Advanced Interference Management Techniques for 5G/6G Wireless Networks: A Brief Overview

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***Abstract*—Multi-hop communications are increasingly becoming critical in 5G/6G wireless networks. However, the technique is confronted with many interference challenges that are also performance-limiting factors, especially in the management of data flows. Conventional methods to mitigate interference are non-optimal and can only be applied in some special cases. The recent advancements in information theory have enabled a paradigm shift towards interference management with the emergence of interference shaping schemes termed Advanced Interference Management (AIM) techniques. The AIM techniques are novel network-side approaches developed, showing promising theoretical performance results. Despite the excellent theoretical performance results, AIM techniques are far from practical implementation, and there remains an open gap in the literature. This brief study outlines two (2) novel, promising AIM techniques: Interference Alignment (IA) and Interference Neutralization (IN). Specifically, some fundamental aspects of IA and IN are discussed, including their concepts, schemes, and applications to 5G and 6G networks. In addition, open research issues that dampen practical applications are presented.**

***Keywords*—5G, 6G, interference alignment, interference neutralization, degree of freedom, channel state information**

I. Introduction

Multi-hop communication has emerged as a key enabler for public safety applications in 5G and emerging networks, facilitating the control of vital human-in-the-loop services. It allows the source and the destination to communicate through one or more intermediate nodes acting as a relay. This approach offers key advantages, such as extended range, improved reliability, and reduced blockage sensitivity, guaranteeing robust communication even under extreme conditions [1]. The evolving architecture, however, introduces network complexity, additional overhead, and high interference on the nodes, as the source-destination path propagates not only the desired signals but also interference signals across the network. This interference phenomenon is a major impairment for reliable 5G/6G communication and a significant performance-limiting factor; Fig. 1 illustrates various sources of interference in 5G/6G. Effectively managing interference poses significant challenges in designing and operating 5G/6G wireless networks [2]. Conventional methods to mitigate interference, such as avoiding interference, treating interference as noise, and decoding interference, are non-optimal approaches and can only be applied in some special cases [3]. Again, these methods perform far below the capacity of the interference networks. Notably, the quest to unlock the network's capacity has continued to elude researchers over the past decades.

Recent advancements in information theory have enabled a paradigm shift toward interference-shaping strategies, allowing numerous independent simultaneous transmissions within the interference domain [4]. This is achieved by employing some sophisticated interference-shaping techniques on the transceivers of a node. The idea of interference shaping is to form interference patterns when transmitters propagate signals, reducing or eliminating the aggregate interference effect at each receiver or before the signal reaches the receiver [5]. The approach is very attractive, radical, and has competitively challenged the traditional interference management methods. Specifically, two (2) key interference shaping techniques with promising attributes are Interference Alignment (IA) and Interference Neutralization (IN), and are at the forefront of interference mitigation [6]. IA is termed a cooperative signaling strategy that aligns interference at the receiver before removing it [7]. On the other hand, IN is a technique that neutralizes interference signals through the selection of relay-forwarding strategies [8]. These techniques are termed Advanced Interference Management (AIM) techniques, and they demonstrate a degree of freedom DoF approach, indicating that they can attain the capacity of an interference network at a very high Signal-to-Noise Ratio (SNR).

Despite excellent theoretical performance, AIM techniques face several constraints that hinder their practical application. IA and IN techniques have been extensively studied in recent years, with numerous reviews available [9−15]. Ghasemi *et al.* [9] introduced the concept of IA; recent research findings have not been incorporated. Ayach *et al.* [10] assessed the practical challenges of IA, including performance in a realistic environment. Detailed work on IA techniques, classification, challenges, and

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applications is presented in Ref. [11]. The fundamental idea of IN is presented in Ref. [12], but the feasibility conditions for achieving IN in a multi-hop network were not fully defined. Subsequent work has identified the necessary and sufficient conditions for achieving IN in a minimum-relay network, highlighting the achievable DoF [13]. The effect of Channel State Information (CSI), a significant drawback for IA and IN, is the focus of ongoing research, as obtaining the CSI for a practical system is very challenging [14]. Finally, the fundamentals, advances, and emerging challenges of Intelligent Networking (IN) in active reconfigurable intelligent surfaces are reviewed in Ref. [15]. Building on this foundation, our work aims to bridge the identified gaps in the literature by focusing on the most critical and relevant issues.

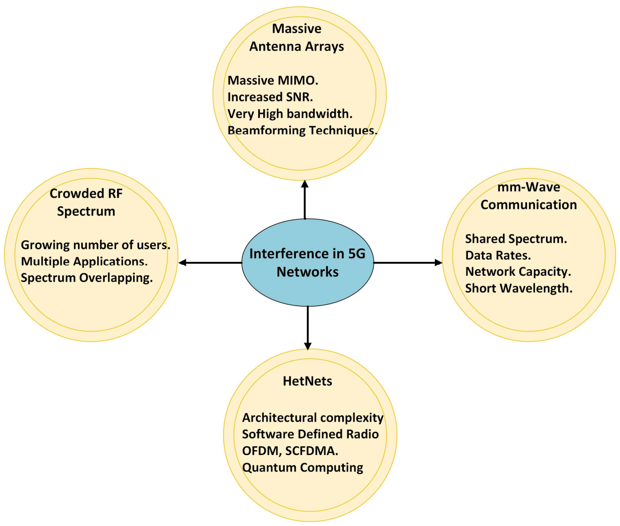

Fig. 1. Some sources of interference in 5G networks.

The paper's organization is as follows. First, Sections II and III provide an overview of IA and IN, which leverage the concept of interference shaping. Section IV then delves into the recent practical challenges facing IA and IN, and explores machine learning techniques to enhance these approaches. Next, Section V presents a comparative analysis of IA and IN as a guide for the selection of appropriate interference management techniques. Finally, we concluded the paper with Section VI.

II. Interference Alignment

The origin of Interference Alignment (IA) can be traced back to the literature in 1998 in the context of informed source coding, and the idea lies in elementary linear algebra [16]. The concept was first considered a coding technique for the two-user MIMO X channel, then later extended to other network topologies, including relay channels. It was proved to achieve a multiplexing gain strictly higher than that of the embedded MIMO Interference Channel (IC), Interfering Multiple-Access Channel (IMAC), and the Interfering Broadcast Channel (IFBC) taken separately. IA can be defined as a cooperative interference mitigation approach that exploits the availability of multiple signaling dimensions provided in time slots, frequency, or antennas. It is an approach to maximise interference-free space for communicating the desired signal and obtaining an optimal Degree of Freedom (DoF). It is revealed that interference can be roughly concentrated into one-half of the signal space at each receiver, leaving the other half available for interference-free communication [17]. Existing IA works are mostly based on dimensions, network topologies, and applications accordingly [18]. With the emergence of massive MIMO, Device-to-Device (D2D) communication, and mm-Wave communication as prominent techniques for 5G/6G, much research on IA is focused on the spatial dimension, including feasibility studies. However, in exceptional cases where IA in space dimension is not achievable, IA in time and frequency dimensions are exploited, but it's mostly impractical due to propagation delay and Doppler-shift effects [18].

To clarify IA's basic idea and motivation, take the case of a K-user classical IA structure in space dimension as depicted in Fig. 2. It is a case of IA in an interference channel with two (2) antennas each at the receivers and transmitters, where each transmitter sends a data stream to its associated receiver. The concept of IA can be achieved by channeling the desired message to one antenna and eliminating interference at the other [19]. Thus, it's a 'half cake' approach available to each user via the decoding matrix. However, it is only achievable when the feasibility conditions for IA are satisfied [20]. Hence, network-based IA is crucially dependent on feasibility conditions, DoF, iterative algorithm, and CSI. These conditions are fundamental to IA-based networks and have attracted significant interest in the practical implementation of IA.

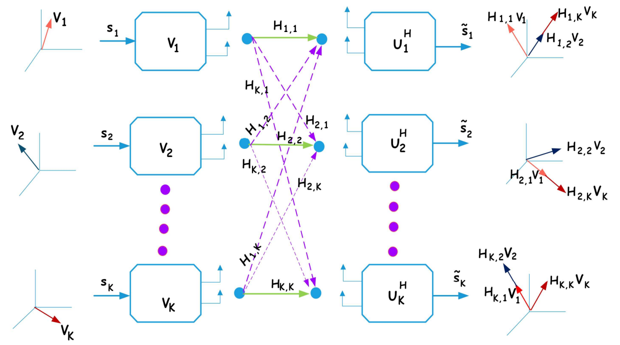

Fig. 2. K-User classical IA structure.

When the following conditions are satisfied in Eqs. (1)–(2), IA is feasible.

$$U_{[k]}^{H} H_{[k,i]} V^{[i]} = 0_{s^{[k]} \times s^{[i]}}, \quad \forall i \neq k \tag{1}$$

$$rank\left(U_{[k]}^{H} H_{[k,k]} V_{[k]}\right) = s^{[k]}, \forall k \in \{1,2,\dots,K\} \tag{2}$$

Eq. (1) ensures that interference at all the receivers can be eliminated, while Eq. (2) ensures that the desired data stream s_k of the k^{th} should not be zero force at the intended receiver. The second condition is a difficult aspect of IA that has attracted considerable attention. Another critical aspect of IA is the DoF; with symbol extension, total achievable DoFs can grow linearly with the number of k-user [21]. Nevertheless, the most challenging issue that impedes IA implementation is the CSI requirements; the feedback is enormous and must be accurate for good results.

IA schemes can be grouped into two categories: centralised IA and distributed IA [22]. The former uses the central controller's global CSI in computing the precoding and decoding matrices. This information is sent to each Access Point (AP), and user, and any AP or specific functional entity can serve as the centralised controller. The centralised IA scheme is best utilised in backhaul scenarios and Time Division Duplex (TDD) mode. The latter obtains precoding and decoding matrices independently at each AP and then sends them to the User Equipment (UE). The scheme is most suitable for no backhaul deployment between APs. Among the several IA schemes are blind interference, retrospective IA, ergodic IA, and asymptotic IA. Blind IA achieves IA without the use of Channel State Information at the Transmitter (CSIT). Retrospective IA demonstrates the idea of achieving IA with completely outdated CSIT, while ergodic IA performs IA with delayed CSI feedback.

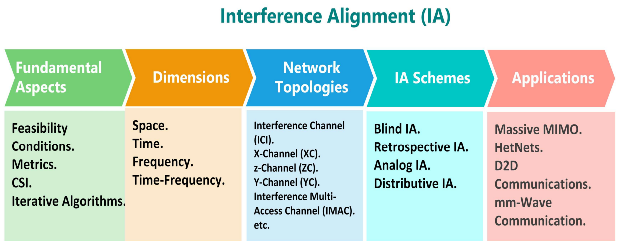

Fig. 3. Summary discussion on IA.

Due to their promising attributes, IA-based schemes are emerging as a general approach for solving interference management problems in 5G networks. In HetNets, macro cells, micro cells, pico cells, and femto cells coexist in a hyper-dense network, with interference across tiers due to power mismatches. IA has been extensively studied in femto- and pico-based networks [23−26]. It has also been implemented in D2D technology, where UEs communicate directly without accessing the core network, but this approach is subject to CCI issues that may hinder its practical application. IA has been exploited to solve interference issues in D2D systems [27−29]. In Massive MIMO, a large number of transceiver antennas are combined, introducing additional spatial DoF and thereby greatly enhancing spectral efficiency and system throughput. Nevertheless, ICI would seriously undermine this advantage, and IA can be leveraged to solve interference challenges in massive MIMO networks based on antenna selection [30−33]. In mm-Wave communication, it offers features that support ultra-dense small cells and mobile data offloading, resolving limited spectrum issues in 5G and emerging networks. But it is subject to inter-cell and intra-cell interference, resulting in a significant number of transmission failures. IA schemes have been proposed to tackle these challenges [34−36]. In fact, IA outperforms conventional methods for managing user interference and can be used across a variety of multi-user networks. With the recent deployment of 5G wireless networks, new IA schemes will surely emerge to improve the existing IA schemes on interference management. Fig. 3 summarizes the discussion of IA in this section.

III. Interference Neutralization

Interference Neutralization (IN) was invented by Mohajer *et al.* [37] while studying the two-hop relay networks. It has received attention over the past decade as an Interference Management (IM) technique, demonstrating that interference cannot only be aligned but also cancelled or partially cancelled across multiple paths. While the terminology appears new, the same fundamentals have existed for many years, under many names such as distributed orthogonalization, distributed zero-forcing, multiuser zero-forcing, and orthogonalize-and-forward [38]. Even though IN has leverage on the idea of IA, it aims to appropriately combine signals from various directions to cancel interfering signals while the desired signals are kept [39]. Hence, IN is a technique that neutralises interference signals by carefully selecting forward strategies as the signal travels from the source through the relay nodes to the destination.

Fig. 4 illustrates the idea of IN in a class of multi-hop interference networks with three (3) transmit nodes, six (6) receive nodes, and a single antenna at each node. Assuming the transmit nodes (T_1, T_2, T_3) are sending the same message x to its intended receiver (R_1, R_2, R_3, R_4) and its unintended receiver (R_5, R_6). Hence, it is required that the interference at (R_5, R_6) from source (T_1, T_2, T_3) be neutralized. Denoting h as the channel coefficient between the receive node j and the transmit node i, and u_i as the precoding matrix at the node i being all complex numbers. Then the received signal y_i can be conveniently decoded been the desired message or the interference.

$$y_i = \left(h_{j1}u_1 + h_{j2}u_2 + h_{j3}u_3\right)x \tag{3}$$

Through careful design of the precoding matrix (u_1, u_2, u_3) at the three transmitters, the intended message at the four receivers can be decoded; thus, the interference message at two receivers can be neutralized, satisfying the following Eqs. (4)−(5):

$$h_{j1}u_1 + h_{j2}u_2 + h_{j3}u_3 \neq 0,\ \ \mathrm{j} \in \{1,2,3,4\} \tag{4}$$

$$h_{j1}u_1 + h_{j2}u_2 + h_{j3}u_3 = 0,\ \ \mathrm{j} \in \{5,6\} \tag{5}$$

Hence, the destination can achieve interference-free decoding as the collective interference becomes zero at each receiver [7]. IN is only feasible if the sufficient condition of $R \geq K(K-1)+1$ relay is met, where $R =$ the number of relays and K comprises the source-destination pairs and the eligibility of neutralization nodes determined [40].

Several schemes have been proposed, advancing the idea of the IN technique: In Ref. [41], an optimal relay strategy IN scheme is proposed to improve the achievable rate. Gou *et al.* [38] and Lee *et al.* [42] introduced a novel scheme called Aligned Interference Neutralization (AIN) to achieve significant DoF on a 2-hop relay network irrespective of the number of antennas. Cooperative interference neutralization manages interference in the context of large-scale multi-hop networks. Other proposed schemes are ergodic interference neutralization, blind interference neutralization, and opportunistic interference neutralization. These schemes perform under imperfect CSI feedback, focusing on decoding the desired information and avoiding the ICI in the cells [43, 44].

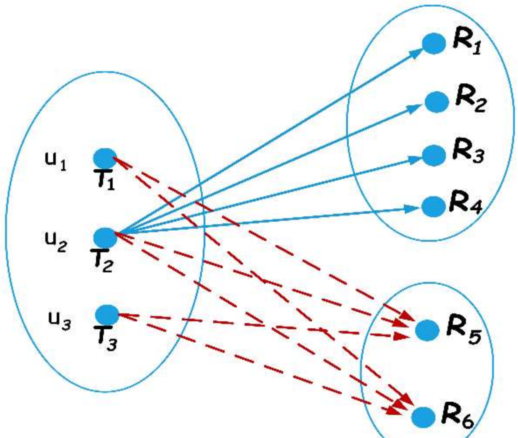

Fig. 4. IN in a multi-hop arrangement.

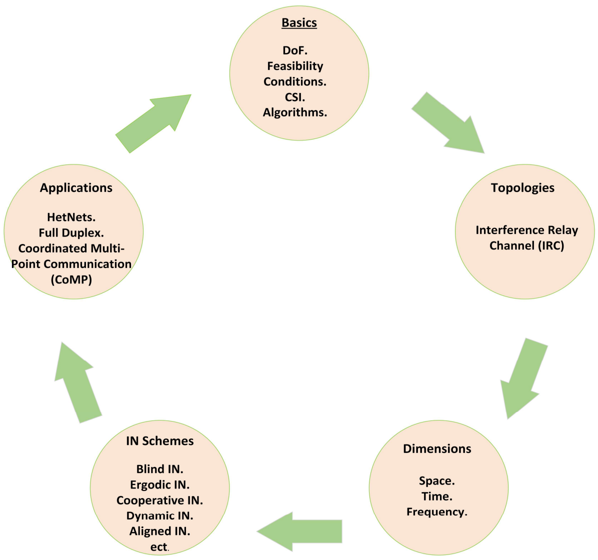

Fig. 5. Summary discussion on IN.

IN is also a promising information-theoretical approach to mitigating interference in 5G and emerging networks while focusing on cooperative schemes. It has been exploited in Coordinated Multipoint (CoMP) communications where the BSs, transmit precoders, and receiver filters are jointly designed. As the simultaneous transmission of multiple data streams is enabled, interference carrying the same data streams is aligned in the opposite direction of a subspace on the network [14]. In Full Duplex (FD) communication, the network throughput is doubled. However, operating in FD mode, the radiated power from the Downlink (DL), i.e., BS, interferes with its desired received signals from the Uplink (UL), resulting in Self-Interference (SI) and Inter-User Interference (IUI). Leveraging the idea of IN, Du *et al.* [12] proposed an innovative scheme with low complexity to neutralize the IUI in FD cellular networks using partial CSIT and two symbol extensions. It considers the general HetNets case, where the number of interferences, desired data streams, pico base stations, and pico user equipment are all variables. In [39], a revolutionary scheme termed dynamic IN (DIN) logically determines the interference to be neutralized while balancing the transmitter power needed for IN with the transmission of the desired signal. Fig. 5 is the summary discussion on IN.

IV. Comparative Analysis between the AIM Approaches

IA and IN are both powerful techniques for managing interference in wireless networks, but they differ in their specific needs. Notably, implementing these methods involves significant complexities that require substantial resources. Nevertheless, the benefits they offer of improving network performance often outweigh the challenges of implementing them. A comparison of IA and IN techniques is provided, highlighting their performance, complexity, and resource requirements as shown in Table I.

A. Complexity

While IA promises significant gains, it comes with substantial mathematical and algorithmic complexities [38, 39]. This problem is known to be NP-hard, making it computationally intensive and challenging to solve optimally. Also, various algorithms such as the Modified Alternating Minimization Algorithm (MAMA) and hybrid algorithms that combine different optimization techniques, have been developed to reduce computational burden. In addition, the practical implementation of IA is challenging in real-world scenarios, further complicating its use.

IN aims to eliminate interference by canceling it at the receiver, but it still presents considerable complexities. It requires complex signal processing techniques, accurate CSI to match the phase and amplitude. In addition, balancing the power used for neutralization is very crucial with the Dynamic Interference Neutralization (DIN) schemes proposed [14]. Furthermore, in multi-hop interference networks, techniques such as Aligned Interference Neutralization (AIN) are used to align and cancel interference across multi-hops, thereby adding a layer of complexity to the network.

B. Performance

IA and IN exhibit unique performance characteristics in wireless communication systems, each with its own distinct strengths, limitations, and practical applications. IA generally offers higher spectral efficiency by maximizing the DoF, making it well-suited for high-density network scenarios [45]. The implementation of IA, however, is complex; it requires sophisticated mathematical and algorithmic requirements, as we need accurate CSI. Notably, IA is highly scalable and can be adapted to accommodate various network sizes and configurations.

IN provides effective interference cancellation, which can also enhance spectral efficiency, particularly in scenarios with predictable interference patterns. However, IN has limitations, such as the additional power requirements to generate a neutralizing signal and the need for precise signal processing and synchronization [46]. Despite these challenges, IN offers greater adaptability by dynamically adjusting the neutralized signal to optimize performance, which can be advantageous in specific scenarios, such as relay-aided and multi-hop networks.

TABLE I. COMPARATIVE ANALYSIS BETWEEN APPROACHES

	IA	IN	Summary
Complexity	Some key points regarding its complexity are: • Mathematical Complexity • Algorithm Complexity • Practical Implementation	Some key points regarding its complexity are: • Signal Processing Complexity • Resource Management • Multi-Hop Networks	IA might be considered more complex due to its mathematical and algorithmic challenges, especially in scenarios requiring high DoF and precise synchronization. On the other hand, IN's complexity lies in its signal processing and resource management requirements, particularly in a dynamic and multi-hop environment.

Performance	Focus is on strengths, limitations, and practical applications:
	• Strength
	  o Maximizing DoF
	  o Scalability
	• Limitations
	  o CSI requirements
	  o Computational complexity
	• Practical Applications
	  o Particularly useful in scenarios with multiple interfering signals, such as multi-user MIMO systems and dense urban environments.
		Focus is on strengths, limitations, and practical applications:
		• Strength
		  o Effective interference cancellation
		  o Dynamic Adaptation
		• Limitations
		  o Power Consumption
		  o Complex Signal Processing
		• Practical Applications
		  o It is well-suited for environments where interference is predictable and can effectively be neutralized, such as relay-aided cellular networks
			IA excels in maximizing spectral efficiency and scalability, making it suitable for dense networks. IN, on the other hand, offers effective interference cancellation and dynamic adaptation, which can be advantageous in specific scenarios like relay-aided and multi-hop networks.

Resource Requirements	It has distinct resource requirements: Relies on accurate CSI Computational Complexity involving precoding matrices, significant power. Sophisticated hardware at the transceiver Precise synchronization	It has distinct resource requirements: • Requires channel knowledge, potentially less precise than IA. • Requires computational complexity, although potentially lower than IA, depending on specific implementation. • It requires advanced hardware capabilities for signal processing and interference cancellation	While the specific resource needs may differ, both IA and IN are resource-intensive techniques. IA generally demands more accurate CSI and higher computational complexity, while IN may have different implementation challenges

C. Resource Requirements

Both IA and IN demand substantial resources, though their specific resource requirements differ. For IA, the computational resources and complexity required to solve complex matrix equations and design optimal beamformers are substantial. Nevertheless, new algorithms have been developed to reduce this computational burden, though they still necessitate significant computational resources. Implementing IA requires precise synchronization and coordination among multiple transmitters and receivers, which requires a robust coordination mechanism and is resource-demanding [47]. In addition, IA often relies on multiple antennas at both the transmitter and receiver ends to achieve the desired alignment. This necessitates advanced hardware capable of supporting MIMO configurations.

IN also has substantial resource requirements; although potentially less complex than IA, it is stringent and must be met. It requires accurate knowledge of the rapidly changing interfering channel to effectively cancel interference. Moreover, implementing IN algorithms involves signal processing operations that demand significant computational resources. The level of complexity depends on the specific algorithm used and the number of interfering signals that are neutralized. Furthermore, IN may require specialized hardware at the receiver, such as multiple antennas and advanced signal processing capabilities, to effectively cancel interference.

In summary, while both IA and IN have their unique strengths, limitations, and applicability, they involve varying complex procedures and perform differently depending on the scenarios. The choice between IA and IN depends on the specific requirements of the wireless systems.

V. OPEN RESEARCH ISSUES

Theoretical research on IA and IN has advanced significantly, from feasibility studies to performance enhancement and applications across various networks and topologies. That notwithstanding, there is a pressing need to convert these theories into practice, showcasing feasible achievements, and that's where the challenge lies. Researchers and industry are at a crossroads with certain decisions and directions, and all the options are very difficult to implement. It is crucial that these complexities be addressed and that the focus shift to system implementation. We briefly highlight some of the recent open research issues that are having an impact on the system implementation of IA and IN on 5G and emerging networks.

A. Testbeds/Practical Systems

The experimental evaluation of IA and IN techniques is critical for better understanding the impacts of practical limitations on their performance, as well as for proposing new research areas. From existing research, IA techniques have been implemented on testbeds as a first step towards experimentally evaluating their techniques in realistic scenarios and are already yielding positive results [48–50]. The first experiment of IA was described in Ref. [48], in which a hybrid approach combining Interference Alignment and Cancellation (IAC) was implemented in a testbed. Its success was followed by another testbed deployment of IA in a MIMO-OFDM interference channel in an indoor and outdoor scenario [49]. In Ref. [50], the blind IA scheme has been experimented on testbeds in the absence of CSI, aided by transmitter and receiver synchronization. Wonjae *et al.* [51] presented the first real-time implementation of IN using a software-defined radio testbed,

All experimental testbed results show gains and consistency with the theoretical simulations.

The testbeds consist of hardware and Software-Defined Radios (SDRs), and in most experiments, the hardware or SDR impairments are ignored, thereby affecting the overall results. There is still a long way ahead, and significant attention should be paid to the following [52]. Testbed Availability: Accessing public testbed facilities for researchers to demonstrate and evaluate their algorithms is difficult. The CorteXlab at the University of Lyon is one of the few large-scale testbed facilities that offer public access to researchers for running automated and manageable experiments of this calibre. Other small-scale publicly available labs are the CREW and CORE+ project consortia. There are also other open-source platforms for implementing IA testbeds, such as National Instruments and Ettus. Unfortunately, the platform's simple architecture and limited resources make complex implementation on these platforms expensive and, many times, unfeasible.

Software Requirements: Discussions on testbeds are mostly dominated by hardware components, but software is also an intrinsic component of the testbeds. There is a need for a central repository for developers to share and improve open-source IA and IN software. An approach like this will improve progress towards in-depth research activities and the expansion of IA and IN applications.

Cost Evaluation of Testbeds: Commercial-off-the-shelf (COTS) products remain the leading solutions for implementing IA and IN within the research community. That notwithstanding, implementing AIM experiments on testbeds is very expensive and influences results, especially with constrained budgets. The University of Bristol and Lund University spent approximately US$2 million to put an IA testbed for a massive MIMO configuration of 16 users, and 128 antennas in a $(9 \times 8,1)^{16}$ DoF scenario. The cost is anticipated to scale up for AIM as the network size increases, hence necessitating a large capital investment.

B. Large Network vs Small Subnetworks

The concepts of IA and IN were initially developed for small networks, aiming to achieve optimal DoF at high SNR and to perfectly eliminate interference generated by users with adequate resources, such as sufficient antennas and CSI. This idea was later extended to large networks, which have also shown promising results. However, the debate remains open regarding the adoption of large networks or small subnetworks in a heterogeneous-scale interference network during practical implementation. The choice ultimately depends on the user's requirement, but each option faces its respective challenges accordingly:

Large Networks: As the interference network grows with an increase in the number of users, the required number of antennas and the complexity of designing precoding and decoding matrices also increase. Additionally, the overhead for acquiring CSI feedback becomes more demanding. Determining the appropriate network scale, whether small or large, is a crucial challenge. If a subnetwork has a limited number of users, interference among subnetworks can become severe, ultimately degrading overall system performance.

Small Subnetworks: When working with small subnetworks, the grouping of users for IA or IN is quite challenging. One approach is to group users based on clustering analysis within the subnetwork, which optimizes system performance, though this comes at the cost of increased computational complexity. Alternatively, the grouping can be done using the distance information of IA and IN users, which is less computationally intensive, but this method is limited to slow channel fading conditions and is unreliable for fast fading channels. One method to achieve that is by calculating the clusters on the subnetwork to enhance system performance.

Another major challenge is determining the appropriate approach for subnetwork grouping, whether through a centralized or distributed decision-making process. A centralized approach may be more straightforward to implement, but it requires feeding all the necessary information back to a fusion station, which can lead to higher overhead and complexity. In contrast, a distributed approach, where decisions are made independently by each user without the need for a fusion station, could be more efficient, but it poses the challenge of how to effectively coordinate and achieve such distributed decision-making.

Lastly, obtaining and exchanging accurate information required for subnetwork grouping remains an open challenge for researchers. Even with a basic distance-based topology management approach, acquiring distance information for each user remains a difficult task.

C. Massive MIMO

MIMO technology is widely recognized as a critical fundamental enabler for 5G/6G cellular networks. The concept refers to equipping BSs with many antennas in hundreds or thousands; the innovation increases network capacity and energy efficiency by 10-fold and 1000-fold, respectively, compared to conventional MIMO. Unfortunately, Massive MIMO is severely vulnerable to interference. First, Inter-Cell Interference (ICI) exists between the different macro-cell systems in the uplink and downlink. Furthermore, cross-tier interference adversely affects the MIMO BSs of macro and micro cells, as well as D2D users, in HetNets. Due to low transmission power, massive MIMO is highly susceptible to Narrowband Interference (NBI), which is common in unlicensed frequency bands. Several IA and IN schemes have been adopted for massive MIMO networks. Nonetheless, applying IA and IN in massive MIMO comes with the following enormous challenges:

Channel State Information (CSI): It is a more severe problem in massive MIMO systems, and it is unreasonable in practical scenarios to ignore it. When IA and IN are used, an overwhelming CSI is exchanged in the network due to the sizeable number of BSs antennas. Although some strategies have been proposed to reduce or eliminate CSI overhead issues, they all come with penalties.

Blind IA (BIA) and Blind IN (BIN) schemes have been proposed to accomplish IA and IN without Channel State Information at the Transmitter (CSIT). However, there are some basic constraints on the transmitters, such as ensuring that channel coherence intervals among users are available at the transmitter. This stringent condition makes BIA and BIN unrealizable, necessitating the development of a more practical algorithm.

Furthermore, some research has focused on IA and IN with imperfect CSI, including limited feedback, outdated feedback, and feedback error due to noise. Retrospective IA (RIA), Retrospective IN (RIN), and several other schemes have been proposed. CSI is transmitted across a wireless medium, and it can be intercepted by enemies. Again, the CSI can be used by eavesdroppers to further break into the legitimate network. This could pose a risk to IA and IN applications.

Closed-Form Solution: With many users, the closed-form solutions for IA and IN still remains an intractable problem for researchers. It is difficult due to the huge number of antennas and the large number of users served by the massive MIMO BSs. As a result, an iterative algorithm that will calculate solutions with minimal complexity will be designed for massive MIMO systems.

D. Weak Interference

Interference is aligned, then eliminated or neutralized over the air using AIM techniques in an interference network. However, applying these strategies to weak signals is unnecessary and a waste of network resources. Hence, treating Interference As Noise (TIN) could be a viable option when it is sufficiently weak and has been proven to be information-theoretical optimal in some cases. To sum up, it has been demonstrated that when a user's desired signal strength exceeds the total strongest interferences from and to that user in an interference network of multi-users, optimum performance in a generalized DoF can be attained by using TIN [45].

Nevertheless, achieving this concept in practical systems becomes very difficult. For instance, the interference at a specific receiver from some transmitters may be weak, while it is substantially stronger from others; it then becomes impractical to segregate users into multiple clusters due to the complex network topology. Some research has focused on this aspect, Zeng *et al.* [46] proposed a partial IA scheme in an IA network to solve this problem. The links with the strongest interference are presumed to be connected, while those with relatively weak interference are deemed detached, and the interference is treated as noise. The approach is successful when the interference between users is quite different, but it is challenging when the interference is marginal. Hence, there should be a trade-off in deciding when to treat interference as noise in specific links of a practical system to achieve optimal performance. This development will enable the use of TIN combined with AIM techniques in the deployment of 5G HetNets.

E. AI to Enhance AIM Techniques

Some Machine Learning (ML) and Deep Learning (DL) techniques have attracted attention for addressing fundamental issues in CSI and for providing closed-form solutions for AIM techniques. To manage these issues, algorithms from ML-based Supervised Learning (SL), Unsupervised Learning (UL), and Reinforcement Learning (RL) are being developed to address these difficulties in IA and IN.

The fundamental approach is to use ML techniques, especially DL, to design encoders and decoders for interference channels. Mishra *et al.* [53] proposed a novel deep learning-based approach to design the encoder and decoder functions that maximize the sum rate of the interference channel for discrete constellations. In Ref. [54], a new IA scheme based on neural networks was developed, which efficiently mitigates interference. This scheme uses a Hybrid Deep Neural Network (HDNN) to learn mappings between received channels with minimal overhead. Yu and He [55] proposed an advanced reinforcement learning algorithm that employs a deep Q network to approximate the Q value-action function, implemented using Google TensorFlow. Wang *et al.* [56] introduced a Deep Deterministic Policy Gradient (DDPG)-based algorithm for IA. Simulation results demonstrate that the proposed algorithms outperform existing ones in terms of performance and broader applicability. Wang and Yuan [57] presented a fast-convergence iterative algorithm for IA based on a partially connected two-interfering K-user MIMO IC, leveraging DL techniques. Model simulations indicate that the algorithm surpasses traditional algorithms in terms of faster convergence and higher DoF performance.

Nguyen *et al.* [58] identified an achievable rate region of a two-hop interference channel with distributed multiple Intelligent Reflecting Surfaces (IRS) that outperforms the benchmark. The application of deep learning to IRS in IN provides near-optimal performance with fewer bits and demonstrates robustness under imperfect CSI. This approach is a promising 6G technology that can improve wireless communication capacity in a cost-effectively and energy-efficient manner. An effective framework, Selective Interference Alignment and Neutralization (SIAN), has been proposed for CoMP transmission networks [59–62]. By leveraging ML algorithms, this framework implements IA and IN to perfectly align and cancel interference signals at the receiver side using ZF and a rechanneling filter. This significantly improves spectral efficiency, achieved data rates, and overall performance.

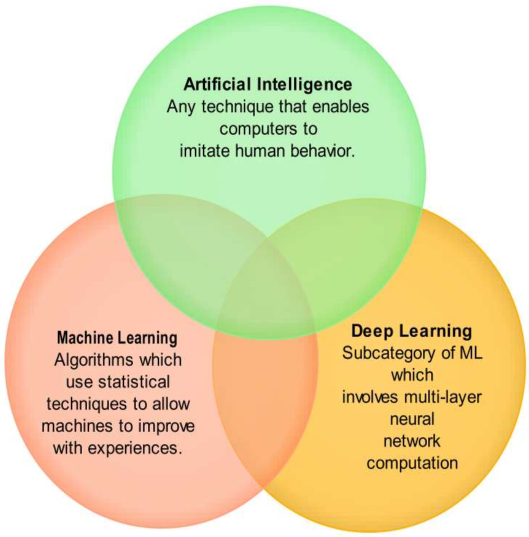

Fig. 6. ML/DL in AIM techniques.

In general, the proposed ML, UL, and DL approaches deploy trained neural networks to handle multiple signals concurrently, thereby reducing CSI acquisition and feedback overhead as a key step. In addition, it learns the interference characteristics data, thereby using multiple permutations and combinations, making more effective decisions as compared to conventional techniques, and can adapt dynamically based on the network and user behaviour. The algorithms can readily handle very complex problems and create effective solutions; they can even anticipate future scenarios, making them the best choice in an unstable environment. Despite the success of AI in AIM, there are still some challenges that need to be overcome before it can be adopted in the production environment. One major challenge is the lack of interpretability of DL algorithms, a concept that deals with model transparency and its ability to explain the intricacies of the model after the fact. The selection of an appropriate AI model and adequate data preparation is also crucial. Another issue is the use of different performance metrics by different researchers to evaluate their algorithms. Another drawback is the time-consuming, computation-intensive training and validation of the DL algorithm. Fig. 6 shows a Venn diagram of the AI process for enhancing AIM techniques.

VI. Conclusion

The advancement of information theory has enabled IA and IN to emerge as attractive solutions for managing interference in 5G and 6G networks. Their feasibility conditions are achievable, and the DoF is optimal. IA aligned the interference, then eliminated it using the precoding and decoding matrices. In contrast, IN appropriately combines signals from different directions to cancel the interference signal while preserving the desired signal. Several excellent IA and IN schemes have been developed for different kinds of 5G and emerging networks, with strong theoretical evidence. Despite these gains, the AIM techniques are not near practical implementation in 5G/6G due to several fundamental issues. To accelerate the transition from theory to practice, future research should focus on accurate CSI acquisition, Testbed validation across more real-world scenarios, and ML algorithms for training AIM models.

In summary, the study of IA and IN is quite broad, and considerable efforts await utilizing these techniques in practical systems due to challenging issues. However, these AIM techniques might lead to a paradigm change in which interference might no longer be considered detrimental.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ebenezer Esenogho: Conceptualization, Methodology, Formal Analysis, Original Draft, and Resource Supervision; Sylvester Akiishi: Conceptualization, Methodology, Review & Editing, Analysis, and Validation; both authors had approved the final version.

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