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A Systematic Review of Interference Mitigation Techniques in Current and Future UAV-Assisted Wireless Networks

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ABSTRACT In unmanned aerial vehicle (UAV)-assisted wireless networks, the potential of the high probability of line-of-sight links could be a disadvantage for other nearby wireless networks because of interference caused by a UAV. For this reason, using interference mitigation techniques (IMTs) for UAV-assisted wireless networks is necessary to minimize interference effects. For instance, the mobility of UAVs gives a chance to manage interference better to avoid being a source of interference or being susceptible to interference. After the first-generation mobile network was introduced in the early 1980s, mobile communication systems were developed through several stages of evolution over the following few decades to satisfy rising demand and more stringent specifications. Different IMTs are needed due to these generations' differences. Unlike previous research, this research presents a systematic review of IMTs in the current and future UAV-assisted wireless networks and discusses their challenges. We also review the current research trends of UAV IMTs and their future insights. Our motivation for conducting this research is the need for a systematic review addressing these issues. In this systematic review, we use a more precise classification of the IMTs for UAV-assisted wireless networks. We classify them into four different techniques, namely, adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control, and sub-channel scheduling. Moreover, we discuss the IMTs for UAVs using B5G wireless technologies such as intelligent reflecting surfaces, rate-splitting, super modular massive multiple-input multiple-output, Terahertz communications, holographic beamforming, blockchain-based spectrum sharing, and artificial intelligence and machine learning schemes. Furthermore, we identify the challenges of UAV IMTs and their open research directions such as wireless radio frequency spectrum scarcity, lack of networking scalability, beam distortion, resource-constrained management, and new sources of interference. We believe this research will help researchers choose the best technique to mitigate the interference effects in UAV-assisted wireless networks.

INDEX TERMS UAV-assisted wireless networks, next-generation wireless networks, 5G, B5G, interference mitigation techniques.

I. INTRODUCTION

UNMANNED aerial vehicles (UAVs) are expanding quickly in various civil application domains because of their high mobility, low maintenance costs, ease of deployment, and hovering ability [1]. In UAV-assisted wireless networks, without investing in wireless systems infrastructure, UAVs can be used as aerial base stations (BSs) to expand wireless coverage, system capacity, and reliability [2]. UAVs can be utilized to distribute information to or gather data from dispersed sensors, to provide wireless

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coverage within a specific geographical area, and to connect distant users without direct connectivity from a ground station (GS) [3], [4].

Many recent research works discuss the UAV assistance paradigm in the wireless communications field. In [5], the authors provide the opportunities presented by the concept of UAV-based data collection for integration into various UAV-based network applications through an in-depth study and detailed discussion based on expanding areas of study in this field. They present the concept of UAV data collection and its elements to better understand how the UAV data collection process is implemented. Then, they comprehensively analyze recent UAV-based data collection systems, classify them based on the proposed taxonomy, and present their objectives, strengths, and weaknesses. This analysis summarized some of the key lessons learned and highlighted the evaluation tools utilized. Finally, they discuss recommended references, future directions, and interesting issues aiming to integrate the UAV-based data collection concept into future UAV-assisted wireless networks.

The authors of [6] present a comprehensive study that reviews and analyzes existing research on UAV-assisted wireless networks such as disaster management, Internet of Things (IoT) networks, cellular communications, data collection, and routing that support these enabling technologies. Throughout the study, classifications, descriptions, and comparative analyses of various UAV-assisted proposals are provided. The future challenges presented in this study are expected to encourage research in this emerging field.

In [7], the authors provide a comprehensive study on 5G network slicing with UAVs. The contributions of this research work are to demonstrate the UAV assistance paradigms, provide a classification of UAVs in the context of UAV-assisted network slicing, and provide research works that contribute to UAV-assisted network slicing. The discussion of network slicing in their research work focuses on three main types: ultra-reliable low-latency communications, massive machine-type communications, and enhanced Mobile Broadband. They present an overview of the technologies that will enable 5G, such as network function virtualization and software-defined networking. They also discuss the roles of UAVs in wireless networks as both assistants and users. Furthermore, they identify the challenges of UAV-assisted network slicing and the open research directions in this field.

In wireless communication systems, generally, interference is a fundamental phenomenon. It results from wireless transmission's superposition, broadcast characteristics, and the spectrum's shared use by numerous users. Due to the mobility of the transmitter and/or receiver as well as the transmission medium, the signal in wireless networks is susceptible to several impairments. When multiple users share a frequency band at once, then co-channel interference (CCI) exists. In adjacent-channel interference (ACI), the receiver's performance is reduced when adjacent channels smear the received signals from one channel due to poor filtering or inaccurate frequency offset estimation. Intersymbol interference (ISI) results from multipath propagation when the channel's delay spread is significant relative to the modulated symbol's duration [8]. In wireless communication systems, the types of interference include CCI, ACI, self-interference (SI), intermodulation interference (IMI), ISI, interference in non-orthogonal multiple access systems, and near-end to far-end ratio interference (NFRI) [9], [10].

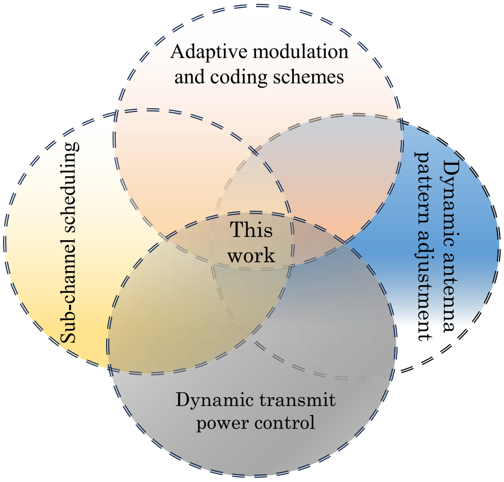

FIGURE 1. Classification of the IMTs for UAV-assisted wireless networks. This Figure shows the IMTs for UAV-assisted wireless networks that have been adopted in this research work. These techniques are adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control, and sub-channel scheduling.

The term used to describe the methods utilized to reduce interference between networks operating in the same or nearby spectrum bands is interference mitigation. The throughput of a wireless system may significantly decrease caused by uncoordinated interference. To achieve the best system performance, managing and controlling interference is crucial [11]. In wireless communication systems, the system-design techniques and receiver-design techniques can be used generally to categorize interference mitigation techniques (IMTs) [12], [13], [14], [15], [16], [17], [18], [19]. The transmission of co-channel signals is precisely managed in system-design techniques so that the power of the received CCI is kept at a manageable level. Contrarily, receiver-design techniques actively reduce the CCI, which cannot be mitigated using system-design techniques. In practical implementations, both techniques are utilized to manage the impact of the CCI. In this research work, we use a more precise classification of the IMTs for UAV-assisted wireless networks. We classify them into four different techniques as shown in Figure 1, namely, adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control and sub-channel scheduling.

Any signal that exceeds the defined signal-to-interference-plus-noise ratio (SINR) threshold for a communication link satisfies the essential requirements for establishing a reliable information transfer [20]. However, when interference levels

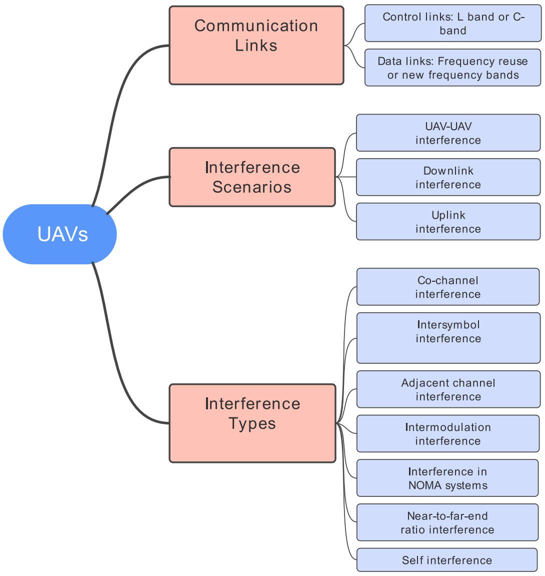

FIGURE 2. **Parameters related to IMTs for UAV-assisted wireless networks. This Figure shows the interference types, communication links, and interference scenarios in UAV-assisted wireless networks.**

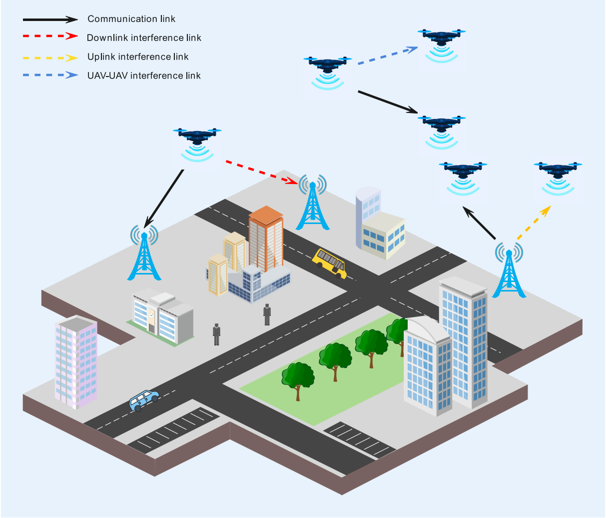

FIGURE 3. **Interference scenarios in UAV-assisted wireless networks. This Figure shows the three common interference scenarios that can occur in UAV-assisted wireless networks, namely, downlink interference, uplink interference, and UAV-UAV interference.**

exceed this limit, it is possible to recover the data without losing any information using IMTs that minimize the interference to a level below the limit. These techniques significantly lower interference while boosting SINR and, consequently, user throughput [21]. These techniques have several drawbacks, one of which is that they adhere to static configurations that are unadaptable to changes in the network [22].

The data and control links are the two main categories of wireless communication links used by UAVs [3]. All UAVs must operate safely, which depends on the control links. For the exchange of safety-critical information between the ground control station and UAVs, as well as among UAVs, these links must be secure two-way communications, low-latency, and highly reliable, typically with a low data rate requirement. Control links should generally operate in a protected spectrum due to the essential functions they must support. Currently, the L-band and the C-band have been allocated for these links [23]. On the other hand, the data links of UAVs seek to support ground terminals' mission-related communications, depending on the application scenarios. The application scenarios significantly impact the required bandwidth for these data links. The data links typically have higher latency and security requirements tolerances than the control links. The UAV data links may reuse frequency bands to support specific applications, causing interference with the existing wireless networks. Alternatively, new frequency bands could be assigned for better performance [24]. Figure 2 summarizes the interference types, communication links, and interference scenarios in UAV-assisted wireless networks.

The rapid advances of UAV-assisted wireless networks face several new challenges such as mutual interference, radio frequency spectrum scarcity, and network connectivity challenges. Utilizing UAVs as aerial BSs has the potential to severely impact the performance of terrestrial wireless networks and reduce their system capacity much more than what is predicted by mobile network operators, thereby lowering the quality of service (QoS) for users. This is because the sub-6G spectrum is heavily utilized in terrestrial wireless networks. Additionally, when performing time-sensitive missions, certain complex environments may block the connectivity provided by UAV in UAV-assisted wireless networks [25].

The current IMTs are intended for terrestrial wireless networks where the network infrastructure is highly stationary depending on safety regulations, applications, and terrain [26]. Using these techniques on UAV-assisted wireless networks is inefficient. The UAV dynamics, such as speed and lifetime, involve dynamic coverage shapes that change rapidly with different parameters such as bandwidth demands, subscribers, and services. The UAV-assisted wireless networks environment here is fluctuating more rapidly, and mutual interference must be detected faster to ensure uninterrupted service. Therefore, expanding the utilization of UAV-assisted wireless networks poses new challenges and requires innovative IMTs.

Three common interference scenarios can occur in UAV-assisted wireless networks, as shown in Figure 3. The first scenario is uplink interference, in which radio signals transmitted by ground BSs can interfere with low-altitude UAVs. Second, downlink interference on ground devices, which UAVs cause during the transmission to GSs. Third, interference between nearby UAVs [26]. Uplink and downlink interference refer to interference experienced in the communication links between UAVs and BSs. Uplink interference occurs when signals transmitted by UAVs toward the BSs are disrupted or degraded by external sources. In the context of UAV-assisted wireless networks, uplink interference may arise when ground BSs emit signals that interfere with the transmissions from low-altitude UAVs to the BS. Conversely, downlink interference happens when signals transmitted from the BSs to the ground users are disturbed or attenuated by external factors. In the context of UAV-assisted networks, downlink interference may occur when signals transmitted from BSs toward ground users are interfering with the transmission of UAVs. On the other hand, UAV-UAV interference refers to interference between multiple UAVs operating within the same vicinity or airspace. This interference may arise due to overlapping transmission frequencies, spatial proximity, or other factors related to the shared use of the electromagnetic spectrum or airspace. UAV-UAV interference can degrade the performance of individual UAVs' communication links and overall network efficiency. In summary, uplink and downlink interference pertain to interference between UAVs and ground BSs, while UAV-UAV interference specifically relates to interference between multiple UAVs operating within the same airspace. Each type of interference requires distinct mitigation strategies to ensure efficient and reliable communication in UAV-assisted wireless networks.

UAV-assisted wireless networks can use a variety of IMTs to enhance the SINR and, thus, the system's throughput. Using power control mechanisms is one way to ensure that the power of the received signal is enough for signal demodulation. Focusing the energy of radiation beams in the desired direction will mitigate interference effects using beamforming. In addition to this, antenna array development for UAVs is crucial to minimize the impact of interference. Frequency hopping, direct sequence, frequency reuse, and radio frequency (RF) planning are other methods that may be utilized for interference mitigation in UAV-assisted wireless networks.

Current IMTs for UAV networks focus on cancellation and coordination mechanisms. For instance, a network of cellular-connected UAVs is proposed in [27], with an interference-aware trajectory planning scheme. The trajectory of each UAV aims to attain a balance between increasing energy effectiveness and reducing wireless interference and latency on the ground network. The optimization problem is solved by proposing a deep reinforcement learning (DRL)-based algorithm. The simulation results demonstrate that the optimal UAV altitude varies depending on the density of the ground network and the data rate requirements of users and is crucial for reducing interference levels on ground users as well as the UAV wireless transmission delay. The authors of [28] jointly optimize the downlink power allocations (PAs) for backhaul and access transmissions, the BS and user associations, and the spatial configurations of the UAVs. To increase the wireless network's overall sum rate, they propose an IMT and utilize the UAVs as hovering aerial nodes. They analyze the performance of two UAV spatial configuration modes, namely distributed UAVs and UAV antenna arrays, and demonstrate how these configurations are connected to the ground users. The simulation results show that UAVs can increase wireless network capacity and improve coverage.

Following the launch of the first-generation mobile network in the early 1980s, mobile communication systems were developed through several stages of evolution over the following few decades to satisfy rising demand and more stringent specifications. The telecommunications sector has faced several new challenges related to effective spectrum usage, security, and, most significantly, interference mitigation. The differences among these generations require different IMTs.

This research presents a systematic review of IMTs in the current and future UAV-assisted wireless networks and discusses their challenges. There are several reasons for covering the IMTs for 4G UAV-assisted wireless networks in this research work. People living in areas not covered by 5G coverage will still need 4G wireless networks. Moreover, the shift from 4G to 5G will require some time. It involves more than just moving between networks. To fully support 5G networks, infrastructure upgrades are required, such as the installation of new antennas and equipment. This process will take several years, which means that 4G wireless networks will continue to play a vital role in the mobile communications market. Additionally, not everyone is a quick adopter of 5G technology. Tech enthusiasts and early adopters want to upgrade to the greatest and latest, but many consumers are happy with their current 4G devices and may not feel the need to make the switch right away.

We also review the current research trends of UAV IMTs and their future insights. Our motivation for conducting this research is the need for a systematic review addressing these issues. Table 1 lists the research studies on UAV IMTs closely related to our research work, highlighting how novel our research work is compared to earlier studies. We believe that this research work will help researchers utilize the appropriate technique to minimize interference effects when considering UAV-assisted wireless networks in their research works. Specifically, the contributions of this research work can be presented as:

- We classify the IMTs in the current and future UAV-assisted wireless networks into four techniques: adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control and sub-channel scheduling.
- We discuss the IMTs for UAVs using B5G wireless technologies such as intelligent reflecting surfaces (IRSs), rate-splitting, super modular massive multiple-input multiple-output (MIMO), Terahertz communications, holographic beamforming, blockchain-based spectrum sharing, and artificial intelligence (AI) and machine learning (ML) schemes.
- We identify the challenges of UAV IMTs and their open research directions, such as wireless radio frequency spectrum scarcity, lack of networking scalability, beam

TABLE 1. A comparison of related research works regarding UAV interference mitigation techniques.

Reference	4G UAV interference mitigation techniques	5G UAV interference mitigation techniques	B5G UAV interference mitigation techniques	Main contribution, challenges, and future insights
[29]			✓	• **Main contribution:** The paper provides an overview of the IMTs relating to the B5G networks, including HeNet, UAVs, UDN, and D2D. • **Challenges:** The paper discusses the challenges such as the requirements to support high-speed communication for UAVs, designing a simple interference coordination strategy for UAVs, consumption of energy, and the influence of a restricted backhaul capacity on the performance of IMTs. • **Future insights:** The paper presents future insights such as the utilization of AI in UAV-assisted wireless networks to enable more adaptive interference coordination, proposing strategies for minimizing interference and maximizing energy efficiency for UAV-assisted wireless networks, and the implementation of efficient techniques with low complexity to enhance the performance of UAV-assisted wireless networks with restricted capacity.
[30]		✓		• **Main contribution:** The research work proposes new IMTs to achieve spectrum-efficient cellular network operation while coexisting UAVs and terrestrial users. • **Challenges:** The research work identifies key challenges that need to be addressed to mitigate interference in UAV-assisted wireless networks, such as air-to-ground interference and inter-UAV interference. • **Future insights:** The research work presents future insights such as the design of interference-aware UAV trajectory, cooperative UAV-to-UAV (U2U) communications, 3D massive MIMO, and utilizing UAV beamforming.
[31]	✓			• **Main contribution:** In this paper, the authors propose several uplink and downlink IMTs for UAV-assisted wireless networks. • **Challenges:** No challenges have been discussed for the proposed IMTs. • **Future insights:** No future insights have been presented.
[32]	✓			• **Main contribution:** A comprehensive overview of interference types in GNSSs and IMTs for unmanned and manned aircraft is provided in this research work. • **Challenges:** The paper discusses the challenges such as advanced coping with radio frequency interference, facing the spoofing risk in aviation, and advanced receiver autonomous integrity monitoring. • **Future insights:** The research work presents future insights such as utilizing alternative solutions to complement existing onboard navigation solutions while providing the reliability required by aviation. Moreover, extending existing algorithms with ML solutions and trajectory control are proposed in this research work as possible future insights.
[33]		✓		• **Main contribution:** In this research work, the authors provide a thorough overview of ML's use in UAV-assisted wireless networks. Various functional and design aspects have been discussed using ML techniques, such as security, positioning, resource management, channel modeling, and interference mitigation. • **Challenges:** The paper discusses the challenges such as the practical implementation of AI/ML-aided UAV-assisted wireless networks, physical layer issues, data link and network layers issues, and security and privacy issues. • **Future insights:** The paper identifies future insights in the field of networks and security and encourages further research on how to apply AI/ML techniques to UAV-based networks.
This work	✓	✓	✓	• **Main contribution:** The paper classifies the IMTs for current and future UAV-assisted wireless networks into four techniques. Moreover, it discusses the IMTs for UAVs using B5G wireless technologies such as IRSs, rate-splitting, super modular massive MIMO, Terahertz communications, holographic beamforming, blockchain-based spectrum sharing, and AI and ML schemes. • **Challenges:** The paper identifies the main challenges of IMTs for UAV-assisted wireless networks such as wireless radio frequency spectrum scarcity, lack of networking scalability, beam distortion, resource-constrained management, and new sources of interference. • **Future insights:** The paper presents future insights to overcome challenges faced by IMTs for UAV-assisted wireless networks such as utilizing intelligent dynamic spectrum access, dynamic clustering for cell-free massive MIMO, quantum computation, edge intelligence servers, and backscatter communications.

distortion, resource-constrained management, and new sources of interference.

This systematic review is structured as follows. We start with a list of the acronyms used throughout this research work in Section II. An overview of the related work, classification criteria, and search strategy are presented in Section III. Sections IV–VI present the IMTs in current and future UAV-assisted wireless networks. Section VII presents the lessons learned from this systematic review and discusses the challenges and their open research directions. Finally, Section VIII concludes this research work. For the readers' convenience, the structure of this paper is illustrated in Figure 4.

II. ACRONYMS

Below is a list of the acronyms used throughout this research work, along with their definitions.

4G	Fourth-generation technology
5G	Fifth-generation technology
6G	Sixth-generation technology
ACI	Adjacent-channel interference
AI	Artificial intelligence
AIS	Alternating interference suppression
APF	Artificial potential field
ATG	Air-to-ground
B5G	Beyond fifth-generation technology
B6G	Beyond sixth-generation technology
BER	Bit error rate
BFV	Beamforming vector
BPSK	Binary Phase-shift keying
BS	Base station
CB	Cooperative beamforming
CCI	Co-channel interference
CLI	Cross-link interference
CoDMA	Constellation-division multiple access
CPE	Customer premise equipment
CR	Cognitive radio
CSI	Channel state information
D2D	Device-to-device
Deep Q-Learning	DQL
DN	Destination node
DoF	Degrees of freedom
DRL	Deep reinforcement learning
D-TDD	Dynamic time division duplex
EE	Energy efficiency
FBMC	Filter bank multicarrier modulation
FD-UAV	Full-duplex UAV
FPK	Fokker–Planck equation
GBS	Ground base station
GNSS	Global navigation satellite system
GS	Ground station
HAP	High-altitude platform

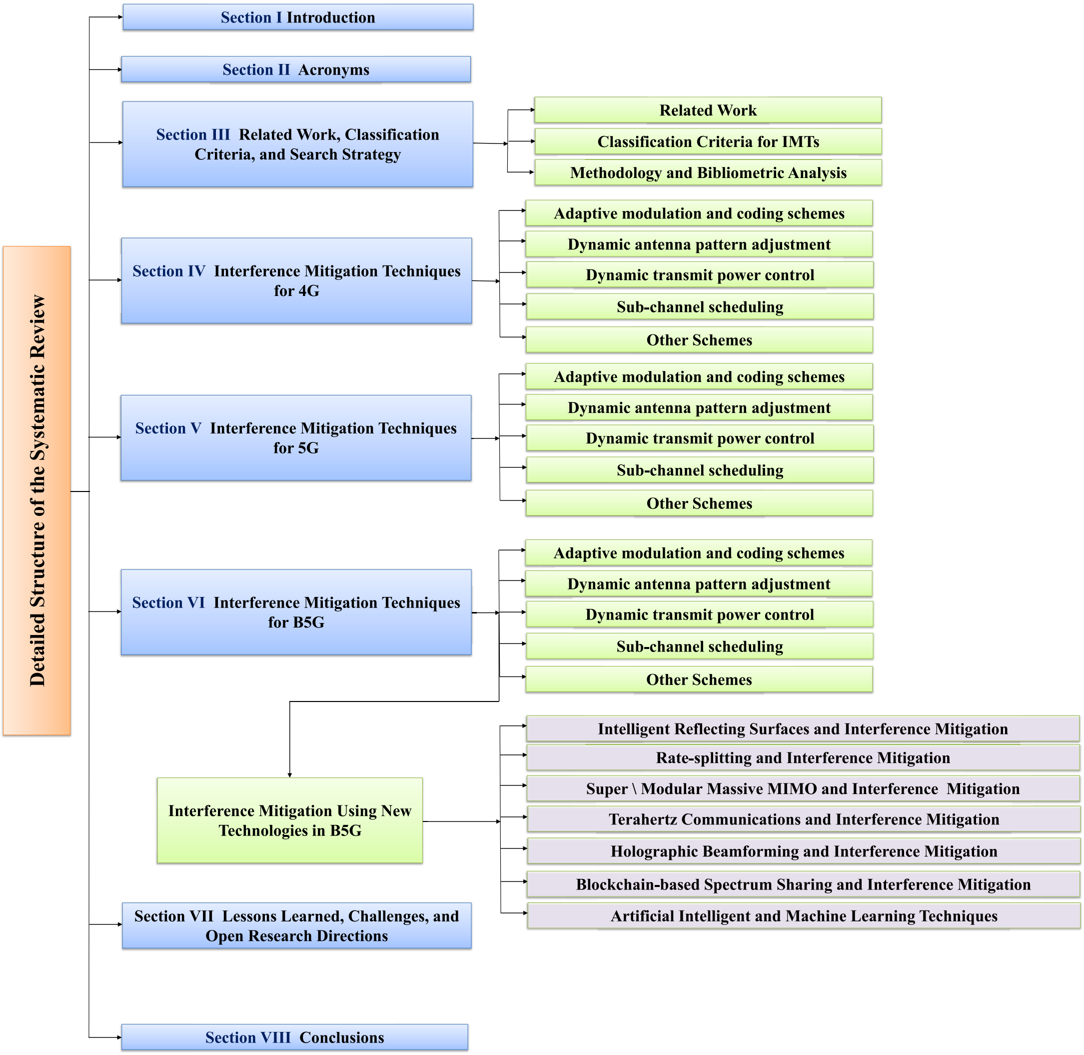

FIGURE 4. Structure of the systematic review.

HARQ	Hybrid automatic repeat request
HBF	Holographic beamforming
HeNet	Heterogeneous network
HJB	Hamilton-Jacobi-Bellman
IAB	Integrated access and backhaul
IC	Interference cancellation
ICI	Inter-cell interference
ICIC	Inter-cell interference coordination
IDSA	Intelligent dynamic spectrum access
IM	Index modulation
IMI	Intermodulation interference
IMT	Interference mitigation technique
IoT	Internet of Things
IRS	Intelligent reflecting surface
ISA	Iterative subchannel assignment
ISI	Intersymbol interference
LEO	Low earth orbit
LoS	Line-of-sight
LSTM	Long short-term memory
LTE	Long-term evolution
MAC	Media access control
MEC	Mobile edge computing
MFG	Mean-field game
MIMO	Multiple-input multiple-output
ML	Machine learning
m-MIMO	Massive MIMO
mmWave	Millimeter wave
NFRI	Near-end to far-end ratio interference
NOMA	Non-orthogonal multiple access
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OMA	Orthogonal multiple access
PA	Power allocation
PHY	Physical
QAM	Quadrature amplitude modulation
QoS	Quality of service

QPSK	Quadrature phase shift keying
RB	Radio block
RF	Radio frequency
RFA	Reverse frequency allocation
RIS	Reconfigurable intelligent surface
RL	Reinforcement learning
RSMA	Rate-splitting multiple access
RSRP	Reference signal received power
S2V	SN-to-UAV
SCA	Successive convex approximation
SCT	Singular case tolerance
SI	Self-interference
SIC	Successive interference cancellation
SINR	Signal-to-interference-plus-noise ratio
SN	Source node
SNR	Signal-to-noise ratio
SP	Stratospheric platform
THz	Terahertz
U2U	UAV-to-UAV
UA	User equipment association
UAV	Unmanned aerial vehicle
UDN	Ultra-dense Network
UE	User equipment
UL	Uplink
URLLC	ultra-reliable low-latency communication
V2D	UAV-to-DN
V2X	Vehicle-to-everything
ZF	Zero-forcing

III. RELATED WORK, CLASSIFICATION CRITERIA, AND SEARCH STRATEGY

A. RELATED WORK

The emerging challenge of UAV-terrestrial interference cannot typically be mitigated using terrestrial networks' conventional IMTs. Recent studies on IMTs for UAVs have primarily focused on single wireless technology generation without considering distinctions among various wireless technology generations. The authors of [29] provide an overview of the IMTs relating to the B5G/6G networks, including heterogeneous networks (HeNet), UAVs, ultra-dense networks (UDN), and device-to-device (D2D). In addition, they present the most relevant studies and discuss the methods, benefits, and limitations of the existing IMTs. Also, they discuss the potential future directions and open issues for minimizing interference effects. The research's conclusions can be utilized to better comprehend the techniques used to reduce interference effects in B5G/6G networks.

To achieve spectrum-efficient cellular network operation while coexisting UAVs and terrestrial users, the authors of [30] propose new IMTs. They first consider the transmission of a UAV's uplink data to ground BSs and propose a novel aerial-ground inter-cell interference coordination (ICIC) method to minimize its significant interference to current co-channel terrestrial users. To enhance the efficiency of the proposed IMT, they also suggest using the non-orthogonal multiple access (NOMA) technique with successive interference cancellation (SIC). Then, to reduce the significant interference made by the co-channel from transmissions via terrestrial network to the UAV, they consider the aerial-ground interference problem in the cellular downlink and propose a new BS cooperative beamforming technique.

The authors of [31] define two types of UAV interference scenarios: uplink and downlink. Due to the potential line-of-sight (LoS) propagation conditions of UAVs to ground BSs, UAVs may cause interference with nearby cells. They demonstrate how this interference can be mitigated by modifying the existing power control framework (i.e., long-term evolution (LTE) physical uplink shared channel). The UAVs suffer from interference because signals from nearby BSs may transmit high power levels to UAVs. LTE coverage extension solutions can be utilized for the downlink scenario to enhance cell acquisition for UAVs.

A comprehensive overview of interference types in global navigation satellite systems (GNSSs) and IMTs is provided by the authors of [32]. The survey's primary scenario is where a ground-based interferer transmits signals into the GNSS bands of a GNSS receiver mounted on an aerial vehicle. The authors present the interference management techniques, including interference detection, classification, localization, and mitigation techniques, documented in the specialized literature on satellite navigation systems during the past forty years. They pay particular attention to algorithms that use omnidirectional antennas, which do not require additional specialized antennas on the aerial vehicle.

The authors of [33] provide a thorough overview of ML's use in UAV-assisted wireless networks. Various functional and design aspects, including security, positioning, resource management, and channel modeling, will be improved by ML techniques. Recently, techniques based on ML have been utilized to mitigate interference in UAV networks effectively. ML could enhance the effectiveness of numerous interference mitigation strategies utilized in UAV networks for seamless handover, UAV-user association, power control, and predicting user mobility and network load. Moreover, utilizing ML to generate the precoding matrices for massive MIMO-enabled UAVs can reduce interference and improve transmission quality.

In [34], the authors propose new IMTs to achieve spectral efficient operations for UAV-assisted wireless networks. In particular, they utilize the powerful detection capabilities for UAVs and idle mode of terrestrial BSs in the network to reduce or eliminate interference. The effectiveness of the proposed IMTs is verified by numerical results, and these results demonstrate their notable improvements in spectrum efficiency over terrestrial IMTs.

To mitigate the UAV's significant interference with co-channel BSs, the authors of [35] propose a novel cooperative interference cancellation strategy for uplink communication of a UAV. This strategy is based on the local cooperation among co-channel BSs and their neighboring assisting BSs. In particular, the assisting BS quantifies the signals received from the UAV and sends them to the co-channel BS. The co-channel BS then decodes messages from the ground users it serves by processing the quantized signal along with its own received signal and using nonlinear/linear IMTs to mitigate the UAV interference. The achievable rates are derived from the proposed strategy using different IMTs as a function of the UAV's rate and transmission power. Moreover, they demonstrate that the proposed strategy is more efficient than the existing strategy based on the decode-and-forward operation of the assisting BSs.

In [36], the authors investigate the uplink transmission of a UAV in UAV-assisted wireless networks using NOMA. In particular, the objective is to maximize the overall uplink sum rate from the UAV to BSs in a given band and from the users that have co-channels with UAV to their associated BSs by improving the precoding vectors of a multi-antenna UAV. To reduce interference, they utilize SIC not only to BSs connected to a UAV but also to BSs connected to ground users in the same frequency band. The formulated optimization problem is non-convex and therefore they convert it into a second-order cone programming using approximations that are based on the first-order Taylor expansion. As a result, an iterative algorithm with low complexity is proposed to find an efficient solution to the optimization problem.

A scheme for aerial-terrestrial networks based on NOMA is proposed by the authors of [37]. In this scheme, the terrestrial user and the aerial user are paired based on NOMA to take advantage of asymmetric gains for their channels and the diversity of rate requirements of the downlink communications. The challenge of high inter-cell interference (ICI) at the receiver of an aerial user is further controlled by providing a directional antenna with adjustable beamwidth to the aerial user thereby establishing beamforming with terrestrial BSs. Then, they obtain the suboptimal power allocation and the optimal beamwidth such that the overall sum rate for terrestrial users is maximized while considering the QoS requirements of aerial users. The formulated optimization problem is non-convex and therefore they utilize the successive convex approximation (SCA) to find a suboptimal solution. Then, they obtain the statistical properties that make it possible to estimate the aggregate ICI. For the case in which the interfering BSs do not have the same elevation angle as the coordinated BSs, the authors approximate the outage probability for the aerial users. Finally, they compare the outage probability and the overall sum rate for terrestrial users in the proposed scheme with several existing schemes.

The authors of [38] study the downlink performance of NOMA for UAV-assisted wireless networks. A new framework based on stochastic geometry is developed for the co-existence of terrestrial users and aerial users where the Poisson point process governs the BSs's spatial distribution. In their analysis, two types of receiving antennas and two user association policies are considered, and an ICIC technique is utilized. Then, they analytically obtain the average rate of terrestrial users and aerial users, and coverage probability as key performance metrics. These results are utilized to obtain quantitative information about various system parameters and their effects including the number of coordinated BSs, antenna beamwidth, user association policy, SIC constraints, power allocation, terrestrial user's distance from the BS, and aerial user's altitude. Based on this analysis, an interference-aware scheme is proposed based on ICIC, directional antenna, and maximum SINR for user association. Moreover, a benchmark scheme is considered based on not utilizing ICIC, omnidirectional antenna, and minimum-distance user association. The proposed scheme boosts the terrestrial user's average rate by six times and the aerial user's coverage probability by three times compared to the benchmark scheme.

In [39], the authors investigate the uplink performance of NOMA for UAV-assisted wireless networks. They assume that the ground users and a rotary-wing UAV are served by ground BSs using the uplink NOMA where the UAV is utilized to send specific data to each target ground BS. In particular, their objective is to minimize the UAV mission time by jointly optimizing the UAV-BS association order and the UAV trajectory, considering the interference of the UAV with non-associated BSs. The formulated optimization problem is non-convex and therefore they utilize the topology theory and graph theory to effectively verify the feasibility of the formulated problem. Moreover, they prove that the optimal trajectory of the UAV should meet the fly-hover-fly structure. Based on this insight, they utilize graph theory techniques to find an efficient solution with predefined hovering placements. Furthermore, an iterative algorithm for UAV trajectory design is proposed using the SCA technique that guarantees a locally optimal solution.

B. CLASSIFICATION CRITERIA FOR IMTS

IMTs are crucial in ensuring reliable and efficient communication for UAVs across different generations of cellular networks 4G, 5G, and B5G. The integration of UAVs into cellular networks introduces unique challenges due to their mobility, varying altitudes, and LoS conditions, which can significantly differ from traditional terrestrial networks, and can lead to more interference issues. The criteria for classifying these techniques vary across different generations of mobile networks due to their distinct technological foundations and service requirements. Therefore, comparing the criteria for IMTs across different generations of cellular networks 4G, 5G, and B5G must consider how each generation addresses the challenges and requirements of wireless communication [28], [40].

- *Adaptive modulation and coding schemes:* In 4G networks, adaptive modulation and coding schemes are primarily used to optimize data rates and link reliability based on the current channel conditions.

Criteria include the ability to adjust modulation and coding schemes dynamically to maintain high throughput and spectral efficiency. However, in 5G networks, adaptive modulation and coding schemes become more sophisticated to accommodate a broader range of services and applications, such as ultra-reliable low-latency communication (URLLC). On the other hand, in B5G networks, adaptive modulation and coding schemes continue to evolve to meet the requirements of emerging applications, such as rate-splitting, IRS, AI, and holographic communications. Criteria focus on adapting modulation and coding schemes to support extremely high data rates, low-latency communication, and ultra-reliable connections in dynamic and challenging environments. [41], [42], [43]

- *Dynamic antenna pattern adjustment:* Antenna systems in 4G networks are typically fixed or have limited adaptability, mainly focusing on beamforming for enhancing coverage and capacity. In this generation, the criteria include the ability to adjust beamforming patterns based on user distribution and signal strength to improve link quality [44]. On the other hand, 5G networks introduce more advanced antenna systems with beamforming capabilities, enabling dynamic adjustment of antenna patterns to track user movements and mitigate interference. Therefore, the criteria for this generation involve supporting MIMO systems and beamforming techniques for interference mitigation [45], [46]. Furthermore, in B5G networks, dynamic antenna pattern adjustment becomes more crucial for addressing the challenges of highly dense and dynamic network deployments for UAV communications links. The criteria for this generation focus on supporting adaptive beamforming and tracking algorithms for seamless connectivity in various scenarios, including urban, rural, and aerial environments [47], [48].
- *Dynamic transmit power control:* Transmit power control in 4G networks is mainly used to optimize coverage, minimize interference, and extend battery life in mobile and IoT devices. The criteria for this generation include the ability to adjust transmit power levels based on signal strength, path loss, and interference levels for uplink and downlink scenarios [49]. On the other hand, the 5G networks use dynamic transmit power control to improve spectral efficiency, support D2D communication, and enable energy-efficient operation. Criteria for this generation include adapting transmit power levels dynamically to meet QoS requirements, mitigate co-channel interference, and optimize network capacity [50]. Moreover, in B5G networks, dynamic transmit power control becomes essential for managing interference in diverse environments with various communication technologies, such as UAVs, and IoT devices networks. Here, the criteria focus on supporting coordinated power control schemes, interference-aware resource allocation, and dynamic spectrum sharing to ensure efficient and reliable communication [51].
- *Sub-channel scheduling:* Sub-channel scheduling in 4G networks is typically based on orthogonal frequency division multiple access (OFDMA), allowing multiple users to share the same frequency band. It also involves the allocation of specific sub-channels to users based on their communication needs and the current channel conditions. The criteria for this generation include the ability to allocate sub-channels dynamically based on user demand, channel conditions, and QoS requirements [52]. On the other hand, the 5G networks introduce advanced scheduling techniques, such as NOMA and grant-free transmission, to improve spectral efficiency and support massive connectivity (Decrease interference to enhance the system's efficiency and increase the number of served users). The criteria involve supporting flexible sub-channelization schemes, dynamic scheduling algorithms, and efficient resource management for diverse services and applications [53]. Furthermore, in B5G networks, sub-channel scheduling becomes more complex to accommodate the diverse requirements of emerging applications, such as maximizing network capacity while mitigating interference. The criteria of this generation focus on supporting hybrid access schemes, terahertz communications, rate-splitting, and intelligent scheduling policies to meet the performance and latency requirements of next-generation services [54].

C. METHODOLOGY AND BIBLIOMETRIC ANALYSIS

Many articles have been published to explore various IMTs for UAVs. However, conducting a comprehensive literature review to identify and analyze relevant articles in this domain can be time-consuming for researchers preparing scholarly articles. Electronic search engines, databases, and journal websites typically rely on keywords to facilitate interested readers' discovery of research papers. Keywords play a vital role in research publications as they straightforwardly capture the core aspects of the field, sub-field, topic, and research focus. Moreover, keywords are a vital navigational tool, helping researchers locate articles relevant to their research inquiries and enhancing a published article's visibility and citation potential.

To facilitate this process and contribute to the research community's collective knowledge, we have generated a keyword network graph using indexed keywords from research articles in the Scopus database. This graphical representation provides valuable insights into the most popular keywords within IMTs for UAV research topics. By offering a visual graph of these keywords, as depicted in Figure 5, we aim to facilitate the work of future researchers, helping them discover relevant publications on IMTs for UAVs. Additionally, we present the occurrences of keywords in Figure 6.

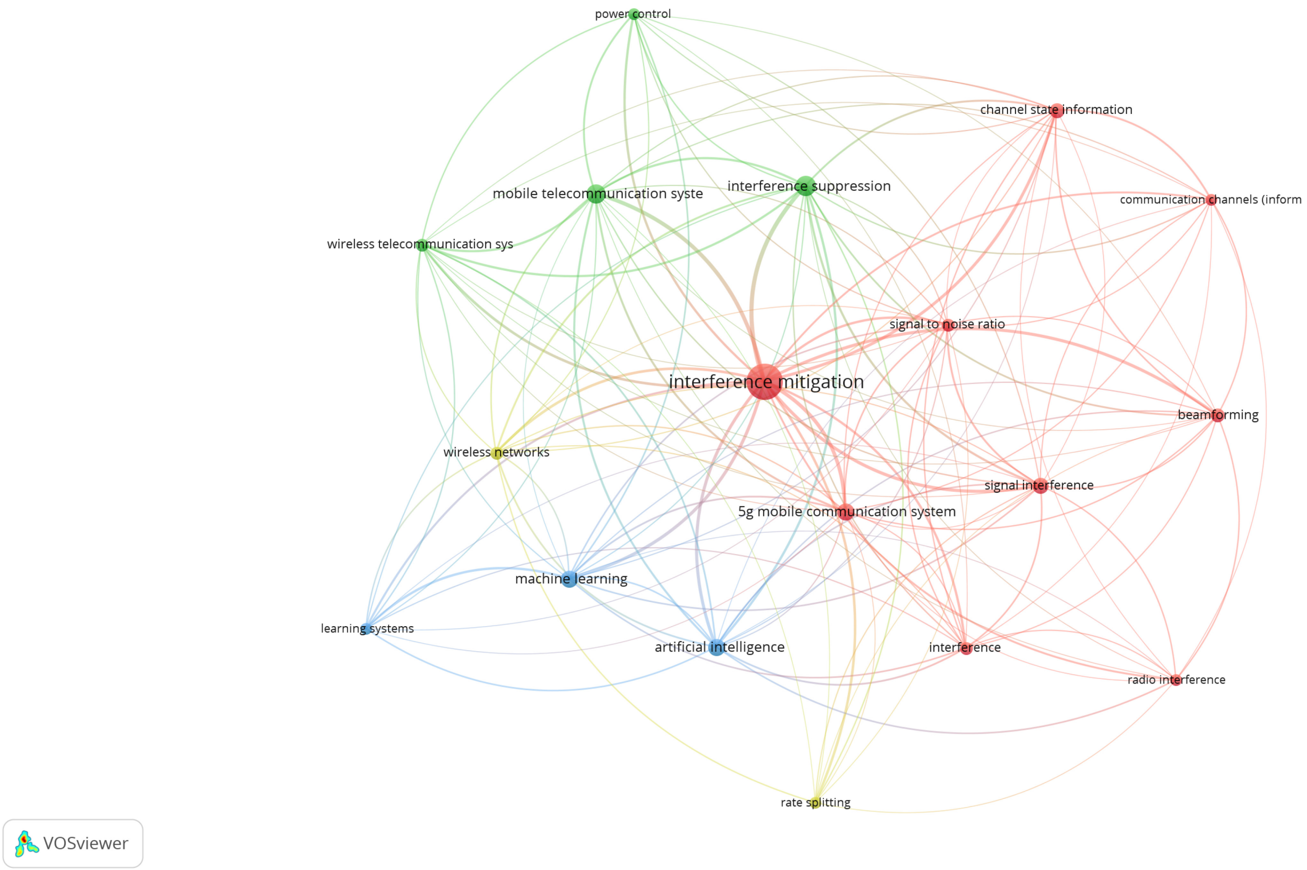

FIGURE 5. Detailed keyword network visualization of IMTs for UAVs. This Figure presents a keyword network graph constructed from a comprehensive database of research articles indexed in Scopus, focusing on the field of IMTs within UAV research. The graphical representation presents the interconnections of these keywords. This network graph guides future research directions by indicating emerging trends in the field. The visualization aims to assist researchers in identifying key concepts and relevant literature for their research on UAV IMTs.

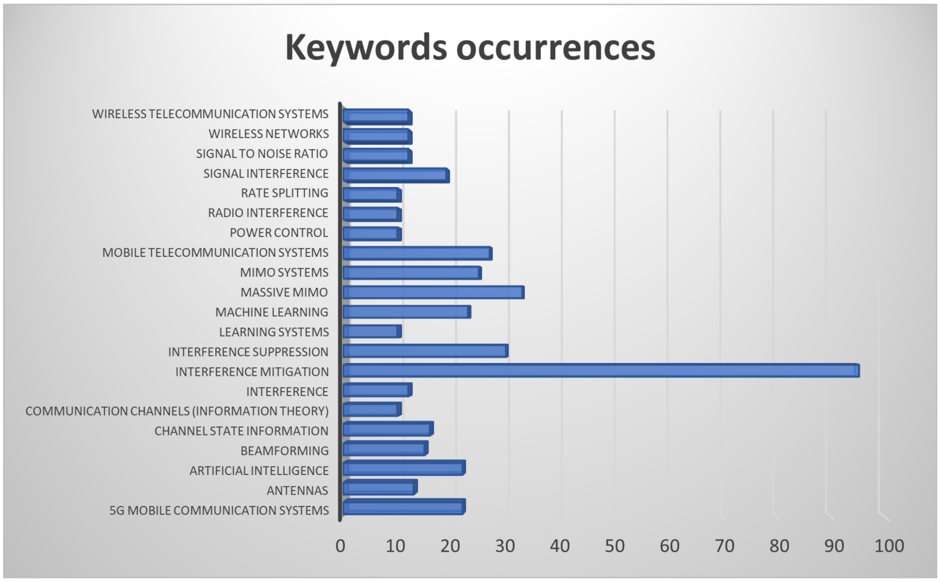

FIGURE 6. Comprehensive analysis of keyword occurrences in IMTs research. This Figure offers a detailed quantitative analysis of the keyword frequencies of IMTs for UAVs.

Furthermore, in the pursuit of identifying research papers on IMTs, a comprehensive search strategy was employed. This strategy encompassed an exploration of common academic databases and search engines, including but not limited to:

- IEEE Xplore
- Springer
- Elsevier
- Wiley

- ACM (Association for Computing Machinery)
- Tech Science Press
- Taylor and Francis
- Science Press
- arXiv
- Google Scholar

These databases and search engines were selected for their wide-ranging coverage of scholarly works, ensuring a comprehensive search for relevant literature.

The inclusion criteria for the literature survey on IMTs within the domains of current and future UAV-assisted wireless networks were identified as follows:

- The article must propose or analyze an IMT for UAVs and relevant to current and future environments.
- The article must address one of the predefined research contributions to interference management in the specified generations of wireless networks.
- The article must contribute to the theoretical or practical advancements in interference mitigation strategies for the current and future UAV-assisted wireless networks.

On the other hand, to maintain a focus on the most relevant research, we exclude the articles that do not directly address IMTs specific to the current and future UAV-assisted wireless networks.

To ensure a thorough examination of articles on IMTs for the current and future UAV-assisted wireless networks, our screening methodology was structured in two stages. Firstly, we assessed the titles and abstracts of the collected articles. This preliminary review aimed to eliminate duplicate research that occurs when an article is presented in multiple forums, such as appearing in journals or conferences and on preprint platforms like arXiv. Moreover, this step also allowed us to confirm the relation of each paper to IMTs within UAV applications for different cellular generations.

In the second stage, the full texts of selected articles have been analyzed. This allowed us to select the articles based on our established inclusion and exclusion criteria. The comprehensive process of our search and screening strategy is presented in the flowchart in Figure 7.

Specifically, bibliometric analysis is a powerful quantitative tool used to measure the impact and trends in research publications. In this systematic review of IMTs for the current and future UAV-assisted wireless networks, the bibliometric analysis serves several purposes:

1) It enables the identification of current and emerging research trends in IMTs for UAVs. Through this analysis, researchers can determine the most focused areas in the field, guiding the direction of future research.
2) Bibliometric analysis assists in finding potential gaps within the existing literature. This finding can lead to the initiation of novel studies addressing these less explored areas.
3) By examining citations and the overall impact of various studies, researchers gain insights into the most significant methodologies, theories, or findings within the field.

To facilitate reading this systematic review, we classify the IMTs for UAVs in each generation into four techniques: adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control and sub-channel scheduling.

IV. INTERFERENCE MITIGATION TECHNIQUES FOR 4G

The advent of the 4G cellular system marked a pivotal moment in the evolution of telecommunications, ushering in an era of unprecedented connectivity and convenience. With its robust data transfer capabilities and low latency, 4G revolutionized communication, work, and play. This transformative technology empowered individuals to stream high-definition videos and engage in seamless video conferencing on their smartphones. It paved the way for a myriad of innovative applications across various industries. From enabling the IoT to enhancing remote medical diagnostics, 4G's versatility has expanded the horizons of what is possible in our interconnected world, underscoring its indispensable role in modern society. Generally, 4G networks utilize frequency ranges primarily within the 700 MHz to 2.6 GHz spectrum. As mentioned earlier, the IMTs for UAVs in 4G can be classified into four different techniques.

A. ADAPTIVE MODULATION AND CODING SCHEMES

In his pioneer paper, a fundamental paper in information theory, Shannon establishes that with improved SINR, higher data rates can be achieved, assuming a fixed spectrum bandwidth [55]. This principle is crucial in determining the maximum achievable data rate over a specific channel in practical wireless communication systems. Adaptive modulation and coding technique is one of the traditional and innovative techniques used in modern wireless systems to enhance data transmission efficiency and adapt to varying channel conditions [41]. When the SINR is improved, the system dynamically responds by adopting a higher-order modulation and coding scheme.

As a result of employing these adaptive techniques, the wireless system can effectively increase the data rate, allowing it to transmit a larger volume of data within a given time frame. Consequently, this leads to a substantial boost in throughput, representing the overall amount of data that can be successfully transmitted through the system in a specific period. Also, this technique improves the reliability and efficiency of wireless communication systems for UAVs [3].

In recent studies, researchers have distinguished modulation schemes into two broad categories: single-carrier and multicarrier [56]. Due to their low complexity and high spectral efficiency, single-carrier modulation schemes such as binary phase-shift keying (BPSK), quadrature phase shift keying (QPSK), and 16-quadrature amplitude modulation (QAM) are widely used in UAV communication systems. On the other hand, multicarrier modulation schemes, such as orthogonal frequency division multiplexing (OFDM)

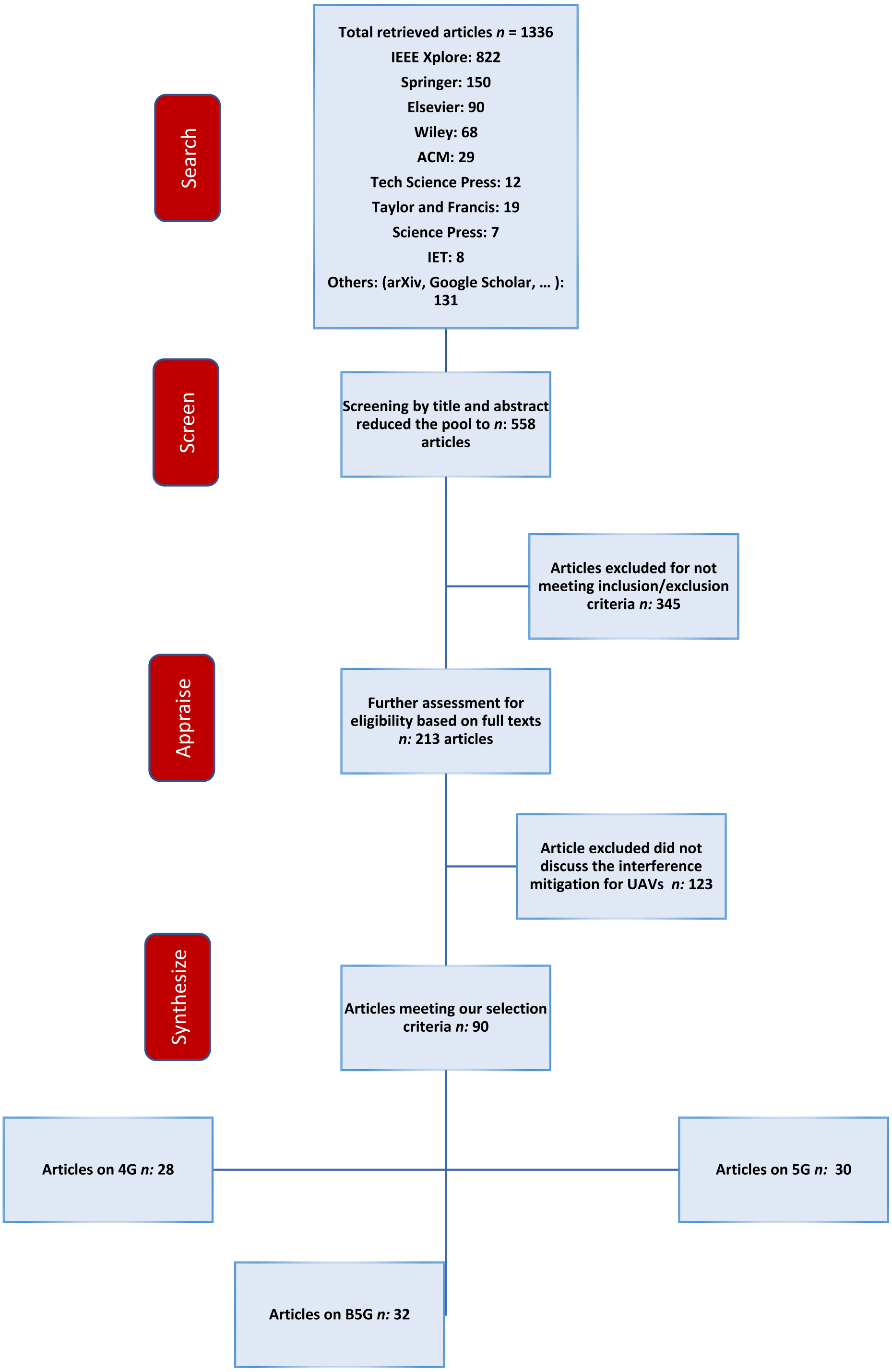

FIGURE 7. Flowchart illustrating the multi-stage screening process for identifying relevant studies on IMT in the current and future UAV-assisted wireless networks.

and filter bank multicarrier modulation (FBMC), are also employed in UAV communication systems due to their robustness against frequency selective fading and their ability to support high data rates [56].

The authors in [57] propose an index modulation (IM)-UAV method, which combines IM with UAV communication systems to improve energy efficiency (EE). A gradient descent-based deployment scheme is designed to maximize the average downlink rate of ground users in the target area. The proposed system uses a low-complexity detection scheme to detect index symbols and data symbols separately, reducing computational complexity on the receiver side. Simulation results show that the proposed deployment method is effective, and the EE is improved by combining IM with UAV communication systems. The low-complexity detection scheme reduces computation complexity but slightly sacrifices bit error rate (BER) performance. Furthermore, several studies have proposed new techniques that combine adaptive modulation and coding with other techniques, such as beamforming, MIMO, and hybrid automatic repeat request (HARQ). These techniques aim to improve the performance of UAV communication systems in challenging environments.

Synthesis and Reflections: Adaptive modulation and coding techniques are pivotal in shaping the intricate landscape of information transmission within wireless communication systems. These techniques, marked by their dynamic adjustments to the ever-changing channel conditions, not only optimize data transmission efficiency but also serve as a sophisticated tool for mitigating interference effects. This becomes particularly critical in the context of UAVs, where reliability and efficiency stand as paramount imperatives. In this realm, the instrumental role of adaptive techniques becomes evident, not just in enhancing data rates but also in fortifying the system against interference challenges.

B. DYNAMIC ANTENNA PATTERN ADJUSTMENT

Dynamic antenna pattern adjustment involves using a directional antenna with adjustable radiation patterns to improve the communication link between the UAV and the GS. This technique enhances the signal quality and reduces interference from other environmental sources [44], [58]. Numerous approaches can be classified under this technique. One approach is to deploy dedicated cells specifically for serving these vehicles. These cells are particularly beneficial in areas with high UAV activity. However, deploying such cells requires additional investment and may only become cost-effective when the number of UAVs connecting to the network increases [59].

Another possible approach is beamforming, whereby UAVs can be equipped with multiple antennas to beamform the uplink signal to the serving cell, reducing interference to neighboring cells. Similarly, a UAV can steer its receiving beam pattern to its serving BS for the downlink to minimize interference from neighboring cells. However, this approach may not be adequate in handover scenarios when the user equipment (UE) needs to synchronize and perform measurements on neighboring cells to identify potential handover targets.

For example, authors in [60] propose a novel approach for interference cancellation (IC) in uplink communication from a multiantenna UAV to multiple ground base stations (GBSs) in a cellular network. The approach uses a multibeam UAV communication scheme, which involves sending multiple data streams to a subset of available GBSs that do not use the same radio block (RB) for terrestrial communications. The decoded messages are then forwarded to the backhaul-connected occupied GBSs for IC before decoding the messages of their associated terrestrial users. This cooperative IC strategy achieved significant degrees of freedom (DoF) gain compared to benchmark schemes with no or local IC. The DoF of the proposed strategy was characterized and optimized by optimizing the associations between each data stream and the available GBSs. The paper concludes with a future research direction that extends the DoF analysis to the case of multi-antenna GBSs with flexible 3D beamforming and investigates the performance of the proposed strategy at the finite-signal-to-noise ratio (SNR) regime.

In [61], the authors propose a novel multi-beam UAV communication scheme for cellular uplink. The technique utilized cooperative IC by exploiting idle/available terrestrial BSs in combination with UAV beamforming to mitigate substantial uplink interference to ground UEs. The proposed solution addresses a pressing issue in UAV communication, and the study results demonstrate its effectiveness in improving the performance of cellular uplink communication.

In addition, the authors in [62] propose a BS cooperative beamforming (CB) technique for mitigating interference in cellular-connected UAV communications. The technique addresses the interference caused by co-channel terrestrial transmissions to the UAV. In addition to cooperatively transmitting the UAV's message, the serving BSs of the UAV utilize a novel CB-based interference transmission scheme to suppress terrestrial interference effectively. The paper formulates a problem to maximize the UAVs received SINR by jointly optimizing PAs at the serving BSs for transmitting the UAVs and co-channel terrestrial users' messages. Then, the authors present a closed-form optimal solution for the particular case of one serving BS and propose an algorithm for the general case. To reduce complexity, a distributed algorithm is also introduced.

Synthesis and Reflections: Dynamic antenna pattern adjustment emerges as a crucial interference mitigation technique in UAV-ground station communication. This approach seeks to optimize signal quality and minimize interference from various environmental sources by deploying directional antennas with adjustable radiation patterns. Among the diverse strategies under dynamic antenna pattern adjustment, deploying dedicated cells for UAVs in high-activity areas stands out. However, its cost-effectiveness hinges on the growing number of UAVs in the network. Beamforming, involving multiple antennas on UAVs to shape uplink signals and minimize interference, is another avenue explored. A novel interference cancellation approach proposed in the literature involves a multi-beam UAV communication scheme, where multiple data streams are sent to select ground base stations for decoding and subsequent interference cancellation.

C. DYNAMIC TRANSMIT POWER CONTROL

Dynamic transmit power control is a technique used to adjust the power of wireless transmissions in real-time based on channel conditions. This helps to optimize the transmission range and reduce interference with other wireless systems operating in the same frequency band [49]. The power control mechanism ensures that the transmit power of various uplink channels is regulated to guarantee that they are received at the BSs with the appropriate power level. The objective is to control the received power to be sufficient for demodulating the channel, known as the target received power, while also preventing the UE's transmit power from being excessively high, which could cause interference to other uplink transmissions [63]. In many standards, such as LTE, the UE's transmit power is determined by the downlink path loss and target received power at the serving BS.

Researchers have proposed new approaches to address uplink interference caused by UAVs. For example, in [64], the authors introduced a novel approach that involves jointly optimizing the UAV's 3D placement or trajectory and using cognitive radio (CR)-based interference-aware transmit power control to achieve maximum throughput for UAV-to-ground secondary communication while ensuring interference to existing primary ground receivers is kept below a tolerable level.

Another example proposed in [65] is an ICIC design for cellular-connected UAVs. This design leverages the CR approach to achieve UAV sensing-enabled opportunistic spectrum sharing. The approach considers UAVs secondary UE in the cellular network and shares the same spectrum as primary terrestrial UEs. By utilizing their LoS-dominant channels with the terrestrial BSs and UEs, the UAVs gain a powerful spectrum sensing capability to detect terrestrial signals over a wider region than their serving BSs. This advantage allows the UAVs to detect transmissions of terrestrial BSs/UEs in a large area, which assists their serving BSs in allocating resource blocks to avoid strong ICI in downlink/uplink communications.

Moreover, the UAV-sensing-assisted ICIC design proposed here incorporates local cooperation between the UAV and its serving BS, thereby substantially extending the interference mitigation coverage compared to conventional ICIC strategies. Specifically, the UAV leverages its sensing capabilities to assess interference levels across the available resource blocks at its serving BS, allowing it to intelligently choose low-interference resource blocks to maximize its data rate in the downlink.

In the uplink (UL), the UAV monitors the UL transmissions of terrestrial UEs within each available resource block, enabling it to anticipate the most challenging interfering channels that affect co-channel BSs. Armed with this information, the UAV collaborates with the serving BS to select resource blocks with minimal sensed power and allocates its transmit power accordingly while adhering to constraints related to worst-case interference power. Numerical results unequivocally demonstrate that the proposed UAV-sensing-assisted ICIC design delivers remarkable performance improvements over conventional ICIC, all without the need for UAV sensing, as depicted in [65]. This innovative approach charts a promising course for enhancing interference management in cellular-connected UAVs and holds the potential to enhance the overall quality of UAV communications while mitigating interference concerns.

Synthesis and Reflections: Dynamic transmit power control offers real-time adjustments to transmission power based on dynamic channel conditions between the UAV and ground users. This technique is instrumental in optimizing transmission ranges, concurrently mitigating interference with coexisting wireless systems operating in the same frequency band. Its primary goal lies in regulating the transmit power of uplink channels, ensuring they reach BSs/UAVs at the appropriate power level for effective demodulation. The delicate balance involves preventing excessive UE transmit power, a potential source of interference to other uplink transmissions. This maximizes throughput for UAV-to-ground secondary communication and ensures interference to primary ground receivers remains within tolerable limits.

D. SUB-CHANNEL SCHEDULING

Sub-channel scheduling involves the allocation of specific sub-channels to users based on their communication needs and the current channel conditions. This technique is essential in enhancing the spectrum utilization efficiency of UAV wireless communication systems, as discussed in [52]. For example, authors in [66] address interference mitigation's critical challenges in UAV-based wireless networks through an integrated approach that includes trajectory control, subchannel assignment, and user association. By formulating the problem as a mixed-integer nonlinear optimization, the paper presents an efficient alternating optimization approach to iteratively optimize these key components until convergence. The proposed iterative subchannel assignment (ISA) algorithm effectively solves the subchannel assignment subproblem. At the same time, the SCA technique enables the convexification and resolution of the nonconvex UAV trajectory control subproblem. The paper demonstrates the superiority of their sub-scheduling technique over a simple heuristic method through extensive numerical studies, showcasing significant rate gains achieved by optimized UAV trajectories compared to circular ones around clusters of ground users. The paper emphasizes the importance of considering the number of UAVs, subchannels, and UAV's maximum velocity, as these factors play a crucial role in determining the achieved max-min average rate.

Synthesis and Reflections: This subsection highlights sub-channel scheduling as one of the interference mitigation techniques that can be used to optimize the efficiency of UAV wireless communication systems. The nature of sub-channel scheduling lies in its reasonable allocation of specific sub-channels to users, considering their communication requirements and the prevailing channel conditions.

E. OTHER SCHEMES

In a recent study [67], the authors focused on the effect of UAV height on the optimal coverage radius to minimize interference. They found that by adjusting the UAV altitude, outage probability can be reduced, and a larger coverage area can be achieved. However, increased altitude can also lead to increased path loss, which needs to be carefully considered.

TABLE 2. Recent research contributions, challenges, and future insights on IMTs in 4G UAV-assisted wireless networks.

Article	Contributions	Interference Mitigation Techniques	Challenges	Future Insights
[57]	Proposed the application of coherent/non-coherent space modulation and its diversity-oriented counterpart, space-time block code with index modulation.	Adaptive modulation and coding technique	The alternation between coherent and non-coherent schemes, the transition between arrangements based on a single transmit antenna and those with multiple transmit antennas, and the adaption between high-diversity and high-spectral-efficiency schemes employing multiple transmit antennas.	Study the effect of detecting the index symbols and data symbols simultaneously on the computational complexity as well as delay time.
[60]	Proposed a new cooperative interference cancellation strategy for the UAV uplink communication. The strategy aims to eliminate co-channel interference at occupied GBSs while maximizing the sum rate to available GBSs. The proposed approach involves the multi-antenna UAV sending multiple data streams to selected available GBSs, which then forward decoded data streams to their backhaul-connected occupied GBSs for interference cancellation.	Dynamic antenna pattern adjustment technique using multi-beam UAV communications	Employing a subset of available GBSs that operate on different resource blocks for terrestrial communications. These GBSs subsequently transmit the decoded messages to the backhaul-connected occupied GBSs, aiming to eliminate interference from the UAV before decoding the messages intended for their respective terrestrial users.	Extend the analysis of DoF to include GBSs with multiple antennas by incorporating adaptable 3D beamforming. Furthermore, explore the performance evaluation of the suggested approach in the practical SNR conditions.
[49]	Proposed ICIC designs to mitigate the strong uplink interference between UAVs and GBSs. The proposed solutions maximize the weighted sum rate of both ground users and UAVs by jointly optimizing the UAV's uplink cell associations and power allocations over multiple resource blocks.	Dynamic transmit power control technique	The optimization problem is non-convex and difficult to be solved optimally.	Enhance ICIC designs by incorporating advanced 3D beamforming at BSs, and explore novel NOMA techniques for both UAV uplink and downlink communications.
[66]	Addressed the trajectory control, subchannel assignment, and user association challenges in UAV-based wireless networks. The goal is to optimize the max-min average rate while considering the data demand constraints of ground users and managing spectrum reuse and co-channel interference.	Subchannel assignment and UAV trajectory control	The optimization problem is a nonconvex optimization problem due to nonconvex constraints. Therefore, it is difficult to solve this problem optimally.	Study the interference mitigation scheme while the number of ground users and UAVs increased.
[68]	Presented a 3D multi-UAV deployment approach aimed at fulfilling QoS requirements for various user distributions while addressing co-channel interference. Also, used the mean-shift technique to classify ground users in order to deploy multi-UAVs.	Optimizing the UAV's altitude and transmit powers	The optimization problem is challenging to solve as it combines nonconvex and integer constraints.	Employ resource allocation design for multicarrier systems with a solar-powered multi-UAV with cochannel interference.

To determine the optimum UAV height that maximizes coverage area for a given SNR threshold, the authors derived a model that accounts for the Ricean K-factor, which increases exponentially with the elevation angle between the UAV and the GS. Although the authors' analysis did not consider the effect of scatterers in the environment, their findings offer valuable insights into optimizing UAV-based wireless communication systems. Specifically, their work provides a promising IMT that can be used to improve the performance of UAV-based wireless networks in various applications, such as emergency response, surveillance, and agriculture.

Synthesis and Reflections: To sum up, this subsection presents potential future directions of interference mitigation techniques for UAVs in 4G wireless networks. One such direction is optimizing the UAV's height to maximize the coverage radius as well as minimize interference. Thus, adjusting UAV altitude could reduce outage probability and expand the coverage area. However, higher altitude might result in increased path loss, necessitating careful consideration.

In conclusion, Table 2 summarizes the recent research contributions, challenges, and future insights on IMTs in 4G UAV-assisted wireless networks.

V. INTERFERENCE MITIGATION TECHNIQUES FOR 5G

Interference seriously hinders dependable and effective wireless communications, and it can harm mobile system operation and penetration. Mitigating interference is a major issue for wireless networks [69]. Besides that, 5G networks can link a large variety of user machinery or gadgets that transfer types of signals that significantly raise network interference, such as ACI, inter-cell and intra-cell interference, inter-channel and intra-channel interference, inter-symbol interference, cross-link interference (CLI), inter-beam interference, and interference from various linked devices, and interference from other connected devices [70]. Therefore, the current studies have addressed various interference mitigation strategies for 5G UAV networks, including adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power regulation, and sub-channel scheduling.

A. ADAPTIVE MODULATION AND CODING SCHEMES

In the context of adaptive modulation and coding schemes, [71] utilized the recently developed coherent/noncoherent spatial modulation and its diversity-assisted space-time block coding using index shift keying counterpart. Such arrangements are capable of significantly improving QoS for UAVs. In addition, they developed a novel adaptive design in which the UAV can adaptively change from coherent to non-coherent schemes according to Doppler frequency, reshape itself between single- and multiple-transmit antenna strategies depending on channel coding rate, and toggle between high-diversity and high-spectral-efficiency multiple-multiple transmit antenna schemes depending on modulation speed. On the other hand, as the position of UAVs controls the UAV-user communication and makes it vulnerable to a variety of environmental disruptions, the authors of [72] examined the effectiveness of UAV-user connection under atmospheric disruptions. Furthermore, an ML-assisted approach was developed that adapts to a modulation strategy which delivers the best possible performance during these environmental disruptions. Their findings demonstrated that the algorithm moves the system to a lower-order modulation scheme under high levels of environmental disruptions, resulting in a reliable connection with optimal data transfer rate and minimum error rate.

Synthesis and Reflections: In this subsection, we focused on how interference can be mitigated using adaptive modulation and coding. In summary, the findings in the papers we presented highlight the significance of adaptable techniques in UAV communications networks. Being able to rapidly alter modulation and coding schemes according to surroundings, Doppler frequency, and other characteristics helps ensure reliable connectivity as well as optimize data transmission rates in harsh environments.

B. DYNAMIC ANTENNA PATTERN ADJUSTMENT

The works in [73] examined the uplink communication from a UAV with multiple antennas to a set of GBSs within its wireless range. The authors did this by looking at a realistic but difficult situation in which the total amount of antennas on the UAVs is less than the number of antennas on the co-channel GBSs. They suggested a new multi-beam transmission approach using the NOMA technique to send data rapidly without affecting current terrestrial telecommunications at co-channel GBSs. This way, they can send data at higher rates without disrupting domestic telecommunications. Notably, the UAV transmits each data packet to a chosen group of the GBSs. These GBSs can decode the UAV's signals and subsequently suppress the interference before decoding the messages of their served terrestrial users. In the interim, the UAV uses Zero-forcing (ZF) beamforming to stop its signals from interfering with the remaining GBSs. In [45], the authors explored the latest methods for multiple access in millimeter wave (mmWave) UAV networks. They additionally examined the most critical issues and design principles related to capacity-achieving multiplexing techniques, such as intra-beam concurrent transmissions, link-adaptive data rate against network dynamics, and the right way to widen the beamwidth for mmWave. They then showed the system-level design of the constellation-division multiple access (CoDMA) for both the physical (PHY) layer and the media access control (MAC) layer by using flexible constellation in rateless code. More specifically, they used the dense constellation to build an orthogonal constellation dimensionality for user access. This way, intra-beam interference can be turned into simultaneous broadcasts, and inter-beam interference from beams next to each other is significantly reduced. In addition, they discussed how to make the UAV transmitter's beamwidth adaptable to handle greater simultaneous broadcasts by adapting to changes in the link. They showed that for the CoDMA method, the UAVs' connection reliability is ensured with an appropriately expanded beamwidth as well as resistance to changes in the network's bandwidth when there is a significant multiplexing gain.

A hybrid beamforming method for UAVs has been presented in [46]. The method is made up of two steps. In the initial phase, the position of the UAV is utilized to do quick beam swapping and multi-level beam selection, eliminating the blind spot challenge. In the second phase, the equivalent digital domain channel matrix is obtained according to the beam selection result of the first stage. Then, the digital beamforming is performed based on the ZF criterion. They perform many simulation tests on the suggested method to test how well beam tracking and IC between beams work. Furthermore, the full-duplex UAV (FD-UAV) relay was proposed in [74] to make mmWave transmission efficient. In particular, the FD-UAV relay is utilized between a source node (SN) and a destination node (DN) to set up a LoS link. Large antenna arrays are used for beamforming to create focused beams that allow significant channel gains. Also, they came up with alternating interference suppression (AIS) for designing the beamforming vectors (BFVs) and the power control factors simultaneously. Within every cycle, the beam gains for the target signals of the SN-to-UAV (S2V) link and the UAV-to-DN (V2D) links are alternately boosted, whereas the interference is decreased. In this time frame, the transmission power levels of the SN and FD-UAV relay for the given position and BFVs are updated in closed form.

Synthesis and Reflections: In this subsection, we studied the effect of dynamic antenna pattern adjustment on interference mitigation. In conclusion, the studies we afforded contribute to the rapidly developing field of UAV communication technologies by tackling challenges and recommending new approaches in uplink communication, multiple access techniques, hybrid beamforming, and full-duplex relay, demonstrating possibilities of enhancing data rates, efficiency, and flexibility in UAV communications.

C. DYNAMIC TRANSMIT POWER CONTROL

The collision avoidance and interference mitigation issue for UAV swarms, where several UAVs monitor the same objective, has been investigated in [75]. They presented a cooperative control strategy facilitated by dual fields to simultaneously handle the problems of collision and inter-UAV interference for UAV swarms. Their significant achievements are outlined as follows.

- They formulated an interference optimization problem to reduce average interference and assure collision avoidance by modifying UAV trajectories and broadcast power. Because the trajectory of UAVs impacts PA and transmission power controls interference, which might also modify the trajectory of UAVs, the trajectory and interference are linked from the standpoint of task collaboration. This interference optimization issue is comprised of two connected subtasks. To tackle this problem, they divide it into two parts: a) collision avoidance and b) power control.
- To tackle UAV jitter and target unreachability issues in the standard artificial potential fields (APFs), they suggested a singular case tolerance (SCT)-APF for the collision avoidance subproblem. It is restated as an approach to the subproblem of power control. A mean-field approximation technique is used to characterize the aggregate effect of inter-UAV interference. The associated Hamilton-Jacobi-Bellman (HJB) and Fokker–Planck equation (FPK) equations were derived, as well as an upwind finite difference approach was given to resolve those two linked equations and achieve the best power control strategy. Addressing these two subproblems independently will not result in optimal UAV swarm performance. As a result, to tackle the interference optimization problem, a cooperative control strategy allowed by the aforesaid dual fields was presented.
- They used simulation to validate the performance of the suggested dual-field collaboration technique. The simulation results show that the optimal power control policy developed by the mean-field game (MFG) may significantly minimize interference compared to current strategies. Meanwhile, their suggested dual-field-cooperation strategy delivers significant interference reduction and throughput gain compared to the single technique.

In [76], they devised novel methods to stop interference to ensure UAVs and grounded UEs may operate together in a cellular network effectively. Remarkably, they used the solid detecting potential of UAVs and dormant BSs in the network to reduce and eliminate interference. In addition to that, [77] looked at a simple yet realistic case of two co-channel cells with asymmetric interference, meaning that just the user in a particular cell gets substantial interference caused by BS in another cell. To reduce this kind of interference, they suggested an innovative cooperative NOMA scheme in which the involved user's serving BS (which could be a flying UAV) sends a superposed signal that includes both the wanted information and the co-channel user's message shared by the interfering BS. The signal from the co-channel user is meant to add to the signal from the interfering BS positively at the receiver of the interfered user. This way, combining interference with greater strength can be processed and canceled. This makes it an unusual challenge to figure out how to use the sending power for the two messages in the best way.

A power control and interference mitigation method based on DRL was created in [78]. This method was deployed in a cloud location and gets UAV measurements via the backhaul using the cloud-based architecture of 5G platforms. A deep Q-learning (DQL) based algorithm was developed to mitigate interference intelligently through power control which needs the UAV to report its positions and the received SINR to the BS every millisecond. However, it does not necessitate knowledge of the channel state information (CSI), obviating the necessity for channel estimates and the related training sequences. Furthermore, because the UAV transmits its coordinates rather than sending specific directives for power control and interference mitigation, the overall quantity of input from the UAV is decreased. Therefore, their technique addresses one of the most significant barriers to establishing 5G-connected UAVs: air-ground interference.

CLI is another kind of interference that needs to be addressed while employing Dynamic Time Division Duplex (D-TDD), which dynamically distributes transmission paths for demand adaption in every cell for 5G networks. In particular, distinct forms of interference are picked up through nearby cells utilizing various transmission directions in D-TDD. The uplink BS gets interference from the BSs in nearby downlink cells, known as downlink-to-uplink interference or BS-to-BS interference. A downlink UE gets interference from the uplink UEs of nearby uplink cells, known as UL-to-downlink interference or UE-to-UE interference. This BS-to-BS and UE-to-UE interference are known jointly as CLI [50].

There have been several CLI mitigation schemes that have been categorized as:

- Coordination-based schemes: These schemes can be used to prevent or mitigate the CLI efficiently. Several coordination-based strategies are cooperative approaches that need knowledge-sharing among cells to make modifications beforehand. Clustering [79], Scheduling and Resource Allocation [80], Power Control [81], and Beamforming [82] are examples of these approaches.
- Advanced receivers: Compared to the coordination-based CLI mitigation strategies used ahead by the transmitting device, the receiving end may suppress and eliminate incoming CLI. These methods necessitate data communication between cells in advance, but the CLI is minimized reactively by inserting advanced receivers [83]. Three kinds of interference suppression

exist: interference suppression, maximum likelihood, and IC [84], [85], [86].

- Sensing-based schemes: The sensing approach is an optional approach that could be employed before using the other CLI mitigation strategies listed previously. The essential premise is to detect whether or not CLI is present to minimize it before transmission. Coordination-based CLI mitigation techniques need an information exchange between nearby cells in advance, which implies they are rendered ineffective if the information exchange signaling fails [87].

Synthesis and Reflections: In a nutshell, this subsection focuses on how dynamic transmit power control can be used efficiently to mitigate interference in the context of UAV communication networks. They provide advanced tactics such as cooperative control, NOMA schemes, deep reinforcement learning for power controlling, as well as different CLI mitigation techniques, demonstrating how collaboration is used to improve the dependability and efficacy of UAV communications across a variety of conditions.

D. SUB-CHANNEL SCHEDULING

In [88], the authors introduced a scheduling mechanism for Vehicle-to-everything (V2X) communication based on NOMA with interference mitigation, a novel block resource allocation mechanism for the 5G network. The primary goal of this method was to decrease interference to enhance the system's efficiency, increase the number of served users, and reduce the binary error rate. On the other side, [53] investigated the combined subchannel assignment and resource scheduling problem in the downlink NOMA system with coordinated multi-point radio networks. Regarding cell-edge user throughput, simulation results demonstrated that the system throughput improved as the interference was effectively mitigated.

A priority-aware resource coordination in a multi-UAV communication network was explored in [89]. Multiple UAVs were managed by a ground control unit and followed a predetermined path to complete specific duties. The optimization problem was formulated to jointly decide the channel assignments and power allocation to achieve the least SINR across all UAVs while adhering to resource restrictions. They investigated the problem under two scenarios: Null-ACI and ACI systems. For the Null-ACI scenario, the Hungarian method was used to get the global best solution. On the other hand, for the ACI scenario, a fast iterative technique for solving such a problem was proposed.

In [90], they tried to optimize the max-min rate based on information transfer requests from ground users. However, it turned out that this problem is a mixed integer nonlinear optimization. Hence, they applied an iterative approach that enhances sub-channel allocation and UAV trajectories controlling till convergence. Furthermore, they used the DC (Difference of Convex Functions) Programming approach and the arithmetic and geometric means contradiction for resolving the non-convex UAV trajectories sub-problem.

Synthesis and Reflections: In conclusion, the papers we explored in this subsection tackled the problem of interference mitigation and, hence, offered scheduling and resource allocation strategies. It turns out that the focus on efficiency, data rate, and interference mitigation underscores continuous attempts to improve the functionality of wireless communication networks, especially in V2X communication and 5G networks.

E. OTHER SCHEMES

In [91], they studied how the air-to-ground (ATG) mobile customer premise equipment (CPE) terminal and 5G BS interact with each other in the 3.5 GHz frequency band. So that the ATG airborne CPE terminal doesn't mess up the 5G BS, there needs to be more separation between the ATG airborne CPE terminal and the 5G BS. In their study, they handled the ATG airborne CPE terminal's send power to meet the need for more separation. As a result, they came up with a multi-head attention-based ML technique for estimating the reference-signal-received-power (RSRP) of 5G BS. The expected RSRP number is subsequently used to determine how much power the ATG airborne CPE device will send out. By comparing the suggested ML-based technique to real measurements, it was made positive that it worked.

Considering both aerial and ground IoT nodes, in [92], they developed a new way to prevent interference in IoT networks that don't talk to each other. It uses the 3D radiation pattern of a dipole antenna. The main idea behind their suggested method for reducing interference is that if a different antenna radiation pattern is employed at the transmitter side based on where the receiving device is in 3D, unwanted signals can be blocked out and boost the needed ones. Generally, in a 2D space structure, they assume the dipole antenna is lined with the z-axis. This gives off radiation in all directions, regardless of the azimuth angle. However, because the power changes with the angle of elevation, such dipole establishing, which may be prevalent in low-cost IoT devices, can't have an omnidirectional radiation pattern in a 3D structure (like networks with aerial nodes). On the other side, if a dipole antenna is pointed in a different direction, like the y-axis, this can change how the signal is sent out.

In [93], the authors looked at the efficiency of the bottleneck uplink coverage of the macro base station edge users when ICI and UAV interference were present. Also, they utilized an effective technique to share resources called reverse frequency allocation (RFA) for interacting with the two ICI and UAV interference.

Synthesis and Reflections: To sum up, the papers we mentioned in this subsection showed that the combination of ML, dynamic antenna radiation patterns, and resource-sharing techniques exemplifies multidisciplinary attempts to deal with interference issues along with optimizing the effectiveness of various communication scenarios, including

TABLE 3. Recent research contributions, challenges, and future insights in 5G UAV-assisted wireless networks.

Article	Contributions	Interference Mitigation Techniques	Challenges	Future Insights
[73]	Studied the UL communication from a multi-antenna UAV to a set of GBSs within its signal coverage when the number of antennas at the UAV is smaller than that of co-channel GBSs.	Multi-beam transmission strategy	Deal with interference problems taking into account the limited number of antennas on the UAV and proposing an effective multi-beam transmission scheme utilizing NOMA.	Adopt the assumption of the dynamic beam pattern in the downlink direction.
[74]	FD-UAV relay is employed to improve the achievable rate of mmWave networks.	AIS algorithm for the joint design of the BFVs and the power control variables	Working with a non-convex optimization issue, establishing hypotheses concerning the surroundings, and establishing an efficient method for interference reduction.	Adopt the assumption of NLoS environment and non-ideal beamforming.
[75]	Studied the collision avoidance and interference mitigation for UAV swarm where many UAVs track a common target.	Power Control	Managing several UAVs in a swarm while considering collision avoidance and interference mitigation into consideration.	Assume a more general scenario regarding U2U communications.
[76]	Proposed a new cooperative NOMA scheme to mitigate the severe uplink interference due to the UAV's LoS channels with ground BSs in cellular-connected UAV communication. It studied the weighted sum-rate maximization problem for the ground UEs and the UAV by jointly optimizing the UAV's uplink rate and transmitting PAs over multiple RBs.	Cooperative NOMA	The limitation of existing NOMA approaches, the optimization of UAV operations, and finding the optimal solution of complex optimization problems.	Including UAV communication in the downlink, the more general case with multiple UAVs, and the practical design under imperfect channel knowledge and limited network coordination.
[77]	New cooperative NOMA scheme for cellular downlink to resolve the strong asymmetric interference issue.	Cooperative NOMA	Effectively mitigates asymmetrical interference in co-channel cells using cooperative NOMA, which requires precisely determining the optimum power allocation for superposed signals.	Increase the number of cells to more than two cells and increase the number of users.
[91]	Studied the cochannel interference between the ATG airborne CPE terminal and 5G BS in the 3.5 GHz frequency band.	ML	Interference control, frequency deployment, isolation criterion regulation, continuous tracking of RSRP, control on the transmitted power, and ML usage in the framework of ATG networks.	Study the proposed algorithm at different frequency bands.
[92]	Proposed and studied an interference mitigation scheme that utilizes the diversity of the radiation pattern in a 3D topology IoT uncoordinated network.	New interference mitigation scheme	Dealing with Interference management in the framework of dense IoT network setups, recognizing interference features in 3D applications, assessing an IoT system's 3D structure, dealing with massive connectivity circumstances, and optimizing receiver heights.	Study the new interference mitigation scheme under other antenna types and more general radiation patterns.
[93]	The bottleneck uplink coverage performance of the macro BS edge users in the presence of ICI and UAV interference.	RFA and decoupled association	Development of very small cells, dealing with drone interference, improving frequency allocation using RFA, introducing decoupled association.	Incorporating fractional power control in the proposed setup.

5G wireless networks, IoT systems with aerial and ground nodes.

Table 3 summarizes the recent research contributions, challenges, and future insights on interference mitigation in 5G UAV-assisted wireless networks. It's worth mentioning here that some researchers have proposed alternative methods to the conventional interference mitigation schemes for 5G wireless networks [94]. These methods are shown in Figure 8. For instance, there has been a growing interest in implementing cell-free networks in dense networks. More specifically, in such networks, several irregularly distributed individual access points are connected to a central processing unit through a backhaul infrastructure that seamlessly supports just a handful of mobile stations. This achieves much higher EE and spectral advantages.

VI. INTERFERENCE MITIGATION TECHNIQUES FOR B5G

Interference mitigation is essential in B5G networks to ensure efficient and reliable wireless communication. As 5G emerges and the ongoing development of B5G, the demand for high-speed, more reliable, and high data rate communication has never been greater. However, with the increasing number of IoT devices and the growing demand for high data rates, the issue of interference has become a significant challenge. Interference can arise from various sources, including other devices operating at the same frequency bands, environmental factors, and unwanted signals.

Developing B5G networks presents significant challenges, including achieving higher spectral efficiency, mitigating interference in dense environments, and ensuring EE, standardization, regulations, and compatibility efforts.

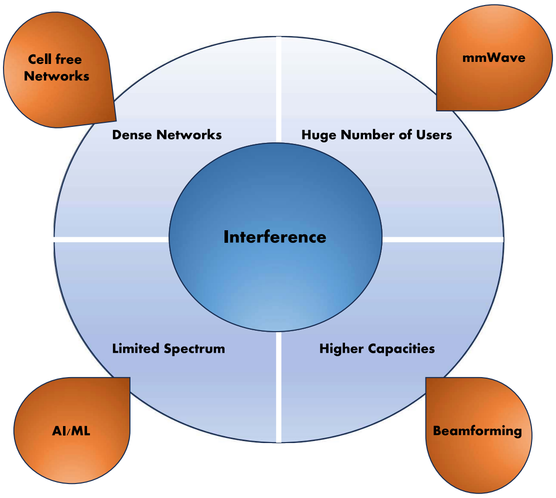

FIGURE 8. Alternatives to the conventional interference mitigation schemes in 5G networks. They can minimize the interference that arises from deploying dense networks in a limited spectrum with a huge number of users requesting very high capacities. These alternatives include the design of cell-free networks, utilizing AI/ML, beamforming, and mmWave.

Researchers are studying different IMTs for B5G networks. These techniques include adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control, and sub-channel scheduling. Sub-channel scheduling involves dividing the frequency band into smaller sub-channels and assigning them to different users based on their communication requirements. This technique reduces interference by ensuring that each user only uses the necessary sub-channels and avoids overlapping with other users' sub-channels.

In this section, we present and discuss the related works in the literature about each IMT, their potential benefits, the addressed challenges, and future trends. Researchers use these techniques to address interference challenges and ensure reliable and efficient communication in B5G networks.

A. ADAPTIVE MODULATION AND CODING SCHEMES

Today, most wireless data transmissions are conducted in digital format, and the selection of modulation schemes has grown significantly in importance. This heightened significance arises from escalating user expectations and the limitations of available spectrum resources. There is a growing utilization of higher-order modulation schemes to enhance bandwidth efficiency. As wireless networks progress from 1G to B5G, modulation techniques have substantially improved, enabling enhanced services and elevated data rates as highlighted in [95]. Most channel adaptation techniques currently rely on CSI, typically conveyed through a feedback message transmitted from the receiver to the transmitter.

In adaptive modulation and coding schemes, the transmitter's role encompasses the selection of a fixed-rate channel code, aligning it with an appropriate rate and modulation scheme. The primary aim of this scheme is to optimize spectral efficiency based on the available CSI. However, for UAV applications, the applicability of this approach faces three predominant challenges. Firstly, the feasibility of obtaining CSI for every device within a UAV-assisted wireless network becomes impractical, especially in scenarios characterized by dense UAV networks and sporadic traffic patterns. Secondly, even if CSI acquisition were achievable for individual devices, the frequent updates of these devices are not practical, given the dynamics introduced by random traffic, device mobility, and activity variations. Thirdly, acquiring CSI necessitates transmitting pilot sequences from the transmitter to the receiver, followed by the reception of CSI via a feedback message, as articulated in [96]. This introduces significant time delays and overhead, posing considerable challenges in scenarios involving dense UAV networks and many devices in the network. Moreover, the associated overhead and delays in getting CSI often counter the latency requirements of numerous delay-sensitive applications, as highlighted in [97]. Consequently, an essential need arises for novel channel codes that operate effectively under very low SNRs and in scenarios where CSI may be absent or fluctuating.

The evolution of wireless technology has witnessed a significant surge in peak data rates, with the transition from 4G to 5G showcasing an incredible 10 to 100-fold increase. It is anticipated that B5G will continue along this trajectory, with the potential for a single decoder in B5G devices to achieve throughputs of hundreds of Gigabits per second [43]. To reduce the number of decoding iterations and enhance the parallelism level of the decoder, it is crucial to consider both code design and the corresponding encoding/decoding algorithms. The codeword length and coding rate of B5G UAV-assisted wireless networks should possess flexibility. Moreover, the channel coding scheme employed in B5G UAV high-reliability scenarios should outperform 5G while maintaining a lower error rate. ML techniques such as deep unfolding can be leveraged to enhance the performance of iterative algorithms through modified polar code constructions. Furthermore, achieving a deeper understanding of the robustness, behavior, and generalization of neural networks will be crucial for these approaches to enhance communication performance.

For instance, in [42], the authors introduce an adaptive deep learning-based design for UAV receivers in coded MIMO systems. These systems experience noise exhibiting correlation among time domains, significantly impacting transmission performance. To address this, they incorporate linear convolutional coding at the transmitter to enhance system performance. Subsequently, they propose an adaptive deep learning-based iterative UAV receiver comprising three key components: a detector (e.g., minimum mean square error or ZF detector), a deep convolutional neural network, which aids in noise suppression by recognizing correlation patterns among the noise, and a decoder (e.g., Viterbi decoding). Simulation results demonstrate that the proposed UAV receiver achieves substantially better BER performance than conventional receivers while maintaining lower computational complexity.

Synthesis and Reflections: The adaptive modulation and coding schemes subsection highlights a range of studies on the evolution and application of adaptive modulation and coding schemes for B5G wireless UAV networks. These studies aim to optimize spectral efficiency and data rates while addressing the dynamic challenges of the UAV network, such as device mobility and CSI acquisition complexities. The works reviewed in this section highlight the necessity for innovative solutions that can adapt to rapidly changing network conditions. Techniques like deep learning-based iterative receivers represent a significant advancement in addressing the noise correlation and performance issues in UAV communications. These solutions enhanced BER performance and introduced computational efficiency, which is crucial for real-time applications. Moreover, the integration of machine learning techniques in coding schemes is a promising solution where communication systems can dynamically adapt to network conditions and user requirements. This adaptability is crucial for achieving the B5G requirements, including ultra-high-speed data transmissions and robust connectivity in UAV networks.

B. DYNAMIC ANTENNA PATTERN ADJUSTMENT SCHEME

The authors in [47] proposed a novel approach to improve the performance of UAV relay-assisted B5G IoT networks. The proposed approach used a hybrid beamforming NOMA scheme, which enhanced the spectrum and EE of the system.

The authors highlighted the importance of interference management to achieve optimal network performance. It addresses interference management through several techniques, including NOMA transmission, hybrid beamforming, UAV relay-assisted systems, and dynamic resource allocation. Using NOMA, the proposed approach allows multiple users to share the same resources, increasing spectrum efficiency while mitigating interference between users who share the same resources.

The simulation results showed that the proposed approach outperformed the conventional orthogonal multiple access (OMA) schemes regarding spectral efficiency, EE, and outage probability. The proposed scheme achieved a higher spectral efficiency by allowing more users to share the same resources. Furthermore, the proposed scheme reduced the outage probability, improving the system's reliability.

The future insights for the proposed hybrid beamforming NOMA scheme for mmWave in [47] can be summarized as follows:

- Interference management techniques can be developed for NOMA to improve the system's reliability and spectral efficiency.
- The proposed scheme can be extended to support multi-UAV relay systems to further enhance the system's performance.
- The proposed scheme can be integrated with other emerging technologies, such as AI and ML, to enhance the system's performance, reliability, and Interference management techniques.

The work in [98] proposed a novel approach to improve the coverage and connectivity of wide-area IoT networks in B5G systems. The proposed approach uses a cell-free satellite-UAV network, leveraging the benefits of satellite and UAV communication technologies. The proposed network architecture consists of multiple satellites and UAVs equipped with various antennas distributed over the coverage area. The network uses a cell-free architecture, eliminates the need for cell association, and enables seamless connectivity over the coverage area. They also used a distributed beamforming technique, which allows the network to dynamically adjust the beam direction and PA based on the location of the IoT devices. This technique improves the network's EE and reduces the interference and outage probability.

The proposed cell-free satellite-UAV network for B5G wide-area IoT networks provides a promising solution to address the challenges of coverage and connectivity in future IoT applications. The following are the future insights for this work:

- The cell-free satellite-UAV network for B5G wide-area IoT networks can be optimized to reduce interference and power consumption and improve EE.
- The cell-free satellite-UAV network for B5G wide-area IoT networks can be integrated with other emerging technologies, such as AI and ML, to enhance the system's performance and reliability.
- The cell-free satellite-UAV network for B5G wide-area IoT networks can be further optimized to support high-speed data transfer and low-latency applications, such as virtual reality, augmented reality, and autonomous vehicles.

Moreover, the authors in [48] proposed a new approach to optimize the deployment of IRSs in wireless communication systems. The work focused on IMTs in wireless communication systems using reconfigurable intelligent surfaces (RISs). This new technology utilizes many small, low-cost reflecting elements to improve wireless communication by manipulating the signals' phase and amplitude. The article discusses various IMTs, including beamforming, precoding, and interference alignment. The authors then propose a new optimization algorithm that uses the complex circle manifold to improve the efficiency of IRS deployment in interference channels. The proposed algorithm outperforms existing optimization methods regarding interference mitigation and system throughput.

The future of IMTs for IRS-based B5G communication systems could focus on improving the efficiency and scalability of the proposed optimization algorithm. There may be research on applying this optimization algorithm to larger and more complex wireless networks and integrating it with other IMTs to achieve better performance.

Synthesis and Reflections: The dynamic antenna pattern adjustment scheme subsection presents various innovative approaches in dynamic antenna pattern adjustment schemes of interference mitigation beyond 5G and B5G networks. The presented approaches, such as the hybrid beamforming NOMA scheme in [47], the cell-free satellite-UAV network in [98], and the IRS optimization in [48], focus on enhancing network performance through sophisticated interference management techniques. Moreover, these studies demonstrate the increasing complexity of IMTs, addressing the growing demands for higher efficiency, reliability, and coverage in next-generation networks. Furthermore, these works highlight the potential for future research to integrate emerging technologies, like AI and ML, to refine and optimize these techniques.

C. DYNAMIC TRANSMIT POWER CONTROL SCHEME

In [51], the authors discussed several IMTs for D2D communication in 5G and B5G networks. Firstly, they presented a power control technique, which involves adjusting the transmission devices' power to minimize interference. Power control can be implemented in different ways, such as fixed, open, and closed-loop power control. Then, they discussed the interference-aware resource allocation technique, which optimizes the allocation of resources, such as time, frequency, and power, to minimize interference between D2D communication. Beamforming is another IMT to control transmission toward the intended receiver. Beamforming uses multiple antennas to direct the transmission toward the receiver, which helps reduce interference from other directions. This technique requires accurate channel information and signal processing algorithms to optimize the beamforming direction and power. They presented ML-based techniques as a promising approach to interference mitigation in D2D communication. ML can be used to predict the interference level of D2D links based on historical data and optimize resource allocation and beamforming. This technique can help improve the efficiency of interference mitigation and reduce the complexity of interference management.

Synthesis and Reflections: The dynamic transmit power control scheme subsection presents the main approaches of dynamic transmit power control for IMT in the evolution of B5G networks. The feature of these approaches is the balancing act of minimizing interference while maintaining effective D2D communication. Techniques such as power control, fixed, open, or closed-loop, offer ways to adjust transmission power in response to varying network conditions.

The synthesis of these methodologies highlights the importance of adaptability in network resource management, presented by the intelligent allocation of time, frequency, and power resources. Furthermore, the application of beamforming, leveraging multiple antennas, highlights the shift towards more targeted and efficient communication strategies. This is achieved by the utilization of ML techniques. Thus, the integration of traditional techniques with advanced ML algorithms paves the way for more autonomous, and efficient B5G networks.

D. SUB-CHANNEL SCHEDULING SCHEME

The work in [99] proposed a novel framework to address the challenges for mmWave-enabled integrated access and backhaul (IAB) in B5G cellular IoT networks. The authors identified the differentiated backhaul capacities of small-cell BSs and various IMTs to maximize the network capacity. They proposed a two-step resource allocation scheme for joint traffic load-balancing and interference mitigation to maximize network capacity. The first step involves a novel backhaul capacity and interference-aware matching utility function using a many-to-many matching model to solve the user equipment association (UA) subproblem. This function considers both the interference penalty and the backhaul capacity of small-cell BSs. Then, the second step tackles the transmit PA subproblem by transforming the non-convex problem into a convex one using the SCA method. The authors showed that the proposed algorithms could improve the network sum rate by 71.9% compared to conventional methods, ensuring a high successful transmission probability. The study suggested that future work should focus on routing path selection for multihop backhaul, bandwidth allocation between access and backhaul links, backhaul bandwidth allocation based on traffic load at each small-cell BS, and optimizing caching strategies. These considerations will improve network performance and IMTs for B5G cellular IoT networks.

Synthesis and Reflections: The exploration of sub-channel scheduling schemes, specifically in the field of mmWave-enabled IAB for B5G cellular IoT networks, provides an insight into the balance of maximizing network capacity while mitigating interference. This subsection presents the importance of innovative resource allocation strategies, emphasizing the novel two-step approach that incorporates both user equipment association and transmit power allocation problems.

The synthesis of these concepts highlights a critical evolution in addressing the challenges of the B5G networks, such as different backhaul capacities and the complexities of mmWave technology. The many-to-many matching model, with its dual consideration of interference and backhaul capacity, reflects an understanding of the multi-faceted nature of network optimization. Similarly, the transformation of a non-convex problem into a convex problem for transmit power allocation demonstrates an optimized approach to problem-solving in network management. This synthesis also highlights the achievements in sub-channel scheduling and acts as a catalyst for future innovation. This demonstrates how network management strategies in B5G technology are always changing and adapting, pushing the limits of what is possible in cellular IoT networks.

TABLE 4. **Recent research contributions, challenges and future insights in B5G UAV-assisted wireless networks.**

Article	Contributions	Interference Mitigation Techniques	Challenges	Future Insights
[51]	Proposed an ML-based approach for D2D communications in 5G and B5G networks.	Reinforcement learning (RL), Deep RL-based resource allocation	The proposed approach may face limited resources and high computational complexity challenges.	The proposed approach can improve network performance and enable efficient resource utilization. Future work could focus on optimizing the approach for practical implementation.
[54]	Proposed a NOMA approach for mmWave communications in B5G networks.	NOMA technique	The proposed approach may face interference management and PA challenges.	NOMA-based approaches can potentially increase network capacity and improve spectral efficiency in B5G networks. Future work could optimize the approach for practical implementation and address interference management challenges.
[99]	Proposed a backhaul-capacity-aware interference mitigation framework for cellular IoT networks in B5G.	Beamforming, IC	The proposed framework may face challenges related to the heterogeneity of IoT devices and limited resources.	The proposed framework can improve network capacity and enable efficient resource utilization in B5G cellular IoT networks. Future work could optimize the framework for practical implementation and address challenges related to devising heterogeneity.
[47]	Proposed a hybrid beamforming NOMA approach for mmWave half-duplex UAV relay-assisted B5G IoT networks.	Hybrid beamforming, NOMA	The proposed approach may face interference management and PA challenges.	Hybrid beamforming NOMA-based approaches can potentially increase network capacity and improve spectral efficiency in mmWave half-duplex UAV relay-assisted B5G IoT networks. Future work could optimize the approach for practical implementation and address interference management challenges.
[98]	Proposed a cell-free satellite-UAV network for wide-area IoT in B5G.	Beamforming scheme for Cell-free communication, satellite-UAV communication	The proposed network may face challenges related to limited resources and the integration of heterogeneous technologies.	Cell-free satellite-UAV networks have the potential to provide wide-area coverage and enable new applications and use cases in B5G networks. Future work could focus on optimizing the network for practical implementation and addressing challenges related to limited resources and the integration of heterogeneous technologies.
[48]	RIS optimization on the complex circle manifold for interference mitigation in interference channels.	IRSs	High hardware cost, limited range.	Integration of AI and ML to enhance RIS performance.
[100]	Rate-splitting multiple access (RSMA): A new frontier for the PHY layer of B5G.	RSMA	High complexity, limited practical implementation.	Development of efficient algorithms for practical implementation.
[101]	Collaborative design of multi-UAV trajectory and resource scheduling for B5G-enabled IoT.	Dynamic transmit power control scheme	Limited battery life, high complexity of coordination.	Development of efficient algorithms for multi-UAV coordination.
[102]	IRS placement optimization in air-ground communication networks toward B5G.	IRS	Limited range, high hardware cost.	Integration of AI and ML to enhance IRS performance.
[103]	Energy-efficiency PA design for UAV-assisted spatial NOMA.	PA, NOMA	Limited battery life, interference management.	Development of efficient algorithms for interference management.

E. OTHER SCHEMES

The work in [54] analyzed and discussed the potential advantages and challenges of using mmWave communications with NOMA for B5G networks. They highlighted the potential benefits of using mmWave frequencies for high-speed wireless communication, such as the availability of considerable bandwidth and the ability to support high data rates. However, they also mentioned the challenges of using mmWave frequencies, such as high path loss and susceptibility to atmospheric absorption and blockage. Then, it discussed the potential advantages of NOMA techniques for improving spectral efficiency and user capacity in mmWave communication systems. NOMA allows multiple users to share the same resources, so it could increase the number of supported users and reduce the spectrum needed. Moreover, they explored the challenges of implementing NOMA in mmWave communication systems, such as PA and interference management.

Synthesis and Reflections: The potential future trends and directions in mmWave communications with NOMA for B5G networks are summarized as follows.

- One trend uses NOMA techniques to improve spectral efficiency and user capacity in mmWave communication systems. With the increasing number of connected IoT devices and the growing demand for wireless data and data rates, NOMA can provide more efficient use of the available spectrum and improve the number of supported users. More research is required to optimize NOMA techniques for mmWave communication systems and to address challenges such as PA and interference management.
- Another trend, this work highlighted the need for further research to integrate mmWave communications with other emerging technologies, such as AI and ML. These methods can improve the interference management techniques and efficiency of mmWave communication systems to enable new use cases.

Table 4 summarizes the recent research contributions, challenges, and future insights on interference mitigation in B5G UAV-assisted wireless networks.

F. INTERFERENCE MITIGATION USING NEW TECHNOLOGIES IN B5G

In this section, we discuss the IMTs for UAVs using B5G technologies such as IRSs, rate-splitting, super modular massive MIMO, Terahertz communications, holographic

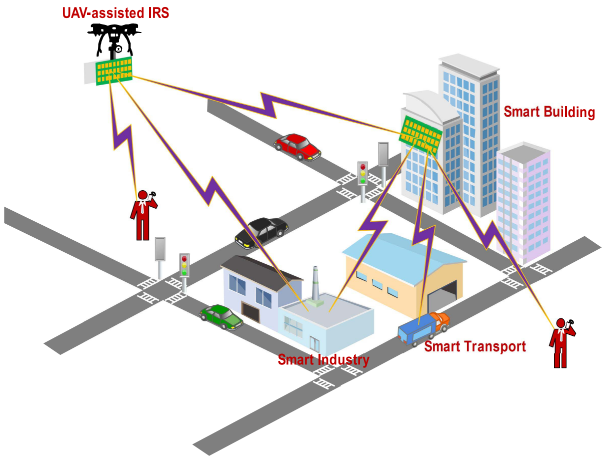

FIGURE 9. Illustration of IRS-assisted UAVs deployment in a smart city environment for B5G networks. This figure showcases the integration of UAVs equipped with IRSs within urban regions. The visualization demonstrates how this novel approach supports and addresses the advanced connectivity needs of a B5G smart city infrastructure.

beamforming, blockchain-based spectrum sharing, and AI and ML schemes.

1) INTELLIGENT REFLECTING SURFACES AND INTERFERENCE MITIGATION

Another possible approach that can be classified under dynamic antenna pattern adjustment is using IRSs [104]. IRSs are a promising technology for enhancing wireless communication systems and their potential utilization in B5G networks. IRS consists of multiple passive reflecting elements that can control the phase and amplitude of incident signals, enabling efficient beamforming and signal focusing. The IRSs can be used to tune their passive beamforming to suppress interference from the BSs in the downlink and suppress interference from the UAV in the UL, thereby facilitating IC at each co-channel BS. This can improve the system's overall performance [105], [106], [107].

IRS can play a crucial role in interference mitigation in B6G networks. By deploying IRS, it becomes possible to dynamically control the propagation of wireless signals and mitigate interference caused by multipath propagation, CCI, and ACI. The reflective nature of IRS allows it to selectively enhance desired signals while attenuating unwanted interference, thereby improving the overall system capacity and spectral efficiency. Moreover, IRS can be intelligently programmed to adapt to varying network conditions, optimizing signal quality and minimizing interference in real-time. For example, the IRS presents an effective solution for interference management in future B5G networks, enabling robust and reliable wireless communication in complex and dense environments [108].

Integrating UAVs with IRSs offers a novel paradigm for B5G networks. Figure 9 illustrates the deployment of IRS-assisted UAVs within a smart city in the context of B5G. As an adaptable and mobile platform, UAVs can deploy IRSs dynamically, creating a flexible and reconfigurable radio environment. This technology allows fine-tuned control over signal propagation, effectively enhancing connectivity, especially in challenging terrains or dense urban settings. UAV-deployed IRSs can assist in steering the reflected signals toward desired users while mitigating interference at undesired locations [109].

The authors in [110] propose a hybrid IC scheme that maximizes the UAV's and ground users' weighted sum rate in the UL to achieve the optimal trade-off between UAV-ground performance. This is done by jointly optimizing the set of BSs applying linear/nonlinear IC and the UAV's transmit power. The simulation results demonstrate the proposed scheme's effectiveness in improving the system's performance compared to other benchmark schemes. The results also provide essential design insights for IRS-aided UAV communication in cellular networks.

2) RATE-SPLITTING AND INTERFERENCE MITIGATION

As the demand for high-speed and reliable wireless communication continues to grow, developing B5G networks is on the horizon, where individual data streams are divided into common and private messages and sent over the same frequency. In this context, using UAVs associated with the rate-splitting technique holds great potential for addressing the challenges associated with interference mitigation in B5G networks. In a B5G network scenario with UAVs, rate splitting can minimize CCI and boost spectral efficiency, critical attributes for ensuring reliable and high-speed connectivity [111], [112].

Incorporating super-modular massive MIMO (m-MIMO) systems into B5G communication networks is a promising technique for addressing the increasing demand for high data rates, reduced latency, and enhanced QoS. With their unique mobility and LoS communication link capabilities, UAVs can be crucial to these advanced wireless networks. Utilizing m-MIMO with UAVs can increase communication performance by providing spatial multiplexing and beamforming, thus enhancing the overall network capacity and reliability. However, interference mitigation is one significant challenge with m-MIMO-assisted UAV networks in B5G scenarios. Considering the broadcast nature of wireless communications, a massive number of antennas in m-MIMO systems may lead to severe user interference, thus degrading the network performance. Recent studies have proposed various approaches to tackle this issue. Advanced signal processing techniques, like interference alignment and cancellation, have been utilized to manage interference in m-MIMO-assisted UAV networks [113]. Moreover, leveraging the IRSs that adaptively adjust the signal propagation environment is another attractive solution for interference mitigation in m-MIMO-assisted UAV communication networks [114]. Future research can focus on developing novel interference management strategies suitable for such environments, potentially incorporating advanced beamforming and predictive AI and ML-based techniques.

3) TERAHERTZ COMMUNICATIONS AND INTERFERENCE MITIGATION

Terahertz (THz) communications with UAVs can be a significant game-changer for interference mitigation in B5G networks. The bandwidth available in the THz frequency band, ranging from 0.1 to 10 THz, supports ultra-high-speed data transmissions. One of the crucial characteristics of THz communications is its high directionality, which helps reduce interference substantially [115]. Unlike lower frequencies, THz signals are much more focused and can be directed precisely to the intended recipient (UAV in this case), thus reducing the chance of signal overlap and subsequent interference with signals from or to other UAVs in the Multi-UAVs network [116].

4) HOLOGRAPHIC BEAMFORMING AND INTERFERENCE MITIGATION

Holographic beamforming (HBF) is a promising technique for improving the performance of UAV-based communication systems in B5G networks. It can be used to create multiple beams that focus on different users or areas, which can help to improve the SNR and reduce interference. HBF utilizes an array of antennas to form and direct the radiation pattern of radio signals toward specific receivers or areas. This can improve the signal quality at the intended receivers and decrease the interference to unintended ones. Some techniques can be used to mitigate interference in HBF systems. One approach is to utilize coordinated beamforming, where the UAVs coordinate their beamforming patterns to minimize interference. Another approach is to use adaptive beamforming, where the UAVs adjust their beamforming patterns in real-time to track users' movement and minimize interference [115], [117].

Therefore, combining HBF and UAVs offers a novel solution for interference management in B5G networks. The dynamic mobility of UAVs and the adaptive nature of HBF could potentially open new dimensions for next-generation UAV communication systems.

5) BLOCKCHAIN-BASED SPECTRUM SHARING AND INTERFERENCE MITIGATION

Blockchain-based spectrum sharing is a promising technique for interference mitigation in B5G networks. It can allocate spectrum resources to UAVs to minimize interference between UAVs and other spectrum users. In a blockchain-based spectrum-sharing system, each UAV has a unique identity and a blockchain ledger that tracks the spectrum resources that it has been allocated. When a UAV wants to transmit, it broadcasts a message to the blockchain ledger. The message includes the UAV's identity, the used spectrum resources, and the transmission duration. The blockchain ledger then checks if the spectrum resources are available, granting the UAV permission to transmit. The ledger rejects the UAV's request if the spectrum resources are unavailable. Blockchain-based spectrum sharing mitigates interference by ensuring that UAVs do not transmit on the same frequencies simultaneously. The blockchain ledger tracks the spectrum resources allocated to each UAV. If two UAVs try to transmit on the same frequency simultaneously, the blockchain ledger will reject one of the requests [118], [119].

6) ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING TECHNIQUES

The authors in [99] proposed a backhaul-capacity-aware interference mitigation framework for the B5G cellular IoT networks. The framework was designed to reduce interference and improve the network's performance, considering the capacity of the network's backhaul links. They identified the key challenges in designing IMTs for cellular IoT networks, including the massive number of connected devices and the limited bandwidth capacity of the backhaul links. They proposed a framework that utilized the backhaul capacity to optimize interference mitigation techniques. The proposed framework included three components:

- A backhaul-capacity-aware interference identification module.
- A dynamic interference mitigation module.
- A resource allocation module.

The interference identification module used deep learning algorithms to identify interference sources in the network. In contrast, the dynamic interference mitigation module adjusted the IMTs based on the network's traffic load. The resource allocation module optimized the allocation of network resources to improve the network's performance further. They evaluated the performance of the proposed framework using simulation and compared it to existing IMTs. The results showed that the backhaul-capacity-aware interference mitigation framework could significantly improve the network's performance, especially for high-traffic network load conditions.

The potential future trends and directions in the design of interference mitigation strategies using AI and ML techniques for B5G cellular IoT networks are:

- One trend was to consider the capacity of backhaul links in designing IMTs. With the growing number of connected IoT devices and the increasing data traffic in IoT networks, the capacity of backhaul links has become a critical factor in the network's performance. Future research may focus on developing more advanced interference mitigation strategies considering the dynamic changes in backhaul capacity and traffic load.
- Another trend was the use of deep learning algorithms for interference identification and mitigation in B5G cellular IoT networks. Deep learning algorithms could provide a more efficient interference identification and mitigation method in large-scale IoT networks.

Synthesis and Reflections: The insights from the research studies discussed in the interference mitigation using B5G wireless technologies section highlight the development of interference mitigation strategies for B5G networks. The

TABLE 5. Recent research contributions, challenges, and future insights in B5G UAV-assisted wireless networks.

Technology/Article	Contributions	Interference Mitigation Techniques	Challenges	Future Insights
IRS [108], [110]	Enhancing wireless communication systems; facilitating IC	Dynamic antenna pattern adjustment; passive beamforming	Managing multipath propagation, CCI, and ACI	Dynamically controlling wireless signal propagation; adapting to network conditions
Rate-Splitting [111]	Addressing high-speed and reliable communication needs	Dividing data streams into common and private messages	Minimizing CCI; boosting spectral efficiency	Implementing in UAV scenarios for B5G networks
m-MIMO [114]	Enhancing data rates, latency, and QoS in B5G networks	Spatial multiplexing and beamforming	Severe user interference due to a large number of antennas	Developing novel interference management strategies
THz Communications [115]	Supporting ultra-high-speed data transmissions	High directionality of signals	Focused signal propagation; reducing signal overlap	Managing interference in Multi-UAVs networks
HBF [117]	Creating multiple focused beams for different users/areas	Array of antennas for directed radiation patterns	Improving SNR and reducing interference	Coordinated and adaptive beamforming strategies
Blockchain-based Spectrum Sharing [118]	Allocating spectrum resources to UAVs	Blockchain ledger for managing spectrum allocation	Preventing simultaneous frequency transmission by UAVs	Ensuring efficient spectrum usage and reducing interference
AI and ML [99]	Backhaul-capacity-aware interference mitigation	Deep learning for interference identification	Massive connected devices; limited bandwidth of backhaul links	Incorporating advanced beamforming; predictive AI and ML techniques

integration of technologies like IRSs, rate-splitting, massive MIMO, THz communications, holographic beamforming, blockchain-based spectrum sharing, and AI and ML algorithms shows the efforts toward addressing the complex challenges of interference in dense, high-demand network environments. These studies also highlight an important transition from traditional methods to more adaptive, dynamic, and intelligent approaches. The use of IRSs in enhancing signal quality and UAV-deployed IRSs in urban environments describes a move towards more flexible and reconfigurable network infrastructures. Similarly, the utilization of rate-splitting, massive MIMO, and THz communications indicates a focus on maximizing spectral efficiency and reducing interference through advanced technological approaches.

Table 5 summarizes the recent research contributions, challenges, and future insights on interference mitigation in B5G UAV-assisted wireless networks.

On the other hand, Figure 10 summarizes the B5G wireless technologies employed for IMTs in UAV-assisted wireless networks.

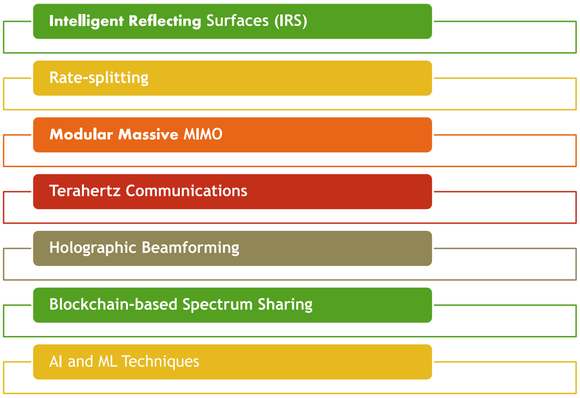

FIGURE 10. B5G wireless technologies for IMTs in UAV-assisted wireless networks. This figure provides a summary of the cutting-edge B5G wireless technologies for mitigating interference in UAV-based communication systems.

VII. LESSONS LEARNED, CHALLENGES, AND OPEN RESEARCH DIRECTIONS

In this section, we present the lessons learned from this systematic review and discuss the challenges and their open research directions.

A. LESSONS LEARNED

In previous sections, we have discussed the IMTs in the current and future UAV-assisted wireless networks. In this subsection, we present the lessons learned from these IMTs. The lessons learned are listed as follows:

- *Adaptive modulation and coding schemes:* To balance the efficiency and quality of wireless transmission, adaptive modulation and coding technology can promptly modify the modulation and channel coding rate of UAV wireless link transmission in response to changes in the communication environment. Under the condition that the system block error rate is less than a predetermined value, the traditional adaptive modulation and coding technology creates a modulation and coding scheme look-up table using feedback SNR information and then chooses the appropriate modulation and coding scheme for the subsequent transmission based on the corresponding look-up table of the current CSI in the actual communication system. It is not a simple linear correspondence between system performance and channel quality. ML can be used to improve the accuracy and effectiveness of adaptive modulation and coding as we move into the AI era. Utilizing AI algorithms can enhance the mapping operation of channel quality indication and modulation and coding schemes to increase the mapping accuracy of the current channel state and channel quality indication, resulting in a higher spectrum efficiency and lower block error rate. The signaling overhead of adaptive modulation and coding technology can be reduced by ML and AI, which have the potential to automatically recognize various modulation signals without the need for signaling assistance.
- *Dynamic antenna pattern adjustment:* Massive antenna arrays for wireless communications have recently been effectively realized using dynamic metasurface

antennas. Streamlined transceiver hardware enables flexible and dynamically configurable analog signal processing and beam tailoring capabilities in the transmitted and received domains. Furthermore, compared to conventional antenna arrays, dynamic metasurface antenna-based architectures consume significantly less cost and power, negating the need for active phase shifters and/or complex corporate feed. For a wide range of operating frequencies, dynamic metasurface antennas may comprise many tunable metamaterial antenna elements that can be designed in small physical dimensions. Because of this feature, they are a desirable technology for the extremely massive MIMO transceivers used in UAV-assisted wireless networks.

- *Dynamic transmit power control:* One of the most essential aspects in the design of UAV-assisted wireless networks is energy consumption. One of the main reasons for the ongoing research into methods to conserve energy for future wireless networks, in addition to the environmental concern, is the need for UAVs to have long battery life. Although energy conservation can be carried out at various system layers, the MAC layer is thought to be the most effective because it directly controls radio, which uses the most power. As a result, the efficiency of adaptive power-saving mechanisms can be increased using ML techniques to predict traffic and separate the data based on priority. Additionally, UAV-assisted wireless networks use retransmissions or transmit power control to boost system performance in high-interference conditions. Such a strategy hurts the system's EE performance. The entire system's improved energy and spectrum efficiency may be achieved by predicting the transmit power based on actual network conditions. For power control challenges, RL techniques are appropriate in helping to face these challenges. It is possible to create models based on anticipated traffic patterns, contextual information for various cells, and the corresponding load metrics using ML-based algorithms to analyze the cell-level traces gathered in a UAV-assisted wireless network. These models can adapt their sleeping schedules and transmit power in response to the behavior of users causing interference in a UAV-assisted wireless network. These models can also be used to dynamically turn on and off aerial BSs to save energy at higher altitudes.
- *Sub-channel scheduling:* Many recent novel techniques, such as mmWave, IRS, and carrier aggregation, have been proposed in recent years. These techniques may create new heterogeneous UAV-assisted wireless networks that exacerbate the complexity of the sub-channel scheduling problems. UDN development will unavoidably become a trend in the next generation of UAV-assisted wireless networks, making the practical solution to this problem a combination of these new techniques and heterogeneous UAV-assisted wireless networks. For instance, an IRS-assisted UAV wireless network can provide a lower power consumption and higher capacity. The IRS's coupled phase shift and transmit power make solving the sub-channel scheduling problem difficult. An open research direction is how to create low-complexity, high-flexibility network models that can be used to enhance heterogeneous UAV-assisted wireless network performance.

B. CHALLENGES AND OPEN RESEARCH DIRECTIONS

In this subsection, we highlight the emerging challenges to be handled and give directions to overcome them. These challenges and their open research directions are listed as follows:

- *Wireless RF Spectrum Scarcity:* Several new challenges such as mutual interference and radio frequency spectrum scarcity are faced by UAV-assisted wireless networks. The performance of terrestrial wireless networks could be significantly impacted by UAVs, as this could limit system capacity and lower user QoS. Intelligent dynamic spectrum access (IDSA) dynamically allocates radio spectrum resources based on current demand and network conditions. By combining AI and ML techniques, IDSA enables UAV-assisted wireless networks to adapt to changing traffic patterns and to allocate spectrum resources flexibly. IDSA ensures that each service's specific requirements are met through more efficient spectrum resource allocation, providing efficient and reliable wireless services for a wide range of applications in UAV-assisted wireless networks. IDSA brings several benefits to UAV-assisted wireless networks. First, it handles the dynamic and diverse spectrum needs in UAV-assisted wireless networks by allocating prioritized and dedicated spectrum resources to mission-critical applications. Second, IDSA enables the coexistence of several wireless technologies in the UAV-assisted wireless networks, encouraging various wireless standards to communicate effectively and without interference. Finally, IDSA makes UAV-assisted wireless networks more efficient and maximizes spectrum utilization by giving devices the ability to access unused spectrum bands thereby maximizing network capacity [120], [121], [122], [123].
- *Lacking of Networking Scalability:* ICI is one of the conventional challenges faced by UAV-assisted wireless networks thereby preventing the scalability of these networks. Cell-free massive MIMO system is mainly developed to address the ICI challenge in traditional wireless networks where all access points are required to serve all UEs simultaneously [124]. However, as the size of the UAV-assisted wireless network grows, this becomes impractical as the signal strength of remote access points will be significantly attenuated after reaching the UE, making the provision of wireless services inefficient. Furthermore, the computational complexity of each access point's network functions and

the bandwidth needed for signal transmission become greater linearly as the number of UEs grows.

One possible approach to overcome the aforementioned challenges is to utilize a user-centric scheme by clustering access points. In this scheme, a set of access points is selected by UE to provide an efficient wireless service. These subsets of access points are different for each UE, so each access point must cooperate with different access points when serving different UEs. Moreover, in mobility scenarios, the UE needs to frequently update the serving cluster, which makes it difficult for the access points to implement resource allocation and synchronize the network state. Dynamic clustering is now an established user-centric collaboration scheme in which a subset of access points can be modified to consider time-variant parameters such as interference conditions, service requirements, and UE locations. Additionally, many algorithms enable UAV-assisted wireless networks to perform scalability depending on dynamic clustering architectures such as scalable downlink precoding, scalable uplink combining, scalable pilot assignment, scalable joint initial access, and scalable power control [125].

However, each UE is covered by fewer access points, which saves bandwidth and computational complexity, but at the cost of system performance. Therefore, it is extremely challenging to develop an advanced access point selection technique that selects the optimal subset of access points for each UE while ignoring the performance loss.

- *Beam Distortion:* Typically, simple point-to-point links in unlicensed frequency bands are used to establish communication between UEs and UAVs, leading to performance limitations. While utilizing UAVs in future UAV-assisted wireless networks, a UAV needs to create a beam to serve the intended UEs and prevent interference. However, because of beam distortion caused by the UAVs' hovering and mobility, the served coverage area may frequently change creating interference to the neighboring cells [126]. This limitation was the motivation for many researchers to utilize dynamic beamforming by improving the 3D placements of UAVs [127], [128]. In distributed beamforming, many transmitters coordinate their signal transmissions to optimize reception at different locations [129]. This approach optimizes the entire communication system including coordinating distributed and effective signaling, expanding coverage, and ensuring effective data transmission to various receiving devices [130], [131]. In conventional beamforming techniques, a steering vector is created in the form of a beamforming vector, which helps direct a narrow beam to a specific UE. However, this requires an accurate CSI between the UE and the UAVs to make data transmission efficient, which is extremely challenging. Due to significant losses caused by UAV hovering and channel fading, the receiver may not be able to detect the pilot signals, which are typically transmitted without sufficient beam gains. Additionally, given the size and power limitations of a UAV, existing beamforming techniques may not be effective for UAV-assisted wireless networks. Quantum computing and information is a revolutionary technology that can support emerging technologies such as blind computing, advanced quantum sensing techniques, and secure communications [132], [133]. By dynamically managing the beam distortion in UAV-assisted wireless networks, directional communication with appropriate beam gains may be created by the utilization of quantum computation [134].
- *Resource-Constrained Management:* One key requirement for B5G communication networks is providing full wireless coverage, which will be extended with the use of UAV-assisted wireless networks [135]. These wireless networks can extend ubiquitous access services and provide full coverage. However, lacking computing power in these networks poses challenges in delivering computing services in rural and remote areas without communications infrastructure [136]. One of the main challenges is minimizing interference by managing resources efficiently to provide intelligent and pervasive services to UEs with limited resources. Conventional computing paradigms using cloud computing result in significant delays due to long-distance transmissions, making it difficult to meet emerging real-time services. Moreover, centralized development and optimization of these complicated computing services result in high development costs and low optimization efficiency [137].

  Future service requests in the UAV-assisted wireless network will require massive computing and communication resources. Effective management of these resources will be an urgent challenge that needs to be addressed. The main purpose of utilizing mobile edge computing (MEC) is the deployment of MEC servers close to resource-constrained UEs to directly provide services, thereby enabling the transfer of large amounts of processed data from the network core to the network edge. By integrating AI algorithms into edge devices with constrained processing capacity, edge intelligence created by fusing AI and MEC can handle edge data more intelligently than conventional MEC. By deploying edge intelligence servers in UAV-assisted wireless networks, the storage, sensing, computing, and communication capabilities will be improved thereby utilizing resources efficiently to deliver computing services to resource-constrained UEs and mitigate interference [138].
- *New Sources of the Interference:* The advent of AI and backscatter communications is propelling the IoT towards tremendous progress. Through the modulation of ambient RF carriers, passive backscatter devices engage in cost-effective and energy-saving

communication techniques. The use of backscatter communications in UAV-assisted wireless networks is becoming increasingly important, especially in the fields of disaster relief, environmental monitoring, and remote sensing [139], [140]. Backscatter communications allow UAVs to communicate with ground UEs without the power consumption of a battery, making these vehicles more energy-efficient. Managing interference in backscatter communication systems is challenging. Lack of scheduling and information for signal transmission causes interference and thereby reduces the quality of the received signals [141], [142], [143].

The integration of AI with backscatter communications in UAV-assisted wireless networks can improve network decision-making, efficiency, and performance. AI algorithms can also assist in handling technical challenges such as network optimization, interference management, and signal detection. This improves the reliability and performance of backscatter communication systems and enables reliable, low-power communication for the devices and applications in UAV-assisted wireless networks. AI-based backscatter communication systems, by utilizing frequency-domain resource allocation and adaptive modulation and coding, can provide effective techniques for meeting spectral efficiency requirements in B5G networks [144]. Future research may focus on the use of AI algorithms for interference management, link scheduling, and optimizing network topology.

VIII. CONCLUSION

In this systematic review, the IMTs in the current and future UAV-assisted wireless networks have been comprehensively reviewed. These IMTs have been classified into four fundamental techniques: adaptive modulation and coding schemes, dynamic antenna pattern adjustment, dynamic transmit power control, and sub-channel scheduling. Then, IMTs for UAVs using B5G wireless technologies, such as IRSs, rate-splitting, super modular massive MIMO, Terahertz communications, holographic beamforming, blockchain-based spectrum sharing, and AI and ML schemes, have been discussed. Moreover, the lessons learned present valuable insights our systematic review has shown, offering a helpful perspective for researchers in the UAV IMTs field. Finally, the challenges and their open research directions of UAV IMTs have been identified, including wireless radio frequency spectrum scarcity, lack of networking scalability, beam distortion, resource-constrained management, and new sources of interference.

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