pressure on operators and governments [12]. In another study, device compatibility is another obstacle, as users must purchase new 5G-compatible devices to enjoy the benefits of this technology [13]. Furthermore, security and privacy issues are of higher complexity [14]. As 5G connectivity increases, networks become more susceptible to security threats involving a greater number of devices and data transmission, raising concerns about privacy protection [15]. The introduction of inconsistencies in international standards can create interoperability challenges for devices and networks [16]. Additionally, the introduction of the deployment of base stations and large-scale equipment has raised concerns regarding electromagnetic radiation and environmental impact [17]. Normative and policy issues also play a role in 5G development, including difficulties in spectrum allocation, policies, and regulations [18]. Finally, given the rapid development of 5G technology, solutions to these problems and challenges are still being explored and continuously improved, leading to a degree of uncertainty [19]. Consequently, the widespread deployment and promotion of 5G require a balanced approach that considers technical, economic, policy, and social aspects to overcome the related challenges [20].

2. Motivation and Contribution

This study delves into the reasons behind signal interference and emerging efficient solutions for signal processing and resource management to disentangle conflicting signals [21]. In multicode MIMO, multiple signal transmissions utilize code division multiplexing, sending signals over the same frequencies using coded sequences [22]. However, overlapping and nonorthogonal codes can clash, resulting in interference [23]. To alleviate this code collision, researchers are exploring optimization techniques such as modifying the code alphabet, adjusting code lengths, and designing codes with lower cross correlation to prevent collisions [24]. For interference cancellation, several proposed techniques can subtract interference from the received signal before decoding [25]. There is ample room for optimizing these techniques to accommodate the high mobility and dynamic topology of 5G networks [26].

Carrier aggregation and cognitive radio have been proposed as solutions to address this challenge [27]. Carrier aggregation can effectively combine fragmented spectrum blocks, thereby enhancing spectral efficiency [28]. Meanwhile, dynamic spectrum sharing allows for the cognitive sharing of the unused spectrum through sensing and access methods [29]. Cognitive radio, on the other hand, facilitates dynamic spectrum access by leveraging awareness, analysis, decision-making, and spectrum mobility [30]. For optimal coexistence, further advancements in dynamic spectrum management are imperative [31]. Additionally, the research has delved into the interference issues caused by network density in 5G heterogeneous networks, particularly through the deployment of tiny cells and massive MIMO [32]. Techniques for managing interference, such as enhanced inter-cell interference coordination and beamforming, have been explored [33]. Massive MIMO beamforming, for instance, spatially focuses signals to minimize interference [34].

This study focuses on the new B5G techniques to address the interference issues brought on by CDMA coexistence and MIMO technologies and offers the following:

1. This paper offers a thorough examination of the most recent techniques for reducing interference in the architecture of B5G networks, with an emphasis on how MIMO and CDMA technologies are integrated.
2. This study first explores the main categories of interference in B5G networks. Following that, this paper offers a comprehensive analysis of the benefits and drawbacks of the available interference management strategies.
3. To guarantee smooth integration and peak performance, this article emphasizes the need for strong interference mitigation strategies.
4. This study identifies important research directions for the future in addition to critically assessing current methodologies.

3. Related Work

3.1. MIMO

With an emphasis on massive MIMO systems, the authors in [35] provide a comprehensive examination of the essential enabling technologies needed for networks that are 5G- and 6G-capable. In addition to discussing some cutting-edge mitigation strategies, in a huge MIMO system, they address all the essential concerns including pilot contamination, channel estimates, precoding, user scheduling, energy efficiency, and signal identification. They provide an overview of current developments in massive MIMO systems, including terahertz transmission, Visible Light Communication (VLC), ultra-massive MIMO (UM-MIMO), deep learning, and machine learning. They also address important open research questions that guide the development of huge MIMO systems for 5G and beyond networks in the future.

The study in the article [36] is conducted on fully digital, hybrid, and analog structures, and a multilayer massive MIMO transmission method is described. The article aims to outline the most widely accepted transmission methods for large MIMO systems, evaluate a few of the more promising ones, and point out any issues or restrictions that may still remain.

The study in article [37]. discusses a thorough analysis of the most recent advancements in cell-free (CF) systems. It starts by reviewing the research on expandable user-centric (UC) CF mMIMO systems and traditional CF systems about the fronthaul connections' capacity limitations and the link between user equipment (UE) and access points (APs). Given that future networks will operate at higher frequencies, it is critical to talk about the effects of the beamforming techniques currently being researched. Ultimately, to demonstrate the main applications for these networks, some of the most promising enabling technologies for CF are shown.

3.2. CDMA

The study in article [38] focuses on the spread-spectrum method and its ability to mitigate interference as it relates to wireless communication are the main topics of this presentation. Spread-spectrum technology allows many signals to be delivered across larger spectrum ranges without interfering with one other or with other signals that are transmitted on the same frequencies. The process of achieving multipath interference rejection in CDMA systems was demonstrated using basic mathematics and diagrams. Code identification at the receiver, a strategy for mitigating interference, is covered in the discussions. The study answers the topic of how interference rejection or mitigation functions in the spread spectrum by assisting in the understanding of the theory of code recognition in the spread spectrum.

The study in the article [39] covers spread-spectrum techniques, ranging from the more contemporary and promising Direct-Sequence Code Division Multiple Access (DS-CDMA) to the more intuitive frequency and time hopping systems. Frequency Hopping refers to the spread of spectrum communication in the frequency space. The usable signal cannot be consistently disrupted by an intentional jamming signal that is unaware of the hopping sequences, and the jamming effects diminish with increasing bandwidth. Time hopping is the term for spread-spectrum communication in the time-space. Direct sequence is the name given to spread-spectrum communication in the code space. First, serial cancellers or serial joint-detection systems try to decode the more dependable users—that is, the users with higher received power. Subsequently, the decoded bits are utilized to eliminate these users' contributions from the overall signal. The parallel canceller, also known as the parallel joint-detection method, works in stages. Table 1 displays a summary of relevant research on CDMA, and massive MIMO in the literature reviewed in this section.

Table 1. Summary of relevant research on CDMA and massive MIMO.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[35]	Discussion with a focus on all the fundamental issues with pilot contamination, channel estimation, and precoding in a massive MIMO system.	Provides an overview of current developments in massive MIMO systems.	Directs the creation of massive MIMO systems for networks that will support 5G and beyond in the future.	Not discussed in enough detail.
[36]	The analysis is conducted on fully digital, hybrid, and analog structures.	A multilayer massive MIMO transmission method is described.	Evaluates a few of the more promising ones.	This approach is very costly.
[37]	Reviewing the research on scalable UC CF mMIMO systems.	Talks about the effects of the beamforming techniques currently being researched.	More practical in dealing with high-speed data and available bandwidth.	Sensitive to Doppler shifts and timing issues.
[38]	The spread-spectrum method and its ability to mitigate interference as it relates to wireless communication are the main topics of this presentation.	The process of achieving multipath interference rejection in CDMA systems is demonstrated using basic mathematics and diagrams.	Code identification at the receiver, a strategy for mitigating interference, is covered in the discussion.	Regulation of D2D communication in an environment of 5G networks is challenging.
[39]	Covers spread-spectrum approaches, from the more user-friendly frequency- and time-hopping systems to the more modern and higher-potential Direct-Sequence Code, DS-CDMA.	Serial cancellers or serial joint-detection systems strive to decode the more trustworthy users—that is, those with higher received power.	Reduces the hardware complications of CDMA systems and facilitates greater capacity and effective interference management.	The hybrid beamforming model requires greater flexibility than full digital beamforming and must be purposefully crafted and fine-tuned.

4. Interference in 5G

5G technology represents a major advancement in mobile network infrastructure, aiming to significantly increase transmission speeds, capacity, and connection density [40]. However, the complex architecture of 5G also brings more complex interference challenges [41]. Because 5G uses higher-frequency bands (such as millimeter wave bands), signals are more likely to be blocked by buildings and natural environments, resulting in signal attenuation and interference [42]. In addition, although the dense arrangement of cells widely used in 5G networks increases network capacity, it also brings potential interference risks of crosstalk and signal overlap [43].

5G networks employ a variety of advanced interference management technologies, including beamforming (pointing signals only in the desired direction to reduce unnecessary radiation), massive MIMO (effectively managing signals and interference through multiple antennas), and network slicing (directing signals into network layers that are separated to enable dynamic resource allocation and reduce inter-layer interference). These technologies are critical to optimizing 5G network performance, ensuring that the potential of next-generation technology is not hampered by interference issues.

Interference in 5G communications includes a variety of phenomena, such as inter-band interference (interference between signals in different frequency bands), co-channel interference (multiple devices interfere with each other on the same frequency), and multipath interference (signals reach the receiving end through multiple paths, resulting in phase differences), etc. In addition, buildings, terrain, and weather conditions (such as rain, snow, and strong winds) can also affect 5G signal transmission, causing interference. The following sections detail the main types of interference in 5G networks and their impact [44].

4.1. Types of Interference

4.1.1. Inter-Cell Interference

Inter-cell interference (ICI) is prevalent in the dense cell environment of 5G networks [45]. When the signal coverage areas of adjacent cells overlap, edge users will be interfered with. Causes of ICI include overlapping base station antenna coverage, signal strength overflow, and insufficient frequency planning [46]. In order to reduce the impact of ICI, the 5G system adopts technologies such as inter-cell interference coordination (ICIC) and cooperative multipoint transmission (CoMP) to improve the communication quality of edge users [47].

4.1.2. Multipath Interference

Multipath interference occurs when a signal travels through multiple paths to the receiving end [48]. These paths include direct line-of-sight paths and paths reflected off buildings, causing the receiver to receive multiple copies of the signal arriving at different times, resulting in signal superposition, fading, and reduced data integrity [49]. The 5G system uses a Rake receiver, multipath diversity, and other technologies to reduce multipath interference by combining the energy of multipath signals [50].

4.1.3. Synchronization Interference

Synchronization interference occurs in communication systems when devices or signals operating in the same frequency band are not properly synchronized, leading to timing mismatches [51]. This can result in overlapping transmissions, where signals interfere with each other, causing data corruption and loss [52]. Other issues include timing jitter, which introduces variations in timing signals and leads to phase shifts and errors, and clock drift, where differences in device clock frequencies accumulate timing errors over time [53]. Inter-symbol interference (ISI) can also occur, where overlapping symbols make it difficult for the receiver to distinguish between them.

4.1.4. Adjacent-Channel Interference

Adjacent-channel interference (ACI) occurs in communication systems when signals from adjacent frequency channels interfere with each other [54]. This is usually due to imperfect filtering that causes the signal to overflow into adjacent channels, causing increased bit error rates and reduced data throughput [55]. In spectrum-dense 5G networks, it is especially necessary to reduce the impact of ACI by improving filter design and spectrum isolation technology [56].

4.1.5. Mutual Interference

Mutual interference occurs in communication systems when multiple transmitters operating in close proximity interfere with each other, leading to signal degradation for all affected devices [57]. This type of interference is common in wireless networks, especially when devices share the same or overlapping frequency bands [58]. Causes include frequency overlap, close physical proximity, and simultaneous transmissions [59]. The effects of mutual interference include increased bit error rates (BER), reduced data throughput, and connectivity issues such as dropped or failed connections.

4.1.6. Internal Interference

Internal interference occurs within a communication system when undesired interactions among the system's internal components or signals lead to performance degradation [60]. This can be caused by crosstalk, where signals from one path interfere with another, electromagnetic interference (EMI) generated by internal electronic components, or intermodulation distortion due to nonlinearities [61]. Additionally, inadequate isolation between different parts of the system and noise generated by oscillators or digital circuits can contribute to internal interference. The effects include signal degradation, increased BER, reduced system performance, and operational instability [62].

5. Materials and Methods

5.1. Interference in MIMO

In MIMO systems, interference refers to problems caused by mutual influence between multiple antennas or mutual interference of signals between multiple pieces of user equipment [63]. In MIMO systems, inherent interference comes in two flavors: interference between user equipment and interference between antennas [64]. MIMO systems can take advantage of the spatial independence between multiple antennas, but this can also cause mutual interference between antennas [65]. If the spatial coherence between the antennas is not controlled, it can cause the received signals to interfere with each other and affect the performance of the system [66]. In MIMO systems, beamforming technology is used to optimize the direction of signal transmission [67]. However, due to changes in the communication environment or errors in antenna arrays, beam shape errors may occur, causing interference between antennas [68]. Multiple pieces of user equipment may share the same spectrum resource [69]. If the spatial separation between user equipment is insufficient or the frequency separation is inadequate, interference between user equipment may occur [70]. If the transmission power of different user equipment is not properly controlled, strong signals may interfere with weak signals, causing interference between user equipment [71].

5.1.1. MU-MIMO Interference

In the MU-MIMO system, the base station dynamically determines which user will be assigned to which antenna for service based on the user's location information, channel status, and communication needs [72]. For each user, the system needs to determine the appropriate beam direction to maximize the strength of the user's received signal and reduce signal reception in other directions [73]. For each user, beamforming is implemented by the base station by altering each antenna's phase and amplitude. Beamforming is used to form directional beams to concentrate the transmitted energy in a specific direction and reduce radiation in other directions. The base station must neutralize user interference at the receiving end since multiple users utilize identical frequency resources. This includes estimating and suppressing interference introduced by other user equipment to improve isolation between users [74]. Base stations use joint transmission technology, which simultaneously transmits data to numerous people using different antennas [75]. This enhances the system's spectral efficiency, enabling the simultaneous transmission of numerous users using the same time and frequency resources [76]. The base station obtains feedback information, especially feedback on channel status, through communication with user equipment [77]. This feedback information is used to dynamically adjust beamforming, user allocation, and scheduling strategies [78]. At the receiving end, user equipment receives signals from base stations and other user equipment through multiple antennas [79]. After these signals are processed by the antenna and front-end, they form the received signal of the user equipment [80]. User equipment needs to use advanced multiuser detection algorithms to separate the data of different users from the mixed signal.

The user equipment uses demodulation to demodulate and decode the received signal to restore the data transmitted by the base station [81]. We study the interference problem in the MU-MIMO system as shown in Figure 1.

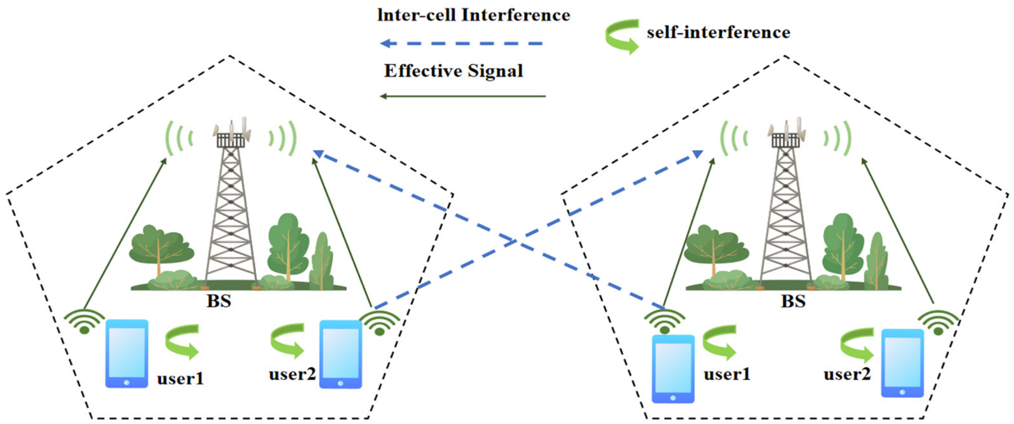

Figure 1. MU-MIMO inter-cell interference.

The study in [82] works on the difficulty of detecting symbols accurately. An algorithmic family based on interference cancellation that can retrieve several symbols with high accuracy. They propose a MU-MIMO receiver that does not require channel state information (CSI) or assume a particular channel model, instead learning to collaboratively identify using a data-driven methodology. Specifically, they put forth what they call DeepSIC—an iterative soft interference cancellation (SIC) approach implemented based on data. The iterative SIC algorithm's foundation for the final symbol detector is the integration of specialized machine learning techniques. Using a limited quantity of training data, DeepSIC may perform joint detection without the need for a linear channel with known parameters. According to numerical calculations, DeepSIC approaches the optimal performance for channels that are linear with complete CSI, which is equivalent to the performance of iterative SIC, and performs better than earlier suggested learning-based MIMO receivers.

The study in [83] focuses on two main variables, including MU-MIMO systems that operate with multiuser interference (MUI) and those that operator with inter-antenna interference (IAI). They proposes the use of singular value decomposition (SVD) precoding and LAS MUD to reduce IAI and MUI. With fewer calculations, the methods can attain BER performance close to optimum, according to simulation results.

The study in the article [84] works on a novel nonlinear detector for MU-MIMO systems that has better interference suppression. The following components come together to form the suggested detector: low-complexity users sorting before QR decomposition (QRD), sorting-reduced (SR) K-best approach, and minimum mean square error (MMSE) preprocessing are among the strategies used. In both additive white noise and heavy interference situations, for all ideal and real channel estimations, the method performs noticeably better than a linear interference rejection combining MMSE naturally or using an interference rejection combining (IRC) method.

The study in [85] focuses on resolving the interference coordination issue for decentralized MU-MIMO. They propose reinforcement learning (RL) based GCA. When compared to previous nonintelligent GCAs, the computer simulation validates that their recently designed RL-GCA can greatly increase the capacity of the downlink link.

The study in the article [86] examines the design challenge of interference-based symbol-level precoding in a hybrid analog-and-digital precoding architecture large-scale multiuser, multi-input, multiuser millimeter wave; they propose creating a hybrid precoder with the smallest possible Euclidean distance between it and the best digital precoder. They divide the problem under consideration into digital and analog precoder design problems using the Alternate Minimization (AltMin) framework, and after that, they solve for each of the analog and digital precoders. The suggest hardware-efficient hybrid precoding architecture's closed-form solution for the digital precoder is acquired by putting the recommended method into practice. This results in the right trade-off between hardware cost, energy use simulation results, and symbol rate of error performance.

The study in the article [87] analyzes the BER performance that deteriorates as a result of transmitting several independent signals from various users using various space–time approaches, which lowers system reliability. Therefore, they propose maximizing the signal-to-noise ratio (SINR) of a MU-MIMO system by transmitting distinct user data from a single base station (BS) to multiple mobile stations (MSs) via multiple antennas at various time slots. They conclude that in the presence of multiuser and multipath interferences, the BER decreases and the capacity increases with an increase in the number of antennas.

The study in the article [88] covers the interference synchronization problem in a multiuser, multi-input communication system is investigated in the paper. In contrast to a simple method based on division of time multiplication, to broadcast symbols of several users, they propose a particular transmission approach allowing for significant savings in time required for transmission slots. The statistical characteristics of the obtained signal-to-noise ratio are examined using the cumulative distribution function and probability density function. Moreover, the system's analytical performance is examined utilizing a moment-generating function-based approach regarding the order of diversity and symbol mistake rate. The theoretical study reveals that when the quantity of users rises, the suggested scheme's error performance deteriorates.

The study in [89] works on a deep learning (DL)-based combined pilot design and channel estimation scheme for MU-MIMO channels. They propose to construct a channel estimator using deep neural networks (DNNs) and a pilot designer using two-layer neural networks (TNNs) that learn to simultaneously reduce the mean square error (MSE) of the channel estimate. They also employ the sequential successive interference cancellation (SIC) method in the channel estimate procedure to efficiently decrease the interference between several users. The suggested method works noticeably better than the linear minimum mean square error (LMMSE) channel estimation approach, according to numerical data. Table 2 provides an overview of the MU-MIMO interference research conducted in the literature reviewed in this part.

Table 2. Summary of research work on MU-MIMO interference in the literature.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[82]	Accurate symbol recognition is challenging.	Suggests a multiuser MIMO receiver that uses data to teach it to jointly detect.	Gains the ability to jointly identify using data-driven methods without needing a particular channel model or CSI.	Sensitivity to channel conditions.
[83]	Reduce both MUI and IAI.	SVD precoding and LAS MUD.	Achieves BER efficiency while utilizing less computing power.	Complexity in decoding multiple codes.
[84]	Enhanced MU-MIMO system interference suppression.	Proposes a new nonlinear detector.	Technique outperforms the naturally occurring MMSE approach or the linear IRC approach.	High hardware complexity.
[85]	Coordination of interference for distributed MU-MIMO.	RL-based GCA.	Improves the downlink link capacity.	Transfer speed slows down.
[86]	Examines the design challenge of interference-based symbol-level precoding in a hybrid analog-and-digital precoding architecture large-scale multiuser, multi-input, multiuser millimeter wave system.	The goal is to reduce the Euclidean distance between the hybrid precoder and the best purely digital precoder.	Gives the ideal balance between power consumption and symbol error rate performance.	High hardware cost.

Table 2. *Cont.*

Reference	Issue	Proposed Method	Advantages	Disadvantages
[87]	Founded on optimizing a multiuser MU-MIMO system's SINR.	Delivers different user data at different times using different antennas from a single BS to several MSs.	The more antennas there are, the higher the capacity.	High hardware cost.
[88]	In a multiuser, multi-input communication system, the interference alignment issue is taken into consideration.	To transfer the symbols of several users, a particular transmission technique is suggested.	The suggested scheme's error performance deteriorates as the user base grows.	The performance of the system is discussed only from two aspects.
[89]	Tackle NP-hard binary quadratic programming.	Offers a combined pilot design and channel estimation technique for MU-MIMO channels that are based on DL.	In terms of (uncoded) bit error rate, the suggested approach performs better than the current systems.	Need to prove that it is superior to current methods in different ways.

5.1.2. Multiantenna MIMO Interference

We study the interference problem in the multiantenna MIMO interference system as shown in Figure 2. This represents the data that need to be transmitted. They are the input to the beamformer on the transmission side. At the transmission side, the beamformer takes the incoming data and processes them using an array of antennas [90]. The purpose of the beamformer is to direct the radio waves into a focused beam toward the receiver. The beamforming technique can significantly reduce interference and increase the signal range and strength by focusing the signal in a specific direction rather than broadcasting it in all directions [91]. This shows the direction in which the signal is intentionally focused [92]. Beamforming helps in steering the beams toward the intended receiver, enhancing the reception quality and reducing the signals sent in other, nonuseful directions [93]. Despite the focus provided by beamforming, some signals can still scatter or reflect off objects in the environment, causing interference. These are depicted as dotted lines diverging from the main beam path [94]. On the receiving end, another beamformer (or a receiving device equipped with beamforming capability) captures the transmitted data. The beamformer at this end works to interpret the incoming signals, filtering out noise and interference, to retrieve the transmitted data accurately.

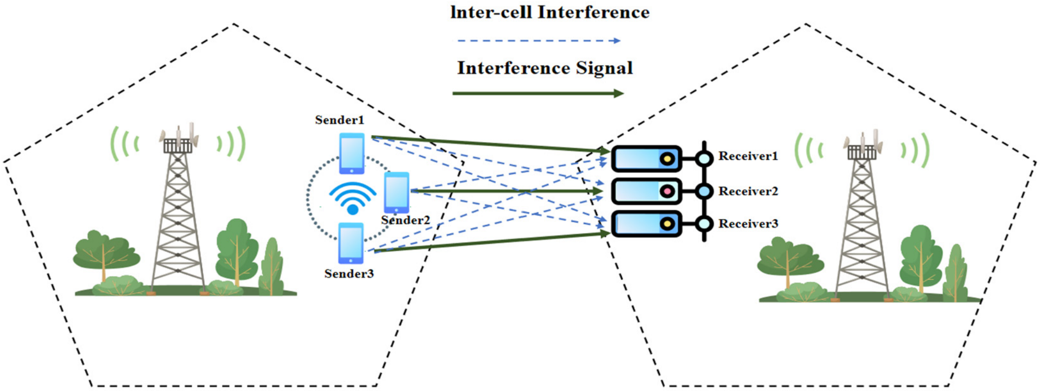

Figure 2. Multiantenna MIMO inter-cell interference.

The study in [95] evaluates the multibeam antenna system's effects on the level of interference in the subscriber channel. They demonstrate the problem of using a 5G network with a huge MIMO antenna system. They propose a simulation study using the MPM and 3GPP standard models for various antenna parameter configurations and propagation conditions that serve as the foundation for the analysis that is conducted. The outcomes serve as a foundation for applying the approach described to the construction of multibeam antenna-based wireless networks.

The study in [96] analyzes the use of many antennas for transmission and the increase in network irregularities for complicated interference control given the dynamics of 3D UAV and line-of-sight (LOS)/non-line-of-sight (NLOS) distribution channels. In order to manage interference in a multiantenna UAV network, they propose a 3D coordination model that combines signal-level cooperation and multicell beamforming. It then uses stochastic geometry to obtain a semi-closed expression of the coverage probability, which is used to examine system performance. Using the novel coordinate system transformation they propose, the coverage probability is calculated via Gamma estimation. The numerical results provide ideal deployment parameters for the deployment of UAVs and agree well with simulations.

The study in [97] works on downlink beamforming, in which several panels working together are shown to be able to suppress inter-panel interference and improve the sum rate. To minimize implementation complexity and reduce the degrading effect of physical antennas on a large-scale MIMO system, they propose a new base station antenna (BSA) arrangement. Zero-Force precoding (ZF) in multipanel sparse arrays is demonstrated to increase the average total downlink rate by as much as 60.2%, 23%, and 11.1% when the number of base station antennas is 10 times that of users, respectively, in pure LOS, rich, and poor multipath environments.

The study in [98] analyzes the impact of numerous antennas on cell-independent MIMO systems, including users, APs, and low-resolution digital-to-analog converters (DACs). Applying an additive noise quantization model that is generalized and a distributed conjugate beamforming receiver for the possible downlink total spectral efficiency (SE), they proposed establishing a closed-form approach. This gives a useful tool to quickly assess the influence of important parameters. The research becomes very complex because of the combined effects of multiantenna gain, channel-hardening qualities, and interference in the group.

In array antennas, reciprocal coupling happens nearly imperceptibly due to space constraints [99]. The paper reviews the effects of mutual coupling on the two most common types of array antennas: phased arrays and MIMO antennas. A few misunderstandings about the mutual coupling effects are exposed. It is demonstrated that once the embedded radiation patterns of the array components (including the mutual coupling effect) are known, it is easy to calculate the steering pattern of a phased array at any scanning angle. Absorption loss rises with decreasing antenna space, although phase terms tend to accumulate constructively with decreasing antenna spacing, potentially compensating for the absorption loss through mutual coupling. Therefore, decreasing the antenna spacing may increase the array efficiency. This effect can be shown using a patch antenna array. Furthermore, it is demonstrated that mutual coupling has no effect on the overall correlations of bigger arrays but tends to decrease the correlation of two-element arrays. Lastly, a brief introduction to some mutual coupling reduction methods is given. The advantages of array decoupling are demonstrated using two practical methods for large planar arrays.

Huge MIMO technology is used in contemporary wireless cellular networks [100]. This method uses a base station's array of antennas to service several mobile devices at once, each of which has a number of antennas on its side. Several precoding and detecting methods are employed for this purpose, enabling each user to receive a signal from the base station that is specifically meant for him. Regularized Zero-Forced (RZF) is a significant class of linear precoding. With a unique regularization matrix that has distinct coefficients for every layer of multiantenna users, they present adaptive RZF (ARZF) in the study. An explicit formula based on the SVD of the user channel matrix defines these regularization coefficients. They examine the optimization problem, which the suggested technique resolves and which is connected to other potential problem statements. For systems with fixed computational precision, they establish theoretical estimates of the condition number of the inverse covariance matrix for both the standard RZF approach and the ARZF method. Lastly, using simulations of the Quadriga channel model, they contrast the suggested technique with cutting-edge linear precoding algorithms. In the same amount of computational time as the reference approach, the suggested method demonstrates a notable improvement in quality.

An enhanced semi-blind uplink interference reduction strategy that was previously suggested is presented in the study [101]. The number of orthogonal sequences needed for channel estimation has an upper limit when the number of spatial multiplexings in a massive MIMO system is increased to increase capacity. As a result, these sequences are used repeatedly in each cell, causing ICI from pilot signals, also known as pilot contamination. It stops inter-user interference (IUI) and ICI from being sufficiently suppressed. The intra-cell channel state information (CSI), which includes pilot contamination, is the foundation of the previously suggested approach. A constant modulus algorithm (CMA) and blind adaptive array (BAA) signal processing can effectively reduce residual interference while capturing desired signals. In the research, beamforming was used at the user terminal side to increase interference suppression performance. Because user beamforming may suppress ICI beforehand but not IUI, it performs better for semi-blind interference suppression. Computer simulations show how successful it is. Table 3 shows the summary of the research work on MU-MIMO interference in the literature discussed in this section.

Table 3. Summary of research on MU-MIMO interference.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[95]	Determining how much interference a multibeam antenna system causes in the subscriber channel.	A simulation analysis for various antenna parameter setups and propagation conditions utilizing the MPM and 3GPP standard models.	A foundation for designing directional wireless networks based on multibeam antennas utilizing the methodology that is described.	Only two models were used.
[96]	Interference management is a complicated problem.	Three-dimensional coordination model employing multicell beamforming and signal-level cooperation in a multiantenna UAV network.	Gives the UAV deployment the best possible deployment parameters.	Only considers the dynamics of the channel.
[97]	Lessening the physical antennas' deteriorating influence in huge MIMO systems.	An updated BSA arrangement.	The average total downlink rate is increased.	A large number of antennas and high cost.
[98]	Examines the effects of various antennas on cell-independent multicast multigroup massively MIMO systems, including users, APs, and low-resolution DACs.	Creates a closed-form phrase that represents the possible total SE in the downlink.	Gives us a strong tool for quickly assessing the impact of important parameters.	The research becomes very complex because of the combined effects of multiantenna gain, channel-hardening qualities, and interference in the group.
[99]	Impact of mutual coupling in array antennas.	Analyzes embedded radiation patterns of phased arrays and MIMO antennas to reduce mutual coupling effects.	Improves array efficiency with reduced antenna spacing; phase accumulation can compensate for absorption loss.	Minimal impact on overall correlation in large arrays; significant reduction in correlation only observed in two-element arrays.
[100]	Interference in multiuser scenarios in massive MIMO systems.	ARZF precoding with regularization coefficients set based on SVD of the user channel matrix.	Enhances signal quality; outperforms conventional precoding methods with the same computational time.	High precision requirements; computational burden increases in massive antenna systems.
[101]	ICI and pilot contamination in massive MIMO systems.	Improved semi-blind uplink interference suppression strategy combined with user-side beamforming.	Reduces intercell interference; effectively suppresses pilot contamination.	Beamforming can only preemptively suppress ICI; limited effectiveness against IUI.

5.1.3. Massive MIMO Interference

We study the interference problem in the massive MIMO interference system as shown in Figure 3. One type of MIMO technology known as massive MIMO is distinguished by the utilization of numerous antennas at the base station to serve numerous users simultaneously [102]. It seeks to enhance communication networks' efficiency, including spectrum efficiency, anti-interference capability, capacity, and reliability, to meet the needs of future communication networks [103]. By placing a high number of antennas at the base station, the massive MIMO system leverages the spatial separation concept to achieve the spatial separation of numerous users [104]. Through beamforming technology, the system can adjust the weight of the antenna to form a directional beam, focusing the signal mainly on the target user and reducing interference to other users [105]. The system needs to intelligently decide which users are assigned to which antennas for service. This usually involves dynamic user allocation and scheduling algorithms, making decisions based on factors such as user location, channel status, and data needs, to optimize system performance [106]. At the receiving end, the system needs to use advanced multiuser detection technology to separate the data of different users from the mixed signal [107]. Higher data transmission rates are made possible by the ability of each user to simultaneously receive signals from numerous antennas and frequency resources. Owing to the extensive antenna placement, massive MIMO systems can take advantage of the characteristics of multipath propagation to transmit signals through multiple paths, improving signal reliability and coverage. This section studies the interference problem of massive MIMO.

The study in [108] analyzes constructive interference (CI) and goes into detail on how CI can be used to the advantage of 1-bit signal design by taking the use of interference from defective hardware components and multiuser interference, which is typically undesirable. They then go over a few 1-bit signal design options to show the improvements that may be made by making use of CI. Lastly, they propose several unexplored issues and potential future research avenues for 1-bit large MIMO systems.

A novel approach to assess the impact of a multibeam antenna network on the intra-cell interference strength in a downlink is shown in the article [109], which could help with accurate modeling and successful mMIMO deployment in 5G cells. The research presented allows the mapping of propagation path trajectories and, as a result, the angular power distribution of received signals based on geometric channel models. The statistical channel model simulation results from the Third-Generation Partnership Project (3GPP) are compared with a multielliptical propagation model (MPM). The obtained results demonstrate that the unique MPM-based approach can be used to estimate the lowest spacing angle between co-channel beams in both LOS and non-LOS circumstances. This enables performance evaluation of mMIMO in 5G cells.

To examine how signal detection techniques affect energy efficiency (EE), the study in [110] focuses on analog-to-digital converters (ADCs) with limited resolution that are utilized in uplink MIMO systems. Assuming that each user has the same transmission rate, they determine the ideal power distribution and their analytic counterparts for ZF and ZF successive interference cancellation (ZF-SIC) receivers. They consider both circumstances with perfect and imperfect CSI. Different receivers are compared with the EE. The findings show that radio-frequency circuitry consumption can be substantial for large MIMO uplink networks with low-resolution ADCs.

The study in [111] aims to reduce neighboring cell cross-link interference in massive MIMO dynamic TDD. They consider BS transceiver noise for a more realistic system model, which would increase the coupling between DL and UL. Through the use of random matrix theory, they propose constructing a precise determinism equivalent of the potential speeds for UL and DL with a matching filtering receiver and optimum ratio transmission precoder. They further exploit these deterministic equivalents to investigate transceiver noise and cross-link interference, demonstrating that both of their impacts scale down as O(M -1), making it easy to eliminate both by greatly increasing the number of antennas.

The study in [112] on the future generations of wireless communication systems suggests they will face a significant challenge from incredibly varied service requirements. First, a transceiver design is provided with the goal of controlling the mixed-numerology spectrum-sharing (SS) broadcast. Subsequently, they examine the inter-numerology interference (INI) and obtain the associated theoretical formulations. A novel INI cancellation approach is presented, which effectively reduces the INI and improves the performance of large MIMO-OFDM uplink systems using the closed-form equations that were obtained.

Table 4 shows the summary of the research work on massive MIMO interference in the literature discussed in this section.

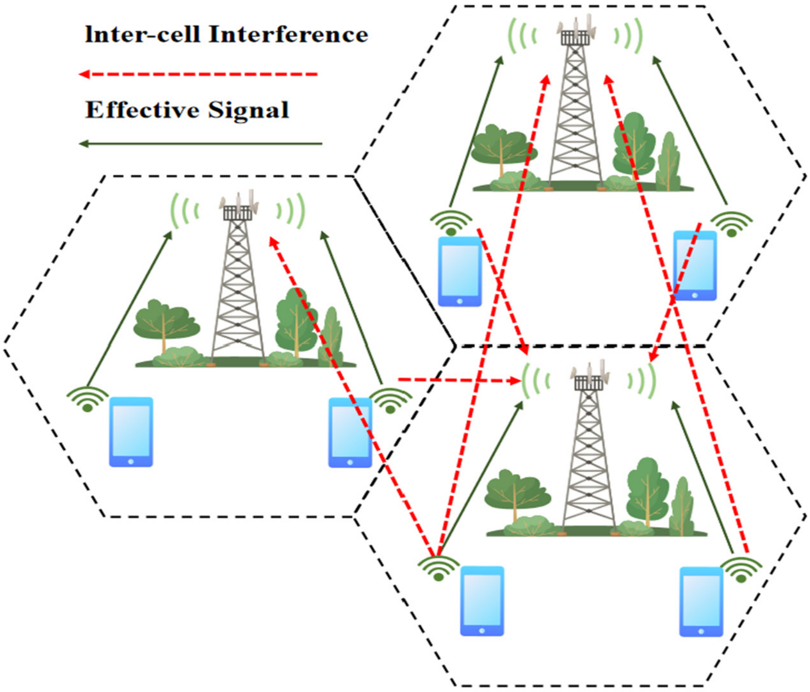

Figure 3. Massive MIMO inter-cell interference.

Table 4. Summary of research work of massive MIMO interference in the literature.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[108]	Show the benefits that can be obtained by utilizing CI.	A summary of numerous 1-bit signal design options.	Some future directions are given.	No calculations or experiments were performed.
[109]	Effective use of mMIMO in 5G networks.	New method for determining how a multibeam antenna system affects the amount of intra-cell interference in a downlink.	Permits evaluation of mMIMO performance in 5G cells.	Sensitivity to channel conditions.
[110]	Uplink MIMO systems' EE.	Signal detection schemes.	Signal distribution is faster.	The power consumption of radio-frequency circuits can be substantial.
[111]	Suppress the neighboring cells' cross-link interference.	Adaptable TDD using massive MIMO.	Their effects both scale down.	High cost.
[112]	Extremely diverse service requirements.	A transceiver design that attempts to control the transmission of mixed-numerology SS.	Improves huge MIMO-OFDM uplink systems' performance.	Cannot mitigate other interference.

5.1.4. Cell-Free Massive MIMO Interference

We study the interference problem in the cell-free massive MIMO system as shown in Figure 4. Cell-free massive MIMO is a wireless communication system architecture that combines massive MIMO technology with a cell-free structure to improve spectrum efficiency, reduce interference, and optimize capacity and coverage [113]. Cell-free huge MIMO systems employ a large number of antennas, which can be distributed in different geographical locations and do not rely on traditional cell division [114]. User equipment is distributed within the coverage area and forms multiple antenna–user associations with deployed antennas [115]. The user equipment performs channel estimation by sending pilot signals and sending the estimated value to the antenna. The CSI transmitted back from user equipment is gathered and aggregated by each antenna [116]. The system uses antenna–user association information to determine the users served by each antenna. The system uses beamforming technology to adjust the weight of the antenna and optimize signal transmission based on the user's channel status information. Through the cooperative work of multiple antennas, spatial diversity is achieved and communication reliability is improved. Joint-detection technology is used to simultaneously consider the received signals of multiple antennas to improve the isolation between multiple users [117].

The study in [118] proposes a solution for a coverage area with multiple wireless access points cooperating to serve users as opposed to isolated cells. A cell-free network like this one might be able to alleviate a lot of the interference problems that arise in existing networks. The primary obstacle lies in realizing the advantages of operating without a cell in a practically possible manner, considering the computing complexity that can increase with big networks that have several users. They present a novel architecture for scalable cell-free massive MIMO systems by leveraging the dynamic cooperative cluster idea from the network MIMO research. They provide novel, flexible methods for cluster development and cooperative early access.

The study in [119] formulates the CF large MIMO frequency assignment problem. In general, the optimization interference problem turns out to be difficult. Although it has been very sluggish, methods like the Lagrange method can be used to find local optima. They suggest a different, two-pronged approach to prevent this problem. Extensive computational simulations that show a discernible enhancement of the effectiveness of the investigated situations are then used to confirm the efficacy of the suggested algorithm.

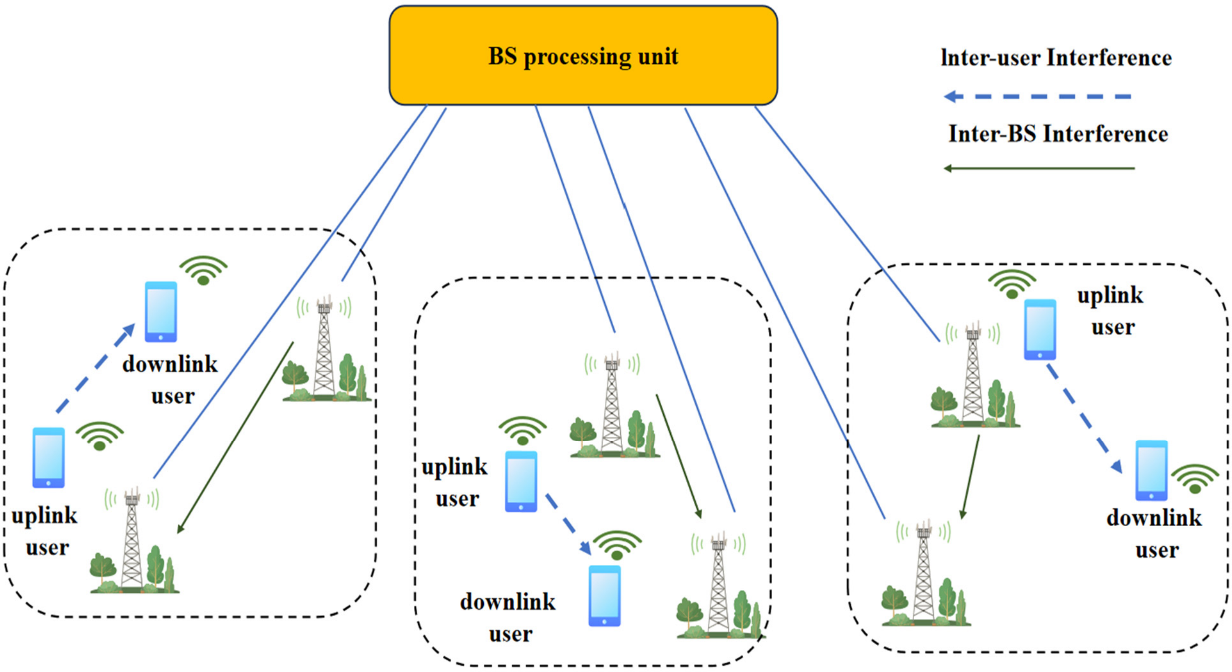

Figure 4. Cell-free massive MIMO inter-cell interference.

The study in [120] suggests that interference management can be achieved by cell-free massive Multiple Input, Multiple Output (CF mMIMO), which coordinates more APs than UE. To achieve cooperative AP-UE pairing and pilot allocation for CF mMIMO, the study suggests an Interference-Aware Massive Access (IAMA) strategy that makes use of large-scale interference features. They provide a novel performance metric called interrupt-aware reward and leverage it to create two iterative algorithms that maximize relevance. The numerical outcomes demonstrate a noteworthy benefit of the IAMA scheme in comparison to the benchmark scheme concerning average SE and user fairness.

The study in [121] presents research on suppressing MUI with MMSE receivers and demonstrates a notable gain in capacity but at the expense of the high complexity of computing and increasing residual MUI. As a compelling substitute for MMSE-based cell-free massive MIMO, they provide JAPSIC, a novel low-complexity and high-capacity method that combines a selective combination of access point (AP) signals with multistage interference cancellation. They validate the significant improvements in spectral and computational efficiency that are suitable for the suggested scheme through numerical analysis and results.

The study in [122] focuses on Multiple-Input, Multiple-Output or cell-free massive MIMO, which is a viable distributed network design for 5G systems and beyond. The research suggests two distributed precoding techniques that enhance spectral efficiency by offering an adjustable trade-off between signal augmentation and interference cancellation. These schemes are called local Partial Zero-Forcing (PZF) and local Partial-Protected Zero-Forcing (PPZF). PZF and PPZF can achieve equivalent performance to the downlink benchmark normalized Zero-Forcing (RZF), and they can outperform Zero-Forcing and maximum ratio transmission by a large margin.

The authors in [123] examine the applications of large-scale MIMO CF systems to low-power IoT. Our suggested EE power control strategy can cut the radiated power of Internet of Things devices by a large margin. The SINR becomes almost independent of the radiated power if you select the radiated power based on the fact that many IoT devices have a substantial degree of interference. They demonstrate that in comparison to standard operation, the technique may cut the radiated power by almost 90%.

The solution in [124] is based on free-of-cells (CF) significant advances in spectral efficiency in MIMO and nonorthogonal multiple access (NOMA) hybrids; however, the kind of precoder employed in the AP influences gain. Using modified regularized ZF (mRZF) precoders, Full-Pilot Zero-Forcing (fpZF), and maximum ratio transmission (MRT), the research thoroughly assesses the system's performance. It considers the impacts of Rayleigh fading channels, intra-cluster pilot pollution, inter-cluster interference, and imperfect SIC to obtain a closed-form sum rate equation. Comparing the system to a similar OMA, the findings show that it supports a substantially higher number of simultaneous users at the same coherence interval. Table 5 shows the summary of the research work on cell-free massive MIMO interference in the literature.

Table 5. Summary of research work of cell-free massive MIMO interference in the literature.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[118]	Obtain the advantages of cell-independent functioning in a way that is actually doable, considering the computational complexity that can grow to accommodate sizable networks with a high user count.	Provides novel algorithms for joint early access and cluster formation.	Proven to be scalable.	There is no study on the feasibility of the proposed algorithm in other aspects.
[119]	Investigates the frequency assignment problem for CF massive MIMO.	Proposes an alternative solution to be twofold.	Optimizing interference problems is relatively fast.	Too few scenarios studied.
[120]	Analyzes how there are more APs than customers. UE can be coordinated to offer effective interference management with CF mMIMO.	Suggests the use of IAMA.	In terms of average SE and user fairness over the benchmark scheme.	Only one new performance metric is proposed.

Table 5. *Cont.*

Reference	Issue	Proposed Method	Advantages	Disadvantages
[121]	Elevated residual MUI and high computational difficulty.	JAPSIC is a novel low-complexity, high-capacity method.	The substantial increases in computational and spectral efficiency are appropriate for the proposed scheme.	Higher cost and few simulation parameters.
[122]	Significantly increase spectral efficiency by offering a modifiable trade-off between signal amplification and interference cancellation.	Suggests local PZF and local PPZF, two distributed precoding techniques.	PZF and PPZF can perform substantially better than Zero-Forcing and maximum ratio transmission.	Only two options were proposed.
[123]	Examines how large-scale MIMO CF systems can be applied to low-power IoT networks.	Presents a power control method for EE.	Lower IoT device radiation power by a large margin.	High energy consumption and high cost.
[124]	The type of precoder used in the AP affects gain.	Optimizes mRZF, fpZF, and MRT precoders to fully evaluate system performance.	Substantially more users concurrently with the same coherence interval as with a comparable OMA.	The effects of spectral pollution are not considered.

5.2. Interference in CDMA

In a CDMA system, every user shares the same bandwidth and frequency [125]. So, co-channel interference may exist. When several users use the identical frequency band to send data, their signals may interfere with each other, making it difficult for the receiving end to correctly decode the target signal [126]. Multipath propagation can introduce signals on different paths, which overlap with each other at the receiving end, causing multipath interference. CDMA systems use spread-spectrum technology, but in a multipath environment, signals on different paths may overlap at the receiving end, increasing the complexity of demodulation. In a CDMA system, different spreading codes (code-division multiplexing) are used between different users [127]. However, inter-code interference may exist between adjacent codes. This interference can cause the receiver to misunderstand the target code due to the mutual influence between the codes [128]. When the user equipment transmits a signal, its code interference may occur due to its code overlap and other reasons. In this case, the receiving end may be affected by the transmitted signal itself during decoding, reducing the reception performance. We discuss the interference issues in Wideband Code Division Multiple Access (W-CDMA) and DS-CDMA.

5.2.1. W-CDMA Interference

We study the interference problem in the W-CDMA system as shown in Figure 5. CDMA is a third-generation (3G) mobile communication standard and one of the 3G standards developed by the IMT-2000 International Mobile Telecommunications Union (ITU) [129]. W-CDMA adopts CDMA technology and transmits data through broadband channels to support higher data rates and multiuser access. The interference problem of W-CDMA refers to the signal interference caused by factors such as multiple users, multiple cells, and multipath propagation in the network [130]. In W-CDMA, cell frequency allocation needs to be determined to avoid frequency conflicts and interference to determine the cell antenna layout, including the location, direction, and height of the antenna. When the user equipment starts up, it scans nearby cells and selects the most suitable cell for access. User equipment registers with the selected community and obtains system identification and authorization information [131]. Different users use different codes for coding to achieve multiple accesses in frequency and time. The system allocates physical channels to users, including shared channels and control channels. Uplink power management is utilized between a base station and the user equipment to ensure the appropriate proportion of signal to noise [132]. In order to accommodate varying user requirements, the base station dynamically modifies the downlink signal power. Data are sent from the user equipment to the base station via a predetermined code. The matching code is used by the base station to send data to the user equipment. Delay propagation caused by multipath propagation is handled using a Rake receiver to combine signals on different paths [133]. The received signal is equalized to eliminate time-varying distortion and frequency-selective fading introduced during transmission. The system dynamically allocates and shares spectrum resources according to network load and user needs to improve spectrum efficiency. Users' devices constantly update their location information so that the network can track their movements. What is discussed here is the interference problem in W-CDMA.

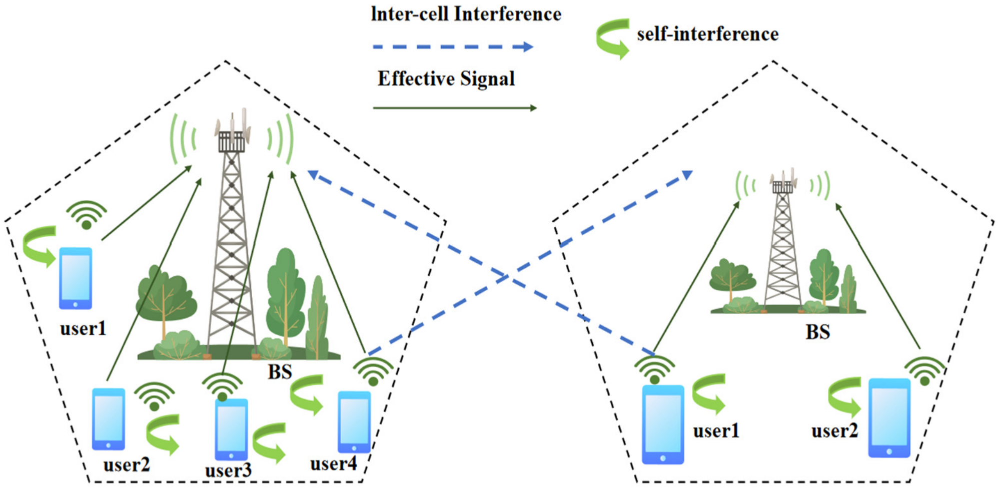

Figure 5. W-CDMA inter-cell interference.

The study in [134] proposes the use of W-CDMA in MIMO interference reduction utilizing the particle swarm optimization (PSO) technique. Interference between co-channel and adjacent channel are two types of interference that can occur in a MIMO network during transmission. Numerous strategies have been developed in earlier studies to lessen these interferences. In order to increase the BER even more and increase the MIMO-WCDMA network efficiency, an optimized method is provided. The paper's simulation results demonstrate a decrease in BER and an improvement in network throughput.

The study in [135] suggests a hybrid Interference Subspace Rejection (ISR) system that divides users into many groups according to their data rates and then uses several canonic ISR modes to nullify them rather than utilizing identical canonic ISR modes to suppress every user. The resulting receiver offers a considerably better trade-off between complexity and performance. According to simulations, a combination of the two most fundamental canonic ISR modes works in addition to the more intricate mode that has 30 to 60% fewer parameters, outperforming the simpler one by dB increases of many with only a minor increase in complexity.

The study in [136] analyzes additive white Gaussian noise (AWGN) in the context of multiple access interference (MAI). The gold sequence and the m-sequence were the simulation models created for the pseudo-random noise sequence. Using the BPSK, QPSK, and 2-PSK modulation schemes over the Nakagami-m fading channel in SIC and conventional detector (CD) receivers, respectively, these models were simulated in 2-USER W-CDMA and 4-USER WCDMA. The throughput and BER were used to assess the WCDMA's performances. It was discovered that for both BPSK and QPSK in the WCDMA system, SIC outperforms CD in terms of the BER and throughput.

The study in [137] aims to determine the effect of base station co-channel interference in multicell CDMA systems, and an analytical model is put forth. The objective is to investigate how surrounding cells' multiple-access interference affects multicell CDMA and W-CDMA systems' throughput. The possibility of using adaptive antennas to improve signal quality and reduce interference in CDMA mobile communication systems is examined. The study demonstrates how system performance can be enhanced by raising base station sensitivity. Table 6 shows the summary of the research work on W-CDMA interference in the literature discussed in this section.

Table 6. Summary of research work of W-CDMA interference in the literature.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[134]	Reduce the interference that may be encountered in MIMO networks during transmission.	PSO algorithm.	BER is reduced.	Increased network latency.
[135]	Interference reduction.	A hybrid ISR scheme.	A much better performance/complexity trade-off.	There is only one way.
[136]	The performances of the W-CDMA were evaluated.	Simulation models were developed for pseudo-random noise sequences, which were the gold sequence and m-sequence.	For both BPSK and QPSK in the W-CDMA system, SIC outperforms CD in terms of BER and throughput.	Need to be evaluated in more aspects.
[137]	Examines how surrounding cells' multiple-access interference affects multicell CDMA and W-CDMA systems' throughput.	To determine the effect of base station co-channel interference in multicell CDMA systems, an analytical model is put forth.	Enhancing base station responsiveness can enhance the system.	The analysis model is not perfect enough and takes into account too few factors.

5.2.2. DS-CDMA Interference

We study the interference problem in the DS-CDMA system as shown in Figure 6. The CDMA concept is used by the wireless communication technique known as DS-CDMA. In DS-CDMA, the signal is encoded using a different code for every user [138]. Since these codes are orthogonal to one another, numerous users can concurrently use the same frequency. Data are often channel-coded to improve transmission reliability and fault tolerance [139]. Different users use different codes, allowing them to transmit at the same time and frequency, achieving separation through code orthogonality [140]. The DS-CDMA system can also dynamically allocate frequency and time resources to meet the communication needs of different users. To ensure the upkeep of an appropriate signal-to-noise ratio and optimize system capacity, uplink power regulation is carried out between the user device and the base station [141]. To accommodate varying user needs, the base station dynamically modifies the downlink signal power. Delay spread caused by multipath propagation is handled using a Rake receiver to combine signals on different paths [142]. The received signal is equalized to eliminate time-varying distortion and frequency-selective fading introduced during transmission. The method dynamically allocates and shares spectrum resources according to network load and user needs to improve spectrum efficiency [143]. The interference problem of DS-CDMA mainly involves multiple users sharing codes on the same frequency band and possibly transmitting in the same time and space. What is discussed here is the interference problem in DS-CDMA.

The study in [144] presents a system for supporting massive Grant-free Multiple Access (mGFMA) called dynamic DS-CDMA (DyDS-CDMA). To detect signals in DyDS-CDMA systems, a low-complexity detector called the MMSE-SICD—minimum mean square error and sequential interference cancellation—is suggested. In the study, they concentrate on the possible execution that the DyDS-CDMA systems with the MMSE-SICD can achieve.

According to our research, the DyDS-CDMA with MMSE-SICD assistance operates with great efficiency in mGFMA situations.

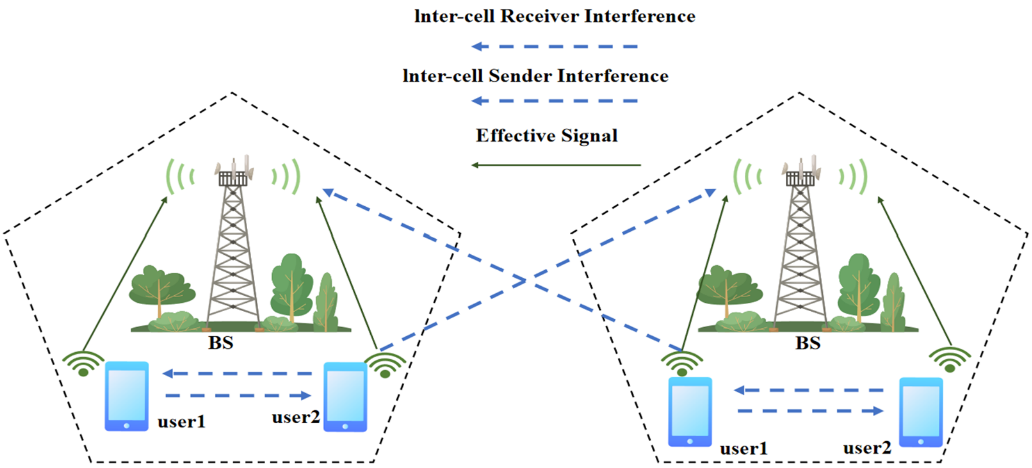

Figure 6. DS-CDMA inter-cell interference.

The study in [145] focuses on MAI, which significantly impairs system performance and is the term used to describe user interference. In the study, the MAI variance equation is used to generate the signal-to-noise plus interference ratio (SNIR) calculation in a significantly packed CDMA. Thus, by assessing the BER and the immediate SNIR, they provide an analysis of a traditional correlation receiver's (CCR) performance. Both synchronous and asynchronous scenarios are examined to see how important parameters like system performance are impacted by the number of users that are active, the length of the spreading order, and the SNR.

The research in [146] examines how well the updated hybrid interference cancellation system technique performs in a Rayleigh fading environment with MAI, multipath propagation, and Doppler shift. The least squares (LS) channel estimate technique is used in the plan. The utilization of the Rake receiver for data estimate is circumvented by the interference cancellation strategy and the method of detection. In the presence of Doppler shift, it is demonstrated that the interference canceller exhibits tolerable BER.

The study [147] proposes a robust and straightforward hybrid interference cancellation detector and tests its performance for both stationary and mobile users in a Rayleigh × fading multipath environment. Convergence is further examined on the detector. By combining the interference cancellation technique with the employed detection strategy, the need for the Rake combiner to estimate transmitted data is eliminated. Both stationary and moving users benefit greatly from the detector's excellent performance, which also ensures its convergence.

The study in [148] focuses on minimizing MAI. The research studies the throughput maximization of low-rate subscribers in a dense multiple-access network using the same feasible modulation method and Forward Error Correction (FEC) code. The subscribers send data to a central node that uses sequential soft interference cancellation, or soft SIC, as a technique. Analyses of comparative performance are conducted with a representative encoder. The results of the simulation demonstrate the superiority of the chosen soft SIC scheme over alternative SIC strategies, achieving meaningful throughput benefits even at high traffic loads.

Good properties of spread-spectrum communication systems include multiple-access capability, resilience to hostile or nonhostile interference, and low likelihood of detection and interception (LPD/LPI) [149]. The most often used type of spread-spectrum multiple access is direct-sequence spread spectrum (DSSS). The study assesses the effectiveness of satellite uplink communication systems that use DS-CDMA. Because of the varying distances between the user terminals and the satellite, the uplink DS-CDMA system is typically asynchronous. Because multiple-access interference must be taken into account, this presents a special difficulty to the system designer. To assess the performance of the DS-CDMA system, the authors expand Pursley's SINR methodology. The investigation examines three important design parameters: the chip pulse waveform, the spreading sequence, and the impact of temporal synchronization. The system designer can use the parametric SINR analysis as a tool to optimize the DS-CDMA design parameters in order to achieve the desired SINR performance.

The study in [150] analyzes ISI and co-channel interference (CCI) as two main challenges that impair the efficiency of wireless communication networks. The study develops an adaptive blind least mean square (LMS) algorithm for additive white Gaussian noise in a Rayleigh multipath fading channel (AWGN) in DS/CDMA. They assess the efficacy of the adaptive blind least squares algorithm and receiver architecture in mitigating the effects of channel fading and noise. The performance of the DS/CDMA system with an auto-adaptive least mean square equalization technique is investigated using MATLAB. The results of the simulation demonstrate that when AWGN and fading channels are present, the suggested approach performs better than the conventional algorithm. Table 7 shows the summary of the research work on DS-CDMA interference in the literature discussed in this section.

Table 7. Summary of the research work on DS-CDMA interference in the literature.

Reference	Issue	Proposed Method	Advantages	Disadvantages
[144]	The maximum performance that the DyDS-CDMA systems with MMSESICD can achieve.	The MMSE-SICD is a low-complexity detector that uses sequential interference cancellation and minimum mean square error.	With the help of the MMSE-SICD, the DyDS-CDMA operates with excellent efficiency in mGFMA situations.	It has only been demonstrated to operate efficiently in the mGFMA environment.
[145]	Examines the phenomenon of MAI, which significantly reduces system performance.	Finds the formula for SNIR in a Code Division Multiple Access system that is a highly loaded CDMA.	The performance of the system is far better than with conventional techniques.	Too few relevant parameters.
[146]	In the context of Rayleigh fading, the effectiveness of the modified hybrid interference cancellation system is examined in the presence of MAI, multipath propagation, and Doppler shift.	The least squares (LS) channel estimate technique is used in the plan.	In the presence of a Doppler shift, it is demonstrated that the interference canceller exhibits tolerable BER.	Only three environments are used to validate the enhanced interference cancellation scheme's performance.
[147]	The detector's performance is tested for both stationary and mobile users in a Rayleigh fading multipath scenario.	Hybrid interference cancellation detector.	Detector functions admirably for both stationary and mobile users.	Fewer relevant parameters are considered.
[148]	Examines how to maximize the throughput of a low-rate subscriber-dense multiple-access network.	Possesses the same functional modulation method and FEC coding.	Achieving meaningful throughput increases in the presence of heavy traffic.	There is only one option.
[149]	Asynchronous multiple-access interference in DS-CDMA satellite uplink communication systems.	Extends Pursley's SINR methodology to assess DS-CDMA performance, focusing on optimizing chip pulse waveform, spreading sequence, and temporal synchronization.	Provides a framework for optimizing DS-CDMA design parameters to achieve target SINR; enhances multiple-access capability, interference resilience, and LPD/LPI.	Differing user-to-satellite distances necessitates careful consideration of asynchronous situations; multiple-access interference presents special design issues.
[150]	ISI and CCI are two main challenges that impair the efficiency of wireless communication networks.	Creates a DS/CDMA adaptive blind LMS method.	In the presence of both AWGN and fading channels, the suggested technique performs better than the conventional algorithm.	This method is advantageous only when AWGN and fading channels are present.

6. Research Challenges

6.1. MUI in MU-MIMO Interference

Interference issues in high-density user environments have a major impact on system performance in MU-MIMO systems [151]. An overview of the interference issue and potential fixes is provided below.

6.1.1. Analysis of the MUI Problem

MUI is a phenomenon that occurs when several users share spectrum resources in a MU-MIMO system, particularly in high-density situations [152]. Constraints of antenna array configuration are as follows: inappropriate antenna array configuration exacerbates user interference, hinders isolation, and interferes with the ability to effectively differentiate signals [153]. Regarding channel dynamic changes, because of user mobility, the channel is always changing, necessitating real-time management and correction. This raises the computational load and compromises system stability.

6.1.2. Possible Solutions and Motivations for MUI

Dynamic beamforming: This technique improves signal gain and system performance by concentrating the signal in the target user's direction while reducing interference from other directions by dynamically altering the beam's intensity and direction [154]. Multiuser detection technology (MUD) improves anti-interference capabilities by efficiently detecting and removing user signal overlap in complicated interference situations through the use of deep learning-driven DeepSIC technology and SIC [155]. Deep learning channel estimation: Reduce interference issues brought on by channel estimation mistakes, forecast changes in the channel, and dynamically modify resources and interference management techniques using deep learning models [156].

6.2. Multiantenna MIMO Interference in Multiuser Scenarios

The complicated signal processing needs between antennas and the competition for spectrum resources, particularly in multiuser scenarios, are the primary causes of the interference issues that multiantenna MIMO systems encounter [157]. An examination of the interference issue and possible fixes is provided below.

6.2.1. Analysis of the Problem in Multiuser Scenarios

CSI accuracy: In order to manage interference, CSI is essential. System performance will be impacted by inaccurate CSI, which will intensify interference [158]. Complexity of precoding and beamforming: Beamforming and precoding designs in multiantenna systems necessitate exact control over the direction of signal transmission, yet the effectiveness of interference suppression may be impacted by intricate computation requirements [159]. Computational complexity and energy consumption: It becomes more challenging to strike a balance between efficiency and performance as the number of antennas in a system increases substantially.

6.2.2. Possible Solutions and Motivations for Multiuser Scenarios

Intelligent beamforming: Enhance directivity, minimize non-target interference, optimize signal pathways through real-time data learning, and enhance beamforming using deep learning [160]. Utilize SVD precoding to maximize signal coverage, minimize interference in high-density networks, and separate signals in space. Adaptive power control: In high-density regions, dynamically modify antenna power to efficiently lower interference while maintaining target users' signal quality [161].

6.3. Massive MIMO Interference Due to Large Number of Antennas

In massive MIMO systems, interference management faces multiple challenges due to the presence of a large number of antennas. The following are key issues and their potential solutions.

6.3.1. Problem Analysis for Large Number of Antennas

Complexity of CSI collection: Massive MIMO systems need to reliably collect channel state information from a large number of antennas, which leads to high computational and transmission overheads, making accurate CSI collection a major challenge [162]. High-dimensional data processing: Due to the large number of antennas, the system needs to process high-dimensional data, which increases computational complexity and may cause higher latency and energy consumption. Cross-interference between user signals: Cross-interference between user signals has a negative impact on system performance, especially in real-time communication scenarios, which require rapid adaptation to changing communication environments [163]. Antenna array design optimization: Reducing mutual interference requires optimizing the design of antenna arrays, which is an important challenge, especially in high-density user environments. Energy consumption problem: Massive MIMO systems have a large number of antennas and a large amount of data, which significantly increases energy consumption. It is necessary to optimize the energy consumption of the system [164].

6.3.2. Possible Solutions and Motivations for Large Number of Antennas

Intelligent beamforming and precoding technology: Advanced beamforming and precoding technologies are used to achieve intelligent control of signal direction and strength and reduce interference from nontarget users [165]. Channel estimation based on deep learning: Use deep learning models for channel estimation and data prediction to improve the efficiency of channel information collection and reduce the delay in processing high-dimensional data. Low-complexity interference cancellation algorithm: Develop a low-complexity interference cancellation algorithm to reduce the computational burden and energy consumption while maintaining high anti-interference efficiency [166]. Antenna design optimization: Optimize antenna layout and array structure to minimize interference between users and enhance the system's signal isolation capability.

6.4. Cell-Free Massive MIMO Interference Management

Cell-free massive MIMO systems face many challenges in interference management. The following are the main interference issues and their potential solutions.

6.4.1. Problem Analysis Interference Management

Antenna interference caused by increased user density: Since multiple users share a distributed antenna array in a cell-free massive MIMO system, increased user density may cause inter-antenna interference, especially when users are unevenly distributed. Frequency selectivity and channel state variation: Frequency selectivity and the time-varying characteristics of the channel make channel estimation more challenging and complicate interference control [167]. The faster the channel changes, the higher the demand for channel estimation and real-time adaptation. Computational complexity of distributed collaboration: Distributed collaboration and signal processing in the system require efficient algorithms to reduce user interference. However, when a fast response to a changing communication environment is required, the complexity and energy consumption of distributed computing increase. Resource allocation problem: In a cell-free massive MIMO system, it is crucial to effectively allocate antenna, power, and spectrum resources [168]. Due to the complexity of resource allocation, how to optimize resource utilization in an interference environment becomes a major challenge.

6.4.2. Possible Solutions and Motivations for Interference Management

Distributed signal processing algorithms: Develop low-complexity distributed algorithms that can effectively reduce interference between users and reduce the computational burden of the system [169]. Intelligent interference management technology: Introduce interference management methods based on machine learning to dynamically adjust channel conditions and adapt to frequency selectivity and time-varying channel environments to achieve better interference control. Frequency-selective channel adaptation technology: For frequency selectivity and rapidly changing channels, an adaptive algorithm is used to improve the accuracy of channel estimation and reduce performance losses caused by interference. Resource allocation optimization strategy: Design a resource allocation strategy based on reinforcement learning to achieve efficient allocation of antennas, power, and spectrum, and improve the overall performance of the system in an interference environment [170].

6.5. Interference in W-CDMA Systems

In W-CDMA systems, interference is an important factor affecting communication quality and system performance. The following are the main interference problems and their possible solutions.

6.5.1. Problem Analysis of Interference in W-CDMA

Near-end user interference: Transmissions from neighboring cells or users may cause near-end user interference, reduce the quality of received signals, and thus affect communication efficiency [171]. Multipath fading and multiuser interference: Due to the fading of signals in multipath propagation and the sharing of spectrum resources by multiple users, multipath fading and MUI occur, which degrades communication quality. Co-channel interference: Transmissions from adjacent cells or frequency bands can cause co-channel interference, resulting in signal aliasing and demodulation errors, further weakening the reliability of the system. External electromagnetic interference: Electromagnetic sources and other external interference may affect the normal operation of the system, especially when channel conditions are complex [172]. Power control complexity: Changes in channel conditions and uneven user distribution increase the difficulty of power control. For users with faster mobility, frequent switching, and rapid fading make interference management more challenging.

6.5.2. Possible Solutions and Motivations for Interference Mitigation in W-CDMA

Advanced signal processing algorithms: Using efficient signal processing algorithms, such as adaptive filtering and interference suppression techniques, can improve the system's anti-interference ability in multiuser and multipath environments. Frequency planning optimization: By optimizing frequency planning and resource allocation, the occurrence of co-channel interference is reduced and the channel utilization efficiency is improved [173]. Intelligent power control strategy: Adopt an adaptive power control strategy, dynamically adjust the user's transmission power according to the real-time channel conditions to ensure signal quality and reduce interference between adjacent users [174]. Multipath interference suppression technology: Use technologies such as Rake receivers to combine the energy of multipath signals, effectively reducing the impact of multipath fading on communication quality. These solutions and technical methods help to enhance the capacity and performance of W-CDMA systems in complex interference environments and improve the system's anti-interference ability [175].

6.6. Interference in DS-CDMA

In DS-CDMA systems, interference is particularly prominent due to the influence of multiple users sharing spectrum resources and multipath propagation. The following are the main interference problems and their possible solutions.

6.6.1. Problem Analysis of Interference in DS-CDMA

Multipath fading and MUI: In DS-CDMA systems, multiple users share the same spectrum resources, and wireless signals are affected by multipath effects during propagation, resulting in multipath fading and multiuser interference, which reduces communication quality [176]. The signals of adjacent users may interfere with each other. Especially in the case of near-end users, interference can easily cause distortion of received signals and affect communication efficiency [177]. Synchronization problem: DS-CDMA systems require precise time–frequency synchronization to avoid misalignment of user signals and reduce the probability of interference. The synchronization problem is one of the key problems that need to be solved in this system. ISI: Inter-symbol interference affects the accuracy of signal demodulation. If it is not controlled, it may lead to an increase in bit error rate. Signal conflict: When multiple users access the system at the same time, signal conflicts may occur, resulting in increased interference and affecting system stability [178].

6.6.2. Possible Solutions and Motivations to Mitigate Interference in DS-CDMA

Strong and weak user power control strategy: Through adaptive power control technology, effectively manage the power allocation between strong and weak users and reduce interference between adjacent users. Inter-symbol interference processing technology: Adopt an advanced inter-symbol interference suppression algorithm to reduce the interference effect in multiuser environments and improve signal demodulation accuracy [179]. Synchronization technology optimization: Optimize the synchronization mechanism of the system to ensure the time and frequency alignment of user signals and reduce interference problems caused by synchronization errors. Multipath interference suppression algorithm: Use multipath suppression technology such as Rake receiver to combine the energy of multipath signals and reduce the impact of multipath fading on communication. Multiuser access protocol and conflict detection: Introduce an effective multiuser access protocol and conflict detection method to reduce signal conflicts and improve the system's anti-interference ability [180]. By implementing these technologies and strategies, the anti-interference performance and communication quality of the DS-CDMA system can be significantly improved to meet the needs of complex communication environments.

7. Discussion

With the development of 5G and future networks, the density and complexity of networks are increasing, and the interference problem is also exacerbated [46]. Although existing interference management methods can alleviate interference to a certain extent, providing optimal effects in high-density and high-mobility scenarios can be difficult with these methods. The main types of interference in B5G networks are classified as inter-cell interference, multiuser interference, and signal overlap interference in MIMO systems. Traditional interference cancellation methods such as enhanced inter-cell interference coordination (eICIC) and power domain interference cancellation technology are effective in 4G and some 5G networks but are no longer applicable to B5G complex scenarios, such as signal attenuation and reflection problems in higher frequency bands (millimeter waves).

In addition, the expansion of MIMO and MU-MIMO technologies allows base stations to connect more users at the same time, causing inter-user interference [181]. This study comprehensively analyzes the currently used MU-MIMO interference management technologies, such as beamforming and joint transmission methods. Although these technologies can reduce interference to a certain extent, they rely heavily on perfect CSI, which is difficult to achieve in high-mobility scenarios.

7.1. Future Research Directions

7.1.1. Collaborative Optimization

Dynamic spectrum management has great potential for interference suppression in multiuser and high-density environments [182]. As spectrum resources become increasingly scarce, traditional static spectrum allocation methods can no longer meet the needs of complex communication environments. Future research can explore dynamic spectrum allocation strategies based on machine learning and reinforcement learning so that the system can automatically adjust spectrum resources according to real-time network needs, user distribution, and interference conditions, thereby maximizing spectrum utilization.

The combination of dynamic spectrum allocation and interference cancellation technology is an important direction for future research [183]. Dynamic spectrum management reduces interference risks by reducing spectrum overlap and optimizing resource allocation, but this is not enough to completely eliminate complex interference in multiuser environments. Therefore, adaptive interference suppression technologies (such as multiuser detection, beamforming, collaborative interference cancellation, etc.) need to work in conjunction with dynamic spectrum allocation. For example, in a high-density environment, dynamic spectrum allocation can reduce direct interference by separating user frequency bands, while beamforming technology can focus signal energy on the target user and more accurately reduce multipath and neighboring user interference. The collaborative optimization strategy of spectrum allocation and interference suppression will significantly improve the anti-interference performance of the system.

7.1.2. Hybrid Mode of Centralized and Distributed Interference Management

Centralized interference management has significant advantages in centralized network architecture and can perform global resource scheduling and interference control through a unified control mechanism [184]. However, with the expansion of network scale and the popularization of distributed architecture, the centralized management mode may face the problems of excessive computing burden and response delay. Future research can explore a hybrid interference management mode combining centralized and distributed management. For example, introducing a distributed control module on the basis of centralized management enables the system to quickly adjust interference in a local range while using centralized management to optimize the configuration of global resources. This hybrid mode will help the system improve its flexibility in a rapidly changing network environment and achieve more efficient interference suppression by optimizing interference management at the local and global levels.

7.2. Emerging Approaches

7.2.1. Intelligent Adaptive Spectrum Management

By introducing deep learning and reinforcement learning, the system can adaptively adjust spectrum resources and interference suppression strategies according to environmental changes [185]. This not only helps to improve spectrum efficiency but also achieves higher stability in a dynamic network environment.

7.2.2. Cross-Layer Interference Management Mechanism

We suggest considering extending interference management from the physical layer to the MAC layer and the network layer, establishing a multilayer collaborative interference management framework, comprehensively reducing cross-layer interference, and optimizing the overall network performance [186].

7.2.3. Interference Management in 6G Heterogeneous Networks

With the move towards 6G systems, interference issues in heterogeneous networks are becoming increasingly important [187]. 6G networks will include a variety of access technologies (such as Wi-Fi, millimeter wave, and terahertz communications), and the frequency band interference and cross-layer interference issues between them need to be studied in depth. Future research should focus on intelligent interference management methods, such as cross-layer interference elimination and multilevel collaborative interference management strategies, to cope with complex interference in 6G heterogeneous network environments. In addition, dynamic spectrum sharing and adaptive beamforming technologies also have potential application value in frequency band coexistence scenarios and can improve the stability and performance of 6G networks through intelligent interference suppression.

7.2.4. Non-Orthogonal Multiple Access (NOMA)

With the introduction of nonorthogonal multiple access (NOMA) technology, the interference problem has become more complicated [188]. NOMA allows multiple users to share the same spectrum resources, increasing spectrum utilization, but it also brings a new type of interference, namely, user-layer interference. In a NOMA system, signals from different users may overlap in the power domain, resulting in serious interference problems during decoding. Therefore, future research needs to be specifically optimized for interference management techniques in NOMA to ensure that users of different power levels can coexist reliably and reduce the impact of power domain interference on system performance.

7.2.5. Intelligent Reflecting Surface (IRS)-Assisted MIMO Systems

An extensive assessment of the literature on intelligent reflecting surface (IRS)-assisted MIMO systems is presented in the work [189]. When combined with MIMO, IRS, a novel and important enabling technology, greatly enhances system performance and is regarded as the leading candidate to realize 6G networks. The fundamental ideas of the IRS were covered first in a poll, after which the authors talked about its benefits and potential uses. Additionally, they gave a thorough description of the various uses for IRS-assisted wireless networks and associated problems. An extensive review of the integration of IRS and MIMO in wireless communication systems is given in the survey article [190]. By adjusting the propagation environment, IRS, often referred to as a reconfigurable metasurface, has become a game-changing technology that improves wireless communication performance. The basic ideas of MIMO and IRS technologies are examined in the paper, along with their advantages and uses. It then explores the energy efficiency and resource allocation synergies that result from combining these technologies, clarifying how beamforming and signal manipulation enhance IRS in MIMO systems. The main study areas, including optimization techniques, beamforming tactics, and practical implementation considerations, were explored through a thorough examination of numerous approaches and state-of-the-art algorithms in resource allocation and energy efficiency. Additionally, the paper offers open research possibilities that specifically address issues like the MIMO IRS system's energy efficiency and resource allocation constraints. The challenges and future developments of MIMO-enabled IRS systems are discussed in the study. The assessment highlights their potential to transform wireless communication paradigms and herald an era of greater coverage, spectrum efficiency, and connectivity by providing a consolidated perspective of the state of the art.

8. Conclusions

This study comprehensively reviews and analyzes existing interference management technologies, especially for the application of MIMO and CDMA in B5G networks. With the evolution of 5G and B5G networks, network density and complexity have increased significantly, and interference problems have become more complex and difficult. Although existing interference management methods can effectively alleviate interference to a certain extent, these methods are no longer able to meet the needs of B5G networks in high-density and high-mobility scenarios. First, this paper studies and classifies the main types of interference in B5G networks, including inter-cell interference, multiuser interference, and signal overlap interference in MIMO systems. In terms of interference management, traditional interference cancellation methods such as eICIC and power domain interference cancellation technology have good effects in 4G and early 5G networks but are insufficient in B5G environments. For example, with the increase in frequency bands (such as millimeter wave bands), signals are more likely to cause more serious interference problems due to attenuation and reflection.

In addition, interference problems in MIMO systems are more complicated. The expansion of MU-MIMO technology enables base stations to connect more users at the same time, but it also brings interference between users. This study analyzes the currently used MU-MIMO interference management techniques, such as beamforming and joint transmission methods. Although these techniques can reduce interference to a certain extent, they rely on perfect CSI, which makes it very difficult to obtain accurate CSI in high-mobility B5G scenarios. At the same time, existing linear interference cancellation methods (such as the minimum mean square error (MMSE) method) are computationally intensive and costly in large-scale antenna systems, making it difficult to achieve an efficient response.

In the evolving B5G network environment, interference suppression remains a critical topic. This article explores interference management techniques in MIMO and CDMA systems and analyzes the advantages and disadvantages of key technologies such as beamforming, interference alignment, and resource allocation. Looking ahead, we can conduct research in the following directions: using artificial intelligence and machine learning algorithms to achieve dynamic adaptation; combining hybrid beamforming for greater robustness and flexibility; addressing interference challenges brought by massive MIMO and millimeter wave integration; and customizing interference solutions through network slicing and edge computing. In the pursuit of seamless B5G connectivity, interdisciplinary collaboration and innovation will be key, and continuing to explore interference management methods will help us build next-generation networks that can cope with complex environments.

Author Contributions: Conceptualization, H.Y. and F.Q.; methodology, F.Q. and S.T.A.J.; validation, K.A.Z.A. and S.H.A.K.; formal analysis, K.A.Z.A. and S.T.A.J.; investigation, S.T.A.J. and F.Q.; writing—original draft preparation, H.Y. and F.Q.; writing—review and editing, F.Q., S.H.A.K. and Q.N.N.; visualization, S.T.A.J.; supervision, F.Q.; project administration, F.Q. and Q.N.N.; funding acquisition, F.Q. and Q.N.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Kebangsaan Malaysia Geran Universiti Penyelidikan having Grant number GUP-2024-009 and Universiti Kebangsaan Malaysia, Fundamental Research Grant Scheme having Grant number FRGS/1/2023/ICT07/UKM/02/1. The research was also supported by Posts and Telecommunications Institute of Technology Research Grant 2023 & 2024.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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